

Nansen-Tutu Centre for Marine Environmental Research

Cape Town, South Africa July 2011

Front Cover

A visually enhanced composite of seasonally averaged images of marine biophysical parameters from MODIS and SeaWiFS remotely sensed data. By Lisa Delaney (University of Cape Town, South Africa)

Foreward

The Nansen-Tutu Centre for Marine Environmental Research was conceived through research collaboration between scientists at the Nansen Centre in Bergen and their colleagues in South Africa. The Centre rests on a joint venture agreement that was signed by its patron, Archbishop Emeritus Desmond Tutu, and representatives of its sponsors from Norway, South Africa and US in May 2010 (http://www.nersc.no/sites/www.nersc.no/files/NTC-Joint-Venture-Agreement.pdf). To launch the scientific activities of the Nansen-Tutu Centre, a Scientific Symposium was held at the Westin Grand Arabella Quays in Cape Town on 7-9 December 2010. This volume provides a record of the proceedings of that symposium.

The Nansen-Tutu Centre is established in order to serve Africa through advancing knowledge of the marine environment and climate system in the spirit of Nobel Peace Laureates Desmond Tutu and Fridtjof Nansen. Its overall goal is "To improve the capacity to observe, understand and predict marine ecosystem variability on timescales from days to decades in support of scientific and societal needs including fisheries, coastal management, maritime security, recreation and tourism". To this end, one of the core activities at the Centre will focus on education and exchange of young researchers and students from different cultures and countries through the Nansen-Tutu Scholarship Program.

The Nansen-Tutu Centre is a member of the Nansen Group which consist of Nansen Centers in Bergen, Norway – St. Petersburg, Russia – Cochin, India and Beijing, China, lead by Prof. Ola M. Johannessen.

The approach adopted by the Nansen-Tutu Centre is to develop and implement state-of-the-art ocean observing and modelling systems related to the unique position of South Africa at the meeting place of the cool Benguela Current adjacent to the warm Agulhas Current, and close proximity to the Southern Ocean. The focus is to study the variability of these current and ocean systems on a variety of time-scales in relation to their mutual local and regional interaction with the atmosphere and land, rainfall patterns, and other weather patterns vital to society. In developing and implementing the technology and expertise to observe and model ocean and climate variability, the skills needed in southern Africa will be updated and expanded through priority research and development activities.

The programme of the Symposium and titles of presentations give a good idea of the broad range of

interests and challenges covered by the Nansen-Tutu Centre. They range from technical descriptions of global ocean modelling projects like MyOcean and Mercator, to ocean-atmosphere interactions, regional modelling, the effects of climate variability on biodiversity and fisheries, and descriptions of the Benguela Current, Agulhas Current, and Southern Ocean Ecosystems and their productivity. In addition technical topics concerning new methods of making routine in situ observations, satellite remote sensing, database management and data assimilation into models were addressed. All in all these presentations lay the foundations for future research, technological development, training activities and capacity building by the Nansen-Tutu Centre. These are essential to develop a observing and forecasting system for the state of the oceans around southern Africa, in much the same way that we to day have routine access to weather reports and forecasts from the weather service.

John G Field

Chair Nansen-Tutu Centre

Ola M. Johannessen

Co-Chair Nansen-Tutu Centre

July 2011

Nansen-Tutu Centre Scientific Opening Symposium

Westin Grand Cape Town, Arabella Quays, Cape Town, South Africa 7-9 December 2010

Bjørn Backeberg, Steward Bernard, Johnny A. Johannessen and Frank Shillington

The Nansen-Tutu Centre scientific opening symposium was organized jointly with the OceanSAfrica: Operational Oceanography and High Performance Computing meeting hosted by the Centre for High Performance Computing in Cape Town, South Africa, from 7-9 December 2010. 90 scientists and technicians from South Africa, Mozambique, Norway, France and the UK attended. Capitalizing on the complementary overarching research and operational goals of the Nansen -Tutu Centre and OceanSAfrica the purpose of the symposium was to assess the capacity to observe, understand and predict the state of the marine environmental and ecosystem in southern Africa on a broad range of temporal and spatial scales. Following the opening session the symposium was broken into three key sessions:

Session 1: Nansen-Tutu Scientific Opening

This session targeted some of the priority research activities of the marine environment of the oceans around southern Africa including the Indian Ocean, the South Atlantic and the Southern Ocean with their distinct regional coastal marine systems, with the aim to outline outstanding research questions and in active open discussions formulate cohesive research challenges and scientific strategies.

Session 2: OceanSAfrica Operational Oceanography & High Performance Computing

The focus of this session was on developing the technical requirements and plans to fully utilize the parallel computing resources at the CHPC, the emerging Very Large Data Base capabilities needed to archive, interrogate, analyze, and visualize large volumes of geo-spatial data, and the resources to disseminate highly refined end products to a diverse user base.

Session 3: Student Posters

This session encouraged the students to present their research activities. A cash prize of R500 was awarded to the student with the best poster presentation.

Program Overview

Opening Session

Chair: Frank Shillington (UCT)

- Welcoming Address by *Ola M. Johannessen (NERSC) and John Field (MA-RE)*
- Overview of the Nansen-Tutu Centre for Marine Environmental Research by *Frank Shillington* (UCT) and Johnny A. Johannessen (NERSC)
- Overview of the OceanSAfrica Programme: Operational Oceanography in Southern Africa by Monde Mayekiso and Ashley Johnson (DEA)

Nansen-Tutu Scientific Opening Session 1

Chair: Johnny A. Johannessen

- Angola-Benguela Frontal Zone by *Mathieu Rouault (UCT)*
- Benguela Upwelling System by *Larry Hutchings (DEA)*
- The Dynamics of the Southern Ocean by *Isabelle Ansorge (UCT)*
- Biogeochemical Cycles in the Southern Ocean by *Pedro Monteiro (CSIR)*

Nansen-Tutu Scientific Opening Session 2

Chair: Einar Svendsen (IMR)/Chris Reason (UCT)

- The Greater Agulhas Region by *Pierrick Penven (IRD)*
- Managing the commons in Southern Africa with applications in the marine environment by *Frank Matose (UCT)*
- Challenges related to ecosystem-based research and management by *Einar Svendsen*
- New gravity field and dynamic topography observations from space by *Johnny A. Johannessen* (NERSC)
- Climate Effects on Biodiversity, Abundance and Distribution of Marine Organisms in the Benguela Region by *Hans Verheye (NansClim)*
- Marine Sciences and Development Challenges by *Antonio M. Hoquane (UEM)*
- Special Invited Presentation on the Arctic Climate by *Ola M. Johannessen (NERSC)*

OceanSAfrica Session 1

Chair: Neville Sweijd (CSIR)

- Operational Modelling: The SimOcean project by Jennifer Veitch (UCT / NTC)
 and Roy van Ballegooyen (CSIR)
- Capabilities and challenges of data assimilation by *Laurent Bertino (NERSC)*
- Operational Earth Observation: The Marine Remote Sensing Unit by *Christo Whittle (UCT)*
- Operational In Situ Ocean Observations by *Mike Roberts (DEA) and Johan Stander (SAWS)*

OceanSAfrica Session 2

Chair: Ashley Johnson (DEA)/Geoff Brundrit (DEA)

- Operational Data Archiving & Dissemination: SAEON by *Wim Hugo (SAEON)*
- OceanSAfrica & the VLDB (Very Large Data Base): Setting the scene for discussions to follow by Stewart Bernard (CSIR)
- MyOcean: technical aspect of operational oceanography by *Eric Dombrowsky (Mercator)*
- Data access and visualisation systems by *Mike Grant (PML)*

Student Poster Session

- The Ocean Surface Layer at high resolution: Satellite observations and ocean-wavesatmosphere coupled dynamics by *Nicolas Rascle*.
- Tropical Temperate Toughs over southern Africa by Neil Hart.
- Southern Ocean chlorophyll in reference to ocean fronts and mesoscale variability by Sebastiaan Swart.
- Developing a climatology of Mesoscale Convective Systems over South Africa by *Ross Blamey*.
- Hydrographic and satellite observations in the Delagoa Bight, southern Mozambique by *Tarron Lamont*.
- Temporal variability of primary production in the Benguela and Agulhas ecosystems by *Ray Barlow*.
- Measuring Phytoplankton Flatulence; VHOCs in the Southern African Marine Troposphere by *Brett Kuyper*.
- Evaluation of the modified advection scheme recently implemented in ROMS, in the waters of

- the Mozambique Channel by Issufo Halo.
- Meso-scale structuring of the pelagic ecosystem in the Mozambique channel: a modelling approach by *Yonss Jose*.
- Hydrodynamics circulation at the Quirimbas's Archipelago region by *Yonss Jose*.
- Can altimetry data be used to predict phytoplankton and zooplankton biomass associated with mesoscale eddies in the Mozambique Channel? by *Jenny Hugget*.
- Zooplankton and ichthyoplankton spatial distributions associated with a dipole eddy system in the western Mozambique Channel by *Jenny Hugget*.
- Can an oceanic gateway alter the evolutionary trajectory of inshore fish species in the Benguela region? by *Kate Munnik*.
- A Primary Validation of MERIS Case 2 Ocean Colour Products in the Natal Bight, South Africa by Marie Smith.
- Numerical modelling of the Southern Ocean mixed layer by *Nicolette Chang*.

Organizing Committee

Tracy Cadle (Event Manager – Walthers DMC South Africa), Jeff Chen (CHPC), Bjørn Backeberg (NTC), Steward Bernard (CSIR), Frank Shillington (UCT), Johnny A. Johannessen (NERSC), John Field (MARE/UCT), Ola M. Johannessen (NERSC), Chris Reason (UCT), Neville Sweijd (CSIR), Einar Svendsen (IMR), Peter M. Haugan (UiB)

List of Proceedings Papers

- 1. Ocean atmosphere interactions in and around Southern Africa by *Mathieu Rouault*.
- 2. The Benguela Current Region: Research and Modelling Suggestions and Issues by *Larry Hutchings* and Astrid Jarre.
- 3. Ocean modelling in the Agulhas Current System by Pierrick Penven, S. Herbette, and M. Rouault.
- 4. New gravity field, mean dynamic topography and surface geostrophic current derived from space by *Johnny A. Johannessen*, *Bertrand Chapron and Bjørn Backeberg*.
- 5. Climate effects on biodiversity, abundance and distribution of marine organisms an overview of the NansClim Project by *Hans M. Verheye and Harald Loeng*.

- 6. Marine sciences and development challenges in Mozambique by *Antonio Mubango Hoguane*.
- 7. SimOcean: Simulating and forecasting Southern Africa's Ocean by *Jennifer Veitch and Bjorn Backeberg*
- 8. High resolution and multi-disciplinary coastal system modelling to meet stakeholder needs by *R. C.* van Ballegooyen, *G. Diedericks*, *M.Rossouw*, *A. Meyer*, *L. Terblanche and P. de Wet*.
- 9. Challenges and capabilities of data assimilation by *Laurent Bertino*.
- 10. The grand challenge of developing in situ observational oceanography in South Africa by *Michael Roberts*, *Andre Share Ashley Johnson*, *Geoff Brundrit*, *Juliet Hermes*, *Tommy Bornman Isabelle Ansorge*, *Johan Stander*, *David Vousden*, *Henry Valentine and Marius Rossouw*.
- 11. OceanSAfrica Data Archiving and Dissemination by Wim Hugo and Wayne Goschen.
- 12. MyOcean: Technical aspects of operational oceanography by *Eric Dombrowsky*.

OCEAN ATMOSPHERE INTERACTIONS IN AND AROUND SOUTHERN AFRICA

Mathieu Rouault(12)

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1 Introduction

Over the last century, Southern Africa has suffered from dramatic interannual variability in climate leading to severe droughts, increased occurrence of floods or disturbance in the marine or terrestrial ecosystems. Such variability of climate affects the agricultural industry, water reserves, fisheries and thus the Gross National Product. It has a particularly detrimental effect on rural subsistence farmers and fishermen, the health of people in rural areas and the management of a sustainable natural environment. Such natural hardship hamper the accomplishment of the Millennium Development Goals defined at the Johannesburg Millenium Summit in September 2000. The Millennium Development Goals are quantified targets for addressing extreme poverty, hunger, disease, lack of adequate shelter, and exclusion while promoting gender equality, education, and environmental sustainability. They are also basic human rights, the rights of each person on the planet to health, education, shelter, and security. During the last decades much has been gained on how the oceans can influence the climate of Southern Africa at the interannual and also decadal time scales. This indicates that the future climate of Southern Africa is likely to be influenced by the future state of the oceans under natural and anthropogenic forcing.

2 Ocean atmosphere interactions

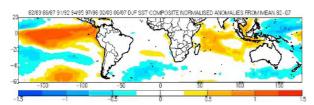


Figure 1: Global sea surface temperature composite seasonal standardized anomalies during mature phase of El Nino in austral summer (anomaly from the mean of December to February divided by climatological corresponding standard deviation for 7 El Nino events) for the period 1982-2007. Blue/green is colder than normal; yellow/red is warmer than normal.

The most severe droughts are happening in Southern Africa during the mature phase of El Niño (Rouault et al, 2005), when the central and eastern Pacific and the

Indian Ocean are warmer than normal (Figure 1 and 2). El Nino and La Nina have also an impact on streamflows, vegetation and the fluxes of nutrients into the ocean as well as the wind field along the coast.

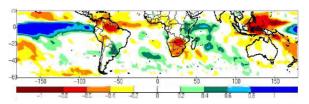


Figure 2: Global rainfall composite seasonal standardized anomalies during mature phase of El Nino in austral summer (anomaly from the mean of December to February divided by climatological corresponding standard deviation for 7 El Nino events) for the period 1982-2007. Blue/green is wetter than normal; yellow/red is dryer than normal.

In the upwelling system of the West Coast of South Africa, the South Benguela, El Nino often triggers lower than normal wind, warmer SST and a weaker upwelling (Rouault et al, 2010). During La Nina the opposite occurs (Figure 3). There is no linear relationship between the strength of ENSO and the strength of the perturbation in Southern Africa climate.

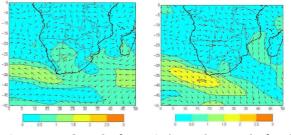


Figure 3: NCEP Surface wind speed anomaly for the mean for the average of 6 la Nina (left) and 6 El Nino event (right) events in austral summer. Stronger (weaker) than normal easterly and South easterly wind occurs during La Nina (El Nino).

Intense ocean atmosphere interactions occur in the Agulhas Current system. The Agulhas Current flows along the east coast of South Africa (Figure 4) before moving offshore near latitude 40°S and subsequently retroflecting back into the South West Indian Ocean. Source of the Agulhas Current includes large eddies originating in the Mozambique channel and the southern

branch of the East Madagascar Current and a recirculation of the Agulhas Current itself (Lutjeharms, 2006, Siedler et al, 2009). Figure 4, an image obtained using 4 × 4 km resolution Advanced Very High Resolution Radiometer (AVHRR) shows the 1985-2007 mean sea surface temperature (SST) around South Africa. The mean absolute geostrophic ocean current vector derived from merged altimetry is superimposed on the image, which shows the major elements of the Agulhas Current system. The main loop is found south of the continent. The Retroflection is located in the domain delimited by 10°E to 20°E and 37°S to 42°S. Eddies shed from the Agulhas Current can be found as far as latitude 50°S but most of them are usually formed in the Retroflection and move northwestwards towards Brazil. The Agulhas Return Current flows eastwards and meanders from 37°S to 42°S.

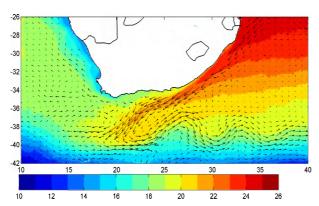


Fig. 4: Mean 1985-2007 AVHRR estimated SST and mean 1993-2007 absolute geostrophic velocity vectors derived from altimetry is superimposed.

High evaporation rates and associated turbulent latent and sensible heat fluxes occur above the Agulhas Current throughout the year due to an important sea surface temperature contrast between the Agulhas Current and its surroundings. Measurements in the Agulhas Current have shown substantial transfers of water vapour in the atmospheric marine boundary layer, a deepening of the marine boundary layer due to intense mixing and unstable surface atmospheric condition (Rouault et al, 1995, 2000). The intensity of mixing in the local boundary layer is such that cloud lines can often be observed above the current (Lee-Thorp et al, 1998). Rouault et al. (2002) have provided evidence of the influence of the Agulhas Current on the evolution of a severe convective storm over southern South Africa that almost killed President Nelson Mandela when a building he was visiting collapsed during a tornado associated with that storm.

3 Ocean climate change

Ocean's temperature has risen globally but not uniformly during the last 50 years (Hansen et al, 2010) due to the anthropogenic increase in CO2. information needs to be gained on how the main modes of climate variability and climate change interacts, there is also a serious need to improve our knowledge on how these large scale variations impact on smaller scales. Indeed these small scales are more relevant for ecosystems, water resources agriculture, fisheries and tourism. We must also keep in mind that the characterization of local impact of climate variability is essential to anticipate the impact of the future climate changes and the need to define adaptation strategies. Closer to Africa the Agulhas Current and the southern Boundary of the Benguela Current system, have significantly warmed up warmed up by up to 1.5 °C (Figure 5) since the 1980's. Rouault et al (2009) hypotheses that this warming was due to an intensification of the Agulhas Current system in response to an augmentation of wind stress curl in the South Indian Ocean due to an increase in trade wind and a shift in westerly wind at relevant latitude. A numerical model that was reproducing the observed sea surface temperature relatively well was used to derive quantities such as transport and fluxes of heat and salt. The model showed that the transport of the Agulhas Current system had increased since the 1980's leading to the observed warming.

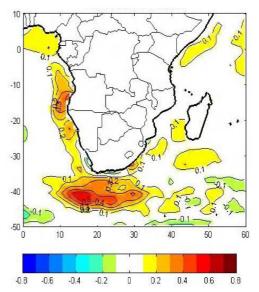


Figure 5: Linear trend of optimally interpolated Reynolds sea surface temperature in degree per decade estimated from merging satellite remote sensing and observation from 1982 to 2009.

A coastal cooling of lesser magnitude is also present in the observation but was not properly modelled. The cooling in the West of the country is present from Cape Agulhas to the Namibian border. All those changes seem to have been triggered by an intensification of the

high pressure system in the South Atlantic and South Indian Ocean and a polewards shift of the westerly wind system that could be anthropogenic in nature. The potential impact of the intensification of the Agulhas Current on the ecosystem has not yet been studied and provides a new paradigm to explain the observed changes in marine ecosystems. During the last few decades, important changes in the geographical distributions of marine resources have occurred in the Benguela Agulhas system. Sardine, anchovy, west coast rock lobster, mussels and horse mackerel have moved southwards and eastwards. In the 1980s and 1990s, anchovy and sardine were concentrated on the West Coast. However, in 1996, anchovy spawners shifted in distribution from the western Agulhas Bank to the central and eastern Agulhas Bank. By 1999, the proportion of sardine biomass located to the east of Cape Agulhas exceeded that on the west coast, and by 2004, sardine were found mainly in the east. Since the late 1980s, west coast rock lobsters have moved southwards into the kelp forests between Cape Hangklip and Danger Point while kelp has increased its habitat in False Bay where cold mussel species can now be found in greater numbers. Before the 1980s, west coast rock lobster were caught mostly on the west coast of South Africa but by the 1990s, more than 90% of West Coast rock lobster caught were on the south coast rather than in the west as had historically been the case. The change described in Rouault et al (2009, 2010) could explain the synchronicity in shifting distributions of marine ecosystems resources in the Southern Benguela.

4 Benguela Niños

Further north, along the west coast Namibia and Angola waters have also considerably warmed up (Figure 4) especially off Angola. Such warming seems to be due to an increased poleward flow of low-nutrient, lowoxygen, warm tropical water well into the Benguela upwelling system that is found south of 17°S (Figure 5). Those regions are influenced by the variability of the Tropical Atlantic Ocean and warm events there are called Benguela Niños by analogy to the Peruvian El Nino (Shannon et al, 1987). In late austral summer, water temperatures up to 30 °C are found in the tropical South-East Atlantic off Angola. Warm coastal oceanic events off Angola have an important impact on coastal Namibian and Angolan rainfall (Rouault et al, 2003). The seasonal cycle dominates the variability in the tropical Atlantic, but equatorial wave dynamics, upper ocean advection, and anomalous surface heat fluxes can generate sea surface temperature (SST) and upper-ocean heat content anomalies that can persist for a few months. Such anomalies are large enough to generate regional atmospheric circulation and rainfall anomalies and to significantly impact on the marine ecosystem. An important climatic feature in the tropical South-East Atlantic is a sharp oceanic front, the Angola-Benguela Front, off the African coast at about 17 °S. $\xrightarrow{}$ 10 m/s

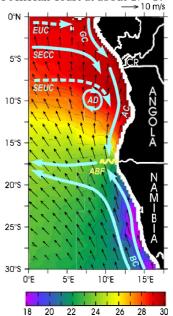


Figure 6: Schematic of the major oceanographic features in the Northern part of the Benguela Current system with mean March TRMM TMI sea surface temperature and QuikScat wind speed and direction. Maximum wind speed is 8 m/s in the south and minimum wind speed is 3 m/s north of the ABF.

Each year in late summer, warm water from the tropical South-East Atlantic penetrates southwards across the Front to about 25 °S and into the upwelling system of the Angola-Benguela Current system. The Benguela Niños usually occur in late austral summer and can last for several months Such events occurred in 1984 1995, 1996 and 2001 (Gammelsrod et al., 1999, Rouault et al, 2003, Ostrowski, 2009) and were linked to reduced trade winds along the Equator (Rouault et al, 2007, Lübbecke et al, 2010). These warm events had a strong impact on the ecosystem when low-oxygen, nutrient-poor tropical water was advected into the upwelling system.

5 Conclusions

The oceans have a profound influence on weather climate and ecosystems of South Africa. This offers predictability at the seasonal scale, for instance El Nino starts several months before it impacts South Africa. El Nino is usually associated with drought in Southern Africa during its mature phase. Likewise during La Nina, conditions are wetter than normal. Benguela Niños are triggered remotely a few months before they impact the Angola/Benguela upwelling system and coastal rainfall. The effect of the Agulhas Current on weather and ecosystem needs to be better ascertained. This is a real challenge for mesoscale models and

weather forecast that do not account very well for the intense turbulent sensible and latent heat fluxes and mixing in the marine boundary atmospheric layer. At last although we strive to improve forecast at all scales, real time monitoring based on in-situ observation, satellite remote sensing and models is readily available and offers valuable information.

Acknowledgements

Mathieu Rouault thanks ACCESS and Nansen-Tutu Centre for financial support.

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THE BENGUELA CURRENT REGION:

RESEARCH AND MODELLING SUGGESTIONS AND ISSUES

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INTRODUCTION

The Benguela upwelling region consists of a narrow ribbon-like feature of cool water extending from 17°S to 35°S, with distinct frontal boundaries between tropical and temperate habitats and a diffuse offshore boundary with the South Atlantic gyral circulation. It is characterised by high mesoscale variability with both remote and local forcing by winds, pressure gradients and atmospheric interactions. A combination of observations, experiments and modelling are needed to develop a proper understanding of the forcing functions driving the ecosystem physics and the responses of the biota under current and future scenarios of climate variability. Three major spatial scales need to be addressed: the ocean basin, the continental shelf and finally embayments and estuaries, while temporal scales from days to decades are of relevance for the dominant planktonic and freeswimming (nektonic) organisms.

Large scale forcing in the Benguela is driven by interactions between the oceanic high pressure zones in the South Atlantic and Indian Oceans, the Inter-tropical convergence zone and the westerlies to the south (Figure 1). We focus here on the zone of strong upwelling winds from 17-35°S. While the southern boundary over the Agulhas Bank displays different physics to the wind-driven west coast, the biological components migrate on to the Agulhas Bank as part of their life history and their distribution extends up to the Port Elizabeth/East London area at 26-28°E, where upwelling is induced by the Agulhas Current diverging from the coast. Major features of the Benguela upwelling region include:

 Upwelling-favourable winds peak at three particular locations at 17°, 27° and 33°S, with notable

- interannual variability, unlinked between the northern and southern Benguela (Fig. 2a).
- Phytoplankton is abundant on the northern Namibian and Namaqua (west coast of South Africa north of Cape Columbine) shelves, particularly in St Helena Bay (Fig. 2b). It is strongly seasonal and in opposite phase at the northern and southern boundaries and moderate interannual variability occurs, with few obvious trends.
- Beneath warm surface water off Angola and over the Agulhas Bank, there is moderate to high phytoplankton productivity, underestimated by satellite imagery but built into productivity models using chlorophyll profiles through the water column.
- Fish catches have varied widely in the northern and southern Benguela over the past 60 years, with some dominant species replacements, driven by fishing pressure and environmental forcing. Sardines were replaced by horse mackerel in the Northern Benguela catches, while sardines and anchovy have dominated alternatively and then simultaneously in the south. Hake have remained dominant in the demersal fisheries in the whole Benguela but have altered yields substantially following heavy fishing pressure. Rock lobster have been in long-term decline.

Aspects articulated in the Nansen-Tutu background documents for detailed study included Benguela Niños, frontal zone processes and mesoscale variability, Benguela upwelling, low oxygen and impacts on the ecosystem, ecosystem variability and fisheries, coastal trapped waves and the poleward undercurrent. Based on those interests, we will articulate a number of research issues which would benefit greatly from modelling approaches, which will allow us to deepen our understanding of the processes at work with realistic

simulation models and help us to predict changes in the ecosystem under scenarios of changed forcing.

THE NORTHERN BENGUELA

Dominant sources of variability include the Angola Current, the Angola-Benguela frontal region, the low oxygen water on the shelf and the Lüderitz and Cape Frio upwelling cells.

- 1. Benguela Niños. Not all Benguela warm water "Niño" events are the same! The roughly 10-year intervals between major events may have a tropical driving mechanism (wind forcing/Kelvin wave/coastally trapped wave) or may be related to changes in the S. Atlantic high pressure zone and decreased coastal pressure gradients and upwelling stress, as sometimes saline water and other times fresher water penetrates southwards into Namibia. Weaker events in the 1970's were not documented and in the 2000's were less extreme but more prolonged. What are the causal mechanisms for extreme intrusions? Modelling changes in the driving forces and responses and comparing with observations may help to decide what combination of events leads to the development of warm water intrusions into the northern Benguela.
- 2. Low oxygen water. A complex interaction of poleward undercurrent, upwelling strength and timing at Cape Frio and Lüderitz, water column stratification and organic loading produce low oxygen water on the Namibian shelf. Can a model reproduce the observed conditions in the northern Benguela and are low oxygen water events likely to alter with a future warming scenario?
- 3. Sardine reproduction and recruitment. When sardines were dominant in the 1970's, they spawned over a wide extent of shelf, up to 70 to 90 nautical miles offshore and many eggs may have been lost beyond the shelf. With a greatly reduced distribution, limited to small isolated pockets close inshore, but still within the same latitudinal range, advection is no longer a problem. So what limits sardine reproductive success? Is it high mortality of sardine eggs and larvae due to predation by jellyfish or horse mackerel, competition with horse mackerel, gobies or jellyfish, starvation in the nearshore zone or fishing (directly and bycatch) relatively heavily on a small spawning population?
- 4. Maintenance of plankton in the shelf region. The cross-shelf and longshore distribution of euphausiids has been described in relation to cross-shelf circulation

patterns. Can coupled biophysical models simulate the distribution patterns for selected copepod and euphausiid species realistically? How will these alter with belt-type (northern Namibia) and point-source (Lüderitz) upwelling patterns?

5. Shelf circulation comparisons with other upwelling systems. Retention mechanisms of plankton in the productive part of the Benguela involve longshore trajectories of plankton in the Benguela, with cross-shelf circulation patterns, poleward flows, vertical migration and sinking. The Humboldt Current is characterised by longshore countercurrents, the California Current has recirculating filaments, the Canary Current ecosystem has a wider shelf than the Benguela system, with inner and outer recirculation cells. How much of the organic production of the Benguela is exported from the shelf region? How do circumpolar organisms maintain high population numbers? How do the retention mechanisms for plankton in the major upwelling systems differ?

THE LÜDERITZ-ORANGE RIVER CONE BOUNDARY AREA.

This area forms a distinct boundary region between the northern and southern regions of the Benguela and it is a semi-porous boundary region, in that several planktonic and demersal organisms persist on both sides while several pelagic species appear as independent populations to the north and south.

- 6. Convergent flow off Lüderitz. This area is apparently a region of convergent flow in the upper 1000m, with some indication of a recirculation feature, which may allow organic material from two productive shelf systems to recirculate and provide a rich feeding area for mesopelagics and hake. Is this likely to be a persistent feature now and in the future?
- 7. The Lüderitz barrier. The Lüderitz upwelling cell poses a strong barrier for pelagic fish but not for demersal or deeper water species. However, anecdotal evidence suggests that under some circumstances anchovy may penetrate into southern and central Namibia and return southwards. Under which conditions is the barrier porous?
- 8. The deepwater hake nursery. Circulation models of the west coast circulation need to be combined with behavioural studies of hake larvae and juveniles. What hydrographic conditions favour the retention and

settlement of deep water hake juveniles in the Orange River cone area?

The next two issues are not strictly linked to the Lüderitz area but its dynamics provide an integral part of the problem.

- 9. Transport of heat and salt through the South Atlantic. A small flow which rapidly transports warm salty Agulhas water towards the Equator may provide an alternative flow path to the larger but much slower transport involved with dissipation of Agulhas eddies in the SE Atlantic. What are the relative magnitudes of the two pathways and is it changing with changes in the Agulhas Current, wind speeds and retroflection area?
- 10. Biogeochemical models of the flux of carbon on the Benguela shelf are only starting to be developed, despite carbon-rich sediments on the shelf. Is the Benguela a source or a sink for CO₂, and what are the major fluxes between the shelf, sediments, water column and atmosphere under a changing wind regime?

THE SOUTHERN BENGUELA

Separated from the northern Benguela by the Lüderitz frontal region, the southern region is dominated by wind driven pulsed upwelling in summer, with a strong frontal boundary and associated jet currents between the inshore upwelled water and warmer offshore waters. Leakage of water of Agulhas origin into the west coast shelf region is important ecologically. The fish spawn in the southern parts and eggs and larvae are transported to the productive nursery grounds, where juveniles feed and grow before migrating southwards as they achieve adulthood.

- 11. Low oxygen water off the Namaqua shelf. The most extensive and minimal distributions of low oxygen water in the inner shelf off South Africa vary dramatically in extent; Can we explain the changes in the extent and intensity of hypoxic water in the southern Benguela in terms of upwelling, productivity and sedimentation? Is there a component of advection from the northern Benguela?
- 13. St Helena Bay. This is the most productive and best studied region in the Benguela, yet its retention time, overall productivity and circulation need to be evaluated in terms of upwelling, stratification, flushing rates, retention times and growth rates of phytoplankton,

harmful algal blooms, low oxygen water, zooplankton maintenance and pelagic fish foraging. What changes can we expect from variability in source water nutrient concentrations, upwelling rates and changes in forage fish biomass and species composition?

- 14. Plankton-fish links. Foraging fish schools of anchovy, sardine, re-eye and horse mackerel recruits move southwards as a "river" of recruits, encountering patchy zooplankton food organisms and acquiring energy reserves for the spawning migration back to the Agulhas Bank. Will changes in the upwelling intensity or patterning alter the growth rates and subsequent recruitment of pelagic fish?
- 15. The anchovy comundrum. Juvenile fish are faced with a dilemma: should they grow in length to escape predators, or fatten up energy reserves for food patchiness and migration? What is the optimal strategy under changing circumstances?
- 16. Pathways to the west coast: Larvae transported to the west coast in the jet current must use selected behavioural responses to increase the probability of reaching the productive nearshore nursery area. How do prerecruits get inshore efficiently? Is slow and convoluted transport in the jet current, with retention in eddies or rings, better for survivorship than fast and far transport alongshore? How much will the transport mechanism change with increased Agulhas Current flow and SE winds, which change the temperature gradients across the front?

THE AGULHAS BANK

This "biological extension" of the west coast system is a complex, productive habitat with a mixture of temperate seasonal cycle and upwelling patterns and numerous ways in which enrichment can occur. It can support up to 12 million tons of forage fish, with the peak biomass having occurred in 2001-2003. There are several enrichment processes where modelling may help to evaluate the relative importance of the different mechanisms:

18. Importance of seasonality. The seasonal cycle involves summer heating of surface waters and intrusions of cold water from below and shipboard measurements are limited to the spring (Oct/Nov) stratification and Autumn (May/June) breakdown periods, not the summer stratified or winter well-mixed periods. The winter period may be the limiting time in terms of plankton

productivity to support the forage fish populations, which is why the reproductive strategy involves the winter recruitment in the west coast nursery grounds, rather than on the Agulhas Bank. What is the seasonal primary productivity of the Agulhas Bank and is there likely to be food limitation for pelagic fish in winter? Is there likely to be climate-induced changes in seasonality on the Agulhas Bank?

- 19. The role of stratification. A time series in midsummer indicates the combined effects of periodic strong winds which erode the thermocline, internal waves, deepening of the thermocline and the diffusion of nutrients through an intense thermocline. Shallow thermocline areas characterise certain parts of the Bank. How will future changes in these patterns in future climate change scenarios affect productivity? Are these shallow thermocline areas likely to change in spatial extent and alter the availability of nutrients to phytoplankton in the upper mixed layer?
- 20. Primary production. Near-surface phytoplankton peaks in the nearshore, the cool ridge, shelf edge eddies and the Agulhas divergence areas. Primary productivity, is estimated from surface chlorophyll measurements and modelled based on (biased) observations of light penetration and typical chlorophyll profiles, collected mostly from November and May pelagic fish surveys. Can we improve the model estimates of water column productivity based on seasonal changes?
- 21. The cool ridge. This prominent yet not permanent feature of the Agulhas Bank has a strong influence on plankton and fish distributions. It is a largely subsurface feature which has interactions both with coastal upwelling and the presence of the Agulhas Current as it curves through the Agulhas Bight off the central Bank. It is closely linked to copepod stage distibution for at least the generation time of the dominant copepod of 15-30 days and pelagic fish spawning "on the edge" between the cool ridge and the Agulhas Current. What are the driving forces which control the intensity and extent of the cool ridge feature and what are the implications for plankton and pelagic fish?
- 22. The eastward shift. Both sardine and anchovy undertook a large scale shift east in recent years (and a return movement recently). What is the relative role of fishing pressure versus environmental forcing in determining the distribution of spawning fish?

- 23. Distributional shifts in anchovy. A relationship exists between the inshore-offshore thermal gradient on the central Bank and the interannual distribution of anchovy. There may be some link between hydrography and zooplankton food on the western and central Bank. How do anchovy anticipate this gradient when migrating across the Bank from the west?
- 24. Transport to and migration from the west coast. The strong physical links between spawning products and their passive transport from the Agulhas Bank to the west coast nursery grounds contrast with the strong biological interactions of survivorship, growth, mortality and migration from the west coast back to the Agulhas Bank, tanked up with energy reserves. What are the major determinants of "success" and how is this likely to change in the long-term?

INTEGRATIVE MODELS

Many of the processes sketched in the above points are relevant for the design and parameterisation of ecosystem models. A particular strength of this class of models is their ability to highlight differences and similarities between different systems, thereby facilitating comparison. They also allow toaddress effects of climate and anthropogenic forcing simultaneously, which can make them suitable as tools to provide scientific advice under an ecosystem approach to management.

Whereas Ecopath with Ecosim ("EwE") models have been established for all major offshore subsystems of the Benguela region, other ecosystem modelling approaches have focussed on the southern Benguela. These include OSMOSE (also coupled with ROMS), Atlantis and frame-based models. All existing models need refinement and exercising, and their relative strengths and weaknesses with respect to the questions asked to them still need to be understood in more detail. Links between different modelling approaches need to be explored, and established where appropriate.

Our understanding of the dynamics of the socialecological systems in the Benguela region is only in its infancy. As for models of the natural systems alone, we expect modelling to be helpful to sharpen our thinking and help with predictions of possible ramifications of global change.

CONCLUSIONS

The research issues and problems in the Benguela region outlined above, on a wide range of spatial and temporal scales, will benefit from adopting modelling approaches, integrating physics, biogeochemistry, biology and ecology. They are in line with GLOBEC suggestions and gaps and IMBER initiatives. Addressing these requires a whole range of modelling approaches, some of which are already underway in the region. There is plenty of room for new initiatives particularly in view of the scarcity of skilled modellers in the region. These, however, need to

tie in carefully with existing collaboration regionally, and with various bilateral and international research projects. As such, these initiatives will provide a valuable training ground to enhance modelling skills in southern Africa. Results of carefully designed and well implemented models will have practical value to management agencies as they shift from single species approaches to ecosystem-based management. Addressing the questions posed in this contribution will also help to keep both field researchers and modellers in touch with reality.

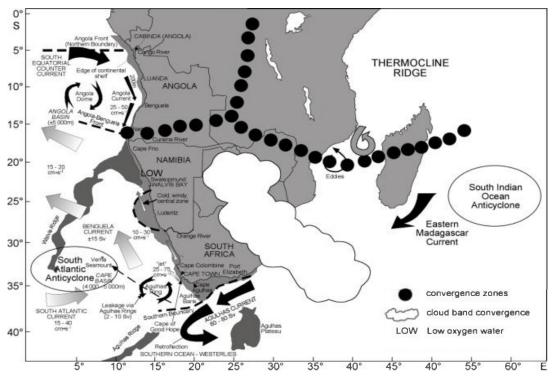


Figure. 1. Large scale features of the Benguela. Adopted from Hutchings et al. 2009, Prog. Oceanogr. 83 15-32.

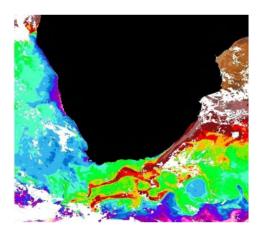


Figure 2a. Thermal image of the Benguela.

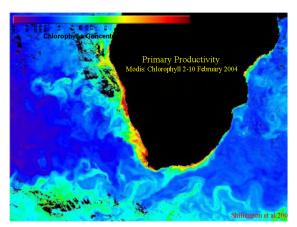


Figure 2b. Productivity image of the Bengula.

OCEAN MODELLING IN THE AGULHAS CURRENT SYSTEM

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ABSTRACT

Ocean models have now reached a sufficient precision to reproduce key elements of the Agulhas Current system, such as the Agulhas Retroflection and the Agulhas Rings shedding. Nevertheless, there are still recurrent biases which are not yet totally understood. Two model solutions show different results for the processes controlling the Agulhas Leakage. Idealized numerical experiments for the subtropical gyre of the Indian Ocean are then conducted to explore the Agulhas Current / Agulhas Leakage relationship. These experiments reproduce the general patterns of the Agulhas Current System and a strong mesoscale variability. For these simulations, the Agulhas Current increases with the wind forcing, and the Agulhas Leakage increases quasi-monotonically with the Agulhas Current.

Key words: Agulhas Current; Agulhas Rings; Agulhas Leakage; numerical models.

1. INTRODUCTION

The Agulhas Current is the western boundary current of the South Indian Ocean subtropical gyre (Lutjeharms, 2006). It takes its sources in the Mozambique Channel and south of Madagascar and flows along the Southeastern coasts of Africa. It transports about 70 Sv towards the south in a narrow band of about 50 km with velocities often above 2 m s $^{-1}$ (Lutjeharms, 2006).

A characteristic of the Agulhas Current is the presence of a retroflection at the South of the African continent, where the flow turns back on itself to return in the Indian Ocean (Lutjeharms and van Ballegooyen, 1988). Levels of eddy turbulence in the Agulhas Retroflection region are among the largest of the world Oceans (Ducet et al., 2000; Gordon, 2003). A recent analysis of subsurface floats and drifters trajectories suggests that at least 15 Sv of the incoming Agulhas Current water spreads into the South Atlantic (mostly in the forms of large anticyclonic eddies: the Agulhas Rings) (Richardson, 2007).

This leakage of Agulhas Current waters into the Atlantic Ocean induces a buoyancy flux which could be critical for the global overturning circulation of the Ocean (Gordon, 1986; de Ruijter et al., 1999; Weijer et al., 1999; Biastoch et al., 2008).

This global effect has been recently confirmed by paleooceanographic studies which have shown that most severe glacial periods are marked by reductions in Agulhas Leakage (Bard and Rickaby, 2009; Zahn, 2009), while sharp increases in Agulhas Leakage are observed at the end of ice ages, causing a rapid return towards interglacials (Peeters et al., 2004). This shows that on top of direct effects on local climate in Southern Africa (Reason, 2001; Rouault et al., 2002), the Agulhas Current could be a key element for the global Earth climate system

The Agulhas Current compensates an equatorward flow forced by a homogeneous positive wind stress curl over the South Indian Ocean. However, the dynamics of the region is complicated by several other elements:

- 1. The South Indian Ocean is not closed and the Agulhas Current is part of a Southern Hemisphere Supergyre, which connects the Pacific, Indian and Atlantic Oceans via the Indonesian Througflow, the Southern Ocean and the Agulhas Leakage (de Ruijter et al., 1999).
- 2. Due to the presence of Madagascar, the flow in the Mozambique Channel is dominated by eddies which propagate in the Agulhas region and affect the retroflection process (Schouten et al., 2002; Penven et al., 2006c).
- 3. Natal pulses, large meanders in the Agulhas Current travel sporadically along the Agulhas Current (de Ruijter et al., 1999; Rouault and Penven, 2011).
- 4. At the southern tip of Africa, the Agulhas Current looses the continent before reaching the latitude of 0 wind stress curl. The current detachment and subsequent Agulhas Retroflection are associated with large inertia (Ou and de Ruijter, 1986) and current

/ topography interactions (Lutjeharms and van Ballegooyen, 1984; Matano, 1996).

5. The levels of eddy energy associated with the Agulhas Retroflection, and the Agulhas rings are the highest in the world (Ducet et al., 2000; Gordon, 2003).

Because of these factors, modelling the Agulhas Current system is still a difficult exercise.

2. NUMERICAL MODELS OF THE AGULHAS CURRENT SYSTEM

The Agulhas Current has been successfully simulated, from its sources to the spawning of Agulhas Rings, using specifically designed regional models as well as global ocean models. In the early days of primitive equations ocean models, Boudra and Chassignet (1988) were able to produce an idealized simulation of the wind driven gyre of the South Indian Ocean at 20 km resolution. They were able to produce a retroflecting Agulhas Current and the generation of Agulhas Rings.

Agulhas Retroflection and Agulhas Rings were also reproduced in the Fine Resolution Antarctic Model (FRAM) (Lutjeharms and Webb, 1995). This first realistic simulation of the Agulhas Current system presents a behavior seen later on in several other models: a mean Retroflection position eastward (upstream) of the observed pattern, and Agulhas Rings following a straight route into the South Atlantic Ocean (Barnier et al., 2006). A similar bias has been noticed in several other model simulations: in global models at 1/10° resolution (POP and OFES) (Maltrud and McClean, 2005; Sasaki et al., 2005), in global models at 1/4° resolution (DRAKKAR and OCCAM) (Barnier et al., 2006, see figure their 12), in a Atlantic model at 1/6° resolution (CLIPPER) (Barnier et al., 2006), and in a regional model at 1/10° resolution (HYCOM) (Backeberg et al., 2009). In global models at 1/16° and 1/32° resolutions such as NLOM a similar pattern with spurious high variability upstream of the Agulhas Retroflection is still present (Wallcraft et al., 2002, see figure their 2). Such upstream variability was also found in a regional model at 1/4° resolution (SAfE) (Penven et al., 2006a). To the exception of the regional models of Biastoch and Krauß (1999); Biastoch et al. (2008) and de Miranda A. et al. (1999), almost all realistic models have encountered an equivalent bias in their representation of the Agulhas Retroflection dynamics. This bias has been reduced (or even removed) by improving the numerical precision (Backeberg et al., 2009) or the conservation properties (Barnier et al., 2006) of the momentum advection scheme, or by smoothing the topography and adding a parameterization for horizontal viscosity (Penven et al., 2006a). Nevertheless, there is not at this time a definite answer on why this type of bias occur, and if it is possible to systematically prevent it. Such recurrent biases in model simulations of the Agulhas Current system emphasize the need for a better understanding of the system.

3. MODELLING THE AGULHAS LEAKAGE

Two model simulations have suggested that the Agulhas Leakage has increased in the last decades with possible important climatic implications (Biastoch et al., 2009; Rouault et al., 2009). Although both studies agree in relating this increase to changes in winds over the Indian Ocean, there is a debate over the process involved. van Sebille et al. (2009) (and also Biastoch et al. (2009) hypotheses) imply an anticorrelation between the Agulhas Leakage and the Agulhas Current transport. In Rouault et al. (2009) simulation, an increased Agulhas Current induces an increased Agulhas Leakage. It occurs in conjunction with a warming at the surface of the Ocean, in agreement with observations. This illustrates the need of a better knowledge of the relationship between the Agulhas Current and the Agulhas Leakage.

A set of idealized numerical experiments based on ROMS (Shchepetkin and McWilliams, 2005) has been specifically designed to explore this relationship. The model generates a subtropical gyre interacting with a topographical feature representing the African continent (Figure 1). The gyre is forced by an analytical wind and a restoring towards surface temperature and surface salinity, all 3 varying only with latitude (Figure 1). After a spinup of 20 years using a basin scale model alone, a 2-way nested grid based on AGRIF (Penven et al., 2006b; Debreu et al., 2011) at 1/9° resolution is introduced (see Figure 1), and the simulation is run for 10 more years.

Although based on simplified geometry and surface forcing, this simulation is able to reproduce the general Agulhas Current properties, such as eddy kinetic energy, mean transport and temperature. Figure 2 presents the modeled temperature after 30 years at sea surface (Figure 2a) and at 500 m depth (Figure2b). For such an idealized model, the comparison with World Ocean Atlas climatology is notable, indicating that the key processes are reproduced. A characteristic is a high mesoscale variability, showing a spectral peak at 43 days (i.e. 8-9/year) for the Agulhas Leakage. This corresponds approximately to the frequency of Agulhas Rings generation (de Ruijter et al., 1999).

To test the sensitivity of the Agulhas Current and the Agulhas Leakage to wind strength, 20 experiments are run with a wind multiplied by a coefficient ranging from 0.1 to 2. The leakage is measured as the westward flux at the southern tip of Africa of a passive tracer restored toward 1 in the Indian Ocean (East of 40°E), and toward 0 in the Atlantic Ocean (West of 5°E). Statistics are made using the last 8 years of each simulation. At equilibrium, the mean Agulhas transport increases linearly with the wind, following approximately the Sverdrup relation. Figure 3 presents the mean Agulhas Leakage as a function of the mean Agulhas transport using 8 years (blue) and 1 year (red) of simulation to compute the averages. These simulations produce an Agulhas Leakage larger than generally observed. The model values obtained by van Sebille et al. (2009) are added for comparison. Using 8 years averages, the Agulhas Leakage increases almost monotonically with the incoming Agulhas transport. For an Agulhas transport below 50 Sv, the slope of the curve is about 0.3, while it more than doubles to reach 0.8 above 50 Sv. There is indication of a slow down of the increase for the highest values. Using only 1 year averages, the perturbations induced by the mesoscale activity creates variations of large amplitude. These experiments present an example of a system where at statistical equilibrium, and in a closed domain, a stronger Agulhas Current could lead to more Agulhas leakage, in agreement with Rouault et al. (2009). The results obtained by van Sebille et al. (2009) are in the same order of magnitude, but the variations of Agulhas transports employed are too limited to derive general conclusions (Figure 3).

4. CONCLUSION

Ocean models have now reached a sufficient precision to reproduce key elements of the Agulhas Current system, such as the Agulhas Retroflection and the Agulhas Rings shedding. Nevertheless, there are still recurrent biases which are not yet totally understood. Two model solutions show different results for the processes controlling the Agulhas Leakage. Specific idealized numerical experiments for the subtropical gyre of the Indian Ocean are conducted to explore the processes controling the Agulhas Leakage. These simulations reproduce the general patterns of the Agulhas Current System and a strong mesoscale variability. For these simulations, the Agulhas Current increases with the wind forcing, and the Agulhas Leakage increases quasi-monotonically with the Agulhas Current. A detailed analysis of these experiments will be made to address the processes associated with the variations of the Agulhas Current and Agulhas Leakage. This idealized model configuration will be also used to test new hypotheses for past and future climate.

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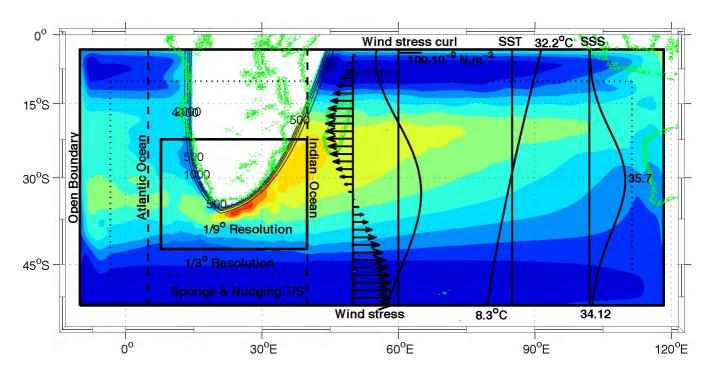


Figure 1. Model grid, bottom topography, surface forcing (wind stress, wind stress curl, sea surface temperature and sea surface salinity) and mean sea surface elevation (1 contour / 10 cm)

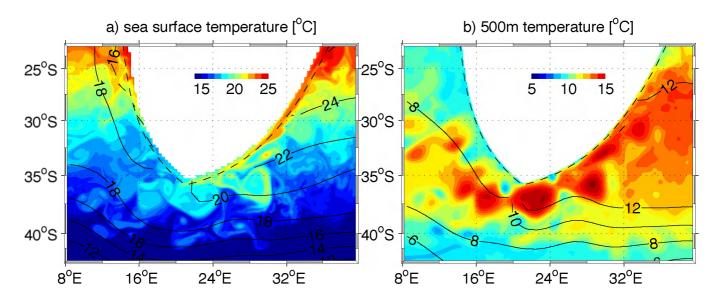


Figure 2. Model temperature for 1 January of year 30 at sea surface (a) and at 500 m depth (b). The contours represents the annual mean from World Ocean Atlas 2005 climatology.

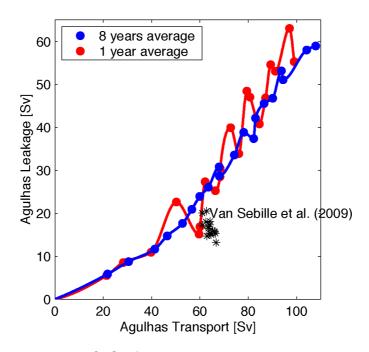


Figure 3. mean Agulhas leakage [$1Sv = 10^6 \text{ m}^3.\text{s}^{-1}$] as a function of the incoming mean Agulhas Current transport [Sv]. Blue: statistics made using 8 years of experiment. Red: statistics made using 1 year of experiment. Stars: results obtained by van Sebille et al. (2009).

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NEW GRAVITY FIELD, MEAN DYNAMIC TOPOGRAPHY AND SURFACE GEOSTROPHIC CURRENT DERIVED FROM SPACE

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1. Introduction

The European Space Agency (ESA) Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission was successfully launched in October 2009 (http://www.esa.int/esaLP/LPgoce.html). GOCE is dedicated to measuring the Earth's gravity field and the geoid with unprecedented accuracy (gravity: ~1-2 mgal; geoid: ~1-2 cm) at a spatial resolution of ~100 km. This will, in turn, advance the quantitative understanding of global and regional ocean circulation (Johannessen et al., 2003). GOCE will also make significant advances in the fields of solid Earth physics, geodesy and surveying. The first GOCE gravity field and geoid model was presented at ESA's Living Planet Symposium in Bergen, Norway, in June-July 2010 (see Figure 1).

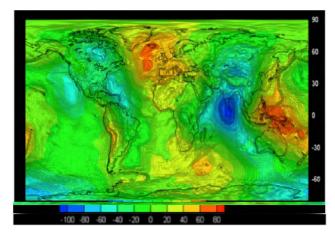


Figure 1. Global geoid map based on 2 months of data. The colour bar is in unit of meters (Courtesy R. Rummel and ESA).

This pure GOCE derived geoid, which can be considered as the surface of an ideal global ocean at rest, is based only on 2 months of data integration, and shows distinct structures deviating up to +/- 100 m from the uniform sphere, including the depression of about 100 m in the Indian Ocean as well as highs of about 60-80 m in the North-East Atlantic and in the West Equatorial Pacific. By combining the new GOCE geoid model with satellite altimetry measured sea surface height, the mean dynamic topography (MDT) is derived from the difference between the geoid height and the

sea-surface height, when both heights are related to the same reference ellipsoid (see Figure 2). This topographic surface is revealing more precise insight into the intense global current regimes such as the Gulf Stream, the Kuroshio in the north Pacific, the Agulhas Current along the South-Eastern coast of Africa and the Antarctic Circumpolar Current in the Southern Ocean. Emerging new applications for studies of the ocean circulation in the high latitude and Arctic Ocean is also expected from these new GOCE based observations.

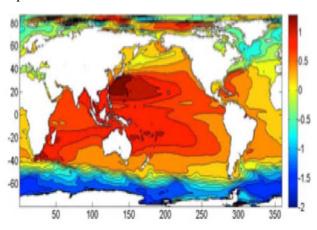


Figure 2. Preliminary GOCE derived mean dynamic topography at a spatial resolution of about 250 km based on the gravity field shown in Figure 1. The colour bar is in units of meter and reveals the presence of the main global and basin scale current regimes directed along the isolines of constant topography such as the predominantly eastward flowing Antarctic Circumpolar Current (Courtesy R. Rummel and ESA)

2. GOCE Mean Dynamic Topography

For almost 20 years, regular and accurate measurements of the sea surface height relative to a reference ellipsoid have been routinely obtained by satellite altimeter missions, such as TOPEX/POSEIDON (Fu et al., 2001; Shum et al., 2011). Today the mean sea surface (MSS) derived from altimetry is known with centimetre accuracy (Cazenave et al., 2009). But, until recently the lack of an accurate geoid has prevented precise computation of the ocean's geostrophic circulation from satellite

altimetry at a resolution of 100 - 500 km (Knudsen et al., 2007; Bingham and Haines, 2006; Bingham et al., 2008).

The basic definition of the MDT is simply the difference between the mean sea surface height (MSS) and the constant geopotential reference surface called the geoid (G) (see schematic illustration in Figure 3). Through the assumption of geostrophic balance, the ocean's mean surface circulation is then closely related to the ocean's MDT. As such the MDT may thus be considered as a streamfunction for the mean ocean surface circulation, whereby the large scale ocean surface currents flow along the lines of equal dynamic topography. In the northern hemisphere, the flow is clockwise around the topographic highs. In the southern hemisphere, the flow is counter-clockwise.

Various methods have been used to calculate the MDT from in situ ocean data. The most straightforward of these uses climatology of temperature and salinity, based on measurement profiles obtained over many decades (Levitus and Boyer, 1994; Levitus et al. 1994), to compute dynamic height relative to an assumed level of no motion (e.g. Siegismund et al., 2007). An alternative method uses an inverse model with certain dynamical constraints to get the barotropic signal (LeGrand et al., 2003). Neither method, however, can represent a uniform time average due to the inhomogeneity of hydrography data. Niiler et al. (2003) have derived a MDT from a 10-year set of nearsurface drifter velocities corrected for temporal bias using altimeter data. Rio and Hernandez (2004) presented a most sophisticated blending of ocean observations to produce an MDT without the use of a model. Recently Maximenko et al (2010) improved the MDT by adding Argo floats and GRACE data, in combination with hydrographic and surface drifter data integrated over 17 years from 1992 to 2009.

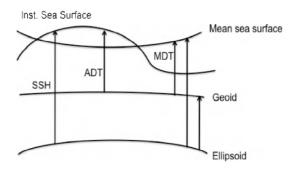


Figure 3. Schematic illustration of the instantaneous sea surface, the mean dynamic topography (MDT=MSS-G), the mean sea surface, the geoid and the reference ellipsoid.

During the last few years the knowledge of the marine geoid has drastically improved thanks to satellite gravity measurements from GRACE (Maximenko et al., 2009) and GOCE (Knudsen et al., 2011; Rummel personal communication, ESA website, http://www.esa.int/esaLP/SEMCJOSRJHG LPgoce 0.html). In turn, the mean dynamic topography (MDT) can now be gradually determined with new and unprecedented accuracy of ~1-2 cm at ~100-200 km spatial resolution.

The magnitude of MDT variations is typically about two orders of magnitude smaller than those of the geoid and the MSS (e.g. around 2-3 meters), which makes the computation of the MDT and the handling of errors challenging (Hughes and Bingham, 2008). It is easy to fail to exploit all of the useful geoid accuracy when calculating the MDT because of the need to obtain a smooth solution. The separation of the MDT from the MSS and the geoid may be carried in different ways, and each methodology contain assumptions where care is needed as addressed by Benveniste et al., (2007). Note that both the methods and the corresponding processing tools used to derive the GOCE MDT are available at the dedicated ESA GUT toolbox website http://earth.esa.int/gut/.

Intercomparison of the preliminary GOCE derived MDT to existing MDTs are very promising (Rummel, personal communication), in particular with respect to the large basin scale structures. However, also some of the sharper topographic features associated with the stronger surface current regimes such as for instance the Gulf Stream, Kuroshio Current, the Agulhas Current and the Antarctic Circumpolar Current are clearly better detected with GOCE (Rummel, personal communication; Knudsen et al., (2011)). In summary the large scale structures and slopes of the MDT (see Figure 2), derived from only 2 months of GOCE data, smoothed to about 250 km and then interpolated to a grid of 0.5 * 0.5 degrees, are clearly in consistence with the major and strong global surface current regimes. The corresponding reconstruction of the major global current regime from this MDT is expected to reveal more distinct features than the CLS-based field (AVISO, 2009) shown in Figure 4.

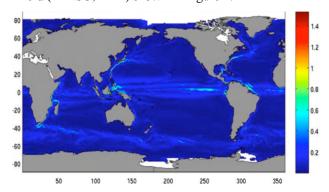


Figure 4. Global map of ocean surface circulation derived from CLS MDT. (Courtesy AVISO, 2009).

The interesting question is how the gradients within these fields sharpen up further when the next expected release of the GOCE based geoid and MDT takes place in spring 2011. This will, for instance, ensure better opportunities for assessing the geoid and MDT associated with the greater Agulhas Current regime.

3. Regional MDT in the Agulhas Current

The Agulhas Current is one of the strongest western boundary currents in the world's oceans. It plays a significant role for the Indo-Atlantic inter-ocean exchange and global thermohaline circulation (Lutjeharms, 2006). Using in-situ current meter measurements, Bryden et al. (2005) calculated the average poleward volume transport of the Agulhas Current (from 5 March - 27 November 1995) to be about 70 +/- 22 Sv (1 Sv = $10^6 \text{ m}^3 \text{ s}^{-1}$). However, routine measurements of the seasonal to interannual current and transport variability of the greater Agulhas Current regime is rare and not adequate to quantify the synoptic spatial structure of the core of the Agulhas Current and the variability in the retroflection region partitioned between the eddy shedding into the South Atlantic Ocean and the Agulhas Return Current. Consequently, we lack the capacity to do comprehensive validations of ocean models for this important region. This will likely change when the high quality GOCE derived MDT becomes available in the 2011 and 2012 time frame.

To illustrate this further we here inter-compare the mean surface geostrophic velocity with a spatial resolution varying from 25 to 50 km derived from three independent sources. These are the HYCOM ocean model (Backeberg et al. (2009), the CLS09 field (AVISO, 2009) and the fully independent range Doppler velocity derived from Envisat ASAR (Rouault et al., 2010). Maps of the corresponding velocity fields are shown in Figure 5. Overall the velocity patterns are similar with the strongest maxima in the Agulhas Current core and with more moderate maxima in the Agulhas Return Current. The best agreement is clearly depicted between the CLS and ASAR mean velocity fields, showing a distinct 100 km wide Agulhas Current with a surface current speed reaching up to 1.4 m/s towards southwest. The topographic steering by the continental shelf break is clearly evident, but appears slightly less distinct for the HYCOM model that also protrudes further westward in the retroflection region than is evident in the CLS and ASAR surface velocity maps. Moreover, the patterns in the Agulhas Return Current in the latter two maps appear less continuous and more meandering with comparable maxima of around 0.5-0.6 m/s.

In order to provide reliable estimates of the fluxes of water and heat associated with the eddy shedding from

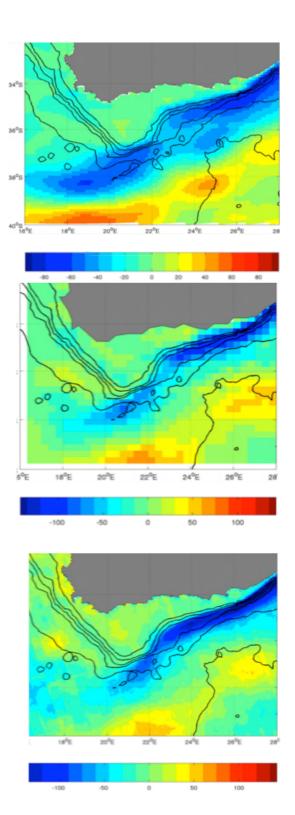


Figure 5. Independent maps of mean surface velocity derived from the HYCOM model (top), the CLS09 dynamic topography field (middle) and the ASAR range Doppler method (bottom). The integration period is from 2007-2009 for HYCOM and ASAR and from 1993-2009 for CLS09. The colour bar indicates the strength of the velocity fields in units of cm/s.

the retroflection region into the South Atlantic Ocean it is highly necessary to ensure accurate quantification of the mean and time varying volume transports in the greater Agulhas Current regime. This will require very precise knowledge of the MDT. As stated GOCE is expected to deliver a final geoid to an accuracy of ~1-2 cm over a spatial distance of 100 km. This is not sufficient to resolve the spatial structure of the MDT across the Agulhas Current. However, when properly validated at this 100 km scale it will become an excellent MDT for constraining and validating other model- and in-situ based MDTs at comparable resolution. Moreover, it will also strengthen the reliable reconstruction of the mean and time varying 2 dimensional surface geostrophic velocity fields at finer scales of about 25 - 50 km when combined with the model and range Doppler based fields shown in Figure

4. Summary

The global ocean circulation can be classified according to characteristic scales, e.g. (i) the slowly varying basin scale mean gyre circulation at spatial scales of order 1000 km; and (ii) the more dynamic mesoscale currents (e.g. ocean eddies that acts as the weather in the ocean) centered at scales of order 100 km. Although these basin and mesoscale circulation regimes are fairly well precise quantitative estimates corresponding volume and heat transports are more rare. In this context the new detailed and accurate picture of the geoid and mean dynamic topography, now emerging from the GRACE and GOCE gravity satellites, will greatly improve this deficiency, as a new scheme for regular determination of the absolute ocean current at scales of 100-200 km will be derived.

For intense surface currents like the greater Agulhas Current regime, for instance, this validated mean topography and subsequent geostrophic current will be further combined with direct range Doppler velocity retrievals from SAR, in-situ drifter data and Argo floats as well as model based fields with spatial resolution down to 10 km. It is therefore expected that studies of the mesoscale thermodynamic properties of the greater Agulhas Current regime will advance regarding both transport calculations of heat and volume, and partition into the mean and the eddy kinetic energy. Eventually the GOCE based MDT will also reach systematic use in assimilation systems http://www.myocean.eu.rog) as discussed by Haines et al., (2011).

Acknowledgement. We grateful to M.-H. Rio and the French Space Agency CNES which gave us access to the CNES-CLS09 Mean Dynamic Topography computed in the framework of the SLOOP project.

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CLIMATE EFFECTS ON BIODIVERSITY, ABUNDANCE AND DISTRIBUTION OF MARINE ORGANISMS – AN OVERVIEW OF THE NansClim PROJECT

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Climate change is defined as a long-term trend in development anthropogenic climate due to influences. In addition, there is natural variability at seasonal, interannual, decadal and multi-decadal scales. There has been a general warming of a large part of the world oceans during the past 50 years [1] and while there are regional differences, in southern Africa a long-term increase of 0.25°C in sea surface temperature has been observed during the last four decades [2]. A recent report from the World Bank states that "overfishing plus climate change means severe depletion of the world's fishery resources, with about half of current gross revenues predicted to be lost under severe climate change scenarios" [3]. The report further states that "adapting fisheries to climate change will not be cheap, especially for developing countries, many of whom lack adaptive capacity".

The NansClim Project (Climate effects on biodiversity, abundance and distribution of marine organisms) is therefore timely. Its primary goal and objectives are to identify, describe and clarify possible trends and variability in ocean climate and corresponding changes in marine biodiversity and fisheries that have been observed in the Benguela Current ecosystem over the past decades.

The project focuses on analysis and dissemination of oceanographic biodiversity data collected in the region through the Nansen Programme surveys combined with other relevant data collected and made available primarily by local national research institutions in the region. This will allow scientists to predict general responses in respect of production and distribution of marine biota in order to set a baseline of observed effects of climate variability. As such, the objectives of NansClim subscribe to the vision of the recently launched Nansen-Tutu Centre for Marine Environmental Research, which is "... to serve Africa through advancing the knowledge of the marine

environment and climate system by improving the capacity to observe, understand and predict the variability of the marine ecosystem on time scales from days to decades".

Forecasting regional climate change and detection of its effects on marine biodiversity in the Benguela Current system have in the past been a key objective of two regional research and capacity building programmes, BENEFIT (Benguela Environment Fisheries Interaction and Training [4]), initiated in 1997 and BCLME (Benguela Current Large Marine Ecosystem [5]), initiated in 2003; both came to an end in 2007. A natural extension of these programmes was the establishment in 2008 of the Benguela Current Commission (BCC), a multisectoral initiative by Angola, Namibia and South Africa to promote integrated management, sustainable development and protection of the environment using an ecosystem approach to ocean governance. Studies of climate effects on the Benguela ecosystem form a major component of the Science Plan of the BCC, as well as that of the newly formed Branch: Oceans and Coasts of the national Department of Environmental Affairs in South Africa.

The project is further closely linked to, and complements the ongoing EAF Nansen Programme, which was implemented by FAO and has a component related to developing indicators of ecosystem change, albeit based on reviews and desktop studies of existing knowledge. In addition, NansClim complements ongoing research on ecosystem change conducted by the EAF Group of the Marine Research Institute of the University of Cape Town, and will benefit from close cooperation with NansClim in terms of data sharing and joint analysis.

The expected outcomes of the NansClim Project are:

- A coordinated database system for physical and biological data;
- Suggestions for marine Ecosystem Indicators;
- A better understanding of the effects of climate change and variability on the marine ecosystem in the Benguela Current region;
- Possible implications of climate change on fisheries and other marine activities;
- Future scenarios of climate effects on marine resources;
- Strengthened regional cooperation;
- Regional competence building on ecosystem effects of climate change;
- Increased public awareness of climate change in relation to fisheries and the marine environment.

The NansClim Project comprises four Modules, through which the project's objectives will be achieved:

- Module 1: Coordination of the Nansen database and other regional data;
- Module 2: Climate variability and climate impact on the marine ecosystem;
- Module 3: Gaps in our knowledge and research needs to address them;
- Module 4: Project management.

Activities of Module 1 are focused on two main tasks; firstly, on the selection and collation of data gathered during surveys onboard the RV *Dr. Fridtjof Nansen* during the Nansen Programme (1985 onward), and secondly, on the linking of this Nansen database to supplementary data. The latter have been collected during a myriad of surveys conducted primarily by the fisheries research agencies of the governments of Angola, Namibia and South Africa, as well as regional (BCC) and international partners working in the region (e.g. GENUS). Only timeseries of quality-controlled data that are relevant in a climate-change context will be considered. They include satellite data and *in situ* data on meteorology, physical, chemical and biological oceanography,

crustaceans and fish, and some of these time-series go back in time to the early and mid 1900s.

There are three tasks addressing the objectives of Module 2, viz. (i) Climate Variability and Change, (ii) Responses of the Pelagic Ecosystem to Climate Change, and (iii) Climate Effects on the Biodiversity of the Demersal Community. Each of these tasks aims at answering a set of specific key questions. The Task Group on 'Climate Variability and Change' aims to identify climate events that have been observed and might have an impact on the marine ecosystem. In order to separate short-term events from long-term trends over the past 50-100 years, a combined time-series analysis approach of fine-scale temporal resolution satellite imagery (to detect trends) and coarser-scale in situ environmental data (to detect events and serve as ground-truthing) will be adopted. Analyses will be done for representative sub-regions of the Benguela ecosystem. The focus is on temporal changes in water mass structure, water column stratification and stability, and concentration of dissolved oxygen, as well as variations in intensity, timing and duration of primary physical forcings, including coastal upwelling and remotely forced poleward water intrusions of Angola Current origin.

The Task Group on 'Responses of the Pelagic Ecosystem to Climate Change' aims to investigate major trends in the biomass and certain population parameters of key pelagic species — including phytoplankton, zooplankton, jellyfish, small pelagic fish, mesopelagic fish, and their predators — and whether these trends are related to climate change indicators. Major distributional shifts of populations will also be examined. Moreover, changes in the location and extent of areas that are critical in the life cycle of species, such as spawning and nursery areas, and their likely causes will be investigated. Finally, direct and indirect impacts of climate on pelagic species will be identified.

In principle, the aims of the Task Group on 'Climate Effects on the Biodiversity of the Demersal Community' are formulated along the same lines, however with a focus on the demersal species assemblages (including fish, crustaceans and cephalopods) where latitude, depth, temperature and dissolved oxygen may affect community structure and distributional shifts.

Following a comprehensive regional data audit, work is currently underway reconstructing up-to-date multi-decadal time-series of environmental indicators and pelagic and demersal key indicator species, which will be analysed using an array of appropriate

statistical analysis and modelling tools; indicators related to distribution and behaviour of species are also being developed. As a result from these analyses, a list of environmental and biological indicators for climate change will be assembled.

While it is recognized that presently only some qualitative answers can be provided to questions regarding climate change, it is appreciated that it is unlikely to account for non-linear effects or multispecies interactions. As a consequence, reliable quantitative information on the response of the Benguela ecosystem to climate change is lacking. A key challenge for the project will therefore be to conduct a comprehensive gaps analysis of knowledge gained during the first part of the project and to suggest research needs and actions to fill these gaps, which forms the object of Module 3.

Project management falls under Module 4. NansClim is a partnership of the Instituto Nacional Investigação Pesqueira (INIP) of the Ministério das Pescas of Angola, the National Marine Information and Research Centre (NatMIRC) of the Ministry of Fisheries and Marine Resources of Namibia, the Branch: Oceans and Coasts of the Department of Environmental Affairs (DEA) and the Fisheries Branch of the Department of Agriculture, Forestry and Fisheries (DAFF) of South Africa, and the Institute of Marine Research (IMR) of Norway, who is also the project's executing agency. The project is funded by Norad, the Norwegian Agency for Development Cooperation, with in-kind contributions from the governments of the three countries bordering the Benguela Current ecosystem.

The project is coordinated by the IMR, who also chairs the Project Management Committee (PMC), made up of two representatives from each of the partner countries and an observer from the BCC. The PMC is responsible for developing work plans and coherent budgets, monitoring progress, stimulate publication of results, organize meetings and workshops, and compile annual progress reports and financial statements. An Advisory Panel has been established to assist with the implementation of and act as supervisors to the project. They provide scientific guidance to the management team, assess the quality of reports and scientific papers that emanate from the project, and may participate in project meetings and contribute to scientific papers where appropriate.

The success of the project relies heavily on close collaboration between scientists from the four partner countries. Therefore, the project facilitates exchange of scientists between these countries to meet regularly in order to collaborate in regional workshops, symposia and the writing of publications. Provision is also made in the project's budget for regional competence building, at post-graduate levels (MSc and PhD), in respect of ecosystem effects of climate change.

Thus far, six workshops have been held in Norway and Namibia, addressing some of the tasks of Modules 1 and 2. A number of scientific papers are already in different stages of publication, and several have been presented and discussed at the project's mid-term progress meeting that was held in Stellenbosch, South Africa in March 2011.

Dissemination of results from the project to the scientific community, the governments of Angola, Namibia and South Africa, their environmental and fisheries managers, as well as fishing communities and the general public is regarded an important aspect of the NansClim Project. For instance, the project already enjoyed much exposure at various outreach activities that were organized at the occasion of World Ocean Day celebrations in Angola, Namibia and South Africa on 8 June 2010. Publications will include scientific articles in peer-reviewed journals, presentations at conferences and symposia, and in popular science magazines newspapers. To that extent, writing groups for each of the scientific tasks mentioned above have been established early in the project, securing momentum in the production of publications from the onset of the project.

The NansClim Project is planned to run for three years (end 2009-end 2012), after which it will be evaluated. It is expected that, through an assessment of the consolidated database (Module 1) and a gaps analysis (Module 3), new research priorities will emerge, which will not be possible to be addressed within this given timeframe. As a consequence, consideration of an extension of the project may be necessary. In addition, the possibility of extending the project to other regions where the Nansen Programme has operated should also not be discounted.

Acknowledgements

This summary is written on behalf of the entire NansClim Consortium with scientists from the Instituto Nacional Investigação Pesqueira (INIP) in Luanda, Angola, the National Marine Information and Research Centre (NatMIRC) in Swakopmund, Namibia, the Departments of Environmental Affairs

(DEA) and Agriculture, Forestry and Fisheries (DAFF) in Cape Town, South Africa, and the Institute of Marine Research (IMR) in Bergen, Norway. Funding from the Norwegian Agency for Development Cooperation (Norad) and in-kind contributions from the governments of Angola, Namibia and South Africa are gratefully acknowledged.

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MARINE SCIENCES AND DEVELOPMENT CHALLENGES IN MOZAMBIQUE

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ABSTRACT

The economy of Mozambique, like developing countries, is based on the exploitation of natural resources such as fish, timber and minerals. The sustainability of these resources is threatened by both natural and anthropogenic pressures, related to oceanic and atmospheric processes, and to population growth. This study examines the major driving forces to which marine and coastal resources are exposed and the role of operational oceanography in boosting the socio-economic development in a developing country. The major gap of knowledge to ensure sustainable use of marine and coastal resources is the lack of our understanding of the ecosystem structure and functioning. Operational oceanography contribute through data and predictive models that can support decision making for resource use and protection of the coastal habitats and associated resources. The Nansen-Tutu Centre, in particular, contribute in capacity building oceanographic and atmospheric data collection and modelling in the region.

1. INTRODUCTION

Mozambique is one of the poorest countries in the world despite its abundant resources. The actual Growth Domestic Product per capita USD428.00, meaning that a Mozambican lives with about one dollar a month [1]. The goods and services that can be provided trough marine and coastal ecosystems have great potential to reduce poverty and boost the economy of the country, if used in a sustainable manner. The goods include fisheries and mangrove timber, and the services include maritime transports and coastal tourism. The fisheries sector and tourism contributes with about 3% each, and the maritime transport contributes about 12-13% of the GDP, as per statistics of 2010. The estimated overall fish production is about 115,000 to 140,000 tones per

year, 87% of which is from artisanal fisheries, with an annual value of over USD 50 million [2], which emphasises the socio-economy importance of fisheries.

There is a need to ensure sustainable use of the resources in order to maintain sustainable development. The challenges for sustainable use of marine and coastal resources are made more difficult by increased pressure on the resources, due to population growth and market demand, and by lack of knowledge of the ecosystem structure and functioning, a key step towards the adoption of sustainable management measures.

Applied marine sciences, and in particular operational oceanography, could contribute to bridge the gap in knowledge required to support decision making with respect to resource use.

This study reviews the major environmental and socio-economic drivers of marine and coastal resource use, identifies the major knowledge gaps to ensure sustainable use of the marine and coastal resources and proposes some research directions for operational oceanography in a developing country.

2. COASTAL AND MARINE ENVIRONMENTAL ISSUES

The marine and coastal ecosystems in Mozambique are relatively well preserved compared to other countries in the region, probably due to the fact that the country is less developed. On the other hand the potential for degradation of those sites is higher and would increase in the future in the view of the current development. The ecosystems near high density cities and villages, such as Maputo Bay, Sofala Bank, Nacala Bay and Mozambique Island may be relatively seriously degraded whereas those in less densely populated areas are slightly degraded or remain in relatively pristine condition [3].

Based on GIWA (Global International Waters Assessment) methodology, four major issues of concern affecting coastal and marine environment in Mozambique were identified: (i) Modification of stream flow (abnormal river runoff, foods, draughts), (ii) Loss and modification of ecosystems and ecotones (erosion, depletion of mangroves, destruction of corals and seagrass beds), (iii) Overexploitation of fisheries resources (shrimp resources, demersal fisheries), and (iv) Destructive fishing practices (use of mosquito nets, dynamites, fish poisoning) [3].

3. DRIVERS OF COASTAL AND MARINE ENVIRONMENTAL ISSUES

The major drivers of coastal and marine environmental issues may be grouped into two categories: (i) those associated to natural processes and (ii) those driven by anthropogenic activities [4]. Fresh water shortage and/or abnormal floods associated to both climate processes (drought/floods) and human activity (effect of the dams, deviation of water for irrigation). Loss and modification of coastal ecosystems are due to both natural processes and human activity. Storms often cause the destruction of the coastal protection (erosion), corals and seagrass beds. Increased ocean temperatures over the last few decades have caused large scale coral bleaching. Destructive human activity in the coastal zone includes overexploitation, destruction of habitats (mangroves, vegetation over the coastal dunes, corals, seagrass beds, and others), including over-grazing and unsustainable tourism practices. Over-exploitation of the resources is primarily driven by subsistence needs and high income demand. Lack of adequate post-harvest fishing facilities (freezers, roads and easy transportation to the markets) leads to a devaluation of the fish products, resulting in ever more pressure on the resources. Use of destructive fishing practices is primarily driven by an inability to acquire adequate fishing equipment. Poor development of other sectors such as industry, agriculture and tourism leave fisheries as the option for subsistence of local preferable community, thus posing more pressure on the fisheries resources.

4. KNOWLEDGE GAPS

One of the major constraints for assuring sustainable use of the marine and coastal resources is the lack of our understanding of the ecosystem structure and functioning. We do not fully understand how most of the ecosystems function, what are the controlling factors, how each intervening factor contributes to the system, nor how the different factors are inter-related to one-another.

The ecosystems of major concern are those that sustain the resources providing nursery grounds, shelter and food to marine and terrestrial fauna such as coastal lagoons and embayments, estuaries, corals and coastal waters in general, and mangroves which provide timber, firewood and charcoal to coastal communities [3]. Therefore, emphasis is put on coastal ecosystems.

Major processes and factors affecting the coastal ecosystems, related to operational oceanography, that need to be better understood and monitored are those related to mixing between sea and coastal waters, flushing and export of the coastal water to the adjacent seas, heat and cooling.

The coastal hydrodynamics, which includes currents and tides, determines the mixing and controls the primary productivity and transport of nutrients. There is a need to model the coastal hydrodynamics which link the physical processes to productivity, in order to support decision making.

The river flow is particularly important for sustaining the ecosystems because they supply energy and nutrients to sustain the food chain in the ecosystems, provide a suitable environment for maintaining animal and plant populations through reproduction or regeneration, dispersal, migration of some species, provide a suitable environment for maintaining natural interactions between species such as predator-prey. There is a need for the development of hydrological models which integrate the downstream and coastal ecosystems.

Where the river meets the ocean a distinctive feature characterized by mixture of fresh and salt waters develops. The phenomenon is called ROFI (Region Of Freshwater Influence), where the most important feature is the density driven bottom current which causes silt, detritus and larvae to accumulate in the coastal zone and the actual import of nutrients from the adjoining estuaries and mangrove swamps [5]. Therefore, there is a need to

conduct research within and in the interfaces of rivers and estuaries and the ocean, in order to understand how these systems interact with each other and how they affect the productivity in the coastal water.

Waves and storm surges often cause flooding of coastal areas and the destruction of the coastal protection (erosion), corals and seagrass beds. The storms in Mozambique are related to tropical cyclones and could be predictable. There is a need to conduct research towards understanding the storm surges, waves and other weather factors that influence the coastal hydrodynamics and ecosystems.

5. THE ROLE OF OPERATIONAL OCEANOGRAPHY

Operational oceanography, as by GOOS definition, is primarily concerned with monitoring of the seas, oceans and atmospheric processes for rapid interpretation, dissemination and use [6]. One of the key products of operational oceanography is the forecast of the state of the sea. So, predictive models are one the major working tools of operational oceanography. In particular, the GOOS-Africa strategic plan puts emphasis on applied research to address the coastal issues aiming at assuring integrated coastal zone management, health and productivity of the marine and coastal ecosystems and protection of the coastal environment [7].

Considering the socio-economic issues and existing knowledge gaps, the priority activities for operational oceanography in Mozambique may be set as follows:

- Monitoring of oceanographic and atmospheric parameters along the Mozambique coast through a network of observing platforms.
- Development of coastal hydrodynamic and ecological models, both predictive and diagnostic models that would contribute toward the understanding of the governing factors, and support the decision making process.

- Collecting *in situ* data that would support the identification of new fisheries and sustainable exploitation of the traditional fisheries resources.
- Collecting in situ data that would support the identification of alternative livelihood, apart from fisheries, for the coastal communities.
- Collecting in situ data that would support the assessment of the potentials and perhaps the exploitation of the energy from the sea.
- Collecting *in situ* data that would support the development of coastal and offshore aquaculture.
- Collecting in situ data that would support the exploitation of mineral resources, with emphasis to oil, gas and sand.

The School of Marine and Coastal Sciences of the Eduardo Mondlane University, established in 2006, whose mission statement is to build capacity through teaching, applied research and extension work for sustainable exploitation of the marine and coastal resources for the benefit of the community and development of the country and the region, have been carrying out applied research and technological development towards addressing overfishing, destruction of habitats, aquaculture as a potential alternative source of income and source of animal protein, developing technology for harvesting solar, wind and tidal energies.

The Nansen-Tutu Center may contribute significantly in building capacity in the region, at the university departments and research institutes for ocean observing and modelling to meet the countries needs.

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SIMOCEAN: SIMULATING AND FORECASTING SOUTHERN AFRICA'S OCEAN

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ABSTRACT

SimOcean is a multi-institutional initiative¹ to develop ocean modelling and forecasting capacity in southern Africa. The modelling platform supports ocean research and operational activities, providing an arena in which modelling expertise, model output, and forecasts are shared. While the overarching goal of SimOcean is to develop ocean modelling capacity in South and eventually southern Africa, the first task of SimOcean is to form the modelling component of a recently initiated operational oceanography initiative, referred to as OceanSAfrica. SimOcean's contribution OceanSAfrica is to set up operational forecasts of the state of southern African oceans, on scales of ~9 km for regional domains and ~3 km for limited area domains. These forecast domains will facilitate downscaling to coastal and bay-scale domains [1], which will provide valuable products for nearshore stakeholders.

1. INTRODUCTION

Numerical modelling is an essential component of integrated ocean monitoring efforts, and is one of the most important tools helping oceanographers, marine biologists and coastal managers cope with the complexity of space and time scales that drive variability in the regional and coastal environments. The development of meaningful early warning and forecast systems requires that the physical processes of the system are thoroughly understood. In this regard, numerical modelling techniques can be invaluable and it is for this reason that the SimOcean initiative has been developed.

Ocean models can be complex or simple. Complex models generally aim to be as realistic as possible and therefore require detailed measurements to drive them, for example: accurate measurements of the sea floor variations, wind field and other atmospheric variables, river discharge rates, tides etc. A large volume of 'data' (computer output) is produced by complex models, which can be helpful in contextualizing spatial and temporal variations of oceanographic features. These

complex models can also be simplified to simulate the fluid dynamics in idealized scenarios that are specifically designed to understand theoretical processes that govern observed oceanographic features. The simplicity of such models allows for robust conclusions and is thus a powerful method of understanding ocean dynamics. Numerical models, both complex and simple, are invaluable tools for a greater understanding of ocean processes.

Over the last decade, ocean modelling capacity has developed significantly in southern Africa, both in simple and complex modelling techniques. SimOcean is a multi-institutional initiative whose aim is to establish a unified southern African ocean modelling working group. It is an arena in which local capacity and expertise in numerical ocean modelling, analyses and operational forecasting can be shared and developed. Within the framework of building capacity in ocean modelling, the SimOcean initiative supports both operational and research activities.

2. OPERATIONAL INITIATIVE

While the full scope of the SimOcean initiative will be to augment and develop numerical modelling capacity in southern Africa in general, both in research and operational capacities, the initial goal will be to set up an operational oceanographic system that delivers regular and consistent nowcasts and forecasts of the state of the ocean. As such, it forms the modelling pillar of the OceanSAfrica initiative (the other pillars being in observations. remote sensing dissemination), which is an integrated and multiinstitutional capability for marine observations and forecasts. It's vision is to "deliver regular systematic information on the state of the ocean that is of known quality and accuracy on open ocean to shelfscales via a combination of observations and modelling". In order to reach these objectives, the 4 pillars of OceanSAfrica need to closely co-ordinate their activities. Communication with users should be maintained throughout the planning, implementation, pre-operational and operational phases. Their feedback on the usefulness of the disseminated products is essential for validating the system and ensuring the sustainability of the system. Potential users include offshore industries, the navy, marine biologists, ecosystem modellers, marine resource managers, marine leisure activities.

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The development of an operational oceanography system is of key interest for the following purposes:

- (i) <u>Marine safety:</u> to improve the predictability of extreme events, such as cut off lows and mesoscale convective systems in the atmosphere; to monitor and predict the pathways and spreading of various tracers including toxic contaminants such as oil spills in the ocean; to support search and rescue of people and goods lost at sea.
- (ii) Marine and coastal environment: to provide rapid environmental assessment in order to monitor and mitigate against the effects of, for example, harmful algal bloom (HAB) and low oxygen water (LOW) events as well as large-scale, climate related changes in the oceans surrounding southern Africa.
- (iii) Marine resources: to provide support information for the offshore oil and gas industries, fisheries management and ecosystem characterization; to condition bio-geochemical modelling of ocean primary productivity.

The dissemination of ocean forecast products to users will also help to promote general interest in marine science and the state of the ocean, in much the same way that the weather forecast has popularized meteorology.

2.1. The two-phased modelling approach

The operational initiative of SimOcean follows a 2phased approach. The first phase (0-2 years) will use resources that are currently available in order to produce a marine forecast product and will serve as a demonstration, or 'proof of concept' project. It will downscale global ocean forecast products to higher resolution regional and limited area southern African domains and use global atmospheric forecast products as forcing (e.g. Fig. 1). As part of an assessment of the ocean model, a hindcast simulation will be run from as far back as the chosen wind forcing and lateral forcing products exist. This simulation will provide output that should prove useful to various fields of marine research. The second phase (2-5 years) will focus on system enhancements and improvements of the forecast system, the emphasis being on research and development. Improvements to the implementation and demonstration phase will include data assimilation, ocean-atmospheric coupling, wave coupling. The potential for additional enhancements is enormous and provides huge scope for interdisciplinary and multi-institutional collaboration.

Phase I

Phase I will focus on implementing, validating and disseminating data from an ocean forecast system. The aim is to provide unassimilated 5-7 day forecasts that are available for a wide variety of users by the end of

Phase I. In setting up a regional ocean modelling system for southern Africa we will adopt a downscaling introducing a series of nested downscaling from the global model to a regional high resolution model (~9 km) which will then provide boundary conditions for a very high resolution limited areas model (~3 km). However, the present computing hardware capacity in southern Africa is not enough to run a global model operationally. Therefore the boundary conditions for the regional model will obtained by collaborating closely with international institutes that produce global operational products. The global operational ocean forecast models used by MyOcean and the HYCOM (the Hybrid Coordinate Ocean Model) Consortium will be thoroughly evaluated and their viability for use as the lateral boundary conditions of the regional system will be assessed. Using the output from global operational systems to force the boundaries of southern African regional domains will forge and maintain useful international collaborations. The regional and limited area models will at first be implemented using the Regional Ocean Modelling System (ROMS; [2]), to be followed by implementation in HYCOM [3]. The benefit of using a multi-model approach is to make the most of the often separate strengths of different models. A long-term hindcast simulation will be run in order to verify that the chosen models (i.e. ROMS and HYCOM) are capable of reproducing all of the salient oceanographic features surrounding southern Africa. This validated hindcast simulation will provide valuable data for various studies, especially those with the aim of understanding oceanic variability around southern Africa. The development of the hindcast simulation will involve an in depth assessment and analysis of the extent to which the chosen models are able to reproduce salient features of southern African oceans, particularly the notoriously difficult to model, Agulhas retroflection. It is crucial that we are able to understand and simulate these dynamics properly in order to produce meaningful model forecasts of the region. The hindcast simulation will be forced by either NCEP (1°, 1948-present) or ERA Interim (1/4°, 1989-present) atmospheric products and its lateral boundaries will be forced by the SODA (0.4x0.25°, 1958-present) reanalysis products.

The ~9 km regional forecasts will encompass fairly large domains, either spanning the entire southern African region, or will be made up of two or three separate domains for the east, south and west coasts. This domain will be forced by a 15 km CCAM atmospheric forecast product produced by the CSIR (Willem Landman, *pers. comm.*) and by either the Mercator or HYCOM global forecast product at its lateral boundaries. Within this domain, higher resolution, limited area domains will be nested for regions of particular interest. A pilot site will be the St. Helena Bay region, that is an important nursery region

for fish and which is periodically subject to harmful algal blooms. For these reasons, it is also routinely monitored and therefore provides a good platform to implement and evaluate an integrated operational oceanography system.

Although the pilot study will focus on the west coast, its implementation will be generic and therefore applicable to any other region of interest. A validation procedure will be designed for hindcast, nowcast as well as forecast products in order to ensure that data of a known quality is supplied to users. In order to develop a robust validation system, it is essential that cooperative activities with the remote sensing and in situ observation pillars of the OceanSAfrica programme, as well as interaction with potential users, commence as soon as possible. An important aspect of developing operational modelling activities, is the routine and consistent dissemination of the forecast products. This will ensure visibility of the initiative, and hopefully attract users, developers and students to the project. Good communication with users, and incorporation of their feedback, is an essential component of developing useful ocean monitoring and forecast products. This will be addressed through outreach programmes such as user forums and workshops.

Phase II

In Phase II, the ocean forecast system, and its products, will be improved and expanded upon. The 5-7 day forecasts will continue to be made available, and in parallel, emphasis during Phase II is placed on system development and research. Enhancements of the forecast system include the implementation of data assimilation techniques, coupling of the ocean current models to atmospheric and ocean wave models, inclusion of additional high resolution nested models of, for example, the Mozambique Channel and the South African East Coast. Some of these additional research and development tasks will be structured into work packages and undertaken as MSc, PhD or Post-doc projects and upon completion, implemented in the operational system. In this manner local capacity in ocean modelling as well as operational implementation is developed, and concurrently the ocean forecast system is continuously improved and kept up to date with cutting edge developments. Data assimilation techniques improve model forecasts significantly and is thus a key component of the second phase of development. It will require very close collaboration with the in situ and remote sensing pillars of OceanSAfrica. In addition to enhancing the system an extensive data archive will be developed, including reanalysis data and the generation of long time series data from the model output. Following the successful implementation and enhancement of the ocean forecast system, to become fully operational and sustainable, it will need to be hosted by an operational institute such as

the Department of Environmental Affairs (Oceans and Coasts), the South African Weather Service (SAWS), or the Navy. Redundancy of the computer system is a major component of an operational ocean forecasting system and is done by duplicating the system, running it in parallel and archiving the data on an backup high performance computer.

3. SCOPE FOR RESEARCH

Locally, the importance of southern Africa oceans lies in its high productivity, particularly associated with the Benguela upwellling ecosystem on its west coast that sustains a successful fishing industry and supports local communities. On global and climate scales the leakage of the Agulhas Current into the Atlantic Ocean forms a key component of the global thermohaline circulation. The fact that southern Africa borders both a locally important eastern boundary upwelling ecosystem and a globally significant highly dynamic western boundary current system presents a unique natural laboratory, in terms of both ocean dynamics as well as biodiversity. As southern Africans, we are perfectly positioned to take advantage of the scientifically bountiful ocean at our shores.

While the initial goal of SimOcean is implementation of an operational ocean modelling system for southern Africa, intrinsic developmental process is the scope for research activities. For example, the archived data from the operational system as well as hindcast simulations could prove instrumental in contributing toward building an extensive oceanographic data-base that could support several research projects including the characterization and study of climate variability in southern Africa. Alternatively, specific problems or features identified in the ocean forecast system can be addressed in separate model simulations that require a more idealized and process-based modelling approach. The expertise that will develop from, and be attracted by, the operational modelling initiative will naturally increase local modelling capacity.

Research activities within SimOcean should be collaborative and inclusive in their approach in order to most efficiently make use of all resources. For instance, the ocean and atmosphere are coupled systems and therefore modellers of either of these systems would benefit significantly from close interaction with the other. Furthermore, the output from ocean models can be used to feed, for example, biogeochemical, sediment, ecosystem and wave models.

4. CONCLUSIONS

Coupled with the potential for invaluable observational

activities, an ocean modelling working group would identify southern Africa as a center of excellence in marine science with the potential to contribute significantly to global climate science. SimOcean aims to develop such a working group that will help to build local capacity and interest in ocean science via the development of a freely-available ocean forecast system (as part of the OceanSAfrica operational oceanography initiative), in parallel with ongoing research activities.

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ACKNOWLEDGEMENTS

We would like to thank Roy van Ballegooyen, Gerhardus Diedericks, Marius Rossouw and Alan Meyer from the CSIR for their contributions to the SimOcean initiative. The CHPC is also gratefully acknowledged for the use of their resources.

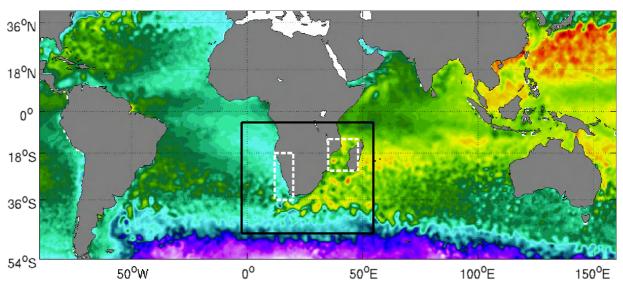


Figure 1: An example of the downscaling strategy, using the Global Mercator ¼ forecast product as the parent domain. The black rectangle represents the potential regional domain and the white dashed rectangles are examples of domains of potential limited area models.

HIGH RESOLUTION AND MULTI-DISCIPLINARY COASTAL SYSTEM MODELLING TO MEET STAKEHOLDER NEEDS

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ABSTRACT

Whilst global-scale operational oceanography products generally are widely available, more localised (regional and coastal) operational oceanography modelling and products to meet stakeholder needs remain less common. Arguably the most important scales to providing operational oceanographic support to stakeholders are at a coastal embayment scale and at higher resolutions surrounding activity hubs in coastal waters.

While customised operational oceanography support at these higher resolutions has been provided to the southern African community for quite some time, this support often has been adhoc.specific/customised and somewhat hindered by the lack of robust regional oceanographic and higher resolution atmospheric modelling outputs to support such Human capacity constraints and limited activities. availability of both funding and high performance computing facilities have also constituted significant constraints.

The present OceanSAfrica initiative plans to remedy this situation and create the necessary enabling environment to enable the setting up a "facility" that is able to provide consistent and reliable operational oceanographic support, particularly at more localised scales. This paper outlines present progress in doing so as well as future plans in this regard.

1. INTRODUCTION

Coastal systems are a critical component of earth systems in that they are the most densely populated areas of the world and provide ecosystem services of disproportionate value to their size (GDP from coastal provinces comprises roughly 40% of South African GDP [1]). These coastal systems display an inherent complexity in terms of synergistic and cumulative impacts associated with the exploitation of natural resources in this domain, the ecosystem services that they provide, and the social-ecological systems dependent on them.

Decision support required by stakeholders in this domain includes the assessment of future development options and the sustainability of ecosystem services from coastal systems, within the context of likely global change. On a more functional and immediate level, many stakeholders require operational oceanographic support to optimize their operations and to manage the risks associated with functioning in these marine environments.

To provide effective advice on both a strategic and operational level requires i) the development of an indepth understanding of how these complex systems function and how they respond to global change, and ii) the development of a robust predictive capability to inform both planning and operational decisions. The focus in this paper is on predictions in support of operational management of activities in these environments.

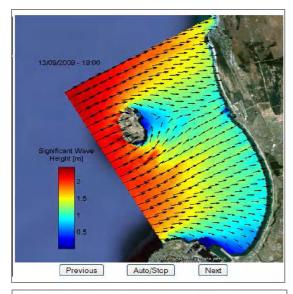
A particular challenge to providing operational advice at these scales is to "down-scale" global forecast products so that they have relevance at the local scale at which most operations happen within the marine environment (e.g. port operations, construction activities, salvage operations, etc). Depending on the type of operation, information requirements may demand that a more integrated view of these coastal systems be taken (e.g. predictions of changes in productivity and the occurrence of low oxygen events) that, in turn, require a multi-disciplinary modeling effort.

2. EXISTING CAPABILITIES

Modelling, forecasting activities and near real-time systems focused on providing operational support in Southern African coastal waters until now have focused primarily on:

- port operations and navigational safety;
- salvage operations,
- · construction activities; and
- mining operations.

Existing near real-time systems include the integrated port operations safety system (IPOSS) operated by the CSIR on behalf of the National Port Authority. This system provides real-time wind, wave and selected atmospheric data to the port authorities. The IPOSS network links all measurement sites to a central hub at the CSIR offices in Stellenbosch where the system is monitored to ensure its uninterrupted operation. The wave data from this system are available in near real-time, together with wave forecasts at selected sites (http://wavenet.csir.co.za). An example of the available forecast outputs are given in Fig. 1.



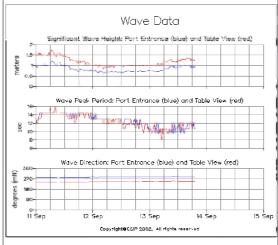


Figure 1: Information available from the CSIR WaveNet system.

More specific systems have been set-up in support of port operations. These include the D-Max system at Richards Bay that ensure loading operations that maintain adequate under keel clearances for vessels leaving the port. The strong cross-currents prevailing entrance to the Port of Durban resulted in a system being set-up to provide a real-time measurements of cross-currents in support of safe navigation of vessels entering and leaving the port.

A wave forecasting system has been operated by the CSIR in the recent past in support of West Coast mining operations. This formed part of an early warning system to ensure safety in term of the maintenance of seawalls protecting diamond mining operations. Similar forecasting services have been provided on an *ad-hoc* basis by the CSIR when requested to do so for marine construction activities (*i.e.* offshore pipelines) and salvage operations. In recent times, other service providers have become more prominent in providing these services.

In 2002 a pilot operational forecast hydrodynamic model was set-up in Saldanha Bay by the CSIR as an operational support demonstration project. This comprised a web-based system that allowed users to specify a simulation period and to specify potential spills or search and rescue scenarios (Fig. 2) during this period. Due to changes in hardware and software systems the site is not longer functional.

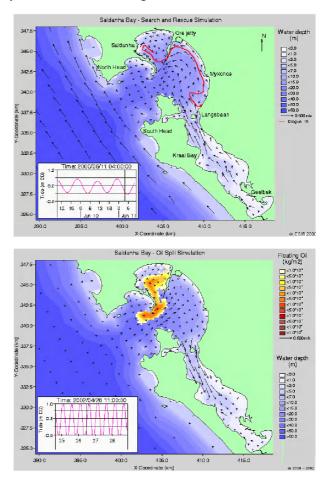


Figure 2: Outputs from the Saldanha Bay operational oceanography demonstration project for i) a simulated oil spill from the oil transfer operations and ii) a search and rescue operation.

Intermittent requests have been received for reconstructions of environmental conditions during marine incidents (collisions, groundings) to help decide liability claims. These reconstructions of environmental conditions prevailing during the incidents, although not operational in nature, require a detailed knowledge of waves, winds and currents at more localised scales and how they interact to create the hazardous conditions leading to these maritime incidents

All of the advice provided above requires an in-depth knowledge of coastal processes at these scales, an ability to predict environmental conditions of relevance and to provide integrated measures of risk.

While the operational oceanographic support described above was in response to a clearly articulated need by one or more stakeholders, operational oceanography has many more potential users interested both in i) risks posed by the marine environment on maritime operations and ii) the risks posed by maritime operations to the marine environment. The South African Navy, authorities and organisations mandated to undertake search and rescue activities and respond to oil spills, the construction industry and the insurance industry all have significant operational oceanography requirements. Often ignored are the public and small boat operators associated with fishing and tourism activities who could also benefit substantially from such information.

In addition to the above needs, there is also a call for seasonal forecasts at large-scales that assess risks associated with harmful algal blooms, low oxygen events, etc that constitute more systemic risks.

3. AN EARLY ATTEMPT AT DEVELOPING A REGIONAL OCEAN PREDICTION SYSTEM

It became clear over time that a more concerted effort was needed to provide an ocean predictions system that consistently provides accurate operational support for maritime and coastal operations. In late 2002 and early 2003, a consortium of local maritime research and educational institutes developed a proposal to implement a pilot regional ocean prediction system (ROPeS). This initiative was not successful at that time due both to a lack of funding but, more importantly, due to a lack of adequate human resources, computational facilities and operational measurement capabilities and associated data streams available to the project at that time. As a consequence, the consortium disbanded and the idea was shelved.

The CSIR did however continue to undertake a survey of stakeholders to determine what their requirements were in terms of operational oceanography and also undertook a technology review [2]. From the review it became clear that the resources available to develop such a system were simply too limited at that time. The stakeholder survey (exceeding 30 interviews) was focussed on potential funders of the proposed system, although others users were also polled to ascertain their particular needs. The stakeholders indicated that the systems had to be simple (with user-customised outputs), fast and reliable. These requirements were obvious, however, the degree to which these requirements would need to be met, was not. Most importantly, it was stated that the accuracy of the system had to be good enough for a stakeholder to consider changing business models and/or the way they handled operational risks, i.e. the threshold for acceptable accuracy is very high suggesting an especially onerous requirement in terms of the accuracy of any proposed system providing operational oceanographic support.

4. THE OCEANSAFRICA INITIATIVE

In the years that followed this early initiative, the human resource capacity and computational facilities, as well as the interest and networks to undertake operational oceanography improved considerably. So much so that, in June 2009, it was deemed timeous to hold a workshop¹ to re-launch such an operational oceanography initiative. At this meeting a steering committee and several sub-committees were set up pursue the development of a comprehensive national operational oceanography system. The sub-committees comprised observational, remote sensing, modelling and data dissemination groupings.

The modelling sub-committee went on to develop an implementation strategy and plan (the SimOcean initiative [3]) to develop modelling capacity in southern Africa to support both research and operational activities. The focus of this initiative is to create an "enabling" environment that supports both the marine research community and stakeholders interested in receiving operational oceanography advice. The system in principle is also intended to facilitate the development of operational products by service providers outside the consortium.

The plan in the SimOcean initiative is to develop regional and limited area models with the ultimate aim of assimilating observational data into these models operationally. Within this initiative, and dependant on the success of the regional and limited area modelling activities, is a plan to develop a modelling capability that provides operational oceanography support at more localised scales.

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Jointly initiated by the African Centre for Climate and Earth System Studies (ACCESS) and the former Marine and Coastal Management Division of the Department of Environmental Affairs and Tourism.

Three specific initiatives are planned at coastal embayment and higher resolution scales:

- The set-up of *pilot operational forecast models in two coastal (or more) coastal embayments.* The success of this initiative in dependent in the regional models being in place to provide open boundary conditions for these nested models and the existence of high resolution atmospheric model outputs to provide appropriate atmospheric forcing at these higher resolutions.
- Implementation of the WaveWatch model at a regional scale to provide the requisite fields for higher resolution wave forecasts in coastal systems and forcing inputs into the hydrodynamic models at coastal embayment and higher resolutions.
- Implementation of a pilot operational biogeochemical and primary productivity modelling system in Saldanha Bay where the model will be set-up to provide operational outputs at spatial and temporal scales of relevance to users of the bay (e.g. seasonal changes in primary productivity, indices of changes in sediment and water quality, etc).

5. PRESENT STATUS

Significant progress has been made in setting up a pilot operational coastal embayment modelling system in Algoa Bay. When an appropriate stage of development has been reached the results will be made available on the existing CSIR WaveNet site (http://wavenet.csir.co.za) and via a site supporting ecosystem-scale integrated coastal management on a coastal embayment scale (http://bavnet.csir.co.za).

The necessary forecast cycles and associated software and scripting has been developed, however a substantive further effort is required to improve the accuracy of the forecast system by including large-scale ocean influences in a more robust manner and to include high resolution atmospheric forcing (for which the forcing fields are not yet available). It is envisaged that a similar system will be available for Saldanha Bay by mid-2011.

Wave forecasts using National Centre for Environmental Prediction (NCEP) wave forcing have been included for selected sites in the CSIR WaveNet system, however little progress has been made to date in implementing a regional WaveWatch model.

An integrated hydrodynamic/sediment/biogeochemical modelling system, operating in a hindcast mode, exists for Saldanha Bay. A similar model is in the process of being implemented for the Natal Bight ecosystem. Both of these modelling efforts are highly reliant on the underpinning hydrodynamic modelling platforms and

consequently can only be further developed once there is adequate progress in developing operational hydrodynamic models of sufficient accuracy and duration of simulations.

It is intended that the above forecast and operational oceanography outputs become available for integration into the data dissemination systems of the OceanSAfrica initiative as these mature.

6. CONCLUSION

A new impetus has been given to operational oceanography in southern Africa supported by the Nansen-Tutu Centre for Marine and Environmental Research, and the African Centre for Climate and Earth System Studies, as well as all of the institutions involved in, and supporting, the OceanSAfrica initiative.

Steady progress has been made in both large-scale and higher resolution atmospheric and ocean modelling since the June 2009 workshop. This together with progress in developing the operational aspects of remote sensing and observational systems bodes well for the implementation and operation of a national capability to provide stakeholders with decision-support for their maritime and coastal operations.

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CHALLENGES AND CAPABILITIES OF DATA ASSIMILATION

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ABSTRACT

This article gives a short bibliographic review of sequential data assimilation methods used in ocean forecasting systems. It recommends what to do and what not to do with data assimilation in view of building the South African capacity for operational ocean monitoring and forecasting. The examples cited indicate the strong potential for building an ocean forecast system for the seas around South Africa using present day's methods and high-resolution numerical ocean models. But the difficulties of modeling the powerful dynamics of the Agulhas Current will not be alleviated with data assimilation, which an old Alpine wisdom would summarize as "A donkey will never run as fast as a horse, no matter how short you cut the ears". The importance of fisheries in South Africa and in neighbouring countries also makes a case for using data assimilation into coupled physicalbiological models of the ocean which are presently used more for research than for operational users. The theoretical and practical challenges faced today in the field of data assimilation are likely to be overcome in a not too distant future, and the key to successful innovations is likely to be the combination of multidisciplinary skills in oceanography, mathematics, statistics, computer science, remote sensing and biology. Those competences are already present in South Africa and the country certainly has an important part to play in the world-wide concert of ocean forecast and reanalysis systems.

Key words: Data Assimilation, forecasting, ocean model.

1. INTRODUCTION

Numerical models need data assimilation to ingest observations and turn them into a forecast. Even if the free running model does resolve the processes of interest, it will develop oceanographic features that evolve in a chaotic manner but are unlikely to match reality. The Nansen-Tutu Center and its local partners have extensive knowledge of numerical modeling of the Greater Agulhas Current system, but are lacking expertise for data assimilation and for developing a South African ocean forecasting and reanalysis system. The present article is an attempt to present the theory, the challenges and capabilities of

data assimilation in the perspective of a nested model of the oceans around South Africa, developed and operated in South Africa.

First, let us examine the reasons why South Africa should bother with data assimilation: Oceanography has traditionally been carried out on the basis of observations and more recently using numerical models as a complementary source of information where no observations are available. Observations of the ocean are bound to be incomplete, whether they are performed from satellite, which only observe the surface of the oceans (sea surface heights with altimeters, ocean colour and sea surface temperatures from optical sensors, surface roughness from SAR images) or from research vessels or autonomous floats like the Argo programme [Fed00]. Even with today's technology, the oceans remain vastly undersampled and a majority of its eddies will remain virgin from any profile. Numerical models on the other side provide a complete 4-dimensional dataset of all the state variables, defined as the irreductible set of prognostic variables. But these are affected by several sources of inaccuracies, either inherited from their input terms or inherent to their formulation:

- Uncertainties in numerical weather data used as input and main driving force of ocean currents.
- Errors in the bottom topography.
- Uncertainties in the data used as initial conditions, usually a climatology.
- Errors due to the limited horizontal and vertical resolution of the model.
- Uncertain values of parameters used to represent sub-grid scale processes (eddy viscosity, mixing due to internal waves, among others).
- Deficiencies caused by the choice of one or the other numerical scheme in the model, that can cause phase and amplitude errors [DB00, SM05, Hig05].

Being given observations and a numerical model of an ocean system, and their respective error estimates, the data assimilation problem therefore consists in determining the "best" estimate of the true state of the system as

well as the associated uncertainty¹. What we defined as "best" is the crux of data assimilation: a mathematical criterion is needed for the notion of "optimality". The Bayes theorem then comes as a useful guide to understand the philosophy of data assimilation. Once a Probability Distribution Function (pdf) is given for both the observations and the forecast state variables the Bayes theorem computes the conditional pdf of the state variables. The Bayes equation would solve completely the data assimilation problem if the associated computational costs did not become prohibitive as soon as we consider dimensions larger than a dozen, and nowadays an ocean model has millions of variables... Fortunately, there is still one theoretical framework that allows an elegant calculation of the conditional pdf with little computational effort: the multi-Gaussian assumption. It should in principle be referred as "multi-"Gaussian because it is a multivariate extension of the classical Gaussian assumption, see [BEW03] for more details. Assuming the model state variables and the observations are multi-Gaussian and further assuming that their errors are not biased², one can concentrate on the first two moments of the pdf, the mean and the variance-covariance matrix, and then compute the Best Linear Unbiased Estimator (BLUE) that minimizes the variance of the analyzed error.

Linear combinations of Gaussian variables remain Gaussian, and it is possible to demonstrate that there is only one solution that minimizes the error variance formed as a linear combination of the model and observations. Finding the optimal weights of this linear combination is the calculation that leads both to the simple Kriging in Geostatistics [CD99] and the Kalman filter for dynamical systems [Kal60b]. The model forecast at time n is defined by the mean vector X_n^f and the variance-covariance matrix C_n^f . Similarly the observations mean and variancecovariance matrix are Y_n and R_n respectively. The following equations give the analysed mean X_n^a , the soughtafter posterior variance-covariance matrix C_n^a and the linear weights K_n :

$$X_n^a = X_n^f + K_n(Y_n - HX_n^f) \tag{1}$$

$$C_n^n = C_n^f - K_n H C_n^f$$
 (2)
 $K_n = C_n^f H^\top (H C_n^f H^\top + R)^{-1},$ (3)

$$K_n = C_n^f H^{\top} (H C_n^f H^{\top} + R)^{-1},$$
 (3)

where H denotes the observation matrix. If the assimilation is behaving well, the weights K_n will pull the analysis somewhere between the forecast and the observations: closer to the observations if the model forecast error is larger than the observations error and vice-versa.

So data assimilation defines optimality as "closeness to the true solution" in a merely statistical sense. where is the physical sense of that definition? What does a minimal variance criterion know anything about the geostrophic and hydrostatic equlibria or even the Courant-Friedrich-Lewy criterion? We surely want the currents to remain consistent after assimilation and avoid a model crash after restarting, otherwise how could we ever call the solution "optimal"?

There are a few input terms to the above equations that should be considered with care, the one that has rightfully received most attention is the variance-covariance matrix of the model forecast C_n^f . We can actually distinguish between most sequential data assimilation methods only by changing this term of the equation. This will be done in the following section of the paper.

For the sake of conciseness, I will leave aside variational data assimilation methods (3DVAR, 4DVAR and the method of representers) since they aim at solving the same problem — minimizing a cost function similar to the analyzed error variance above — but using a different formalism inspired from optimal control instead of statistics. Variational methods search for an optimal trajectory of the system by varying its control parameters. The result has the advantage of being a consistent model trajectory over the length of an assimilation window, but delivered without indication of uncertainties neither in the final state variables nor for the optimized control parameters.

With linear models, all methods will provide the same result at the end of the assimilation window and therefore the same forecast. With non-linear systems, the theoretical framework breaks down for both approaches and comparing them becomes uneasy in the technical complications. However, the analogy between 3DVAR and Optimal Interpolation methods is strong and the 4DVAR method also shares a lot with the Kalman Filter. For more background on variational methods, see [Ben92]. We will now review sequential data assimilation methods.

OPTIMAL INTERPOLATION

The Optimal Interpolation (OI) is the most classical form of data assimilation: It uses a constant forecast covariance matrix C^f , also called "background covariance" in the variational literature, it is then fully equivalent to the Simple Kriging known in traditional geostatistics. The C^f matrix concentrates all the information about the spatial structure of the errors (how changes at one point affect all other points in the domain) and between different variables. A classical example in oceanography is found in [CH96] and has been used extensively for assimilation of altimeter data into large-scale ocean models. The covariance translates the principle of linear geostrophy that links the density structure, the geostrophic currents and the sea surface heights. This approach works well in places where geostrophy dominates the currents and where anomalies of sea level can be translated into vertical movements of the isopycnals and the associated geostrophic currents. On the other hand, it does not handle well any other effect than geostrophy, for example the topographic steering or the

¹There will remain residual errors, even after assimilating the data and an indication of their amplitude is needed.

²There are actually other assumptions: the independence of model and observations errors and absence of temporal correlation, but they are fortunately not as painful as the two previous ones.

Ekman pumping on the Shelves. The [CH96] method has been expanded to include more processes and a related method is used in the real-time HYCOM model presently run at NRL [CBB+09]. To avoid writing explicitly all physical interactions, empirical statistics can be derived from the output of a long model simulations: after all, if the model is supposed to know all about the physics, why should the assimilation procedure rewrite then one more time? This type of OI is called Ensemble OI [BS01, Eve03, OSGB05, EnOI] which is used operationally in the Australian BlueLINK system. It is also very similar with the constant basis SEEK filter presently used at Mercator Océan, for a comparison of this type of methods in a regional application of the Gulf of Mexico, see [SCB+11]. The EnOI-type of methods are able to preserve linear properties from the static ensemble, which is the collection of model outputs that is used as a square root of the \mathbb{C}^f matrix [Eve03]. This thus encompasses the geostrophic equilibrium as in [CH96] and also accounts for other linear constraints like the absence of currents normal to the coast. However, using the results from a long historical model run essentially means that the temporal variability produced by the model is meant as representative of the changes to be applied by the data assimilation procedure at the time of assimilation. This may not always be the case and the EnOI is often improved when the static ensemble undergoes a selection of output taken in the same season [XCZB11]. EnOI methods are able to assimilate many different data types, predominantly altimeter data, SST, temperature and salinity profiles and are generally able to constrain the mesoscale activity [OSGB05, CBB+09, CB09a], but more seldom sea ice data beause the multivariate corrections between sea ice and surface water properties change sign close to the ice egde and it is uneasy to assemble a static ensemble where the ice edge is located close to its actual position, this is partly the reason why techniques with a dynamical basis have distinguished themselves in the Arctic coupled ice-ocean system [LRE03]. Current velocity data from moored instruments or drifting buoys are still seldom assimilated, but the main limitation is their high sensitivity to sub-grid scale processes rather than a shortcoming of the assimilation method. A real methodological limitation of OI methods is their ignorance of any source of errors: Where the method works, it works, where it does not, it provides little clue on what might have gone wrong. In order to shift the question from "What can I do to correct the system?" to a more rewarding "Why is the system in error?" another type of method is needed, that explicitly resolves model errors and propagates them into the forecast error covariance matrix.

3. KALMAN FILTERING METHODS

The Kalman filter was originally introduced by engineers [Kal60a] for controlling flying objects with a limited number of degrees of freedom (aircrafts, missiles and rockets). The method is elegant in that it is optimal within a well defined theoretical framework: a linear forward model F and, one more time, Gaussian state variables

allowing the use of the BLUE scheme as in Equation 1 (this is why the weight matrix is noted K as Kalman gain). The forecast error covariance matrix is re-using the analyzed covariance from the past analysis and includes the new model errors Q_n between the assimilation cycles n-1 and n: $C_n^f = FC_{n-1}^aF^\top + Q_n$. The term Q_n is the one which requires the full creativity of the oceanographer in answering the following question: What are the sources of errors? Different terms can be added corresponding to errors in the forcing fields: momentum fluxes and heat fluxes from the atmosphere as in [LEL07, HE02], the bathymetry [MMLP04] or the tidal boundary conditions [BAG+10]. The goal is to excite all these sources of errors assuming a statistical description of their spatial and temporal structures so that the forecast error is as realistic as possible. Your critical eyes may have noticed that none of the above references actually uses the classical Kalman filter. There are two main reasons for that: first the Kalman filter becomes too computationally demanding when used in high dimensions and second, it is not designed for nonlinear systems. The computational demands are mostly related to the computation of the forecast covariance matrix C_n^f . Today's supercomputers sustain the operations of regional and global models of several millions of grid cells, which is the order of magnitude of the state dimension. This makes C_n^f a monster square matrix requiring several petabytes of memory for storage and several millions of model integrations in order to fill in its lines and columns. Clearly not an option. The main approach to cut down the costs is to consider only a low-rank square root of C_n^f , as initially suggested in [Jaz70]. But this would only solve one of the two problems. Oceanographic processes are essentially non-linear and the degree of nonlinearity is bound to increase together with the grid resolution. The Kalman filter has been adapted for applications in non-linear systems: first with the Extended Kalman Fiter [Jaz70] using a first order expansion of the covariance propagation equation. But this approach has proven unstable in the simplest quasi-geostrophic model [Eve92].

The breakthrough has been inspired from Monte Carlo methods with the Ensemble Kalman Filter [Eve94, EnKF] that proved the stability of the method with ensembles of only 100 members, which means that the method is about 100 times more expensive than an OI, and some model resolution needs to be sacrificed³. The EnKF was incidentally first demonstrated with real satellite data in a quasi-geostrophic model of the Agulhas currents by [EvL96]. Since then, the main progress in the method has arisen from the square-root flavours of the method, see [SO08a] for a review. A 100 members EnKF is run since 2007 for the HYCOM model in the TOPAZ system at a resolution of about 12 km over the North Atlantic and Arctic oceans [BL08]. In addition to the observations mentioned above, the TOPAZ system also assimilates different sea ice observations and the EnKF makes it convenient to assimilate asynchronous data [SEB10] such

³For 1/10th of the cost, an ensemble forecast system can be plugged on an OI as in [CB09b].

as the Lagrangian sea ice drift vectors. Assimilation into ecosystem models is also increasingly often undertaken with an EnKF [NE03, SB09]. The assimilation in this type of models is presently limited by the heavy complexity of ocean ecosystems, so that data assimilation in ecosystem models is remaining at the research level and has not made its way to operations so far.

The EnKF however relies on the same linear update as Equation 1, which means that the linear properties are conserved, but not the other: for example, when temperature and salinity are state variables, then the density — a non-linear variable of the two above — is not conserved and some biases are to be expected in waters where the curvature of the equation of state is strong. Further extensions are proposed to cope with isues of non-linearities and non-Gaussianities [BPW10] and in particular the Particle Filters (also known as Sequential Importance Resampling Filters) have an immense potential for assimilation in non-linear systems, but their performance is limited in high-dimensional systems and they are likely to require too many particles⁴ in realistic implementations.

4. CONCLUSION

Reading through the literature cited above, it appears that data assimilation is able to relocate resolved ocean features (eddies in an eddy-resolving model, larger systems in a model of coarser resolution) at the right place and the right time, but it is not meant to introduce unresolved processes in the model. In other words, it cannot change a donkey into a horse. Data assimilation has thus a central role in ocean forecasting, it can also provide other information that was not detailed in the above: parameter estimates can be obtained together with estimates of the state of the system [Eve09, BAG⁺10] and the optimal location of observations can be designed objectively [SO08b]. In view of the computational costs related to the EnKF and similar methods, my suggestion would be that an EnOItype of method is used to forecast the seas around South Africa, in order to assimilate the main source of observations in the region: altimeter data, sea surface temperatures and Argo profiles, while more advanced methods are used for training students on idealized models as proof of concept. More advanced methods can be used in realistic eddy-resolving models of the Agulhas currents whn the supercomputing power is sufficiently available and the user support from the national High-Performance Computing center well established.

The research is not completed in data assimilation, I would rather consider the field as in its infancy because two major assumptions are regularly violated in oceanographic systems: the multi-Gaussian and the non-bias assumptions required for the BLUE update. The non-Gaussianities have been adressed above, but not the bias issues, which one would expect in a model of the Agulhas currents: the retroflection may be modeled too far to

the East and the frequency of eddies may also not be correct in the free running model. An assimilation system may correct these features, but without being designed for it. So it is not clear whether the assimilation system will react correctly or not: one may expect that the bias is transferred linearly to other variables during the update and accumulates at each assimilation step. There are practical ways to estimate a bias, by detecting systematic features of past errors, so that their negative effects can be attenuated [LZW08].

The above description of data assimilation may disappoint the oceanographer wishing some physical reasoning rather than heavy statistics but the two should not be dissociated. Data assimilation requires multidisciplinary skills of mathematicians and oceanographers so that the basic principles of statistical optimality and physical consistency are not violated (or as least as possible).

ACKNOWLEDGMENTS

The author acknowledges the eVITA-EnKF grant from the Research Council of Norway (contract number 178894), and several years of collaboration with his colleagues P. Sakov, F. Counillon and E. Simon at NERSC. My gratitude goes to J. A. Johannessen for sacrifying his bonus points to pay my plane tickets to Cape Town.

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THE GRAND CHALLENGE OF DEVELOPING IN SITU OBSERVATIONAL OCEANOGRAPHY IN SOUTH AFRICA

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ABSTRACT

With a view of implementing operational oceanography in South Africa, the scientific community in 2009 initiated a demonstration project, OceanSAfrica, which integrates ocean modelling, in situ observations, remote sensing, and data dissemination and products. This paper presents progress towards establishing the in situ observations component. Led by the newly formed Oceans & Coasts (Department of Environment Affairs), numerous existing monitoring efforts, which include ship surveys, tide gauges, underwater temperature recorders (UTRs), wave buoys, as well as locally developed in situ measurement sensor and platform prototypes (dial-out UTRs, coastal and deep ocean buoys) have been incorporated into a regional in-situ observational network. A modular process has begun which will expand this initial network into an operational in situ observational service by 2016. This will include regional high resolution underway observations during the SANAP relief voyages- namely Good Hope, Cape Town-Gough Island and Cape Town- Marion Island transects, participation in SAMOC, at least five coastal buoys, moorings across the Agulhas Current and the Benguela Jet, coastal radar, dial-out UTRs and coastal weather stations. Most will be linked in real-time. This network will be integrated with the regional in situ observational arrays of PIRATA in the Atlantic and RAMA in the Indian Ocean, and the Benguela Current Commission (BCC) and Agulhas and Somali Current Large Marine Ecosystem (ASCLME) programmes. Equally important will be the inclusion of science and technology projects to support and interpret the in situ observations. Apart from providing information to benefit local marine activities, these in situ data will ultimately be used to improve ocean and weather model skill through validation and assimilation, and contribute international efforts in climate change research. Training and capacity building strongly feature in the OceanSAfrica initiative. Overall, this endeavour will strongly advance DEA's objective of providing an

operational service on ocean state, DTi's (THRIP) objective stimulate technology innovation. to manufacturing and jobs, and DST's 2008-2018 Grand Challenge for Global Climate Change Science strategy to use South Africa's unique proximity to the Antarctic, the Southern Ocean, the Agulhas and Benguela Currents to become a world leader in climate change science.

1. OCEANS AROUND SOUTH AFRICA

The marine environment around southern Africa is one of the most diverse, complex, variable and energetic systems in the world (Figure 1; Lutjeharms 2001). The east coast and outer Agulhas Bank are strongly influenced by the warm, fast-flowing (~ 2 m s⁻¹) Agulhas Current. This well-defined western boundary current with a volume transport of some 75 Sv has origins near 26° S where there is a confluence of flows from the Moçambique Channel, the East Madagascar Current and the South Western Indian Ocean gyre (Lutjeharms, 2001). At the southern tip of the Agulhas Bank, the Agulhas Current undergoes a number of configurations which include retroflection eastwards along the Subtropical Convergence into the South Indian Ocean (Agulhas Return Current), the formation of anticyclonic rings shed into the South Atlantic (Lutjeharms and Van Ballegooyen 1988; Duncombe Rae, 1991), or continuous flow along the shelf edge of the western Bank (Lutjeharms and Cooper, 1996). The latter two mechanisms inject water masses (freshwater, salt and heat) originating in the Indian Ocean into the South Atlantic forming a critical link in the Atlantic Meridional Overturning Circulation (MOC) — an important component of the global ocean circulation (Figure 2).

The oceanography on the outer Agulhas Bank is dominated by associated shear boundary processes, such as meanders, eddies, and break-away filaments (Lutjeharms et al., 1989) of the Agulhas Current. Upwelling is common on the shelf east of Port Elizabeth

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caused by the Agulhas Current moving farther offshore (Lutjeharms *et al.*, 1999). Intense thermoclines, induced by shelf-edge upwelling and insolation, are characteristic of the eastern and central Agulhas Bank (Largier and Swart, 1987). The inner shelf is influenced

by wind-driven coastal upwelling, particularly during summer (Schumann *et al.*, 1982). Upward doming of the thermocline in an offshore, elongated formation is often found on the central Agulhas Bank. This feature, referred to as a "cold ridge", is commonly associated

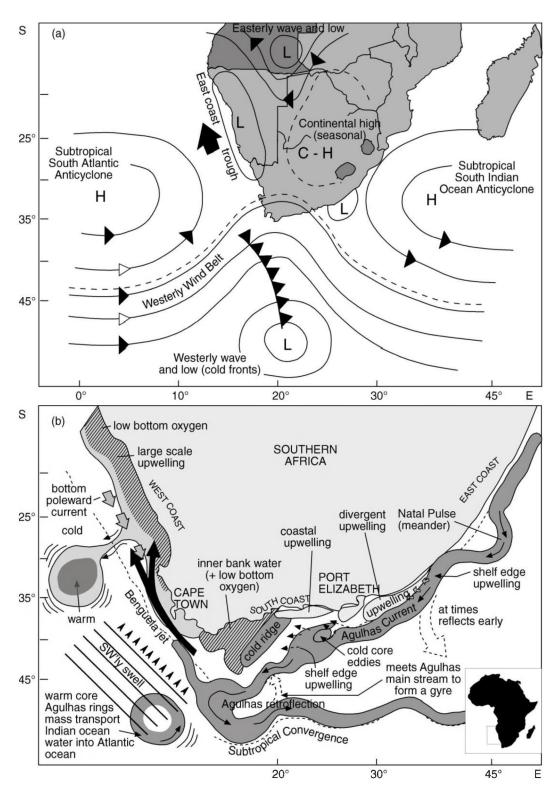


Figure 1: (a) The complexity and variability of the marine environment around southern Africa is partly due to the latitude and associated weather. In summer, the oceanic high pressure cells either side of southern Africa dominate the wind field, causing south-easterly winds on the west coast and north-easterly winds on the eastern Agulhas Bank and east coast. In winter, the westerly wind belt migrates north, moving cold fronts and strong westerly winds to southern Africa. (b) The oceanography is also dominated by the warm Agulhas and cold Benguela Currents. These drive many of the physical processes and key features on the shelf (taken directly from Roberts 2005).

with high levels of primary and secondary production (Boyd and Shillington, 1994). Large, solitary, transient meanders in the Agulhas Current, known as a "Natal Pulse", are found on South Africa's east coast 3–4 times a year (De Ruijter et al., 1999). These have profound influences on the shelf oceanography and have been associated with early retroflection and ring formation (Roberts et al., 2010; Van Leeuwen et al., 2000). At times large freak (rogue) waves occur in the Agulhas Current known to inflict severe damage on ships, particularly super tankers (Grundlingh 1994).

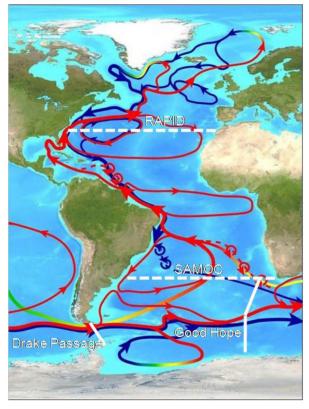


Figure 2: Schematic showing the Atlantic Meridional Overturning Circulation and the oceanic teleconnection between the south and north ocean basins. Red arrows represent surface flow (upper 1000 m) with blue corresponding to the deeper (>2000 m) return flows. The RAPID array in the North Atlantic, SAMOC line in the South Atlantic and mooring line across the Drake Passage are also depicted (white lines).

The west coast is very different to the east coast, and is dominated by the cold Benguela upwelling system (Shannon and Nelson, 1996). This is one of the largest eastern boundary upwelling systems in the world, driven by the South Atlantic High Pressure (anticyclone) and associated south-easterly winds. The region is abundant in production which frequently leads to low levels of dissolved oxygen in the bottom layer, and at times, almost anoxic conditions (Chapman and Shannon, 1987). The outer shelf is influenced by the slower north-

flowing (0.25–0.50 m s⁻¹) Benguela Current (Boyd et al., 1994). This eastern boundary current is less defined than the Agulhas Current and is the eastern element of the South Atlantic gyre. A narrow frontal jet, known as the Benguela Jet, is commonly found along the shelf edge between the Cape Peninsula and Cape Columbine. The Benguela Jet is a small current with maximum velocities reaching $\sim 0.75~\text{m s}^{-1}$ and a transport of 1--7Sv (Shannon and Nelson, 1996). It plays a crucial role in connecting the western Agulhas Bank to the west coast. North of Cape Columbine the jet undergoes bifurcation, moving onto the wider shelf and into the South Atlantic towards the Walvis Ridge. Agulhas rings (Duncombe-Rae et al., 1992) and other offshore mesoscale features such as eddies and filaments (Lutjeharms and Matthysen, 1995; Nelson et al., 1998) at times interact with the shelf causing water to be drawn offshore into the Atlantic Ocean. A poleward undercurrent on the shelf and continental slope varies in strength and seasonality (Nelson, 1989).

The Agulhas Current and the atmospheric high-pressure cells situated over the SE Atlantic and SW Indian are therefore major drivers of the many physical processes found on the shelf around southern Africa. Variability in the wind field is influenced by the north-south seasonal migration of the SE Atlantic and SW Indian Ocean High Pressure cells, and concomitantly, the expansion of the westerly belt (Tyson and Preston-White, 2000). The eastward tracking cyclones with their associated cold fronts produce strong westerly winds and large swells during winter, with cyclogenesis occurring in the southwest Atlantic Ocean. Modelling and observational studies indicate that increased transport of warm Agulhas water southwards and to the southwest of South Africa into the Atlantic strengthens local storms and increases rainfall over large parts of South Africa (Rouault et al., 2002). Many flood disasters have resulted from cut-off lows that intensify when the southern Agulhas Current is anomalously strong and warm (Singleton and Reason, 2007).

In summer, the westerly belt contracts southwards, and the wind field over the shelf is then largely driven by the two anticyclones often ridging and causing coastal upwelling on the west coast and Agulhas Bank (Shannon and Nelson, 1996; Schumann et al., 1982).

To the south of Africa lies the Southern Ocean with the region immediately south of the Agulhas Bank being a critical crossroad for the inter-ocean exchange of water, salt, heat, biota and anthropogenic tracers between the subtropical South Indian, South Atlantic gyres and the cooler Southern Ocean waters. The Southern Ocean, similar to the MOC, plays a major role in the global ocean circulation (Figure 2) and in particular on regional and global climate (Siedler et al., 2001).

MARITIME ACTIVITIES

The cold west coast of South Africa is stark and sparsely populated with few major cities. Apart from Cape Town, the only other major harbor on the 700 km coast is Saldanah Bay which is used to mostly export iron ore. Large scale commercial fishing, oil/gas and seafloor mining dominate activities on the shelf region. The high biological production (plankton) in the ecosystem which supports the commercial fish stocks often leads to harmful algal blooms (HABs) and rock lobster walkouts.

The east coast by contrast is rich in biodiversity but is low in biomass. It is heavily populated with most of the country's major ports located here. Industrialization and ocean outfalls are concentrated in Kwa-Zulu Natal, although the newly built Koega Industrialized Development Zone (IDZ) is destined to substantially expand industrialization in Algoa Bay.

Twenty three MPAs have been established between Saldanha Bay and the Mozambique border to conserve the diverse coastline with all but two east of the Cape Peninsula. Apart from protecting the biodiversity, these play important roles in the management of the much depleted line fishery. The warm water, beaches, biodiversity and close proximity to the hinterland large cities, has led to the east coast, particularly KZN, being a prime tourist destination. East of Algoa Bay, shipping lanes are close to the coast as a result of the narrow shelf and the southward flowing Agulhas Current.

Mariculture (mussels and oysters) is practiced in the sheltered embayments of Saldanah Bay, Knysna Lagoon and Algoa Bay. Marine ecotourism (whale watching, shark diving, sardine run) is also well established on the south and east coasts.

Of growing importance is the renewable energy sector interested in generating electricity from the Agulhas Current and using wave power in marine pump storage schemes.

3. EXISTING MONITORING

The complexity and high energy of the ocean systems surrounding southern Africa present a challenge to the many marine activities which occur here and affect parameters such as operations, performance and safety, as well as to the management of ecosystems, fisheries, coastal communities, disasters, and weather prediction. In recent times, the effects and implications of climate change are also becoming a concern. A number of monitoring initiatives have therefore been underway, some for many years, to provide information on the state of the ocean, and in cases, includes prediction.

3.1 Fisheries

Marine monitoring in South Africa has been strongly influenced by the need to manage the commercial fisheries — mainly pilchard, anchovy, rock lobster, hake and squid — all of which undergo fluctuations in biomass and catches (Hutchings et al., 2009a). The Sea Fisheries Research Institute (SFRI) which then became Marine & Coastal Management (MCM), and in 2010 dissolved into the Department of Agriculture, Forestry

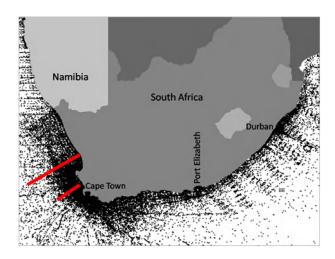


Figure 3: Positions of CTD stations undertaken between 1982 and 2008 using South African research vessels. These data are in the South African Data Centre for Oceanography (SADCO). The monthly sampled SHBML (red long line) and SARP (short red line) monitoring lines are shown

and Fisheries (DAFF), has conducted scientific cruises as far back as the 1950s, but routinely since 1982 using the research vessels Agulhas, Africana, Benguela, Algoa and more recently the Ellen Khuzwayo, regularly covering the Southern Ocean, the Agulhas Bank and the west coast (Figure 3). This dataset of 28 years is invaluable and almost unrivalled worldwide. To understanding fluctuations in the biomass of pilchards, anchovies, demersal species and rock lobster, the monthly sampled St Helena Bay monitoring (SHBML) and Sardine-Anchovy Recruitment Program (SARP) lines were established in 2000 (Hutchings et al., 2009b). This is an area of great interest in terms of the transport of pilchard and anchovy eggs and larvae from the Agulhas Bank via the Benguela Jet, development of Harmful Algal Blooms (HABs), low oxygen events and rock lobster walkouts.

3.2 Underwater Temperature Recorder (UTR) Network

With an increasing awareness of climate and ocean variability, the SFRI in 1990 also began establishing a

long-term network of delayed-time Underwater Temperature Recorders (DT-UTRs) in depths of 5-15 m around the South African coast (grey triangles in Figure 4). These were deployed deliberately to monitor coastal processes, mainly coastal upwelling cells (Figure 1). At first the *Hugrun* self-recording temperature recorder was used but these were replaced in 2001 with the *Starmon mini*. Scuba divers service the instruments every 4-6 months and the data are uploaded to the internet (demonstration website www.cfoo.co.za). Two deeper sites were also established — one in the Tsitsikamma National Park on Middlebank in 36 m (1998), the other in Kromme Bay (St Francis Bay) in 25

m (1992). Both have thermistor arrays with the former an ADCP (Roberts and van den Berg 2005) which has recorded hourly currents since then.

During the first phase of the *African Coelacanth Ecosystem Program* (ACEP I), between 2002 and 2007, more UTR sites were established in the Mozambique Channel, Comoros Isles, Tanzania (including Zanzibar) and the Seychelles, but these were standardized at a depth of 18 m so as to measure subsurface physical processes such as shelf edge upwelling. When funding is available, every effort is made to establish new sites in the WIO. For example, in October 2010 an UTR was

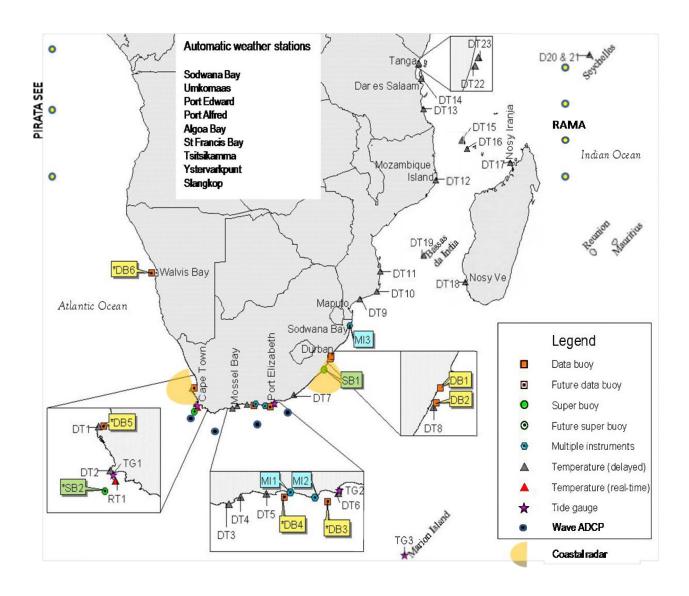


Figure 1: The *in situ* observational network around southern Africa: DT=Delayed time UTR, DB=Data Buoy, SB=Super Buoy, TG=Tide gauge. This network is strengthened by the PIRATA SEE Atlas buoys in the Atlantic Ocean and the RAMA Atlas buoys in the Western Indian Ocean. Note that not all DBs and SBs are deployed yet. Deployment of the automatic weather stations will begin in 2011 in collaboration with SAWS. All buoys also have meteorological sensors. Coastal radar stations will be established at Port Edward and St Helena Bay in 2013 and 2014 respectively

deployed on Mnemba Island off the east coast of Zanzibar, and in May 2011, an UTR was deployed near the north tip of Mauritius (1.4 km off Trouaux Biches). Two UTRs will be deployed on the Kenyan coast in November 2011.

3.3 CSIR WaveNet

The Council for Industrial Research (CSIR), which operates in commercial sectors of the marine environment, has developed a real-time monitoring network for waves (CSIR WaveNet) with a 48 hr prediction capability for the National Port Authority. This uses a combination of *Datawell Directional Waverider* surface buoys, and recently bottom-mounted ADCPs deployed at 9 sites on the South African coast (not shown in Figure 4). Twelve CSIR owned coastal

completed in 1989. Initially the float and stilling well type of gauge was used but this method has now been replaced with radar tide gauges. Durban, Cape Town and Simons Town are connected to international networks — the Global Sea Level Observing System (GLOSS www.gloss-sealevel.org) and the UNESCO Tsunami Warning system (www.ioc-tsunami.org) — and are fitted with satellite transmitter and GPS for real-time data transmission and land movement monitoring. More detail is provided in Rossouw et al. (in prep.).

3.5 Long term monitoring in Algoa Bay

More recently, the *South African Environmental Observation Network* (SAEON) which has a mandate to establish key long-term environmental monitoring sites in South Africa, has initiated a substantial network of

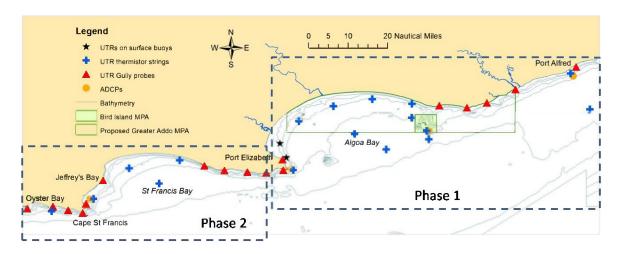


Figure 5: The SAEON long term monitoring network of instruments (see key). Phase 1 covering Algoa Bay and Port Alfred was initiated in 2008. Phase 2 to be implemented in 2011 will extend the network into the neighbouring St Francis Bay area

weather stations located mainly at the harbours are also integrated into CSIR WaveNet. These are independent of the SAWS coastal AWSs (see section 3.8). These data are available on the internet at http://wavenet.csir.co.za. In situ deep sea wave measurements to the southwest of the continent are still required to improve model skill. More detail is provided in Rossouw et al. (1999) and Rossouw et al. (in prep.).

3.4 SANHO Sea Level Network

The South African Navy Hydrographic Office (SANHO) is responsible for the installation and maintenance of tide gauges in the principal harbours in South Africa. SANHO is also responsible for the acquisition, processing, archiving and dissemination of sea level data (www.sanho.co.za). The network which now comprises 10 sites was initiated in 1957 and

DT-UTRs, thermistor arrays and ADCPs in Algoa Bay (Figure 5) — one of the largest embayments on the South African coast (Goschen and Schumann, 2011). The intention is to track long-term changes in this open bay system. Data are available on request.

3.6 Regional ocean-climate monitoring

Good Hope transect

To understand the exchange mechanisms of water masses south of Africa, the equatorward flux of heat and salt in the MOC and the possible influence on climate — it is critical that the inflow of Indian Ocean water into the Atlantic is quantified and monitored. To this end the Good Hope programme was initiated in 2004 as a joint partnership between South Africa, France and Germany (Ansorge et al., 2004). This provides an intensive underway monitoring platform in which the

physical structure, volume flux of waters, and carbon signature are measured where the inter-basin exchanges occur. The Good Hope line aims to integrate high resolution physical, bio-geochemical and atmospheric observations with along-track satellite and model data. To date over 22 underway lines have been completed along the Good Hope transect. It is anticipated that the occupation of the Good Hope line will continue indefinitely.

In addition to the Good Hope line, new underway transects between Cape Town-Gough and Cape Town-Prince Edward Islands are to commence in 2012 as part of the SAMOC international programme, Agulhas Current SCOR working group 136 strategic plan, and the SANAP.

South Atlantic Meridional Overturning Circulation (SAMOC)

At present there is only one monitoring system of the MOC in the North Atlantic, namely RAPID/MOCHA array deployed at 25° N (Figure 2; Bryden et al., 2005). However, given the complexity and the worldwide extent of the MOC, it is necessary that monitoring change elsewhere is undertaken — in particular the teleconnection between the South and the North Atlantic oceans. This connection results in the southward flow of cold and salty water masses from the North Atlantic and a compensating northward warm water pathway. Recent investigations have shown that this pathway may be further intensified by regions of mesoscale variability, particularly high at the Brazil/Malvinas Confluence, at the Retroflection and within the Southern Ocean. Indeed. given the close relationship between the north and south Atlantic basins it is likely that any change in the net heat, salt and mass fluxes will result in repercussions farther afield.

In 2008, a new MOC line was established across the South Atlantic at 40° S (Figure 2) as part of the South Meridional Overturning Atlantic Circulation Programme (SAMOC). This will be augmented with moorings adjacent to the continental shelves of South Africa and Brazil. To monitor the inter-ocean exchange between the South Atlantic and South Indian Oceans, and importantly the exchange associated with the Agulhas Current, as well the Pacific Ocean - SAMOC will incorporate a number of ongoing lines such as the Good Hope line south of Africa and the mooring line across the Drake Passage (http://www.clivar.org/organization/southern/timeseries. htm; Chereskin et al., 2009).

The inclusion of South Africa as a major collaborator in the Good Hope and SAMOC programmes, as well as the local establishment of sustainable monitoring transects to Gough, Marion and Prince Edward Islands will strongly advance the DST 2008–2018 Grand Challenge for Global Climate Change Science strategy (reference): namely, to use South Africa's unique proximity to the Antarctic, the Southern Ocean, and the Agulhas and Benguela Currents to become a world leader in climate change science.

3.7 Agulhas Current Time series

Most recently in 2010 a large subsurface mooring array comprising 7 moorings and 4 C-PIES, spanning a distance of 340 km along a TOPEX/Jason altimetry ground track, was deployed across the Agulhas Current directly off Hamburg (Beal et al. 2009). This project, referred to as the Agulhas Current Time-series (ACT), is funded by the National Science Foundation (NSF) of the United States and aims to measure, *in situ*, the Agulhas Current transport for a period of 3 years. These measurements will be correlated with patterns of along-track sea surface height variability from a satellite altimeter to produce a proxy (or index) for Agulhas Current transport. This can be extended forwards and backwards in time — and will be a contribution to the Global Ocean Observing System.

3.8 South African Weather Service (SAWS)

The SAWS is responsible for the provision of maritime weather, forecasts and warnings in METAREA VII (second largest in the world; Figure 6). These are supported by their coastal Automatic Weather Stations

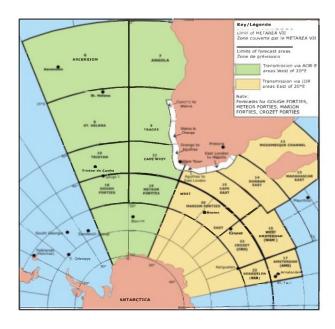


Figure 6: The SAWS is responsible for the provision of maritime weather, forecasts and warnings in METAREA VII (green and orange sectors).

(AWS) network, weather stations on the Sub Antarctic Islands and Antarctic base (SANAE), wave data and forecasts from CSIR WaveNet, and Voluntary Observing Ships (VOS). The SAWS deploy SVP drifter buoys and Argo floats for the JCOMM community. The SAWS has indicated that real-time measurements for air and water temperature, humidity, wind, pressure and swell are still required in the South Atlantic – Southern Ocean.

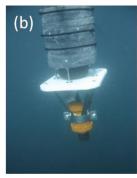
LOCAL DEVELOPMENT OF IN SITU SHELF MEASUREMENT PROTOTYPES

Already back in the mid 1990s, it was well recognised that marine monitoring capabilities in South Africa needed to be extended farther offshore and in real-time. But it was only in 2006 that a local project of this nature was established in the Technology and Human Resources for Industry Program (THRIP) using funding from the Department of Science and Technology (DST) and industry. Apart from delivering prototypes, this program emphasises innovation, capacity building, student training, and the creation of jobs with increased manufacturing capacity in South Africa.

4.1. Data Buoy project

Between 2006 and 2008 funding was obtained from THRIP to develop a coastal real-time monitoring buoy for South African conditions. *Sappi* and the *South African Squid Management and Industrial Association* (SASMIA), both with ocean monitoring requirements,





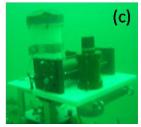


Figure 7: Data Buoy is a real-time coastal monitoring buoy (a) surface buoy which transmits data to a cellular network GPRS (b) data are received from a benthic instrument platform (c) using acoustic modems

were recruited as industrial research partners. The final product known as *Data Buoy* (Figure 7) was a pencilshaped, light weight (80 kg), inexpensive, and easily deployable/retrievable coastal buoy which makes a variety of measurements throughout the water column. Data are transmitted from the surface buoy via satellite, GPRS or radio to a website for immediate access and data products (www.cfoo.co.za). Sensors depend on the application and include measurements of wind, air temperature, humidity, water temperature, dissolved oxygen, turbidity, ocean optics (fluorescence), currents, and wayes.

The surface buoy uses a dual anchor mooring which withstands currents $> 2 \text{ m s}^{-1}$, wave heights of 6 m, and maintains a tight buoy position. Instrumentation is attached to a benthic platform placed independently on the seafloor where it is safe from storms, ships and theft (Figure 7c). In depths < 40 m, scuba divers service the platform. Acoustic release technology is used for deeper deployments. Data Buoy can be deployed using a small craft such as an 8 m inflatable boat.

Complex data such as ADCP and wave measurements are processed on the seafloor and transmitted to the surface buoy via acoustic modems, eliminating cables (Figure 7b). *Data Buoy* and the associated instruments require maintenance approximately every 4 months. The first demonstration buoy was deployed in 36 m near the Sappi effluent pipeline in April 2008 and has been online 86% of the time. A second demonstration prototype *Data Buoy* (//), was deployed off Amanzimtoti (KZN) in February 2011 to monitor ocean conditions for automated effluent discharge.

4.2. Super Buoy project

In 2009 funding was again obtained from THRIP to design and build a larger buoy system to monitor the Agulhas Current and the Benguela Jet — both key currents around South Africa. Eskom (national electricity utility) and SASMIA were recruited as industrial partners — the latter strongly committed to harnessing renewable marine energies. This is an ambitious project as few buoys have ever survived more than a few months in any of the western boundary currents world-wide, and non have transmitted data in real-time.

Super Buoy is a much larger system than Data Buoy, designed to withstand the harsh offshore environment with greater depths, currents in excess of 3 m s⁻¹, waves of 10 m, storm winds and distances of 10s of kilometers from the coast. It comprises a subsurface mooring positioned in the middle of the water column, in this case at a depth of 500 m, and a surface buoy which is position several kilometers way (Figure 8) on the nearby shelf where conditions are less severe. The name is

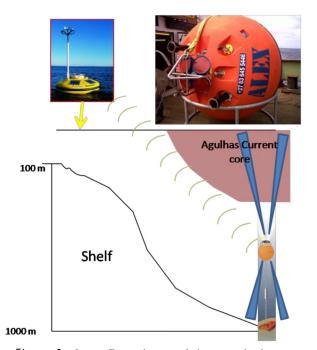


Figure 8: Super Buoy is a real-time monitoring system designed to withstand the severe conditions in the Agulhas Current. The syntactic float housing two ADCPs is deployed in 1000 m with the surface buoy deployed on the shelf edge in about 300 m. Data are transmitted from the ADCPs to the surface buoy using acoustic modems.

derived from the large syntactic float which has a diameter of 76 inches. The size and weight of the surface buoy and mooring requires a ship for deployment and retrieval.

The subsurface syntactic float accommodates two oppositely orientated Teledyne RDI 75 kHz, self contained, ADCPs. These instruments measure current velocity and direction above and below the mooring throughout the 1000 m water column, and temperature. Two acoustic modems, each dedicated to a single ADCP, transmit data to the surface. The surface buoy receives the transmitted data from the ADCPs, and together with data collected by surface metrological instruments, transmit these via GSM to a country-wide, land-based, cellular network approximately 20 km away, and then to a server based in Cape Town (www.cfoo.co.za).

Successful trails for the *Super Buoy* prototype were completed in the Agulhas Current off Port Edward between September 2010 and January 2011. After some minor improvements, and the installation of atmospheric sensors on the surface buoy, the system was permanent deployment in May 2011.

4.3. Multi-Mooring Single Surface Buoy Array (M2S2A) project

The Super Buoy project has paved the way for a second system to be deployed in the Benguela Jet off the Cape Peninsula in 2013. This current, although less energetic than the Agulhas Current and found in shallower water (~400 m), is narrow and displays substantial horizontal displacement. This is problematic when monitoring its behavior using a single bottom-mounted mooring.

A new 3-year THRIP project will be initiated in 2012 to develop a 5-point, real-time, bottom-mounted mooring system to monitor a horizontal distance of 20 km, ranging in depth between 100 and 800 m. The ADCP data will be transmitted horizontally from one mooring to another via acoustic modem (i.e. daisy chain) to the principal *Super Buoy* benthic mooring, and then to a surface buoy deployed inshore in 200 m of water. From here the data will be sent via GPRS to the main server in Cape Town.

The project will also attempt to incorporate into each mooring the new generation *Vemco* VR 4 acoustic tag receiver. These instruments will be supplied by the Ocean Tracking Network project (OTN) and used, in conjunction with the developed ADCP acoustic modem network, to provide an upload facility (node) for fish behaviour data collected by electronic tags deployed on various marine animals. These data will then be displayed on the worldwide web together with environmental data.

4.4. Real-time (RT) UTR project

The DT-UTRs have provided invaluable time series temperature data that have led to the discovery of physical processes and their monitoring. Now that some sites have 20 years of data, the network is used to track regime changes associated with climate change. Nonetheless, waiting for data for 6 months has caused frustration, particularly for fishermen who need near real-time temperature data.

To improve data delivery, the design of a cellular, dialout UTR was locally initiated in 2010. The project was sponsored by the *South African Environmental Observational Network* (SAEON). The first prototype was deployed at Cape Point in June 2010 but lacked the battery power to meet the criteria of 6-monthly maintenance. Data are sent to <u>www.cfoo.co.za</u>. Prototype II, which now utilises a mini solar panel, will be deployed in June 2011. Once proven at Cape Point, three RT-UTRs will be deployed on the southern KZN coast to complement the *in situ* observational network being established there (see Module II).

4.5. Wave measurements from a moored ADCP

Well proven methods to measure sea surface waves include the real-time surface moored *Datawell Waverider* buoy and the DT quartz crystal shallow water pressure sensor which is limited to depths of 20 m. In the last decade however, ADCP technology has become more attractive because it also measures currents, and being moored subsurface, has less chance of suffering from a mooring failure or ship collision. The problem is, the ADCP needs to be attached to a fixed platform which limits this method to water depths of < 60 m. Mooring lines easily extend the depth range but the sway in large swells introduces error in the data.

In May 2011 a project was initiated to develop a method whereby waves can be measured using an upward orientated ADCP attached to a mooring line. The technique uses an accelerometer attached to the ADCP to remove mooring motion.

4.6. HABs real-time monitoring

A coastal buoy has also been developed for early detection of HABs in St Helena Bay by the CSIR and DAFF (Fawcett et al., 2006). This measures currents, fluorescence and reflectance, with data and products available at habs.org.za.

5. THE OCEANSAFRICA INITIATIVE

The collaborative *OceanSAfrica* initiative was first conceived at a workshop on operational oceanography arranged in Cape Town in July 2009 under the auspices of the Applied Centre for Climate and Earth Systems Science (ACCESS). International experience showed that operational oceanography is multidisciplinary in nature and cannot be done by one institution alone. Coalition with specialist organizations was necessary.

In view of this, *OceanSAfrica* aims to develop operational activities in South Africa, and through a combination of modeling and observations, to deliver regular and systematic information on the state of the ocean that is of known quality and accuracy on open ocean to shelf scales — ultimately with forecasts. Partners include the Department of Environmental Affairs (DEA), University of Cape Town (UCT), Council for Scientific and Industrial Research (CSIR), South African Environmental Observation Network (SAEON), Marine Remote Sensing Unit (MRSU), South African Weather Service (SAWS), the Institute for Maritime Technology (IMT) and Bayworld Centre for Education and Research (BCRE).

OceanSAfrica comprises 4 pillars — in situ observations led by DEA, remote sensing led by the CSIR, modeling led by the Simocean grouping (UCT, CSIR and Nansen Tutu Institute), and data

dissemination led by SAEON. The four pillars host and manage their own websites, which are also accessible OceanSAfrica through the portal http://www.cfoo.co.za/oceansafrica (URL is temporary). R&D, collaboration and reporting are coordinated through the OceanSAfrica Technical Task Group (TTG) which meets bimonthly and is mandated its Statement of Intent http://www.cfoo.co.za/oceansafrica). With the successful demonstration of the viability of an operational oceanography system, the emphasis will shift to designing and implementing a sustained operational oceanographic service for South Africa, under the leadership of DEA Oceans & Coasts. This will require the integration of all 4 pillars, a role out program of monitoring equipment, additional levels of technical support, data quality control and round the clock maintenance — aspects all well suited to government funded agencies.

INTEGRATION AND DEVELOPMENT OF A REGIONAL /N-S/TU OBSERVATIONAL NETWORK

Advances in technology now allow for the most comprehensive real-time monitoring systems using fixed and mobile platforms, and satellites, all with an increasing number of reliable sensors types. Examples are the Atlas mooring arrays TAO/PIRATA/RAMA placed around the planets equatorial regions (http://www.pmel.noaa.gov/tao/data_deliv/deliv.html) and Subsea Cabled Observatory Network Systems with coupled use of gliders, ascending CTDs, ROVs, AUVs, etc (http://oceannetworks.ca/). Mindful of the costs of such systems and the resources needed to successfully maintain them, it is however only prudent that South Africa as a developing country selects a more modest approach which meets its specific needs, and importantly, is realistically sustainable.

A fully developed operational oceanographic service such as MyOcean (www.myocean.eu.org) is highly desirable, but this will take time to achieve. At the moment weather and ocean models, fisheries, MPAs (coastal and offshore) and ecosystem shifts as a result of global change are important activities and issues which require observational data and monitoring to address them. An in situ observational network will therefore need to be strongly orientated towards ecosystem functioning which implies measuring and monitoring key physical (and biological) processes such as currents, stratification, winds, upwelling, production as well as providing data to improve both atmospheric models, and long-term datasets (Figure 1). Some distant monitoring is also necessary to validate and ultimately improve the skill of both regional atmospheric and ocean models.

These will be complimented by satellite observations collected by the MRSU.

In January 2011, the newly formed branch *Oceans & Coasts* in DEA formally adopted *Operational Oceanography* as one of its 4 core programs with emphasis initially on establishing an operational *in situ* and long-term monitoring network and service. The domain was determined by the atmospheric and ocean models and South Africa's EEZ (Backeberg et al., this issue). The network, comprising both real-time and delayed time sites, will cover key coastal, shelf, and deep ocean processes and regions, and include atmospheric measurements (Figure 1). Deep ocean monitoring will be developed through collaboration with regional programs in the Atlantic, Indian and Southern Oceans.

A modular plan has been adopted by DEA Oceans & Coasts to be implemented between 2011 and 2016. While the modules link together to ultimately produce an operational *in situ* observational service, many can be and must be undertaken simultaneously.

6.1. Module I: Observational ship data

DEA Oceans & Coasts will immediately take over and manage the 28-year old research ship environmental dataset for the South African shelf region. It will maintain all principal physical (CTD, S-ADCP, continuous) and meteorological (atmospheric pressure, wind direction and speed) sensors on the research vessels, including calibration and data quality control. Copies will be provided to the South African Data Centre for Oceanography (SADCO) for back-up. The SHBML and SARP will similarly be maintained. In collaboration with SAEON, products for individual cruises and climatologies will be developed and made available online for model validation and users.

The observational system will be expanded to include three region monitoring lines outlined in section 3.6: the existing Good Hope line and the establishment of the two new monitoring lines Cape Town-Prince Edward/Marion and Cape Town-Gough Island.

6.2. Module II: Integration and demonstrated delivery — KZN observational node (2011-2013)

DEA Oceans & Coasts will integrate existing delayed mode and real-time monitoring networks to form the base of its *in situ* observational network, i.e. the routine ship-based sampling (DAFF), the South African UTR network, the CSIR WaveNet and the SA Navy Hydrographic Office tide gauge network. It will take over the maintenance of the two demonstration real-time coastal buoys off Umkomaas (*Data Buoy I*) and Amanzimtoti (*Data Buoy II*) which already monitor

maritime conditions south of Durban harbour and perform important roles in ecosystem monitoring, effluent discharge management, recreational diving and fishing, and tanker activities at the petroleum refinery's Single Buoy Mooring (SBM) off the Bluff — these activities all beginning to define the user group of an operational system. Southern KZN has the greatest concentration of maritime activities in South African waters and is the ideal location for initiating operational oceanography.

In keeping with the theme of demonstrated delivery of a manageable but comprehensive operational system the offshore Super Buoy project near Port Edward will also be adopted by DEA Oceans & Coasts, but this will be complemented in 2012 with a shore-based radar system to provide surface currents and waves: while the two upward and downward orientated ADCPs on Super Buoy can provide data throughout most of the 1000 m water column on the continental slope and in the core of the Agulhas Current, data deteriorate near (~50 m) the seabed and sea surface boundaries leaving gaps in the delivery of information. To complete an operational oceanography service, it is anticipated that the Port Edward Super Buoy and radar will also provide in situ data to calibrate satellite derived Synthetic Aperture Radar (SAR) data, which in turn will make available surface maps of the currents on the east coast of South Africa — a product long desired by shipping. Shorebased metrological stations will be deployed at Port Edward and Amanzimtoti.

Critical to the success of this operational oceanography service are (1) committed long-term budgets, (2) speedy procurement of equipment and services, (3) ship time for maintenance, (4) increased human resources with the necessary skill sets, and (5) easy public access to the data and products. These will need to be developed alongside the operational network to ensure the goal of 90% online for all measurement platforms. To assist in obtaining the correct skill sets, a training program is now in place with the Cape Peninsula University of Technology (CPUT) where students will obtain a Masters degree in Technology (M Tech degree) specialising in physical and observational oceanography.

Once established by the end of 2012, the southern KZN observational node consisting of one DT-UTR, three RT-UTRs, two metrological stations, the two coastal *Data Buoys*, *Super Buoy*, and a radar station will be maintained operationally for a period of two years to complete this phase.

6.3. Module III: Expansion of the *in situ* observational network in South Africa

This phase will see the upgrade and expansion of the UTR network along the South African coast with RT-UTRs, the deployment of *Data Buoys* in Algoa Bay to complement the SAEON network (Goschen and Schumann, 2011), the Tsitsikamma National Park existing monitoring site (Roberts and van den Berg, 2005), and St Helena Bay to complement the existing trans-shelf monitoring line (SHBML). A second *Super Buoy* will be deployed off the Cape Peninsula to begin monitoring the Benguela Jet (and complement the SARP line).

These will be complimented by an offshore delayed-time network comprising 5 ADCP moorings, which aside from bottom temperature and currents, will measure the wave field on the Agulhas Bank along the 80 m contour between Cape Columbine and Algoa Bay (Figure 4). These data will complement the existing CSIR's WaveNet as well as used to validate/calibrate models and remote sensed data from satellite and radar.

6.4. Module IV: Regional expansion, integration, data quality and training

The lack of funding and ship time to maintain the Western Indian Ocean (WIO) component of the UTR network is a major problem. This network of sensors, all at the depth of 18 m, is becoming extremely valuable as a long-term temperature dataset (Figure 4) and is unique to the region. It complements satellite data and other larger, deep ocean arrays such as the tropical RAMA and Mozambique Channel LOCO arrays by providing shelf data — all focused on climate variability and global change. Finding funding to maintain and expand the existing WIO DT-UTR network must be a priority and achieved before the data memory of the instruments in the field become full.

As indicated in Phase III below, the modelling pillar of OceanSAfrica will require in situ data from remote locations in the model domain to improve skill. Some of these data can be provided by the RAMA array in the Indian Ocean and the south-eastward extension (SEE) of the PIRATA array in the Atlantic Ocean. The latter in particular will only happen if South Africa shows a strong desire to have these observations, and moreover, is prepared to deploy and maintain Atlas buoys as Brazil is already doing on the western side of PIRATA. This implies South Africa must become a member of PIRATA and RAMA, develop the skills necessary to operate the Atlas buoys, guarantee ship time, and purchase several buoys. Training will need to come from the PIRATA and RAMA stake holders i.e. NOAA and IRD. Additional platforms outside of the PIRATA-SEE and RAMA areas of interest may well

be required to improve model skill. Positions need to be directed by the model studies and analysis but clearly will involve large buoy systems such Atlas buoys.

6.5. Module V: Assimilation of in situ observational data into models

Once the *in-situ* observational network is operational and robust, the real-time transmitted data will be sent to the ocean modelling group (*Simocean*) based at the University of Cape Town for assimilation into, and validation of the regional ocean model. As indicated in module III, optimisation of the *in situ* measurement network (particularly position in the model domain) will need to be undertaken to improve model skill.

6.6. Module VI: Science and technology to support in situ observations

Paramount to any *in situ* observational system is a scientific understanding of the physical (and biological) environment it is measuring. In South Africa many of the physical (and biological) processes have received attention but this is mostly in the Benguela upwelling region on the west coast where the major commercial fisheries are based (e.g. Shannon and Nelson, 1996). The Agulhas Current has also received considerable attention as evident in Lutjeharms (2006). But in contrast, the Agulhas Bank and the east coast shelf have received much less attention.

Areas and processes which need attention for the in situ observational system to be most useful are: the cold ridge on the Agulhas Bank which is thought to be an important process for production. Notwithstanding several studies, the mechanism under laying this feature is still not known even with modelling (Chang 2008). The Benguela jet has also received considerable attention because of its importance in transporting eggs and larvae from the spawning grounds of the Agulhas Bank to the feeding grounds of the west coast. But the dynamics are not well understood. Another is the Tsitsikamma coastal counter-current (Roberts and van den Berg 2005). This plays an important role in the transport of biological material in the Tsitsikamma National Park, and also transports away from the cold ridge region. Its dynamics are quite well understood but its origin, termination and width are unknown. Apart from some S-ADCP cruise data (Boyd et al, 1994; Roberts 2005), very little is known about the mid and outer shelf currents on the eastern, central and western Agulhas Bank. Average S-ADCP data suggest a continuous net westward flow which feeds into the Benguela jet, but moorings need to be deployed to test this. Also the temporal behaviour of the Agulhas Current along with cyclo-genesis (Natal pulse and Durban break-away eddy) off southern KZN coast require attention. Of great importance is the effect of these cyclones on the shelf oceanography and ecosystem of the KZN, the Transkei and eastern Agulhas Bank. For example, monitoring cyclo-genesis could be useful in predicting the arrival of sardines in KZN. These studies will additionally provide information and data to improve and validate the oceans models (*Simocean*).

R&D must continue on the in situ observational system to improve the sustained delivery of reliable and accurate data. Platforms, sensors and communication technology will need improvement to meet local conditions and with latest products. For example, while Data Buoy has been successful in terms of ocean measurements, the surface buoy tilts in a current > 1 m s⁻¹ which might be compromising the meteorological sensors. This could require a new buoy design necessitating wave and current tanks. There is also the development of the expanded Super Buoy project and the measurement of waves from deep, swaying moorings, these both requiring advances in modem acoustic data management and signal processing. The ADCP mooring wave project requires R&D in signal processing.

Although DEA Oceans & Coasts may not be directly involved with the development of SAR products, the radar data will be useful for calibration purposes which will provide the South African *in situ* observational system with horizontal regional current data.

7. CONCLUSION

The diversity, complexity and high energy of the ocean systems surrounding southern Africa have been highlighted. These present a challenge to the many marine activities which occur here and affect parameters such as operations, performance and safety, as well as to the management of ecosystems, fisheries, coastal communities. disasters, and moreover, prediction. In terms of climate change research, this region is also pivotal in the transportation of heat and salt from the Indian Ocean into the South Atlantic Ocean, providing a source for the equatorward flux in the Meridional Overturning Circulation (MOC). The OceansAfrica initiative, through its four complimentary pillar projects (in situ observations, remote sensing observations, modeling and data dissemination), is a partnered scientific community and governmental (DST and DEA) response to these challenges which aims to understand, monitor and predict key elements of these ocean systems and importantly to freely disseminate information into the public domain as a service. In this paper, the modular plan to develop and implement the *in* situ ocean observational network for the region is presented. This builds on existing monitoring efforts by a number of institutions and includes local R&D of buoy and sensor prototypes suitable for the energetic

conditions found in this region. This observational network will be linked into the regional PIRATA and RAMA tropical arrays, and will form key components of the BCC and ASCLME proposed long term ecosystem monitoring programmes. Ultimately, these data will be used to provide an ocean state and prediction service to the public.

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OceanSAfrica Data Archiving and Dissemination

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1. INTRODUCTION

Worldwide standardisation, and interoperability initiatives such as GBIF, Open Access and GEOSS (to name but three of many) have led to the emergence of interlinked and overlapping meta-data repositories containing, potentially, hundreds of millions of entries collectively. This forms the backbone of an emerging global scientific data infrastructure that is both driven by changes in the way we work, and opens up new possibilities in research methods and approaches.

Several initiatives are concentrated on building a generalised, shared, easily available, and indefinitely preserved scientific data infrastructure to aid future scientific work. The vision is that of the 'fourth paradigm', where massively data-intensive research opens new areas of enquiry and insight.

This article first provides a general overview of the meta-data driven management landscape, with the parallel aspect of the meta-data that will be used to support the global scientific data infrastructure, and then proposes measures whereby current infrastructure managed by SAEON can be used to provide the OceanSAfrica initiative with a data dissemination service.

2. CURRENT INFRASTRUCTURE

SAEON is currently building infrastructure with metadata repositories as its main driving force: this is already operational and available for cataloguing and disseminating the collective information resources of the OceanSAfrica initiative. The infrastructure forms part of a shared platform that hosts the SAEON Data Portal [1], The South African Risk and Vulnerability Atlas [2], the South African Earth Observation System (SAEOS) [3], the CSIR GSDI GeoPortal [4], and a prototype World Data Centre for Biodiversity and Human Health in Africa (WDCBHH) [5].

The platform is based on a shared and aggregated metadata repository, and the meta-data repository is capable of accepting and working with a range of well-established meta-data standards. These include Dublin Core, SANS 1878, the ISO 19115 family, EML, and FGDC. The list is likely to be extended from time to time to accommodate other standards in widespread use by a user community or new data provider, and should in future include standards widely in use in the Oceanographic Community.

The platform and its hosted portals are designed to serve a stakeholder community as a resource for the referencing, description, discovery, management, and optional archiving of relevant data sets and information objects. It also allows the composite visualization of distributed data sets, provided that access to these sets is automated and standardized.

The platform also provides *collaboration*, *sharing*, *and content composition facilities* for the distributed creation and management of value-added themes, discussions, blogs, community pages, and more.

SAEON is currently the implementation agent for the platform and its hosted portals, and can assist with

- guidelines in respect of choice of meta-data standard and supporting open source software,
- creation of meta-data,
- guidelines in respect of applicable standardized data standards and services, and
- hosting or archiving of data in most circumstances.

In the recent past, the development programme has extended the platform to accommodate a *range of meta-data standards* (ISO19115, SANS 1878, EML, Dublin Core, and FGDC), and to allow automated harvesting of such meta-data from repositories offered by data providers and stakeholders. In addition, the platform also contains an OpenLayers-based *mapping component, capable of constructing map views from distributed sources*, persisting those views for logged-in users, and dynamically searching any GEOSS-

compliant CSW service for new layers to include into the map. It is envisaged that the finished component will be registered in the GEOSS repository.

2.1 GEOSS

The platform is being prepared for *GEOSS integration* through the development of CSW-compliant meta-data services [6]. This will allow other GEOSS components to harvest from the collective meta-data catalogue of the shared platform. These include the in-situ observations emanating from SAEON and its stakeholders, the contributions of the CSIR's Satellite Application Centre (SAC) [7], the biodiversity and downscaled climate change sets contained in the Risk Atlas, in-situ demography, and many more. Most available meta-data will be uploaded for operational use during the early part of 2011.

2.2 HOW DOES DATA ACCESS WORK?

Access to data sets is determined by the preferences of the provider community, and can range from the ideal situation of open, automated standards-compliant services (WFS/WMS, NetCDF, etc.) through download links or redirection to provider-determined websites.

Under ideal circumstances, *data providers curate their own data holdings* on a platform that is acceptable to them, and the links to data sets are included into metadata records. The platform can also host data on behalf of a provider should the requirement exist.

Options for providing access to data include the following:

- 1. Automated access to data, in any of the following standardized formats:
 - a. A Web Map Service (WMS) or Web Feature Service (WFS) commonly used to serve spatial data over the web.
 - b. KML files located anywhere at a valid web address (URL);
 - c. GeoRSS services located anywhere at a valid URL;
 - d. Any link to a valid web-based document (such as a PDF, ZIP, or data file).

- e. NetCDF and HDF formats (in the pipeline).
- 2. Any valid link to a web page maintained by the provider, where a prospective user
 - a. Can be asked to register or log in if already registered;
 - b. Fills in a request for data to be processed off-line;
 - c. Constructs a query to subset data for download or visualization;
 - d. Is provided with contact details so that a data set can be obtained manually.

SAEON has developed a <u>comprehensive data policy</u> that regulates meta-data and data access, and can be used as a basis for formalized agreement between a data provider and the platform. Moreover, both meta-data and data access can be controlled through a finely-grained publication life cycle and user management subsystem.

SAEON is also currently researching the user requirements for access frequency and user behaviour reporting to providers and will aim to implement services to support this towards the early part of 2011.

3. OCEANSAFRICA DATA DISSEMINATION

3.1 STATEMENT OF INTENT

The statement of intent with respect to data dissemination was agreed between OceanSAfrica participants:

- Specify and develop a set of guidelines, standards, and reference implementations for a data management system capable of ensuring inter-operability for operational oceanography, which remains appropriate beyond the demonstration phase of OceanSAfrica.
- Amalgamate the web-sites, set up by the various pillars, into an integrated delivery mechanism of products of value to an extended user community.
- Build and host a standardised meta-data repository whereby products, data sets,

documentation, and appropriate reports can be discovered.

3.2 DESIGN CONSIDERATIONS

To realise these intentions, most effort will be required in agreeing the guidelines and standards: the technical support for these already exist in the shared platform in one form or another, or are the subject of planned extensions to the platform. The design considerations in respect of this are the following:

- Data should be:
 - O Portable;
 - O Self-describing requires metadata conventions, many of which exist:
 - "CF" standard: developed for the exchange of climate model results, Argo and WOCE data [6];
 - 'COARDS' Cooperative Ocean-Atmosphere Research Data [7];
 - ncML extends GML with NetCDF Semantics and Geography [8].

Two types of meta-data may be required:

- O In formats such as NetCDF, the meta-data is linked directly to the data set. This is convenient for NetCDF clients, but is not useful to others.
- O It must be possible to extract and publish the NetCDF meta-data, together with additional non-technical extensions, through standardised services, such as CS/W.

Other considerations:

- Use an open source project for Network Data Access Protocol (OPeNDAP, formerly known as DODS [9] implementations;
- Consider the (US) National Virtual Ocean Data System - a data portal compatible with OpeNDAP servers [10];
- Live Access Server to be considered highly configurable web server designed to provide flexible access to geo-referenced scientific data [11];

• Thematic Real Time Environmental Data Distributed Services (THREDDS) is widely used in this environment [12].

3.3 INTERFACES AND ARCHITECTURE

The data standards, infrastructure, and conventions developed in the wider 'fluid sciences' environment are functional and mature, but have to date had little relationship to the wider data standards landscape [13] in terms of discovery and dissemination. This is being remedied in various ways by the international fluid sciences community, and it should be possible within the next year to develop an integrated architecture that exposes both OGC-compliant services and the traditional fluid sciences interfaces to users. A possible architecture to accomplish this is shown in Fig. 2.

In this architecture, three important new interfaces are required:

- 1. OGC standards require discovery through Catalogue Services for the Web (CSW), and an interface is required to translate THREDDS Catalogues into a CSW output.
- 2. OpeNDAP is used to sub-query and aggregate distributed NetCDF data sources, but these could also be required as Web Coverage Services (WCS). A GML/ GeoTIFF service that translates NetCDF aggregations will be required to do this.
- 3. WCS clients may want to issue sub-queries of their own, which need to be translated into OpeNDAP requests before they can be performed.

4 WORK PROGRAMME

The following is a summary of the work programme envisaged for the shared platform for the next 12-18 months.

- 1. There is an on-going programme to add new data providers and meta-data sources.
- 2. DST is funding a joint programme that includes SAEON, Meraka Institute and the Agricultural Research Council to implement SensorWeb technology for the shared portal. The aim is to kick-start greater integration with GEOSS. The outputs include visualisation tools.

- 3. A joint programme with OceanSAfrica and the Marine Remote Sensing Unit (UCT/ CSIR) to create visualisation tools (maps and charts) for distributed NetCDF data sources.
- 4. Implementation of distributed Web Processing Services.
- 5. Implementation of 'mediation' technology, whereby distributed visualisations and processes can be persisted for future re-use. A prototype system exists for use as a field-based data capturing/ Citizen Science tool.
- 6. Automated linking to and integration with online data publishing initiatives, such as LiquidPub and CITE.
- 7. Measures to allow remote authentication into data provider sites, and mechanisms to support data providers with detailed, service-based usage metrics of their data and meta-data.

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- [2] Funded by the South African Department of Science and Technology as part of their Grand Challenge Research Plan.

- [3] SAEOS is funded by DST (Department of Science and Technology) as part of their contribution to GEOSS.
- [4] Previously known as 'CoGIS', funded jointly by CSIR, SAEON, and other stakeholders.
- [5] Funded by NRF/ SAEON and the US Geological Survey/ NBII.
- [6] The Global Earth Observation System of Systems, as promoted by GEO. http://earthobservations.org
- [7] Includes SPOT, CBERS, and SACC series, as well as derived data.
- [8] Based on inputs from Bjorn Backeberg and Stuart Bernard.
- [9] http://cf-pcmdi.llnl.gov/
- [10] http://www.opendap.org
- [11] http://ferret.pmel.noaa.gov/NVODS/
- [12] http://ferret.pmel.noaa.gov/LAS/
- [13] http://www.unidata.ucar.edu/projects/THREDDS
- [14] OGC (Open Geospatial Consortium) http://opengeospatial.org/
- [15] ISO (International Standards Organisation)
 Technical Committee 211 http://www.isotc211.org
- [16] W3C (World Wide Web Consortium) http://www.w3.org/

Fig 1: Typical Use Cases in Portals providing Data Access and Collaboration Support

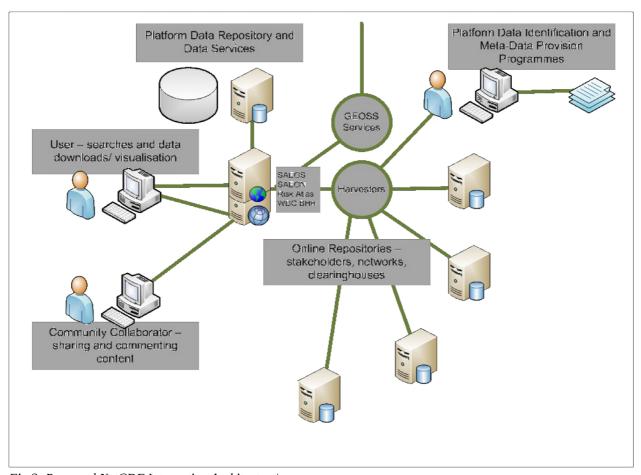
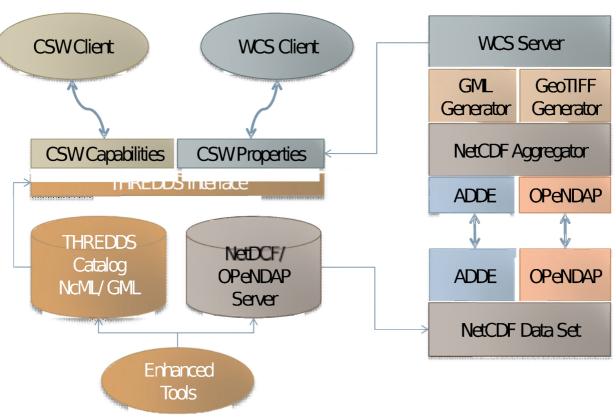


Fig 2: Proposed NetCDF Integration Architecture\



MYOCEAN: TECHNICAL ASPECTS OF OPERATIONAL OCEANOGRAPHY

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ABSTRACT

This short note is an extended abstract of the talk given by the author at the "Joint Nansen-Tutu and OceanSAfrica meeting" held in Cape Town, south Africa in December 2010. This talk was dedicated to the presentation of the MyOcean and Mercator Océan operational oceanography experience and achievements, in order to help south African operational oceanography emerging project to develop taking into account the experience gained in Europe in the same domain.

It presents a status of the MyOcean project, taking Mercator Océan example to illustrate the capacity developed, Mercator Océan developing in particular the global forecasting component of the MyOcean system of systems which covers the region of interest (i.e. the Aghulas, Bengela region).

1. MERCATOR OCEAN IN A NUTSHEL

Mercator started in 1995 as an idea originally pushed by the French research community that it was possible and opportune to build operational oceanographic systems, based on the assimilation into ocean models of oceanic observations, to deliver usefull services to a wide range of users, including civilian, military, public or private (including commercial) and contributing positively to climate and seasonal forecasting.

It was endorsed by the French major agencies concerned by oceanography, and was organised as a project. Rapidly after, a public company was established to run this project.

Mercator Océan is today a non profit French organisation, which has been recently renewed for 15 years. It is currently supported by the CNRS (Centre National de la Recherche Scientifique), IFREMER (Institut Français de Recherche pour l'Exploitation de la MER), IRD (Institut de Recherche pour le Développement), Météo-France and the SHOM (Service Hydrographique et Océanographique de la Marine).

Mercator Océan is also a team of about 50 people, most of them being oceanographers, who work on the research, development, operation and validation of global and regional ocean model which assimilate real-time observations from satellite altimeters, SST and in situ T/S profiles, and who provide to the users numerical ocean prediction data (4D ocean state), global reanalysis and oceanographic expertise.

Products and services can be requested through the service desk products@mercator-ocean.fr.

Mercator Océan is a member of several international organisations, among which are GODAE OceanView (www.godae-oceanview.org) and EuroGOOS (www.eurogoos.org).

In the recent years, Mercator Ocean has been selected by the European Commission (EC) to lead the MyOcean project (www.myocean.eu), funded by the 7th Research and Development Framework Program of the EC. This project is building the bases of the European Marine Core Service of GMES (Global Monitoring for Environment and Security).

Following the definition provided in the GODAE Strategic Plan, operational oceanography means:

"Operational means whenever the processing is done in a routine and regular way, with predetermined systematic approach and constant monitoring of performances."

2. THE MYOCEAN CONCEPT

Web site: www.myocean.eu

Contact: MyOcean@mercator-ocean.fr Service desk: servicedesk@myocean.eu.org

MyOcean concept is 3-fold:

- 1- MyOcean as a project: this is a FP7 3-year project building the GMES "Marine Fast Track service". It started in April 2009 (will end in April 2012). It costs ~20m€year, with ~11m€year EC funding.
- 2- MyOcean as a service: MyOcean is the main component of the GMES "Marine Core Service", implementing the Global and Regional Ocean Monitoring and Forecasting capacity
- 3- MyOcean as a team: MyOcean is a consortium of 61 partners from 29 countries (mainly European countries). The total project effort is ~150 person.year. Twenty out of the 61 partners are strongly committed to the operational work. They have been chosen in Europe among the more skilled monitoring and forecasting system operators.

The Core Service concept has been defined in Europe as the provision of oceanic information (namely the oceanographic variables, T, S, currents, sea level, ice, biogeochemistry...) at any time (forecast, hindcast, reanalysis) and everywhere based on the assimilation of the real-time

observations delivered by the GOOS (Remote sensing: satellite altimetry, sea surface temperature, ocean colour, sea ice and wind measurements, and in situ: temperature and salinity profiles, current measurements, tide gauges, ...) in state-of-the-art ocean model configuration covering the global ocean (at typical resolution of 1/12°, i.e. eddy resolving), with an enhanced capacity (increased resolution, more physics such as high frequencies and tides, locally tuned, using local observations) in the European regional seas, namely the Med, the Baltic, the Black sea, the north-eastern Atlantic and in the Arctic ocean.

The system which supports the delivery of this core service is a system of systems, gathering the best skills in Europe in terms of modelling centres (7 centres), and thematic centres dealing with the processing of the observations (5 centres). These system components are all linked to a centralized information system which ensures the operational flow of information through this complex organisation. At the end, a centralized service organisation (single service desk) helps the users that can access to the products and services through a webportal. The users are served homogeneously whatever the product source (the physical centre that have build the products) is. Figure 1 shows the coverage of the 7 Monitoring and Forecasting Centers which cover the Global ocean (Mercator Océan), the Arctic Ocean (met.no/NERSC, Norway), The Baltic (DMI, Denmark), the North West Shelves (The Met Office, UK), the Iberian Biscayan and Irish seas (IBI, Puertos Del Estado, Spain), the Med (INGV, Italy) and the Back Sea (MHI, Ukraine).



Figure 1: The 7 MyOcean modeling centers, and their interactions

3. THE MYOCEAN SERVICE STATUS

4 areas of benefit have been identified:

Area 1- Marine Safety: marine operations, oil spill drift, ship routing, defense, search & rescue, ...

Area 2- Marine Resources: fish stock management, ICES, FAO, ...

Area 3- Marine and Coastal Environment: water quality, pollution, coastal activities, ...

Area 4- Climate and Weather Forecasting: climate monitoring, IPY, seasonal forecasting, ...

For these 4 areas of benefit, services are delivered. They consist of numerical products described in one single catalogue, delivered through a single point of access (catalogue of products and services available on the web portal), under an open and free access data policy.

The version 0 of the service, operated from the project kick-off until December 2010 was based on the assets of previous projects. The first real service deployed with MyOcean has been opened to the users on December 16th 2010: this is the version 1 of the MyOcean core service, opened 21 month after the project kick-off, and delivering improved services and products as compared to V0.

Before launching the service V1, we have conducted a user survey to better understand them and what they need. 41 users of the service for the period from March to July 2010 filled the questionnaire.

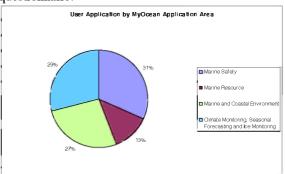


Figure 2: the MyOcean users per area of benefit

Figure 2 shows one of the result of this survey. The users of the MyOcean service for this period belong mainly to the Area 1: Marine Safety (31%). They consist of users working for Marine Operations (23%), Defence (10%), Search & Rescue (15%), Weather forecasting (19%), Ship routing (10%), Environmental Hazard (23%).

Then comes Area 4: Climate and Weather Forecasting (29%). These users work on Seasonal Forecasting (20%), Climate Monitoring (63%), Ice Monitoring (17%).

Then is the Area 3: Marine and Coastal Environment (27%). They work on Coastal Activities (34%), Water Quality (34%), Pollution (32%).

Only a small amount of users for this period work on Area 2: Marine resources (13%). They all work on Fish Stock Management.

This survey was a first attempts to understand better the users. It provides only a first preliminary indication of what is the demand for such services, but already provide useful information.



Figure 3: the MyOcean users (after 18 month of V0 service)

Before the launch of V1, users from 39 different countrys (65% European, 35% outside Europe) were connected to the MyOcean services. They are mainly intermediate users, i.e. service providers who use this core service to deliver value-added services to their final end-user.

The number of services delivered has augmented regularly every month since the launch of the V0, as illustrated in Figure 4. The number of services delivered reached 2000 in October 2010 (not shown).

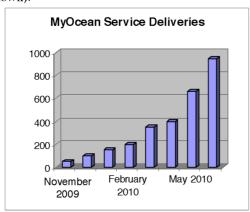


Figure 4: number of services delivered by MyOcean for the 8-month period from Nov 2009 to June 2010

4. THE MERCATOR OCÉAN SYSTEMS

The Mercator Océan systems are part of the MyOcean: they contribute to the overall system of system (Global Monitoring and Forecasting Centre, and backup of the Iberian Biscayan and Irish sea (IBIROOS) Monitoring and Forecasting Centre to be operated by Puertos Del Estado by June 2011). Mercator Océan currently runs 3 types of forecasting systems:

- I- Global eddy permitting (since 2005)
 - Global coverage at ¼°
 - NEMO/LIM, SEEK assimilation of altimetry, T/S and SST, weekly forecast
- 2- Regional eddy resolving (since 2002)

- North Atlantic + Mediterranean (1/12°)
- NEMO/LIM, SEEK assimilation of altimetry, T/S and SST, daily forecast
- 3- Global low resolution (since 2004)
 - Global coverage at 2°
 - Since June 2008: OPA8, SEEK assimilation of altimetry, T/S and SST, weekly forecast

In addition, 3 new capacities are under development:

- 1- Global eddy resolving (to be operational at the end of MyOcean)
 - Global coverage at 1/12°
 - NEMO/LIM+SEEK, assimilation of altimetry, T/S and SST, weekly forecast
 - Has been demonstrated in April 2008 and is Pre-operational since July 2010 (weekly)
- 2- Northeastern Atlantic high resolution (to be Operational at the end of MyOcean)
 - Covering the IBI domain at 1/36°
 - NEMO 1/36° +SEEK + Tidal free surface
 - Initialised and constrained at the boundaries by the assimilative regional 1/12° Daily forecast
- 3- Global biogeochemistry
 - Global coverage at 1°
 - Coupled offline to the global ¼°
 - Based on PISCES biogeochemical model

All our model configurations are run using NEMO (Madec 2008) code on the same ORCA tripolar grid (Madec and Imbard, 1996) as illustrated in Figure 5.

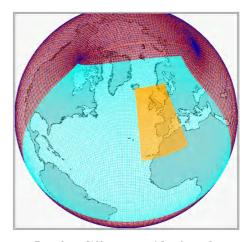


Figure 5: the different grids for the model configurations. All systems are on the ORCA grid at different resolution: yellow: IBI 1/36, Cyan: NATL+ MED 1/12, red and blue: Global systems (2, 1/4 and 1/12°)

The operational capacity over the South African region is for the moment relatively modest (1/4°). However, the global 1/12° which resolves the eddies, provide a very interesting depiction of the

main features in this region as illustrated in Figure 6 (from Tranchant et al. 2010).

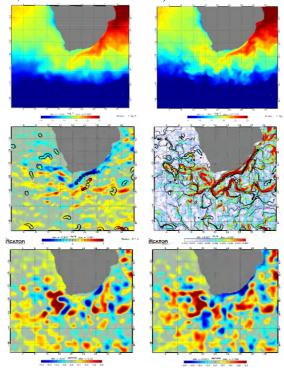


Figure 6: The Agulhas region as simulated by the Global Mercator Ocean eddy resolving system for a given date: Nov 25th, 2009. Top raw SST. Left OSTIA (obs derived product), right Mercator. Middle raw surface current (left zonal, right total) velocities superimposed on drifter data (circle size indicate the distance between the observation date and the map date. The larger, the closer, colours indicate velocity). Botton row: sea level. Left from altimeter data (DUACS products), right from Mercator forecast forecast.

In a recent paper, Biastoch et al. (2009) argue on the need to capture realistically the mesoscale processes in order to have a good representation of the Agulhas leakage. We see in Figure 6 that the main surface features are well represented in a 7day forecast obtained with the 1/12° Mercator system: main eddies have the same shape and the same location in the forecast and in the altimeter observations (bottom raw) the main differences being located near the coast where the observation errors are the highest. We note also the more detailed representation of the features in the forecast than in the observation derived OSTIA product (top row). Moreover, comparisons with drifter's buoys show good agreement (middle row) for the main features, especially the retroflection area. The Agulhas current and the Agulhas Return Current (meander) are very well represented by the model forecast.

5. CONCLUSION

MyOcean is the major European initiative to provide core ocean services. Engineering effort has been dominant during this first half of the project: development of the MyOcean Information System (MIS), leading to the opening of the first version of the integrated MyOcean service in December 2010. Mercator Océan is the operator of the global ocean monitoring and forecasting centre within MyOcean. In that context, it is implementing a full suite of operational systems from global 1/4° to regional 1/36° (including tides) based on NEMO configurations on ORCA grids, assimilating altimeter, SST and T/S profiles.

Global 1/12° system is developed and operated in demo mode. The target date for operational service with this global 1/12° is the end of the MyOcean project (V2, Beg of 2012). This system has a good capacity to simulate the Agulhas region, and the eddy activity associated with the retroflection.

South African initiative to develop operational oceanography is very much welcome, and Mercator/MyOcean products are available, access to them is open and free. We hope the Mercator/MyOcean capacity and experience will help South Africa to develop its operational capacity.

ACKNOWLEDGEMENTS

MyOcean project is funded under FP7-Space-2007-1-CT-218812-MYOCEAN grant agreement.

The author was invited by the local organiser and all the expenses related to the participation of the author to the meeting were covered by the South African Centre for High Performance Computing (CHPC).

We are particularly very grateful to Bjorn Backenberg and Laurent Bertino who provided us this unique opportunity to participate to this outstanding event.

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Annex

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