OCEAN, WEATHER AND CLIMATE: SCIENCE TO THE SERVICE OF SOCIETY

PROCEEDINGS OF THE NANSEN-TUTU CENTRE 10-YEAR ANNIVERSARY SYMPOSIUM

10-12 March 2020, Cape Town, South Africa
Foreword

The celebration of the Nansen-Tutu Centre 10-years anniversary brought together around 90 researchers, postdoctoral fellows, PhD, and MSc students for a 3-days symposium at the University of Cape Town Graduate School of Business located at the Waterfront, Cape Town, South Africa from 10-12 March 2020. Attendants came from Cameroon, Mauritius, Togo, Benin, Namibia, Mozambique, Madagascar, Tanzania, Kenya, Nigeria, Democratic republic of Congo South Africa, Ethiopia, France, Italy, Germany, Norway, Netherlands, United Kingdom and USA.

The anniversary symposium (https://www.nansentutusymposium.com/) focused on “Ocean, Weather and Climate: Science to the Service of Society” and offered a very nice program with a mixture of invited keynote talks, thematic presentations, and panel discussions. In addition, time was set aside for dedicated poster sessions. The level of the presentations was very impressive and early career scientists from the African continent demonstrated high scientific quality of their work in a multitude of ocean, atmosphere, and climate related disciplines with significant importance to societies in southern Africa.

The event also marked the signatory ceremony for the launch of the 4th 3-year phase of the Nansen-Tutu Centre Joint Venture Agreement from 2020 to 2022. A take-home message for the continuation into the 4th phase recommended that the Nansen-Tutu Centre should play a coordinating role to initiate a training workshop for early career scientists targeting the UN Decade of Ocean Science for the sustainable development goals and to help to the development of Operational Oceanography in Southern Africa.

University of Cape Town, the Nansen Centre, Nansen Scientific Society, University of Bergen, Institute of Marine Research, and the Research Council of Norway are acknowledged for their financial support which allowed us to waive the conference fee for all students and postdoctoral fellows. In addition, the attendance of three African students were fully sponsored. The registration fee for the senior scientists was, moreover, substantially lowered thanks to the financial support. The Symposium was also endorsed by CLIVAR.


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# Table of Contents

## Invited and Keynote Presentations

1. **Scientific highlights and achievements of the Nansen Tutu Centre**  
   Rouault, M; Backeberg, B; Johannessen, JA

6. **The United Nations decade of ocean science for sustainable development**  
   Haugan, PM

11. **Ocean circulation and climate**  
    Speich, S; Visbeck, M

17. **The annual cycle of turbulent latent heat flux in the Agulhas current system**  
    Imbol Nkwinkwa, AS; Rouault, M; Johannessen, JA

20. **Ocean currents shaping the fate of coastal upwelling system south of Madagascar**  
    Ramanantsoa, JD; Rouault, M

23. **The Benguela: a short review of what we think we know and what we need to fill the gaps**  
    Veitch, JA

27. **Plankton variability around Southern Africa**  
    Lamont, T; Barlow, RG; Verheye, HM

30. **Benguela Niños**  
    Imbol Koungue, RA; Lübbecke, JF

33. **Length-scales of mesoscale variability and eddies in the tropical South-East Atlantic Ocean based on satellite Altimetry observations**  
    Halo, I; Raj, RP; Korosov, A; Rouault, M; Johannessen, JA; Penven, P

## Ocean, Weather and Climate: Science to the Service of Society

Session 1

37. **Using satellite-based visualization tool to study the dynamics of the Agulhas Current: The early retroflection**  
    Johannessen, JA; Lamont, T; Russo, C; Raj, RP; Collard, F; Chapron, B

42. **Biogeochemical operational modeling in the Arctic using the TOPAZ forecasting system**  
    Samuelsen, A; Yumruktepe, C; Wakamatsu, T; Daewel, U; Bertino, L

45. **SAWS Marine forecast and information services: current capabilities and planned efforts**  
    de Vos, M; Daniels, T; Ramjukadh, C; Lyttle, C; Barnes, M; Rautenbach, C

48. **Towards operational oil spill trajectory forecasting in Algoa Bay, South Africa**  
    Fearon, G; Veitch, J

52. **Preliminary assessment of the potential for particle trajectory modelling to support ocean search and rescue operations**  
    Hart-Davis, MG; Backeberg, BC

57. **Scaling observation error for optimal assimilation of CCI SST data into a regional HYCOM EnOI system**  
    Luyt, H; Counillon, F; Backeberg, BC; Akella, S; Veitch, J

61. **Analysing modelled nearshore wave climate variability and change as relevant to the South Coast small-scale handline fishers of South Africa**  
    Lyttle, C; Rautenbach, C; Backeberg, B; Jarre, A
Regional Oceanography
Session 2

65 Mean barotropic vorticity balance in the South Western Indian Ocean
Penven, P; Tedesco, P; Gula, J; Ménesguen, C

69 The response of mesoscale variability in the northern Agulhas Current and its sources to changing the wind forcing in a forced ocean simulation
Braby, L; Backeberg, BC; Krug, M; Reason, CJC

73 Numerical modelling of wave-current interaction in the Agulhas Current towards better sea-state estimation
Gweba, B; Krug, M; Penven, P; Collard, F

76 Impact of the Agulhas Current mesoscale variability on surface dispersion in the KwaZulu-Natal Bight
Heye, S; Krug, M; Veitch, J; Rouault, M; Hart-Davis, M

80 The variability of retention in St Helena Bay
Manyakanyaka, A; Veitch, J; Rouault, M

82 Marine heat waves in the Mozambique Channel
Mawren, D; Hermes, J; Reason, CJC

85 Modelling the Agulhas Ocean Current with Delft3D FM, with a focus on the related shallow water hydrodynamics within the Durban Bight, South Africa
Naidoo, K; de Graaff, R; Irazoqui Apeceche, M

88 Atmospheric and climatic drivers of tide gauge sea level variability along the east and south coasts of South Africa
Nhantumbo, BJ; Backeberg, BC; Nilsen, JEØ; Reason, CJC; Shillington, FA

91 Understanding variability across the Crossroad Transect from 3 years of hydrographic data
Sejeng, MC; Ansorge, IJ; Lamont, T

Marine Ecosystem
Session 3

94 Acoustic Detection of the short pulse call of Bryde’s Whales based on time domain features and hidden markov model
Babalola, OP; Ngateu, GVW; Versfeld, DJJ

100 Identifying suitable satellite Sea Surface Temperature (SST) products for monitoring the Southern African marine region
Carr, M; Lamont, T

103 The localization of Bryde’s whales based in time of arrival principles
Cormick, J

105 Contribution of local communities organization in sea turtle and marine mammals in Zanzibar
Mirobo, F; Hamed, SS; Jiddawi, NS

109 Hidden Markov Model (HMM) with eigenspace decomposition-based feature extraction algorithm for the detection and classification of cetacean species
Usman, AM; Versfeld, DJJ
Climate Variability, Meteorology and Ocean-Atmosphere Interactions

Session 4

112 Link between the Mozambique Channel Trough and Southern African rainfall
Barimalala, R; Desbiolles, F; Blamey, R; Reason, CJC

116 Large rainfall events during the extended summer (ONDJFM) over the winter rainfall region of the South Western Cape: A case study of the past Day Zero drought
De Kock, W; Blamey, RC; Reason, CJC

119 What do control water vapor transports seasonality over Central Africa
Longandjo, GN; Rouault, M

122 Rainfall variability over Eastern Cape, South Africa
Mahlalela, PT; Blamey, RC; Reason, CJC

125 Mesoscale Convective Systems over the east coast of South Africa
Morake, DM; Blamey, RC; Reason, CJC

128 Impact of the Agulhas Current on storm development
O’Connor, J; Rouault, M

131 Atmospheric moisture source linked to extreme rainfall precipitation in the Limpopo River Basin, southern Africa
Rapolaki, RS; Blamey, RC; Hermes, JC; Reason, CJC

134 Strong gradients in dry spell frequencies over southern Africa and their core in the Limpopo River basin
Thoithi, W; Blamey, RC; Reason, CJC

Southern Ocean, Prince Edwards Islands and Antarctic

Session 5

137 SEAmester 5 years on – Where are they now?
Ansorge, I; Morris, T; Henry, T; Hermes, J

140 Comparison of sea ice detection methods in the Atlantic sector of the Southern Ocean
de Jager, W; Vichi, M; Melsheimer, C

144 Intriguing phytoplankton dynamics: An IOP and biogeochemical validation of the Equivalent Algal Populations (EAP) model; introducing a carbon component
Morrison, F; Bernard, S; Vichi, M; Robertson-Lain, L; Thomalla, S

147 Summer Observations of submesoscale instabilities in the ice-free Antarctic Seasonal Ice Zone
Giddy, I; Nicholson, S; Swart, S

149 Transition from ERA Interim to ERA5: the suitability of a polar cyclone tracking algorithm to higher spatio-temporal resolution reanalysis data
Pramlall, S; Vichi, M

153 On the response of phytoplankton to iron addition in the Weddell Sea and along the Dronning Maud Land ice edge during austral autumn
Singh, A; Ardrelan, M; Fietz, S; Fransson, A; Sanchez, N; Thomalla, SJ; Ryan-Keogh, TJ

156 Seasonal variation of surface hydrographic conditions around the Prince Edward Islands
Toolsee, T; Lamont, T; Rouault, M
Scientific highlights and achievements of the Nansen Tutu Centre: 2010 to 2019
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1 Introduction

In 2010, the University of Cape Town (UCT), the Nansen Environmental and Remote Sensing Center, the University of Bergen and the Institute of Marine Research in Bergen, Norway set up a joint venture for marine environmental research and training. The joint venture, located at Department of Oceanography, UCT, was named the Nansen-Tutu Centre for Marine Environmental Research in honour of two men – a Norwegian and a South African – who have demonstrated a passion for the natural environment and humanity. Dr Fridtjof Nansen was honoured as a Nobel Peace Laureate in 1922 for his humanitarian work in helping to resettle millions of people displaced by famine political boundaries after World War I. But he was also a noted sportsman, scientist, explorer, and philosopher, who led the successful drifting expedition in the Arctic Ocean from 1893 to 1896. He is widely regarded as one of Norway’s greatest sons. Similarly, Archbishop Desmond Mpilo Tutu, awarded the Nobel Peace in 1984 and a “rabble-rouser for peace”, is one of South Africa’s greatest sons. He campaigned peacefully against apartheid, chaired the Truth and Reconciliation Commission after South Africa’s first democratic elections in 1994 and has worked tirelessly for peace in the world since his “retirement” as Archbishop of Cape Town. The Nansen-Tutu Centre is greatly honoured by Archbishop Tutu in allowing his name to be associated with this partnership. Archbishop Desmond Mpilo Tutu was present at the inaugural signing ceremony. The Nansen-Tutu Centre for Marine Environmental Research focusses on studying the three oceans surrounding southern Africa and their impact on climate, weather and the marine ecosystem. Southern Africa is juxtaposed by the Indian, South Atlantic and Southern Oceans. The Angola Benguela upwelling system, the greater Agulhas Current system and the Mozambique Channel add to the regional ocean dynamic complexity, giving rise to unique marine and terrestrial ecosystems with high biodiversity, rich fisheries and superb natural resources that contribute not only to food production but also to South Africa’s vibrant tourism industry. The global and regional ocean also has a great influence on drought, floods and natural climate variability inland. It is therefore important, from an economic and ecological perspective, that one further develop local capacity and expertise towards understanding and predicting the state of the ocean surrounding Southern Africa. The Centre is hosted at UCT and in addition to receiving financial support from the three above mentioned Norwegian partners, several other national and international institutions contribute to the activities of the Nansen-Tutu Centre by making their staff available as associate researchers of the Centre and hosting and co-supervising students supported by the Centre. Institutions that collaborate with the Centre in this way become signatories of the joint venture agreement, which is renewed every three years. Moreover, the signatory partners of the joint venture agreement become members of the Centre’s Advisory Board which meets annually in Cape Town and guides the Centre’s strategic direction.

2 Research Priorities

The Centre’s research priorities are grouped into 4 themes:

1) Ocean modelling and prediction
2) Ocean-atmosphere, climate and regional impact
3) High resolution satellite remote sensing of the regional shelf seas
4) Regional sea level variability and global change

Since the Centre’s inauguration in May 2010, the Centre priority research activities (see Figure 1) have contributed significantly to generating new knowledge about the ocean circulation around Africa and the variability of African climate. This has, in particular, been accomplished through research collaboration combined with training and supervision of graduate students and postdoctoral research fellows.
There have been a total of 44 research exchanges from South Africa to Norway (red) from 2010 to 2019. One of the key mechanisms supporting successful intercontinental collaboration is the Nansen-Tutu Scholarship Programme, where graduate students, postdoctoral research fellows and young researchers are given opportunities to visit partner institutions for supervision and to undertake collaborative research. There have been a total of 44 research exchanges from South Africa to Norway and 26 exchanges from Norway to South Africa directly funded by the NTC (see Figure 4). The Centre also supported visits to and from partner institutions in other European countries, notably France, although they were not always directly funded by NTC.

In addition to the many research exchanges, the Centre also arranged and hosted three summer schools and three international conferences.

3 Funding

The Centre has two main sources of funding (Figure 5). As mentioned, it receives seed-funding from Norway, and in addition it applies for national and international research grants. During the first 3 years of the Centre, it relied almost exclusively on seed-funding from Norway to fund its activities, but from 2013 onwards, the Centre was extremely successful in attracting project money through open research proposals, allowing the Centre to grow, which is also reflected in the Centre’s output.

4 Highlight of publications

A total of 91 peer review papers have been published since the Centre’s inception in 2010 (Figure 6) till 2019. 23 papers were published with researchers from the Norwegian signatory partners, and 29 papers were published with researchers from the French signatory partners, while 6 papers were published in collaboration with Norwegian and French signatory partners. 33 papers were published where NTC researchers collaborated with researchers whose institutions are not signatory partners of the Centre. The extent to which the Centre has been able to facilitate collaborative research is reflected in these publication statistics, highlighting the value of the joint venture.
their interaction with the northern branch of the Agulhas Current. An overall reduction in eddy kinetic energy (EKE) over the domain was found and the representation of Agulhas Current velocities was improved. Vermeulen et al. (2019) used the Agulhas Current Transport Array measured transport of the Agulhas Current at 34°S for a period of 3 years and compared it with the HYCOM model. The HYCOM configuration in this study contained exaggerated levels of offshore variability in the form of frequently impinging baroclinic anticyclonic eddies. Holton et al. (2017) investigated the variability of Agulhas leakage in six ocean model simulations. When determined by a passive tracer method, 60% of the magnitude of Agulhas leakage is captured and more than 80% of its temporal fluctuations, suggesting that the method is appropriate for investigating the variability of Agulhas leakage. In all simulations but one, the major driver of variability is associated with mesoscale features passing through the section. Malan et al. (2018) used ocean models and satellite observations, to examine how meander events change the way in which the Agulhas Current interacts with the continental shelf of southeast Africa. They found that meanders influence the pathways by which water is upwelled from below the Agulhas Current up onto the shelf, thus influencing the supply of nutrients to the shelf ecosystem. Nchungu et al. (2020) analysed timescales of variability in the time series of an Agulhas Current transport proxy and absolute dynamic topography at the core position, at the ACT array and compared these to monthly mean sea level records. The results suggest that, on timescales ranging from a few months to decades, coastal sea-level is associated with the Agulhas Current through absolute dynamic topography variations in the Agulhas Current core. Krug et al. (2010) examined 2 years of surface current retrievals in the Agulhas Current region derived from Envisat Advanced Synthetic Aperture Radar (ASAR) and concluded that time-averaged maps of ASAR-derived surface current velocity seem able to accurately capture the position as well as the intensity of the Agulhas Current. The ability of the ASAR to pick up the smaller features of the circulation along the shelf break also shows that variability along the Agulhas Bank is of the same order of magnitude as that observed in the Agulhas retroreflection. Helfrich et al. (2014) using satellite altimetry observations from 1993 to 2009 show that the mesoscale variability of the Agulhas Current system, as well as in the Mozambique Channel and south of Madagascar, had intensified. This seems to result from an increased South Equatorial Current driven by enhanced trade winds over the tropical Indian Ocean. Overall, the intensified mesoscale variability of the Agulhas Current system is reflected in accelerated eddy propagation, in its source regions as well as the retroreflection area, where eddies detach and propagate into the South Atlantic Ocean. Halo et al. (2014a, 2014b) studied both eddy properties in the Mozambique Channel, based on satellite altimetry and two ocean circulation models as well as eddy variability in the southern extension of the East Madagascar Current. Hart-Davis et al. (2018) assessed the accuracy of the GlobCurrent geostrophic current and Ekman current

The following focus on the joint publication with South Africa and Norway. The Agulhas Current took centre stage in the collaboration between Norway and the Nansen Tutu Centre through modelling, air sea interaction and process studies using models, satellite remote sensing and data assimilation. Backeberg et al. (2014) developed a regional implementation of the Hybrid Coordinate Ocean Model (HYCOM) and assimilated along-track satellite altimetry sea level anomaly (SLA). While the assimilation of along-track SLA data introduced a small bias in sea surface temperatures, the representation of water mass properties and deep current velocities in the Agulhas system was improved. De Vos et al. (2018) looked at the impact of assimilating along-track SLA into HYCOM and compared it with an unassimilated simulation. Assimilation yields improvements in eddy rich regions. Notably, it was found that not assimilating significantly underestimates the number of eddies south of Madagascar, with only slight improvements introduced through assimilation. Braby et al. (2020) compared two simulation experiments in HYCOM based on two different wind forcing and used an eddy-tracking algorithm to quantify the local effect of the changed wind stress on the source region of eddies and

**Figure 5.** Chart of the annual funding received by the Centre, blue represents seed-funding from Norwegian partners, and red represents funding generated from research proposals from 2010 to 2019.

**Figure 6.** Chart of the annual number of peer-reviewed papers published by the Centre. Blue indicated the number of publication NTC research co-authored with partners not officially participating in the Centre’s activities, red represents the number of papers published together with collaborating Norwegian co-authors, orange the number of papers published with collaborating French co-authors and green indicates the number of papers published jointly with collaborating Norwegian and French co-authors.

NANSEN-TUTU 2021 | PAGE 3
product by coupling it to a synthetic particle tracking tool and comparing the virtual trajectories to those of surface drifting buoys drogued at 15 m in the greater Agulhas Current region. On average the GlobCurrent underestimates the velocity in the greater Agulhas Current by approximately 27% with the smallest error found in the Agulhas Current retroflection region. Deploying 10,000 virtual drifters in a 1° × 1° box within the southern Agulhas Current shows a convergence of trajectories towards the core of the current, while higher divergence is evident in the retroflection area. Air sea interaction above the Agulhas Current led also to several papers with application to meteorology, climatology and oceanography. Imbol Nkwinkwa et al. (2018) demonstrated that the Agulhas Current, because of its high turbulent latent heat flux (LHF), has an impact on rainfall of the eastern coast of South Africa and above it. They present evidence that the Agulhas Current influences the atmosphere, and the underlying mechanisms may be like those found for the Gulf Stream. Imbol Nkwinkwa et al (2019) used in-situ observation, climate reanalyses, and satellite remote sensing data to study the annual cycle of LHF in the Agulhas Current system. The study included a comprehensive comparison of several products to assess whether the datasets represent the intense exchange of moisture that occurs above the Agulhas Current along the pathway from northeast towards the retroflection region. The highest LHF of 250 W/m² is found in the retroflection area in winter. The lowest LHF (~100 W/m²) is off Port Elizabeth in summer. East of the Agulhas Current, specific humidity is the main driver of the amplitude of the annual cycle of LHF, while it is the wind speed in the retroflection area and both in between. Wind increase above the core of the Agulhas Current was investigated by Krug et al (2019). They found that the surface wind increase by about 20% above the current but that the current leads to overestimation of the effect at the inshore edge of the current. Rouault et al. (2018) used an Agulhas Current eddy as a natural laboratory to study near surface wind increase above SST gradients and found similar wind increase to that reported by Krug et al (2019), although no linear relationship between SST gradient and wind increase from the cold to the warm side was discovered. Koseki et al. (2018) found that the Agulhas Current and the Drakensberg had a role in the diurnal cycle of rainfall along the Coast of South Africa. At last, Dieppois et al. (2015) found two major 20-25- and 10-12-years cycles in Southern Africa rainfall both present in the winter and summer rainfall and linked to variability in the Pacific Ocean. The Indian Ocean has also featured well in the Norwegian South African collaboration. Vianello et al. (2017) used a cruise dataset and satellite remote sensing to characterise the ocean environment of the Mascarene Plateau and its influence on the equatorial current system. Shalin et al (2018) looked at improving the delineation of marine ecosystem zones in the northern Arabian Sea during winter. Salvanes et al (2015) found that he spatial dynamics of the bearded goby and its key fish predators off Northern Namibia and Southern Angola varies with climate and oxygen availability with a major impact of Benguela Niños and ocean warming of Northern Namibia. Turning to the Northeast Atlantic Ocean and Nordic Seas several papers were also written on mesoscale eddies in the Lofoten Basin and their interaction with the large scale Norwegian North Atlantic Current circulation in the Norwegian Sea (Raj et al., 2015, 2016a, 2016b, 2020) 

**References**

**Ocean modelling and prediction**


**Ocean-atmosphere, climate and regional impact**


High resolution satellite remote sensing of the regional shelf seas


Regional sea level variability and global change


Others


The United Nations decade of ocean science for sustainable development (2021-2030)
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The United Nations Decade of Ocean Science for Sustainable Development (hereafter the Ocean Decade) is starting on 1 January 2021. This decade is poised to boost capacity in ocean science and related activities in support of society with its vision to provide ‘the science we need for the ocean we want’. Fifty years after the International Decade of Ocean Exploration (IDOE), the new Ocean Decade is a once-in-a-lifetime opportunity for ocean scientists. By aligning research priorities with Sustainable Development Goals (SDGs), ocean scientists and ocean science managers can help the world get the ocean we need for the future we want. The Ocean Decade is not only about SDG 14 Life Below Water, but about the role of the ocean in the entire Agenda 2030 with its 17 SDGs. Through the decade ocean science has to move beyond diagnosing problems in the ocean to developing solutions for food, ocean-based renewable energy, sustainable ocean transport and management of all human activities from the coastal zone to areas beyond national jurisdiction. To provide more healthy food from the ocean, we need a clean and productive ocean. We need research on how to protect effectively, produce sustainably and prosper equitably. We need capacity building, sharing of ocean data and information and improving the science – policy interface. We are entering an important and exciting decade!

1. The Ocean Decade

The website https://oceandecade.org/ explains what the Ocean Decade is about and will continue to inform about its progress. Key elements from the official documents are referenced here.

The vision of the Ocean Decade is ‘the science we need for the ocean we want’ and the mission is ‘to catalyse transformative ocean science solutions for sustainable development, connecting people and our ocean’.

Seven outcomes describe the ‘ocean we want’ at the end of the Ocean Decade:

1. A clean ocean where sources of pollution are identified and reduced or removed.
2. A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed.
3. A productive ocean supporting sustainable food supply and a sustainable ocean economy.
4. A predicted ocean where society understands and can respond to changing ocean conditions.
5. A safe ocean where life and livelihoods are protected from ocean-related hazards.
6. An accessible ocean with open and equitable access to data, information and technology and innovation.
7. An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development.

The Ocean Decade will be implemented on a voluntary basis within the legal framework of the United Nations Convention on the Law of the Sea (UNCLOS). The Ocean Decade will facilitate the generation of data, information and knowledge needed to move from the ‘ocean we have’ to the ‘ocean we want’.

The Ocean Decade will not set ocean policy, but it will build scientific capacity and generate knowledge that will directly contribute to the goals of the 2030 Agenda for Sustainable Development and other relevant global legal and policy frameworks. The Ocean Decade will also support SDG17 – Partnerships for the goals, that seeks to strengthen global partnerships to achieve the ambitious targets of the 2030 Agenda.

The Decade Implementation Plan has been approved at the highest level the United Nations General Assembly. However, the plan is not prescriptive or binding at the UN Member State level in terms of activities. It is the explicit intention that programmes, projects, activities and contributions will grow and flourish at the local, national or regional scales according to specific contexts and priorities. Capacity development, including improved access to data and technology, increased ocean literacy, and the creation of an enabling environment that ensures broad inclusivity, including gender, generational and geographic diversity, will be essential elements at each stage of the process.

The ambition of the Ocean Decade is beyond the capacity of any single nation, any single stakeholder group, any single generation, or any single scientific discipline. The Ocean Decade will convene a wide range of stakeholders to collectively align their research, investments and initiatives around a set of common priorities, so that the result of their shared efforts is exponentially greater than the sum of the parts.
What will be the implications for ocean science practitioners? And what may the role of the ocean in a sustainable future actually become?

2. The planning process and related developments

In order to be able to discuss the two questions above in a meaningful way, it is necessary to briefly introduce some elements of the history of the Ocean Decade planning process, some recent scientific and technical developments which make it possible for the decade to be launched at this time with realistic promise of delivery, as well as some key political initiatives. The contextual information provided in the present section points the way towards the future prospects to be discussed in section 3.

The Ocean Decade planning process

In December 2015 The United Nations General Assembly (UNGA) approved Agenda 2030 with its 17 SDGs and 169 targets. This came after a long process with strong involvement of civil society and Non-Governmental Organizations (NGOs) in addition to the negotiating parties, the UN Member States. While the former Millennium Development Goals largely addressed problems in developing countries, the SDGs recognized that all countries have to change in order for the world to stay within planetary environmental boundaries while simultaneously securing a social and economic foundation for all citizens. The concept of sustainable development had been around for several decades, but the all-inclusive narrative of the SDGs was new and convincingly presented as a common agenda.

Like many other specialized agencies, the IOC was active in the deliberations leading to Agenda 2030. When the newly elected IOC officers (chair and 5 regional co-chairs) met with present and some past key staff (heads of sections) for a getaway in Gilleleje in Denmark in January 2016, there were two foci for the strategy discussions. One was an analysis of how to best communicate with and serve the main constituencies of the organization, ranging from ocean science practitioners and professional ocean science managers via national delegates at UNESCO level to non-specialist high level diplomats and the public at large. The other was how to respond to Agenda 2030 and serve its purpose while at the same time maintaining science support to existing key ocean related agendas notably for disaster risk reduction, climate, biological diversity and small island developing states.

The need for a decadal scale ocean science effort had been raised in internal IOC discussions during the last part of 2015, but it was at the January 2016 gathering that the idea was first discussed in depth. The meeting recommended that the IOC should initiate planning of an ocean science decade tentatively called the Second International Decade of (Integrated) Ocean Exploration, inspired by the former IDOE in the 1970s but this time with emphasis on serving sustainability. A roadmap and other documents began to be produced. By the time of the IOC Executive Council (EC) in June 2016 the developments were reported under a recurring agenda item on the Future of the IOC.

The vision “Towards the ocean we need for the future we want” was not written into the mentioned documents for the IOC EC in 2016, but it was conscientiously used in statements including the opening statement by the chair, discussions and consultations. It was well recognized that more than science is needed to reach the global ocean we need with its desired properties and providing the services that the world needs. It was also recognized and agreed that the IOC itself should stick to its mandate of scientific and technical support to policy making of its Member States rather than taking an active role in policy development. But the bold vision was deliberately kept broad in the hope that others could be inspired to join the efforts.

The fact that a separate ocean goal was included among the 17 SDGs was helpful for the global discussion of interlinkages and the role of the ocean for global sustainability. The 2017 UN Ocean Conference was framed as partnering for the implementation of SDG 14 which is about conservation and sustainable use of the oceans, seas and marine resources, but in reality the conference served to showcase the wider importance of the ocean also for other SDGs. At this stage consultations and elaboration of plans for the Ocean Decade had advanced considerably but at the Ocean Conference the status of the Ocean Decade was nothing more than a voluntary commitment from the IOC. It was only at the IOC Assembly a few weeks later that the Ocean Decade was formally anchored in a resolution of an IOC governing body. However, that resolution was approved by acclamation following a series of statements of support by several UN agencies and other bodies as well as the then president of the UNGA, later UN Secretary-General’s Special Envoy for the Ocean.

The proposal for an International (UN) Decade of Ocean Science for Sustainable Development was then submitted from the IOC to the UNGA which already in December 2017 proclaimed the Ocean Decade. The IOC was asked to coordinate the implementation of the decade and periodically report back to the UNGA. In 2018 a Decade Executive Planning Group was appointed. It produced a draft Decade Implementation Plan which elaborates the vision, mission and outcomes as well as more detailed goals and ways of operating and structuring the implementation. A series of global and regional planning meetings have been
held during 2019–2020. Organisations like the UN Global Compact have joined. National plans have been produced and an Ocean Decade Alliance has been set up with heads of state, leading philanthropists and others as patrons. Overseen by the UNGA and coordinated by the IOC, the Ocean Decade implementation has now been set in train.

Much more could have been said about the planning of the decade (Ryabinin et al., 2019). The present vision ‘the science we need for the ocean we want’ is more precise and to the point for a science activity than the former ‘the ocean we need for the future we want’. However, the broader reach of the earlier vision may have been useful in catching the attention of wider circles. In 2016–2017 the first goal of the initiators was to reach beyond the science community and achieve UN level consensus and support. Having achieved the UN status and maintaining the mission of providing transformative solutions, it is now important to move beyond the UN level to action including interoperability between science, society, industry and governance from local to global scales (Claudet et al., 2020).

**Scientific and technical possibilities**

But to what extent can ocean science and technology actually contribute to achieve a sustainable future? Much of ocean science has traditionally dealt with observations of a vastly under sampled domain. Mostly near surface observations primarily of physical variables have in recent decades provided a basis for assessments as well as predictions ranging from climate to storm surges and tsunamis. But in the deep sea, the biology is largely unknown and even chemical and physical features are poorly described. And only during the last few years has it been possible within the Global Ocean Observing System to move towards global standards for observations of biogeochemistry, biology and ecosystems. The 136 OceanObs 2019 conference papers (https://www.frontiersin.org/research-topics/8224) provide a recent overview of the state of art. Sensors, platforms and data analysis systems need a significant upgrade if we are to deliver even a fair description of the state of the ocean and its resources, so necessary for intelligent human interactions with the ocean. Still, it is perhaps in the improvement of observations and predictions that a decadal scale effort has the best starting point for achieving related outcomes. The challenge is daunting, but it is largely scientific, technical and well defined.

But does science also have transformative solutions to offer? Solutions which will not only be identified by 2030 but have also contributed significantly to sustainability at that time? Achieving the third outcome ‘A productive ocean supporting sustainable food supply and a sustainable ocean economy’ requires the ocean to be clean (first outcome) with healthy ecosystems (second outcome). These are massive challenges that depend not only on documenting the state of the ocean and presenting the evidence, but also devising affordable and implementable methods for clean-up, restoration and protection in combination with strongly reduced pollution and increased production. A sustainable ocean economy needs to produce not only nutritious food but also renewable energy and other commodities for the global population. In addition, the ocean needs to support safe navigation and transport in an increasingly crowded space calling for inclusive marine spatial planning and sustainable ocean planning efforts to allow reduced pressure on terrestrial ecosystems. These are challenges which reach far beyond the ocean science community and SDG 14 (von Schuckmann et al., 2020). In addition to ingenious and dedicated science and technology efforts, tight interaction with policy makers, industry and other stakeholders beyond the ocean community will therefore be necessary in every step addressing these challenges.

**Political initiatives**

This raises the question of appropriate science-policy interfaces and whether there is willingness and dedication of policy makers to work with ocean science and finance to deliver and scale up ocean solutions in time. One promising example pointing in this direction is the High Level Panel for a Sustainable Ocean Economy established in 2018 on invitation from the Norwegian Prime Minister and consisting of 14 acting heads of state or government. This Ocean Panel delivered its political Transformations document in 2020 building upon a total of 20 commissioned and peer reviewed topical expert reports as well as interactions with an Advisory Board of industry, UN bodies and civil society (See oceanpanel.org for details). The Transformations details 74 priority actions in the 5 key areas Ocean Wealth, Ocean Health, Ocean Equity, Ocean Knowledge and Ocean Finance and a commitment to sustainably manage 100% of their ocean areas under national jurisdiction by 2025. This is significant since together these 14 serving leaders of 14 countries cover nearly 40% of the world’s coastlines and 30% of the ocean Exclusive Economic Zones. Others are now invited to follow their recommendations with a view to 100% sustainable management of all ocean areas under (and preferably also beyond) national jurisdiction by 2030.

The Ocean Panel is committed to the Ocean Decade which is explicitly referenced in the Ocean Knowledge section of the Transformations. Further synergies between the Ocean Panel and the Ocean Decade have been identified (report available at oceandecade.org) and include using the combined power and visibility of the Ocean Decade and the Ocean Panel to accelerate the generation and use of
ocean science for effective ocean Protection, sustainable Production and equitable Prosperity (The three Ps) at all scales. Whether this joining of political and scientific forces will deliver as hoped for by 2030 remains to be seen. Many advancements need to be made notably in sustainable fisheries and aquaculture, harvesting at lower levels in the food chain etc. But significant and rapid progress is being made in some fields including the scale up of ocean-based renewable energy, notably offshore wind, and in global initiatives to reduce pollution which have accelerated significantly in recent years with the increased public attention to plastic pollution.

Can we solve all the problems? The final comprehensive expert report delivered to the Ocean Panel (Stuchtey et al., 2020) provides both a narrative and some encouraging examples of practical steps that can be taken immediately. Realising the new vision requires an integrated, rather than a sectoral, approach that is based on five building blocks: (i) Using science and data to drive decision-making, (ii) Engaging in goal-oriented ocean planning, (iii) De-risking finance and using innovation to mobilise investment, (iv) Stopping land-based pollution, (v) Changing ocean accounting so that it reflects the true value of the ocean. There is now an unprecedented political momentum to use ocean science to achieve a better world.

3. Key actions and prospects

In section 1 above two distinct questions were raised: the implications of the Ocean Decade for ocean science practitioners, and the role of the ocean in a sustainable future. The term ocean science practitioners should here be taken to mean a much wider group than just researchers who publish scientific papers on properties and processes in the ocean. It includes all personnel involved in related technical and administrative operational activities as well ocean science managers, educators, ocean literacy practitioners, and users of ocean data and information in government, business and society. As briefly discussed above and more in detail in references, the decade offers a global platform and mechanism for developing knowledge and informing actions that ocean science has probably never seen before. Links between science practitioners and high-level policymakers as well as industry have been significantly strengthened during the past 5 years. Ocean science practitioners will miss this opportunity if they return to business-as-usual science planning. There may be a danger that inclusivity of UN processes including IOC coordination in combination with the attractiveness of being listed as contributing to the Ocean Decade will allow too many contributions which are not really transformative but only more ‘science we need’ from a narrow science perspective. National science funding agencies and other competent cross-sectoral bodies have a crucial role to play to ensure that the science community takes the global challenges seriously and engage. However, if ocean science practitioners remember the overarching goals that provide the high-level motivation for the Decade (Ryabinin et al., 2019):

- To generate the scientific knowledge and underpinning infrastructure and partnerships needed for sustainable development of the ocean.
- To provide ocean science, data and information to inform policies for a well-functioning ocean in support of all Sustainable Development Goals of the 2030 Agenda.

and good forces go together, this can be a golden decade for ocean science practitioners.

Concerning the second question on the role of the ocean in a sustainable future, Ocean Panel Reports have shown that the ocean and ocean economy sectors including ocean-based renewable energy can play a larger role than expected in curbing climate change. As elaborated in Stuchtey et al (2020) a healthy ocean is critical to meeting the SDGs. This fact is now realized at higher political levels than ever before. Lubchenco et al (2020) list five priorities for a sustainable ocean economy: (1) Manage seafood production sustainably, (2) Mitigate climate change, (3) Stem biodiversity loss, (4) Seize opportunity for economic recovery, (5) Manage the ocean holistically. All of these are hard but possible to achieve and they all depend on ocean science-policy interaction. The only way to get there is by going together.

Disclaimer

The author was the elected chair of the Intergovernmental Oceanographic Commission (IOC of UNESCO) from 2015 to 2019 and is a co-chair of the Expert Group of the High Level Panel for a Sustainable Ocean Economy from 2018. The present write-up draws upon personal experience from related processes. It is not written on behalf of and does not necessarily represent the views of the IOC or the Ocean Panel or any organization that I am affiliated to.

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Ocean Circulation and Climate
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The ocean is an integral component of the Earth’s climate system. It acts as its primary reservoir of heat and carbon, absorbing over 90% of the surplus heat and about 30% of the carbon dioxide associated with human activities, and receiving close to 100% of fresh water lost from land ice. The ocean’s tight linkage with the atmosphere makes understanding its behaviour vital for forecasting weather and climate conditions from local to global scales. Delivering adequate information on the present and future state of the ocean is one of the most significant challenges we must address in the next decade.

1. Introduction

Natural variability and change in the Earth's climate have critical global, regional and local societal impacts. Due to its large heat and carbon capacity and relatively slow turnover dynamics, the ocean plays a vital role in climate. It is an important source of climate predictability on a monthly, seasonal and longer time scales. In particular the upper ocean provides the boundary condition and thus interacts actively with the atmosphere, and thus conditions and modifies atmospheric weather. Thus, the ocean is an integral part of the climate system. Improved understanding of the ocean system allows to assess climate change and variability. Our climate is noticeable changing today and will alter the ocean’s physical, chemical and biological properties in the future. Predicting the longer term evolution of the coupled ocean and climate system and its flow back to human society is a major scientific and societal challenge alike.

The ocean has significantly moderated climate change by absorbing almost all of the excess heat (90% compared to 1% for the atmosphere; von Schuckmann et al., 2020) and between a quarter and a third of the CO2 emissions (Friedlingstein et al. 2020) associated with anthropogenic fossil fuel emissions and land use changes. Ocean dynamics, and in particular the global ocean overturning circulation, has allowed the surface heat and CO2 input to be largely transferred to the deep ocean. Despite that dilution, significant modifications of marine ecosystems through warming and acidification that are documented today (IPCC SROCC, 2019). But this accumulation is not homogeneous in time and space, and the processes responsible for this variability, largely natural, are being investigated.

The importance of the Ocean to meet societal needs (e.g. Visbeck et al. 2014 and Visbeck 2018) is illustrated by the number of international bodies and policy instruments related to the Ocean (von Schuckmann et al., 2021). The IPCC 1.5°C (2018) and SROCC (2019) reports have provided the scientific evidence to call for immediate mitigation actions to protect the climate and ocean systems and to inform effective climate change adaptation measure. In these reports and those of other international bodies such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment Reports provide scientific insights in how the climate induced changes in the ocean affect marine biodiversity and marine ecosystem services (Doney et al., 2020).

Ocean science is hence needed and will continue to be required for understanding processes, changes, impacts as well as their future evolution. This is the only approach for national and international communities, stakeholders and policy makers to efficiently address mitigation actions and adaptation measures and this within the framework of the UN Sustainable Developing Goals (Visbeck et al. 2014; UNGA, 2015; Luchchenco et al., 2015; Colglazier 2018; Visbeck, 2018)

Key to understanding the ocean’s role in the Earth’s climate system, assessing the human pressure on climate and on the ocean, and deliver sustainable development, a healthy Ocean and a habitable planet is monitoring changes in the ocean circulation, heat and carbon content, freshwater, biogeochemistry, sea level, as well as studying the interactions of the ocean with the atmosphere, cryosphere, land, and ecosystems (Stammer et al., 2019; Schmidt et al., 2019).

In addition, an in-depth knowledge of the evolution of the physical environment is fundamental to understand the ocean biogeochemistry and the functioning, variability and change of marine ecosystems. Obtaining high quality ocean climate observations on a sustained basis (e.g. Global Climate Observing System, https://gcos.wmo.int) is also essential for attributing observed changes in the state of the ocean and thus for obtaining reliable climate predictions for a wide range
of applications and users (Stammer et al., 2019; Sloyan et al., 2019).

2. The Atlantic Ocean and the SAMOC Initiative

The Atlantic Ocean is the smallest of Earth’s ocean basins, thus it interacts intimately with its bordering lands, strongly influencing their weather and climates, and is readily accessible by the region’s inhabitants. At the same time, it plays a disproportional role in the global climate system. Through the Atlantic Meridional Overturning Circulation (AMOC), it delivers nearly half a petawatt of energy from the Southern to the Northern Hemisphere, and it has marked impacts on the global ocean circulation as well as on regional dynamics. While the key water mass transformations and deep ocean ventilation happens in the North Atlantic (e.g. Buckley et al. 2015), the South Atlantic Ocean plays a unique role in the Earth’s climate as the sole basin connecting the Arctic and North Atlantic Oceans to the rest of the world ocean basins. The current systems of the Atlantic carry and redistribute heat, freshwater, carbon and other gases not only poleward but there is a net heat transport from the southern to the northern hemisphere tightly linked with the AMOC (Frajka-Williams et al., 2019).

![SAMOC Diagram](image)

**Figure 1. A schematic of the in situ SAMOC observing system for measuring volume, heat, and freshwater fluxes.**

Most of the AMOC observations have been focused in the North Atlantic where the largest volume of new deep water is formed (Frajka-Williams et al., 2019). Numerical model studies have shown, however, that the South Atlantic is not just a passive conduit for the deep water masses formed in the North Atlantic and Southern Ocean, but instead actively participates in their transformation as they are exchanged with the other ocean basins.

Recognition of this led to the formation of a group dedicated to both advancing our understanding of the role of the South Atlantic Ocean in the AMOC system and the establishment of an observing system to capture key components of the circulation: this initiative is known as South Atlantic Meridional Overturning Circulation, or SAMOC (Fig. 1: www.noaa.aoml.gov/). The main objectives of SAMOC are to measure the strength and variability of the AMOC as well as the meridional heat and freshwater transport in the South Atlantic, all of which are crucial to improving our understanding of climate system variability, the international scientific community to share results on the AMOC in the South Atlantic and to design an integrated observational system.

The SAMOC initiative is supported by a remarkably large number of countries and organizations (15 institutions across Argentina, Brazil, France, Germany, Spain, Mexico, Norway, Russia, South Africa, Uruguay, the United Kingdom, and the United States). Together and since 2003 they have building a shared very successful observing system (Speich et al., 2010; Ansorge et al., 2015) that delivered completely new insights on the South Atlantic circulation, AMOC intensity and variability as well as assessments on observed changes at basin scale (Garzoli and Matano, 2011; Meinen et al., 2018; 2020; Kersalé et al., 2020; Manta et al. 2021) but also at local scale (Kersalé et al., 2018; Laxenaire et al., 2018; 2019; 2020).

Linked to global warming, extreme weather and marine events are likely to become more frequent. In particular, prolonged periods of abnormally high ocean temperatures, known as Marine Heat Waves (MHWs), can have a major impact on marine biodiversity and ecosystems and on the economics of regional fisheries (Sen Gupta et al., 2020). In the Atlantic, MHWs start to appear, and well-documented ‘iconic’ events have been observed in the Tropical and South Atlantic (Rodrigues et., 2019). In particular, the South Atlantic 2013/14 event was responsible for a dengue fever outbreak that tripled the usual number of fatalities, water shortages in São Paulo, the world’s fourth most populated city and reduced Brazilian agriculture production, which led to global shortages in coffee, for example, and worldwide price increases (Rodrigues et al., 2019).

MHWs is an example of the large impact of the ocean, its variability and changes on ecosystems (not only marine) and human society. It shows that delivering adequate information on the present and future state of the ocean is key to understand the changing ocean impact on the environment and society. It also shows that this information is essential to the whole set of operational services (from weather to climate, but also from coastal to fisheries management) as well as economical and governmental operators.
3. AtlantOS

In the Atlantic Ocean the realization of the stringent need of sustained and fit-for-purpose ocean information has pushed governments from around the Atlantic Ocean and stakeholders to join forces and push for the implementation of coordinated observing effort through two seminal policy agreements: the the Galway (2013) and Belém (2017) Accords.

With the ambition to improve and innovate the Atlantic ocean knowledge and services to society, to build on the All-Atlantic framework of the Galway (2013) and Belém (2017) Accord, the European Union’s Horizons 2020 project AtlantOS has initiated in 2015 a momentum to unite the Atlantic scientific community and stakeholders to articulate the needs and elements for an integrated Atlantic Observing System. This effort is now continued under the All-Atlantic Ocean Observing System (AtlantOS, www.atlantos-ocean.org) program for a forward-looking framework and basin-scale partnership to establish a comprehensive ocean observing system for the Atlantic Ocean as a whole (deYoung et al., 2019).

Figure 2. Global ocean observing system (GOOS) status map for February 2021 (Source: OceanOPS). Map of the Atlantic Ocean showing the location of ocean platforms (drifters, moorings, buoys, etc.) with onboard instruments collecting ocean observations. Coverage map is of observing activities by GOOS network members.

AtlantOS build on existing elements and networks (Fig. 2) and promote a more sustainable, multi-disciplinary, efficient, and fit-for-purpose system. AtlantOS recognizes that platforms, networks, and systems already exist that operate at various maturity levels. AtlantOS wishes to go beyond the status quo by bringing together the countries of the Atlantic basin providing the opportunity to join and support the system. AtlantOS builds upon the coordinated work of the Global Ocean Observing System (GOOS) and the Group on Earth Observations Blue Planet Initiative (GEO), two international bodies that support and coordinate global ocean observing. AtlantOS seeks to complement those efforts and offers a new approach to organize ocean observing, and this across societal requirements and disciplines and all ocean compartments (from the surface to the sea-floor, from the open-ocean to the coast). It has articulated a ocean value chain that connects societal need for ocean information through observing system infrastructure (space and in-situ) via international data centres, data model fusion approaches to ocean state estimates, predictions and future scenarios (Fig. 3). This information is then delivered in an equitable and timely manner to key stakeholders.

Figure 3. The AtlantOS program value chain.

4. The UN Ocean Sciences Decade

The ocean is essential to our society – it regulates the global climate, provides us with natural resources such as food, materials, important substances, and energy. It is essential for international trade and recreational and cultural activities. Ocean observations touch our lives every day from the food we eat, to the clothes we wear, to how we spend our leisure time. The ocean is estimated to be the seventh largest economy in the world (OECD, 2016). Goods and services from coastal and marine environments have been estimated at 2.5 trillion each year worldwide. Together with human development and economic growth, increased use and overuse of ocean resources and services have exerted strong pressure on the marine environment, ranging from overfishing, unsustainable resource extraction, and alteration of coastal zones to various types of thoughtless pollution including CO2 emissions causing climate change - the ocean is warming, acidifying, deoxygenating and sea level is rising.

International cooperation in science and effective local, regional and global governance are required to protect the marine environment and promote the sustainable use of marine resources to preserve an ‘healthy’ and productive ocean to keep delivering fundamental ocean services to meet the needs of future generations.

Pendleton et al (2020) argue, that the current scale, pace, and practice of ocean scientific discovery and observation are not keeping up with the changes in ocean and human conditions. We need fundamental changes in the way that researchers work with decision
makers to co-create knowledge that will address pressing development problems. Researchers need to share their data more freely and sooner so that their work can inform decisions in near real time. Academia, government, and industry need to find new and better ways to collaborate and innovate. Huge gaps in scientific capacity and capability around the world will require that we fundamentally change the way we train and employ researchers from developing countries. Above all, we need to dramatically expand the breadth of disciplines that are directly involved in new transdisciplinary ocean research.

Against this backdrop and in recognition of the importance of the ocean dimension of the UN 2030 Agenda for Sustainable Development and associated Sustainable Development Goals (SDGs) the United Nations (UN) General Assembly has established a Decade of Ocean Science for Sustainable Development (2021–2030), to develop the frameworks and tools required for the sustainable development of the ocean. The aim of the Ocean Decade is to create a new movement for bringing together researchers and stakeholders from all relevant sectors to generate a new scientific process to inform policies that ensure a well-functioning, productive, resilient, and sustainable ocean (IOC-UNESCO 2019, Ryabinin et. al 2019). The Ocean Decade articulates seven outcomes and one of them is a ‘An accessible ocean with open and equitable access to data, information, and technology and innovation’ and more specifically the 8th of the ten ocean decade challenges calls for ‘… a sustainable ocean observing system that delivers timely data and information accessible to all users on the state of the ocean across all ocean basins’ (Ocean Decade Implementation Plan, 2020). Thus, we need an integrated basin-scale ocean observing system to support ocean science, assessment and ocean governance. Coordinated basin-scale activities will lead to better monitoring, modeling, and forecasting products (e.g. through alignment of observing network activities as well as supporting data management and integration). This information needs to be assessed and knowledge based recommendations for development pathways given. We need both a better understanding of ocean change and its challenges as well as more knowledge about new opportunities in order to develop towards a more sustainable relationship between humans and the ocean. Sustainable and accessible ocean observing and modeling systems are needed to monitor the many dimensions of the ocean from the physical to the ecosystem and from global to local scales (e.g. OceanObs’19 community white papers, and outcomes; Speich et al., 2019; oceanobs19.net). Oceanographic data and scientific capacity must be secured through sustainable financial and political agreements. Local, indigenous and cultural knowledge systems must be linked to science and technology. Strong knowledge systems to provide operational ocean services to society. Within these objectives, the way forward is a holistic approach that embraces sustainable Ocean stewardship informed by best available science, data and services to support society and the economy. The UN Decade of Ocean Science for Sustainable Development provides a once-in-a-lifetime opportunity to achieve these objectives.

References


The annual cycle of turbulent latent heat flux in the Agulhas current system
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We are using data from in-situ observations, climate reanalysis and satellite remote sensing to study the annual cycle of the turbulent flux of moisture from ocean to atmosphere also called the turbulent latent heat flux (LHF). We first assess if the various datasets adequately represent the intense exchange of moisture that occurs above the Agulhas Current system. We are using monthly fields of turbulent latent heat flux and various parameters used to calculate the LHF: sea surface temperature (SST), surface wind speed, saturated specific humidity at the temperature of the sea surface (Qsst) and air specific humidity at 10 m height (Qa). We use MODIS SST and the satellite derived QuikSCAT SCOW wind climatology as reference for SST and surface wind. Compared to MODIS SST, all products underestimate the SST in the core of the Agulhas Current. The differences in LHF are also due to the difference in Qa and surface wind speed. We study the annual cycle of LHF and its drivers in four locations of the Agulhas Current system: offshore Durban; offshore Port Elizabeth; in the Retroflection area and in the shelf water offshore Cape Town outside of the Agulhas Current system. The highest LHF of about 250 W/m² is found in the Retroflection area in winter. The lowest LHF is 100 W/m² off Port Elizabeth in summer. In Durban, Qsst - Q10 is the main driver of the amplitude of the annual cycle of LHF. The annual cycle of LHF follows the wind speed in the Retroflection area. Both Qsst - Q10 and wind speed variations drive the annual cycle of LHF off Port Elizabeth.

1. Introduction

The greater Agulhas Current system is composed of the core of the Agulhas Current which is about 100 km wide; the Retroflection region with a loop diameter of 350 and the Agulhas Return Current that meanders in an eastward direction. Substantial turbulent latent heat fluxes as well as marine boundary layer modification were measured above the core of the Agulhas Current, the Retroflection region and the Agulhas Return Current (Rouault et al., 2000). These measurements show that the turbulent latent heat flux which is akin to the turbulent flux of moisture at the air-sea interface increases substantially in the Agulhas Current system. Gimeno et al., (2010) showed that the Agulhas Current system is a source of moisture for the Southern Africa rainfall. Nkwinkwa Njouado et al. (2018) linked the high LHF to higher rainfall above the current and at the coast adjacent to the current. The turbulent latent heat flux is underestimated in models if the resolution does not represent the SST field within the core of the current that is about 100 km wide (Rouault et al., 2003). The core of the Agulhas Current is important because of its thermal contrast with the surrounding water leading to a fivefold increase in the turbulent fluxes of latent heat. Radiosondes launched during the ACASEX cruise show that the core of the current literally produces a wall of moisture (Rouault et al., 2000) that can reach up to 2000 m above the Agulhas Current. The LHF measured above the Agulhas Current were not well reproduced in older climate reanalysis (NCEP1, NCEP2 and ERA40). However, recent reanalysis for ERA-Interim, ERA5, CFSR and MERRA-2 are now available at a higher resolution. At the same time numerous new air sea interaction datasets derived from satellite remote sensing such as SEAFLUX (Curry et al., 2004) have been produced at a resolution that allows to represent the core of the Agulhas Current. The aim of this study of the air-sea exchanges in the Agulhas Current system is threefold: (i) explore whether the new climate reanalysis and satellite derived datasets have sufficient spatial resolution and representations of the LHF; (ii) examine the magnitude of uncertainties in the basic parameters (wind, SST, surface specific humidity) used to calculate the LHF; and (iii) quantify the annual cycle of the LHF and its drivers in the Agulhas Current system.

2. Data and method

Various parameters are analysed including, latent heat flux, sea surface temperature (SST), surface wind speed at 10 m, specific humidity of air at 10 m (Qa) and saturated specific humidity (Qsst). Saturated specific humidity is not available for all products and is calculated using the Clausius-Clapeyron relation and the SST. The averaging periods are ranging from monthly to seasonal and are constrained by the availability of satellite datasets. When datasets were not available at the same period, for example ERA-40 we use the same amount of time (8 years) for the averaging to have a consistent result. We analyse the gridded monthly data (version 2) derived from the National Oceanography Centre Southampton (NOCS)
based on Voluntary Observing Ship (VOS). Two satellite-based data products are used, notably the third version of the Hamburg Ocean Atmosphere Parameters and Fluxes (HOAPS3) product with a spatial resolution of 0.5° x 0.5°, and the high-resolution air-sea turbulent fluxes (SEAFLUX) available on a grid of 0.25° x 0.25° (Curry et al., 2004). The Moderate Resolution Imaging Spectroradiometer (MODIS) is used to provide reference SST data because of its very high resolution (4 x 4 km) that evidently represents the fine spatial structures of the Agulhas current, especially near the coast. The Scatterometer Climatology of Ocean Winds (SCOW) is used as reference wind speed and direction in this study. Five reanalysis products are used. The Climate Forecast System Reanalysis (CFSR, MERRA-2, ERA-Interim, ERA 40 and NCEP)

3. Results

Figure 1: Annual cycles of latent heat flux (W/m²). In Agulhas Current off Durban (31.5-32.5°E; 30-31°S), off Port Elizabeth (25-26°E ; 34.5-35.5°S), Agulhas Retroflection (19-20°E ; 38-39°S) and off Cape Town (16-17°E ; 33.5-34.5°S) for SEAFLUX (blue), CFSR (red), MERRA-2 (green), ERA-5 (purple), ERA-Interim (yellow), NCEP2 (cyan), ERA-40 (purple), and NOCS (black). Shades areas represent the standard errors calculated as the standard deviation divided by the square root of the number of years.

The first objective is to investigate whether the recent climate reanalyses (CFSR, MERRA-2, ERA-5 and ERA-Interim), satellite-based (SEAFLUX and HOAPS3) and in-situ observation-based (NOCS) LHF products have a good representation of the intense turbulent flux of moisture that occurs above the Agulhas Current, compared to older reanalyses (ERA-40 and NCEP2), because the Agulhas Current is not adequately resolved in the coarser-resolution (ERA-40 and NCEP2). HOAPS3 compares quite well with SEAFLUX, but HOAPS3 does not have data along the coast. Compared to the SEAFLUX LHF, the ERA-40 and NCEP2 LHF fail to represent the structure of the Agulhas Current. The new reanalysis products, on the other hand, have a better representation of the current, therefore, can adequately represent the LHF in the Agulhas Current system, except ERA-Interim that underestimates the fluxes. CFSR is relatively like MERRA-2 and ERA-5 but has higher LHF. Between the four new reanalyses, surprisingly ERA-Interim has the lowest fluxes (100-200 W/m²). This result is unexpected in view of the higher spatial resolution of the ERA-Interim (0.75° x 0.75°) compared to ERA-40 (2.5° x 2.5°). It is most likely due to its low wind speed although the LHF is compensated by high values of Qsst-Qa. The improved version of ERA-Interim (ERA-5) represents better the LHF in the Agulhas region. The phase of the seasonal cycle of NOCS LHF is reversed in the Retroflection region compared to other products. This might indicate that not enough vessels pass through the Agulhas Retroflection region. Another reason for the uncertainties in NOCS is due to measurement uncertainty. To conclude, CFSR, MERRA-2, and ERA-5 show good representation of the Agulhas Current and will be used for further analysis to investigate the relation between the intense flux of moisture over the Agulhas Current and the weather and climate in Southern Africa, and to validate mesoscale atmospheric models such as the Weather Research and Forecasting model (WRF)

The second aim of this study is to identify the level of uncertainties introduced by the basic parameters: SST, wind (U), surface specific humidity (Qa), ocean current (Us) used to estimate the LHF (e.g., Equation 1)

\[
LHF = \rho_a C_E (|U - U_s|)(Qsst - Qa) \quad (1)
\]
The differences between each product and the reference products from MODIS are calculated for SST, SCOW for wind speed and SEAFLUX for Qsst-Qa. CFSR SST is higher than MERRA-2 SST compared to MODIS SST. This may explain higher values of the LHF from CFSR compared to MERRA-2, as SST is used to compute Qsst. Between all the new reanalyses, MERRA-2 has the highest wind speed and CFSR the highest Qsst-Qa. ERA-Interim has the weakest wind speed in the Agulhas system compared to SCOW. This explains the lowest values of the ERA-Interim LHF. In the Agulhas Current system, CFSR and MERRA-2 wind speed are similar. ERA-Interim has the strongest Qsst-Qa compared to other reanalyses. This compensates for the low wind speed in the calculation of ERA-Interim LHF but not enough. Qsst-Qa variability is mostly influenced by the variation of Qa. The differences in Qa between the products clearly have a greater impact than the discrepancies in wind speed and ocean surface temperature. For the satellite-based products, the retrievals of air temperature (Ta) and specific humidity (Qa) at the surface continue to be problematic in regions with strong vertical gradients. Another source of specific uncertainties for the reanalyses is incomplete account of the surface current speed. Looking at the annual mean of the Agulhas Current from the GlobCurrent data repository, the surface current speed can be more than 1.5 m/s. During the ACASEX (Rouault et al., 2003), Surface current speeds of up to 2 m/s were measured. Thus, neglecting a 2 m/s current speed at a near-surface wind speed of 4 m/s may lead to a 50% error in the LHF estimation. Finally, the annual cycle of the LHF and its drivers in the Agulhas Current system is investigated using SEAFLUX. SEAFLUX is used to recalculate the LHF using a climatology Qsst-Qa and/or wind speed, as it has a high spatial resolution (0.25° x 0.25°) and reliable SST and wind speed [45].

Three locations, representative of various regions of the Agulhas Current system (off Durban, off Port Elizabeth and Retroflection) and one point outside the Agulhas system (off Cape Town) were selected for the comparison. In the Agulhas Current system, the lowest LHF of 100 W/m² is found off Port Elizabeth in late summer. In contrast, the largest LHF of ~250 W/m² is in the Retroflection region in winter. In the Agulhas Retroflection region, large values of LHF are due to stronger wind speed in the Retroflection area. Off Durban higher values of the LHF can be explained by the difference of specific humidity. Off Port Elizabeth and Cape Town, values of LHF can be explained by the combination of Qsst-Qa and the wind speed. On a shorter timescale (5-day averages climatology), correlation between LHF and wind speed is higher off Port Elizabeth, in the Retroflection region and off Cape Town. Off Durban, the correlation is low. Therefore, the wind speed is not the main driver of the amplitude of the annual cycle of LHF in this region. To summarize, off Durban, LHF is mostly driven by the surface specific humidity. In the Retroflection region LHF is mostly driven by the wind speed. Off Port Elizabeth it is a combination of the specific humidity and the wind speed.

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Ocean currents shaping the fate of coastal upwelling system south of Madagascar
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Using in-situ datasets, satellite observations, and numerical model, the study is aimed to encapsulate the role of the East Madagascar Current (EMC) and the Southwest Madagascar Coastal Current (SMACC) leading modulation of the coastal upwelling cells south of Madagascar. Although upwelling south of Madagascar is favourable for wind-driven upwelling, the southern extensions of both ocean currents, EMC and SMACC, tend to promote and inhibit respectively the strength of the upwelling cells Core 1, southeast, and Core 2, southwest of the island. (1) The EMC favours the upwelling through the mechanical interaction between the bottom topography and the EMC flow inducing a bottom Ekman veering. However, the Early-Retroflection of EMC southern extension interrupts this mechanical process and reduces consequently the upwelling cell Core 1 occurrences. (2) The SMACC is a poleward surface warm current driven by the local wind stress curl. The SMACC carried very warm water intruding into the upwelling cell Core 2. This intrusion of warm water disrupts the wind-driven upwelling mechanical conditions. Hence, the SMACC poses a threat of probable extinction of the upwelling cell Core 2, while upwelling cell Core 1 occurrences are also disrupted due to the instability of the EMC inducing sudden eastward retroflexion.

1. Introduction

Madagascar's southern coastal marine zone is a region of high biological productivity which supports a wide range of marine ecosystems, including fisheries. This high biological productivity is attributed to a coastal upwelling which is composed by two separated upwelling cells: upwelling cell Core 1, located at the southeast coast, and the upwelling cell Core 2 lying at the southwest of the island (Ramanantsoa, et al. 2018). Both upwelling cells are highly associated with ocean currents. Previous work described that upwelling cell Core 1 water masses are coming from the East Madagascar Current (EMC), while upwelling cell Core2 water masses are predominantly with the Southwest Madagascar Coastal Current (SMACC) (Ramanantsoa, 2018). Both upwelling cells variabilities are highly associated with ocean currents modulations (Ramanantsoa, et al. 2018b). The study focus is to evaluate the role of the EMC and SMACC influencing the strength and occurrences of the upwelling cells south of Madagascar. Using various datasets and numerical model, tracking technique of the southern extension positioning for EMC and SMACC will be computed to measure their respective influences on the upwelling. This work is outlined as followed, first detail on the data and approaches used, following description of findings and their discussions, lastly will be the conclusion.

2. Data and Approaches

Satellite altimetry sea surface height (SSH), distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS), is used to derive geostrophic velocity of EMC and to detect the retroflection spatial extent for the period of 1993 to 2017. The Multi-Scale Ultra-High Resolution (MUR) SST is a gridded, blended, and gap-free dataset developed by NASA-JPL on a 0.011° grid is used to detect the warm tongue intruding into the upwelling cell Core 2 (Vazquez-Cuervo et al., 2013). The EMC retroreflection is identified from satellite altimetry data by selecting a specific sea surface height contour as a streamline representative of the EMC path. This methodology is equivalent to the one applied for the Agulhas Current by Backeberg et al. (2012); Loveday et al. (2014); Renault et al. (2017). The selected contour is chosen as the mean sea level in the EMC southern extension region (42°E to 50°E and 22°S to 28°S), over a bathymetry ranging from 200 m to 2000 m, and with current speeds higher than 35 cm/s. The westernmost position of the contour determines the EMC retroreflection returning point. Monthly southernmost positioning of the intrusion of warm water carried by SMACC southern extension are also tracked using SST adopting a similar method detecting the retroflexion. The southernmost contour position of the SST determines the extension of the intrusion of warm water into the upwelling.

3. Results and discussions

3.1 SMACC and upwelling cell Core2

The SMACC is a poleward warm surface current flowing at the southwest of Madagascar. It extends from 22.5°S and usually does not exceed the limit of 25.2°S at its southern extension. The SMACC is driven by the local cyclonic wind stress curl due to the bending of the southern tip of the island. It carries very warm water from the Mozambique Channel and intruded into the upwelling cell Core 2 (Ramanantsoa et al., 2018b).
This intrusion of warm water tends to superimpose the surface signature of the upwelling cell Core 2. However, the SMACC water masses are noticed to extend beyond the southern extension limit latitude (25.2°S). The intrusion of warm water tends abnormally to invade the whole upwelling area of the Core 2. This is due to the intensification of the cyclonic wind stress curl with a significant contribution of high vorticity of cyclonic eddies enhancing the SMACC in vicinity of 24.52°S.

Figure 1: Synoptic development of warm water intrusion carried by the SMACC. Maps are the sea surface temperature at the indicated periods. Circle consists to emphasize only in the upwelling area. Contours depict the isolines representing the SMACC thermal signature above the 28 degree Celsius. Blue stars are the southern-most of the warm water intrusion.

Figure 1 shows a synoptic development of the intrusion of the warm water spatial tracking at the southern tip of Madagascar. The tracked southernmost positioning is defined by the blue stars. Figure 1 demonstrates that SMACC water masses start to intrude completely the upwelling cell Core 2 in a scale of week and reach the southernmost limit of the current. Consequently, the intrusion of warm water disrupts the wind-driven upwelling mechanical conditions. The coastal offshore Ekman transport induced by alongshore wind is obstructed by the water masses coming from the Mozambique Channel. This therefore inhibits the occurrence and the strength of the upwelling. Related to that, Ramanantsoa 2018 also highlighted that an abnormal cyclonic wind stress curl drives the enhancement of the SMACC volume transport integrated over the first 200 m depth and tends a massive intrusion of the SMACC’s water masses into the upwelling Core 2. This mechanism appeared to shut down the upwelling physical processes. In a recent work (not shown), the SMACC surface speed has been intensified using Simple Ocean Data Assimilation reanalysis over the 37 years, due to the progressive enhancement of the local wind stress curl. The southern extension of the intrusion of warm water consequently tends to exceed 25.5°S. This suggests that the SMACC may pose a probable extinction of the upwelling cell Core 2 in a global warming scenario.

3.2 EMC and upwelling cell Core1

The upwelling cell in Core 1 is primarily forced by the EMC (Ramanantsoa, 2018c). The role of the EMC as a main driver of variability for Core 1 was confirmed through an analysis of model solutions from a high-resolution numerical simulation over the region. The interannual variability of the upwelling index in Core 1 is highly associated with the EMC volume transport integrated over the 1000 m depth computed from the model solution over a period of 24 years (Ramanantsoa, 2018c). This result confirmed that a stronger EMC volume transport drives an intensified upwelling in Core 1.

The bottom Ekman transport at the southern extension of the EMC, computed using the linear bottom stress theory (Schaeffer et al. 2014), demonstrated that the along-shelf advection of the EMC generates an uplift of bottom water due to high bottom stress in the vicinity of 24.5°S. The interannual variability of this Ekman bottom transport co-vary with the upwelling surface signature interannual variation in Core 1. This result strengthens the hypothesis that interactions of the EMC with the topography drive a dynamic upwelling in Core 1 (Ramanantsoa, 2018).

However, the EMC southern extension is perceived to retroflect toward the Indian Ocean. It was found that over 47% of the EMC water retroflects eastward, while the rest flows straight toward the Agulhas Current. Retroflection appears in three forms: (1) EMC early-retroflection, occurring around 25°S; (2) canonical retroflection is the returning point located beyond the southern tip, lastly; and (3) no-retroflection is the retroflection positioning tracked close to the African coastline and in the Agulhas Current system area. The EMC early-retroflection has a direct impact on the upwelling cell Core 1. The early retroflection is EMC strength dependent. It is found that abnormal high-volume transport of the EMC promotes an early retroflection. Plus, high vorticity of anticyclonic eddies drifted from the central Indian Ocean tend to enhance the EMC around 23°S. However, the same anticyclonic eddies drift the core of the EMC in the vicinity of 25°S and induce a sudden eastward retroflection. Figure 2 demonstrates the influence of an anticyclonic eddy, represented by a high absolute dynamic topographic at the south-east of the island, deforming the EMC core flow inducing a sudden eastward drift.

The EMC early-retroflection tends to disrupt the bottom Ekman veering inducing the vertical motion for the upwelling Core 1. This is due to the sudden drift of the EMC core before 25°S which inhibits the alongshore bottom upwelling mechanical processes responsible for the strength of Core 1. The
intensification of the EMC may promote a bottom Ekman transport leading upwelling, but the frequent occurrences of an early retroflection disabled the mechanical process for an upwelling.

Figure 2: Synoptic development of EMC Early-Retroflection, Jun 20 to Sep 13, 2014 from the onset to the full formation. Blue stars represent the returning point of the southern extension of the EMC.

4. Conclusion

In summary, the SMACC poses a threat of probable extinction of the upwelling cell Core 2, while upwelling cell Core 1 occurrences are also perturbated due to the instability of the EMC southern extension inducing sudden eastward retroflection. Hence, this study demonstrates that the upwelling cells south of Madagascar are perturbed by ocean currents mechanical instabilities. Therefore, the collapse of the upwelling may be anticipated in the near future for both upwelling cells if the SMACC which continues to intrude massively, and the EMC early-retroflection occurrences will become more frequent. An alert should be communicated accordingly to the local population who depends on this upwelling for their entire livelihoods.

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The Benguela: a short review of what we think we know and what we need to fill the gaps
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The Benguela Current system encompasses the coastal upwelling regime, as well as the large-scale offshore northwestern flow of the Benguela Current. It’s northern and southern boundaries are associated with intense frontal systems: the Angola Benguela Frontal Zone (ABFZ) in the north and the alongshore-oriented Benguela Jet in the south. Remote drivers of change in the Benguela system penetrate through these boundaries and include tropical Atlantic anomalies and Agulhas Current interactions. The former resulting in warm anomalies off Angola and Namibia and the latter not only producing a region of intense turbulence in the Cape Basin region, but also modulating the intensity of the Benguela Jet current. The coastal upwelling regime is closely tied to the alongshore winds that are unfortunately often misrepresented in model simulations, that fail to capture the wind drop-off in the near-coastal zone. This underscores the need for improved and sustained coastal wind measurements that can be used to improve the models. In order to support good governance and adaptable management of the Benguela ecosystem in a climate that is changing, it is essential that we continually improve our understanding of these local and remote drivers. To do this we need: improved and sustained observations, optimized models and satellite processing techniques and open data policies.

1. Introduction

Driven by equatorward winds that arise from the adjacent oceanic high and continental low pressure systems, the world’s four major eastern boundary upwelling systems (EBUSs) are characteristically cool and highly productive. As a result, they sustain both lucrative fishing industries and local fishing communities and are associated with dry land boundaries due to reduced convection over the colder waters. In these respects, the Benguela is no different. However, it is distinctive because it is the only EBUS that interacts directly with a western boundary current system, namely the Agulhas Current. This occurs because the poleward limit of the African continent does not extend into the mid-latitude westerlies as is the case for the land-boundaries associated with the other EBUSs. The Benguela system is therefore the only EBUS that is associated with warm tropical waters at both its northern and southern boundaries (Figure 1). In this short review, key features of the Benguela Current system, ABFZ in the north to Agulhas interactions in the south, will be highlighted. Gaps in our knowledge and suggestions for the way forward will be presented.

2. The northern boundary: the ABFZ

The ABFZ at the northern boundary is where the cool waters of the northern Benguela upwelling system meet the warm, southward-flowing, Angola Current and manifests as an intense meridional sea surface temperature gradient (Veitch et al 2006). Its position is maintained by the wind stress curl that drives the South Equatorial Counter Current of which the Angola Current is the coastal extension, while its intensity is controlled by the alongshore wind that drives coastal upwelling (Colberg and Reason, 2006). While the surface expression of the ABFZ stays remarkably stable, with only a slight seasonal cycle, occasionally it extends much further south, resulting in warm anomalies off the coasts of Angola and northern Namibia in events known as Benguela Nino’s (Shannon et al., 1986). These events can have severe impact on rainfall variability (Rouault et al., 2003, 2007; Hansingo and Reason, 2009) as well as marine biodiversity (e.g. Monteiro and van der Plas, 2006 and Bachelery et al., 2019) and are thought to be related to wind anomalies in the central-western equatorial Atlantic that excite equatorial Kelvin waves that send some of their energy southward along the African continent (Florenchie et al., 2003; Kountgue et al, 2017; Rouault et al., 2018) but it has also been suggested that they may be associated with anomalous local wind forcing (Richter et al, 2010). While the Angola Current does not generally penetrate southward of the ABFZ at the surface it does so at depth, following the shelf-edge as a poleward undercurrent until Lüderitz, where it veers offshore (Veitch et al., 2010). The poleward undercurrent is driven by the wind stress curl and has implications for low oxygen water (LOW) and hypoxic events on the Namibian shelf as it transports LOW from the highly retentive Angola Dome region.

3. The southern boundary: Agulhas interactions

The southern boundary is similarly associated with a particularly intense frontal system: this time oriented alongshelf, where the cool waters of the coastal upwelling meet warm waters associated with Agulhas
leakage. The existence of a strong alongshore jet current associated with this front was first anticipated and then measured by Bang and Andrews (1974). Recent observations confirm that it is a robust feature, situated between the 300-500 m isobaths, and model experiments explicitly show that it is driven by highly variable offshore warming associated with Agulhas influx juxtaposed against the highly seasonal nearshore cooling associated with the upwelling regime (Veitch et al., 2017). The importance of the jet lies in its role in transporting fish eggs and larvae from their spawning ground on the Agulhas Bank to their nursery area in St Helena Bay (Ragoasha et al., 2019). Furthermore, model results show that the intensification of the jet by the influx of Agulhas waters has a retentive effect on the southern Benguela shelf to about 30°S, which is important for productivity and LOW dynamics. The influx of the Agulhas Current, in the form of rings, filaments and eddies produces a region of intense turbulence where they interact with the Benguela Current and the upwelling front. As a result, the Cape Basin (offshore of the shelf-edge and south of the Walvis Ridge) has come to be known as the ‘Cape Cauldron’ (Boebel et al., 2003) due to its extremely turbulent nature. The influence of the extreme sub-mesoscale interactions in this region on the marine ecosystem is not well known, but it has been suggested by Gruber et al (2011) and Rossi et al. (2008) that enhanced horizontal mixing, as one would expect in a turbulent regime such as this, leads to reduced chlorophyll.

4. The offshore boundary: large – scale processes

The depth integrated, large-scale currents of the Benguela system reveal distinctly different northern and southern regions. The flow in the northern region is driven by the wind stress curl (via the Sverdrup relation) and is characterized by a sluggish cyclonic flow in the northern Benguela, with a poleward current extending along the shelf-edge, veering offshore at Lüderitz and then extending northward. In the southern Benguela on the other hand, where turbulence is high and non-lineairities cannot be ignored, the wind stress curl cannot be used to derive the large-scale flow regime. Model experiments have explicitly revealed that the Agulhas contributes ~10 Sv to the transport of the Benguela Current and that the mean meandering Benguela Current is a manifestation of the passage of Agulhas Rings (Veitch and Penven, 2017).

5. The land boundary: coastal upwelling

The coastal upwelling regime is strongly tied to the alongshore wind stress that has a strong seasonal cycle in the south (stronger winds during austral spring and summer months) that lessens considerably toward the north. The Lüderitz upwelling cell experiences strong upwelling favorable winds year-round and, because of this constantly strong offshore Ekman transport, retention is low and productivity reduced (Demarcq et al., 2007). Provided 2D upwelling theory holds true, the alongshore wind stress provides an excellent proxy for upwelling rates, via Ekman transport dynamics. However, there are places in the Benguela system where geostrophic currents converge upon or diverge away from the coast, essentially inhibiting (in the far northern Benguela) or enhancing (far southern Benguela in relation to the intense jet current) coastal upwelling rates. These processes are not accounted for by Ekman transport dynamics (Veitch et al., 2010; Marchesiello and Estrade, 2010; Rossi et al., 2013). Despite the relatively straightforward dynamics of coastal upwelling, both global and regional models struggle to capture the nearshore temperatures sufficiently: a warm bias is common in coupled climate models, while a cool bias is common in regional uncoupled models. The latter is almost certainly related to the poor representation of the wind drop-off in the atmospheric forcing product used, while the former is thought to be related to several factors including the underestimate of the stratocumulus clouds, errors in the winds and lack of offshore transport by ocean eddies because of too-low horizontal grid resolution (Richter, 2015). A further troubling aspect of modelling EBUSs is that satellite-derived sea surface temperatures that are routinely used for model evaluations are notoriously unreliable near the coast particularly in the vicinity of extreme frontal systems, such as coastal upwelling regions (Carr et al., in production).

6. Conclusion: what do we need?

This review has highlighted some aspects of the Benguela system that are either integral to its functioning, such as the coastal upwelling regime itself, or that can significantly impact its functioning via remote drivers that penetrate either its northern or southern boundary. To support good governance and adaptable management of the Benguela ecosystem in a climate that is changing, it is essential that we continually improve our understanding of these local and remote drivers. To do so, we need:

1. improved and sustained observations in key locations such as system boundaries and coastal monitoring sites. Every effort should be made to sustain existing monitoring arrays, new mooring arrays could be deployed in locations of historic arrays to capture long term changes and models could be used to objectively guide new deployments.

2. optimized models. Model improvement relies not only on sufficient computing infrastructure, but also strongly on access to reliable in situ data, both for assimilation as well as for evaluations.

3. satellite post-processing strategies appropriate to upwelling systems.
4. Data sharing policies. As we move into the Decade of Ocean Science, in a climate that is rapidly changing, it is more crucial than ever that we can synthesize all available information on the state of the ocean expeditiously to support policy and governance frameworks most meaningfully.

References


Figure 1: Schematic of the Benguela System with model-derived sea surface temperature images (courtesy of Pierrick Penven) capturing the cold coastal waters and the intense frontal features at the northern and southern boundaries of the system.


Variations in wind stress and upwelling, as well as changes in temperature, nutrients, and the amount of photosynthetically available light, are among the environmental drivers known to modify plankton biomass and production. Seasonal and interannual variations in phytoplankton biomass and primary production have been documented, but to date, there is no clear evidence of decadal-scale changes. Upwelling-favourable winds have decreased in the northern Benguela (NB), while increases have occurred in the southern Benguela (SB) and on the Agulhas Bank (AB). Phytoplankton communities appear to have responded by showing increasing trends of chlorophyll $a$ (chla) and microphytoplankton in the NB, and on the AB shelf during summer, with decreases observed in the SB. In contrast, zooplankton communities in both the NB and SB have shown substantial long-term changes in biomass, abundance, production, as well as species and size composition. Since the mid-1990s in the SB and mid-2000s in the NB, copepod abundances have declined, and there has been a concomitant shift in prevalence from larger to smaller species in both sub-systems. These variations in plankton communities are locally and differentially mediated by both bottom-up and top-down forcing mechanisms. Although the relative importance of these mechanisms is still uncertain, changes in plankton populations have substantial effects on biogeochemical processes, food web structure, and ecosystem resilience, making them ideal indicators of ecosystem change. Dedicated research is required to further understand plankton variability and drivers thereof, and consistent long-term monitoring of environmental conditions and plankton communities is of paramount importance to better establish their influences on trophic structuring and the sustainability of food security.

1. Introduction

The marine environment surrounding southern Africa plays a key role in global ocean circulation and biogeochemical cycling and comprises a complex interaction between various major oceanic systems, including the Benguela upwelling system, the greater Agulhas Current system, and the Southern Ocean. On the west and south coasts of southern Africa, the Benguela upwelling system is highly productive and supports a complex food web and a wide variety of commercially harvested resources (Hutchings et al., 2009).

Microphytoplankton communities usually dominate in the near-shore shelf regions, responding quickly to the uplift of nutrients into the euphotic zone. However, nanophytoplankton are also important in this environment due to their larger spatial extent. Copepods make up the majority of the zooplankton biomass in most pelagic ecosystems. Along the West and South coasts their biomasses, species and size composition have fluctuated in the long term, not only in response to dynamics of phytoplankton assemblages, which is their primary food source, but also as a result of predation by stocks of shoaling small pelagic fish (sardine and anchovy), which prey differentially on copepods in a size-selective way (Verheye et al., 2016).

On the east coast of southern Africa, the Agulhas Current system and Mozambique Channel are usually characterized as oligotrophic, with nano- and picophytoplankton dominance, but previous studies have demonstrated the importance of microphytoplankton in some small localized shelf areas and in response to eddy dynamics (Barlow et al., 2014). A recent study has demonstrated four distinct large-scale zooplankton assemblage distributions within the Western Indian Ocean, in agreement with surface circulation patterns (Cedras et al., in press).

South of Africa, the Southern Ocean is important in regulating the global flux of organic carbon, and modulates the supply of nutrients to thermocline waters, which drives productivity at lower latitudes (Sarmiento et al., 2004). This ocean basin is uniquely characterised by high nutrient concentrations, but generally low phytoplankton biomass which exhibits high spatial and temporal variability. Zooplankton distributions in the Southern Ocean tend to be zonal, with the fronts of the Antarctic Circumpolar Current acting as biogeographic boundaries, separating distinct zooplankton communities (Atkinson et al., 2012).

2. Data and methods

In this study, we review the present state of knowledge on plankton variability in the marine environment around southern Africa. We incorporate findings
derived from historical in situ measurements of plankton biomass and composition, and illustrate recent findings derived from remotely sensed observations.

3. Results and Discussion

Unsurprisingly, knowledge on plankton variability around southern Africa is heavily biased toward regions of elevated productivity, with far more studies having been conducted in the Benguela upwelling system than in the Agulhas Current system or in the Southern Ocean. This has resulted primarily because of the Benguela’s substantial economic value related to commercial fishing, marine aquaculture, offshore oil and gas production, diamond mining, and coastal tourism, among others.

While phytoplankton research and monitoring in the Benguela upwelling system started in the 1870s, zooplankton studies lagged far behind, only becoming a focus in the early 1950s with the development of pelagic fisheries (Verheye et al., 2016). Since then, numerous studies have documented the dominant phyto- and zooplankton assemblages in the region, and there have been a variety of studies to estimate biomass and production. However, compared to other Eastern Boundary Upwelling Systems, these observations have been relatively infrequent and very spatially limited. The ever-increasing costs associated with in situ sampling of plankton communities, and the severe decline in taxonomic expertise in recent decades, has pushed the research community toward more cost- and time-effective ways of conducting phyto- and zooplankton research and monitoring in the region.

As a result of limited societal drivers, much less research and monitoring effort has been directed along the east coast of southern Africa. While the Agulhas Current off South Africa has received some attention in recent decades due to its important role in the global thermohaline circulation, the adjacent shelf regions have been largely deprived of in situ sampling. Most in situ studies along the East Coast have been heavily geographically constrained, and isolated to individual surveys. However, the recent establishment of numerous Marine Protected Areas along South Africa’s east coast have resulted in new efforts to understand oceanographic variability and its impacts on biological communities (Russo et al., 2019; Barlow et al., 2020).

Recent studies have demonstrated the utility of satellite observations in characterizing phytoplankton variability around Southern Africa, at spatial and temporal scales not possible from conventional in situ measurements (Fig. 1). Lamont et al. (2018) refined a global three-component phytoplankton size class model using local pigment observations and described previously unknown seasonal and spatial variations in chlorophyll a (chl a) and phytoplankton size structure in the shelf and open ocean regions.

Figure 1: Long-term mean MODIS-Aqua chlorophyll a around southern Africa, illustrating regions of persistently elevated phytoplankton biomass (from Lamont et al., 2018). Demarcated regions are the Northern Benguela (NB), Southern Benguela (SB), Agulhas Bank (AB), Agulhas Current region (AR), Mozambique Channel (MC), northern Antarctic Circumpolar Current region (NACC), southern Antarctic Circumpolar Current region (SACC), and the Prince Edward Islands (PEI). Dotted black contours indicate the 1000 m isobath and solid black contours indicate the 1 mg m⁻³ isoline.

In the first 20-year study of phytoplankton biomass and size structure in the Benguela, Lamont et al. (2019) demonstrated an increasing trend of chla and microphytoplankton in the shelf and open ocean regions of the northern Benguela (NB). In contrast, decreases were evident in the shelf regions of the southern Benguela (SB), while the open ocean area showed small increases in austral winter and a decrease in spring. Chla and microphytoplankton on the Agulhas Bank (AB) have shown increases in summer and declining trends during other seasons. Similar long-term studies have not yet been conducted for the east coast of southern Africa, nor for the Southern Ocean area south of Africa, but Lamont et al. (2018) illustrated distinct differences in seasonality between the shelf and open ocean regions along the east coast. A study by Thomalla et al. (2011) revealed a complex pattern of regional variations in the seasonal expression of chla in the Southern Ocean.

These trends in phytoplankton are in general agreement with zooplankton trends for autumn in the SB and during spring on the Agulhas Bank, with decreases in chla and microphytoplankton associated with decreases in zooplankton abundance and a shift in community structure from dominance of larger species to dominance of smaller species. In contrast,
decreases in zooplankton abundance in summer on the AB shelf seem to be associated with a small but significant increase in chla. Decreases in zooplankton abundance in the NB shelf region seem to be related to small but significant increases in chla and microphytoplankton, and an overall decrease in upwelling-favourable wind conditions in recent years.

Although the usefulness of satellite observations of phytoplankton biomass and size structure is well known and globally accepted, several inconsistencies in longer-term variations and trends have been highlighted, with in situ and satellite time-series sometimes showing seemingly contradictory patterns. The applicability of satellite observations to only the surface layers presents a critical gap in the sampling of phytoplankton communities from space and emphasizes the need for sustained long-term subsurface measurements.

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Benguela Niños
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In this review, based on our keynote presentation at the Nansen Tutu 10-year anniversary in Cape Town, we summarize the current knowledge on Benguela Niños, a tropical Atlantic climate phenomenon. Benguela Niños and Niñas are extreme warm and cold events that develop off the coast of Angola and Namibia on interannual time scales with a tendency to peak during the months of March to May. These high anomalies in sea surface temperature (SST) have a large impact on regional rainfall and the local marine ecosystem. While the events are predominantly remotely forced from the equatorial Atlantic through the propagation of equatorial Kelvin and coastal trapped waves, local wind stress fluctuations and other local processes are not negligible. Both the local and the remote forcing can be linked to variations in the strength of the South Atlantic high-pressure system.

1. Introduction

The Benguela Upwelling System is one of the most productive ecosystems in the world. The upwelling is driven by Ekman dynamics through the equatorward winds along the coast that are part of the South Atlantic anticyclone (SAA). It is a unique upwelling system in that it is encircled by warm waters at both boundaries, i.e. by the equatorial waters in the north and the Agulhas Current system in the south. Towards the north, a sharp gradient in sea surface temperatures (SSTs) marks the region in which the warm equatorial waters meet the cooler waters that are transported equatorward by the Benguela current. This Angola-Benguela Front (ABF) is located at about 17ºS. In this region extreme warm and cold events in which the SST can be up to 4ºC warmer or cooler than in the climatological average have been observed. These events can last for several months and are of great socio-economic importance for the countries of Southern Africa due to their impacts on climate, rainfall, marine productivity and fisheries in the Benguela Upwelling System. Due to their similarity with the El Niño phenomenon in the Pacific Ocean, they have been termed Benguela Niños (Shannon et al., 1986). In the following, we will give an overview over the characteristics of Benguela Niños and the mechanisms that generate them as well as their impacts and the prospects of forecasting them.

2. What are Benguela Niños?

Benguela Niños are intermittent, acute, extreme warm events that occur near the border between Angola and Namibia. The corresponding cold events are called Benguela Niñas. To define Benguela Niño and Niña events, time series of SST are typically averaged either over the Angola Benguela area (ABA, 20ºS to 10ºS, 8ºE to 15ºE; Florenchie et al., 2003) or over a 1º coastal band off Angola and Northern Namibia (e.g. Rouault, 2012) and the seasonal cycle is removed to focus on the interannual variations. Prominent warm events occurred in 1963, 1984, 1995, 2001, and 2011 with additional minor events in between. Major cold events took place in 1982, 1992, 1997, and 2010. The events tend to develop in the beginning of the year and peak in austral fall, i.e. between the months of March and May, when SSTs are climatologically highest and the ABF is in its southernmost position. A composite evolution of Benguela Niño events occurring in 1976/1977, 1984, 1995, and 2001 is shown in Figure 1 from an ocean model simulation.

![Figure 1: Composite maps of detrended anomalies of T₁₀ (in color; in °C) and surface wind stress (arrows; N/m²) computed from four selected extreme warm coastal events (1976/1977, 1984, 1995, and 2001) and averaged during (a) December–January (three months before peak), (b) January–February (two months before the peak), (c) February–March (one month before the peak), (d) March–April (peak), (e) April–May (one month after the peak), and May–June (two months after the peak), from Imbol Koungue et al., 2019.](image)

3. Forcing mechanisms

SST variability in the Angola Benguela area can in general be driven by both local processes and by remote forcing from the equatorial Atlantic. While local processes can be important for the development of individual events such as in 2016 (Lübbecke et al.,...
2019) most studies point to the dominant role of remote equatorial forcing.

3.a Local Forcing

Changes in wind-driven upwelling caused by variations in the alongshore coastal winds can lead to SST anomalies. Results by Richter et al., (2010) based on observations and coupled model simulations indicated that this process can play an important role for the generation of Benguela Niño events. Other local processes that can impact SSTs in the Angola Benguela region include changes in the net heat flux, e.g. by reduced latent heat loss due to weakened winds, variations in the meridional currents, and anomalous freshwater input that impacts the stratification. All of these processes have been suggested to contribute to the warm event that took place in early 2016 (Lübbecke et al., 2019).

3.b Remote Forcing

Despite the importance of local forcing in the generation of individual events, the vast majority of studies agrees on the dominance of remote equatorial forcing of Benguela Niño and Niña events (e.g. Florenchie et al. 2003, 2004; Lübbecke et al., 2010; Bachelay et al., 2016; Imbol Koungue et al., 2017). Wind stress anomalies in the western equatorial Atlantic can excite equatorial Kelvin waves that propagate across the basin. Once they reach the eastern boundary, part of their energy is transmitted poleward as coastal trapped waves. A weakening of the trade winds results in downwelling Kelvin waves while a strengthening of the winds results in upwelling Kelvin waves. Along the Southwestern African coast, a downwelling coastal trapped wave is associated with a positive anomaly in sea level and a deepening of the thermocline. It also strengthens the poleward flow of warm tropical waters and reduces the vertical velocity, generating a positive subsurface and subsequently surface temperature anomaly. In contrast, an upwelling coastal trapped wave is associated with a negative sea level anomaly, a shallower thermocline, weaker poleward flow and stronger upwelling, resulting in a cold temperature anomaly (Bachelery et al., 2016). Recent results from a regional model study indicate that about 60% of the interannual SST variability in the ABA is due to remote equatorial forcing (Bachelery et al., 2020).

3.c Large Scale Conditions

As described in the previous subsections, Benguela Niño (Niña) events are forced by a relaxation (strengthening) of the alongshore equatorward and/or the western equatorial trade winds. The strength of both of them is actually related to the strength of the high-pressure system in the South Atlantic, the South Atlantic anticyclone (SAA). Consequently, the strength of the SAA in February is well correlated with ABA SST anomalies one to two months later (Lübbecke et al., 2010). The weakening of the basin wide winds prior to the Benguela Niño event can also be seen in the composite evolution in Figure 1.

4. Impacts on regional rainfall and the marine ecosystem

4.a Impacts on regional rainfall

The impacts of coastal extreme warm events on humidity flux and precipitation are investigated in the study of Rouault et al. (2003). Their results suggested that the coastal extreme warm events occurring around the ABF zone modulate the local moisture flux circulation and induce enhanced precipitation along the African coast. The coastal warm events reinforce the local evaporation and cumulus convection resulting in the active precipitation over the coastal southwestern Africa. This leads to floods in the arid Namibia coastal area. Similar conclusions are reached by studies of Hanshingo and Reason (2009) and Manhique et al. (2015).

However, Koseki and Imbol Koungue. (2020, submitted) have for the first time investigated the influence of coastal extreme cold events, i.e. Benguela Niñas, on the regional atmosphere in March–April using state-of-the-art reanalysis data sets and high resolution Atmospheric General Circulation Model (AGCM). Composite analysis of the reanalysis data based on 5 extreme Benguela Niña events revealed that the precipitation along the Angolan coast is significantly reduced. Additionally, other rainfall anomalies are found over the African Continent and the equatorial Atlantic. These anomalies of precipitation are highly consistent with the anomaly of vertically-integrated moisture flux divergence and convergence. The numerical simulations forced by a localized cold SST anomaly show a similar reduction of the precipitation along the Angolan coast and moisture flux anomaly, but other anomalies of precipitation are less significant, indicating that the Benguela Niña impacts are locally limited.

4.b Impact on the marine ecosystem

Regarding the impacts on the marine ecosystem, Boyer et al. (2001) observed between 1993 – 1996 in the northern Benguela waters a poor recruitment and a decrease catch rate in the stock of sardines. Those negative factors were associated with the presence of hypoxic shelf waters in 1993/94 and the occurrence of the Benguela Niño in 1995. During this coastal extreme warm event, SST anomalies exceeded 3°C in March 1995. Similar results were obtained by Gammelsrød et al. (1998) off Angola-Namibia, but they also observed a poleward shift of the Sardinella populations from Angola which were probably looking for better environmental living conditions.
5. Predictability

Due to their impacts on marine ecosystem, rainfall and climate, the prediction of these coastal warm and cold events is very important for the countries of southern Africa and especially for the coastal communities. A recent study from Imbol Koungue et al. (2017) has tried to work toward this goal. The authors combined dynamic height from three real-time equatorial PIRATA moorings (23°W, 10°W and 0°E), sea surface height (SSH) from an ocean linear model and SSH from altimetry at each mooring position to build an index of equatorial Kelvin wave activity based on the PIRATA records to predict the warm and cold events along the ABF zone. They found a lag of 1 month when a second mode equatorial Kelvin wave leads SST anomalies along the ABF zone. This lag of 1 month usually occurs between the season from October to April, indicating some predictability during these months.

References


Length-scales of mesoscale variability and eddies in the tropical South-East Atlantic Ocean based on satellite Altimetry observations

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Mesoscale eddy occurrence and distribution in the tropical South-East Atlantic Ocean has been investigated using twenty-four years of satellite altimetry observations. Maps of absolute dynamic topography spatially gridded at ¼, on a daily basis were used covering a period between 1993 and 2017. The eddies spatial coverage has shown a significant equatorward decrease of their population, with increasing size. The cyclones and anticyclones exhibited similar Gaussian distribution, with no significant statistical difference between them, with predominant eddies having a radius of 70 km. Maps of horizontal length-scales of oceanic geostrophic flows, namely, the first baroclinic Rossby radius of deformation and the Rhine scales were inspected in order to explain the meridional distribution patterns of the eddy field. Both, the Rossby and the Rhine scales appeared to overlap to the north of 12°S, at about 100 km radius, in agreement with an early study which suggested an onset of a critical latitude in the region around 11.5°S. According to theories of 2D geostrophic turbulence these relations appear to explain the sharp equatorward transition of mesoscale regimes between nonlinear eddies and linear Rossby waves which are frequently observed in the region.

1. Introduction

As reviewed by Shillington et al. (2006), the main physical oceanographic processes in the South-East tropical Atlantic include the following: a dominant equatorward wind stress that induces coastal upwelling process along the coasts of South Africa and Namibia, instabilities of oceanic fronts, filaments, frontal jets, eastward/westward propagation of Kelvin/Rossby waves respectively (Koumgue et al., 2017), internal waves (Ostrowski et al., 2009), and poleward propagation of coastal trapped waves along the Angolan coast (Rouault et al., 2007; Illig et al., 2019). Nevertheless, the oceanography of this region remains under studied, knowledge of the eddy occurrence and properties remains scanty, even though eddies are important geophysical structures in the region, capable to shape the ocean biology, and the climate variability and predictability. To complement the existing knowledge, in this study we have investigated the eddy occurrence and their distribution by assessing the horizontal length scales of mesoscale geostrophic flow variability inferred from the relation between the first baroclinic Rossby radius of deformation and the Rhines scale.

2. Data and Methods

The data used to map the first baroclinic Rossby radius of deformation in this study was derived from The global dataset published by Chelton et al. (1998), which is computed using the equation:

\[ RD = \int_{-h}^{0} \frac{N}{\pi f \delta z} \text{d}z \]  \hspace{1cm} (1)

Where \( N \) is the Brunt-Vaisala stratification frequency, \( h \) is oceanic depth level, and \( f \) is Coriolis parameter. The Rhines scale \( L_R \) was determined following Rhines (1975), using the equation

\[ LR = \sqrt{\frac{U_{rms}}{2\beta}} \]  \hspace{1cm} (2)

Where \( U_{rms} \) is the eddy's rotational speed, estimated from eddy kinetic energy \( EKE = \frac{U'v'}{2} \), using the relation, \( U_{rms} = 2EKE \). The \( EKE \) was calculated using the fluctuations of the horizontal components of the geostrophic velocities \( u' \) and \( v' \), determined from maps of the absolute dynamic topography, measured by satellite altimetry. The data is gridded at ¼ in longitude and latitude, on a daily timescale, and the period used here spans from 1993 to
The eddies were extracted from the eddy field tracked by Halo et al., [submitted]. The equivalent eddy mean radius $R$ was estimated using the relation proposed by Souza et al. (2011).

$$R = \sqrt{\frac{\sum A}{N\pi}}$$  \hspace{1cm} (3)

Where $A$ is the eddy’s surface area, assumed to have a circular geometry, and $N$ is the total number of eddies.

3. Results

Figure 1a shows the spatial distribution of the eddy generation sites and the eddies trajectories. Only eddies with a lifespan of 7 days and greater were selected. Blue dots represent cyclonic, and red represents anticyclonic eddies. The statistics performed by Halo et al [submitted], suggests that a total of 1642 eddies are present in Figure 1a. This corresponds to 52.3% anticyclonic (red) and 47.7% cyclonic (blue). The result also suggests that there are more eddies being formed in the southern parts than in the northern parts of the domain. The generation of eddies in the vicinities of the continental shelf in the northern sector (between 5°N S and 2°N) (Figure 1a) resembles coastal trapped eddies documented by Djakoure et al. (2014) in the Gulf of Guinea. Results from their numerical model simulation have indicated that these eddies are formed mostly by mean of flow interactions and barotropic instabilities associated with the Cape Palmas and Cape Three-Points, located to the western and eastern of Ivory Coast respectively (Djakoure et al., 2014). Nevertheless, they fall outside of our region of interest, thus are not investigated further in the present study. On the other hand, the generation of the eddies in the southern sector, supports the hypothesis presented by Colberg and Reason (2007), which suggests the prevalence of eddies across the Angola Benguela Frontal Zone, as also documented by Meeuwis and Lutjeharms (1990). The latter attributed to frontal instabilities as the driving physical mechanism responsible for their formation. Figure 1b shows the histograms of their density distribution, expressed in terms of frequency of occurrences in %, as function of eddies radii in km. The eddies have been clustered between radius of 50 and 170 km, at every 10 km interval. The dark grey (cyclones) and light grey (anticyclones) for the eddies determined in the tropical South-East Atlantic Basin. The overlay lines represent eddy non-linearity parameter ($r$), for cyclones (blue), and anticyclones (red), from Halo et al. [submitted].

Figure 1b is that $r$ decreases consistently with increasing radius. As discussed in Halo et al. [submitted], Theiss (2004) computed an equivalent $r$, using the relation between the first baroclinic Rossby radius of deformation ($R_o$) and Rhine scale ($L_R$), whereby $r=R_o/L_R$. He demonstrated that for $r>1$ the waves do not transfer energy into zonal flows, permitting the emergence of eddies. Whereas for $r<1$ the waves dissipate into zonal alternating flows (Theiss, 2004). Halo et al [submitted] demonstrated that in this region a critical latitude value...
corresponding for \( r=1 \) is achieved at about 11.5°S. This is further corroborated in Figure 2, where the relationship between \( R_D \), \( L_R \) can be inferred by comparing Figure 2a against Figure 2b respectively.

Figure 2: Spatial distribution of the horizontal length-scales of geostrophic flows, a) first baroclinic Rossby radius of deformation from Chelton et al. (1998), determined from equation 1, b) Rhine scale, determined from equation 2, and c) radii of the tracked eddies, estimated with equation 3.

It is evident that an overlap of the length scales occurs only to the north of 12°S, which supports the onset of critical latitude towards 11.5°S. In Figure 2c, \( R \) represents the eddy radius. Notice that it is towards this latitudinal band that a maximum eddy size is achieved (Figure 2c). Overall in Figure 2, it is notable that all these length scales grow equatorward. \( R_D \) ranges from 40 km in the south to 150 km in the north. \( L_R \) ranged between 80 km and 120 km without a specific spatial pattern, and \( R \) between 60 km and 120 km, with a relatively clearer spatial distribution than \( L_R \), with its lower ranges more in the south and upper ranges more in the north. Also it is evident that \( R \) grows zonally from the coast towards off-shore (Figure 2c).

4. Conclusions

In this study we have demonstrated that mesoscale eddies are present in the tropical South-East Atlantic Ocean. They are more prevalent in the Cape Basin than in the Angola Basin, indicating an equatorward decrease of their population. Both cyclonic and anticyclonic showed similar near Gaussian distribution, and had almost the same prevalence, 52% (anticyclones) and 48% (cyclonic). Their maximum sizes were predominantly observed to the north of 12°S, where \( R_D \) and \( L_R \) overlaps, allowing for the determination of a critical latitude band, whereby the theories of 2D geostrophic turbulence would favour regime transition between nonlinear eddies and linear waves. This may explain why there are fewer eddies to the north of 12°S, when compared to other regions of the world oceans.

References


Using satellite-based visualization tool to study the dynamics of the Agulhas Current: The early retroflection
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Abstract: Retroflection describes the ability of the Agulhas Current to curve backward on itself at the southern tip of Africa to become the Agulhas Return Current as first observed by closely spaced in-situ bathythermograph surface temperature readings (Bang, 1970). Lutjeharms (1981) corroborated these findings by satellite-derived thermal infrared imagery. The retroflection is key to the understanding of the regional upper ocean dynamics (Lutjeharms, 2006). Whereas the retroflection usually is located at about 18-20° E, early retroflections have been encountered as far east as 26° E (Lutjeharms, 2006; Dencausse et al., 2010; van Aiken et al., 2013). In this proceedings paper we demonstrate the value of applying a data visualisation portal (SynTool) to investigate the spatial and temporal evolution of early retroflections of the greater Agulhas Current system. The data are available from the GlobCurrent project and includes satellite-based surface geostrophic currents from altimetry, Ekman currents jointly derived from scatterometry, surface drifters, and Argo profiling floats, as well as microwave radiometry-based sea surface temperature fields. The analyses suggest that the early retroflection is triggered by the north-to-south co-alignment of an eddy inshore of the Agulhas Current core with the large meander of the Agulhas Return Current centered at about 24-26° E.

1. Introduction

The greater Agulhas Current system is very energetic with complex and intense upper ocean dynamics expressed by distinct collocated gradients in the sea surface temperature (SST), the sea surface height (SSH) and the surface current. Benefitting from satellite sensor synergy one can derive daily to weekly maps of both the surface temperature and velocity fields and hence monitor the temporal and spatial evolution of these gradients as demonstrated by the GlobCurrent project (http://www.globcurrent.org) funded by ESA from 2014 to 2019. The GlobCurrent project has delivered global data products covering a 27-year period from 1993 to 2020. The products include surface geostrophic currents and Ekman currents (at the surface and 15 m depth) derived from a combination of satellite altimetry, gravimetry and scatterometry together with in-situ data (Argo floats, surface drifters) and further complemented with satellite-based passive microwave SST fields. The data are interpolated to a common grid with a spatial resolution of 25 km and a temporal resolution of three hours for the Ekman components and daily for the geostrophic current and SST fields. The readers are referred to (Rio et al., 2014; Chapron et al., 2019) for a detailed explanation on how these products are derived. Infrequent episodes of early retroflection of the Agulhas Current have been reported to last from weeks to months (e.g. Lutjeharms, 2006; van Aiken et al., 2013; Dencausse et al., 2010). In particular, Dencausse et al. (2010) analysed an altimeter-based time series of the longitudinal position of the retroflection point from 1993 to 2005 and found an extreme eastward position of an early retroflection in 2000-2001 at 26° E. In comparison to the mean retroflection position of 18° E, this implies an eastward retreat of about 440 km. A recent study by Russo et al. (2020) presented a novel method to objectively detect the Location of the Agulhas Current Core and Edges (LACCE) from mapped altimetry fields, and used it to describe the spatial and temporal variability of the Agulhas Retroflection. The LACCE method identified a total of seven early retroflection events between 1993 and 2019. Four of these events (in 1999, 2000-2001, 2008, and 2019) reached easternmost longitudes > 24° E. In comparison, the remaining three events (in 2013, 2014, and 2018) were much less extreme, with easternmost longitudes between 22 and 23° E, and more closely resembled Agulhas ring shedding events, as opposed to early retroflections (Russo et al., 2020). In spite of these reported observation-based findings there is evidently no explicit explanation for the mechanism that triggers early retroflection. Nor have numerical ocean models been able to properly simulate these events. In this proceedings paper we demonstrate the value of SynTool applied to the GlobCurrent data to investigate selected cases of early retroflection in the greater
The preconditioning has thus been established, and the
Agulhas Current system (Lutjeharms, 2006; Johannessen et al., 2018). The Agulhas Current retroflection is key to the understanding of the regional upper ocean dynamics. Retroflection describes the Agulhas Current’s ability to curve backward on itself at the southern tip of Africa to become the Agulhas Return Current (Bang, 1970). Bang’s findings based on closely spaced bathythermograph surface temperature readings, were later corroborated by satellite thermal infrared imagery (Lutjeharms, 1981). It is estimated that up to 55 Sv of the net transport of 95 Sv is returned to the Indian Ocean by the Agulhas Return Current, via the retroflection. The remaining water is transported into the South Atlantic by filaments as well as eddy shedding. These eddies, often named “Agulhas rings”, can reach 200-300 km in diameter, and transport large amounts of heat and salt from the Indian to the Atlantic Ocean. Their lifetimes have been estimated to reach more than two years.

In section 2 the data and methods are presented, together with an analysis and discussion of results. The summary and outlook are then addressed in section 4.

2. Data and analyses

The mean dynamic topography (MDT) (Rio et al., 2014) of the greater Agulhas Current system is displayed in Figure 1. It clearly expresses strong gradients in the SSH related to the poleward flowing Agulhas Current core, the retroflection and the eastward flowing Agulhas Return Current. Maximum mean surface geostrophic currents of about 1.5 m/s are encountered in the current core with a typical width of 100 km. Extending to more than 1000 m depth the corresponding volume transport are reported to reach up to 121 Sv (Bryden et al., 2005; Gordon et al., 1987). The mesoscale variability is particularly characterized by distinct poleward propagating clockwise rotating eddies (Natal Pulses) triggered by upstream meandering of the core and by eddy shedding in the retroflection region. In contrast, the large meandering pattern of the return current appears to be more semi-permanent due to topographic steering. However, this state of the greater Agulhas Current system appears to undergo a significant modification during episodes of early retroflection.

The SynTool visualization portal was initially developed within the ESA funded OceanVirtualLab (OVL) (https://ovl.oceandatalab.com) and GlobCurrent (http://www.globcurrent.org) projects. The portal has been demonstrated to be an innovative and attractive tool to display the increasing amount of satellite data, in a user-friendly manner. In particular, SynTool enables efficient colocation and exploration of the multi-variables derived from satellite sensor synergy, both in near real time and offline modes. In turn, one can better describe and understand the upper ocean dynamics and their evolution at different spatial and temporal scales.

It is desirable to demonstrate this by revisiting the temporal-spatial evolution of the observed strong early retroflection event in 2000-2001 reported by Dencausse et al. (2010), and more recently by Russo et al. (2020). SynTool clearly reveals a shift from the presence of a distinct south-westward flow of the Agulhas Current core to an early retroflection as seen in Figure 2. In fact, this appears to occur twice between 28 October and 30 November 2000 as seen in the linked animation (https://ftp.odd.bzh/odd/globcurrent/early_rf_2000.gif).

The hypothesis is that upstream meandering of the Agulhas Current core has triggered the poleward advection of a clockwise rotating eddy (Natal Pulse) of about 100 km in diameter on the nearshore side of the Agulhas Current core. At around 24-26° E the eddy becomes co-aligned with a larger scale semi-stationary clockwise curving meander in the Agulhas Return Current with a dimension of 300 – 400 km. The evolution to this north-to-south co-alignment is considered to be a pre-conditioning phase that subsequently may trigger a transition to an early retroflection as schematically illustrated in Figure 3. Going to the October-December 2019 event, the SynTool displays a comparable early retroflection in the Agulhas Current system that also evolved around the three distinct phases illustrated in Figure 3. A south-westward propagating cyclonic eddy inshore of the Agulhas Current core, a remnant of a Natal pulse formed around 10 September, is gradually seen to co-align with a meander in the Agulhas Return Current centred around 24-26° E between 28-30 October 2019. The preconditioning has thus been established, and the
transition into an early retroflection is reached on 5 November 2019, consistent with the hypothesis schematically shown in Figure 3. In contrast to the 2000-2001 event, this early retroflection only lasted for 11 days from the preconditioning phase, via the transition phase, to the early retroflection phase (see animation https://ftp.odl.bzh/odl/globcurrent/early_rf_2019.gif).

On 18 October 2019, the Agulhas Current core extends to the normal retroflection area at about 18-20° E followed by the large eastward meandering Agulhas Return Current (Figure 4, upper). In comparison, the snapshot of the combined SST and surface current structures on 15 November 2019 clearly captures the presence of a cyclonic eddy inshore of the current core, co-aligned with the large meander in the return current centred in a north-south direction at about 24-26° E (Figure 4, lower). This co-alignment is evidently triggering an early retroflection upstream followed by an elongated anticlockwise circulation downstream.

An early retroflection will have distinct influence on the dynamics of the Agulhas Current system and also drive major changes to the heat and volume transports. This is demonstrated by the tracer information derived from the time series evolution in the SST field from early October 2019 to end of November 2019. The evidence of early reflection is depicted in the SST field as a gradual decrease in the south-westward transport of warm water by the Agulhas Current from about 25° E. In contrast, the return to a normal retroflection located at about 19-20° E is then traced by the gradual increase in the SST field associated with the return to a continuous south-westward heat transport by the Agulhas Current core.

In complement and consistence to the SST and surface current fields shown in Figure 4b the 5-days average vorticity field (∂v/∂x − ∂u/∂y + f) derived from 10 to 15 November 2019 (see Figure 5) expresses clear evidences that the normal path followed Agulhas Current core (as noticed in Figure 4a) has broken down. Instead the structure of the vorticity field manifests the presence of the early retroflection at about 25° E as well as the location of a larger elongated anticyclonic meander to the west.

![Figure 3](image)

**Figure 3.** Schematic illustration of the evolution towards early retroflection. (upper) Preconditioning phase ensured by co-aligned eddy in the Agulhas Current core (red curving-arrows) and larger semi-stationary meander in the Agulhas Return Current (light brown curving-arrows). (middle) Emerging of the transition phase. (lower) Formation of the early retroflection.

![Figure 4](image)

**Figure 4.** Snapshot display of the SST (colour) and surface current field (white lines) derived on 18 October 2019 (upper) and 13 November (lower) revealing the transition towards early retroflection. A mark the nearshore clockwise rotating eddy; B the downstream large elongated anticlockwise circulation; and C the early retroflection.
An additional complementary way of identifying the expression of early retroflection is by extracting the Lagrangian Coherent Structures (LCS) based on the Finite-time Lyapunov Exponent (FTLE) method (Haller, 2000) as shown in Figure 6. In so doing the GlobCurrent data that encodes the time-dependence in the velocity field are used to derive the particle trajectories over the 5-days interval from 10-15 November 2019. Evidently, the structure of the trajectories associated with this early retroflection are revealed by the distinct and strong deformation in the north-south direction centered at about 25° E.

Figure 6. Deformation field derived from the Finite-time Lyapunov Exponent for 10-15 November. The color scale marks the strength of the deformation in units of day⁻¹.

3. Summary and Outlook

In this paper the temporal and spatial evolution of selected early retroflections of the Agulhas Current system has been investigated using GlobCurrent-based satellite and in-situ data products. The analyses and findings suggest the following stepwise transition from a preconditioning phase via a transition to an early retroflection, notably:

(i) A Natal pulse forms and starts to propagate south-westward as a cyclonic eddy (~100 km diameter) along the near shore side of the Agulhas Current core;
(ii) In parallel a distinct large bell-shaped clockwise curving meander (~300 - 400 km) in the Agulhas Return Current becomes topographically steered by the Agulhas Plateau at about 38° S and 25° E;
(iii) The cyclonic eddy co-aligns with the large meander in a north-south direction at about 24-26° E and the so-called precondition is reached;
(iv) The current pattern manifesting the presence of the cyclonic eddy and the large meander gradually merge to set-up the transition phase;
(v) The upper ocean current subsequently restructures and reshapes, and the early retroflection is formed.
(vi) The early retroflection ceases to exist when the Agulhas Current core reshapes to form a continuous flow steered along the shelf break of the Agulhas Bank.

Although the two early retroflection events addressed in this study both started in October-November, it is inadequate to claim that there is a seasonality in the occurrences of this event. Two of the seven events identified by Russo et al. (2020) between 1993 and 2019 took place during winter, while the remaining events occurred in summer and spring. In addition, while the position of the Agulhas Retroflection was located further east (39.75° S; 18.25° E) during summer, and further west (39.5° S; 18.25° E) in winter, these differences were not statistically significant. Moreover, whereas the 2000-2001 case lasted for 5-6 months, the recent 2019 retroflection event was only present for close to two weeks.

The adjustment in the thermodynamics of the Agulhas Current system associated with early retroflection significantly changes the south-westward heat and volume transport and probably also the eddy shedding. This may, in turn, have impact air-sea interaction as well as the ecosystem in the greater Agulhas Current system. It is therefore timely and highly important to build on the regular satellite-based monitoring capabilities and advance data assimilation and numerical ocean model predictions of the early retroflection as well as the break-down of this extreme event. The characteristics of the 3D hydrography and velocity fields as well as changes in the coupled physical-biological structures might then also be better explored to strengthen ecosystem management for societal benefit.

References


Biogeochemical operational modeling in the Arctic using the TOPAZ forecasting system

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The TOPAZ system provides forecasts of ocean, sea-ice and biogeochemistry using data assimilation. The system is used for basic research, but its main application is in operational oceanography as the central tool for providing marine forecasts in the CMEMS Arctic Marine Forecasting Center. The focus is on the Northeast Atlantic and Arctic, though the present model covers the entire North Atlantic. The physical system has been operational for more than 15 years, while the biogeochemical model has been operational since 2011. In addition to a 10-day forecast, a long-term reanalysis for biogeochemistry including data assimilation of biogeochemical observation is also produced. In the upcoming update to the reanalysis the assimilated observations will be expanded to include in-situ observations of nutrients in the water column. The present operational biogeochemical model consists of ECOSMO coupled to the ocean model HYCOM. Some recent developments of this model include the addition of prognostic chlorophyll and carbon chemistry. An optional module for calcifying algae has also been added to the model but is not yet part of the operational system. Here we present an overview of the biogeochemical operational system, operational products, and planned developments.

1. Introduction

Prediction systems for marine biogeochemical variables are now more common, and both regional and global operational models exist (Fennel et al., 2019). Uses of these models include assessment of environmental conditions and identification of habitats for fish or marine mammals. Operational model-based products typically are either forecast, a forward prediction started from the best possible initial conditions, or a reanalysis - a reconstruction of the past that assimilates available observations. The forecasting system is restricted to assimilate real time data, which for biogeochemical forecasts currently is limited to ocean colour from satellite and observations from BIO-Argo. The assimilation of both have been demonstrated in different systems, although the impact of assimilating ocean colour is better established. For the reanalysis, which extends back in time, an extended data set containing more and better quality controlled variables can be used.

Our group is developing a biogeochemical forecasting system for the Arctic as part of the TOPAZ forecasting system, which is used by the Arctic Marine Forecasting Centre (ARC MFC) within the Copernicus Marine Environment Monitoring Service (CMEMS). The biogeochemical model has been operational since 2011. In 2017 a major change was implemented as we changed from the biogeochemical model NORWECOM to ECOSMO. ECOSMO is comparable in complexity to NORWECOM, but has a more detailed handling of bottom sediments as well as including a flexible carbon-to-chlorophyll a ratio. The latter is an advantage when assimilating observations of chlorophyll. Here we present the model system at the base of the operational system (section 2), the status of both the biogeochemical forecast and reanalysis (sections 3 and 4) and finally an outlook for development of the system (section 5).

2. Data and methods

The TOPAZ system consist of the physical ocean model HYCOM (Sakov et al., 2012), a sea ice model with EVP dynamics, the biogeochemical model ECOSMO (Daewel & Schrum, 2013), and an EnKF data assimilation system (Evensen, 2009). The present forecasting and physical reanalysis domain has 12km resolution and covers the North Atlantic and Arctic. The model is forced by atmospheric forcing, including the short-wave radiation used by phytoplankton for photosynthesis, from the ECMWF. River runoff are computed by a hydrological model (TRIP) forced by ECMWF reanalysis precipitations, likewise the nutrient loads in rivers are derived from a global model of nutrient loads (Seitzinger et al., 2010). The river forcing consists of monthly climatologies for volume fluxes and an annual climatology for nutrient loads and the model therefore does not simulate any interannual variability of nutrient fluxes. The biogeochemical model is computed on the same grid as the physical ocean model and uses the same time-step. Presently the model is parameterized so that no light enters the ocean in sea-ice covered regions.
3. Biogeochemical forecast

The biogeochemical forecast is initialized together with the physical forecast. Data is assimilated in the physical ocean model, including sea surface temperature from satellite and temperature and salinity profiles from Argo-floats and other in-situ measurements. Assuming that hydrodynamics control the nutrient distribution and the lower trophic levels of the ecosystem, improvements of the hydrodynamics, such as the correct placement of eddies and correction of the surface mixed layer, will additionally lead to an improvement of the quality of the biogeochemical forecast. The biological state variables are updated at every assimilation step to account for changing vertical positions of the model isopycnic layers so that mass conservation is ensured when layers thickness is changed by the assimilation. We have not yet exhibited that the assimilation of physics improves the forecast, but we have demonstrated that it provides reasonable results and does not lead to negative effects, such as unphysical mixing of tracers (Samuelsen et al., 2009). The variables provided from the forecast are nutrients (nitrate, silicate, phosphate), as well as phyto- and zooplankton biomass. In addition we provide oxygen concentration, chlorophyll and light attenuation coefficient, which is computed from the modeled chlorophyll. In general we have higher confidence in the system at the nutrient/phytoplankton level, than for zooplankton. This is both because nutrients and phytoplankton are more closely coupled to the physical variability and less dependent on uncertain biogeochemical parameters, and because the amount of observations available on these variables for evaluating the model results is substantially larger and methodologically more reliable. The forecast is operated by the Norwegian Meteorological Institute and subject to weekly evaluation of the forecast error and bias as compared to ocean colour observations.

![Figure 1: The forecast of chlorophyll a together with the sea-ice concentration on 19. July 2019. Large blooms can be seen in the central Norwegian Sea and along the sea ice edge.](image)

4. Biogeochemical reanalysis

The present reanalysis is performed on a model grid with 30 km resolution, to account for the demanding computational requirements, and covers a four year time period (2007-2010) (Simon et al., 2015). This pilot reanalysis was based on HYCOM-NORWECOM and it employs a joint state-parameter estimation data assimilation system. Chlorophyll from ocean colour was assimilated over the open water, excluding observations less than 50 km form the coast. The assimilation of chlorophyll did improve the chlorophyll estimates in this product. In the Nordic Seas, where we had nutrient observation, the nutrient estimates were mostly unchanged compared to the free run simulation without data assimilation.

At present a new reanalysis for the time period 2007 to 2017 is under production. This reanalysis is generated using HYCOM-ECOSMO and assimilates both ocean colour chlorophyll and historical nutrient profiles, it also uses an assimilation scheme that has an additional smoothing step suitable for biogeochemical models and parameter estimation (Gharamti et al., 2017). Joint state and parameter estimation is applied, meaning that optimal values of selected model parameters will be estimated at the same time as the state. The updated reanalysis is computed with the same resolution as the pilot reanalysis.
4. Future developments

An update of the biogeochemical forecasting system from 12 km resolution to 6 km resolution and double vertical resolution is expected in 2021. Furthermore, the new forecast receives boundary conditions from a global operational model also provided by CMEMS. In the upgraded model, the sea-ice model is upgraded to CICEv5 and the model now allows light to pass into the water column in regions with partial or thin ice cover, allowing for primary production to also occur below the sea ice.

Recently a more flexible sinking scheme and an extension to fish groups was implemented on ECOSMO. We plan to implement the improved sinking scheme in the operational system in the near future, while the addition of the fish group is expected within a few years, but is pending the testing of migration parameterizations, which is important in the Arctic. The addition of the fish group will allow us to include also top-down controls on the ecosystem which may have positive effects on the zooplankton population. It can also make the model more applicable towards ecosystem studies/management.

A big step forward will be the assimilation of real time biogeochemical observation in the forecast system. One future development will include the assimilation of both remote sensing observations and measurements from autonomous platforms such as BIO-Argo. It is an open question how many BIO-Argo-floats are necessary to impact the forecast, but probably the present number of buoys is too low in the Arctic. The use of both empirical methods and machine learning methods to extend the surface observations given by the ocean colour satellite into the water column are currently under investigation. This resulting extended dataset should eventually be assimilated into the biogeochemical model.

5. Data availability

All forecast and reanalysis can be browsed and downloaded (registration required) from https://marine.copernicus.eu/. The regular evaluation of the forecast compared to ocean color observations can be found here: http://cmems.met.no/ARC-MFC/V2Validation/chlA/index.html

References


NANSEN-TUTU 2021 | PAGE 44
SAWS Marine forecast and information services: current capabilities and planned efforts
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In April of 2019, the South African Weather Service (SAWS) Marine Unit launched its Marine Portal. The Portal consists of various operational marine meteorological (or met-ocean) forecast tools and services, serving a wide range of user demands. A focus on high resolution as well as published validation in peer-reviewed literature underpinned this research and development. In this way, it was envisaged that an enhanced service offering, better describing the complex met-ocean dynamics around South Africa’s coastal zone, could be brought to a wide range of recreational and commercial coastal users. Current operational products include regional and local-scale wave forecasts, and regional tide, water level and storm surge forecasts. Associated products are freely available on a newly designed web interface, which also hosts observational information and login-based functionality for users seeking tailored or specialist services.

The next phase of development for the SAWS Marine service seeks to enhance and refine the first-generation systems, as well as to introduce new offerings to the catalogue as research develops.

1. Existing Forecasting Products and Services

The SAWS Wave and Storm Surge (SWaSS) forecasting system (Rautenbach et al., 2020) forms the foundation of the SAWS met-ocean prediction capability. The system provides wave, tide (Rautenbach et al., 2019) and water level forecasts with a lead time of 72 hours and is run at 00:00 UTC and 12:00 UTC each day. Associated products and services are thus updated twice daily. The system is built in Delft3D, utilizing the Delft3D shallow water model for hydrodynamics (tide and water level) and Simulating Waves Nearshore (SWAN: Booij et al., 1999) for waves. The hydrodynamic model has a horizontal resolution of 1/16°, which equates to roughly 7 km for the domain. The wave model consists of a parent domain at 1/16° (~ 7 km), as well as 8 nested domains in key coastal areas, dynamically downscaled to 1/48° (~ 2.3 km) from the parent domain. By incorporating high resolution (~ 4.4 km) atmospheric surface forcing from the SAWS Unified Model, the benefit of higher spatial resolution hydrodynamic and wave grids can be leveraged. This is key in providing met-ocean forecasts which are fit for purposes such as maritime decision-support, in complex embayments such as False Bay and Algoa bay (see Figure 1). In places such as these, global models cannot capture the variability in conditions at spatial scales relevant to local marine operations, and the resolution of atmospheric forcing modulating local wave conditions should be sufficient (Daniels et al., 2020). The operational framework includes postprocessing protocols which facilitate the range of public good services provided by SAWS forecasters to stakeholders such as Disaster Risk Management centres, and dissemination of specialised products to certain marine stakeholders. SWaSS has been integrated into routine SAWS forecasting workflows, as well as coastal impact-based forecast initiatives. Various automated warnings are also provided by the system, elevating the level of marine meteorological awareness among

Figure 1: Examples of wave forecast maps from high resolution nested domains in key port areas. These products are available to the public on the SAWS Marine Portal.
relevant stakeholders. A comprehensive description of SWaSS is provided in Rautenbach et al. (2020).

2. Planned Developments

The next generation of developments related to the SAWS operational marine offering is largely concerned with the enhancement of the SWaSS framework (see Figures 2, 3 and 4). Two specific projects are the extension of the 72-hour lead time – a constraint imposed by the temporal extent of the high-resolution atmospheric forcing – to 7 days, and the development of an ensemble forecast. A longer forecast lead time is to be accomplished by integrating forecasts with lower spatial resolution atmospheric forcing at longer lead times with those forced by higher resolution atmospherics at 72-hour lead times. As a result of the technical set up, this process also adds further redundancy to the SWaSS configuration – a key concern for operational centres. Regarding ensembles, work is underway to build a framework to leverage atmospheric ensembles in providing wave and water level ensemble forecasts. Initial appraisals of the storm surge forecast during Autumn of 2020 suggest that this is an area with great potential, given the sensitivity of the storm surge forecast to the timing, placement and intensity of wind and pressure systems in the atmospheric forcing.

Further afield, research is underway to answer specific questions surrounding sea ice in the Southern Ocean by integrating remote-sensed and numerical forecast data with data collected by SAWS Marine in-situ. This is aimed at better serving WMO mandates concerned with safety of life at sea through the provision of sea ice charting and short-term forecasting services. Preliminary research suggests that Lagrangian sea ice edge forecasts, utilising domain-specific sea ice characteristics (derived by research in-situ) can outperform global models in a robust and computationally efficient framework as shown in Figure 5 (de Vos et al., 2020). Such approaches are well-suited for integration of forecaster/analyst workflows and provide a valuable bridge between “yesterday’s” sea ice field from near-real time remote sensing products and “today’s” ice distribution, which is of critical importance to mariners.

Figure 2: Example of a surge forecast map, showing elevated water levels of up to 50 cm along the South African south coast as a result of a passing storm system. These elevated water levels are potentially hazardous when coincident with spring tides, increasing the reach of high frequency surface gravity waves onto the coastline.

Figure 3: An example of a time series water level forecast from June 2020. Assessing the total water level in relation to the state of the astronomic tide, with reference to levels such as chart datum and highest astronomic tide, allow forecasters to anticipate coastal impacts of abnormal water levels.

Figure 2 : Water level forecast trial comparison between the deterministic operational SWaSS and an ensemble configuration forced with atmospherics from the 21-member Global Ensemble Forecast System (GEFS) from the National Centers for Environmental Prediction. Location is Mossel Bay.
References


Towards operational oil spill trajectory forecasting in Algoa Bay, South Africa
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The ongoing offshore bunkering (fuel transfer) operations in the anchorage areas of the Port of Ngqura, South Africa, pose a threat to ecologically sensitive receptors within Algoa Bay. Ocean dynamics of the bay are complex and largely influenced by circulation patterns and water column structure set up by meanders in the Agulhas Current. The environmental risks involved, the highly dynamic offshore boundary and the relatively good network of measurements in the bay have led to it being identified as a pilot site for the development of an operational forecast system. To this end, a step by step approach is being followed in order to produce a downscaled system optimized for this region. The first step is to develop high-resolution, limited duration hindcast simulations that are evaluated with respect to in situ observations within the bay. A downsampling approach is followed, whereby boundary conditions for a Delft3D-FLOW model are obtained from the 1/12° global assimilated ocean reanalysis product produced by the HYCOM consortium, while surface forcing is obtained from a 3 km WRF model run by the Climate Systems Analysis Group (CSAG). Oil spill trajectory modelling is undertaken using the D-Waq PART model to quantify the ecological impact of hypothetical oil spill scenarios. Comparisons with temperature recorders at the mouth of the bay and within the bay show that the model is successful at reproducing the observed features near the surface and at the bottom. On the other hand, while simulated currents in the bay show reasonable agreement with ADCP measurements, the model does not capture as much directional variability, particularly for lower current amplitudes. Overall, the results indicate that the adopted downscaling methodology represents an effective approach for the simulation of nearshore oil spill events in Algoa Bay.

1. Introduction

In January 2016 the operation of offshore bunker fuel transfers was authorised in the port of Ngqura anchorage areas in Algoa Bay, South Africa. The bunkering operations however pose a significant environmental threat due to the proximity of the anchorage areas to the penguin colony islands of St Croix and Jahleel. Two small operational spill events of 14 August 2016 and 6 July 2019, which necessitated significant clean-up operations due to affected sea birds, highlighted the need for real-time tracking and trajectory forecasting of any future events. Oil spill forecasting requires a thorough understanding of both the local bay-scale winds and ocean currents which determine the trajectory of surface oil after a spill. The ocean dynamics in the region are complex, as Algoa Bay is situated at the edge of the ‘spatially bi-modal’ Agulhas Current, where it transitions from being relatively stable upstream of 26°E, to unstable as the continental shelf broadens in the downstream direction to form the Agulhas Bank. As one of South Africa’s largest bays it provides a degree of shelter from the southern hemisphere’s most powerful western boundary current. The dynamics of the bay are however largely influenced by circulation patterns and water column structure set up by meanders in the Agulhas Current, as revealed by in situ observations in the bay (Goshen et al., 2015). Given the environmental risks involved, the highly dynamic offshore boundary and the relatively good network of measurements in the bay, Algoa Bay has been identified as a pilot site for the development of an operational forecast system. In this study we present the first step toward this goal, being a high-resolution, limited duration hindcast simulation optimized for the region. The model solution has been extensively evaluated with respect to in situ observations within Algoa Bay. Oil spill scenario modelling was carried out to quantify the environmental risk posed by hypothetical spill events to sensitive receptors in the bay.

2. Data and method

All modelling for this study was undertaken using the open source Delft3D suite of numerical models developed by Deltares. The Delft3D-FLOW model (Deltares, 2017a) was used to simulate the hydrodynamics over the region of interest. The horizontal resolution of the curvilinear grid decreases from ~ 500 m within Algoa Bay to ~ 3 km at the model boundaries. The vertical grid is defined by 17 sigma layers with a resolution of 1.5% of the total water depth for both surface and bottom layers, gradually increasing to 10% of the total water depth at mid-depth. A downsampling approach was adopted, whereby boundary conditions for the Delft3D-FLOW model were obtained from daily fields of surface elevation, temperature, salinity and velocity components from a 1/12° global assimilated ocean reanalysis product from the HYCOM consortium. As Delft3D-FLOW precludes the specification of both water levels and currents at all boundaries (due to continuity...
constraints), their combined effect were included through the specification of ‘Riemann’ type boundaries on the southern and western boundaries and a ‘water level’ type boundary for the eastern boundary. Water level variations due to astronomical tides were excluded. Atmospheric forcing for the model (wind stress and surface heat fluxes) was obtained from a high resolution (3 km) Weather Research and Forecasting (WRF) model developed by the Climate Systems Analysis Group (CSAG) at the University of Cape Town (UCT). The atmospheric model forms part of the Wind Atlas for South Africa (WASA) project and has been extensively validated against land-based in-situ measurements (Lennard et al., 2015). Figure 1 shows the extent of the model and the effective downscaling of the global HYCOM reanalysis product to high resolution over Algoa Bay. The Delft3D-FLOW model was integrated over the period 01 May 2009 to 01 December 2011 (2.5 years), providing a basis for comparison with available in-situ measurements over this time. Oil spill trajectory modelling was carried out using the lagrangian particle tracking software D-Waq PART (Deltares, 2017b). Although several hypothetical spill scenarios were tested, here we present the results for a spill of 1000 m$^3$ (the maximum probable spill event) of intermediate fuel oil (IFO) at an inshore location. Oil weathering (evaporation and dispersion) was simulated as a simple exponential decay of the volatile fraction of surface oil, based on sensitivity tests carried out with the ADIOS2 oil weathering model developed by the National Oceanic and Atmospheric Administration (NOAA, 2016). An ensemble of 200 simulations was generated, where the trajectory of surface oil was tracked over 7 days from initialization. The start date of each simulation was incremented by 3.65 days, thereby sampling different combinations of winds and currents over a two years period. The ensemble of simulations for each spill scenario was used to compute the probability of surface oil thickness exceeding defined surface oil thickness thresholds for ecological impact, as well as the minimum time to oiling.

**Figure 1**: Snapshot of sea surface temperature and surface current vectors, illustrating the effective downscaling of the global HYCOM reanalysis product to Algoa Bay using the Delft3D-FLOW model.

3. Results

A primary objective of this study is to evaluate the extent to which the employed downscaling strategy can be used to reproduce observations of water mass properties and circulation within Algoa Bay. Figure 2 presents a 2-year time-series comparison of modelled and measured temperature at the St Croix underwater temperature recorder (UTR) at depths of 15m and 30m. The instrument was deployed in a total water depth of 30 m, in close proximity to the ongoing bunkering operations. The data shows strong interannual and seasonal variability in the water column. Winter months are characterized by low variability and weak stratification, while the summer months exhibit higher variability and some strong stratification events (e.g.
January 2010). There is significant interannual variability between the summer events, for instance February 2010 was characterized by a warm event, while temperatures over the same month the following year were persistently more than 5°C cooler. The model is shown to capture both the observed seasonal and event-scale variability surprisingly well. A similarly favorable comparison between observed and modelled temperature was found at the entrance to the bay, in approximately 80 m water depth (not shown). Comparison of the model with observed currents from three ADCP moorings located in the western, northern and eastern peripheries of the bay (not shown) revealed that while the current magnitude and major axes of variability are well captured, the observed currents generally exhibit greater directional variability, particularly for lower current amplitudes. The favorable comparison with observed water mass properties and circulation suggests that the adopted approach is a promising first step towards a local operational forecast model for Algoa Bay.

Figure 2: Time-series of modelled and measured temperature at the St Croix UTR (~30 m total water depth) from November 2009 to December 2011.

The second objective of the study was to carry out oil spill trajectory modelling to quantify the ecological risk to the surrounding sensitive receptors, in the event of hypothetical spill events. Here we present the impact of the maximum probable spill event from the oil bunkering operations. Figure 3 presents the probability of oil thickness exceeding 1 µm, considered as an ecological threshold for smothering of seabirds, as computed from the ensemble of 200 oil spill simulations. The results indicate that the surrounding penguin colony islands of St Croix and Jahleel have a ~50% probability of impact in the event of such a spill, while the minimum time to oiling was computed as ~2.5 hours. These results provide valuable input to planning and management of the bunkering operations and highlight the severity of the potential impact. An oil spill trajectory forecasting tool, built upon sound environmental forcing, would significantly mitigate against environmental impact in the event of a future spill as cleanup operations could be focused on areas where the spill is most likely to impact.
Figure 3: Probability of surface oil thickness exceeding 1 μm, considered as an ecological threshold for smothering of seabirds, as computed from the ensemble of 200 oil spill simulations of the maximum probable spill of Intermediate Fuel Oil (IFO).

References


Preliminary assessment of the potential for particle trajectory modelling to support ocean search and rescue operations

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Abstract. Finding a person (or object) lost at sea is like looking for a needle in a haystack. The ability to provide more precise search area coordinates for rescuers to conduct their searches will help optimise search and rescue operations. A particle trajectory model for at sea search and rescue applications is presented. The model incorporates the effects from wind, surface currents, as well as stochastic diffusivity in order to determine the horizontal trajectory of each virtual particle released. Two scenarios are presented based on real-life search and rescue scenarios which occurred along the coastline of South Africa. These scenarios demonstrate the abilities of the particle trajectory model in search and rescue operations for varying object types and in different regions of the Greater Agulhas System.

1. Introduction

Objects lost at sea are subject to forcing from ocean currents, winds and waves. How much an object is influenced by these processes depends on the object's characteristics. Each year numerous incidents, varying from ships sinking and colliding, recreational and professional marine activities and objects falling overboard, occur in the world’s open oceans and in the coastal regions. In South Africa, a significant part of these incidents involves the National Sea Rescue Institute (NSRI) which, in 2017, conducted 1,050 rescue operations (NSRI, 2018). This resulted in the rescuing of 1,224 people and 2,723 hours of operational activity (NSRI, 2018). In order to reduce operation times and costs and to improve the overall quality of operations, several new and innovative techniques have been developed. In search and rescue operations, the focus is on estimating the search area based on a number of factors and computing the evolution of the search area over time (Breivik and Allen, 2008). These factors include physical forces that would act on an object such as winds, currents and waves. The complexity increases when computing the motion of different objects with varying shapes in the ocean (Breivik and Allen, 2008). Initial techniques looked at the current wind direction and magnitude, making a rough estimation on the position of the object based on the object type and position in the water column. The improved ability of numerical models to make estimations about the ocean state has resulted in these models being increasingly used to estimate the pathway of objects in the ocean. Several tools have been created to account for the type of object being tracked in order to better understand their drift (Breivik et al., 2011, Hart-Davis et al., 2018a). The tools presented in (Breivik et al., 2011, Hart-Davis et al., 2018a) independently combine the use of particle tracking and the leeway object divergence methodology presented in Chapter 5 of (Allen and Plourde, 1999). Lagrangian analyses of ocean fluids from virtual particles, advected with the background flow information from ocean models, have been increasingly used to study physical and biogeochemical oceanographic processes (van Sebille et al. 2018). The tool has broad and diverse application to a variety of objects (including persons) lost at sea, with great potential for optimising search and rescue operations in the future. Here we demonstrate the usefulness of using a virtual particle tracking tool forced with ocean and wind forecast data and adjusted for windage using empirical relationships provided by the NSRI to predict the trajectories of objects lost at sea in two separate scenarios.
2. Data and method

Particle Trajectory Model
Particle tracking is the observation of the motion of an individual particle within a fluid. Particle tracking uses a Lagrangian modelling framework that moves with the flow of the ocean and is particle specific instead of being point specific (MacDonald et al. 2006). In the case study presented here, a Lagrangian particle tracker known as Parcels ("Probably A Really Computationally Efficient Lagrangian Simulator") (Lange and van Sebille 2017) was used. Parcels is a virtual particle tracking tool aimed at exploring novel approaches for Lagrangian tracking of virtual ocean particles (Lange and van Sebille 2017). Parcels requires gridded velocity data to compute the Lagrangian trajectories of virtual particles. Here, virtual particles were forced using both ocean surface currents from the operational Mercator global ocean analysis and forecast system and global surface wind forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF). Additionally, the response of the virtual particles to winds, known as windage (\( u_{\text{wind}} \)), was incorporated based on wind drift tables made available by the NSRI. For the two case studies, the following windage parameters were used: Capsized Catamaran: \( u_{\text{wind}} \times 0.04 \) and Rigid Inflatable Boat: \( (u_{\text{wind}} \times 0.03) + 0.08 \).

Operational ocean current and wind forecasts
The operational Mercator global ocean analysis and forecast system provides 10-day 3D global ocean forecasts on a daily basis. This 3D product includes daily files of temperature, salinity, currents, sea level, mixed layer depth and sea ice parameters. It also includes hourly mean surface fields for sea level height, temperature and currents. The global ocean output files are available at a 1/12° horizontal resolution with regular longitude/latitude equirectangular projection and 50 vertical levels ranging from 0 to 5500 meters. The ocean model is forced using winds from the ECMWF (European Centre for Medium-Range Weather Forecasts) Integrated Forecast System, which are also the winds used to account for the wind drift of the virtual particles. The ocean current data are available from the Copernicus Marine Environment Monitoring Service.

The ECMWF produces operational ensemble-based analyses and predictions that cover time frames ranging from medium-range, to monthly and seasonal, and up to a year ahead. These are available to its Members and the Co-operating States, as well as through licenses via the World Meteorological Organization (WMO) and the academic and commercial sectors. The South African Weather Service routinely receives these forecast data. Here, the 3-hourly 1/10° wind forecasts 10m above the ocean surface are averaged to daily mean winds and interpolated to the 1/12° Mercator ocean forecast grid to obtain consistent spatio-temporal resolution between the ocean and wind forecasts products used to advect Parcels.

Case studies

Capsized Catamaran
On 14 December 2014 Anthony Murray (58), Reginald Robertson (59) and Jaryd Payne (a 20-year-old first-time sailor) set sail from Cape Town to deliver a luxury catamaran (a Moorings A5130, Sunsail RC044-978) to Phuket, Thailand. Tragically, they were last heard from on 18 January 2015 approximately 2190 Nautical Miles north-west of Perth, Australia, and after multiple attempts to establish their whereabouts, the catamaran was reported missing by the Maritime Rescue Coordination Centre (MRCC) in Cape Town on 11 February 2015 and the search and rescue activities were officially closed on 15 May 2015. Approximately 1 year after the search was called off, on the 18th of January 2016 a Brazilian Navy Ship, Amazonas, spotted the upturned hull approximately 113 Nautical Miles off Cape Recife, near Port Elizabeth, South Africa. 5 days later on 22 January 2016, the National Sea Rescue Institute (NSRI) found the capsized catamaran south of Cape Agulhas. Unfortunately, while the tug, the Peridot, was towing the capsized catamaran back to Cape Town, the tow line broke (due to adverse sea conditions) and the catamaran was lost. However, the approximate locations of the vessel being spotted off Cape Recife (25° 41’ 59.46”E and 34° 24’ 11.08”S) and being found off Cape Agulhas (20° 07’ 32.58”E and 35° 01’ 31.94”S) provide a good case study to test the application of virtual particle tracking tools in search and rescue applications.

Rigid Inflatable Boat
At 17h03 on the 4th of June 2019, the NSRI were activated following reports of a vessel that had lost power within False Bay in Cape Town, South Africa.
**Figure 1:** A simulation of 1000 virtual particles deployed at the location where the (left) capsized vessel and (right) rigid inflatable boat were last seen (white circle). The color bar represents the time in days since deployment of the virtual particles. The orange dots represent the mean trajectory of the 1000 particles with the white star indicating the position where the objects were eventually found. The black and blue contours respectively represent the mean winds and surface currents over the period for which the particle trajectory model was run.

**Figure 2:** Density plots of the final position of the virtual particles. The grey lines represent all the trajectories of the 1,000 virtual particles, with the orange line representing the mean trajectory.
The vessel was a five-meter rigid inflatable boat that was last seen near Roman Rock, at 34° 10' 48"S and 18° 27' 36"E, with an unknown number of people on board. After an extensive search in strong winds and heavy seas, the vessel was later recovered almost two days later on the south coast near a beach known as Gaansbaai (19° 20' 05.11" E / 34° 35' 19.14"S). The complexity of this scenario due to the vessel containing sailors on board as well as due to the heavy sea conditions provides an extremely challenging scenario to assess the ability of the particle trajectory model in real-life scenarios.

3. Results

The particle trajectory model was used in two different search and rescue scenarios to assess its ability in estimating the trajectory of objects lost at sea. For each scenario, one thousand virtual particles were deployed at the location where the object was last seen (Figure 1). Each virtual particle, incorporated windage to account for the characteristics of the object (capsized vessel and inflatable boat respectively) following the Leeway approach presented in Allen and Plourde (1998). The virtual particles were deployed for the duration that the object was lost at sea and the particles were forced by the Copernicus surface current data and ECMWF 10m wind product. In each scenario, the effects of stochastic motion were applied to the virtual particles to account for the unresolved physical process not present in the forcing data (van Sebille et al 2018). Figure 1 shows the trajectories of all virtual particles deployed for both case studies. The orange dots represent the mean of all trajectories and the stars indicate the position where the two objects were eventually located by the NSRI. Additionally, the mean currents and winds for the duration of the simulation experiments with Parcels are overlaid. It is evident from these figures that wind plays an important role in determining the trajectories of the virtual particles. The parameterised stochastic motion accounting for sub-grid scale effects is responsible for the spread of the trajectories. Calculating the mean of these and taking into consideration the position where the two objects were found, highlights the importance of adding stochastic motion to the virtual particles in terms of determining accurate search area coordinates. Using the data from the 1,000 virtual trajectories, one can calculate the density of the particles for each time step and contour these on a map. Figure 2 shows the density of the virtual particles in percentage of the total particles deployed for both case studies. The areas outlined by, for example the 90% contour, indicate regions where virtual particles accumulate. This information could be used to inform search and rescue operations in terms of optimising their search efforts to those regions.

4. Discussion and Conclusion

It is shown that, by incorporating wind and surface current data into the particle trajectory model, the model predicts the drift of the two different objects to a reasonable degree of accuracy. Incorporating the impacts of stochastic motion into the model facilitates a spread of trajectories (Figure 1 & 2). By then calculating the mean trajectory and density distribution of the virtual particles (Figure 2) highlights the ability of the particle trajectory model to estimate the location where the objects were found with a relatively high degree of confidence. There remains scope for improvement however, in particular the global wind and ocean forecast models used in both scenarios are not optimised for regional or near coastal applications, the latter requires careful downscaling to the requisite fine coastal scales (Kourafalou et al., 2015). Despite this the test cases demonstrate the need to combine both wind and ocean currents correctly when simulating trajectories of different types of objects lost at sea. Moreover, the application demonstrates skill in open ocean as well as near coastal environments under different dynamical ocean conditions, despite limitations in the global reanalysis and forecast products used to force the particle trajectory model. Addressing limitations of the global reanalysis and forecast products, this study highlights the importance of using appropriate parametrisation for sub-grid scale processes when using these data to force particle trajectory models applied to search and rescue. Additionally, accurate positions of the objects' initial conditions (in time) is a critical factor. Future work to further improve the accuracy of the application includes adding tidal currents, Stokes drift, as well as incorporating improved drift responses of different objects, taking into consideration both ocean currents and winds. Furthermore, integration with traditional search and rescue workflows will further enhance support for search and rescue operations.

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Scaling observation error for optimal assimilation of CCI SST data into a regional HYCOM EnOI system

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There is no operational regional data assimilative ocean model in place tailored to the unique South African environment comprising the Agulhas and Benguela currents. Initial efforts towards this goal have been made and resulted in a system using a regionally optimised Hybrid Coordinate Ocean Model (HYCOM) along with the Ensemble Optimal Interpolation (EnOI) assimilation scheme. Adding Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) to the assimilation did not seem to improve the forecast skill. Aiming to address this issue and improve the forecast skill, a more recent data set, namely the Climate Change Initiative (CCI) SST, is assimilated into the system. Both the SST data and the associated estimate of analysis errors are used, with the latter used as an observation error. Since observation errors in data assimilation are used to determine whether more confidence should be placed in the model or observations in producing the analysis, overconfidence in observations can artificially ‘shock’ the model and result in unrealistic values, leading to model crash. To circumvent this issue, a scaling factor is applied in the assimilation code. A scaling factor of 25 was found to produce a favourable result with lowest mean root mean square error (RMSE; 1.098°C) between the model and SST data over time. Postulating the error to be overconfident, a floor, or ‘threshold’, value is introduced in order to set a minimum value for the observation error thereby reducing confidence in the SST data. These experiments fared less favourably with a floor value of 0.5°C and a scaling factor of 14 producing the best mean RMSE (1.118°C). A scaling factor of 25 will be used in upcoming work where assimilation of the CCI product will be compared to the assimilation of along track SST variants.

1. Introduction

South Africa boasts a suite of decision support tools hosted by the National Oceans and Coastal Information Management System (OCIMS), an operational regional wave forecast system produced by the South African Weather Service (SAWS) and a bay-scale forecast product for Algoa Bay is currently in development. However, there is currently no operational ocean forecasting system for the purpose of predicting ocean state variables (e.g., temperature, salinity, velocities) for the entire coastline and offshore areas. Such a system would be a valuable asset for marine industries including the commercial fishing, maritime, offshore mining and sea rescue sectors, to name a few. Thus far, initial efforts to produce an ocean forecasting system for South Africa have used a regionally optimised Hybrid Coordinate Ocean Model (HYCOM) harnessing the Ensemble Optimal Interpolation (EnOI) assimilation scheme (Backeberg et al., 2014; de Vos et al., 2018). However, the model’s predictive skill is still not ideal in select areas, exhibiting a warm bias in upwelling regions even when assimilating satellite retrieved data. In an initial step to improve this system, this research aims to address the assimilation of gap free level-4 (L4) sea surface temperature (SST) data, as if they were observations. Present work describes experiments with assimilating SST data only. In previous efforts, Rapeti & Backeberg (2016) assimilated Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA; Donlon et al., 2012) SSTs produced by the UK Met Office (UKMO), but the benefit isn’t clear. This research proposes to assimilate the Climate Change Initiative (CCI) L4 SST product produced by UKMO for the European Space Agency (ESA) because it uses a more recent SST data processing system (Merchant et al. 2019). However, there are significant differences between the two SST products. OSTIA SST is an estimate of foundation SST, whereas CCI SST is nominally for 20cm depth. Here we postpone a discussion of these differences to future work. In a Bayesian assimilation scheme, the magnitude of the observation error represents the confidence of the observation and, in turn, whether the analysis relies more on the model or the observation during the assimilation procedure. However, the exact amplitude of the error of the observation is unknown. It is also common to add a ‘representativity term’ into the observation error that accounts for all processes that the model does not resolve (Janjić & Cohn, 2006; Oke & Sakov, 2008). In addition, small observation error magnitudes in the assimilation can shock the model system and cause crashes. Therefore, a scaling factor is used to optimally adjust the observation error.
magnitude synoptically and result in a stable simulation while still updating the analysis significantly. Here, the progress made in adjusting the CCI observation error scaling factor for producing an optimal assimilation of the product into the model will be shown.

2. Data and methods

The CCI L4 SST product is produced from the synthesis of observations from Advanced Along-Track Scanning Radiometers ((A)ATSR), the Sea and Land Surface Temperature Radiometer (SLSTR) and Advanced Very High Resolution Radiometers (AVHRR). The L4 product has been adjusted to 20 cm depth and has a horizontal spatial resolution of 0.05°. Version 2.0 of the CCI product was used for this study and is available from the Copernicus Marine Environment Monitoring Service. The regional HYCOM model encompasses the region 0–60°E and 10–50°S at 0.1° resolution. It is nested within a basin-scale HYCOM model of the Indian and Southern Oceans providing 6-hourly boundary conditions (George et al., 2010). HYCOM harnesses hybrid vertical coordinates, allowing each of the 30 vertical layers to transition between z-, ρ- and σ-coordinates which are ideally suited for dynamic upper-ocean mixed layer events, stratified open oceans and shallow coastal regions, respectively. The model code used is the official HYCOM 2.2.37, with some modifications applied to the code (Sakov et al., 2012). More information on the model setup can be found in Backeberg et al. (2014).

The EnOI assimilation scheme is a less computationally expensive data assimilation scheme compared to those relying on Monte Carlo simulations, such as the Ensemble Kalman Filter. Instead of generating a new ensemble of model states at each assimilation step, the EnOI makes use of a historical static ensemble of model states from which it produces a single forecast to create a new analysis (Oke et al., 2002; Evenson, 2003). However, this reduction in computation cost comes at the expense of underrepresentation of synoptic scale variability. The analysis is calculated as

\[ \psi^A = \psi^f + \alpha A^T H (\alpha H A^T H^T + TT^T)^{-1} (d - H \psi^f), \]

where \( \psi^A \) is the analysis, \( \psi^f \) is the forecast, \( \alpha \) is a scaling factor, \( A \) is the centered historical ensemble, \( H \) is a measurement operator relating the prognostic model state to the measurements, \( TT^T \) represents the observational errors and \( d \) represents the observations. In Eq. (1), adjusting \( \alpha \) is equivalent to adjusting the observation error term, \( TT^T \). This means that the scaling factor inversely affects the observation error

\[ R_\alpha = \frac{1}{\alpha} TT^T. \]

A larger (lower) scaling factor results in a weaker (stronger) fit to the observations. When making these adjustments, the aim is to assimilate observations in such a way that over time, the root mean square error (RMSE) between the model and the observations for the entire model domain are at their lowest. Assimilating with a strong constraint to observations may yield a faster reduction of the error but will reach a larger mean RMSE value than a system that assimilates with weaker constraint.

For determining the optimal scaling factor, the model is run over the period 18 December 2008 to 18 October 2009 during which assimilation takes place every 7 days. This period is chosen so as to coincide with a portion of the Backeberg et al. (2014) study period and to allow enough time for the impact of the scaling factor to be observed. Furthermore, to reduce shock to the model during initial assimilation, the assimilation is progressively introduced over the first 5 assimilation cycles.

3. Results

The first scaling factor experiments can be seen in Figure 1. All of the simulations show the progressive introduction of the assimilation with the initial reduction of RMSE over the first 5 cycles. Not shown here are the initial experiments at scaling factor values below 16, all of which did not finish but rather ended with the model crashing. Each of the simulations shown in Figure 1 ran to completion with the scaling factor of 25 proving to provide the best result with an RMSE\(_{\text{mean}}\) of 1.098°C. SF17 exhibits a very similar RMSE\(_{\text{mean}}\) of 1.10C. The scaling factor values in the successful simulations are considerably higher than that used by Rapeti & Backeberg (2016) for assimilating OSTIA SSTs (scaling factor of 5). Investigating the differences in observation error between CCI and OSTIA (Figure 2) for the experiment period, there are regions where the difference exceeds 1°C (Figure 2a). CCI claims
high accuracy (blue) for large expanses of the study area and significantly reduced accuracy (red) around the Angola Benguela Frontal Zone (~16°S 11°E) and the Agulhas Current Retroflection (~41°S 17°E), regions which also show similar (white) error values for both products. Figure 2b shows that CCI exhibits a consistently lower observation error mean compared to OSTIA.

Figure 2: CCI and OSTIA (a) mean spatial difference (CCI - OSTIA) and (b) mean observation error time series for experiment duration (18 December 2008 to 18 October 2009).

Postulating that the CCI observation error values are possibly overoptimistic, a floor value, or minimum threshold, for the observation errors was introduced. It should be acknowledged that the representativity error is typically larger than the instrumental error, so it is expected that reducing the instrumental error does not yield a drastic change of the overall optimal observation error. Therefore,

\[ R = \max\{R_{\text{floor}}, R_{\alpha}\} \]  

and recall from Eq. (2),

\[ R_{\alpha} = \frac{1}{\alpha} \text{TT}^T. \]

The results of the introduction of a floor value are shown in Figure 3.

Figure 3: Time-evolution RMSE of the SST for scaling factors 7, 10, 12 and 14 with varying floor values of 0.4°C, 0.5°C and 0.7°C.

Floor values of 0.4°C, 0.5°C, and 0.7°C were tested. For a value of 0.5°C, scaling factors of 10, 11, 12 and 14 were tested with 10 and 11 both resulting in model crash. Best performing was the value of 14 with an RMSE\text{mean} of 1.118°C. Implementing a floor value of 0.7°C, scaling factors of 7 and 10 were tested with both running to completion and 10 exhibiting the better RMSE\text{mean} of 1.142°C. Only a single scaling factor (12) was tested with a floor of 0.4°C but the result was identical (RMSE\text{mean} of 1.136°C) to using a floor of 0.5°C with the same scaling factor. Trends in the former two floor experiments displayed an increased RMSE\text{mean} with reduced scaling factors and so no further experiments were deemed necessary.

Introducing a floor value allowed for reduced scaling factors and therefore more aggressive assimilations, but the mean RMSE over time was still not as low as using a scaling factor of 25 without a floor value.

4. Conclusion

This study aims to find an optimal observation error scaling factor for CCI SSTs to be assimilated into a regional HYCOM using the EnOI. Using A larger (lower) scaling factor results in a weaker (stronger) model fit to the observations. Values lower than 16 resulted in model crash. An optimal value of 25 was found to result in an RMSE\text{mean} of 1.098°C. A value of 25 is significantly larger than that used for assimilating OSTIA SSTs into the same system (scaling factor of 5). Postulating the observation errors to be overoptimistic,
a floor or minimum threshold value for the observation errors was introduced. These simulations still resulted in \( \text{RMSE}_{\text{mean}} \) values greater than that of using a scaling factor of 25 without a floor, with the combination of a scaling factor of 14 with a floor value of 0.5°C being the best result (\( \text{RMSE}_{\text{mean}} \) of 1.118°C). Hereafter, a scaling factor of 25 will be used in upcoming work where assimilation of the CCI product will be compared to the assimilation of along-track SST variants in the same forecasting system.

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Analysing modelled nearshore wave climate variability and change as relevant to the South Coast small-scale handline fishers of South Africa
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Understanding climate variability and change together with fishing activities and pressures can help with implementing improved sustainably driven management strategies of marine coastal systems. Fishers from the South African South Coast small-scale handline fishery have reported that recent increasing climate variability has deteriorated the sea state and decreased the number of sea days, and that higher waves are increasing difficulty when exiting rivers and harbours. High resolution spectral wave model outputs of the South African coast spanning 17 years (1997-2014) were used to investigate the fisher’s observations. The simulated nearshore wave climate around the launch sites (and/or harbours) of four South Coast fishing towns were analysed over the months of the main fishing season (summer, from December to February). Nearshore summer wave heights, regional swell wave heights and wind speeds increased significantly along the South Coast over the summer study period. During the mid-to-late 2000s along the South Coast, the annual average summer wave heights experienced a regime shift towards higher waves. The positive tendency in wave heights and the positive wave height regime shift over the last decade along the South Coast, agrees with the recent fishers’ reports of deteriorating sea state conditions. These results indicate that climate variability and change in terms of wave climate is an important consideration for small-scale fisheries management strategies and sustainable development of South Coast coastal fishing communities.

1. Introduction

The South African south coast, within the southern Benguela Current marine ecosystem, is home to a small-scale traditional commercial handline fishery. Increasing variability and regime shifts within the system over the past few decades (Blamey, Howard, Agenbag, & Jarre, 2012; Blamey et al., 2015; Howard, Jarre, Clark, & Moloney, 2007; Watermeyer, Hutchings, Jarre, & Shannon, 2016), together with overfishing due to the previous management strategies, are currently preventing the recovery of the primarily targeted Silver Kob species (Argyrosomus inodorus). While the overall aspect of changes in the Kob stocks and catches are well understood (Winker, Kerwath, & Attwood, 2016), the influence of environmental forcing’s are not. This may be because complete and high resolution nearshore environmental datasets in the region are sparse (Blamey et al., 2012; Lamont, García-Reyes, Bograd, van der Lingen, & Sydeman, 2018).

Understanding how environmental forcing’s impact the South Coast social-ecological system can be improved by overlaying incomplete scientific knowledge with higher resolution sources of information, such as local stakeholder knowledge (Ward, 2018). The South Coast fishery’s local fishers have reported a recent deterioration of sea state and reduced number of sea days, because of increased wind variability (Duggan, 2012; Gammage, Jarre, & Mather, 2017). Additionally, they have reported that bigger waves are increasing difficulty when exiting rivers along the coast and/or harbours (Gammage, 2015). While it was not explicitly mentioned, the higher waves could also be deteriorating sea state and thus be reducing the number of sea days. Considering high resolution winds have already been studied in this region (Ward, 2018), this study aims to complement the observations made by the fishers with available high resolution Simulating WAVes Nearshore (SWAN) model significant wave height (Hs01) data (Theron et al., 2014).

2. Data and methods

The SWAN Hs01 dataset (1997-2014) analysed in this study were produced and validated during the Department of Environmental Affairs and the Council for Scientific and Industrial Research (DEA-CSIR) South African Coastal Vulnerability Assessment phase 2 project (Theron et al., 2014). The analyses in this study were performed on the combined-forced (forced by both wind and swell from the National Centres for
Environmental Prediction (NCEP) $H_{m0}$ data over the fishery’s main fishing season (austral summer months of December to February), taken from near to the known main launch site and/or harbour of four South Coast fishing towns (Witsand, Still Bay, Gouritz, Mossel Bay).

In order to investigate the fisher’s statements of deteriorating sea state, the SWAN modelled South Coast summer nearshore wave climate, as well as the NCEP driving forces, were analysed on interannual timescales in terms of variability and trends. The Empirical Mode Decomposition (EMD) method (Huang et al., 1998) was applied to the SWAN summer $H_{m0}$ dataset for each study site, as well as the NCEP summer $H_{m0}$ and wind speed datasets, to determine the various scales of variability and the trend (hereafter “tendency” because of length of dataset) embedded in the timeseries. Regression analyses were performed on the EMD tendencies to determine if they were significant or not; and the Sequential Regime Shift Detection (SRSD) software (Version 2.1; Sequential Regime Shift Detection [Computer software], 2005) was applied to the annual average anomaly timeseries (determined from the EMD interannual results), in order to compare results to other studies which have detected wind variability and strength regime shifts in the region using this method (Blamey et al., 2012; Howard et al., 2007; Ward, 2018).

3. Results and discussion

The tendencies shown in Fig. 1 indicate that the South Coast nearshore wave climate experienced an increase in wave height over the summer study period, and the regional South Coast area experienced an increase in wave height and wind speed. While all the increases were only a few centimetres to decimetres, they were all determined as statistically significant with p-values well below 0.05 (p<0.001).

The simulations performed in this study where the increase in regional wind speeds and wave heights drove the increases in the nearshore wave heights could potentially explain how the fishers observed a deteriorating sea state. A deteriorating sea state in terms of increasing nearshore wave heights could have been driven by the recently observed increase in Southern Ocean wave heights (Hemer, Church, & Hunter, 2010; Rhein et al., 2013; Young, Babanin, & Zieger, 2011).

Considering that swell waves which hit the South Coast come from the South Atlantic Southern Ocean region (J. Rossouw, 1989; Shillington & Harris, 1978), increases in wave heights here could manifest in increases in the regional swell waves along the coast. Additionally, a recent increase in regional upwelling favourable winds along the South Coast (Lamont et al., 2018), particularly during summer (Blamey et al., 2012, 2015), could be increasing local wind-sea wave heights and thus contributing to the total increase in nearshore wave heights along the nearshore South Coast.

Fig. 2 shows the SWAN and NCEP summer SRSD results that were determined as appropriate for further analysis, following a sensitivity analysis which helped to determine sound results. The SRSD results indicate that the South Coast nearshore region in terms of wave height, as well as in terms of regional wave height and winds speeds, experienced a positive mid-to-late 2000s shift. Therefore, around 2006/2007, the nearshore and regional wave heights became anomalously larger and the regional wind speeds became anomalously stronger. The shift in terms of waves along the South Coast agree with Veitch et al. (2019) who found that Cape Point waves prior to 2006/2007 were smaller.

The positive 2006 shift in terms of nearshore wave heights for Still Bay and Gouritz is inline with the regional wave height shift, while Witsand and Mossel Bay experience their positive shift a year later. The theory around this is that the Still Bay and Gouritz study sites are situated in more southward-facing open bays, compared to the Witsand and Mossel Bay study sites which are situated in more south-eastward-facing bays with headlands protruding from their western borders. Therefore, Still Bay and Gouritz are more directly exposed to the predominantly approaching south-westerly swell and thus display similar results to that of the regional waves, while Witsand and Mossel Bay are more sheltered and thus their wave climates could be experiencing a more delayed reaction to any changes in the regional waves. Considering that the shifts in study sites wave heights are more inline with...
the regional swell shift suggests that the study sites wave climates could be more influenced by changes in the regional waves compared those of the regional winds and thus local wind-sea waves. These findings agree with M. Rossouw, Terblanche, & Moes (2013) who found that the South African South Coast is dominated by swell compared to shorter period wind-sea waves. Even though the regional winds in this study are perhaps not very influential on the simulated nearshore waves along the South Coast, the nearshore wave height shift is in line with other studies in terms of upwelling favourable winds. Easterly upwelling favourable winds were found to be stronger on average after 2006/2007 by Lamont et al (2018), and particularly during summer by Ward (2018). The mismatch between the regime shift in the regional winds observed in this study and those in the other studies mentioned here could be an artefact of the data itself in terms of temporal scale, especially considering that the detection of shifts can be influenced by the cut-off length used in the SRSD method which is an artefact of the length of the data record length itself.

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4. Conclusion

This study aims to investigate recent observations made by the local small-scale fishers of the South Coast, which include that of a deteriorating sea state and a reduction in fishable days which may be influenced by larger waves. The nearshore South Coast wave climate simulations helped to determine that there definitely could have been a distinct shift in the nearshore marine physical system along the South Coast during the mid-to-late 2000s; additionally, together with the regime shifts, the tendencies indicate that the wave climate and thus the sea state could have recently deteriorated in terms of wave heights and thus could have made it more difficult for the fishers to go out and fish, reducing their days out at sea; and lastly, this study suggests that the driving forces of the deteriorating nearshore South Coast sea state could be mostly driven by remote wind systems compared to the local ones. However, more research needs to be performed in terms of attributing the drivers of the increasing nearshore South Coast wave heights in order to make more confident conclusions here. Additionally, more communication with the fishers needs to occur in order to fully understand how wave heights play a role in sea state deterioration and the act of fishing. This study shows how important it is to understand climate change and variability on small-scales considering the impacts it can have on the small-scale fishers and thus their well-being.

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Mean barotropic vorticity balance in the South Western Indian Ocean
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1. Introduction

In the context of a western boundary current regime, the ocean circulation in the South Western Indian Ocean (also known as the greater Agulhas Current System) is particularly rich and energetic (Lutjeharms, 2006). When reaching the East Coast of Madagascar, the South Equatorial Current splits into two western boundary currents: the East and North Madagascar Currents (Schott, 2009). After rounding the northern tip of the island, the North Madagascar Current splits again into two other branches, the southern one feeding the Mozambique Channel in the form of large anticyclonic rings (Halo et al., 2014a). Mesoscale eddies are also generated south of Madagascar (Halo et al., 2014b) and both turbulent regions feed the Agulhas Current along the east coast of southern Africa. As the strongest western boundary current of the southern hemisphere, the Agulhas Current transports 75 Sv (1 Sverdrup = 10⁶ m³ s⁻¹) (Beal et al., 2015). It retroreflects south of the continent to form the eastward flowing Agulhas Return Current, joining the Antarctic Circumpolar Current (Lutjeharms, 2006). From the Agulhas Retroreflection, about 15 Sv leaks into the South Atlantic Ocean mostly in the form of Agulhas Rings (Richardson et al., 2003), contributing to the return loop of the meridional overturning circulation with global climatic implications (Beal et al., 2011).

Although important progress has been achieved in the reproduction of the oceanic circulation in Ocean General Circulation Models (Danabasoglu et al., 2014), large biases still occur for the Agulhas Current region (see for a recent example Zhu et al., 2018; or Penven et al., 2010 for a review). Knowledge of the controls of the circulation in the region could facilitate a better representation of the system and its variability.

Western boundary currents were originally thought to be controlled by frictional (Stommel, 1948; Munk 1950) or inertial (Charney, 1955) processes. More recently, when looking at regions large enough to filter out non-linear terms in the barotropic vorticity balance, Hughes and de Cuevas (2001) have highlighted the importance of bottom topography for their adjustment. This dominance in bottom pressure torque is indeed valid for the Gulf Stream independently of model vertical grids, numerics or horizontal resolutions (Schoonover et al., 2016).

Although a barotropic vorticity balance has already been used to separate specific regions at global scale (Sonnewald et al., 2019), such large-scale approaches could not resolve he intricacies of the greater Agulhas Current System. Here, using online diagnostics in a regional high-resolution model of the South Western Indian Ocean, we illustrate the controls of a few selected dominant processes in the region.

2. Data and method

The regional numerical experiments are done using the Coastal and Regional Ocean COmmunity model (CROCO, Debreu et al., 2012), a recent evolution of ROMS (Shchepetkin & McWilliams, 2005). CROCO solves the hydrostatic primitive equations using a topographic following vertical coordinate and higher order numerical schemes. To reach a sufficient resolution in the Agulhas region, three levels of horizontal grids (1/4°, 1/12° and 1/36° resolution) are embedded into each other following a 2-way nesting approach (Debreu et al., 2012). GLORYS 1/4° oceanic reanalysis (Ferry et al., 2012) provides the lateral boundary conditions for the largest grid. The daily ERA-ECMWF reanalysis (Dee et al., 2011) feeds a bulk formula for the surface boundary conditions. Relative winds are used to derive the wind stress for a more realistic stability of the Agulhas Retroreflection (Renault et al., 2017). The experiments are run for 21 years, from 1993 to 2014, after 2 years of spin-up. Comparisons within situ observations and satellite altimetry show how this simulation is able to reproduce the structure and variability of the Agulhas Current (Tedesco et al., 2019).

Following Hughes and de Cuevas (2001), Gula et al. (2015), Schoonover et al. (2016), Sonnewald et al. (2019) and Le Corre et al. (2020), a barotropic vorticity balance in the presence of topography is derived by vertically integrating the momentum equations and taking the curl. Since we are here only looking at the mean circulation, this balance simplifies too:

\[
\beta \nabla \cdot = J(\bar{P}_b, h) - \text{Adv} + \nabla \times \frac{\tau_{\text{wind}}}{\rho_0} - \nabla \times \frac{\tau_{\text{bot}}}{\rho_0}
\]

where \( \beta \) is the meridional gradient of the Coriolis parameter, \( V \) the meridional transport, \( P_b \) the bottom pressure, \( h \) the bottom topography, \( \text{Adv} \) the non-linear advection terms, \( \rho_0 \) the reference density, \( \tau_{\text{wind}} \) the wind stress and \( \tau_{\text{bot}} \) the bottom drag. The overbar accounts for a temporal average over 1993-2014. To avoid aliasing, each individual term of the barotropic vorticity
balance (Equation 1) is derived at run time by vertically integrating and taking the curl for each term of the horizontal momentum equation (including the time tendency) has described by Gula et al. (2015). They are subsequently averaged over time. They are divided by $\beta$, so they are all consistent as contributors to a mean meridional transport [m$^2$s$^{-1}$].

3. Results

Figure 1 presents horizontal maps of the terms of the mean barotropic vorticity balance for the model zoom at 1/36º resolution (the 5 terms plus the addition of bottom pressure torque and advection terms: bottom left). A primary equilibrium is noticeable locally at small scale between the inertial terms (advection, Figure 1 – bottom middle) assuring a tendency of the flow to carry on along a straight path and bottom pressure torque (Figure 1 – top middle) inducing a constraint to follow topographic contours. This results in a small-scale oscillatory pattern when bottom currents are in presence of large slopes. These oscillations are also present (albeit with larger length scales) in the 1/4º and 1/12º runs.

Figure 1: Maps of the terms of the mean barotropic vorticity balance for the model zoom at 1/36º resolution. All terms are divided by $\beta$, so the units are consistent with a meridional transport (m$^2$s$^{-1}$). Note that the wind stress curl term is multiplied by 10.

Adding the 2 terms together allows the emergence of a larger scale inviscid balance for the Agulhas Current between advection of planetary vorticity (seen as a meridional transport in Figure 1 - top left) and the result of the addition (Figure 1 - bottom left).

As resolution increases (here seen at 1/36º), two new patterns arise. Firstly, although the wind stress curl is locally negligible at lower resolution, the current feedback on the wind stress results in a strip of positive curl along the inshore edge of the Agulhas Current (Figure 1 – top right; note here multiplied by 10). This could influence the shelf mean circulation. Secondly, with increasing resolution, bottom friction induces positive/negative patterns linked with topographic accidents such as seamounts, canyons, and shelf edges (Figure 1 – bottom right). They are directly balanced by bottom pressure torque and non-linear terms (Figure 1 – bottom left), with no significant influence on the meridional transport (Figure 1 – top left).

The terms presented in Figure 1 are averaged over specific regions of different characteristics, such as the Agulhas Current, the Agulhas Return Current, and, for lower resolution at larger scale, the Subtropical Southern Indian Ocean

![Figure 2: Mean transport function (contours in Sverdrup; 1 Sv = 10$^6$ m$^3$s$^{-1}$) from the larger scale simulation used to define the different regions (colors).](image)

![Figure 3: Mean barotropic vorticity balance over the southern Indian Ocean subtropical gyre (SubtropGyre region on Figure 2).](image)

In the interior (east of 50ºE), the Subtropical Southern Indian Ocean is divided into two gyres separated by the South Equatorial Current (around 17ºS): the tropical gyre in the north (SEC of Figure 2) and the subtropical gyre in the south (SubtropGyre on Figure 2). For both gyres, the bottom pressure torque and non-linear terms are relatively small and cancel each other, leading to a quasi-Sverdrup balance (Wind stress curl - advection of planetary vorticity) with a net transport poleward for
the tropical gyre and equatorward for the subtropical gyre. Note that this results in the largest Sverdupian interior transport seen in the subtropical gyres of the world oceans (see for example Tomczak and Godfrey, 2003).

![Diagram](image1)

**Figure 4:** Mean barotropic vorticity balance over the Agulhas Current for the 1/4º (top), 1/12º (middle) and 1/36º (bottom) runs.

The inviscid control seen in other western boundary currents such as the Gulf Stream (Gula et al., 2015; Schoonover et al., 2016) applies also to the Agulhas Current (Figure 4). Nonlinear advection acts in conjunction with bottom pressure torque in balancing the poleward transport in the 1/4º and 1/12º simulations, increasing with resolution. The role of advection appears reversed in the 1/36º run.

4. Conclusion

Here, using regional numerical simulations of the circulation in the South Western Indian Ocean, we have separated the different terms of the mean barotropic vorticity balance to assess their role in controlling the mean circulation in the region. A compensation occurs at small scale between advection and bottom pressure torque over the slopes. This appears to have an oscillatory pattern as seen by Le Corre et al. (2020) and is here directly dependent on the model resolution. Bottom friction also gains importance in general at higher resolution.

Nevertheless, a quasi-Sverdrup relation exists in the subtropical Indian Ocean. This confirms previous works which were using wind stress curl to explain changes in the incoming transports in the Agulhas Region (Rouault et al., 2009; Loveday et al., 2014).

As seen in other western boundary currents (Hughes and de Cuevas, 2001), the advection of planetary vorticity in the Agulhas Current itself is balanced by non-linear advection and bottom pressure torque. In contrast to the Gulf Stream (Schoonover et al., 2016), this balance presents a dependence to the resolution when comparing the 1/4º, 1/12º and 1/36º runs. This may be dependent on the region of integration, the mean structure of the current or it’s variability. For the non-linear terms, we need to determine the role of eddies as done by Le Corre et al. (2020). This could also be important for the intensity of the recirculation loop just offshore of the Agulhas Current, east of the Agulhas Plateau. This loop can be exaggerated in some simulations (Penven et al., 2010).

Here just a few selected domains have been presented but others have contrasting dynamics such as the Agulhas Return Current (ARC on Figure 2) where the balance is controlled by advection and β terms (typical for standing Rossby waves) or the Benguela System and the Mozambique Channel dominated by passing large rings. This approach could also be extended as a framework for model inter-comparisons as proposed by the LEFE project AFRICA.

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The response of mesoscale variability in the northern Agulhas Current and its sources to changing the wind forcing in a forced ocean simulation

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Much of the variability in the northern Agulhas Current is influenced by the arrival of deep ocean eddies at the offshore edge of the Agulhas Current. Whilst existing numerical models are successfully able to capture many aspects of the Agulhas Current, many models are unable to accurately represent the observed eddy dissipation and interaction processes, affecting our understanding of mesoscale variability within the current. In this study, we compare two forced simulation experiments in a regional Hybrid Coordinate Ocean Model (HYCOM), where we change the wind forcing from absolute to relative winds (the wind speed relative to the current speed). In the relative wind forcing simulation experiment there is an overall reduction in eddy kinetic energy (EKE) of 33% over the Agulhas Current domain. Additionally, the modified wind forcing results in significantly different mesoscale eddies in the regional HYCOM.

1. Introduction

Western boundary currents, such as the Agulhas Current, are known to be sinks for eddy energy (Zhai et al., 2010). It has been observed that source region eddies dissipate as they propagate towards the Agulhas Current, thereby affecting the velocity and position of the Agulhas Current core (Braby et al., 2016). Many numerical models are unable to accurately represent the observed eddy-current interaction and dissipation processes and instead show eddies propagating polewards along the offshore edge of the Agulhas Current (Backeberg et al., 2014, Durgadoo et al., 2013, Loveday et al., 2014). Studies have shown that coupled ocean-atmosphere models are better able to simulate mesoscale variability than uncoupled models (McClean et al., 2011; Putrashan et al., 2015; Renault et al., 2016a; Renault et al., 2016b; Renault et al., 2017). This is because coupled models are able to incorporate important air-sea interactions, such as current-feedback to the atmosphere, through the inclusion of small-scale processes in the ocean which enable the atmosphere to be more realistically forced (Renault et al., 2017). Several studies (Duhaut and Straub, 2006; Dawe and Thompson, 2006; Eden and Dietze, 2009; Renault et al., 2016a; Renault et al., 2016b; Abel et al., 2017; Renault et al., 2017; Renault et al., 2019) have shown that the inclusion of surface currents in wind stress calculation caused a significant reduction in the energy of coupled ocean-atmosphere models through “mechanical damping”. In this study, we compare two regional HYCOM simulation experiments, in which we change the local wind forcing, and using an eddy-tracking algorithm we quantify the local effect of the current feedback on source region eddies and their interaction with the northern Agulhas Current.

Although neither of the simulations are coupled ocean-atmosphere models, the effect of the surface current on the wind is accounted for in the forcing. The first simulation experiment is forced by absolute winds (ABS); the second is forced by relative winds (REL). It is anticipated that through the process of “mechanical damping”, a reduced EKE would enable a more accurate representation of eddy dynamics in the source region of the Agulhas Current and that the eddy-current dissipation processes shown by Braby et al. (2016) would be better simulated in the regional HYCOM.

2. Data

Two forced simulation experiments are used in this study in order to determine the impact of current feedback on wind work and EKE in a regional HYCOM model with 1/10° resolution. Weekly averaged output from 1993 until 2013 were used from both simulations. In the ABS experiment, the forcing speed in the wind stress calculation is determined from wind velocity only. In this model, the wind stress is calculated using the equations:

\[ W = \sqrt{(U_{10})^2 + (V_{10})^2} \]

\[ \tau_x = \rho_{air} C_d W U_{10} \]

\[ \tau_y = \rho_{air} C_d W V_{10} \]

where \( \rho_{air} \) is the density of air, \( C_d \) is the drag coefficient and \( U_{10}, V_{10} \) are the wind velocities at 10 m in the zonal and meridional directions, respectively.

For REL, the forcing speed in the wind stress
calculation is found by taking the difference between the wind velocities at 10 m and the surface current velocities. In REL, wind stress is calculated using:

\[
W = \sqrt{(U_{10} - U_{\text{Ocean}})^2 + (V_{10} - V_{\text{Ocean}})^2}
\]

\[
\tau_x = \rho \text{air} C_d W (U_{10} - U_{\text{Ocean}})
\]

\[
\tau_y = \rho \text{air} C_d W (V_{10} - V_{\text{Ocean}})
\]

where \(U_{\text{Ocean}}, V_{\text{Ocean}}\) are the surface current velocity in the zonal and meridional directions, respectively. AVISO Satellite altimetry data were used in this study. In order to compare the two simulation experiments to a reference data set which is more representative of the truth, both models were compared to altimetry data. Gridded maps of Absolute Dynamic Topography (MADT) at a resolution of 0.25° were extracted for the period of 1993 until 2013.

3. Methods

In order to determine whether the change in wind forcing causes a reduction in energy over the Agulhas Current system, the changes in EKE and mean kinetic energy (MKE) are determined using the following equations, respectively:

\[
\text{EKE} = \frac{(u'^2 + v'^2)}{2}
\]

\[
\text{MKE} = \frac{\bar{u}^2 + \bar{v}^2}{2},
\]

where \(u'\) and \(v'\) are the time fluctuations of horizontal components of geostrophic velocities derived from Sea Surface Height (SSH).

The eddy-tracking algorithm developed and best described by Halo et al. (2014) was used in this study. The algorithm uses a combination of the Okubu-Weiss method and geometric method to detect if eddies are present in successive frames and was applied to SSH output from both model simulations as well as to the MADT data. The eddy-tracking algorithm calculates different eddy properties, for all eddies present, at each time step. These properties are then compared against each other in order to quantify the impact that changing the wind forcing in HYCOM has on the eddy characteristics.

4. Results and Discussion

We used an ocean only model to investigate the response of mesoscale variability to current feedback in the regional HYCOM. The reduction in EKE from ABS to REL in this study is approximately 33% (Figure 1a, b). It is evident that results from REL are more representative of the EKE observed in the AVISO compared to ABS. Whilst the altimetry product is more representative of actual EKE values, it is important to note that the altimetry likely underestimates EKE. The effect of the current feedback on EKE is similar to that demonstrated in a previous study using a coupled ocean-atmosphere model of the Agulhas Current system (Renault et al., 2017). Our results suggest that the “mechanical damping” process observed by Duhaut and Straub (2006), Dawe and Thompson (2006), Eden and Dietze (2009), Renault et al. (2016a), Renault et al. (2016b) and Renault et al. (2017) can also be induced by changing the formulation of the wind forcing in the regional HYCOM model from absolute to relative winds.

![Figure 1](image_url)

Figure 1: The mean surface EKE for a) ABS b) REL and c) AVISO data; the mean surface MKE for d) ABS, e) REL and f) AVISO data.

The MKE from ABS to REL is also significantly reduced (Figure 1d, e), with the exception of an increase in MKE in the core of the Agulhas Current as well as the South East Madagascar Current (Figure not shown). Backeberg et al. (2008) show that the velocities of the Agulhas Current in the HYCOM simulation are weaker than observed in the satellite product. An increase in the MKE from ABS to REL, indicates that the change in wind forcing has improved the representation of the Agulhas Current.
Results from Figure 2 reveal how eddy properties in the two simulation experiments compare to the AVISO eddies. A subset of results is selected showing only the eddies which passed through a geofenced region, 32°−50° E and 25°−31° S, between 1993 and 2013. Eddy properties indicate that a change in wind forcing in the regional HYCOM has a significant damping effect on the eddies themselves. Figure 2 shows a reduction in anti-cyclonic eddy lifespans, as well as eddy amplitudes and circum-averaged speeds for both anti-cyclonic and cyclonic eddies. The change in wind forcing has resulted in a more accurate simulation of anti-cyclonic eddies in the regional HYCOM. However, this has made the simulated cyclonic eddies which were already undersized even smaller.

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Numerical modelling of wave-current interaction in the Agulhas Current towards better sea-state estimation

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Ocean currents such as the powerful Agulhas Current have a direct influence on the wavefield propagation. Southwesterly swells formed by strong westerly winds, approach the Southwest Indian Ocean in a direction opposing the flow of the Agulhas Current. The interaction between swell waves and currents alter wavefield propagation and result in cross-seas which ultimately can cause rogue waves. These extreme events are known to be too hazardous for ships navigating around the main current systems. Thus, the principal aim of this study is to investigate the interactions between waves and currents along the South African east coast, thereby improving the sea state monitoring and forecasting. In this study, WaveWatch III (WWIII) numerical wave model has been used to quantify the wave-current interactions along the Agulhas Current region. WWIII simulations with and without the surface currents have been conducted. Preliminary results show there are eminent changes in the significant wave height induced by surface currents. Model results were validated against buoy observations, except for the peak period and wave direction, the significant wave height agrees well with the available wave measurements along the South African coast. However, the model still represents lower wave heights poorly.

1. Introduction

Ocean waves which are generally referred to as wind-generated waves are regarded as an important factor of sea-state. They have an impact on a wide range of activities such as shipping, fisheries, and offshore operations (e.g., oil platforms/rigs) (Quilfen et al., 2018; Chen, 2018). They can disrupt harbor traffic and cause problems for ship routes as well as endanger offshore operations or make it difficult to install offshore marine structures (e.g., Wave Energy Converters). A good understanding of open and coastal ocean wave fields and its evolution in time and space is thus of vital importance. Numerical modeling provides a better way of understanding the variability of ocean surface properties (e.g., surface winds, waves, and other essential variables) (Babanin et al., 2017). The Agulhas Current flows along South African eastern shores and has a direct influence on the wave field propagation (Ardhuin et al., 2017). The south-westerly swells which approach the south-west Indian Ocean in a direction opposite to the Agulhas Current, alter the wavefield and result in wave steepness and crossing seas which can lead to extreme wave conditions (e.g., Rogue waves). To the authors’ knowledge, there are few wave models that account for the influence of the ocean currents on the wavefield (e.g., Meteo France Wave Model). Thus, in this study, we aim to investigate the effect of the Agulhas Current and the Agulhas Return Current on the properties of wave fields. High resolution numerical wave model WWIII forced with the reanalysis wind and current products are used to quantify the effects of strong surface currents. Two cases are considered, simulations with and without surface currents.

2. Data and method

Numerical wave model, WWIII version 6.07 (Tolman, 2019) 10 km by 10 km was implemented in this study over gridded bathymetry for both global and regional domains. GEBCO gridded data was used to construct the bathymetry map. The global model was executed to generate boundary conditions for the regional model. Accurate wind field forcing is needed to provide better wave predictions and forecasts. In this study, the global reanalysis winds from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of 0.125° x 0.125° and temporal resolution of 6 hours have been used to force the numerical wave model. Glorys surface currents with the spatial resolution 0.083° x 0.083° was used to couple the model with currents. The regional model domain covers 14.50° to 34.0117° E and 27.13247° to 42.94180° S, with a spatial resolution of 0.0278° x 0.0278° and temporal resolution of 3 hours. The in-situ observations from 5 locations along the South African coastline have been used in this study to validate the WWIII model results. Skill metrics such as correlation coefficient, root mean square error and standard deviation was used to assess the model performance.
3. Results

Figure 1: The spatial distribution of the significant wave height with and without surface currents along the South African coast for 2017 - 01 – 24 at 18:00 UTC.

In this study, the impact of surface currents on the wavefield characteristics is investigated using the numerical model WWIII. Two cases are considered, simulations with and without the surface currents to quantify the effects of the surface currents. For the purpose of the analysis, we have considered 2017 monthly simulations. Figure 1 shows the spatial variability of the significant wave height with and without the surface current. The influence by the surface current along Agulhas Current region is quite eminent, especial along the Agulhas Bank, retroflection and return regions as shown by Figure 2. This is caused by the wave-current interactions, where these cases oppose each other.

Figure 2: The spatial distribution of the significant wave height differences with and without current along the South African coast for 2017 - 01 – 24 at 18:00 UTC.

Figure 2 indicates that the wave-current interactions are not limited locally (not far from East London and Ngqura regions) but extends further away from where the interaction occurred. This is illustrated by the Agulhas Retroflection and the Agulhas Return Current regions. These areas show a large difference in wave height which is attributed to the relative direction between incoming waves and surface currents. It can also be noticed that there is a reduction in wave height between East London and Durban stations (Natal Valley). This is due to the wave refraction induced by bottom topography in that region. It is quite clear that surface current intensity has a major impact on wavefield propagation.

The model results showed a lot of biases compared to observations as illustrated in Figure 3. Most of the buoys along the South African coast are in sheltered areas and coastal topography tends to affect the quality of simulated wind fields, as a result, affect the wavefield simulations (Christakos et al., 2020). A study conducted by Ardhuin et al., (2007), showed that the quality of wind input degrades when approaching the coastal and semi-enclosed areas, especially areas with orographic effects. Due to such reasons, we can assume that the model performance is different in the open seas and coastal areas.
Figure 3: Significant wave height time series comparison against buoy observations at Cape Point and Richards Bay stations.

3. Conclusion

The model needs to be further calibrated to buoys data. Also improving the wind forcing for the model should improve the agreement of the model results against observations. This will help to provide a reliable wave prediction and early warning of extreme events that often occur along South African coasts.

References


Impact of the Agulhas Current mesoscale variability on surface dispersion in the KwaZulu-Natal Bight

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The KwaZulu-Natal (KZN) Bight has dynamic upwelling cells and retention zones which result in favourable conditions for recruitment. As a result, several Marine Protected Areas (MPAs) were established, including the uThukela Banks MPA (within the KZN Bight), the iSimangaliso MPA (north of the KZN Bight) and the Aliwal Shoal MPA (south of the KZN Bight). In this study, a Lagrangian approach is used to investigate the impact of the Agulhas Current’s mesoscale variability on the surface dispersion in the KZN Bight. Virtual particles are released in a high-resolution ocean model, in a region encompassing the iSimangaliso MPA. They are then left to drift within the model for 32 days, in a steady and in a meandering Agulhas Current, and their outputs are analysed. Drifters are used as a comparable observational dataset. The results show that the residence times of the virtual particles are the longest over the continental shelf (inshore of the 200m isobath) with typical residence times of 4 to 8 days. The residence times over the shelf are very variable, reflecting the ocean variability. Residence times over the shelf break (between the 200m and 1000m isobaths) are short with the virtual particles either moving inshore or being advected offshore into the Agulhas Current. A steady Agulhas Current favours the retention in the KZN Bight, as a greater percentage (49.83%) of virtual particles move onto the shelf compared to when the Agulhas Current is meandering (9.52%). These differences are due to the presence of an anticyclonic eddy when the Agulhas Current is meandering as well as the different alignment of the Agulhas Current relative to the isolobaths. The anticyclonic eddy pulls particles offshore and the meandering Agulhas Current has an isobath-following trajectory near the KZN Bight, which does not favour the inshore movement of the virtual particles. A steady Agulhas Current has a cross-isobath flow, allowing virtual particles to move inshore of the KZN Bight. It also has a northward circulation in the northern KZN Bight, which favours the connectivity between the iSimangaliso and uThukela Banks MPAs. Overall, the steady Agulhas Current forms more favourable conditions for recruitment.

1. Introduction

The KwaZulu-Natal (KZN) Bight is situated on Africa’s south-east coast. It is an area which stretches from Cape St Lucia to Durban (30.5° - 32.5°E, 28° - 30.5°S). Here the otherwise straight south-east African coastline, which generally has a narrow continental shelf and steep slope, is interrupted by a widening of the shelf and a slightly bay-shaped coastline. The KZN Bight is considered to be a retention zone which traps water from the adjacent Agulhas Current (Hutchings et al., 2002). The strong south-westward flowing Agulhas Current is generally oligotrophic/mesotrophic (Bustamante et al., 1995). However, the KZN Bight is richer in nutrients due to dynamical upwelling processes, driven by the Agulhas Current or local cyclonic eddies, and nutrient inputs from rivers such as the Thukela River. The region offshore of Cape St Lucia, for example, is a well-known upwelling cell (Meyer et al., 2002 and Lutjeharms et al., 1989). The retention of water and the higher nutrient concentrations in the KZN Bight make this region an interesting study area which is likely to be biologically important for the recruitment of many species (Hutchings et al., 2002). However, not much research has been done on the biology of the KZN Bight, resulting in large knowledge gaps (Ayers & Scharler 2011). The CAPTOR (Connectivity And disPersAl beTWEEN prOtected aReAs) project, funded by the African Coelacanth Ecosystem Programme (ACEP), focuses on examining the connectivity and dispersal between marine protected areas (MPAs) and adjacent areas along South Africa’s east coast. In particular, the project aims at determining if the MPAs of iSimangaliso, uThukela Banks, Aliwal Shoal, Protea Banks and Pondoland form a network. In this study, we use outputs from a high-resolution ocean model to gain insight on the pathways and dispersion of surface particles across the iSimangaliso and the uThukela Banks MPA domains. Large mesoscale meanders in the Agulhas Current are major drivers of variability for the coastal and shelf regions. A recent study has shown that the Agulhas Current is likely to broaden rather than intensify in the future, possibly due to an increase in the Agulhas Current’s meandering (Beal & Elipot, 2016). Therefore, it is important to understand how meanders impact particle dispersion in the KZN Bight and what the potential implications for larval retention and fish recruitment are.
2. Data and method

We present in-situ observations from surface drifters as well as trajectories derived from virtual particles deployed in a high-resolution hydrodynamic ocean model to better understand how passive drifting surface particles such as fish larvae are transported and dispersed in the KZN Bight. The ocean model used for the virtual particle tracking experiments is CROCO (Coastal and Regional Ocean Community). We used a triple-nested simulation with the two-way nesting approach between each grid. From the data provided, the daily mean outputs of 32 days from 1st February 2012 and 32 days from 1st March 2014 are investigated and compared. March 2014 has an exceptionally stable Agulhas Current trajectory and in February 2012 a large meander starts to form in the KZN Bight. A total of 10890 virtual particles are released in the surface waters of the Agulhas Current in the model just north of the KZN Bight, in the iSimangaliso MPA, in an area stretching from 32°E to 33°E and from 27.25°S to 27.75°S. Their pathways are tracked using 6-hourly intervals and forward integration in time. The tool used for the virtual particle tracking is Parcels (Probably A Really Computationally Efficient Lagrangian Simulator, Delandmeter and van Sebille (2019)). The surface drifters used, which act as an observational comparable dataset, are NOAA drifters with a 15m drogue (https://www.aoml.noaa.gov/phod/gdp/) and CARTHE drifters, which have a very short drogue (https://www.marinetechnologynews.com/news/carthe-drifter-553428). Spatial masks of the areas inshore of the 200m isobath, the 1000m isobath and between the 200m and 1000m isobaths are applied to the virtual particles and drifters. Assuming that virtual particles and drifters within the Agulhas Current are lost to the system, the rationale behind selecting these depths is to see what happens to them once they are inshore of the Agulhas Current front (the 1000m isobath), to see how many of these are then advected across the shelf break (between the 200m and 1000m isobaths) and onto the shelf (inshore of the 200m isobath). We anticipated that larvae have the best chance of successful recruitment on the shelf. The pathways of the virtual particles in a steady and in a meandering Agulhas Current and the residence times in the different inshore regions are compared to each other and to the results of the drifters.

3. Results and Discussion

![Figure 1](image1.png)

**Figure 1**: Virtual particles that move inshore of the 200m isobath. In a), the virtual particles are released in a stable Agulhas Current and in b) the particles are released in a meandering current. The trajectories are colour coded by the time in days that the particles spend in the water after being released. The particles are blue on the day on which they were released and on the last day of the month, the particles are red. The black box is the box in which the investigated virtual particles were released.

When the Agulhas Current is stable, close to half of the virtual particles (49.83 %) end up on the shelf (inshore of the 200m isobath) (figure 1a). Virtual particles which are released further offshore move southwards faster than the virtual particles which are released further inshore. Therefore, the KZN Bight acts as a retention area, trapping virtual particles for up to one month, particularly in the southern section of the KZN Bight. In the inshore northern section of the KZN Bight, the circulation seems less variable as the virtual particles move together and most are about 10-15 days old. A northward movement can be observed. In the inshore...
southern section of the KZN Bight, the circulation seems more variable as adjacent virtual particles have very variable ages.

When the Agulhas Current is meandering, fewer of the released virtual particles (9.52%) move inshore of the 200m isobath. The released virtual particles at first tend to stay within the isobath in which they were released, until they move south of Richards Bay, where the virtual particles slowly start to move offshore (figure 1b). A large inshore eddy is observed slightly north of Durban which traps some particles for the rest of the month, indicating a retention area. In this case very few virtual particles move inshore within the northern section of the KZN Bight, and therefore it is difficult to make a statement on the water dynamics in this section. The eddy inshore of the 200m isobath and slightly north of Durban (31.2 - 31.5°E, 29.5 - 29.7°S) traps virtual particles for the entire duration of the month. Therefore, the residence times are longest in the mid- and southern sections of the KZN Bight.

Less virtual particles move inshore of the 200m isobath when the Agulhas Current is meandering because the current has more of an isobath-following trajectory in this case, compared to the inshore moving cross-isobath flow of the stable Agulhas Current (figure 1). Additionally, an anticyclonic eddy, which results in the formation of the Natal Pulse (Schouten et al., 2002) and is therefore present when the current is meandering, pulls virtual particles offshore and is also responsible for less virtual particles moving inshore of the 200m isobath when the current is meandering. Therefore, overall, the KZN Bight is more favourable to recruitment when the Agulhas Current is steady. It allows more virtual particles to move onto the sheltered shelf and their residence times on the shelf are longer. The connectivity between the iSimangaliso and uThukela Banks MPAs is also stronger when the current is steady, which is due to the presence of a northward flow in the northern KZN Bight only observed in the steady current.

Figure 2: A map of the trajectories of drifters in the KZN Bight region. The pathways of drifters that went inshore of the 200m isobath are plotted in blue while the pathways of drifters that went inshore of the 1000m isobath, but not inshore of the 200m isobath, are plotted in red. The 200m and 1000m isobaths are plotted as black lines.

The observational drifters display similar dynamical features as the virtual particles. These include an offshore anticyclonic eddy (32.5 - 33.5°E, 29.2 - 30.3°S) and a Durban Eddy, which is south of Durban between the 200m and 1000m isobaths (Guastella & Roberts, 2016). However, the residence times cannot be compared to those of the virtual particles because some of the drifters were released within the KZN Bight rather than north of it, affecting the results. Overall, only 12 drifters moved onto the shelf of the KZN Bight. This study demonstrates the strong impact of the Agulhas Current mesoscale variability on the particle pathways, dispersion and recruitment success in the KZN Bight. Understanding how the Agulhas Current varies and how this variability might be impacted by climate change is necessary for the successful management of MPAs in and near the KZN Bight. Virtual particle tracking can help to understand the pathways of larvae and recruits (Singh et al., 2018), which are otherwise difficult to obtain due to factors such as their small sizes. Additional observations and further work in this region, using both forward and backward particle tracking, are needed to improve our knowledge of the connectivity between MPAs.

Acknowledgements:

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References:


The variability of retention in St Helena Bay
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The circulation in St Helena Bay and the variability of the retention of the bay are investigated using seasonal climatology of the Regional Ocean Modelling System (ROMS). While retention has been studied from a biological point of view, the seasonality of the hydrodynamics contributing to the retention have received less attention. In this study we explore how the sea temperature, atmospheric forcing and currents contribute to the seasonal recirculation dynamics in St Helena Bay. Ichthyop, a Lagrangian particle tracking method is used to study the spatial variations of local retention rates, with the particles released in the Bay. The circulation on the shelf of the west coast is dominated by the equatorward boundary current, the Benguela Current. St Helena Bay is protected from the direct impact of the Benguela Current by coastal geographical features. A cyclonic circulation pattern is observed in the bay especially in autumn and winter. However, the results suggest that the recirculation patterns are prominent in summer and spring due to the intensification of the Benguela Jet and the nearshore southward current that flows along the coast. Similar cyclonic features are observed at 100 m depth in the water column. An analysis of the particle tracking reveals that more particles are retained in winter than in summer, supported by what is observed in the circulation patterns. Moreover, more particles are retained in the surface waters than the deep waters.

1. Introduction

The Benguela Current Large Marine Ecosystem (BCLME), one of the four major eastern boundary currents, is in southern Africa on the west coast. The BCLME is a region where upwelling continuously takes place throughout the whole year between 15 °S - 30 °S but with high seasonality between 30 °S -34 °S. The upwelling in the area is driven by Ekman transport offshore which drives the warmer waters offshore allowing the colder upwelled waters to come to the surface. The surface currents are generally equatorward with a narrow and strong shelf edge jet that is also equatorward, and a poleward undercurrent exists along the bottom of the shelf. The aim of this study is to understand the seasonality of water retention in St Helena Bay and the mechanisms responsible for it. Further, it is investigated how the retention changes at differing depths through the water column using high resolution numerical modelling and particle trajectory modelling to quantify.

2. Data and methods

ROMS with a horizontal grid resolution of 1/36°, producing daily averages from 1991 to 2011 is used. The Climate Change Initiative (CCI) satellite data version 1.1 spanning from 1991-2010 with spatial resolution of 0.05 °C was used. The St Helena Bay Monitoring Line (SHBML) transect data containing 12 stations was used. The SHBML transect data contains CTD measurements of temperature, salinity and dissolved oxygen, from the surface to a depth maximum of 1466 m offshore. Ichthyop Lagrangian dispersion tool, is an open-source java tool developed to study the effects of oceanographic fields on ichthyoplankton dynamics produced by models such as ROMS. 8000 particles were released on the first of every January and July from 1991 to 2011 throughout the entire water column where the drifters were advected by ocean currents for 30 days. Figure 1 shows a comparison between the satellite observations and the model. The bias was determined by subtracting the CCI SST from the ROMS SST. A warm bias is observed over the St Helena Bay region in all four seasons.

Figure 1: The difference between the model and the satellite SST (℃). Positive (red) values indicated the regions where the model overestimates the SST and the negative (blue) values show the regions where the model underestimates the SST values. The white line show areas where there is zero difference. The black line indicates the SHBML.

The bias is higher in summer when upwelling is strongest and is lower in winter. This may be due to ROMS overestimating the temperature due to variations in upwelling. Alternatively, the SST overestimation in summer and spring along the coast can also lead to a stronger density gradient producing stronger jets. The reason for the warm bias may be a dynamic response to too much of a nearshore poleward flow that brings in warmer waters from the north of Cape Columbine cell transporting the water southward.
3. Results

The seasonal circulation patterns explain the seasonality of the retention. Along the coast, the wind stress curl is negative. Interestingly, it is most negative at Cape Columbine and southwards in summer and spring. This coincides with the SST (figure 2) where cooler temperatures northwards of Cape Columbine is visible. The cooler inshore and warmer offshore waters create a negative gradient which is indicative of a northward flow strongest in the summer and spring season. This northward flow is better observed nearer to the coast as compared to offshore. An upwelling plume identified using the surface currents (figure 3) as the Benguela Jet, flowing north-westward, following the bathymetry of the shelf edge. A poleward counter current, more distinct in the alongshore velocities together with the Jet create a cyclonic circulation in St Helena Bay. This cyclonic circulation combined with the upwelling plume provide a mechanism for retention. At depth, the same features are observed however, not as prominently which affects the potential of retention at depth.

Using the Lagrangian particle tracking tool, the results show that more particles are retained in winter than summer. The surface waters also retain more drifters than deep water (figure 4).

![Figure 2](image2.png)

Figure 2 Surface seasonal SST (°C) climatologies. Isobaths of bathymetry are displayed at 200 m and 500 m in black.

Discussion and conclusion

Looking at retention through the water column, more drifters were retained in the surface than in the deep water. In summer, more drifter particles were retained in the deep water than in the shallower water. At depth, the currents are moving slower than the surface with less influence from atmospheric forcing. The Benguela Jet is weaker at depth with the nearshore poleward current is stronger. The cyclonic circulation is more defined at depth in contrast to the surface.

![Figure 3](image3.png)

Figure 3 Seasonal surface current speed (m/s) and direction climatologies. Isobaths of bathymetry are displayed at 200 m and 500 m in white.

![Figure 4](image4.png)

Figure 4 Seasonal particle dispersion separated by the surface and deep waters.

References


Marine Heat Waves in the Mozambique Channel
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Marine heatwaves (MHWs) are becoming more frequent and intense around the world leading to long-term impacts on the ecosystems. To date, there has been no study of MHWs in the Mozambique Channel despite this region containing ecologically sensitive areas with high marine biodiversity and being important to the economies of southeastern Africa. An assessment of the annual cycle shows that MHWs here tend to be more intense in summer than at other times of the year, particularly in the southern channel to the west of southern Madagascar. During the 1982-2018 study period, 5 intense events occurred and were associated with severe coral bleaching in this area. Evidence is shown that suggests that MHWs in the southern Mozambique Channel may be associated with eddy activity and with changes in the regional winds.

**Keywords:** Marine Heat Waves, Mozambique Channel, Ecosystems, Coral bleaching, Eddies

1. Introduction

Several prominent marine heatwaves (MHWs) - prolonged periods of anomalously high sea surface temperatures (Hobday et al., 2016) - have had severe impacts on marine ecosystems in recent years. Climate stressors have become more prevalent, especially along the coast and these new challenges have the potential to push marine social-ecological systems past their adapted range of variability. Thus, strong MHWs can have severe impacts for the well-being of hundreds of millions of people whose livelihoods depend on fisheries or coastal tourism, particularly in the developing world. The El Niño Southern Oscillation (ENSO), which is the most significant global climate anomaly on an inter-annual time scale, is one of the drivers of sea surface temperature (SST) extremes such as MHWs (Oliver et al., 2018a) and has substantial impacts on SST in the Mozambique Channel region (Reason et al., 2000). SST variability due to ENSO has been shown to globally impact the ecosystem structures on various spatial scales. In 1998, an El Niño event led to mass coral bleaching in the northern part of the Mozambican coast (Muthiga et al. 2008). In addition to ENSO, the Subtropical South Indian Ocean Dipole (SIOD) [Behera and Yamagata, 2001; Reason, 1999, 2001, 2002] is also known to influence the SST of the South Indian Ocean, including the Channel and regional rainfall over southern Africa. Among the coral affected by major bleaching events since the late 1980s are reefs off the southwestern coast of the island of Madagascar. Some reefs lost nearly 99 percent of their coral cover, and still show little signs of recovery. Coastal waters off the southern leeward side of Madagascar have experienced a marked temperature rise of -0.016°C yr⁻¹, which is about 3 times greater than those near the northern regions of the island at ~0.006°C yr⁻¹ (McClanahan et al., 2007a). Increases in East African waters (Kenya, Tanzania, and northern Mozambique) are -0.010°C yr⁻¹ (McClanahan et al. 2007b) are also less than that along the southwest coast of Madagascar. Southwest Madagascar reefs were among the most degraded reefs studied, as indicated by their low numbers of coral taxa and dominance of erect algae and are probably among the most degraded reefs in the western Indian Ocean (McClanahan et al. 2007a). The present migration of traditional fishers is symptomatic of the many challenges faced by poor coastal people in the Mozambique Channel region resulting from the widespread degradation of coastal ecosystems and fisheries. It is therefore timely to assess the characteristics of MHWs in this region particularly as no study to date has been carried out for MHWs in the southwest Indian Ocean. Therefore, the aim of this paper is to characterize the seasonality and interannual variability of marine heatwaves in the Mozambique Channel, understand their potential physical drivers and assess their ecological impacts.

2. Data and methods

A standardized MHW definition was computed using daily remotely sensed National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST V2 high resolution (1/4°) gridded SST data for 1982–2018 (Banzon et al., 2016). This dataset is used as the spatial and temporal sampling in OISST has adequate coverage in the Mozambique Channel and extends over a sufficiently long period. MHWs were defined as prolonged, discrete and anomalous warm water events in the upper ocean. The climatology and the threshold values (90th percentile) were calculated for each day of the year, using an 11-day window centered on each specific date over 37 years. A 30-day moving average was then applied to generate a smooth climatology and threshold time series, following the MHW detection methodology of Hobday et al. (2016). A MHW event has a specific start and end time and occurs when the seasonally varying threshold was exceeded for at least 5 consecutive days. To examine the properties of a MHW event, the cumulative intensity (the integrated temperature anomaly over the duration of the event) is considered, as it is one of the key characteristics
impacting the local marine environment. Another categorization scheme similar to that used to describe atmospheric heat waves and tropical cyclones is used in this study, whereby the definitions of Category I, II, III and IV marine heat waves are based on the level to which water temperatures exceed local averages. This anomaly between the climatological mean and the climatological 90\textsuperscript{th} percentile differs by location and time of the year (Hobday et al., 2016). Magnitude of scale descriptors, defined as moderate (1–2\times, Category I), strong (2–3\times, Category II), severe (3–4\times, Category III), and extreme (>4\times, Category IV), can be allocated at each point in space and time of an MHW event, based on the intensity (I) measure. The baseline period for determining these thresholds should be fixed, where in this case a 37-year baseline period of 1982–2018 is used.

3. Results and Discussion

There is a strong seasonal signal in the mean intensity of MHWs in the Mozambique Channel (Fig. 1). Generally, MHWs are more intense in the summer half of the year than in winter and tend to be stronger in the southern half of the channel than in the northern half in all seasons. The most intense MHWs tend to occur in the region southwest of Madagascar. Typically, the intensification of MHWs here begins between September and October with an average intensity ranging between 0.8–1.2 °C. MHWs southwest of Madagascar in mid-summer tend to occur over a larger area and reach an average intensity of about 1.6 °C. Those in late summer have an average intensity of 1.2 - 1.6 °C with a smaller spatial extent than those occurring in November to January.

![Figure 1](image1.png)

**Figure 1:** Monthly (Jan, Apr, Jul, Oct) spatial distribution of the intensity (°C) of Marine Heat Wave events in the Mozambique Channel.

In addition to intensity, there is also a clear seasonality to the duration (in days) of MHWs in the Channel as well as their frequency of occurrence (not shown). There are several factors that may help explain the seasonality of these MHW characteristics in the southern Mozambique Channel. Associated with prevailing north-easterlies of the Northeast monsoon (austral summer), a warm southward current, flows along the west coast of Madagascar (Ramanantsoa et al., 2018), carrying warmer water from the northern Mozambique Channel towards southwestern Madagascar. Such a warm southward flow results in a relatively deep thermocline along the southwestern shores of Madagascar. In this case, although winds are upwelling favorable, warmer waters are upwelled, resulting in a weak upwelling signature in SST (Ramanantsoa et al., 2018). Changes in the trade winds at the southern tip of Madagascar leads to the southeast Madagascar current tending to follow a westward path in winter but adopting a more northwestward path in summer as it reaches the Mozambique Channel (DiMarco et al., 2000; Ho et al., 2004). Intrusion of warm eddies from the southern tip of Madagascar into the channel during summer (Halo et al., 2014) can also contribute to the intensification of the southwest Madagascar Coastal Current (Ramanantsoa et al., 2018) thereby favoring more intense MHWs in this region during this season. The monthly time series of the mean cumulative intensity of MHWs against their onset dates (Figure 2) was averaged over the region south west of Madagascar (22°E - 25°E extending 100 km off the coast) where MHWs tend to be stronger and occur over a large area (Figure 1a). Over the period 1982-2018, a total of 178 MHW events were detected, among which the years 1983, 2000, 2016-2017 recorded the highest duration and intensity (Figure 2). Figure 2 shows that 168 out of the 178 MHW events were classified as Category-1 and Category 2 (blue) while only 5 - Category 3 (1997, 1998, 2005, 2006, 2015) and 5 - Category 4 (1983, 1985, 1993, 2004, 2018) events were detected. Of interest are the year 1983 contained a Category 4 event, lasting for almost 3 months and occurring during both the positive phase of ENSO and IOD. On the other hand, the year 2000-2001 has a strong cumulative intensity of about 61°C days but occurred during the negative phase of ENSO. According Ahamada et al., (2008), it is likely that Toliara’s (southwest Madagascar) reefs suffered another widespread bleaching in 2001 due to the high degree heating weeks values and low coral cover.

![Figure 2](image2.png)

**Figure 2:** Monthly variations of the cumulative intensity of MHWs southwest of Madagascar over the period 1982-2018 overlaid with Category-3 (3 \times threshold value) and Category-4 (4 \times threshold value) events calculated using NOAA Optimum Interpolation (OI) SST V2 high resolution (1/4\degree) gridded SST data for 1982–2018.
There may be some relationships between some large-scale climate modes and MHW characteristics at certain lags. The SIO, PDO and SAM are key climate modes contributing to the SST variability in the South Indian Ocean. The modulation of MHW intensity between November to January shows a strong link with SIO and PDO at zero-lag and a weak relationship with La Nina events. SAM also shows a strong positive link prior to MHW events in this region at 2-3-month (Sep-Nov) lag. Investigation of the regional circulation suggests an influence of the northeast monsoonal winds at zero-lag and strong south-easterlies at 2 month-lag with MHW intensity.

4. Conclusion

In this study, MHW in the Mozambique Channel were analysed to find that those southwest of Madagascar during austral summer tend to be the most intense. It is suggested that the southward flowing current along the west coast of Madagascar in summer and the intrusion of warm eddies from the southern tip of Madagascar may favor this seasonality and location of strong MHWs in the channel. Over the period 1982-2018, a total of 178 MHW events were detected, among which the years 1983, 2000-2001, 2016-2017 recorded the highest duration and intensity. Some relationships of MHWs here with large scale climate modes may exist and are being analysed further.

5. References


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Modelling the Agulhas Ocean Current with Delft3D FM, with a focus on the related shallow water hydrodynamics within the Durban Bight, South Africa

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Coastal currents can be significantly influenced by boundary ocean currents when these ocean currents travel along the edge of a continental shelf and when this shelf is narrow. These ocean currents are a result of large-scale temperature and salinity differences and eddies or gyres can form from them. Global ocean models, such as the model operated by E.U. Copernicus Marine Service Information (CMEMS), include the Agulhas Current, but are not suitable for coastal applications due to their relatively coarse resolution. For this reason, the Agulhas Current was down-scaled from the CMEMS ocean model to a local scale Delft3D-FLOW Flexible Mesh model of KZN, by applying appropriate boundary conditions, a new nudging technique and adding tide- and wind-forcing. With a relatively limited area coastal model and high-resolution grid on top of the shelf, feeding the offshore Agulhas current in the model by means of nudging and adding tidal and wind forcing, realistic currents were shown to develop along the relatively shallow Durban and KZN coast. The modelling results were verified and compared to ADCP data from the ACEP project collected by SAEON.

1. Introduction

The coastal city of Durban, KwaZulu Natal (KZN), is located on the eastern boundary of South Africa. It is evident from global circulation models that a strong ocean current runs close by both Durban and its neighbouring coastal cities in KZN, namely the Agulhas Current. The Agulhas Current is one of the strongest ocean currents in the world reaching speeds up to and beyond 2.5 m/s. The current runs in a southerly direction along the eastern edge of South-Africa’s continental shelf. Lutjeharms and Van Ballegooyen (1988) advocated that the current is responsible for influencing the circulation of the relatively shallow coastal waters at the city of Durban and the wider KZN coastal area.

As a result of the narrow shelf at the Durban coast the tide- and wind-induced currents are limited to only a few m/s. It is therefore very likely that currents that are influenced from other offshore factors, such as the Agulhas Current, may significantly contribute to or even dominate the currents in the relatively shallow waters along the Durban and KZN coast.

As ocean currents move closer to a coastline, circulation is largely affected by the topography of that region (Roberts et al., 2016). The East Coast of South Africa has a steep continental slope which is consistent throughout most of the continental shelf. The Agulhas Current hugs the boundary of this shelf (red area in Figure 1), extending well below 1000 m depth (Roberts et al., 2016). As the main current travels further south along the eastern coastline, the slope gradually begins to retreat northwards at Cape St Lucia, resulting in a widening of the shelf. Here the continental shelf extends to almost 50 km, forcing the Agulhas Current to recede further offshore (Lutjeharms, 2006). This is constant until the shelf edge retracts at Thukela River towards the Durban coastline. South of Durban the shelf width reduces as the bathymetry runs parallel to the coast. The region between Durban and Cape St Lucia is known as the KZN bight or historically referred to as the Natal Bight (blue area in Figure 1) (Roberts et al., 2016).

Figure 4: The KZN Bight, Durban Eddy and The Agulhas Current, adapted from Scharler et al. (2016) and Pearce et al. (1978).
At the shelf edge water spins away from the main Agulhas Current and these “break off” waters lengthen and form a loop and ultimately create what is known as an “Eddy”. This causes coastal and shelf currents to mix and encourages the upwelling of cooler waters in the KZN Bight (Lutjeharms, 2006). The “Durban Eddy” (orange area in Figure 1) is a semi-permanent mesoscale cyclonic circulation which occurs in the southern half of the KZN bight and finds its way into the northward inner and mid-shelf regions (Roberts et al., 2010, 2016). The ellipsoidal shape can grow to a size of between 60 to 90 km in length and 30 to 50 km in width, deeming the cyclonic eddy as mesoscale. The Durban Eddy produces counter currents acting against the main Agulhas Current that are half as strong (Guastella and Roberts, 2016). Guastella and Roberts (2016) suggested that the behaviour of this eddy and its frequency is manipulated by the actions of the Agulhas Current. The Durban Eddy could have major influence on the near shore coastal currents within the KZN bight (demarcated with red arrows in Figure 1) and in particular, the Durban bay, rendering the coast susceptible to influences from the Agulhas Current and its spin off features.

2. Data and method

A three-dimensional Delft3D-FLOW Flexible Mesh model was developed with 40 Z-layers and a spatial resolution of 5km at the open boundaries to about 250 m along the Durban coast. At the open boundaries the model was forced with physical variables extracted from the CMEMS Global Forecast Analysis model (spatial resolution of about 8 – 9 km), including: temperature, salinity, sea surface height and ux/uy current velocities. Other external data sources integrated into the model were GEBCO and local mapping bathymetry, and ERA5 (ECMWF) wind and atmospheric pressure data. Tidal constituents were brought in from the global FES2012 model. A new technique was used to assimilate data from the CMEMS model in order to generate the main Agulhas Current in the Delft3D-FLOW Flexible Mesh model, a model suited numerically for coastal ‘shallow-water’ flows, prone to numerical diffusion for ‘deep-water’ oceanic flows. The assimilation of data in the Delft3D-FLOW Flexible Mesh model is referred to as the “nudging technique”. This technique has been implemented in Delft3D-FLOW Flexible Mesh to allow for the input of temperature and salinity parameters within a regional scale model from their respective variables in an ocean/global model. In doing so, both a large-scale ocean circulation model in deep waters and a 3D hydrodynamic model closer to the coast is used to represent near-shore interactions with ocean boundary currents. Nudging is implemented by adding the following damping term to the state variable equation of interest. In the case of salinity, this reads as:

\[ \frac{\partial S}{\partial t} = ... + \frac{S_{\text{nudge}} - S}{\tau_{\text{nudge}}} \]

With $S$ the model salinity, $S_{\text{nudge}}$ the target field value and $\tau_{\text{nudge}}$ the user-defined nudging time-scale (strong nudging in deep ocean area, own solution computation of hydrodynamic model in shelf area, and interaction between the two).

3. Results

Water level (tide), temperature and salinity parameters were successfully implemented in the model. Temperature and salinity outputs represented similar results to that of CMEMS global products with higher accuracy towards the coast.

![Figure 2: Modelled temperature (left) versus CMEMS temperature (right) for 01-01-2009 at a depth of 2m below the surface.](image)

After many trials and tribulations, a stable model simulation was achieved including the Agulhas Current and secondary currents for the period of June 2009 up until July 2010. Figure 3 presents an example of a computed surface current field.

![Figure 3: Surface currents computed by the Delft3D Flexible Mesh model, using nudging and CMEMS boundary conditions. The Agulhas Current is seen hugging the continental shelf as can be expected.](image)

With the newly implemented nudging technique the Agulhas Current developed in the model and kept along the eastern coast of South Africa (see Figure 3). Closer
to the coast circular currents develop, including the distinct Durban Eddy.

Using data collected from the African Coelacanth Ecosystem Programme (ACEP), comparisons were made with the Flexible Mesh model outputs, the CMEMS global data and the ADCP measurements from ACEP.

![Velocity Time Series at depth 60m from surface](image)

**Figure 4:** Time series for the year 2009 depicting a station located in deep water near possible locality of Durban Eddy which shows velocity magnitude of: CMEMS data (in black), ACEP data (in red) and Delft3D model data (in green).

Figure 5 depicts the Durban Eddy in more detail and its influences within the receding bay further north. The red arrow represents a data point indicating velocity magnitude and direction obtained by The Southern African Data Centre for Oceanography (SADCO). As illustrated in Figure 5, the data point and the black arrows (modelled results) show both similar direction and magnitude.

![Durban Eddy Formation with Velocity Magnitudes 05-Jun-2009 12:00:00](image)

**Figure 5:** Map output for the Flexible Mesh 3D model showing velocity magnitudes and direction, including a red arrow that represents a data point from observed ADCP measurements off the coast of Durban.

**Summary**

The objective of this research was to down-scale an ocean current from a global model (CMEMS) to a local scale model, using the Delft3D Flexible Mesh model and a newly implemented nudging technique. First comparisons between model output and measurements show that the model reasonably well represents the main Agulhas Current and its counter-currents. Further simulations and analysis are still to be conducted for this research to achieve a reliable and accurate representation of the combined ocean, tidal- and wind-induced currents along the relatively shallow waters along the coast of Durban and KZN.

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**References**


Atmospheric and climatic drivers of tide gauge sea level variability along the east and south coasts of South Africa
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Atmospheric forcing and climate modes of variability on various time-scales are important drivers of sea level variability. However, the influence of such drivers on sea level variability along the South African east and south coast has not yet been adequately investigated. Here, we determine the timescales of sea level variability and their relationships with various drivers. The Empirical Mode Decomposition (EMD) was applied to seven tide gauge records and potential forcing data for this purpose. The oscillatory modes identified by the EMD were summed to obtain physically more meaningful timescales; particularly, the sub-annual (less than 18 months) and the interannual (greater than two years) scales. At the sub-annual scale, sea level responds to regional zonal and meridional winds associated with mesoscale and synoptic weather disturbances. Ekman dynamics resulting from variability in sea level pressure and alongshore winds are important for the coastal sea level at this timescale. On interannual timescales, there were connections with ENSO, the IOD and the SAM although the results are not consistent across all the tide gauge stations and are not particularly strong. In general, El Niño and positive IOD events tend to increase coastal sea level and vice versa whereas there appears to be an inverse relationship between SAM phase and sea level.

1. Introduction

A rise in sea level is one of the most important consequences of climate change. As a result, several studies have pointed out the urgency for understanding regional sea level variability and rise due to its direct socioeconomic impacts on coastal zones (Milne et al., 2009). With a major migration of populations to coastal cities and both urban and peri-urban sprawl, it is imperative to understand the nature of the sea level changes at sensitive low lying areas. In addition to this, because of the likely increased storminess of the Southern Ocean (a major wave generation area for southern Africa), and the impact of tropical disturbances on the low lying areas such as Mozambique, combined impact of storm surges and wind waves, increased saltwater intrusion of farmlands, and coastal erosion are likely to affect many of the local resident populations (e.g. Singleton and Reason, 2007). Thus, understanding southern African sea level variability and rise is critical for all forms of coastal development. Tide gauge measurements are useful to advance the understanding of how oceanographic and climate processes affect the coastal zone (Prandi et al., 2009; Komar et al, 2011). Shorter term sea level variability, especially on local scales, is challenging to understand given the difficulty of linking it with known driving mechanisms and to assess whether observed changes are due to natural or anthropogenic causes. Some authors have claimed that atmospheric forcing and climate modes on various time-scales are important for driving sea level variability (Brundrit, 1984; Brundrit et al.; 1984; Soumya et al., 2015). However, the influence of such drivers along the South African east and south coasts has not yet been adequately investigated. Thus, the aim of this study is to determine the timescales of sea level variability in this region and their relationships with various physical drivers.

2. Data and methods

To better understand the possible driving mechanisms of sea level variability here, different data sets from several data sources are used (detailed below). Analysis of the embedded timescales of variability of both large scale oceanographic and climate data, and monthly mean sea level records of seven individual tide gauges, from the east and south coasts of South Africa was performed. These data included monthly mean gridded reanalysis sea surface pressure (SLP) and wind at 10 m, sea surface temperature (SST; and time series of monthly mean Dipole Mode Index (DMI), Multivariate ENSO Index (MEI) and Southern Annular Mode (SAM). The timescales embedded in each of the datasets are determined through the Empirical Mode Decomposition (EMD) method (Huang et al., 1998; Huang and Wu, 2008).

3. Results

It was found to be challenging to identify which driver is embedded in the data when interpreting each mode (timescale), as also found in similar studies in other regions (e.g. Haigh et al., 2014). Thus, the oscillatory modes identified by EMD were aggregated to obtain physically more meaningful timescales. These are the
sub-annual timescale, which was the sum of the modes with a periodicity lower than approximately 18 months, and the interannual timescale or aggregate of modes with a periodicity longer than approximately two years. The results suggest that at the sub-annual time scale, sea level responds to regional zonal and meridional winds associated with mesoscale and synoptic weather disturbances. Ekman dynamics resulting from variability in sea level pressure and alongshore winds are important for the coastal sea level at this timescale (Figure 1).

At the interannual timescale, the results suggest a connection between coastal sea level variability and climate indices, although it is not consistent across the tide gauge stations nor particularly strong. Strong El Niño events tend to increase coastal sea level and strong La Niña events the reverse, although the relationship is not consistent. Overall, strong Indian Ocean Dipole (IOD) events tend to have a similar influence as the strong ENSO events. The results also suggest that, in general, negative Southern Annular Mode (SAM) events lead to high coastal sea level events. It was noticed that particular strong ENSO and IOD events were in phase with sea level variability suggesting a need for further studies to understand to what extent ENSO and IOD directly modulate coastal sea level.

**References**


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Understanding variability across the Crossroad Transect from 3 years of hydrographic data
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A synergy of data is used ranging from satellite altimetry to in situ observations along the Crossroad transect. An annual study ranging from available hydrographic data is analyzed from 2013 to 2015. Short Term Average (STA) data, using a 3-minute average of the ADCP data was processed up to maximum depth of 501 m. About 17 full-depth Conductivity Temperature Depth (CTD) stations were collected. During each voyage, the vessels keel mounted 75 kHz Teledyne RD Instrument SADCP was set for data collection. The Soil Moisture and Ocean Salinity (SMOS) data was used along with Aviso products. Variability in current measurements was observed, where velocity ranging from 2 to 2.5 m/s represented the Agulhas Current and 1.4 to 1.7 m/s, Agulhas Return Current. In addition, the position of the Agulhas Current and Agulhas Return Current displayed variation from 2013 to 2015, with the Agulhas Return Current exhibiting a meandering pattern in 2014 along the transect. The salinity signature on the other hand denotes more saline waters observed in the open ocean relative to shelf water. The study therefore advances knowledge by potentially complementing small scale features in surface fields through integrating remote sensing satellite sensors with in situ measurements to the full spatio-temporal variability of both mesoscale and sub-mesoscale features across the Crossroad transect.

1. Introduction

Considering the general overview of the Agulhas system, the variable Agulhas Current and its sources, Agulhas Retroreflection, Agulhas leakage and Agulhas Return Current occur interdependently to form the Agulhas Current system. This system functions effectively by integrating all the physical and thermodynamic processes. One of the primary roles of the Agulhas Current is to transport ocean water and its biota into the southern part of the southwest Indian Ocean and thereby influencing the ocean’s dynamics and ecology (Lutjeharms and de Ruijter, 1996). The Agulhas Current generates coastal upwelling at the Agulhas Bank and carries a large body of water to influence the distribution of pelagic species through advection (Lutjeharms, 2006). Warming has been identified across the Agulhas Current system as a response of increased wind stress curl in the South Indian Ocean (Rouault et al., 2009). Research as documented by Rouault et al., (2009) show that these warm sea surface temperatures approximate up to 0.7°C per decade of warming within the system. Consequently, the variation associated with the Agulhas system contributes to the impact on the climate of South Africa (Rouault et al., 2009), leading to environmental, poverty, health, and safety challenges on different disciplines (Morris et al., 2017). Sampling along the Crossroad transect was commenced in 2013 with the primary goal of analysing both the Agulhas Current and the Agulhas Return Current. However, data collected along this route remains incomplete. Examining both the basin and mesoscale features across the Crossroad transect given the inherent advantage of satellite remote sensing and access to different in situ datasets forms the main objective of the study. The study also investigates and compares distinctive water mass properties using different ocean instruments, which include the Conductivity Temperature and Depth (CTD), Thermosalinograph (TSG) and Shipboard Acoustic Doppler Current Profiler (SADCP). In addition to using these instruments, different resolutions highlight different properties, allowing an analysis of diverse range of scales from basin to submesoscale. In order to achieve the goals of the study the following key questions are observed: (i) What basin scale features are observed across the Crossroad transect, (ii) how do observations of basin and mesoscale features differ when using different datasets and (iii) Are there interannual similarities and differences in the basin and mesoscale variability observed along the Crossroad transect between 2013 and 2015?

2. Data and method

Surveys of the Agulhas Current system along the Crossroads Transect were conducted annually between 2013 and 2015, consisting of a single transect, which followed under altimetry track N198. Station positions were designed to resolve the nature
of both the Agulhas and Agulhas Return Currents with a total of 17 full-depth Conductivity Temperature Depth (CTD) stations collected. During each voyage, the vessels keel mounted 75 kHz Teledyne RD Instrument SADCP was set to collect data. The Soil Moisture and Ocean Salinity (SMOS) and Aquarius satellite are intently considered in this study as they exhibit the main characteristics of the global sea surface salinity, temperature and height distribution (Köhler, 2015). The SMOS and Aquarius measurement intensity is based on the electromagnetic radiation in the L band with a frequency of approximately 1 to 2 GHz. The advent of SMOS makes it feasible to quantify the assessment of the mechanisms that govern the ocean surface variability and infer on the salinity budget (Durand et al., 2013). The primary objective of SMOS is ultimately to remotely sense the moisture of the continental surfaces and surface salinity content of the oceans. The satellite data used in the study are also obtained from Aviso (Arching, Validation and Interpretation of Satellite Oceanographic). The altimetry results observed are based on gridded Maps of Absolute Dynamic Topography Heights (MADTH) obtained from the SSALTO/DUACS data products (www.aviso.altimetry.fr).

3. Results

Figure 1: Surface temperature and salinity measurements collected from Thermosalinograph data along the Crossroad Transect.

Figure 2: Maps showing ssh (m) south of Africa. Overlaid along the Crossroad transect is the corresponding surface ADCP data as indicated by the vectors in black. The blue (black) circles indicate anticyclonic (cyclonic) eddies. The overlaid vectors show the magnitude and direction of geostrophic currents with a reference of 0.08 m/s. Dynamical properties such as temperature and salinity along the surface are observed. As seen in Figure 1, the interdependent components of the Agulhas system (AC and ARC) are observed with the AP annotated between 40° and 42°S. Sea surface temperature signals along the Crossroad transect varies with temperature ranging from approximately 13.5°C to 24.5°C. Therefore, variability in temperature observed...
along the sea surface is possibly due to the north and south movements of fronts, and as the transect intersects either cyclonic or anticyclonic eddies. The interannual variability across the Agulhas System plays a defining role in determining its behaviour. However, notable is the decreasing surface temperature at the same latitude (39° to 40°S) in 2015. From 2013 to 2015 the submesoscale features are evident, with a horizontal length scale of approximately 1 to 10 km. These features are apparent throughout the transect indicating a region of high variability. The differences in surface temperature observed along the transect are mostly documented along the ARC from approximately 37° to 39°S. In 2013 the surface temperature indicated a decrease from 24.5°C to 16.3°C, while in 2014 a decrease in surface temperature from 24.5°C to 17.5°C is observed and 2015 exhibits surface temperature decrease from 24.5°C to 21°C suggesting altogether that the ARC is relatively warmer in 2015 as shown by maximum temperature compared to the 2013 and 2014. The anticyclonic eddy observed in 2013 has relatively low surface temperatures ranging from 13° to 16°C. Also notable is the size of the eddy with a large spatial proximity of more than 150 km. In 2014 maximum surface temperatures ranging from 16° to 19°C are observed along the anticyclonic eddy with a relatively small spatial proximity of approximately 100 km. In 2015 however, the surface temperature illustrates a decreasing pattern from approximately 19° to 13.5°C. The salinity signature observed along the transect is similarly subject to variability although more consequential relative to temperature, due to its conservative property. The salinity measurements along the transect are less varied. A notable distinction as seen once more in Figure 1 (salinity) between the AC and ARC. The ARC exhibits more saline surface waters relative to the AC. The difference is possibly due to temperature differences between the currents. Anticyclonic eddies in the southern hemisphere are characterized by warm temperature, therefore as a result of the presence of the eddy observed along the AP warmer surface waters are observed ranging from 13° to 19°C. Represented in Figure 2 are sea surface height maps indicating the basin scale features within the Agulhas Current System. The colour bar shows positive and negative values indicating sea surface elevation. Overlaid on the maps along the transect are in situ data collected from the ADCP. A noticeable variability in current measurements was observed, where velocity ranging from 2 to 2.5 m/s represented the Agulhas Current and 1.4 to 1.7 m/s, Agulhas Return Current. Similarly, the position of the Agulhas Current and Agulhas Return Current displayed variation from 2013 to 2015, with the Agulhas Return Current exhibiting a meandering pattern in 2014 along the transect.

To recapitulate, the ability to combine altimetry and in situ data also contributed to the analysis of the results. Therefore, given the inherent advantage of satellite and in situ measurements, an overview of the variability across the Crossroad transect was determined. The study outlines the essence of understanding the decisive role played by basin scale and mesoscale features on a local, regional and global context. These include their spatio-temporal variant nature and impact on the ocean circulation. Although progress has been achieved in the last 2 decades in characterizing and analysing different ocean fields using both altimetry and in situ data, our understanding of mesoscale and submesoscale dynamics remains incomplete. Nonetheless, the importance of the ocean observations, which was to highlight the salient features of the Agulhas system has been achieved successfully.

References


Acoustic Detection of the Short Pulse Call of Bryde's Whales based on time domain Features and Hidden Markov Model

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The biological group of cetaceans is frequently studied nowadays as passive acoustic monitoring (PAM) is commonly used to extract the acoustic signals produced by cetaceans, in the midst of noise sounds made by either man during shipping, gas and oil explorations or by natural sounds like seismic surveys, wind, and rain. In this research work, the acoustic signal of short pulse calls of inshore Bryde's whales is detected using time-domain features and hidden Markov models (HMM). HMM is deployed as a detection and classification technique due to its robustness and low time complexity during the detection phase. However, some parameters such as the choice of features to be extracted from the acoustic short pulse call of inshore Bryde's whales, the frame duration of each call and the number of states used in the model affect the performances of the automated HMM. Therefore, to measure performances like sensitivity, accuracy and false positive rate of the automated HMM; three time-domain features (average power, mean and zero-crossing rate) were extracted from a dataset of 44hr26mins recordings obtained close to Gordon's bay in False Bay, South Africa. Moreover, to extract these features the frame durations of each vocalization were varied thrice; 1 ms, 5 ms, and 10 ms. Also, the HMM used three different numbers of states (3 states, 5 states, and 10 states) which were varied independently so as to evaluate the HMM. On overall performance, the HMM yields best performances when it uses 10 states with a short frame duration of 1 ms and average power as the extracted feature. With regard to this, the automated HMM shows to be 99.56% sensitive, and dependable as it exhibits a low false positive rate of 0.1 with average power inferred as the best time domain feature used to detect the short pulse call of inshore Bryde's whales using the HMM technique.

1. Introduction

Acoustic signal processing is based on the principal concept of extracting critical information from noisy, ambiguous measurement data, while signal processing is the process of acquiring, storing, displaying, and generating signals (Hartmann, 2007). Acoustic signals are responses to a specific stimulus, which are used by most marine mammals to relate with the environment. The biological group of cetaceans like whales, dolphins, and porpoises communicate with each other and their surroundings, identify their sexual partners and even echo-locate preys using the acoustic signals they produce. The acoustic signals or vocalizations produced by some species are known as moans, clicks, and pulses are contain different kinds of noise like anthropogenic noise (manmade, shipping, pile driving), noise from ocean fauna (whales, fish) and natural non-biological noise (wind, rain, waves, seismic). The presence of noise in these vocalizations makes it difficult to identify a cetacean by its acoustic signal. So, there is a need to detect specific marine mammal's vocalization and an attempt to localize them relative to a towed array. Usually, acoustic sensors are used to survey and monitor marine mammals in the ecosystem. Sound recorders like passive acoustic monitoring (PAM) are deployed in the field to collect acoustic data which may last for hours, days or weeks. These recordings are processed after collection to extract ecological and acoustical data of interest, such as detecting calls from particular marine mammals. The recorded dataset can later be used to estimate species habitat, abundance, population density and group composition, track marine mammals' behavioral spatial and temporal patterns, and measure acoustic representations for biodiversity metrics (Browning et al., 2017).

There are two main allopatric forms of Bryde's whales as members of the \textit{Balaenopteridae} family in the class of cetaceans (The Society for Marine Mammalogy, 2020). The inshore allopatric form of Bryde's whale scientifically called \textit{Balaenoptera edeni} was discovered in (Anderson, 1878). This inshore Bryde's whales with short pulse calls are considered in this study since they are one of the world's most endangered marine mammals. The population growth of Bryde's whales is quite small, though not ample information is provided regarding their population size estimate. Anthropogenic and marine activities are major threats preventing Bryde's whales from properly communicating, navigating, and feeding. In Oleson et al. (2003), Bryde's whales' vocalizations from Eastern Tropical Pacific, Southern Caribbean, and Northwest Pacific report a frequency range from 21 Hz to 207 Hz and a time span from 0.35 - 2.8 s. Other Bryde's whales call from Southeast Brazil [9a] disclose more call types lasting for 0.8 - 1.5 s within a frequency range of 9 - 670 Hz. Moreover, for a case study of Bryde's whales in the Gulf of California, the whales' sound is described to have fundamentals varying between 90 - 900 Hz and a duration interval of 25 ms to 1.4 s (Tershy, 1993). Ocean noise is often at low frequency, just like the low-frequency range of Bryde's whale sounds. Therefore, the ocean noise tends to interrupt Bryde's whales' possibility of properly listening to other environmental
sounds, and this may eventually cause them to dislocate and even get extinct. Thus, it is important to recognize this particular short pulse call of the inshore Bryde's whales' in the presence of many other sounds. A better approach to ensure this is to begin by detecting their presence in the oceans. This implies developing a detector (HMM) characterized by the short pulse call of the Bryde's whale.

Therefore, this paper focuses on developing a detector to find a specific signal, being the short pulse call of inshore Bryde's whales. Speech recognition approaches are borrowed in this context to detect wanted acoustic signals since acoustic signals are similar to speech. For instance, the statistical-based approach has shown to be the most suitable detection technique given its robustness, efficiency and reduced computational time (Shaikh & Deshmukh, 2016; Singh, 2016). The statistical model employed in this study is the Hidden Markov Models (HMM), which is in the class of probabilistic graphical model. The HMM is used for predicting a sequence of unknown (hidden) variables given a set of acoustic characteristics, known as the observations.

2. Data and method

2.1. Data collection

The raw sound data in this study was collected by our research group using PAM, within a couple of days in January 2019. The dataset consists of short pulse calls of inshore Bryde's whales together with dissimilar sounds like those of other marine mammals and noise of various forms. This dataset is obtained from four different recordings with a total of 44hr26mins which is provided to analyze the inshore Bryde's whales short pulse calls. In terms of the geographical location, the data was recorded close to Gordon's Bay harbor situated at 34°8’57.5”S 18°51’26.7”E and in False bay situated at 34°12’38.9”S 18°38’27.3”S, South Africa, as seen in Figure 1.

Normal protocols were stringently followed as stipulated by the South African Department of Environmental Affairs. Among others was observing the recommended minimum distance on the sighting of whales. Dipped hydrophones were used for the series of recordings done. In the process of carrying out this task, a hydrophone was joined to a Zoom H1N recorder. Specifically, Aquarian Audio H2A – XLR Hydrophone with sensitivity –180 dB re 1V at a frequency interval of 10 Hz - 100 kHz and the recorder working at 24 bit resolution at a sampling frequency $f_s = 96000$ Hz.

The raw data was stored as a .wav file, that is, in an uncompressed and lossless format, to keep its original properties. The hydrophone was immersed to a depth of approximately 7 m from a sailboat of about 8 m.

2.2. Data preparation

Following the recordings and collection of the acoustic dataset, the raw data was processed before any further use. Of interest, is maintaining wanted signal quantities and removing undesired ones. This is achieved by using the established MATLAB Butterworth bandpass filter given its smooth frequency response in the passband. Passband frequency was chosen between 90 Hz and 46000 Hz since the fundamental call frequencies of Bryde’s whale are generally greater than 90 Hz (Oleson et al., 2003), and the upper band frequency is half the sampling rate of the data. Moreover, to remove any average voltage (DC components) from the Butterworth bandpass filter’s acquired data, the mean is subtracted from this data. Thus, a pre-processed data is obtained with less attenuation since a 3rd order Butterworth bandpass filter was used. Hence, the data is segmented for further analysis.

2.2. Data annotation and segmentation

The pre-processed sound dataset is analyzed by visual and auditory inspection on a Sonic Visualizer - version 3.2.1 as seen in Figure 2.

The analytic step involves annotating the pre-processed dataset into two segments. The segments include the Bryde's whale vocalization labeled as Whale snippet W5, and any sound (produced either by anthropogenic activities or other marine mammals) other than the Bryde's whale call is labeled as Noise snippet N5. Thus, the pre-processed data is visually observed to be:

![Figure 2: Sound data annotation on Sonic Visualizer](image)
\[ D = \left[ d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8, d_9, d_{10}, d_{11}, d_{12}, \ldots \right] \]

\[ \begin{align*}
\text{WS}_1 & = \left[ W_{S1} \right] \\
\text{WS}_2 & = \left[ W_{S2} \right] \\
& \vdots \\
\text{WS}_p & = \left[ W_{Sp} \right] \\
\text{NS}_i & = \left[ N_{S1} \right] \\
& \vdots \\
\text{NS}_q & = \left[ N_{Sq} \right] \\
\end{align*} \]

where \( d \) represents the \( n \) sampling points of the preprocessed data, \( p \) and \( q \) are the total numbers of whale and noise snippets obtained from annotating \( D \) respectively.

Also, from \( D \), it is seen that each respective snippet has a different length or call duration. Hence, all the annotated and categorized snippets are stored in two corresponding sets \( \text{WS}_i \) and \( \text{NS}_j \) such that:

\[ \begin{align*}
\text{WS}_i & = \left[ \begin{array}{c}
W_{S1} \\
W_{S2} \\
\vdots \\
W_{Sp}
\end{array} \right] \\
\text{NS}_i & = \left[ \begin{array}{c}
N_{S1} \\
N_{S2} \\
\vdots \\
N_{Sq}
\end{array} \right] \\
\end{align*} \]

where \( i = 1, 2, \ldots, p \), and \( j = 1, 2, \ldots, q \).

### 2.3. Frame extraction

Both whale and noise snippets are eventually split into frames. The frame extraction process is based on the frame size or frame length \( F_i \) and the number of sampling points \( r \) in each snippet. The frame length is derived by multiplying the sampling frequency \( F_z \) by the frame duration \( F_d \) as:

\[ F_i = F_z \times F_d, \]

where \( F_i \) represents the number of sampling points in a frame. In this study, the frame duration is chosen in terms of a short, medium, and long duration assumed as 1 ms, 5 ms, and 10 ms respectively. Consequently, the number of frames \( x \) in a snippet is obtained as:

\[ x = \frac{r}{F_i} \]

Hence, every whale and noise snippet stored in the corresponding sets \( \text{WS}_i \) and \( \text{NS}_j \) is split into frames by dividing each of them with the frame length.

For a better understanding of the frame extraction process, suppose an arbitrary whale snippet to be:

\[ \begin{align*}
\text{WS}_i & = \left[ \begin{array}{c}
r_1, r_2, r_3, \ldots, r_a, r_{a+1}, \ldots, r_{2a}, r_{2a+1}, \ldots, r_{3a}, \ldots
\end{array} \right] \\
& \text{divided by each of them with the frame length}
\end{align*} \]

where \( f_1, f_2, \ldots, f_x \) represents the frames, \( x \) is the number of frames, and \( a = F_i \). Worthy to note is that, in cases where \( r \) is not evenly split by \( F_i \), then \( r \) is padded with zeros to maintain consistency while evenly splitting \( r \) by \( F_i \). Similarly, any other noise snippet is split into frames as illustrated by \( WS_1 \). Once the frames have been extracted, depending on the kind of feature aimed at extracting and detecting, the feature extraction step is performed on every frame.

### 2.3. Feature extraction

Three time-domain features are used to extract wanted characteristics from the segmented dataset in this study. The extracted features are average power \( P_{avg} \), mean \( \mu \), and zero-crossing rate \( ZCR \).

#### 2.3.1. Average Power (\( P_{avg} \))

The average power of a signal is the sum of the absolute squares of its time-domain samples \( X \) divided by the signal length \( N \). In other terms, given a frame with \( N \) sampling points, which is equivalent to the frame length of a snippet, the value of these sampling points are squared, added and divided by \( N \) as:

\[ P_{avg} = \frac{1}{N} \sum_{n=1}^{N} X_n^2. \]

\( P_{avg} \) indicates the loudness of the frame. \( P_{avg} \) is chosen as a time-domain feature because it provides a basis for separating voiced from unvoiced components of a speech signal. Also, it is a good measuring tool to differentiate detectable and silent sounds with a high signal-to-noise ratio (Zhang & Kuo, 2001).

#### 2.3.2. Mean (\( \mu \))

The mean of an acoustic signal sums up all the \( N \) sampling points per signal frame such that:

\[ \mu = \frac{1}{N} \sum_{n=1}^{N} X_n. \]

In general, the mean is used to reduce the background noise or remove the DC component which could most probably alter the signal's waveform. So, the computed mean per frame of a sound snippet serves as the time domain feature vector.

#### 2.3.3. Zero-crossing rate (\( ZCR \))

The \( ZCR \) measures the frequency content of a sound signal without necessarily working in the frequency domain which is computed as (Zhang & Kuo, 2001):

\[ ZCR = \frac{1}{2(K - 1)} \sum_{n=1}^{K-1} [\text{sgn} \{ x_{n+1} \} - \text{sgn} \{ x_n \}], \]

where \( \text{sgn} \{ x_n \} \) is a signum function such that:

\[ \text{sgn} \{ x_n \} = \begin{cases} 
1, & x_n \geq 0 \\
-1, & x_n < 0
\end{cases} \]

\( ZCR \) is considered as a time-domain feature extraction since it measures a wide variance and amplitude range for the \( ZCR \) curve (Zhang & Kuo, 2001), which is the case for Bryde's whale vocalization as it falls within an amplitude band.
The process of extracting each feature is performed at three different frame lengths as a result of the three assumed frame duration of 1 ms, 5 ms, and 10 ms. This process is implemented on all the whale and noise snippets. Consequently, two respective sets of extracted features are obtained for both the whale and noise snippets denoted as $W_f$ and $N_f$ respectively.

Let $p_i$, $m_i$, and $z_i$ be the respective $P_{avg}$, $\mu$ and ZCR extracted feature samples corresponding to the $i$th frame $f_i$, where $i = 1, 2, ..., x$. The set of extracted features for all the whale snippets is represented as:

$$W_f = \begin{bmatrix}
    f_1 \\
    f_2 \\
    \vdots \\
    f_x
\end{bmatrix}
\begin{bmatrix}
    p_1 & m_1 & z_1 \\
    p_2 & m_2 & z_2 \\
    \vdots & \vdots & \vdots \\
    p_x & m_x & z_x
\end{bmatrix}
$$

while the set of extracted features for all the noise snippets is represented as:

$$N_f = \begin{bmatrix}
    f_1 \\
    f_2 \\
    \vdots \\
    f_x
\end{bmatrix}
\begin{bmatrix}
    p_1 & m_1 & z_1 \\
    p_2 & m_2 & z_2 \\
    \vdots & \vdots & \vdots \\
    p_x & m_x & z_x
\end{bmatrix}
$$

Different feature values are obtained as the frame durations are varied from 1 ms, 5 ms, and 10 ms. These extracted features or observation sequence will be further used to train and evaluate the model.

2.5. Training

The extracted features are selected such that 70% is used to train the corresponding whale and noise models while the remaining 30% is later used as another sequence of observation or test data, to evaluate the model. The HMM begins the training process with key model parameters such as the initial state probability distribution $\pi$, the transition probability $\tau$, and emission probability $\epsilon$. The number of states used in the process of training the models is varied from 3 states, 5 states, and 10 states. The performance of the HMM is influenced by varying three parameters; frame durations, extracted features, and the number of states used in the models. Hence, the training process of an HMM is faced with an optimization problem. Thus, Expectation Maximization (EM) (Rabiner, 1989) is employed in this case since the process iteratively attempts to estimate the Maximum Likelihood (ML) of the model parameters $\pi, \tau, \epsilon$ given an observation sequence.

The training process is iterative and therefore, it is expected to end. That is, attaining a convergence criterion. An end criterion is terminating the process when the difference in overall log-likelihood is infinitesimal. Another stop criterion could be to end at the maximum number of iterations (Durbin et al., 1998).

The Whale sound model $M_w$ and the Noise model $M_n$ is combined into a single model after training. This is attained by using the estimated parameters $\pi_w, \tau_w, \epsilon_w$ and $\pi_n, \tau_n, \epsilon_n$ for $M_w$ and $M_n$ respectively. The initial state probability distributions are concatenated as:

$$\pi_{wn} = \{\pi_w, \pi_n\}.$$  

The transition probability matrices are represented as a block diagonal matrix:

$$B = \begin{bmatrix} \tau_w & 0 \\ 0 & \tau_n \end{bmatrix},$$

where $\tau_w$ is an $N \times N$ matrix with states $\{w_1, w_2, ..., w_N\}$, and $\tau_n$ is an $N \times N$ matrix with states $\{w_1', w_2', ..., w_N'\}$.

2.6. Decoding

The decoding step finds the best state sequence given an observation sequence and a model. This is performed such that each extracted feature sample from each snippet is evaluated on a state distribution likelihood. This implies the probability that a feature sample or an observation belongs to one of the existing states that comprise that model. The decoding is achieved based on the Viterbi algorithm (Viterbi, 1967; Forney, 1973) and at the end of the process, the maximum probabilities of the state distribution likelihood are considered for the corresponding frame. The states thereby form a path known as the best state sequence to have generated the observation sequence given the model as well.

2.6. Detection

The detection phase verifies how performant the automated HMM evaluated in comparison to the Bryde’s whale call or as a Noise sound, to have been detected by the HMM exactly as identified or otherwise. Here, we check the occurrence of a successful (positive) or unsuccessful (negative) detection of the Bryde’s whale call often produced four outcomes; 1.) True Positive $T_P$, 2.) False Positive $F_P$, 3.) False Negative $F_N$, and 4.) True Negative $T_N$. Furthermore, the performance parameters of the automated HMM evaluated in comparison to the extracted features are:

1. Sensitivity (True Positive Rate $TPR$)

$$TPR = \frac{T_P}{T_P + F_N},$$

2. Accuracy ($Acc$)

$$Acc = \frac{T_P + T_N}{T_P + F_P + F_N + T_N},$$

3. False Positive Rate $FPR$

$$FPR = \frac{F_P}{T_N + F_P}.$$
3. Results

We consider a numerical analysis of the automated HMM detector by severally varying the three major parameters: the frame duration, extracted feature, and the number of states. Of importance, the time domain features (average power, mean, and zero-crossing rate) are computed depending on the frame duration of a snippet.

3.1. Frame duration – 1 ms

Table 1 shows the performances of the $P_{\text{avg}}$, mean, and ZCR extracted features using different states with a frame duration of 1 ms. It is observed in Table 1 that the three extracted features have the highest percentage of sensitivity when 10 states are used compared to when 3 and 5 states are used. Likewise, the extracted features are mostly accurate when 10 states are used by a model compared to 3 and 5 states. Moreover, the false positive rate performances of $P_{\text{avg}}$, mean, and ZCR indicate that using 10 states produce the best performance as compared to the model with 3 and 5 states. Consequently, the performances of each extracted feature are analyzed using 10 number of states.

In this case, the $P_{\text{avg}}$ is the most sensitive (99.56%) feature compared to 96.99% and 95.71% sensitivity for mean and ZCR respectively. Furthermore, Table 1 shows that the feature $P_{\text{avg}}$ is most accurate since it yields 96.34% as compared with the mean and ZCR that produce 94.69% and 93.55% respectively. In addition, the $P_{\text{avg}}$ continues to show the best performance as it exhibits the lowest false positive rate (FPR) of 0.10 in comparison to the mean with 0.13 FPR and ZCR with 1.42 FPR. By implication, ZCR will produce the least performance, followed by the mean. But, the $P_{\text{avg}}$ has the best performance with regard to Table 1 and could be considered as a time-domain feature for an HMM.

<table>
<thead>
<tr>
<th>$N$</th>
<th>Sensitivity</th>
<th>Accuracy</th>
<th>FPR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{avg}}$</td>
<td>$\mu$</td>
<td>ZCR</td>
</tr>
<tr>
<td>3</td>
<td>97.69</td>
<td>95.43</td>
<td>90.81</td>
</tr>
<tr>
<td>5</td>
<td>98.98</td>
<td>96.54</td>
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<tr>
<td>10</td>
<td>99.56</td>
<td>96.99</td>
<td>95.71</td>
</tr>
</tbody>
</table>

Table 1: Performance comparison of Feature Extraction at frame duration = 1 ms.

3.2. Frame duration – 5 ms

Table 2 indicates the performance comparison of each feature extraction with an increased frame duration from 1 ms to 5 ms. This implies that fewer number of frames are used, thus reducing the computational time to train and detect the dataset. Similar to the frame duration of 1 ms, the features exhibit the best performances in terms of sensitivity, accuracy and false positive rate when 10 states are used in a model as compared to using 3 and 5 states. As a result, we analyze each extracted feature based on the sensitivity, accuracy and FPR measures when $N = 10$. The percentage of correctly identified sounds being the sensitivity presents a $P_{\text{avg}}$ feature of 3.32% and 8.09% more than the mean and ZCR respectively. More so, the $P_{\text{avg}}$ exhibits 3.43% and 8.24% accuracy gain over the mean and ZCR respectively. In addition, the $P_{\text{avg}}$ shows a low FPR of 0.11 in comparison to 0.16 and 1.59 FPR produced by the mean and ZCR respectively. This result indicates that extracting the $P_{\text{avg}}$ as a feature enhances the performance of the model compared to the mean and ZCR features.

However, a trade-off occurs between the computational time and all the three performance parameters (sensitivity, accuracy, and FPR) considered for the model. For sensitivity, $P_{\text{avg}}$, mean and ZCR yield a performance loss of 0.11%, 0.86%, and 4.35% respectively in Table 2. A similar performance loss of 0.63%, 2.41%, and 6.08% is obtained for $P_{\text{avg}}$, mean and ZCR respectively, with regard to accuracy in Table 2. Also, considering the FPR, the extracted features in Table 2 produce 0.01%, 0.03%, and 0.17% performance less than Table 1. The performance loss is due to the use of less amount of data (as features vectors) during the training and detection phases.

<table>
<thead>
<tr>
<th>$N$</th>
<th>Sensitivity</th>
<th>Accuracy</th>
<th>FPR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{avg}}$</td>
<td>$\mu$</td>
<td>ZCR</td>
</tr>
<tr>
<td>3</td>
<td>97.65</td>
<td>94.84</td>
<td>82.42</td>
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<tr>
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</tr>
<tr>
<td>10</td>
<td>99.44</td>
<td>96.14</td>
<td>91.54</td>
</tr>
</tbody>
</table>

Table 2: Performance comparison of Feature Extraction at frame duration = 5 ms.

3.3. Frame duration – 10 ms

Table 3 shows a further increase in frame length. This is to verify the performance of the extracted features based on an increase in the frame duration from 5 ms to 10 ms. Similar to Tables 1 and 2, the model exhibits the best performance when 10 states are used. Here, $P_{\text{avg}}$ yields a 99.25% sensitivity measure as compared with mean and ZCR that produce 95.82% and 90.40% respectively. In addition, the $P_{\text{avg}}$ has an accuracy performance of 94.73% compared to 91.51% of the mean and 85.37% of the ZCR. Therewithal, the $P_{\text{avg}}$ exhibits the least FPR of 0.14 as compared to 0.20 and 1.70 of the mean and ZCR respectively. Hence, the $P_{\text{avg}}$ exhibits an overall performance gain compared to the mean and ZCR, making it the most competent time-domain feature for the automated model.

<table>
<thead>
<tr>
<th>$N$</th>
<th>Sensitivity</th>
<th>Accuracy</th>
<th>FPR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{avg}}$</td>
<td>$\mu$</td>
<td>ZCR</td>
</tr>
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</tr>
<tr>
<td>10</td>
<td>99.25</td>
<td>95.82</td>
<td>90.40</td>
</tr>
</tbody>
</table>

Table 3: Performance comparison of Feature Extraction at frame duration = 10 ms.
3.4. Different frame durations for \( N = 10 \)

<table>
<thead>
<tr>
<th>Frame duration (ms)</th>
<th>Sensitivity Mean</th>
<th>ZCR Mean</th>
<th>Accuracy Mean</th>
<th>ZCR Mean</th>
<th>FPR Mean</th>
<th>ZCR Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.56 ( \pm ) 96.99</td>
<td>96.34</td>
<td>94.67</td>
<td>93.55</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>99.58 ( \pm ) 96.13</td>
<td>95.72</td>
<td>92.28</td>
<td>87.47</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>10</td>
<td>99.28 ( \pm ) 95.82</td>
<td>94.79</td>
<td>91.68</td>
<td>86.38</td>
<td>0.14</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 4: Performance comparison of Feature Extraction at different frame durations for \( N = 10 \)

Table 4 illustrates that increasing the frame duration from 5 ms to 10 ms results in a reduced sensitivity of 0.2%, 0.31%, 0.96% for \( P_{\text{avg}} \), mean, ZCR respectively. Comparing the sensitivity measure of Tables 1 and 3 shows an ample difference of 0.31%, 1.17%, 5.31%, for \( P_{\text{avg}} \), mean, ZCR respectively. Likewise, the accuracy performance of each extracted feature (\( P_{\text{avg}} \), mean, ZCR) is reduced by 0.98%, 0.77%, 2.1% and 1.61%, 3.18%, 8.18%, when the frame length increases from 5 ms to 10 ms and 1 to 10 ms respectively. Furthermore, the FPR measure shows a decrease in \( P_{\text{avg}} \), mean, ZCR of 0.03, 0.04, 0.11 and 0.04, 0.07, 0.28 as a result of an increase in the frame duration from 5 ms to 10 ms and 1 ms to 10 ms respectively.

4. Conclusion

An automated acoustic detector for Bryde’s whales’ vocalizations, based on time-domain features (average power \( P_{\text{avg}} \), mean, and the zero-crossing rate ZCR) and the hidden Markov model technique is developed in this work. The number of states used in a model during the training process was varied as either 3, 5 or 10 states. On a general observation, the model exhibits best performances when 10 states are used. Also, with regard to the frame duration of the snippets, the model yields an overall best performance when a short frame duration of 1 ms is considered, in comparison to 5 ms and 10 ms. Moreover, the model has offered the best performance while using the \( P_{\text{avg}} \) as the extracted feature, in comparison to the mean and ZCR extracted feature. However, the mean presents a similar low false positive rate as the \( P_{\text{avg}} \) when the model has 5 and 10 states, at 1 ms frame duration. Also, with respect to these three time-domain features, the model has shown to be sensitive and dependable as it yields a low false positive rate in the overall performance. From the analysis and discussion of the results obtained in this study, it can be inferred that average power is the best time domain feature used to detect the short pulse call of inshore Bryde's whales based on the hidden Markov model technique.

References

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Identifying suitable satellite Sea Surface Temperature (SST) products for monitoring the Southern African marine region

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A total of 25 daily satellite Sea Surface Temperature (SST) products were compared to determine those best suited for research and monitoring applications of southern African region. The comparisons showed good agreement (variance < 0.4 °C²) between SST products for most of the southern African marine region including the South African east coast, Mozambique Channel and offshore regions of the South African west coast. However, strong disagreement (variance from 0.4 – 1.2 °C²) between SST products was observed at the Angola Benguela front, Lüderitz upwelling cell, the Cape Peninsula upwelling cell, the upwelling region at Port Elizabeth and at the retroflection of the Agulhas Current. The above-mentioned upwelling regions were characterised by a strong seasonal signal, with substantially more disagreement between products during austral summer months. Furthermore, the disagreement between products was shown not to be influenced by the resolution of the SST products. The comparisons suggested that the choice of SST product is likely to strongly influence research and operational outputs in regions of strong SST gradients and intense upwelling, suggesting that additional measurements in these ecologically and economically important regions are required to supplement satellite observations.

1. Introduction

Sea Surface Temperature (SST) plays a vital role in numerous research applications and operational oceanography systems, which in turn are used to inform academic research, industry, the government sector and the general public (Donlon et al., 2007). The increased demand for SST data has led to the development of numerous routinely generated, freely available satellite products. There are large regional discrepancies between the SST products, resulting from inherent differences in the development techniques, which may strongly influence operational and research outputs (Martin et al., 2012). While inter-comparisons of SST products have been carried out globally and for specific regions (Xie et al., 2008; Martin et al., 2012; Dash et al., 2012); there are relatively few comparative studies focused on the southern Africa marine region (Smit et al., 2013; Dufois et al., 2012). The need for comparative studies of the SST products within the southern African marine is imperative as the region is characterized by numerous, highly dynamic SST features including both a western (Agulhas) and eastern (Benguela) boundary current system as well as numerous local upwelling systems. In order to identify the satellite SST data best suited for research applications and monitoring of the shelf and open ocean regions surrounding southern Africa, a total of 25 SST products were compared.

2. Data and method

The SST products were selected on the basis that the dataset was still active (i.e. presently being updated by the developers), freely available, produced daily or hourly, and the processing level had to be either Level 3 (L3) or Level 4 (L4). The products naturally had to cover the entire southern African region (-10°S - -40°S, 10°E - 51°E). Two of the 25 products had a limited regional coverage, while the rest had a global spatial coverage. Although only remotely sensed data products were included in this study, some of the SST products have included model and/or in situ data in their development. The original spatial resolution of the SST products ranged 0.25° and 0.01°. In order to account for the wide range of spatial resolutions, the products were grouped by spatial resolution, low resolution (≥ 0.25°), medium resolution (0.24° - 0.06°) and high resolution (≤ 0.05°) products. Each product in the respective resolution groups (low, medium and high) was then re-gridded onto a common spatial grid; low resolution products (≥ 0.25°) were re-gridded to 0.25°; medium resolution (0.25°- 0.06°) products were re-gridded to 0.1°, and high resolution (≤ 0.05°) products were re-gridded to 0.05°. The period of data analysis was limited to the longest common period shared by all 25 SST data products (01-01-2016 to 01-01-2019).
3. Results

The variance was used to distinguish the spatial and temporal variability amongst the selected SST products around southern African. At each grid cell and for every timestep, the variance between the SST products was calculated and then averaged over a common 3-year period (01-01-2016 to 01-01-2019), providing a mean variance between SST products at each grid cell. This calculation was repeated for the low, medium and high-resolution products, respectively. The variance provides a measure of the spread between the observed data at each grid point; highlighting regions where the spread of observed temperatures was greater and, therefore, were characterised by increased variability or disagreement between the SST products. There was good agreement between SST products (variance < 0.4°C²) for most of the southern African region including the east coast, Mozambique Channel, and offshore regions of the west coast. However, strong disagreement (> 0.4°C²) was observed at the Angola Benguela front, Lüderitz upwelling cell, the Cape Peninsula upwelling cell, the upwelling region at Port Elizabeth, and at the retroflection of the Agulhas Current. Within these regions of high variance, extreme values (> 0.8°C²) were observed at Lüderitz (LU), Cape Peninsula (CP) and Port Elizabeth (PE). The spatial distribution of the variance between observed SST was consistent across the low (0.25°), medium (0.1°) and high (0.1°) resolutions SST products, indicating that the observed disagreement between products was not a function of the spatial resolution.

The Lüderitz, Cape Peninsula and Port Elizabeth upwelling regions were characterised by substantially more disagreement among products during the austral summer months (December, January, and February) compared to austral winter months (Jun, July, and August). In contrast, the high variance (>0.4°C²) observed at the Angola Benguela front (ABF) and Agulhas Current retroflection region (ACRR) was consistently high throughout the year and showed little seasonal difference. The regions where the disagreement between SST products was highest clearly corresponded to oceanographic features characterised by complex temperatures structures and strong SST gradients. The relationship between SST gradient and the variance between SST products was prevalent at the Lüderitz and Cape Peninsula upwelling cells; highlighted by a strong correlation between the SST gradient and variance between products at these locations. The comparison illustrated that all the SST products perform similarly well for most of the southern African region and, therefore, the choice of SST products is likely to have a large influence on research or operational outputs. The agreement among SST products is greatly reduced in regions of high SST gradients and thus the choice of SST product is likely to strongly influence research and operational outputs. These findings highlight the need for additional high-resolution observations, both spatially and temporally, to complement the presently available satellite datasets in order to effectively observe and monitor these highly variable regions which have substantial ecological and economical significance to the Southern Africa marine sector.

4. References


The localization of Bryde’s whales based in time of arrival principles
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There is an issue faced by many research groups across the world that the location of various forms of ocean life cannot accurately be determined until said creature breaches the surface of the water and can be seen. This problem can be solved by implementing a system that can passively detect the location of a selected species of sea life while under the water and interfering with them as little as possible. There are however two main conditions that must be met in order to develop this system that must be addressed. The sea creature in question must be able to make audio calls that can be detected by the equipment so that it can be identified. In addition, the system must be trained using audio calls by the species that are known to be the correct acoustic signals that have been obtained and verified in the past. The detection and locating the position of whales and various other sea life involves many different processes working in unison. There are 4 main components to the system which must work in tandem in order to be effective. These are; a detecting algorithm which can determine whether a signal is the species of sea creature that is being located, knowing and transmitting the location of the detectors, accurate timestamping for the signals and a time of arrival algorithm which is uses the data given to it to mathematically locate the source of the signal that has been detected.

1. Introduction

When out at sea there are multiple problems faced by researchers from different fields who are there to study sea life. A common problem faced is that sea life, especially mammals like whales and dolphins can only be seen and identified in real time when they surface. The system developed not only has the capability to identify whether an audible call from an ocean animal is from the preselected species, but it can also triangulate the position of the sound source. The former of the mentioned capabilities is possible with the use of a dynamic time warping algorithm that has been redesigned and the latter is made possible by using time of arrival techniques. In order to locate the sea animal in a 2-dimensional plane one would need to make use of 3 sensors in order to locate the position of the sound source. The sensors are designed to be free floating in the ocean thus they need a way to communicate their positions so that they can be found, and the position of the sensors is required for the time of arrival algorithm. The sensors consist of a Raspberry Pi running the software that the system functions on via python, a zoom U22, a hydrophone, a GPS module with an antenna and a LoRa module with an antenna.

2. Data and method

In order to detect whether a signal that has been read in by the system from the hydrophone is a call from an animal species that is being searched for one would need to make use of a detector algorithm. The detecting algorithm used by the system is called the dynamic time warping algorithm (Abdullah and Keogh, 2016). This algorithm has the ability to identify similar signals to those that it has been trained with regardless of variation in the signal period or position in the time series where the signal is. The training signals used are those of a Bryde’s whale. In order to get as much variation in signals as possible signals used for the training data are taken from various recordings from different excursions out to sea where Bryde’s whales were visually identified.

When the algorithm has determined that the signal is the correct one being searched for it transmits a timestamp to the control module equipped with a screen on the boat via radio waves making use of LoRa technology (Noreen et al., 2017). When timestamps from the three detectors have been received the time of arrival algorithm (Rison, 2008) can mathematically locate the sound source using the equations as seen below. The algorithm has been designed to make use of hyperbola to locate the source of the sound. Three hyperbolas are drawn and where they overlap is determined to be the origin of the signal. The hyperbolas are created by incorporating the positions of the sensors, which have a known location due to the GPS modules, and allocating them in pairs as the foci of each hyperbola.

Equation 1: \[ a^2 + b^2 = d^2 \]

Where \( d \) is the distance between the sensors/foci

Equation 2: \[ |d1-d2| = 2a \]

Where \( |d1-d2| \) represents the difference distances between the sound source and the respective sensors/foci. The difference is used because the time that the sound occurs is not known however the difference can be found by taking the difference in the timestamps and applying the speed of sound in salt water to find the appropriate distance thus \( d1 \) and \( d2 \) should not be considered as 2 separate variables but rather as one compound variable.
Equation 3: \[
\frac{y^2}{a^2} - \frac{x^2}{b^2} = 1
\]
The above equation is the basic equation for drawing hyperbola if all the variables are known.

3. Results

Figure 1: The circles in the simulation above represent the sensors in the ocean. The square is the known location for the sound source and it can be seen that the hyperbolas overlap at the square and thus have located the source at the correct position.

Figure 2: It is presumed that there will be marginal error when timestamping the moment of confirmation that the signal is correct. This is because each sensor system will run independently of each other. In order to test the accuracy of the system with a delay error introduced various plots are made using the same algorithm as seen in figure 1 however these signals now have a gaussian distributed time delay introduced. It can be seen that the system is still accurate though there is a larger area where the sound source could have originated from.

4. Conclusion

To conclude it can be seen that the simulation for the location of the signal source works acceptably even with time delays introduced. The LoRa communication system was chosen because of its simplicity and excellent range. LoRa was chosen over 3G as there is not always a suitable 3G signal when at sea. A problem that was experienced with the LoRa communication was that buildings tended to block the signal between the antennas. However this problem was disregarded as there is usually a direct line of sight between the sensors and the boat when at sea.

It was found that the dynamic time warping library found in python was not operating fast enough to reliably detect the signals, thus the algorithm was personally rewritten in a C file which the python files that run the software of the system can call. While testing is still ongoing, from the results seen one would not be wrong to be highly optimistic with the outcomes of this research, especially when considering the practical applications that the system has for a range of sea life.

References


Abdullah Mueen, Eamonn J. Keogh: Extracting Optimal Performance from Dynamic Time Warping. KDD 2016: 2129-21
Contribution of local communities organization in sea turtle and marine mammals in Zanzibar
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Contribution of the coastal communities in sea turtles and marine mammals’ conservation in Zanzibar is still low. The study on participation of coastal communities in sea turtles and marine mammals’ conservation” was conducted to local communities of Unguja Island Tanzania. The aim were to evaluate the community contributions, social economic benefits, knowledge level, methods applied in conservation including the use of indigenous knowledge and status of marine resources conservation. Data collection was conducted by using questionnaire, interviews and focus group discussion which covered 90% of the total community groups involved in sea turtles and marine mammals’ conservation. Findings from the present study revealed that 91.7% of the respondents were involved in marine resources conservation specifically sea turtles and marine mammals. The modern techniques such as satellite tagging and traditional knowledge including turtle nest marking, aquarium were commonly used by the existing organizations. Also, the use of aquarium system utilized as tourism attraction and educational tools in conservation related knowledge as well as keeping the sea turtles accidental caught by fisherman before releasing back to the ocean. However, the aquarium system diversifies employment opportunities for the local communities, has negative impact on natural behavior of sea turtles. Apart from scientific research done by universities and international organizations, little has been done in local community regarding marine mammals’ conservation due to the nature of the organisms and lack of advanced conservation tools and strategies. Since the local communities are the one who interact with marine organisms during daily activities such as fishing, the involvement of local communities in the conservation of marine resources ensure the sustainable existence resources.

1. Introduction

Sea turtles and the marine mammals have been declared as world endangered species by the act of 1973 ESA (Drews, 2012). They are listed as endangered species by IUCN and CITES in appendix I, which are illegal to harm, collecting their meat and eggs (Drews, 2012; WWF, 2012). Marine turtles spend most of their lives in the continental shelf waters where, globally there are 7 species including, Leatherbacks, Hawksbills, Loggerheads, Green turtles, Olive ridleys, Kemp’s ridleys and Flatbacks (WWF, 2012). Marine sea turtles are globally distributed in tropical and subtropical water however two species have been restricted in ranges that is kemp’s ridleys occur mainly in the Gulf of Mexico and the fatback turtle around northern Australia and southern Papua New Guinea (Drews, 2012). Marine mammals’ such as whales, dolphin and dugong are among the listed endangered species in IUCN and CITES as well. Worldwide there are approximately 119 marine mammals species where 34 species of marine mammals inhabit the Western Indian Ocean region, of these 8 are baleen whales, 2 sperm whales, 13 toothed whales, 10 dolphins and 1 sirenian (the Dugong) (Richmond, 2010). In Tanzania, 5 species of sea turtles and 19 marine mammals are frequently encountered along coastal waters (Gill et al, 2016).This include sea turtles species, whales, dolphin, and dugong (Howell and Mindo, 1996). Sea turtles, dolphins and dugongs are common inhabited in the coastal water of Tanzania including Zanzibar Island while whales are migratory species which are encountered in coastal water of Tanzania between June and December when they migrate from south hemisphere to north hemisphere due to variation in temperature (WWF, 2012). The green turtles and hawksbills are mostly common and widespread species in Tanzania where hawksbills are widely distributed but less abundant and mostly concentrated number of nests are seen in Zanzibar, Mafia, Misali Island and Mnemba Island in Zanzibar and possibly the Songo archipelago and they mainly nest in February and July (Muir, 2005). Other species of sea turtles such as Oliver riddle and loggerhead are no longer reported to nest, but they were observed during their migration periods (WWF, 2012). To date the contribution of the local communities organization in sea turtle and marine mammals conservation in Zanzibar, is low and this create a knowledge gap regarding what communities organization perceive to be their role in sea turtles and marine mammals conservation. Therefore, the study was undertaken to examine the contribution of the local communities’ organization in sea turtle and marine mammals’ conservation in Zanzibar. (i) To determine the contribution of the local communities organization in sea turtles and marine mammals conservation activities in Zanzibar. (ii) To identify social economic benefits gained by local communities organization in sea turtles and marine mammals’ conservation in Zanzibar. (iii)
To examine the main threats facing sea turtles and marine mammals’ conservation in Zanzibar. (iv) To explore the knowledge used by local communities organization in sea turtle and marine mammals’ conservation in Zanzibar.

2. Study site, method and data analysis.

This study was conducted in Zanzibar Island, specifically the study sites were Nungwi, Kizimkazi, Jozani and Fukuchani. The sites were selected because they were among the sites within the island of Zanzibar with a lot of sea turtles and marine mammals’ distribution and there were a lot of conservation projects taking place within these sites. Both the primary and secondary data were collected by using household structured questionnaire which covered 30% of the total population and it was both open and closed ended, semi structured questionnaires for key informants which involved a set of predetermined questions and highly standardized techniques of recording and group discussion which allowed the villages to exchange different ideas they had among themselves in accordance with the nature of questions asked by the researcher. The data collected through questionnaire were examined, variable coded and then imported to SPSS version 22.0. For the data collected through interviews and group discussion was qualitative in nature hence there was no need to proceed with the analysis, all key issues was recorded by the researchers, summarized, and provided explanation of those findings.

3. Results

![Figure 6: Contribution of conservation areas to local communities’ development.](image)

![Figure 7: Gender of respondents.](image)

![Figure 8: Age of the respondents.](image)

![Table 1: Skills used in the conservation of endangered marine organisms. Source: Field survey data 2017.](table)

<table>
<thead>
<tr>
<th>Skills for marine turtles and mammals conservation</th>
<th>Frequency</th>
<th>Percent</th>
<th>Valid Percent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
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<td>83.3</td>
<td>83.3</td>
</tr>
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<td>Total</td>
<td>12</td>
<td>100.0</td>
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<td></td>
</tr>
</tbody>
</table>

Table 1: Skills used in the conservation of endangered marine organisms. Source: Field survey data 2017.
4. Discussion

In this paper, the participation of female in the conservation of these endangered marine organisms has been seen to be less compared with that of males (See Figure 2), as most women play part in taking care of the family and therefore females are less involved in marine resources conservation. The age of the respondent mostly involved in conservation of marine resources were youth between the age of 25-31(See Figure 3) which means that they were able to get formal education which enables them to read and write (See Table 2). In attaining objective one of this paper, the local communities contribute to the protection of these endangered marine mammals by building aquariums for keeping turtles, protecting their nesting sites, spread awareness to people on turtle conservation, putting tags and pingers to the fishing nets to avoid bycatch of sea turtles as shown in (Plate 2). On the other side, the local community groups also spread awareness on dolphin conservation, attending ethical boat driver training on how to operate and conserve dolphins while doing tours and putting pingers as well to the fishing nets to avoid dolphin getting stuck in the fishing nets (See Plate 2).

Objective 2 on social economic benefit, all the local communities involved in the conservation of these marine creatures get employment opportunity by employing themselves and being able to generate income, there is improvement of infrastructure to most villages where this conservation project are taking place, growth of tourism industry, as most people all over the world travel all the way from their home countries to come and see these beautiful marine creatures and hence generate growth of economy in the county by gaining foreign currency as presented by (See Figure 1). Object 3 of this paper was the main threat to this marine organisms is the existence of the gill nets in the conservation area (See Plate 1) which accelerate the rate of bycatch to both sea turtles and dolphin. There is a need to stop the use of such nets by encouraging the use of other fishing nets within the conservation areas. The last objective 4 of this paper was to explore the knowledge used in conservation, as most of the respondents were able to obtain the skills of conserving theses endangered marine animals from different books addressing conservation of endangered marine organisms, (See Table 1) and also by attending the number of workshops and training that were offered.

<table>
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<th>LEVEL OF SATISFACTION</th>
<th>PERCENT</th>
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<tr>
<td>satisfied</td>
<td>25%</td>
</tr>
<tr>
<td>dissatisfied</td>
<td>8.3%</td>
</tr>
<tr>
<td>highly dissatisfied</td>
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</table>

**Table 04: Level of education of respondents**

<table>
<thead>
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<th>R/</th>
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<td>o level education</td>
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<td>Total</td>
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<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

by the Revolution government of Zanzibar in collaboration with other world organizations. Upon all these efforts made by the local communities, half of the total community groups were well satisfied with the level of conservation effort of these endangered marine animals (See Figure 4), as the other half they were also interested to increase effort on conservation of theses endangered animals. In that regards, sea turtles and dolphin are important for the survival and livelihood of the communities around the conservation areas.

Acknowledgement:

This accomplishment could not have been met without the University of Dodoma and the HESLB which provide the fund to carry out this study. Foremost, I wish to express my sincere thanks to my lovely mother, Annie Sabath Mirobo, for her moral support to ensuring that I complete this work in good health. My deepest gratitude goes to the Institute of marine sciences Zanzibar-Tanzania, Deep sea authority and the Department of fisheries in Zanzibar for their support in accomplishing this work. Finally, my deep-heated thanks goes to WIOMSA and The Nansen Tutu Center Marine Research for supporting my participation to attend the 10th anniversary of Nansen Tutu marine research center at University of Cape Town and being able to share the knowledge concerning marine resources conservation in Zanzibar-Tanzania.

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www.seaworld parks and entertainment / conservation and research, 01/01/2017;4.41pm
Hidden Markov Model (HMM) with eigenspace decomposition-based feature extraction algorithm for the detection and classification of cetacean species

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¹Stellenbosch University, South Africa

The cetaceans have elicited the attention of policy makers and researchers in recent years due to their importance to the ecosystem and their economic values. There is continuous increase in public demands for ecotourism business which reportedly involve over 87 nations and territories including South Africa. Cetaceans are also of great importance in maintenance of state of health of ecosystem and serving as sentry species for the state of marine ecosystem. However, their existence is continuously under threat due to human anthropogenic activities. These anthropogenic activities, which have been detrimental to marine fauna include shipping, offshore exploration, geophysical seismic surveys and naval sonar operations. Ecosystem managers are particularly interested in conserving these mammals by constantly searching for ways to mitigate the effects of human activities within the marine ecosystem in order to support their conservation and protection. The digital signal processing (DSP) field has come handy in helping ecosystem managers understand the behavioral patterns of cetaceans by developing tools for the analysis of their signals. Over the years, different techniques have been developed for the automatic detection and classification of the over 82 known different species of cetacean. The performance accuracy of detectors and classifiers are greatly influenced by the quality of the features extracted from the raw signals. This implies that the more accurate the extracted feature vectors, the better the detection and classification accuracy. Our current work proposes the design of new feature extraction algorithms to be adapted with the hidden Markov model (HMM), based on the theory of eigenspace decomposition. The suitability of these algorithms to carry out detection on their own will also be explored. Therefore, our focus is to improve the performance accuracy of the HMM with introduction of new feature algorithms.

1. Introduction

The increasing human anthropogenic activities have significantly changed the soundscape in oceans. This has continued to threaten the existence of ocean mammals including the cetaceans because they utilize sound for navigation, communication, avoidance of predators, recognition of prey for survival and to function properly within their ecosystem (Blair, Merchant, Friedlaender, Wiley, & Parks, 2016; Dunlop, 2016; Merchant et al., 2016; Putland, Ranjard, Constantine, & Radford, 2018a; Williams et al., 2015). These anthropogenic activities, which have been detrimental to marine fauna include shipping, offshore exploration, geophysical seismic surveys and naval sonar operations. The potential negative effects of these activities include (a) physical injury, (b) physiological dysfunction: permanent or temporary loss of hearing sensitivity, (c) behavioral modification: decrease in exploration efficiency, or inefficient use of environment, separation of mother-calf pairs, (d) masking- difficulty in recognizing crucial sounds as a result of increase in background noise, (e) avoidance and displacement from critical feeding and breeding grounds, (f) decrease reproduction rate (Richardson, Greene Jr, Malme, & Thomson, 2013; Slabbeekorn et al., 2010; Weilgart, 2007). Though, reactions of these marine mammals to these negative impacts varies due to factors such as species, age, gender, previous noise experience, location or body of water and behavioral state (Weilgart, 2007).

There have been growing research on the consequence of these human activities on marine mammals in recent years (Gillespie, Caillat, Gordon, & White, 2013; Peso Parada & Cardenal-López, 2014a; Richardson & Würsig, 1997). Ecosystem managers are particularly interested in conserving them by constantly searching for ways to mitigate these effects (Putland, Ranjard, Constantine, & Radford, 2018b) in order to support their conservation and protection (André et al., 2011; Zimmer, 2011). However, they are faced with the challenge of inadequate knowledge on the ecosystems of these mammals (Zimmer, 2011) because they spend their entire life in water. Passive acoustic monitoring (PAM) is a popular method used for monitoring cetaceans in their ecosystems. However, the data accumulated using PAM are often large, thus making it unfeasible to manually inspect. Hence the need to have an algorithm that can automatically detect and classify these large volumes of data. The digital signal processing (DSP) field has come handy in helping ecosystem managers understand the behavioral patterns of cetaceans by developing tools for the analysis of their signals. Over the years, different techniques have been developed for the automatic detection and classification of the over 82 known different species of cetacean. The techniques include Gaussian mixture models (GMM), hidden Markov models (HMM), support vector machines (SVM), spectrogram cross-correlation (SPCC), matched filtering (MF) and dynamic time warping (DTW), among others have been developed for the automatic detection and classification of signals of cetacean species. These techniques are centered on signal processing, pattern recognition and machine learning concepts. The cetacean vocalizations are recorded using hydrophones and preprocessed. The
preprocessing includes extraction of features. This is followed by the detection and classification stages. The detection stage is the process of identifying the presence of the targeted cetacean signal in the dataset from other unwanted signals that may be present. These unwanted signals may include background noises (non-bioacoustics signals), presence of signals of non-targeted species in the recording area, and so on. The classification stage is the process of assigning the detected signals to a predefined category (species-specific) (Rickwood & Taylor, 2008; Yakc, Barlow, Rankin, & Gillespie, 2009) having been guided by a previous knowledge of what is expected, usually by a human expert. The primary focus of this project to develop a tool to enhance the automatic detection and classification process.

2. Method

The Hidden Markov model (HMM) is one of the most popular techniques used for the automatic detection and classification of cetacean vocalizations due to its ability to manage duration variability through non-linear time alignment (Putland et al., 2018b; Ren et al., 2009; Rickwood & Taylor, 2008). The model has shown better performance under the same condition in comparison with other detection and classification techniques (Ren et al., 2009; Weiburn, Mitchell, Clark, & Parks, 1993). Nonetheless, its performance accuracy is greatly influenced by the quality of the features extracted from the raw signals (Seger, Al-Badrawi, Miksis-Olds, Kirsch, & Lyons, 2018). This implies that the more accurate the extracted feature vectors, the better the detection and classification accuracy of the HMM. The Mel-scale frequency cepstral coefficients (MFCC) and linear predictive coefficients (LPC) are the two most utilized feature extraction techniques used with the HMM. However, the MFCC-HMM and LPC-HMM do not exhibit good performance when implemented on whistles and pulsed calls (Peso Parada & Cardenal-López, 2014b). This research proposes the design of new feature extraction algorithm to be adapted with the hidden Markov model (HMM), based on the theory of eigenspace decomposition. The theory is capable transforming into non-stationary data into spatiotemporal coherent patterns that will distinct prominent features of the data. The snapshots of data \( x_k \) is assembled from a dynamical system at a number of times \( t_k \), where \( k = 1, 2, 3, ..., m \). These extracted information structurally describes the inherent physical properties that dominate the entire data. The method will collect data, break them into snapshots \( x_1, x_2, ..., x_m \), as they change in time. The data are then organized into big matrices \( X \) and \( X' \) as shown in Equations (1) and (2). It then finds the best-fits linear operator \( A \) matrix that advances into \( X' \) by approximating the leading eigendecomposition (the eigenvectors and eigenvalues) of \( A \) without computing the \( A \) matrix. The cost of the algorithm is the singular value decomposition (SVD) (Kutz, Brunton, Brunton, & Proctor, 2016) of the snapshot matrix constructed from data \( x_k \). The snapshots form dynamic modes. These modes will be modified to form feature vectors to be fed into a HMM.

\[
X = \begin{bmatrix}
    x_1 & x_2 & \cdots & x_{m-1}
\end{bmatrix}
\]

\[
X' = \begin{bmatrix}
    x_2 & x_3 & \cdots & x_m
\end{bmatrix}
\]

Essentially, two parameters are needed in the data conversion process. The number of spatial points saved per time snapshot and the number of snapshots taken.

3. Conclusion

This research seeks to improve the performance accuracy of the HMM technique for the automatic detection and classification of cetacean vocalizations with the introduction of a new feature extraction algorithm.

Reference


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Link between the Mozambique Channel Trough and Southern African rainfall
R. Barimalala¹, F. Desbiolles¹, R. Blamey¹, C.J.C. Reason¹

¹Department of Oceanography, University of Cape Town, South Africa

The role of the Mozambique Channel Trough (MCT) in modulating the southern African rainfall is investigated. Numerical experiments using regional climate model reveals that a flatter than normal topography over Madagascar results to a weak MCT and anomalously high moisture flux from the Indian ocean. These lead to a significant increase in rainfall over mainland southern Africa and a decrease over Madagascar. The interannual variability of the trough is dominated by moist convection in the Mozambique Channel. Overall, strong MCT years are associated with drier than normal mainland southern Africa and more rainfall over Madagascar and the neighboring ocean.

1. Introduction

The driving mechanisms of the southern African rainfall consist of a combination of large scale forcing, regional sea surface temperature (SST) and regional atmospheric circulations. One of the important regional circulation patterns is the Mozambique Channel trough (MCT), characterized by a low-pressure area over the central and southern Mozambique Channel. The MCT is known to be generated by a dynamical adjustment of the easterlies flowing over the topography of Madagascar which consists of a north-south mountain chain, reaching up to 2000m in places. The trough could, then, be sustained by the local air-sea interaction over the channel’s relatively warm SST. The MCT is located near the source of the South Indian Ocean Convergence Zone (SICZ), a dominant driver of the southern African rainfall (Cook 2000; Lazenby et al., 2016), thus possibly affects the mean rainfall and variability over the subcontinent. The role of the MCT in southern African climate is however not well understood. Munday and Washington (2017) found that climate models with weak MCT tend to have excessive rainfall over the subcontinent. Cook et al., (2004), in addition, suggest that the cyclonic feature in the channel drives away moisture from the mainland and leads to a decrease in rainfall in the area. In addition, a recent work by Pascale et al., (2019) shows that a weakening of the MCT leads to stronger northerly moisture flux penetrating to the African mainland and triggers an increase in regional rainfall. These studies suggest that MCT likely plays a key role in southern African climate, but such link has not been thoroughly investigated. In this work, we analyze the results from numerical experiments to investigate the role of the topography of Madagascar in modulating the strength of the MCT and in influencing rainfall over southern Africa. Reanalysis data is then used to investigate the interannual variability of the trough and its relationships with regional rainfall.

2. Data and model description

Four experiments, using the Advanced Research WRF (Weather Research Forecasting) regional climate are designed. The details of the configuration are provided in Barimalala et al., (2018). Overall, the experiments differ only over Madagascar as follows:

- CTRL: a control run with the full topography of Madagascar,
- 75TOPO: every grid point over Madagascar is reduced to 75% of its original level.
- FLAT: any areas above 300m is set to a uniform height of 300m over the island
- SEA: the island is completely masked to become ocean grid points

Each experiment is run for 17 summers (September to April 2000 to 2016) and differences in climatology between the last 3 experiments and CTRL are investigated to highlight the importance of the topography on the strength of the MCT and the role of the trough on mean rainfall. However, only the differences between FLAT and CTRL will be discussed here given that the results from SEA and 75TOPO are the same but with different magnitudes. It is worth noting that the output from CTRL is evaluated with respect to the CFSR (Climate Forecast System Reanalysis, Saha et al., 2010, 2014), which is also used for the experiments boundary conditions. To analyze the seasonality and variability of the MCT, low level (850hPa) monthly relative vorticity, geopotential height, specific humidity, total cloud cover, wind, and mean sea level pressure from the ERA-Interim reanalysis (Dee et al., 2011) for the period of 1980-2017 are used. The impacts of MCT on rainfall is studied in section 3.3, using CHIRPS (Climate Hazards group InfraRed Precipitation with Station data, Funk et al., 2015) and CMAP (Climate Prediction Center Merged Analysis Product, Xie et al., 1997). We also make use of the HadISST (Hadley Center global Sea Ice and Sea Surface Temperature, Rayner et al., 2003) products, as well as the NOAA outgoing longwave radiation at the top of the atmosphere (OLR, Liebmann and Smith, 1996).

3. Results

3.1. The Mozambique Channel Trough
In this study, the MCT index is defined as the area average of the relative vorticity at 850hPa in the southern Mozambique Channel (35°–44°E, 16°–26°S). The seasonal cycle of the MCT from the four simulations and CFSR are plotted in Figure 1a. Overall, the model depicts the observed seasonal cycle reasonably well. The month of December is shown as the onset of the MCT (start of negative vorticity) in CFSR and CTRL. In the other experiments, no trough is depicted until January, which then followed by a weak negative vorticity until March. These suggest the importance of the topography of Madagascar on the strength and timing of the MCT. Figure 1b shows the December-March (DJFM) MCT index versus the mean topography over Madagascar. It confirms that the lower the topography, the weaker the MCT. In addition, the difference in mean topography between CTRL and 75TOPO is slightly lower than that of 75TOPO and FLAT, but the MCT index for 75TOPO is much closer to that of FLAT. These indicate a non-linearity of the topography-MCT relationship as well as a possible threshold height for models to generate a realistic MCT. While the MCT is generated by the adjustment of the easterlies flowing over the topography of Madagascar, the seasonal cycles of the trough and the observed SST over the channel show that MCT peaks when the channel is at its warmest state. In addition, the trough is strongest in the presence of monsoonal westerlies in the northern Mozambique Channel (Barimalala et al., 2019). These imply that the strength of the MCT is sustained by local air-sea interaction and circulation.

3.2. Mean low level circulation and rainfall responses to MCT

Differences in 850hPa moisture flux and divergence between CTRL and FLAT are displayed in Figure 2a. Significant zonal moisture flux anomalies (hatched areas) originating from the Mozambique Channel and transported to the African landmass are depicted. These strong fluxes reduce the moisture divergence in CTRL along the eastern coast of South Africa and Mozambique. In addition, the fluxes feed more moisture from the Indian Ocean into the Angola low, which often acts as the source region for the main summer rain-producing weather system (tropical-extratropical cloud bands). As a result, the moisture convergence over the central and western parts of the subcontinent is enhanced, producing more favorable rainfall conditions and strengthen the SICZ.

![Figure 1](image1.png)

**Figure 1:** (a) MCT index seasonal cycle (in s⁻¹); (b) MCT index versus mean topography of Madagascar.

![Figure 2](image2.png)

**Figure 2:** Difference between FLAT and CTRL in (a) 850hPa moisture flux (arrows in kg·kg⁻¹·ms⁻¹) and divergence (shading); (b) precipitation (in mm·day⁻¹). The hatched areas show where the differences are statistically significant at 95% using Student’s t test.

Figure 2b shows the difference in rainfall between FLAT and CTRL. A significant decrease up to 10mm/day occurs over the northern and eastern Madagascar and the neighboring ocean, while an increase in rainfall covers the central part of mainland southern Africa, western Madagascar and the Mozambique Channel. Along the Mozambican coast, enhanced rainfall of about 1.8mm/day (48% of the mean DJFM observed precipitation in the area) is shown in FLAT. Although weaker, significant positive anomalies are also seen over Zimbabwe, Malawi.
Zambia and southern Angola). The dipole in rainfall anomaly over Madagascar is explained by the absence of orography in FLAT, while enhanced convergence with anomalous easterly moisture transport from the Mozambique Channel is responsible for the increase in rainfall along the eastern coast of southern Africa. Over the central and western part of the subcontinent, strengthened moisture from the east, along with increase in convergence in the SICZ area explains the positive anomaly in rainfall.

3.3. Variability in MCT and its link to regional rainfall

By using the ERA-interim reanalysis data, a detrended time series of standardized anomalies in the MCT indices for JFM (when the trough is strongest) displays a strong interannual variability. An evaluation of the different terms in the vorticity budget equation shows that the vorticity tendency is dominated by a balance between the vertical advection, tilting and residual terms. These indicate a strong influence of local forcing on the MCT variability. With the criterion of at least 1 standardized departure from the mean on the MCT index, the years of 1982, 1984, 1989, 1994, 2002 and 2012 are identified as strong MCT summers, whereas 1981, 1990, 2006 and 2017 are considered weak MCT summers. The vertical profiles of the different terms from the vorticity budget during strong/weak years show that the vertical advection term is reduced to almost zero when MCT is weak. In addition, the composites of specific humidity at 850hPa display a negative (positive) anomaly over the Mozambique Channel during weak (strong) MCT years. These suggest that the MCT variability could be associated with moist convection over the Channel. Among the strong MCT years, 1989 and 2012 are characterized by La Nina conditions, whereas 1982 is a strong positive IOSD (Indian Ocean Subtropical Dipole). By removing these three years, the composite in rainfall during strong MCT summers show a significant decrease over most of mainland southern Africa while the Mozambique Channel, parts of coastal Mozambique and Madagascar are characterized by a significant increase in rainfall. Barimalala et al., (2018 and 2019) argue that during strong MCT years, the cyclonic circulation draws moisture away from the Mozambique Channel into mid-latitude, impacting the key moisture transport corridor. The anomalous moisture flux and uplift over Madagascar favor a relocation of the cloud bands to be over the ocean, therefore an increase in rainfall in the area. In addition, during strong MCT summers, the cyclonic circulation stretches from the Mozambique Channel into mid-latitude, impacting the key moisture transport corridor. The anomalous moisture flux and uplift over Madagascar favor a relocation of the cloud bands to be over the ocean, therefore an increase in rainfall in the area. On the other hand, most weak MCT summers occur during strong IOSD. However, the relationship between MCT and IOSD is not linear but instead depends on the location of warm SST pole in the South Indian ocean (Barimalala et al., 2019). An increase in rainfall is therefore seen over mainland during weak MCT. It is caused by anomalous moisture transported from the Indian Ocean to the source region of cloud bands. Over Madagascar, a subsidence associated with an enhanced Mascarene and decrease in cloud cover leads to a decrease in rainfall.

4. Summary

This study described the generation, mean state and interannual variability of the MCT, along with its impacts on regional rainfall. The trough forms due to the adjustment of easterlies passing through the high topography of Madagascar during austral summer. The MCT is sustained by warm SST in the channel and the westerly monsoon north of Madagascar. Strong MCT leads to a reduced (increased) rainfall in mainland southern Africa (Madagascar) and vice versa for a weak MCT. The interannual variability of the trough is associated with moist convection in the Mozambique Channel and is modulated by the location of the warm SST in the South Indian Ocean. Strong MCT years are characterized by anomalously high (low) rainfall over Madagascar (mainland) and reduced rainfall over mainland (Madagascar). On the other hand, most weak MCT years are associated with IOSD. These results have important implications for the representation of the mean state and variability of rainfall over southern Africa where climate models struggle with significant biases.

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NANSEN-TUTU 2021 | PAGE 114


Large rainfall events during the extended summer (ONDJFM) over the winter rainfall region of the South Western Cape: A case study of the past Day Zero drought

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Although the South Western Cape receives most of its rainfall between May and September, there are substantial rainfall events in summer. In this study, large rainfall events (LREs) over the South Western Cape during the drier October – March months are investigated. Focus is placed on the 2017-2018 summer which is of interest since it follows the devastating 2015-2017 “Day Zero” greater Cape Town drought. Level 6 water restrictions (50L per person per day) were implemented in summer 2017-2018 to curb water use. South African Weather Service (SAWS) weather station data are used to identify LREs. Estimated data from the City of Cape Town show that major dam levels in the South Western Cape increased more than 1% in some cases after LRE’s in 2018-2019. This increase is significant as dam levels often decrease by several percent per month during summer. Such dam level increases in the driest months of the year may provide much needed relief following drought given the tendency by the public to use more water in hot summer weather. An atmospheric river contributed to at least one LRE during summer 2018-2019. Atmospheric rivers are a common contributor to winter rainfall and are associated with strong winds and large quantities of rain. Large rainfall can have positive effects on the catchment areas in the South Western Cape.

1. Introduction

The South Western Cape of South Africa is predominantly a winter rainfall region (Mahlalela et al. 2019) with most of its rain occurring between May and September. The region is home to around 5 million people and is of large economic and agricultural importance (McEwan et al. 2015). Since severe winter droughts can occur about once or twice per decade (Reason et al., 2002; Burks et al., 2019), it is of interest to determine whether large, anomalous rainfall events (LREs) during the summer months can sometimes help mitigate winter drought. Such an event occurred in December 2018 following the Day Zero drought. Most of the South Western Cape’s rainfall is brought about by cold fronts with cut-off lows (CoLs) as well as occasional thunderstorms associated with west coast troughs / cloud bands that help bring moist tropical air southwards over the region. In winter, most LREs over the Western Cape are due to cold fronts associated with atmospheric rivers (Blamey et al. 2018). Atmospheric Rivers. (ARs) are long (>2000 km) narrow plumes of moisture feeding into mid-latitude regions from the tropics (Ramos et al. 2015). These narrow plumes of moisture are associated with strong winds and widespread rain (Ramos et al. 2019).

2. Data and methods

Daily rainfall data were obtained from 18 South African Weather Service (SAWS) stations for 1960-2019. The South Western Cape was subdivided into 3 sub-regions (boxes in Fig. 1) based on the amount of rainy days (>2.5mm) and mean rainfall per dry season (ONDJFM) (Fig. 1). To define LREs, the monthly average was calculated for rainfall for each station and the 95th percentile determined. The mean,(M in mm) was then calculated for each of the sub regions. The fraction of stations that show a positive LREs for that area was then calculated as a percentage over the sub-region (N in %). It was then possible to quantify the intensity and area covered for each LRE as:

(i) \[ R = M \times N \]

Each identified LRE has an R value which varies across the whole domain of the study region and is an integrated measure of rainfall intensity. Once the dates of the LRE’s were identified, The National Centers for Environmental Prediction (NCEP) reanalysis II data (2.5° x 2.5° grid) were used to calculate the moisture flux of a particular level as follows:

(ii) \[ Q = q \times V_h \]

Where q is the specific humidity and \( V_h \) is the magnitude of the horizontal wind at that level.

3. Results

Fig. 2 shows the LREs occurring over the region during the 2018/19 summer following the Day Zero drought. The events of January and March are important given that the mean monthly rainfall for those months is 6 mm and 7 mm respectively. The 10th March 2019 event showed the largest rainfall amounts occurring over all 3 sub-regions during the extended summer period. The impact in the Cape Town dams (red bars) may be seen in Table 1 which indicate that the highest contribution to dam levels due to LRE’s
occurred in November and December. There is considerable spatial variability in the distribution of LRE within the region (Fig. 2). Given that frontal tracks shift southwards in summer and ridging anticyclones along the south coast are more likely to advect moist air towards the south coast in summer as the South Atlantic Anticyclone shifts south-eastward (Vigaud et al. 2009; Weldon and Reason, 2014), it is not surprising that the south west coast (black box in Fig. 1) shows larger rainfall amounts during summer 2018/19. Climatologically, this region is also wetter than the west coast during the summer.

![Figure 1: The study region and SAWS stations. The boxes show where stations were subdivided based on mean rainfall and number of rainy days > 10 mm.](image)

**Figure 1:** The study region and SAWS stations. The boxes show where stations were subdivided based on mean rainfall and number of rainy days > 10 mm.

Table 1 shows dam level increases in the greater Cape Town catchment area before and after each 2018/19 summer LRE. Dam level increases are a reasonable indication as to how much rainfall falls over a catchment region during a particular event. However, it is also important to note that dam location is generally in mountainous areas where rainfall amounts are enhanced relative the rainfall closer the coast. The largest increase (over 1%) occurs following the 6 December 2018 event.

**Table 1: Estimated dam levels from the City of Cape Town after the date of the top 6 largest events in ONDJFM 2018/9.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Before(%)</th>
<th>After(%)</th>
<th>Difference (%)</th>
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</thead>
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<tr>
<td>2018/10/29</td>
<td>73.31</td>
<td>73.8</td>
<td>0.49</td>
</tr>
<tr>
<td>2018/11/04</td>
<td>73.64</td>
<td>74.71</td>
<td>1.07</td>
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<td>2018/12/06</td>
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<td>1.22</td>
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</tr>
<tr>
<td>2019/03/10</td>
<td>51.58</td>
<td>52.63</td>
<td>1.05</td>
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This 6 December 2018 LRE appears to be associated with an AR. Satellite derived water vapour images (not shown) indicate a narrow plume of moisture stretching right across the South Atlantic towards the South Western Cape from the Brazilian coast similar to those analysed in Ramos et al (2019). The associated moisture flux and 850 hPa winds derived from NCEP II re-analysis data is shown in Fig. 3 for the 6 December event. A narrow band of large moisture flux is evident impacting on the South Western Cape. This band represents the eastern half of the AR. Blamey et al (2018) showed that ARs are responsible for the vast majority of LRE in winter over the Western Cape and that, on average, they contribute significantly to the rainfall in that season. However, to date, there has been no study of AR for the summer season.

![Figure 3: Case study of 06 December 2018 showing the moisture flux (g/kg, m.s⁻¹) of the region and wind field using NCEP reanalysis specific humidity and wind vector data (0.25° x 0.25° grid resolution)](image)

**Figure 3:** Case study of 06 December 2018 showing the moisture flux (g/kg, m.s⁻¹) of the region and wind field using NCEP reanalysis specific humidity and wind vector data (0.25° x 0.25° grid resolution).

Assessing the extent and intensity of LRE’s over the South Western Cape in summer is important. Although they may vary across the region, on occasion they can help mitigate the impacts of anomalously dry winter seasons. Such a case happened in summer 2018/19 following the devastating 2015-2018 Day
Zero drought in greater Cape Town. Understanding rainfall patterns and the conditions that bring about LRE’s will allow for better water management and water catchment within the Western Cape winter rainfall region.

References


What do control water vapor transports seasonality over Central Africa
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Atmospheric circulation over central Africa is dominated by the tropical easterly jet, the African easterly jet, and the low-level westerly jet. Confined at lower troposphere, the Congo Basin Cell is a shallow overturning circulation located over Central Africa. This key feature is more essential to destabilize the stable lower troposphere than by to build up mass convergence at the Congo Air Boundary, reminiscent of the ventilation mechanism. In fact, the Congo basin cell is a closed thermodynamic cell that transports water vapor and temperature from the warm central African landmass to the cold eastern equatorial Atlantic. More importantly, the water vapor is transported into the central Africa landmass through the low-level westerly jet, highlighting the crucial role play by Atlantic Ocean. Finally, the Congo basin cell is a key feature that couples the lower circulation associated with subsidence and the mid-upper circulation associated with deep convection.

1. Introduction

Wind plays crucial role in redistributing the energy and moisture, which in turn, influence temperature and precipitation patterns worldwide. Over central Africa, the seasonal cycle of rainfall is primarily dominated by the change in atmospheric pressure and its associated circulation, water vapour and latent heat, rather than the local temperature (Longandjo et al. 2020). But little is known about the large-scale circulation over central Africa. McCollum et al. (2000) reported that the westerly low-level jet over Atlantic supplied moisture into central Africa landmass and Vigaud et al. (2007) outlined the importance role of this low-level westerly jet for deep convection occurring during summer. Nicholson and Grist (2003) found the existence of African easterly jet (AEJ) and tropical easterly jet (TEJ) in mid (~600 hPa) and upper (~200 hPa) troposphere over central Africa, respectively. However, there is an inconsistency for what supplies the water vapour into Central Africa in the literature: Atlantic Ocean trough the low-level westerly jet or Indian Ocean through the TEJ (Dyer et al. 2017). Central Africa receives more rainfall than its surrounding regions, but there is no consistent pattern of rainfall distribution in merged satellite rain-gauges, reanalyses, and climate models datasets (Washington et al. 2013). For reanalyses, these rainfall differences are due to lower and middle zonal tropospheric circulation (Hua et al. 2019). Thus, the best the zonal Walker circulation is reproduced, the best the drought over central Africa is captured (Hua et al. 2019). Moreover, the deep column of ascent air mass over Central Africa is decoupled from the underneath circulation below 850-hPa associated with subsidence (Nicholson, 2018). Another point of view is to consider this low-level transport of moisture as the lower branch of the Walker-type cell over central Africa. No consensus has been made on the Walker circulation over central Africa. Some papers (Flohn, 1971; Webster, 1983; Yu and Zwiers, 2010; Yu et al. 2012; Thorsten and Richter, 2014) suggested the existence of a Walker-type cell over central Africa. Flohn (1971, Figure 12) depicted a dominant asymmetric overturning circulation over Central Africa, with lowlevel westerlies suppling water vapour fluxes from eastern Atlantic as lower branch. Over the Rift Valley highlands, warm air uplifts, while at upper levels, dominant easterlies form the return branch. Finally, over the eastern Atlantic, the air subsides, constituting the closing branch. On the other hand, Webster (1983) and recently Thorsten and Richter (2014, Figure 13) found a symmetrical overturning cell, with convergent branches, at low levels, flowing moist air from surrounding Oceans into central Africa. Ascending branch of warm air is located over Central Africa landmass. At upper levels, the upward motion diverges and is considered as the return branches, before sinking over eastern Atlantic and western Indian Oceans respectively, closing the circulation. In addition, using the mass-weighted streamfunctions (Yu and Zwiers 2010; Yu et al. 2012), the Walker-like circulation is centred at low-levels (~800-700 hPa). It may be this low-level position of the walker-like cell that was mistaken by Pooka et al. (2014) and Kerry and Vizy (2015) as an overturning circulation confined at lower troposphere (below 800-hPa). Here, we want to find out what might explain the decoupling between the lower and aloft (above 850-hPa) circulations over central Africa.

2. Data and method

We used state-of-art reanalyses: European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) because this dataset better represents the hydrological cycle over central Africa than other datasets (Siam et al. 2013) and from the National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP)-II Reanalysis (NCEP-2) data (Kanamitsu et al. 2002) because they better capture geopotential height fields over central Africa than do other reanalyses (Hua et al. 2019). The Japanese reanalysis (JRA-55) dataset
produced by the Japan Meteorological Agency (JMA) numerical assimilation and forecast system (Kobayashi et al. 2015) is also used to evaluate its ability to capture the regional-scale zonal circulation over central Africa. Various parameters are examined including, horizontal wind (meridional and zonal components), air temperature, specific humidity and geopotential heights. To understand the regional-scale zonal circulation over central Africa, we compute the mass-weighted streamfunction as it is commonly used for its counterpart Hadley circulation. The primary reason is that the mass-weighted streamfunction help us to objectively define indices that describe the regional-scale circulation over central Africa in terms of intensity and width on various time scales. Instead to consider that the atmosphere over central Africa is driven by a thermally divergent component of the zonal wind (Pokam et al. 2014; Yu and Zwiers 2010; Yu et al. 2012; Bayr et al. 2014; Cook and Vizy 2016), we assume that the low-level circulation over central Africa is driven by the land-ocean thermal contrast between warm central Africa landmass and cold eastern Atlantic Ocean.

3. Results

Figure 1 represents the climatological annual mean of the mass-weighted streamfunctions (contours) and its associated vertical motion (shaded) over central Africa in ERA-Interim, NCEP2, and JRA-55. The regional-scale zonal circulation over central Africa consists mostly of a predominant clockwise circulation associated with a strong rising motion, indicative of deep convection. This dominant easterly circulation has an ascending branch over the Rift valley highlands (33°E), suggesting a surface forcing and a subsiding branch over the equatorial Atlantic (west of ~1°W) (Fig. 1a–c). The induced strong convection associated with the resulted vertical motion occurs mainly over the central Africa landmass rather than over the surrounding oceans, as indicated by negative value of vertical velocity. The convection over the central African landmass is stronger in ERA-Interim than in JRA-55 and NCEP. At upper levels (~200 hPa), strong TEJs (Nicholson and Grist 2003) constitute the return branch, before gradually subsiding over the equatorial Atlantic. Associated with the subsidence over the equatorial Atlantic, the low-level circulation remains easterly (west of ~1°W) so that there is no closing branch to complete this regional-scale zonal circulation. Neupane (2016) also reported the lack of the closing branch for the zonal circulation at low levels over west Africa. These low-level easterlies over the equatorial Atlantic (at west of ~1°W) are driven by the South Atlantic anticyclone through ocean–atmosphere processes (Cabos et al. 2017). This regional-scale zonal circulation is somewhat identical to the Walker-like circulation (Yu and Zwiers 2010; Yu et al. 2012; Bayr et al. 2014), with strong ascent motion over central Africa, except at low levels, where there is a closing branch. The regional-scale zonal circulation over equatorial central Africa with no closing branch at low levels will be referred as the central African “pseudo” overturning cell in comparison with the complete zonal overturning circulation reported in Yu and Zwiers (2010); Yu et al. (2012); Bayr et al. (2014). At low levels (between the surface and 800 hPa), a separated single, closed, counter-clockwise, and shallow asymmetric zonal overturning cell is located between the climatological annual mean position of the ascending branch at ~20.25 ± 5.68°E over the central African landmass and the climatological annual mean position of the sinking branch at ~1.11 ± 4.25°W over the equatorial Atlantic in ERA-Interim, consistent with Neupane (2016).

![Fig. 1. Climatological annual mean (all months) of the zonal mass-weighted streamfunction (contours; Sv) and vertical velocity (shaded; Pa/s) and rainfall (bottom part of the panels; mm/day) over central Africa for (a) ERA-Interim from 1979 to 2017. Gray and black contours represent positive and negative values of mass-weighted streamfunctions. Contour intervals are 20 Sv between 5 and 100 Sv, 75 Sv between 150 and 600 Sv, and 150 Sv up to 700 Sv. Vertical black bars represent the zonal limit of the central African region.](image-url)
flowing from equatorial Atlantic to central Africa inland, and so closing the circulation by forming a zonal shallow overturning cell (Figs. 1a–c). Hereinafter, this separated, closed, zonal, shallow overturning cell confined in the lower troposphere will be referred to as the Congo basin cell.

4. Discussion

The Congo basin cell is a thermally direct circulation, with warm, moist air over the upward branch and relative cold air associated with subsidence over the descending branch. This near-surface land–ocean thermal contrast ($\Delta T_{ATL}$) generates the land–ocean zonal surface pressure gradient ($\Delta P_{ATL}$) that triggers a monsoon-like circulation at lower troposphere. More, this advection of relatively low moist static energy from eastern Atlantic Ocean into central Africa landmass destabilizes mostly the boundary layer, reminiscent of ventilation mechanism than the building up of mass convergence at the Congo Air boundary (Longandjo et al. 2020). As result, this deepened convection over central Africa is associated with more rainfall from October to April. To balance the latent heat release related to deep convection and rainfall, the midlevel easterly jet is formed, as the Congo basin cell is reminiscent of a small engine (Longandjo and Rouault, 2020). In May/June to September, the northward intrusion of high surface pressure over central Africa is associated with the development of cold tongue SST over eastern Atlantic and the westward extension of the Walker-like cell due to Indian ocean warming. This subsidence decreases the temperature and subsequently the water vapour through the Clausius-Clapeyron relation; and so, breaks the ventilation mechanism and leads to less rainfall, indicative of low rainfall (dry) season. This occurs despite strengthened low-level westerly jet via the increasing of the land–ocean thermal contrast. These findings suggest that the Atlantic Ocean not only provides more water vapour into central Africa than from Indian Ocean but also play important role in formation of rainfall over central Africa.

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Rainfall variability over Eastern Cape, South Africa
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Parts of the Eastern Cape has been experiencing frequent protracted dry periods over the last three decades, which have had major socio-economic effects leading to economic losses and freshwater depletion. Although a significant amount of work has been done in understanding local rainfall characteristics over some parts of southern Africa in recent years, Eastern Cape which forms part of the south-east coast has been generally understudied. This region forms a boundary between the winter and summer rainfall regions. The complex meteorology due to the interactions between systems from these two regions and paucity in spatial and temporal coverage in the rainfall gauge network has been a limiting factor for long-term analysis. This study investigates rainfall variability over the region using CHIRPS, 0.05° gridded data to complement limited available station data. CHIRPS provides a large spatio-temporal coverage and thus makes it possible to assess rainfall characteristics, trends, and variability over the region. Rainfall over the region shows a high degree of spatial and temporal variability. A persistent pattern of below average rainfall since 2010 is observed for the summer months (December to February). An analysis of circulation patterns indicates wet (dry) summers are associated with a cyclonic (anticyclonic) circulation over the interior of the country, which increases uplift (subsidence) therefore creating favourable conditions for rainfall.

1. Introduction

South Africa is facing severe pressure with respect to water security due to an increased water demand with increasing population, poor planning, and management of water resources, limited investment into water reservoir infrastructure, and recurring droughts over the past decade. Since the 2000s, South Africa has been experiencing prolonged dry periods at a different time and spatial scales. In February 2018, the Western Cape province was declared a disaster area after a severe drought which occurred between 2015-2017 (Pienaar and Boonzaaier, 2018; Sousa et al., 2018; Mahlalela et al., 2019); this saw the province enforcing water restrictions due to dam levels falling dangerously low. The interior and eastern part of the country recorded its driest summer (Oct-Mar) in 2015-2016 (Blamey et al., 2018) which led to a considerable loss in agricultural produce including crops and livestock, and thus resulting in an increase in food prices. The Eastern Cape province was declared a drought disaster region in October 2019 following water shortages in several towns (Grahamstown, Graaff-Reinet, Bedford and Queenstown). This ongoing drought has cost the province R120 million for drought relief measures. Due to the increased threat to water security in the country, understanding the variability and trends in rainfall that influence water availability over this region are of crucial importance for effective management and planning. South African rainfall is strongly seasonal with the eastern and interior regions mainly receiving rainfall during austral summer (December-February) while the southwest tip of the country mainly receives rainfall during austral winter months (June-August). The south coast is an exception. Here pronounced seasonality is absent and substantial rainfall is received each month with peaks in spring and autumn like southeast Australia (Engelbrecht and Landman, Weldon and Reason, 2014), Engelbrecht and Landman (2016) and Engelbrecht et al. (2015) have shown that rainfall over this region is specifically linked to cut-off lows (CoLs), cloud bands (TTT) and ridging highs with each system contributing 16, 28 and 46 percent, respectively to annual totals. Although a significant amount of work has gone into understanding rainfall characteristics over most of South Africa, our knowledge of the south-east coast is limited to a few studies (Jury, 1993; Weldon and Reason, 2014. Engelbrecht and Landman, 2016). This is concerning given the fact that this region is prone to extreme climate events that have devastating socio-economic impacts. Due to the threat to water security, the objective of this study is, therefore, to analyse interannual variability and identify the key circulation patterns linked to wet and dry years over the Eastern Cape. A better understanding of rainfall characteristics is of importance for this agriculture intensive community as it will facilitate proper planning and better water resource management.

2. Data and methods

The Climate Hazards Infrared Precipitation with Stations (CHIRPS) daily values are used to highlight interannual variability. The CHIRPS dataset is a merge of different products including satellite imagery and station values, created for trend analysis and seasonal drought monitoring purposes, which increases confidence in rainfall estimates for the region. It is available at 0.05° (5 km) spatial resolution on a quasi-global (50°S–50°N) grid, for the period 1980 to present (Funk et al. 2015. Daily values were converted to seasonal totals and the season considered here is austral summer (Dec to Feb; DJF). A composite approach is used to understand the circulation patterns for DJF periods that were anomalously wet or dry but with the condition that these wet (dry) periods should occur in the same year as the overall extended summer (SONDJFMAM).
being wet (dry). National Centers for Environmental Prediction (NCEP)-Department of Energy (DOE) Second Atmospheric Model Intercomparison Project (AMIP-II) reanalysis data (Kanamitsu et al. 2002), at a spatial resolution of 2.5° and on monthly time scale for the period 1981–2017, are used to determine the circulation anomalies. The variable used here is geopotential height. Moisture fluxes were computed from the horizontal winds and specific humidity.

3. Results

Figure 1: Core summer (DJF) standardised anomalies (no units) for eleven locations across Eastern Cape corresponding to the location of 11 SAWS stations, station names are indicated at the top of each panel. Years indicate the last year of the season (1985 represents the season 1984/1985).

The time series in Figure 1 shows an analysis of rainfall variation measured in standardized anomalies for the period 1981 to 2018. The austral summer; DJF, is of interest as it has the largest contribution (60%) to annual totals. The year 1983 stands out as an extremely dry year across stations and 2000 an extremely wet year. While stations generally show an agreement in wet and dry years, the severity is not uniform across the region. This highlights the degree of spatial and temporal variations in rainfall across the Eastern Cape. This is expected given the different factors that play a role in the local rainfall, such as the proximity to the ocean and local topography. The region is prone to protracted dry periods, all stations show dry conditions for the past five years. This multi-year event has been the longest in the record, five of the eleven stations: Humewood, Addo Elephant Park, Grahamstown, and Port St Jones indicate below average rainfall since 2004/2005. The DJF moisture flux mean (Figure 3a) highlights the climatological sources for the Eastern Cape coast are a westerly flux from the southeast Atlantic. Rainfall over the South African interior is also associated with the easterly south Indian Ocean flux and north-easterly monsoon flux which are also evident in this season (Rapolaki et al., 2019). Other features of importance for rainfall production are the Angola low illustrated by a cyclonic circulation over Angola/ Botswana and the Mozambique Channel trough (MCT). These features are important for the development of cloud bands which are a prominent rain-bearing system for this season.

Figure 2: DJF Geopotential Height composite anomaly (m; contours) at 500 hPa for wet and dry years. The contour interval is 5 m.

Figure 3: (a) The mean DJF moisture flux at 850 hPa, (b) and (c) show moisture flux anomalies for wet and dry years, respectively. Vectors indicate direction and shading shows the magnitude (Kg.m.s⁻¹).

Wet years are associated with an enhanced westerly flow from the southeast Atlantic (Figure 3b). During dry summers, anticyclonic anomalies develop over the south of South Africa which leads in a poleward shift in the moisture corridor and less rainfall over the southeast coast (Figure 3c). Barimalala et al. (2018)
suggest a weaker (stronger) MCT leads to increased (reduced) moisture advection into southern Africa and enhanced (reduced) precipitation over the Southern African interior. This is however not observed in our results, wet (dry) summers are characterised by a stronger (weaker) MCT.

References


Mesoscale Convective Systems over the east coast of South Africa
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Mesoscale convective systems (MCSs) are severe weather phenomena that account for much of global precipitation and are responsible for flooding, severe winds, hail and sometimes tornadoes. Previous studies on severe weather in South Africa have often focused on synoptic-scale systems such as cut off lows, tropical extratropical cloud bands, and tropical cyclones. As a result, MCSs in South Africa remain poorly understood with there being little evidence of any long-term climatology studies of these systems over the region. In this study, a climatology of MCSs over the east coast of South Africa for the extended summer months (Sep-Apr) is developed. Most systems trigger near the eastern escarpment where topography, LLJ, upper-level westerly waves and wind shear interact favourably in such a way that it favours the development of MCSs. These systems are found to predominantly occur between November and January, with a peak during November and December. The peak in MCS activity in early summer may be related to stronger temperature and moisture gradients in the region at that time. The results also indicate that there is considerable variability in the MCSs frequency on interannual time scales.

1. Introduction

Mesoscale convective systems (MCSs) are large convective storms that result when smaller convective storms merge and organise into a single cloud system. These systems are defined as a long lived (< 3h) cumulonimbus cloud system that contains a precipitation area extending at least 100 km in at least one direction (Houze, 2004). Long-lasting, slow moving MCSs can result in flooding, severe winds, hail and sometimes tornadoes (Maddox et al. 1986). Development of MCSs is typically the result of many interacting processes, operating on range of different scales which include strong heating of sufficiently moist and unstable air masses over land, available moisture sources (e.g. warm ocean), a lifting mechanism (e.g. flowing over high topography), and favourable wind shear. Although there are numerous types of MCSs, most well-known are squall lines (linearly organised) and mesoscale convective complexes which are a particularly large and long-lasting subset of the quasi-circular organised systems. MCSs occur in various tropical and mid-latitude areas (both land and ocean) in all continents except the Antarctic (Maddox, 1980, Laing and Fritsch, 1993a). Previous studies on these systems have mostly been conducted outside Africa with a few studies that have included Africa being focused on Sahel Region (e.g. Laing et al. 1999) or subtropical southern Africa (e.g. Blamey and Reason, 2012, 2013). Studies on the global distribution of favourable severe weather environments (e.g. Brook et al. 2003) and of intense thunderstorms (Zipser et al. 2006) have identified southeastern Africa and the Agulhas Current as a convective “hotspot”. However, previous studies on severe weather in South Africa have often focused on synoptic-scale systems such as cut off lows, tropical extratropical cloud bands or tropical cyclones. As a result, MCSs remain poorly understood with relatively little known about South African MCSs. Apart from the 9-year climatology of MCCs developed by Blamey and Reason (2012, 2013), there are no long-term studies of MCSs over the region.

Since these events often result in severe flooding, damage and sometimes loss of life, it is important to better understand the seasonality and interannual variability in their frequency of occurrence, preferred tracks and intensity. As an example, the MCS event which occurred over the east coast of South Africa on 3 January 2005 (Fig.1) left approximately around 500 people homeless, with much infrastructure damage and led to eight deaths from lightning. Some KwaZulu-Natal stations (Fig.1) experienced approximately 70 mm of rain in an hour. Thus, the aim of this study is to develop a climatology of MCSs over the east coast of South Africa for the period 1985-2008 and to understand the variability of MCS frequency, track and intensity on intraseasonal, seasonal and interannual time scales.

2. Data and methods

a. MCSs dataset

This study uses the Huang (2017) MCSs dataset which is a quasi-tropical (30°N-30°S) MCSs dataset covering the period 1985-2008. The identification of the MCSs used a brightness temperature (BT) threshold, an area

Figure 1: An MCS reported over Kwazulu-Natal, South Africa, 03 January 2005, 12:00-17:00 UTC (left) and rainfall (mm) derived by TRMM data from 03 January 2005.
coverage threshold, and an overlapping threshold (see Huang et al. 2018). The climatology is based on European Union Cloud Archive User Service (CLAUS) project data (Hodges et al. 2000), a global dataset based on the calibrated International Satellite Cloud Climatology Project (ISCCP) B3 radiance data (Rossow and Schiffer 1999). The CLAUS dataset has been widely used to detect convective activity globally (e.g., Nguyen and Duvel 2008; Dias et al. 2012; Dong et al. 2016). The CLAUS data provides 3-hourly global brightness temperature (BTs) with intervals sampled at a 30 km (1/3°) resolution. The Huang (2017) dataset contains basic trajectory information along with the following characteristics for each MCS: intensity, area, eccentricity, speed, direction, and lifetime etc. Note that the MCSs identified in January 1985 or December 2008 are excluded since those two months lie outside the period covered by the CLAUS dataset.

Figure 2: Topography of Southern Africa with red box indicating study region (mask). The bottom right figure is a reference of our domain on the global map.

b. MCSs identification

All pixels in the region of interest (red polygon in Fig. 2) from the 1985-2008 Huang (2017) dataset with BT values colder than a threshold of -52°C were considered as potential MCSs provided that the corresponding area covered was at least 10,000 km². A MCS was then defined provided that these two criteria were met for at least 6 h. These criteria are based on those of Augustine et al. (1989) and similar to other MCS studies (e.g. Garcia-Herrera et al. 2005, Nuryanto et al. 2019). The red polygon was chosen as the south-eastern African region downstream of the high-lying eastern escarpment extending out over the greater Agulhas Current system to 40°E since previous work (Blamey and Reason, 2012, 2013) had shown this to be where MCCs typically occur in the region. However, MCSs that are not initiated within the polygon but who subsequently track somewhere through the red polygon are excluded from the MCS statistics.

3. Results

In this analysis, a total of 777 MCSs were identified and tracked over the east coast of South Africa during the period 1985-2008. Figure 3 shows the origin points of these MCSs.

Figure 3: The origin or trigger location of MCSs over the east coast of South Africa for period (1985-2008). The grid spacing is at 1° resolution.

Figure 4: Monthly totals of MCSs over the east coast of South Africa for period (1985-2008). The numbers above each bar represent the total number of systems for each particular month.

It is evident from Fig. 3 that most systems trigger near the eastern escarpment where there are sharp topographic gradients, like MCS locations elsewhere in the world (Laing and Fritsch, 1993a; Bernardet et al. 2000; Pan et al. 2004). Garstang et al. (1987) found that the interaction between topography of the northeastern escarpment and the upper air westerly waves propagating across the southern tip of Africa can lead to the development of strong convection over the east coast of South Africa. Note the southern border at 30°S is due to the Huang (2017) dataset limits. The monthly
frequency of these systems over the east coast of South Africa varies considerably during the summer half of the year (Fig. 4) with a sharp increase from September to November, a peak in December followed by a slow decrease through the late summer. The larger frequencies in November and December compared to late summer could be linked to the large-scale environment since temperature and moisture gradients over South Africa tend to be stronger in early summer than in late summer. The peak of MCSs activity in November and December has been documented in other parts of the Southern Hemisphere, such as South America (Velasco and Fritsch, 1987; Durkee and Mote, 2009). On interannual time scales, it is found that there is also considerable variability with some summers containing up to twice the number of other summers. In summary, MCSs occur most frequently in November and December over the east coast of South Africa and seem to be triggered by flow over the eastern escarpment. This is a region of very strong topographic gradients and is also close to a source of moist unstable air (northern Agulhas Current).

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Impact of the Agulhas Current on storm development
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A high-resolution atmospheric model (WRF) is used to investigate the impact of the Agulhas Current on the storm development. A sensitivity experiment is conducted to analyse the influence of the Agulhas Current’s sea surface temperature (SST) on rain producing, synoptic scale weather features. Two model configurations: Control (CTL) and Smooth (SMTH) are analysed to understand the effect of the Agulhas Current’s SST and high latent heat fluxes on storms that develop directly over the current as well as those that propagate over it. The two configurations are identical except that the SMTH simulation has the SST signature of the Agulhas reduced by smoothing out the strong SST gradients associated with the current. This results in the current core decreasing by approximately 1.5°C in the SMTH simulation. Storm events were identified using daily synoptic weather charts and the TRMM 3B42 3-hourly 0.25 x 0.25° precipitation product. All available model output years (2001 – 2005) are then analysed and ten storm events are identified using five model output variables. These five variables are used as a proxy for the storms’ intensity. Results indicate that from these ten storms, ten show lower 850mb geopotential heights (m), nine show faster surface wind speeds (m.s⁻¹), seven show have increased rain rates (mm.hr⁻¹), eight show higher Eddy Kinetic Energy (EKE) (m².s⁻²) and nine show greater upward moisture flux at the surface in the CTL simulation once the storm matured over the current. Indications of intensification over the current is prevalent amongst all selected storms however not all storm output variables show a clear and obvious difference between the CTL and SMTH simulations. These results nonetheless provide a strong case for the impact of the Agulhas on the evolution of rain producing weather events.

1. Introduction

As the strongest Western Boundary Current (WBC) in the Southern Hemisphere (Stramma & Lutjeharms 1997), the Agulhas Current plays a pivotal role in the climate system of Southern Africa by transporting heat poleward and releasing it into the atmosphere. Sharp sea surface temperature (SST) gradients found between the current and surrounding waters results in high turbulent latent and sensible latent heat fluxes above the Current (Rouault et al. 1995). Latent heat losses from WBCs have been observed to be much larger during extreme weather events. Xue et al. (1995) found latent heat fluxes up to 1000 W.m⁻² during a storm passage across the Gulf Stream and Rouault & Lutjeharms (2000) recorded 500 W.m⁻² over an Agulhas eddy. Latent heat fluxes increase fivefold over the Agulhas Current whereas wind speed, wind stress as well as the negative stability parameter are also found to increase at the location of warmer sea temperatures (Rouault et al. 1995). According to Lee-Thorpe et al. (1999), latent heat makes up the majority (80 – 90%) of the total turbulent heat flux over the Current and thus indicates a substantial injection of moisture into the overlying atmosphere. This study makes use of the Advanced Research version of the Weather Research and Forecast (WRF) model to run two simulations: Control (CTL) and Smooth (SMTH). The evolution of storms over the Current in these two simulations are analysed. The impact of the Agulhas Current on atmospheric variables is quantified by taking the difference (CTL – SMTH) between the two model configurations.

2. Data and Methods

Version 3.7.1 (Skamarock & Klemp 2008) of the WRF model is used to explore the impact of the Agulhas Current on storm development. Model specifications include spatial resolution of 25km, 56 vertical eta-coordinates and 3-hourly temporal output from 2001 to 2005. Using a spatial filter, SST boundary conditions in the SMTH configuration are smoothed out thereby lowering the SST of the Agulhas core by roughly 1.0 – 1.5°C and surrounding region by 0.25 – 1.0°C (Figure 1). Lateral boundary conditions in the CTL configuration are observed SST data, unchanged. Reducing SSTs in the SMTH simulation results in lower (100 – 150 W.m⁻²) latent heat fluxes in the core of the Agulhas current (24 - 37° S & 21 - 38° E) in the SMTH run. Storms were identified using daily weather charts provided by the South African Weather Service (SAWS) and the Tropical Rainfall Measuring Mission (TRMM) 3B42 v7 3-hourly precipitation reanalysis product. All synoptic scale, rain-producing low-pressure system propagating over the Agulhas Current were identified and their dates recorded. The model output for these dates were then analysed. Five atmospheric variables were used as proxies for the study of each storm’s intensity. The evolution of the 850mb geopotential height (m), surface rain rate (mm.hr⁻¹), surface wind speed (m.s⁻¹), eddy kinetic energy (EKE) up to the 850mb level (m².s⁻²) and turbulent moisture flux at the surface (g.m⁻².s⁻¹) were all analysed. Once each storm had developed over the Agulhas Current (24 - 37° Sand & 21 - 38° E averages of the difference (CTL – SMTH) values above the storm in a square domain of each atmospheric variable of each storm were then calculated to quantify the impact of the Current on each variable.
3. Results

Two hundred synoptic scale storms were identified passing over the Agulhas Current from 2001 to 2005. Seventy were found to produce significant rainfall. After analysing the model output of these 70 synoptic scale, rain producing storms, it was found that 10 showed intensifying development over the Current whereas 28 storms showed cases of sustained storm intensity over the Agulhas Current and 32 showed instances of dissipation over the Current region. Most storms with sustained storm intensity turned out to be large scale mid-latitude cyclones and cold front whereas many of the dissipating storms were smaller low-pressure systems, namely coastal and interior lows. Of the 10 storms that did intensify over the Current region, three different categories of storm were found. Category A storms were small low-pressure cells that developed directly over the Current region (Figure 2 and 3). Category B storms were mid-latitude cyclones with associated cold fronts and finally category C storms were interior low-pressure cells that developed over land and then eventually propagated offshore over the current. Statistics of the grey box values of the difference (CTL – SMTH) of each variable for each of the ten developed storms are as follows. In the CTL run, all ten had lower geopotential heights, seven had higher rain rates, nine had faster surface wind speeds, eight had higher EKE values and nine had greater turbulent moisture fluxes at the surface once each storm had developed over the Agulhas Current. It should be noted that not all the variables intensified over the Current for the ten storms. However, the most popular evolution pattern amongst the 70 storms analysed in the model output was either sustained or intensified storm strength whilst the storm was centred over the current followed by a weakening of storm intensity once the system had moved away from the Current region.

Figure 2: Storm A1. WRF model 850mb geopotential height (m). From top to bottom: 19 July 03:00; 19 July 09:00; 19 July 15:00 & 19 July 21:00. (Left) CTL simulation (middle) SMTH simulation & (right) Difference (CTL – SMTH). Orange boundary encloses area where SSTs are 0.25 - 1°C warmer in CTL simulation. Red boundary encloses area where SSTs are > 1°C warmer in CTL simulation. (Bottom) Grey box encloses developed storm.

Results also indicated that the Agulhas had an impact of category A and C storms (small low-pressure systems) by producing stronger storms in the CTL run whereas no difference between the two simulations was found in the evolution of category B storms (mid-latitude cyclones).
This is probably due to the size difference between these storms as mid-latitude cyclones are roughly 1500 km in diameter and the Current is only 80 – 100km wide.

Figure 3: Storm A2. WRF model eddy kinetic energy up to the 850mb level (m².s⁻²). From top to bottom: 5 March 18:00; 6 March 00:00; 6 March 06:00 & 6 March 12:00. (Left) CTL simulation (middle) SMTH simulation & (right) Difference (CTL – SMTH). Orange boundary encloses area where SSTs are 0.25 - 1°C warmer in CTL simulation. Red boundary encloses area where SSTs are > 1°C warmer in CTL simulation. (Bottom) Grey box encloses developed storm.

References


Atmospheric moisture source linked to extreme rainfall precipitation in the Limpopo River Basin, Southern Africa

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In this study, atmospheric moisture sources linked to extreme precipitation over the Limpopo River Basin (LRB) in southern Africa were identified using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Input for HYSPLIT was based on NCEP (2.5°×2.5°) reanalysis data for the initial conditions. The 10-day air parcel backward trajectories were produced over the basin during the extended wet season (October-April) from 1981-2016. Only trajectories during wet and dry years and those linked to extreme rainfall daily events were selected for the analysis. Dry and wet years and extreme rainfall events were identified using 0.05° gridded CHIRPS data. Analysis of specific humidity along backward trajectories indicated six moisture source regions for the LRB, which include a local continental source (LC source), Southeast Atlantic Ocean source (SEA source), Equatorial South Indian Ocean source (ESI source), tropical South Indian Ocean source (TSI source), Southwest Indian Ocean source (SWI source), and the Agulhas Current source (AC source).

1. Introduction

The Limpopo River Basin (LRB) in southern Africa is a semi-arid to arid region dominated by agricultural activities. Most of the population there is relatively poor and depends on direct rain-fed sources for farming and drinking water. The LRB sometimes experiences flooding events during the summer rainy season (October-April), due to various synoptic weather systems (Rapolaki et al., 2019). These systems include cloud bands (Hart et al., 2010), tropical low-pressure systems (Malherbe et al., 2012), mesoscale convective systems (MCS; Blamey and Reason, 2012), and Cut-off lows (COLs). The mean annual precipitation ranges between about 160 mm and 1100 mm, with higher rainfall amounts occurring over the eastern parts of the basin (Rapolaki et al., 2019). Most rainfall occurs during late summer months (January to March) a period when extreme rainfall events are also most frequent. To date, little is known about where moisture originates or how it is transported for such extreme events. In general, the main moisture sources for the LRB during summer are associated with the northeast monsoon across the tropical western Indian Ocean, south-easterly flow from the southwest Indian Ocean (SWIO), or north-westerly flow from the tropical Southwest Atlantic Ocean (Cook et al., 2004; Reason et al., 2006; Rapolaki et al., 2019). Westerly flux anomalies extending from this part of the Atlantic have led to flood events over the eastern LRB (Manhique et al., 2015). These westerly anomalies are thought to prevent the export of moisture away from the western subcontinent and act to oppose the mean easterly flow from the SWIO, leading to moisture convergence over the LRB (Rapolaki et al., 2019). Moisture flux into the LRB varies significantly due to the regional prevailing circulation patterns, and large-scale climate modes of variability. However, these previous findings are primarily based on analysis using the Eulerian method, in which moisture-laden air reaching the LRB cannot be traced back to their source regions. As a result, the amount of moisture leading to rainfall into the LRB and its transport pathways has not been quantified. Thus, the aim of this study is to identify and quantify the main moisture source regions into the LRB linked to extreme rainfall events using the HYSPLIT model. The full analysis and discussion of the extreme rainfall events used here are presented in Rapolaki et al. (2019).

2. Data and method

To determine moisture flow linked to extreme precipitation over the Limpopo River Basin, the HYSPLIT (Draxler and Hess, 1998) model was run for a 36-year (1981-2016) period based on the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis data (Kalnay et al., 1996). A similar approach has been adopted in earlier studies (e.g. Chu et al., 2019). NCEP/NCAR data are available on the global grid at 2.5° spatial resolution with 17 vertical levels, from 1948 to near present. The “particles” representing air parcels were released from a single location (22°S,30°E) at 1500 m above the ground level (~850 hPa), four times a day (6-hourly), and tracked backwards at an hourly interval for 240-hours (10 days). The 10-day period is the average residence time for moisture in the atmosphere. Only trajectories linked to extreme rainfall events over the Limpopo River Basin described in Rapolaki et al. (2019), during the period 1981 to 2016 were selected for analysis. The Curve Clustering Toolbox (Gaffney, 2004) was used to separately cluster trajectories of the air parcels linked to dry years, wet years during early and late summers.
3. Results

The first aim of this study was to examine the air parcel trajectories linked to early (OND) and late (JFMA) summers over the Limpopo River Basin (Fig. 1). Rainfall standardised anomalies above (below) 1 (\(-1\)) were defined as wet (dry) seasons. During the early (OND) wet summers (Fig. 1a), 5 out of 7 air parcel branches were associated with the southerly flow into the LRB, with the remaining associated with the north-easterly and the easterly flows, respectively. The south-easterly branches into the LRB originated over the subtropical South Atlantic Ocean (green; 21%), the Atlantic sector of the Southern Ocean (magenta; 44%), Southeast Pacific Ocean (red and magenta; 19%), while the north-easterly and easterly flow originated over the tropical southwest Indian Ocean (blue; 15%) (north of Madagascar) and the Southwest Indian Ocean (dark green; 44%) (southern part of the Mozambique Channel). Although only 2 out of 7 originated over the tropical South Indian Ocean (15%) and the Southwest Indian Ocean (44%), their net contribution is higher than those from the South Atlantic Ocean, Atlantic sector of the Southern Ocean, and the Southeast Pacific Ocean. For early (OND) dry summers (Fig. 1b), 6 out of 7 branches were linked to south-easterly flow, with the remaining linked to easterly flow (across Madagascar). Also, the north-easterly branch tends to disappear during the dry early summers. In the late (JFMA) wet summers (Fig. 1c), only 3 out 7 branches originated over the Atlantic sector of the Southern Ocean (cyan and red: 31%) and the Southeast Pacific Ocean (black: 5%), while the remaining branches entered the basin through the westerly (green: 21%), north-easterly (blue: 29%), and easterly (dark green and magenta: 27%) directions, respectively. Notably, the green trajectory originated over the continent and reached the basin from the west during both wet and dry late summers (Figs. 1c and d), unlike during the early summer. The north-easterly flow (north of Madagascar) is similar in both the early and the late wet summers (Figs. 1a and c). During dry late summers (Fig. 1d), the air parcel branches into basin are like the wet JFMA (Fig. 1c), except for the absence of the north-easterly branch from the north of Madagascar. Examination of specific humidity along the air parcel trajectories linked to extreme precipitation can be used to identify the atmospheric moisture source region for the LRB. Figure 2 shows backward trajectories for the top 200 rainfall extreme events over the LRB. Furthermore, the analysis can be performed for specific types of extreme events. Analysis of specific humidity (greater than 15 g kg\(^{-1}\)) linked to cloud bands (Fig. 2b) indicate that moisture originated from the Southeast Atlantic Ocean (SEA source) (off the Angolan-Namibia coast), tropical South Indian Ocean (TSI source), Southwest Indian Ocean (SWI source), and over the local continental (LC source) regions. For tropical low systems (Fig. 2c), moisture mostly originated over the equatorial South Indian Ocean (ESI source), Southwest Indian Ocean (SWI source), and locally (LC source) over tropical southern Africa.

Notably, trajectories with high humidity (10-15 g kg\(^{-1}\)) occurred mostly in the southern part of the Mozambique Channel, and to the east of Madagascar. Unlike other synoptic systems, moisture for mesoscale convective systems (Fig. 2d), originated over the Southwest Indian Ocean (SWI source), northern Agulhas Current region, including tropical South Indian Ocean (TSI source) northeast of Madagascar, with less contribution from the continental (LC) source. For cut-off lows events (Fig. 2e), high humidity regions occurred mostly over the tropical South Indian Ocean (TSI source), associated with north-easterly flow and over the Southwest Indian Ocean.

Figure 1. 7 mean groups of air parcel backward trajectories into the Limpopo River Basin for the (a) Wet OND, (b) dry OND, (c) Wet JFMA, (d) JFMA. The seasonal (OND/JFMA) rainfall standardised anomalies above (below) 1 (\(-1\)) are defined as wet (dry) seasons.

4. Summary

Generally, although most of the air parcel branches reaching the LRB originate over the subtropical South Atlantic and the Atlantic sector of the Southern Ocean their contributions are less in terms of the amount of the air parcels arriving in the basin. Most air parcels into the LRB tend to originate from the South Indian Ocean or more locally over tropical southern Africa. Also, the moisture content along the tracks from the subtropical South Atlantic, Southeast Pacific and the Atlantic sector of the Southern Ocean tends to be lower (humidity less than 10 g kg\(^{-1}\)) and lie at the upper atmospheric levels (not shown). In contrast, moisture content along the branches over the tropical South Indian Ocean, the Agulhas Current, the Southeast Atlantic Ocean, and locally over the subcontinent tends to be higher and lie at the lower atmospheric levels. This result also implies two notable differences between wet and dry summers for the LRB; the
presence of the additional north-easterly branch (ESI source) during wet summers, and the presence of the westerly (LC source) during the late summer (JFMA) which is more prominent in the wet summers. Moreover, the number of the South Indian Ocean branches is reduced in the dry summers, which could be related to the stronger Mozambique Channel Trough (MCT; Barimalala et al., 2018) and its associated cyclonic flow which leads to a weaker moisture inflow into the LRB and southern Africa.

Figure 2. Top 200 extreme rainfall events backward trajectories for the Limpopo River Basin with their specific humidity (g kg⁻¹) values during the extreme rainfall events. The colour bar denotes the specific humidity (units: g kg⁻¹). The abbreviations (a) CB, (b) TL, (c) MC, and (d) COL denotes cloud bands, tropical lows, mesoscale convective systems, and cut-off lows synoptic systems respectively.

References


1. Introduction

Rainfall over southern Africa exhibits pronounced variability on a wide range of timescales. Except for the south coast and southwestern part of South Africa, southern Africa is predominantly a summer rainfall region (Taljaard, 1986). The region is heavily reliant on rainfed agriculture as a source of food production. As a result, anomalous rainfall events can lead to widespread crop failure and consequently, severe hardship for rural communities. Seasonal rainfall anomalies have been linked to large scale modes of climate variability such as El Niño–Southern Oscillation (ENSO) and the Subtropical Indian Ocean Dipole (Nicholson and Kim, 1997; Reason, 2001). Additionally, rainfall variability has been linked to anomalies in regional circulation features such as the Angola Low and Botswana High (Cook et al., 2004; Reason, 2016; Munday and Washington, 2017; Blamey et al., 2018; Créat et al., 2018). Any rainy season is made up of intraseasonal wet and dry spell events that occur after some defined onset date and before some defined cessation date of that season. Knowledge of the spatial and temporal distribution of rainfall characteristics such as dry spell frequencies provides more detailed information about rainfall needed by user groups such as farmers than total seasonal estimates do. Such knowledge is especially important for populations which are heavily dependent on rain-fed agriculture. For example, frequent occurrence of dry spells is highly unfavourable for agriculture since crops ideally require a consistent distribution of rainfall throughout the season. Although some studies have previously assessed dry spell frequencies over southern Africa as a whole (Usman and Reason, 2004) or for certain smaller sub-regions (Hachigonta and Reason, 2006; Driver and Reason, 2017), the results obtained could be questioned from their relatively coarse resolution (1-2.5°), or short period of analysis. Thus, this study uses a much higher resolution gridded dataset (0.05°) extending over a longer period (37 years) to examine the characteristics of dry spell frequency over southern Africa during the summer rainy season. Focus is placed on the Limpopo River Basin (LRB) which contains a relatively large and impoverished rural population and is prone to frequent droughts (Reason et al., 2005). The LRB lies within the broad drought corridor defined by Usman and Reason (2004) as the southern African zone that, on average, contains more than half of the rainy season consisting of dry spells. However, given that study used 2.5° resolution data over only a 21-year period, it is important to reassess this result with the much higher resolution data now available for a considerably longer period. Furthermore, the LRB is also prone to heavy rainfall events resulting from both tropical and midlatitude systems (Rapolaki et al., 2019). These aspects make the LRB an interesting region to study.

2. Data and methods

Pentad (5 day) rainfall data from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) pentad dataset which has a spatial resolution of 0.05° x 0.05° were used to quantify dry spell frequencies over southern Africa. Dry spells were taken to be pentads containing less than 5 mm of rainfall occurring between the onset and cessation of each rainy season from 1981/1982 to 2017/2018. Based on the rainfall requirements needed to grow maize (the staple crop over the region), the onset of each season was taken as the first pentad of a two-pentad period having at least 25 mm of rainfall followed by a four-pentad period receiving at least 20 mm of rainfall. The cessation was taken to be the first pentad of a period of six consecutive pentads each having less than 10 mm of rainfall. Intensity-frequency of dry spells over the region was calculated as the number of summer rainy seasons each having half or more of the eighteen-pentad season consisting of dry spells. To assess potential relationships with ENSO, time series of dry spell frequencies were compared with the Niño 1+2, 3, 3.4 and 4 indices from Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST).
3. Results

Fig. 1 shows that two strong gradients in dry spell frequency exist during the summer rainy season in southern Africa. The most pronounced is a roughly west-east gradient across the western margins of the Kalahari Desert that runs through southern Angola, Namibia, southern Botswana, and central South Africa and which roughly marks the western boundary of the preferred location of continental cloud bands (Hart et al., 2013) – these cloud bands are the main synoptic rain-producing system over southern Africa. Another strong gradient extends in a north-south direction from central Zimbabwe/northern Botswana to northern South Africa with maximum dry spell count centred on the LRB. High dry spell frequency here suggests that it is a region with inconsistent rainfall distribution despite being located relatively close to the major moisture sources of the tropical western Indian Ocean and South West Indian Ocean.

![Figure 1: Mean dry spell frequencies over southern Africa for the period 1981/82 - 2017/2018.](image)

To get a better idea of the vulnerability of southern Africa to dry spells, Fig. 2 shows an Intensity-Frequency map. Again, the centre of the LRB stands out with between 75-90% of the thirty-seven summer rainy seasons each having more than half of the season (18 pentads) containing dry spells. This region therefore appears as susceptible to summer dry spells as the western Kalahari Desert in western Botswana/south-eastern Namibia, posing great challenges for its rural population. This region along the Zimbabwe / South Africa border is therefore one where the population is particularly vulnerable to multi-year droughts or to long-term drying associated with climate change.

![Figure 2: Intensity-frequency map of dry spell frequencies over southern Africa for the period 1981/82 - 2017/2018.](image)

4. Summary

High resolution rainfall data provides a much clearer depiction of the drought corridor in subtropical southern Africa than previously available datasets and highlights the central LRB as a key region within this very drought prone region. This drought corridor (which is zonally oriented) forms one of two very strong gradients which exist in dry spell frequency across southern Africa during the summer rainy season. The other gradient, which is more meridionally oriented, roughly corresponds to the western margins of the Kalahari Desert and the westernmost location of continental cloud bands which are the main summer rainfall producing synoptic system in the region.

References


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SEAmester 5 years on – Where are they now?

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South Africa’s Department of Science and Innovation’s (DSI) Global Change Grand Challenge programme calls for platforms that will “attract young researchers and retain them by exciting their interest in aspects of global change, while developing their capacity and professional skills in the relevant fields of investigation”. To meet these challenges in marine science SEAmester – South Africa’s Floating University and a joint NRF/SAEON/UCT initiative was started in 2016. Now into its 5th year and with 176 students from 23 universities all over South Africa having participated in these cruises, this report looks at how successful this programme has been and what has become of some of the SEAmester students.

Introduction: The need for a Floating University

In the past access onto the SA Agulhas II was only possible through the SA National Antarctic Programme (SANAP). So traditionally, this meant that Universities such as UCT, SUN, Wits, and Pretoria could venture to sea on this vessel through various Antarctic and Southern Ocean research projects. But South Africa is bigger than these handful of Universities – and the problem has always been how do students at the Universities of Venda, Limpopo, Walter Sisulu, Free State and many more get onboard? The SA Agulhas II is South Africa’s pride and joy polar research vessel and a National Facility and therefore must be open to all students and researchers wishing to get involved and experience a research cruise. SEAmester is about breaking these boundaries and allowing everyone access to the ship. It is a fair and open process that anyone studying an Earth systems related subject from any University across South Africa can apply. SEAmester allows both students and researchers to get involved, gain hands-on training and establish new collaborations. The Table below highlights the impact SEAmester has in “opening up” the SA Agulhas II nationwide

The strength of SEAmester is that postgraduate students from all over South Africa combine theoretical classroom learning with the application of this knowledge through ship-based hands-on research. The course outline is intense throughout the cruise and would not have been possible without the dedication and commitment of the growing number of lecturers from UKZN, NMU, UWC, UCT, UP, Wits, CPUT, RU, UJ, Bayworld Museum, SANSA, SAIAB, SAEON, DEA, Varsity College and many more.

The state-of-the-art SA Agulhas II provides an ideal teaching and research platform for this programme, its size, comfort and shipboard facilities including two auditoriums allow large groups of students and

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5 Years on - what do the students say?

In August 2019 all SEAmester students were contacted to provide information on where they are now with their studies and whether SEAmester had benefited their academic career paths. Out of 176 students 132 responded. The results are shown below in both comments and pie charts.

The graph highlights the number of SEAmester students per institute since the start of the programme in 2016. In addition, the pie-chart divides the total number of students by race. A key goal of SEAmester is to be diverse in race and culture of the 176 students 46% are black with 63% of this group male, 36% are white, 13% coloured and 5% Indian.

Miss Gracious Ncube from UFH who joined SEAmester in 2019 is now studying at the Ocean University in Qingdao in China, her travels to China were funded through SEAmester; while Miss Sizewaki Yapi a SEAmester 2017 student from UKZN is now a recipient of the VCs Womxn in Science grant under the leadership of Dr Katye Altieri at UCT. Other students have gone onto international cruises including Miss Rudzani Silima an MSc student at NMU who will be participating in the Antarctic city youth cruise to the Antarctic Peninsula in February 2020. Miss Thobile Dlamini a SEAmester 2018 student studying for an MSc in Nature Conservation at TUT, spent 2019 working with several research groups at UP, TUT and UCT and also joined the 2019 Marion Island expedition as an oceanographer. Mr Sean Evans a joint UP/UCT MSc student who joined SEAmester in 2017 is now living on Marion Island as a sealer collecting seal foraging data for his MSc in Oceanography. A Btech student at CPUT in 2017, Miss Jordan van Stavel is working at SAEON and heads up the science arm of the SEAmester cruises. During SEAmester 2019, Jordan was in charge of all science planning as co-chief scientist.

For many students, their experience on SEAmester has been life changing.

I have been able to attend more scientific cruises due to the skills I gained during SEAmester Jan van Aswegen NWU SEAmester 2017.

I met my current supervisor (Professor Dorrington) in 2017 during SEAmester and we stayed in contact during the course of my MSc. I am now a part of her research group in marine drug discovery – all thanks to SEAmester. Luthando Madonsela 2017...

...it did inspire me to continue studying and learning more about ocean dynamics. Most importantly I have received in-depth knowledge of the instrumentations (CTD, Bongo nets etc) that are deployed for ocean studies. Phumemelani Mbuqwa 2019

SEAmester also helped me find a new project for my MSc thesis. Before, SEAmester, I wasn’t interested in studying microplastics but look at me now, busy with them and enjoying every minute of it. SEAmester made a huge impact in my life and I’ve beyond grateful to have been part of it. I couldn’t stop talking about it and I even convinced my friends to apply for it and they did and guess what? They were part of SEAmester this year and they loved it. Mulivhuweni Pettleen Mphaphuli SEAmester 2018

Mr Gerhard de Jager a SEAmester student in parasitology from UFS in 2017, became a SEAmester lecturer in 2018 and will now be participating on the end of the year cruise to Antarctica as a researcher to collect parasites across the Southern Ocean. He says...“SEAmester opened incredible doors for me to study how parasite communities respond to differing ocean regions – from the sub-tropics off South Africa to the harsh Antarctic continent. If it had not been for SEAmester and meeting so many scientists none of this exciting and novel research would have been possible”
SEAmester encouraged me to choose a research topic in aquaculture, which I am loving - Olufemi Emmanuel Akanbi UFH SEAmester 2017

SEAmester students – Where are they now?
Since 2016, 176 students have participated in the SEAmester programme. Of these students 79 are male and 97 females. The graph below outlines the 23 Universities involved in this programme and the numbers of students from all 4 SEAmester cruises. Of the 176 SEAmester students 68% stay in Higher Education either at their own institute or transferring to other universities with an additional 17% establishing 1-2-year internships at DEA Oceans and Coasts, DAFF, SAEON, V&A Aquarium, SANCCOB, CSIR.

*1% Business is Stephen Peel a SEAmester 2016 student who started a micro-brewery called Shackleton Brewery Company in Cape Town after joining the SANAE 2016-2017 cruise and visiting South Georgia (https://www.shackletonbc.co.za/)

SEAmester also provides a strong networking platform across Universities with students from WSU and UFH moving to Rhodes, UFH to UCT, UFS to Wits, SUN to UCT, UKZN to UCT and many more. Two examples are

Miss Luthando Madonsela from UKZN who joined SEAmester in 2017 said
I always wanted to do my Honours degree in a different institution from that of my undergrad but I never pursued that idea so meeting and networking with so many students from different institutions triggered that and made me want to explore more for my academic experience. Now an Honours student at Wits SEAmester 2018

Finally, SEAmester is an extremely rewarding programme, where young postgraduate students from all corners of South Africa become inspired to continue their postgraduate education and, in many cases, form lifelong friendships. The programme offers an unparalleled opportunity to live and work in the marine environment, and in doing so leaves a tangible and lasting impression that postgraduate students are able to make a meaningful contribution to the field of marine science.

"I am writing to tell you about the positive role that SEAmester had in my career up to today. When I attended last year I was doing my honours at Wits on microalgae and SEAmester exposed me to different fields in science such as the mini project I worked on with Fannie involving acoustics. My interest on acoustics continued to grow even after the program and long story short I am actually doing my MSc in acoustics this year. I got an offer from SAIAB here in Eastern Cape and for my project I am using acoustic telemetry to study the behavior of an invasive fish, common carp at Groenvlei. Overall I would really like to thank all of you in the email and the team behind the scenes for making this happen, I think I found what I am passionate about and going forward I would like to explore this field and I hope to collaborate with you in the future. – email from Dinah Mukari SEAmester 2019.

Greater awareness of the ocean’s physical, biogeochemical and ecological response to climate change, highlighted through these ship-board experiences, has already started to inspire and attract students into the marine sciences – a critical step if a new generation of South African marine scientists with a far higher calibre in the sciences are to be trained, and a key objective of government’s National Development Plan is to be realised.

Special thanks to Tracy Klarenbeck for her ongoing support to this programme and jumping through all the logistical and governmental hoops to make SEAmester happen!
Comparison of Sea Ice Detection Methods in the Atlantic Sector of the Southern Ocean
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Antarctic sea ice is characterized by large spatial and temporal variability. Remote sensing is a fundamental tool used in observing this variability, however, almost all satellite derived sea ice concentration detection methods have been developed for Arctic conditions. In this study, different remote sensing products have been compared against known sea ice conditions obtained during two cruises of the SA Agulhas II. The AMSR-2 derived products used in this study included the Arctic radiation and turbulence interaction study Sea Ice (ASI), bootstrap (BST) and the Environment Canada’s Ice Concentration Extractor (ECICE), which allows identification of Antarctic ice types based on a novel algorithm. This study shows that the traditional sea ice concentration-only based ASI and BST products are insufficient at describing important sea ice processes and mechanisms associated with short term sea ice variability. This was shown by considering two case studies, both of which investigated the effect of meteorological forcing on the Antarctic sea ice. The ASI and BST products showed the response of the 15\% concentration ice-edge well but failed to show any response in the ice interior. Conversely, the preliminary ECICE product showed substantial change at both the ice-edge and the ice interior, illustrating important processes that were not captured by the ASI and BST products. These processes show that both the ice-edge and ice interior are not only influenced by meteorological forcing, but also that these processes happen within daily timescales. Here it is argued that it is therefore necessary to further improve and validate dedicated ice-type detection methods for Antarctic sea ice up to the sub-daily scale because concentration-only based products do not sufficiently explain short term sea ice variability.

1. Introduction

Antarctica is surrounded by seasonally-varying sea ice. Sea ice plays a major role in ocean and atmosphere interactions, primarily acting as a heat and mass insulator between the surface water and overlying air masses and so sea ice coverage significantly influences polar and global climate. Satellite passive microwave (PM) scanning can be used to estimate sea ice distribution. This is a method whereby a satellite-mounted radiometer captures the blackbody radiation emitted by a surface area, which is then used to infer the type of surface observed. Various remote sensing products exist, all of which are developed to best capture the specific identifiable properties of the surface of interest. Traditionally, sea ice concentration (SIC, a measure of the proportion of ice-covered water to water not covered by ice) has been used to estimate the location of the ice-edge and infer the sea ice extent. In this case, we focused on two remote sensing products developed and validated to determine the SIC of Arctic sea ice and a third preliminary and unpublished product that adapt an Arctic algorithm to Antarctic conditions. This analysis will present two case studies designed to highlight the strengths and weaknesses of each product’s ability to detect important sea ice features.

The marginal ice zone (MIZ) is an area of sea ice cover significantly affected by the ocean and atmospheric boundaries. This is traditionally defined as the region of sea ice between 15\% and 80\% SIC, but this definition is arbitrarily due to estimated sensor uncertainties and not linked to ice features. Most SIC-products do not distinguish between the three main ice types: multi-year ice (MYI, sea ice that has survived at least one melt season), first-year ice (FYI, sea ice that has formed in the most recent freeze season and a thickness greater than 30 cm) and young ice (YI, sea ice that has formed in the most recent freeze season and a thickness less than 30 cm) (WMO, 2009).

Almost all currently available PM SIC detection products have been designed, developed and validated against Arctic sea ice (Cavalieri et al., 2010). However, due to differences between Arctic and Antarctic regions, it cannot be assumed that the accuracy at which these products determine Arctic SIC is equivalent to that of Antarctic SIC. Arctic sea ice is constrained by land; restricting the motion of sea ice in the Arctic Basin and therefore limiting the volume of sea ice export from the basin (Maksym, 2019). Additionally, intense stratification of Arctic surface waters act as insulation which prevents large vertical heat fluxes in the water column (Carmack et al., 2015). Arctic sea ice is therefore thicker, with large regions of MYI in the central Arctic. By contrast, Antarctic sea ice is unbounded by land as it grows and advances northward towards the Antarctic Circumpolar Current (ACC). Here the sea ice extent is constrained due to the influence of diverging surface waters at the ACC (Martinson, 2012), and overlying cyclone passages and strong wave action causes intense sea ice break-up in the Southern Ocean (Uotila et al., 2011, Kohout et al., 2014). The weak stratification of Antarctic surface waters means ocean heat fluxes are typically tenfold greater in magnitude.
than that of the Arctic (Martinson & Iannuzzi, 2013). Due to the dynamic and thermodynamic characteristics of the Southern Ocean, Antarctic sea ice is therefore thinner (<1 m), with very few areas of MYI, usually found in the Weddell and Ross Seas. Reliable satellite-detected SIC estimates date back to 1978 (Turner et al., 2016), datasets which now provides the backbone of polar climatological analysis and are fundamental to our understanding of climate variability (Parkinson, 2019). Decreasing sea ice extent has become one of the more concerning and obvious effects of global warming. Over the period of satellite observations from October 1978, there are downward linear trends in Arctic sea ice extent and thickness for all months (Serreze and Meier, 2019). These trends are not seen in the Antarctic. Instead, large variability in the Antarctic SIE is seen - far more dramatic than that of the Arctic. Record high Antarctic SIE in 2012, 2013 and 2014 occurred, followed by record low Antarctic SIE in spring 2016 and 2017 (Maksym, 2019).

2. Data and method

Remote-sensing products

The Advanced Scanning Radiometer II (AMSR2) determines the brightness temperature - a derivative of the microwave radiance - of a surface area. Brightness temperature is the temperature at which a blackbody would be to emit the measured radiance, and is calibrated against regions of known SIC. The fraction of SIC per area unit is then determined using a known calibrated brightness temperature range and a SIC-specific processing product. This study will focus on three SIC-products: the 6.25km spatial resolution AMSR2-ASI product (Arctic radiation and turbulence interaction study Sea Ice), the 12.5km spatial resolution AMSR2-BST product (Bootstrap) and the 12.5km spatial resolution ECICE Ice-type product (Environment Canada Ice Concentration Extractor), adapted to Antarctic sea ice by the Institute of Environmental Physics, Bremen University, Germany (Melsheimer et al., 2019). This product allows to detect the relative SIC fraction of YI, FYI and MYI.

Case Study 1: 2017 Explosive Cyclone

In early July 2017, an Antarctic voyage on the SA Agulhas II saw the ship encounter an explosive cyclone while approaching the ice-edge along the 30°E meridian. The effects of this explosive polar cyclone crossing the MIZ have been presented in Vichi et al. (2019), including large ice drift and changes in SIC and overlying atmospheric temperature. Some of these observed changes were seen in the AMSR2-ASI SIC data, primarily along the ice edge. This case study will compare the SIC determined by each product on July 3rd 2017, which corresponds to the day in which both the minimum mean sea level pressure was observed and the eye of the cyclone crossed over the MIZ. Daily anomalies (ASIC) of all products were computed by subtracting the mean SIC field of July 2nd from that of July 3rd. From this anomaly field, the SIC along two latitudinal transects were considered. The center of the cyclone was located on the 9° meridian at midday on July 3rd, propagating in a south-easterly direction. The leading and trailing latitudinal transects were positioned 12° eastwards and 12° westwards of this centre respectively (Figure 1).

**Figure 1:** The sea ice concentration on July 3rd 2017. The trailing latitudinal transect line at 3°W is indicated by white squares and the leading latitudinal transect line at 21°E is indicated by white circles. Black contours and arrows show midday MSLP and 10m wind vectors respectively.

**Case Study 2: 2019 High Pressure Cell**

During the 2019 Winter Southern Ocean Seasonal Experiment (SCALE) cruise on board the SA Agulhas II, it was noticed that the expected gradual northward advancement of the sea ice temporarily halted between July 19th and July 21st along the Good Hope transect at 0°E. This pause coincided with the presence of a high mean sea level pressure cell approximately 15° north of the ice-edge. This case study will compare the daily SIC determined by each product from July 17th to July 24th. The high-pressure cell intensified from July 18th and weakened on July 20th, thus the daily SIC anomaly will be considered before the development of the high-pressure cell, during its existence, and after it has diminished. The daily mean latitude of the 15% SIC contour was then computed using each SIC product. To do this, a subregion between 10° east and 10° west of the Good Hope line was considered, and the latitude of all grid cells with a SIC values between 15% and 20% were extracted.
3. Results

Figure 2 shows the ΔSIC determined by each product along two latitudinal transects. Here along this leading transect the ice-edge and interior has primarily been exposed to northerly winds. Alternatively, sea ice along the trailing transect has primarily been exposed to southerly winds. Figure 2 emphasizes the variation in SIC detected at both the ice edge and ice interior when specific ice types are considered. The ASI and BST products show similar ΔSIC across the ice-edge and interior (Figure 2). Both products show small variability between 67°S and 69°S. The higher resolution of the ASI product results in much finer variability compared to the smoother variability of the BST product. Apart from this, neither the ASI or BST product detects any considerable ΔSIC in the ice interior across both the leading and trailing transects. The ASI and BST products showed maximum ΔSIC increase of approximately 80% and 45% respectively along the trailing transect (Figure 2a), and a maximum decrease of 80% and 100% respectively along the leading edge (Figure 2b). These maximum ΔSIC occurred at the ice-edge, meaning that the effect of the cyclone on the MIZ detected by the BST product agrees with the ASI-product shown by Vichi et al. (2019). In contrast, the ECICE product detects far greater variability in ECICE-YI and ECICE-FYI ΔSIC over the ice interior. Figure 2 also emphasizes the reversed trends of the two ice-type ΔSIC. Over the interior (about 800 km away from the edge), the trailing transect shows decreasing ECICE-YI and increasing ECICE-FYI (Figure 2a). Conversely, the leading transect shows increasing ECICE-YI and decreasing ECICE-FYI over the ice interior (Figure 2b). Like the ASI and BST products, the greatest ΔSIC in ECICE-YI shown by Figure 2 also occurs at the ice edge.

Turning to the second study case in winter 2019, Figure 3 illustrates the mean position of the 15-20% ice-edge measured by each product. Initially, the mean latitude of the ice-edge determined by the ASI, BST and ECICE-YI products are similar, while the ECICE-FYI ice edge is shown to be roughly 1° further south. The ASI, BST and ECICE-YI products all show an initial advancement of the ice-edge from July 17th to 18th, while the ECICE-FYI shows an ice-edge retreat. This represents the period before the development of the high-pressure cell north of the ice-edge. The high-pressure cell begins to develop from July 18th to 19th. During this period, the BST and ECICE-FYI products show a retreat of the ice edge, while the ASI and ECICE-YI products show a slowing of the initial ice-edge advancement. As the pressure gradient intensifies from July 19th to 21st, very little change in the mean latitude of the ice-edge is observed by the ASI and BST products. This corresponds to the pause in the advancement of the ice-edge, which is supported with in situ observations (unpublished data). Conversely, this is the period of greatest change according to the ECICE-YI and ECICE-FYI products. The mean latitude of the young and first year ice-edge decreases and increases respectively. As the pressure gradient weakens on July 21st, the ASI and BST products show a continuation of the ice-edge advancement, thus ending the pause-period experienced from July 19th to July 21st. All four products then show a continued advancement of their respective ice-edge from July 23rd. The latitudinal variability of the ECICE-YI ice-edge was much larger than that shown by the

![Image](image_url)

**Figure 2:** The measured changes in sea ice concentration (ΔSIC) over one day along the (a) trailing latitudinal transect at 3°W and the (b) leading latitudinal transect at 21°E by the SIC products.

![Image](image_url)

**Figure 3:** The latitude of the 15-20% sea ice concentration ice-edge between 10°W and 10°E from July 17th to July 23rd, 2019 is shown as scattered dots. The mean latitude of the 15%-20% sea ice concentration ice-edge is shown as a solid line. Shading indicates the ±1 standard deviation of the latitudinal position of the ice edge.
ASI, BST and ECICE-FY1 products. The different trends shown by the ECICE-YI and ECICE-FY1 highlights the importance of using a product which can distinguish between these different ice types. Additionally, it is necessary to collect measurement of the Antarctic SIC at a sub-daily timescales so that the mechanisms which drive these daily changes in SIC can be identified.

References


Intriguing phytoplankton dynamics: An IOP and biogeochemical validation of the Equivalent Algal Populations (EAP) model; introducing a carbon component

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The phytoplankton community structure plays an integral role in the nutrient and carbon cycle. Phytoplankton supplies approximately 50 percent of global net primary production. The different phytoplankton species display different characteristics, such as size structure, taxonomic composition or their functions, and can be characterised as Phytoplankton Functional Types (PFTs). This work focuses on the optical identification of PFTs, aiming to further develop the UCT/CSIR Equivalent Algal Populations (EAP) model of phytoplankton Inherent Optical Properties (IOP). Phytoplankton optics in this model are driven by pigments (dominated by chlorophyll a) and particle size, and a key focus of this research is to incorporate the optical effects of intracellular carbon into the model. Validating the model with IOP measurements from the Southern Ocean (SO) and Southern Benguela, is an integral part of this work. The EAP model allows for the systematic examination of the biophysical drivers of optical variability. Extending the model in this way can further inform the development of algorithms for satellite and in-situ applications, improving characterization of the phytoplankton community. Once applied to the Southern Ocean and Benguela ecosystems, these algorithms can be used to improve our understanding of the response in phytoplankton community to episodic events, seasonal and decadal drivers, in the context of climate change.

1. Introduction

The SO is a well-established CO$_2$ sink and plays an essential role in the global carbon cycle. The capacity of the Southern Ocean to act as a long-term carbon dioxide sink, will only be revealed upon a better understanding of the impacts of various forcing mechanisms on phytoplankton physiology, and community structure. By examining a large variety of in situ bio-optical and physiological parameters, the aim is to develop and validate appropriate regional ocean colour algorithms. Understanding of the response of SO phytoplankton to climate change is important to predict the future state of the ecosystem, and the effects of physical and biotic change in the SO. This can be used to assess the impacts on fisheries and endangered species. It is useful to monitor Phytoplankton Functional Types (PFTs) from satellite-based remote sensing of ocean colour, at high spatial and temporal resolution. A model of Equivalent Algal Populations (EAPs) has been developed that focuses on the optical identification of PFTs, leading to a better characterization of naturally occurring assemblages. It has been tested in the high biomass Benguela coastal region. The EAP model has a proper characterization of phytoplankton scatter and backscatter. The real refractive index relates to backscatter. Carbon can relate to the real refractive index. The EAP model therefore provides an opportunity to relate backscatter to carbon. The aim of this study is to further develop the UCT/CSIR EAP Inherent Optical Properties (IOPs) model, from chlorophyll and size, to also explore the impact that intracellular carbon variability has on the IOPs. The adaptation of the EAP refractive index basis vectors is used to parameterize carbon, and to generate a particulate organic carbon amount. From the further development of the existing phytoplankton particle population model, information on size based PFTs, can be retrieved. This includes distribution, size, carbon content and physiology. These can be validated with in-situ data. The EAP model primarily addresses the phytoplankton backscatter driven by particle size and intracellular carbon content. All other particulate backscattering is described as a detrital component, modelled using an exponential Jungian size distribution.

2. Data and method

A primary focus of the research is to develop the necessary bio-optical, biogeochemical and physiological methodologies. Also, to gather the necessary data needed to allow us to adequately characterize the in-situ phytoplankton community so that the EAP model can be validated for the regions of study. The validation of the model’s IOPs allows the investigation of how much of the variability in ocean colour signals can be attributed to changes in various biophysical characteristics of the phytoplankton assemblage. The aim of the in-situ measurements is to provide sufficient assemblage information, to be able to model algal populations with a high level of confidence. This, therefore, allows for the linking of the carbon content, size distribution and taxonomic composition of algal communities, to optical properties. Data obtained from the Southern Ocean Seasonal Experiment (SCALE) winter and spring cruise and the SANAE 59 summer voyage 2019, will be used. In addition to these, historical cruise data will also be used. The EAP model is based on a spherical two-layered geometry (Bernard et al., 2009), used for studying the impact on optical interactions. Phytoplankton are represented as an outer layer chloroplast sphere (20%) and an inner cytoplasm
sphere. The chloroplast is where the carbon is found. The use of suitable chloroplast refractive index ranges is important in this study. The real refractive index of a homogeneous algal cell is mainly responsible for the magnitude of algal scattering (Morel and Bricaud, 1986). This will be shown in my results.

3. Results

For the phytoplankton part of the two-layered spherical code, the amount of absorption changes with cell size changes, as shown by the orange and purple lines in Figure 1. The absorption amount, however, does not change significantly with changes in the real part of the refractive index, as indicated by the green lines in comparison to the other lines.

![Figure 1: Phytoplankton absorption outputs from the EAP model for an effective diameter of 4 and 12 μm and a refractive index of 1.04 and 1.1.](image1)

Figure 2 shows the amount that the scattering changes by cell size change, as well as when there is a change in the real part of the refractive index (as shown by the green lines). It is worth noting, the increase in the real part of the refractive index, shows an increase in the scattering and backscattering.

![Figure 2: Phytoplankton scattering outputs from the EAP model for an effective diameter of 4 and 12 μm.](image2)

4. Conclusion

Optical identification of PFTs improve the Equivalent Algal Populations (EAP) model of phytoplankton Inherent Optical Properties (IOP). Phytoplankton optics presented here this model are driven by pigments dominated by chlorophyll. Further work will be to validate the model with IOP measurements from the Southern Ocean and Southern Benguela, is an integral part of this work. The EAP model allows for the systematic examination of the biophysical drivers of optical variability. Extending the model in this way can further inform the development of algorithms for satellite and in-situ applications, improving characterization of the phytoplankton community.

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Summer Observations of submesoscale instabilities in the ice-free Antarctic Seasonal Ice Zone
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The ocean surface boundary layer in the Southern Ocean plays a critical role in heat and carbon exchange with the atmosphere. Submesoscale flows have been found to be important in setting mixed layer variability in the Antarctic Circumpolar Current (ACC). However, sparsity in observations, particularly south of the ACC in the Antarctic Seasonal Ice Zone (SIZ) where the horizontal density structure of the mixed layer is influenced by the massive seasonal cycle sea ice melt/formation and mesoscale stirring, brings into question the ability of climate models to correctly resolve sea-ice, mixed layer variability, and subsequently the atmosphere-ocean-ice interactions in this region. We present three months of novel fine-scale observations of the activity of submesoscale variability in the ice-free Antarctic SIZ using underwater gliders. Salinity-dominated density fronts of O(1)km are observed less than a week after the winter ice melts, associated with strong horizontal buoyancy gradients. Associated with these lateral buoyancy gradients we compute submesoscale fluxes of competing magnitude to atmospheric fluxes. The continuous spring-summer glider time series shows a gradual mixed layer deepening (from ~40m to 60m) together with decreasing horizontal buoyancy gradients, suggesting a seasonal cycle in submesoscale flows. We posit submesoscales are important in Antarctic Seasonal Ice Zone during summer and play a role in modulating mixed layer properties through the austral summer season.

Introduction

Around Antarctica, sea-ice forms a thin (~1m) layer over the ocean, which, at its maximum, covers an area roughly equivalent in size to that of the Antarctic continent itself, and retreating to an area of ~3.1 million km² in summer (Parkinson, 2019). This annual cycle shift is thought to play a critical role in the climate system, regulating the flux of heat, gases, and momentum between the atmosphere and the ocean. It also has a dominant seasonal force in the structure and dynamics of Southern Ocean marine ecosystems, and by impacting the salinity of the Southern Ocean, influences the properties of surface waters and therefore water mass transformation, influencing global ocean circulation. With the melt out of sea-ice during late spring/early summer, a mass of freshwater (more than 15 trillion liters) is rapidly reintroduced into the surface waters. This phenomenon is associated with a net freshening and lightening of the mixed layer (Barthelemy et al., 2015), which reduces convection in the surface waters by increasing stratification. Ocean processes occurring at the submesoscale (Ro=O(1); Ri=O(1)) critically impact transport and mixing in the upper ocean, leading to substantial vertical motions and modifying the mixed layer stratification (Capet et al., 2008). Mixed layer submesoscale flows are energized by the evolution of sharp fronts (with horizontal scales of 100m-10km, and time scales of hours to days) (McWilliams, 2016).

While it has been shown that the influx of sea-ice melt water enhances vertical stratification and decreases convection, and theory supports the hypothesis that submesoscale eddies would be active in ice impacted regions, the role that lateral gradients in salinity, introduced by the influx of sea-ice melt water, have on the sea-ice sectors summer surface waters is almost unobserved in the Antarctic.

This study aims firstly to evaluate, at high observational resolution, the properties of the mixed layer in terms of the mixed layer buoyancy budget, stratification and lateral gradients. We then quantify the role of submesoscale activity in relation to atmospheric forcing in the Antarctic Seasonal Ice Zone and discuss their potential for modulating the properties of the mixed layer.

Data and method

The Robotic Observations and Modeling of the Marginal Ice Zone (ROAM-MIZ) is an ongoing (2018-2020) field campaign set in the Antarctic Marginal Ice Zone with a key objective of characterising the role of submesoscale flows in the sea ice-impacted Southern Ocean. More specifically, it aims to determine the relative importance of submesoscale flows, atmospheric forcing and freshwater fluxes from ice-melt on the mixed layer variability by using autonomous platforms as a primary observations approach. To investigate the role of the freshwater input on the development of submesoscale instabilities, a Seaglider was deployed at the start of summer (14th December 2018), just 4 days after the melt of winter sea-ice when the surface heat flux into the ocean was almost at its maximum. The glider was deployed at around 60S, 0E, just south of the Southern Boundary of the Antarctic Circumpolar Current (ACC).

Atmospheric Reanalysis (ERA5), SSALTO-DUACS
altimetry data and AMSR2 Sea-Ice concentration data were used to supplement the analysis.

**Results**

In this paper, the first objective is to describe the properties of the mixed layer over a summer season in the Antarctic Seasonal Ice Zone. The depth of the mixed layer is ~40m ± 8m during the summer, gradually decreasing towards the end of summer. In early summer, density is set by variations in salinity, which are largely driven by freshwater input from advected sea-ice melt, precipitation and entrainment from the winter water beneath. Towards the end of summer, as the surface waters are mixed, temperature variations begin to play a more important role in driving density variations. Concurrently, we find that both horizontal and vertical stratification is set by salinity, especially early in the summer season.

The second aim of this study is to quantify the potential for submesoscale activity in the observed mixed layer and decompose the relative contributions of submesoscale and atmospheric surface buoyancy fluxes. We find an active submesoscale field, especially in early summer, where submesoscale fluxes are intermittently of equal or greater magnitude than atmospheric fluxes. Winds blowing along lateral fronts which energise submesoscale Ekman Buoyancy Fluxes are also found to play an important role relative to ageostrophic baroclinic instabilities because of the shallow mixed layers. Even though large, rapid variations in the mixed layer, characteristic of submesoscale instabilities are not observed, we find that small perturbations in the mixed layer have a large impact on the mixed layer properties due to the steep vertical gradients in temperature and salinity.

In conclusion, we posit that submesoscales are important in Antarctic Seasonal Ice Zone during summer and play a role in modulating mixed layer properties which impact the following seasons sea-ice growth potential as well as water mass transformation. While submesoscales in summer in the SIZ are active, the impact that improved submesoscale parameterizations would have if included in coupled-GCMs remains to be determined.

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**Figure 1:** Timeseries of a) Mixed layer horizontal density anomaly, glider latitudinal transects are shown in light grey b) ERA5 derived surface buoyancy fluxes, c) ERA5 wind stress, d) Submesoscale fluxes
Transition from ERA Interim to ERA5: the suitability of a polar cyclone tracking algorithm to higher spatio-temporal resolution reanalysis data

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Atmospheric reanalyses are essential tools for the tracking of synoptic systems such as polar cyclones. The European Centre for Medium-Range Weather Forecast (ECMWF) has recently released the fifth-generation reanalysis, referred to as ERA5, which will be replacing ERA Interim by November 2019. ERA5 incorporates numerous advancements, the most notable difference being its higher spatial and temporal resolution. To deduce the relative advantages of ERA5, a single cyclone identification and tracking algorithm was applied to mean sea level pressure data from ERA5 and ERA Interim products, at parameter settings. To determine the differences between products, five case studies based on individual cyclone tracks observed in the Atlantic sector of the subantarctic region during winter 2017 were compared. In this study it was shown that the number of cyclones identified by ERA5 were substantially less than that of ERA Interim. Additionally, the ERA5 reanalysis product has displayed many improbable and broken tracks, which is suggestive of unsatisfactory performance of the tracking scheme when applied to a higher spatio-temporal resolution dataset. The portions of ERA5 tracks that were detected, displayed a close correspondence with ERA Interim atmospheric variables, and in some cases provided additional information that was lacking in ERA Interim. The main atmospheric features associated with cyclones, such as warm and cold fronts, cyclonic wind direction and minimum mean sea level pressure were similar in both products; the only difference being that the resolution of ERA5 markedly improved the details of these features. This study concludes that ERA Interim is sufficient in determining fundamental cyclonic features on a larger scale, however smaller scale features and details are better represented by ERA5 data. Additionally, to better represent the ERA5 product using the cyclone identification and tracking scheme, parameters need to be adjusted to accommodate the higher resolution data.

1. Introduction

The Antarctic region appears to be affected by many facets of variability and change in recent decades, which have implications on a complex matrix of interactions between sea ice, ocean, and atmosphere (Simmonds et al. 2003). The atmospheric variability responsible for much of the weather in the mid-latitudes can be accounted for by the occurrence of cyclones and their associated frontal systems (Trenberth 1991). Extratropical cyclones are prevalent atmospheric features dominating the middle and high latitudes of the Southern Hemisphere (SH). Quantifying and tracking extra-tropical cyclones contributes to our understanding of the general atmospheric circulation of the Southern Hemisphere, and the factors that drive the Southern Ocean. The generation of the reanalysis products has enabled atmospheric studies of the high southern latitudes to be undertaken with an unprecedented level of confidence (Simmonds, Keay & Lim, 2003). The recently released ERA5 reanalysis update of the ERA-Interim provides what is arguably the highest quality analysis spanning 1979-2019, available for the high southern latitudes (Dee et al. 2011). It therefore offers an excellent starting point from which to assemble a modern, comprehensive, and reliable picture of synoptic activity in the sub-Antarctic region (Simmonds, Keay & Lim, 2003).

The purpose of the present study is to compare the reanalysis products, ERA Interim and ERA5, using a single cyclone identification and tracking algorithm based on research by Pinto et al. (2005). Pinto et al. (2005) modified the algorithm, originally developed by Simmonds et al. (1999), to detect a wide variety of Northern Hemisphere cyclones. The algorithm was designed to suit the resolution of ERA Interim data, and we will explore the sensitivities of this algorithm to the input of a higher resolution dataset under certain parameter settings. This allows us to assess the readiness of the algorithm to handle comprehensive ERA5 data and to compare simulation results. To analyze the differences between the detected tracks, individual cyclones observed in the Atlantic sector of the Antarctic region during a research cruise in winter 2017 (Vichi et al., 2019) were selected as case studies.

2. Data and method

The target datasets are the ERA5 and ERA Interim reanalysis products provided by the European Centre for Medium Range Weather Forecasts (ECMWF). ERA5 is the recently released 5th generation reanalysis product that will replace ERA Interim, which is currently outdated by 10 years. The most notable difference between ERA5 and ERA Interim reanalysis products is the higher spatial and temporal resolution of the ERA5 product. ERA5 has a horizontal grid resolution of 0.25° ~ 0.25° for the atmosphere and an hourly temporal resolution, a significant improvement from the 0.75° ~ 0.75° horizontal grid resolution and 6 hourly temporal resolution of ERA Interim. This upgrade should allow for a better representation of meso- to synoptical-scale atmospheric features such as cyclones (Hoffmann et al., 2019). In this study, the winter period comprises of four months (April, May, June, and July). This decision is based on the ‘core-less
winter’ phenomenon experienced in Antarctica, where the winter atmospheric temperature regime is established in April, with only negligible deviations in temperature being experienced over the following five months (Bromwich & Parish, 1998). Mean sea level pressure (MSLP), wind speed (based on 10 m zonal and meridional), 2 m atmospheric temperature and sea ice cover concentration are analyzed in this study and obtained from ERA5 hourly estimates of variables on single levels, and ERA Interim 6 hourly surface analysis. Daily averaged sea ice concentration (SIC) data is obtained from the AMSR ASI algorithm (https://seaice.uni-bremen.de/start/data/amsr2/asi_daygrid_swath/3125/2017/).

3. Results

![Figure 1: The corresponding cyclone tracks selected from ERA5 and ERA Interim for the four case studies.](image)

The main objective of this study is to examine the similarity of cyclone tracks obtained from the different products. To achieve this objective, a comparison of individual, known cyclone tracks identified by the different products is performed. An empirical comparison of the individual tracks is done spatially and temporally, in order to analyze the deviation of the trajectories. We will focus on four case studies of the 5 cyclones (Figure 1) that were observed between 1-20 July 2017, during the winter expedition on the SA Agulhas II research vessel along the WOCE I06 transect (Vichi et al., 2019). Spatial analysis is done to distinguish the relative paths of ERA5 and ERA Interim cyclone tracks, and their associated temperature and sea ice fields. This includes analysis of the trajectory relative to the sea ice, as well as location of the start and end points of cyclone tracks according to ERA5 and ERA Interim. The purpose of the temporal analysis is twofold. Firstly, a time series of the cyclone characteristics throughout the track duration is generated by considering the MSLP, temperature, and maximum wind speed along the trajectory. The MSLP and temperature variables are associated with the cyclone core, and the maximum wind speed of the cyclone is searched within a radius of 300 km from the core. Wind maxima are in the southwest flank of the cyclone in the Southern Hemisphere (Schultz et al., 2018). The way these variables change over the duration of the cyclone life cycle and in relation to the sea ice edge and concentration is noted and compared between ERA5 and ERA Interim tracks. Secondly, the similarity in trends exhibited by the corresponding ERA 5 tracks, provides additional confirmation that the appropriate tracks were selected. Figure one shows Cyclone 1, which provides an example of a track that develops in the open ocean in the higher latitudes and crosses the ice edge. Cyclone 2 and Cyclone 5 show storms that exist in the open ocean, parallel to the ice edge. Cyclone 3 shows a cyclone that was generated on ice and stays on ice. And Cyclone 4 is a unique case of a storm that starts in the open ocean, crosses the ice and transitions back to the open ocean. The application of a single cyclone identification and tracking method to different reanalysis products comes with the expectation that differences between the number of tracks detected by ERA5 and ERA Interim will be observed. Pinto et al. (2005) explored the effect of resolution changes and found a reduction of the number of cyclones detected when using lower resolution data. Contrary to this expectation, the lower resolution dataset, ERA Interim, detected 1028 cyclone tracks, which is a substantially higher quantity than that of ERA5, which detected 802 tracks, despite having a greater spatio-temporal resolution. In addition to identifying strong synoptic systems, higher resolution data is known to detect smaller, weaker or fast-moving systems that would otherwise be neglected by lower resolution data (Blender & Schubert 2000, Pinto et al. 2005). Having ERA5 detect fewer cyclones than ERA Interim is a peculiar scenario, which may be attributed to the present algorithm settings being designed to suit the resolution of ERA Interim data.

Using the current parameter settings, the results obtained from the ERA5 reanalysis product have displayed many improbable and broken tracks in comparison to the ERA Interim product, which is suggestive of unsatisfactory performance of the tracking scheme when applied to a higher spatio-temporal resolution dataset. Pinto et al. (2005) encountered a similar scenario when applying daily temporal resolution to the tracking scheme, where he found track inaccuracies and segmentation for the lower resolution, but not for the 6-hourly resolution. Having the tracking scheme perform incorrectly when daily and hourly datasets are applied, suggests that there may not be an issue of transitioning to or from a higher or lower resolution, but rather the algorithm not being suited to another resolution besides 6 hourly data, for which it was designed. The broken tracks produced...
by ERA5 appear to have preferential detection regions along the cyclone life cycle. Cyclone 1 and 2 detect the track during the middle and end portions of the ERA Interim track, where they extend further during the cyclolysis portion of the trajectory. A supplementary portion of the track being detected during cyclolysis exhibits the capability of the ERA5 data to identify systems further into their dissipation stage, compared to ERA Interim. This is one instance where the higher resolution of ERA5 exhibits an advantage over the ERA Interim data, and this agrees with other studies that found that higher resolution datasets are able to detect weaker systems (Pinto et al., 2005). For the segments of ERA5 tracks that are detected, the trends in atmospheric variables during the cyclone life cycle correspond well between ERA5 and ERA Interim data, particularly for MSLP and near-surface temperature, but less so for maximum wind speed. The temperature of the cyclone track has a direct correlation to their spatial distribution; when over the ocean the cyclones have a substantially higher temperature than when they occur over the ice, and changes in temperature can be indicative of their positions between these two locations. For all the cyclones originating from the mid-latitude regions (Cyclone 1, 2 and 4), a clear declining temperature trend is seen as they move poleward, which is portraying their role of balancing the energy flux over the SH and transporting heat to the higher latitudes (Grieger et al. 2018, Vichi et al. 2019). A decrease in MSLP indicated deepening of the cyclone core and the growth of the cyclone, until it reached a minimum MSLP value indicating peak intensity, followed by an increase in pressure, which indicates the weakening of the system during its dissipation stage. The underlying factor of cyclone strength, may be responsible for the inverse relationship between MSLP and wind speed, seen in all case studies. When analyzing large-scale features, such as in this study, a lower resolution dataset such as ERA Interim is sufficient in detecting these features, and the results between ERA5 and ERA Interim are not fundamentally different. However, the detection of smaller features, like when the cyclone crosses the ice or the wind circulation around the core is better identified by a higher resolution dataset, as shown by ERA5. Case study 4 is a prime example of the advantages of a higher spatio-temporal dataset when analyzing the intricacies of the cyclone crossing the ice, showing a narrower range of the possible times and locations at which, the cyclone was over the ice, thus providing greater details in the estimation of the cyclone track. The increased information provided by the higher density of wind vectors are shown in all case studies, and particularly by Cyclone 5, where ERA5 data provides an exceptional case of increased insight into wind speed orientations. Without the increased detail of winds portrayed in Cyclone 5, we would be ignorant of the intricacies of the wind direction, and we would underestimate the extent to which it crosses the ice. From this study, we can conclude that ERA Interim is sufficient in determining fundamental atmospheric features on a larger scale, however smaller scale features and details are better represented by ERA5 data. Additionally, due to the spurious points and segmented tracks, we can conclude that the current parameter settings used by the algorithm are not suited for a higher spatio-temporal resolution dataset such as ERA5. The portions of ERA5 tracks that were detected, displayed a close correlation with ERA Interim atmospheric variables, and in some cases (such as cyclolysis regions) provided additional information that was lacking in. ERA Interim. Therefore, to see the benefits of the higher spatio-temporal resolution provided by the ERA5 product, parameters need to be adjusted to accommodate the higher resolution data.

References


On the response of phytoplankton to iron addition in the Weddell Sea and along the Dronning Maud Land ice edge during austral autumn
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The High Nutrient-Low Chlorophyll (HNLC) conditions characteristic of the Southern Ocean are generally thought to be caused by the low bioavailability of the micronutrient iron, which plays a key role in phytoplankton photosynthesis. These regions, nonetheless, experience seasonal blooms of high primary productivity, even in late autumn, when spring and summer productivity is expected to have utilized all available iron. This high autumn productivity is likely linked to nutrient resupply mechanisms such as remineralization. To better understand the autumn productivity, the photophysiological response of phytoplankton to iron addition was investigated in the Weddell Sea and along the Dronning Maud Land (DML) ice edge in the Southern Ocean during austral autumn. Preliminary photophysiological results showed minimal responses to iron addition, with no significant differences in the photochemical efficiency (Fv/Fm) between the treatments (iron addition and control). This suggests that photosynthesis was not iron limited in these regions during autumn.

1. Introduction

The Southern Ocean is known to play a significant role in the drawdown of atmospheric carbon dioxide (CO2), which is driven by a combination of the CO2 solubility pump, and the biological carbon pump (Geider and La Roche, 1994). Phytoplankton growth occurs in the upper sunlit layer of the oceans and is influenced by nutrient availability. The export of production to the ocean interior when biomass sinks, drives the biological carbon pump. Southern Ocean phytoplankton are typically seasonally limited by both light and iron (Fe) (de Baar et al., 1990; Martin et al., 1991), resulting in the HNLC conditions characteristic of the region. Fe is an essential micronutrient for photosynthetic proteins and is required in the photosynthetic electron transport chain (Kirk, 1994). Fe in the upper sunlit ocean arrives from external sources such as sea ice (Lannuzel et al., 2008) and atmospheric dust (Mahowald et al., 2005) as well as internal recycling through remineralization (Ratnarajah et al., 2018; Tagliabue et al., 2017).

Variable chlorophyll fluorescence measurements conducted on incubation experiments assist in evaluating the photophysiological response of phytoplankton to Fe-addition, by providing information on the photochemical efficiency (Fv/Fm) (Geider, 1993; Kolber et al., 1988, 1994). Recent studies in other areas and seasons of the Atlantic Southern Ocean (Ryan-Keogh et al., 2018; Viljoen et al., 2018) showed that some phytoplankton communities responded to Fe-addition at certain times of the year, whilst other communities did not. Hence, responses do not appear to be uniform across the Southern Ocean and across all seasons. However, these experiments were all run for long time periods (>24hrs), where substantial changes in community structure could occur, potentially influencing the photophysiology (Ryan-Keogh et al., 2013; Suggett et al., 2009). Therefore, short-term (24hr) experiments, where no significant changes in chlorophyll (i.e. biomass) are likely to occur, can provide information on changes in photophysiology due to nutrient limitation without any concomitant changes in community structure.

Seasonal phytoplankton blooms are initiated in spring when there is sufficient light and nutrient supply driven by winter overturning (Mtshali et al., 2019). Blooms typically subside when nutrients are depleted in Autumn. However, there are alternate Fe supply mechanisms following summer blooms such as remineralization (Tagliabue et al., 2017) and storm-driven entrainment (Mtshali et al., 2019). To determine whether these mechanisms are sufficient to support phytoplankton growth in autumn, a series of on-board, short-term incubation experiments were conducted in the Weddell Sea and along the Dronning Maud Land ice edge to assess the phytoplankton photophysiological response to Fe-addition.

2. Data and method

The incubation experiments were conducted on-board the Norwegian polar research vessel, Kronprins Haakon, during the Dronning Maud Land Ecosystem Cruise (DML2019-702). Trace Metal Clean (TMC) seawater samples were collected across the Weddell sea and along the sea ice edge of Dronning Maud Land in
the Kong Håkon VII Hav (KHH2019) during March 2019.

TMC seawater was obtained using two sampling protocols: (1) a TMC torpedo towfish towed underway sampling at ~5m depth, across the Weddell Sea; and (2) a TMC 8L Go-Flo array deployed overboard to collect seawater at ~20m depth (Bruland et al., 1979) along the DML sea ice edge. The samples were transferred unscreened into 3 × 1L polycarbonate bottles as triplicate controls and 3 × 1L samples inoculated with 2 nM FeCl$_3$. Sampling and subsampling was conducted under laminar flow on-board, in a built-in Class-100 trace metal clean laboratory (“TMC bubble”). The incubation bottles were placed in an on-deck incubator, with flowing seawater, to mimic in situ temperatures. The light inside the incubator was reduced to 48% of Photosynthetically Active Radiation at sea surface.

Each treatment was subsampled to conduct measurements of chlorophyll fluorescence using Fast Repetition Rate fluorometry (FRRf). FRRf measurements were performed using a FastOcean FRRf with a FastAct laboratory system to determine phytoplankton photophysiological response through changes in the photochemical efficiency (F$_{\text{v}}$/F$_{\text{m}}$).

3. Results

The F$_{\text{v}}$/F$_{\text{m}}$ as measured prior to the Fe-addition and subsequent incubation averaged at 0.20±0.02 (n=4) along the Weddell Sea cruise transect, with slightly higher values (0.25±0.04) were observed along the sea ice edge (n=6) (Figure 1). Photophysiological responses to Fe-addition varied considerably throughout the cruise. In figure 2 this variability is illustrated by highlighting two stations that showed a contrasting response (Figure 2).

![Figure 1](image1.png)

**Figure 1**: Initial F$_{\text{v}}$/F$_{\text{m}}$ values measured at each incubation station prior to the experiment.

The first example from the Weddell Sea illustrates a community that showed a positive response in photochemistry to Fe-addition (Figure 2a). Here, a higher F$_{\text{v}}$/F$_{\text{m}}$ and in extension, potentially higher primary productivity, was observed after Fe-enrichment compared to the control treatment (without Fe-addition). The second example is from the sea ice near the Astrid Ridge, illustrating a community that does not seem to be susceptible to Fe-addition, since the F$_{\text{v}}$/F$_{\text{m}}$ and in extension, potentially higher primary productivity, did not increase or decrease compared to the control treatment following Fe-addition (Figure 2b).

![Figure 2](image2.png)

**Figure 2**: F$_{\text{v}}$/F$_{\text{m}}$ for the control (blue) and Fe-addition (maroon) samples from a station sampled (a) off the Antarctic Peninsula in the Weddell Sea that showed a significant response to Fe-addition, versus a station sampled (b) along the ice edge near Astrid Ridge that showed no significant response to Fe-addition.

To further examine the changes in the photochemical efficiency, the difference between the Fe-amended and control bottles were calculated for each experiment. The resulting ΔF$_{\text{v}}$/F$_{\text{m}}$ increased gradually from south to north along 6˚E (stations CTD105, CTD97 and CTD53 in Figure 3), moving away from the ice edge towards open water (and away from an anticipated Fe source). However, ΔF$_{\text{v}}$/F$_{\text{m}}$ at all three stations further east remained low despite offshore movement. In the Weddell Sea, ΔF$_{\text{v}}$/F$_{\text{m}}$ showed variable changes with no obvious latitudinal or major changes across sea (Figure 3). Nonetheless, most ΔF$_{\text{v}}$/F$_{\text{m}}$ values were small, i.e. <0.02. Thus, even though incubations at some stations did show a positive response to Fe-addition, suggesting potential Fe depletion (e.g. Figure 2a), minimal Fe limitation is evident at most stations during autumn in the Weddell Sea and along the ice edge of DML (e.g. Figure 2b and Figure 3). This is likely due to the presence of re-supply mechanisms, such as
remineralization (Tagliabue et al., 2017) which sustain and promote phytoplankton blooms in Autumn beyond the spring to summer bloom season.

References


Seasonal variation of surface hydrographic conditions around the Prince Edward Islands
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The Prince Edward Islands (PEIs), situated in the Southern Ocean, are known through previous studies to be a key location for the identification and understanding of disturbances associated with climate change. The importance of understanding the seasonal cycle in the oceanographic conditions around the PEIs is critical in developing a comprehensive overview of the interaction between the oceanography and the biology at the islands. The current study characterised the seasonal cycle of surface hydrographic conditions and examined whether there were differences in those conditions upstream and downstream of the PEIs. Different satellite products were used to calculate monthly climatologies, from 1993 to 2018, of Absolute Dynamic Topography (ADT), Geostrophic Velocity and Sea Surface Temperature (SST) from which the seasonal cycle associated with each variable was examined. Hovmöller diagrams of those monthly climatologies were then plotted to investigate the differences between the upstream and downstream regions of the PEIs. No clear seasonal pattern, with the same meridional gradient of lower values (< 0.2 m) south and higher values (> 0.1 m) north of the study area were observed in the ADT throughout the year around the PEIs. The seasonal pattern associated with the geostrophic current showed highest speed in the resultant (0.3 m s⁻¹) and zonal flow (0.2 m s⁻¹) during winter which appeared to be closely related to the seasonal cycle of the westerly winds blowing at the latitudes of the PEIs. SST values were highest in summer (8°C) and lowest in winter (2°C). This seasonal cycle of SST showed high coherence to the intensity of solar radiation incident on the surface of the ocean in the vicinity of the PEIs. The southern branch of the sub-Antarctic Front showed a deflection slightly south of the PEIs during winter and was positioned north of the islands during the rest of the year while the northern branch of the Antarctic Polar Front showed no variation in its position within our study area. The region of high variability associated with the interaction of the Antarctic Circumpolar Current with the Andrew Bain Fracture Zone in the southwest region of the PEIs mentioned by several previous studies was also perceived over a long timescale using the standard deviation of the monthly climatological means (> ± 0.12 m in ADT, > ± 0.10 m s⁻¹ in geostrophic velocity and > ± 0.65 °C in SST) in the current study. Due to the close interaction between the oceanography and the biology at the PEIs, the results of the current study can be used by the scientific community and governmental departments to better implement conservation regulations regarding the marine protected area in the region.

1. Introduction

The Prince Edward Islands (PEIs) which includes two islands, Marion Island (270 km²) and Prince Edward Island (45 km²) are located at 46°50'S; 37°50'E. Being part of the South African official territory since 1947, they have recently been proclaimed a Marine Protected Area as a contribution to South Africa’s attempt at global initiative towards the protection of offshore and deep ocean area (Government Notice 426, 2013). Both volcanic islands, which are 250 000 year old, are surrounded by a complex bottom topography which strongly influences the oceanography around them (Ansorge and Lutjeharms, 2002). On the western side of the PEIs lies the South West Indian Ridge (SWIR) which expands from the north-east to south-west of the islands. This SWIR is covered by many fracture zones with the closest one to the PEIs being the Andrew Bain Fracture Zone (ABFZ) located at 50° S; 30° E. The Antarctic Circumpolar Current (ACC), a strong eastward flowing current that extends throughout the entire Southern Ocean, was shown by previous studies to flow in close vicinity to the PEIs (Lutjeharms and Valentine, 1984; Duncombe Rae, 1989b; Belkin and Gordon, 1996; Durgadoo et al. 2010; Durgadoo et al. 2011). The flow of the ACC is concentrated at several high speed cores namely the sub-Antarctic Front (SAF), which flows north of the PEIs, and the Antarctic Polar Front (APF), which flows south of the PEIs (Sokolov and Rintoul, 2009b). Those fronts are each divided into three branches namely the northern (N-SAF/N-APF), middle (M-SAF/M-APF) and southern (S-SAF/S-APF) branch.

As the ACC flows across the SWIR, it splits into different paths. The northern and middle branches of the SAF (N-SAF and M-SAF) flow further north and the southern branch of the SAF (S-SAF) converges with all the branches of the APF and flow through the ABFZ. The S-SAF and APF separate again downstream of the ABFZ with the S-SAF deflecting north of the PEIs and the APF flowing south of the islands (Froneman et al. 2002 and Ansorge and Lutjeharms, 2005). This interaction between the fronts of the ACC and the complex bottom topography of the...
SWIR results in regions of high-mesoscale variability downstream of the ABFZ which transport physical and biological characteristics of the Antarctic towards the PEIs bringing great advantages to the islands’ marine and terrestrial ecosystem (Ansorge et al. 2010; Durgadoo et al. 2010).

Studies involving satellite data on a large scale basis have been extensively done for the entire Southern Ocean region which do not necessarily apply to the oceanography around the PEIs due to the presence of “hotpots” of variability such as the SWIR as explained above (Orsi et al. 1993; Belkin and Gordon, 1996; Giglio and Johnson, 2016). Although satellite data and in situ products have been used to study eddies and the oceanography conditions in the area surrounding the PEIs (Lamont et al. 2019; Ansorge et al. 2010; Durgadoo et al. 2010; Durgadoo et al. 2011), long term investigations using satellite data to study the seasonal cycle of surface hydrographic conditions around the PEIs have not yet been done. The only studies of the seasonal cycle of oceanographic parameters that have been conducted so far at the PEIs is the seasonal cycle of Sea Surface Temperature (SST) described by Melice et al (2003) which only used in situ data collected from a single location at Marion Island to identify the seasonal cycle of SST and Rouault et al (2005) which used a combination of SST satellite product and in situ data recorded daily to assess climate variability such as the Semi-annual Oscillation (SAO) at Marion Island. This study thus serves as a good baseline against future studies involving the seasonal cycle of hydrographic parameters at the PEIs. The objective of this study is therefore to use satellite data for a period of 25 years to characterise the seasonal cycle of the surface hydrographic conditions around the PEIs.

2. Data and method

To analyse the seasonal variations, satellite data were used to plot monthly climatologies of Absolute Dynamic Topography (ADT), Geostrophic Velocity and Sea Surface Temperature (SST). The altimetry product which includes the variables ADT and the zonal (Ugos) and meridional (Vgos) component of the Geostrophic Velocity was obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) website (http://marine.copernicus.eu/). The resultant Geostrophic Velocity (Rgos) was then calculated from Ugos and Vgos through the equation below

\[ R_{gos} = \sqrt{U_{gos}^2 + V_{gos}^2} \]

The Sea Surface Temperature (SST) product, ‘GHRSSST Level 4 AVHRR_OI Global Blended Sea Surface Temperature Analysis (GDS version 2)’ was obtained from the Physical Oceanography Distributed Active Archive Center (PODAAC) platform (http://podaac.jpl.nasa.gov). Both gridded products were at a processing level 4 with a ‘Daily’ temporal resolution from 1993 to 2018 and a horizontal spatial resolution of 0.25° (Latitude) x 0.25° (Longitude).

Monthly means and standard deviations of each variable were calculated from the daily satellite data and then plotted into monthly climatologies. Hovmöller diagram were then plotted from values along the longitude (37.125°E) upstream and downstream (38.375°E) for the mean and standard deviation of the resultant geostrophic velocity and its zonal and meridional component. The position of the sub-Antarctic Front (SAF) and the Antarctic Polar Front (APF) were identified using sea surface height contour based definitions similar to Sokolov and Rintoul (2009a, 2009b) and Swart et al. (2010) who used a combination of in situ profiles and altimetry data to study the temporal mean and variability of the SAF and APF’s location. Each branch of the fronts have their own sea surface height value namely, S-SAF: -0.17 m, M-SAF: 0.03 m, N-SAF: 0.24 m, S-APF: -0.63 m, M-APF: -0.48 m and the N-APF: -0.30 m.

3. Result and Discussion

The same meridional pattern of higher Absolute Dynamic Topography (ADT) (> -0.1 m) north and lower ADT (< -0.2 m) south of the PEIs was observed throughout the year (Figure 1). Sea Surface Temperature (SST) showed the same decreasing meridional gradient with highest SST values north (> 5°C) and lowest SST values (< 7°C) south of the PEIs (Figure 3). Geostrophic Velocity showed the opposite north-south gradient with lower values (< 0.2 m s⁻¹) north of the islands and higher values (> 0.2 m s⁻¹) south, which was linked to the presence of the Antarctic Circumpolar Current flowing south of the PEIs (Figure 2). While no seasonal pattern was found in ADT around the PEIs, clear seasonal cycles have been observed in geostrophic velocity and SST. The resultant and zonal component of the geostrophic velocity showed highest values in winter (0.3 and 0.2 m s⁻¹ respectively) and lowest in summer (0.15 and 0.05 m s⁻¹ respectively), following the seasonal pattern of the westerly winds, blowing strongest in winter and weakest in summer at the latitude of the PEIs.
Figure 1: The monthly climatology of the mean of Absolute Dynamic Topography (m) around the PEIs from January to December (a-l). The black solid line represents the position of the Middle sub-Antarctic Front (M-SAF), the dashed black line represents the position of the Southern sub-Antarctic Front (S-SAF), the brown solid line represents the position of the Northern Antarctic Polar Front (N-APF), and the dotted brown line represents the position of the Middle Antarctic Polar Front (M-APF).

Figure 2: The monthly climatology of the mean of Geostrophic Velocity (m s\(^{-1}\)) around the PEIs from January to December (a-l). The black solid line represents the position of the Middle sub-Antarctic Front (M-SAF), the dashed black line represents the position of the Southern sub-Antarctic Front (S-SAF), the brown solid line represents the position of the Northern Antarctic Polar Front (N-APF), and the dotted brown line represents the position of the Middle Antarctic Polar Front (M-APF).

The meridional component of the geostrophic current, however, showed opposite pattern, with strongest flow (0.15 m s\(^{-1}\)) in summer and weakest flow (-0.1 m s\(^{-1}\)) in winter, following the seasonal pattern of northerly winds (strongest in summer) affecting the region of the PEIs. The seasonal cycle associated with SST showed highest temperatures in summer (> 6°C) and lowest (< 6°C) in winter, in agreement with the amount of solar radiation reaching the surface of the ocean during these seasons.

A seasonal pattern in the position of the southern branch of the sub-Antarctic Front (S-SAF) was observed with a deflection north, away from the PEIs, in summer and a movement slightly south, closer to the PEIs, in winter. Similar to the S-SAF, the northern branch of the Antarctic Polar Front (N-APF) also has high influence over the oceanography around the PEIs.

Figure 3: The monthly climatology of the mean of Sea Surface Temperature (°C) around the PEIs from January to December (a-l). The black solid line represents the position of the Middle sub-Antarctic Front (M-SAF), the dashed black line represents the position of the Southern sub-Antarctic Front (S-SAF), the brown solid line represents the position of the Northern Antarctic Polar Front (N-APF), and the dotted brown line represents the position of the Middle Antarctic Polar Front (M-APF).

The N-APF, however, does not show seasonal variability in its position in the current study. Similar to previous studies, an area of high variability was observed in the southwest region of the PEIs which could be linked to the high abundance of eddies originating from the Andrew Bain Fracture Zone (ABFZ). For each variable, higher standard deviation was seen south of the PEIs (> ± 0.12 m in ADT, > ± 0.10 m s\(^{-1}\) in geostrophic velocity and > ± 0.65 °C in SST). Considerable differences in this standard
deviation were also observed upstream and downstream of the PEIs. For each variable, higher standard deviation occurred upstream compared to downstream of the islands. These differences were attributed to the interaction of the flow of the ACC with the shallow bathymetry surrounding the PEIs.

References


