A Review of Physical Oceanographic research undertaken in South Africa, 2003-2006

I J Ansorge

Department of Oceanography, University of Cape Town

The purpose of this article is to review progress in the fields of atmospheric science and physical oceanography made by workers based at South African institutions over approximately the last 4 years. Most published research in these fields falls within the broad areas of climate variability, climate change, seasonal forecasting, numerical modelling (both atmospheric and oceanic), Southern Ocean dynamics and the physical oceanography of the Agulhas and Benguela current systems.

A number of interesting results have been achieved in the field of physical oceanography in South Africa during the past few years. This is all the more remarkable since this has been a period in which a large number of international research programmes in the region have come to an end (Reason et al., 2006a). This has included the KAPEX (Cape of Good Hope Experiment) (Boebel et al., 1997; Lutjeharms et al., 1997), the MARE (Mixing in Agulhas Rings Experiment) (Lutjeharms et al., 2000; de Ruijter et al., 2006) and the ACSEX (Agulhas Current Sources Experiment) (de Ruijter et al., 2006; Ridderinkhof et al., 2001), there has been a near total cessation of environmental papers from the branch of Marine and Coastal Management of the state Department of Environmental Affairs and Tourism (Anonymous, 2002, 2004, 2006) and the environmental unit of the CSIR (Council for Scientific and Industrial Research) has not produced any research papers either. In the latter case this is notwithstanding the management decision of that body to reverse the policy of the 1980s to become a purely commercial consultative body (Lutjeharms and Thomson, 1993). This demise of physical oceanography in a number of institutions in South Africa has meant that just about all research in this field is now being carried out at the University of Cape Town. Notwithstanding this rather dismal picture, there have been a number of highlights.

Along the west coast of southern Africa the BCLME (Benguela Current Large Marine Ecosystem) programme has continued successfully into a second phase, leading to many new insights into the workings of that system. For the east coast an ASCLME (Agulhas and Somali Current Large Marine Ecosystem) programme has been drawn up, been approved and will kick off during 2007. The African Coelacanth Ecosystem Programme (ACEP) has been very active in this same region (viz. Lutjeharms, 2006a, b). In the Southern Ocean physical oceanographic research has continued under the auspices of the DEIMEC (Dynamics of Eddy Impacts on Marion's Ecosystem) in the general vicinity of the Prince Edward Islands (Froneman et al., 2002; Pakhomov et al., 2003; Ansorge et al., 2004a), building on 25 years of previous research in the region (Ansorge and Lutjeharms, 2000). An ambitious international programme to monitor the Antarctic Circumpolar Current between Africa and Antarctic, GoodHope, has also seen its first successful cruises (e.g. Ansorge et al., 2004b) and a novel project to investigate the direct surroundings of the island Tristan da Cunha has started.

In addition, the effects of the Boxing Day Tsunami on the Southern African coastline have been investigated using tide gauge observations by colleagues at UCT (Merrifield et al., 2005).

The quality of much of this research is high. Work on the Benguela Niño (Florenchie et al., 2004) has received the Stanley Jackson Award from the South African Society for Atmospheric Sciences for the best atmospheric or oceanographic research to be produced in South Africa. One of South Africa's physical oceanographers was awarded the Fridtjof Nansen medal of the European Geosciences Union, the first such award to a person outside Europe or the US (viz. Lutjeharms, 2006c). Furthermore, during this period three major books on the oceans were produced in South Africa: *The Agulhas Current* (Lutjeharms, 2006d), a book based on the BCLME *Benguela: Predicting a Large Marine Ecosystem* (Shannon et al., 2006) and even an English-Afrikaans dictionary for oceanology (Lutjeharms, 2004).

Research that has been completed during the period 2003-2006 is reported here under the headings of the three neighbouring oceans: the Southern Ocean, the South-West Indian Ocean and the South-East Atlantic Ocean.

Southern Ocean

Ongoing investigations in the vicinity of the Prince Edward Islands in the Indian sector of the Southern Ocean have concentrated on the formation of mesoscale eddies at the South-West Indian Ridge, downstream of these islands (Ansorge et al., 2004a). It has been demonstrated that the Antarctic Circumpolar Current is constricted at a fracture zone of this ridge, substantially increasing mesoscale turbulence here (Ansorge and Lutjeharms, 2005). The cold eddies thus spawned at the Antarctic Polar Front carry cold water equatorward, acting as a negative heat pump (Ansorge et al., 2006). This localised flux of heat is believed to have significant climatic implications. These results and much previous work have been summarised (Lutjeharms and Ansorge, 2006) for a forthcoming book on the Prince Edward Islands as a changing ecosystem.

The variable flux of the Antarctic Circumpolar Current has, in a similar fashion to the eddies at the South-West Indian Ridge, global climatic implications. It has been shown that varying temperatures at the sea surface at the Prince Edward Island track the Antarctic Circumpolar Wave (Mélice et al., 2005) that gives this flux an inter-decadal signature. To this end the baroclinic volume flux of the Antarctic Circumpolar Current is being monitored south of Tasmania and in the Drake Passage. The international GoodHope programme (Ansorge et al., 2004b) attempts to do the same south of Africa, over a much greater distance. An analysis by Legeais et al. (2005) has shown that this transport can be effectively monitored by lines of stations at which XBT (expendable bathythermograph) probes are launched. When applied, this result will conceivably make the monitoring effort considerably easier.

Determining the transport flux of the ACC has been an observational goal for many years. Our understanding of how and why this transport varies with time and seasonally remains incomplete due to the severe lack of observations. The aim of GOODHOPE is to establish an intensive monitoring line that will provide new information on the volume flux of the region south of South Africa. Such observations have been conducted during the World Ocean Circulation (WOCE) experiment during the 1990s in which repeat transects across the ACC were restricted to 3 chokepoints. Intense and periodic monitoring of both the Drake Passage and south of Tasmania have continued since WOCE. To date a total of 7 GoodHope lines have been completed since the start of the project in 2004. GoodHope has been endorsed by the International Polar Year committee and will continue with a large field campaign in 2008 and 2009.

Other South African work in the Southern Ocean has focused on the changing climate at the Prince Edward Islands. Sumner et al. (2004) have demonstrated that snow fields which have been present on Marion Island (one of the two islands forming the Prince Edward islands, the other being Prince Edward Island itself) since 1940 are now melting. The increase in temperature has also been seen at the sea surface where it is now 4.1º C warmer (Mélice et al., 2003) than 50 years ago. In an innovative study, Rouault et al. (2005) have shown that this change may have its origins in changes in the upper atmosphere and not necessarily in global warming. Relationships between the Antarctic Oscillation (AAO) and winter rainfall over western South Africa have been investigated (Reason and Rouault 2005). It is found that 6 of the 7 wettest winters during 1948–2004 occur during negative AAO phase. The mechanisms by which the AAO appears to influence winter rainfall involve shifts in the subtropical jet, and changes in the low-level moisture flux upstream over the South Atlantic and in the mid-level uplift, low-level convergence and relative vorticity over the region.

An important investigation (Llido et al., 2005) has addressed the vexing question of the intermittency of increases in chlorophyll-a at the Subtropical Convergence. It has been shown that these increases come as event-scale blooms with limited geographical extent. These blooms may interact with the Agulhas Return Current, the trajectory of which was shown to be clearly discernable from the tracks of surface drifters (viz. Lutjeharms et al., 2004). South Africans were even involved tangentially in experiments at sea (Walter et al., 2005) to stimulate biological productivity in the Southern Ocean by seeding it with iron. Other studies on the Subtropical Convergence in the South Atlantic (Burls and Reason, 2006) have shown that over the central to eastern part of the Atlantic basin a substantial interannual variability in the strength and latitudinal location of the STC. Over the central to eastern part of the basin, the analysis suggests that there is substantial interannual variability in the strength and latitudinal location of the Northern and Southern Subtropical Front

South-West Indian Ocean

Some seminal advances were made in understanding the Agulhas Current system by judicious modelling (Speich et al., 2006). The role of the bathymetry in steering the current and in controlling the inter-ocean exchanges south of Africa was illuminated. The current has numerous effects. Its influence on the distribution of organisms was shown for siphonophores (Thibault-Botha et al., 2004) whereas its influence on rainfall on the east coast of Africa was modelled successfully (Singleton and Reason, 2006). The influence of sea surface temperatures on the weather and climate remains of great interest. Hermes and Reason (2006) have modelled a dipole in the sea surface temperature of the Indian Ocean successfully and have also modelled the variability in the Agulhas Current system as a whole (Hermes et al., 2006).The region around Madagascar is one that is particularly variable and has therefore attracted a lot of interest.

It has been demonstrated that a series of vortex dipoles can be formed south of Madagascar (De Ruijter et al., 2004) and after having drifted across the Natal Basin may interact dramatically with the Agulhas Current proper. In fact, it has been shown in a model (Penven et al., 2006) that the downstream behaviour of the Agulhas Current is controlled by the presence of the land mass of Madagascar and that without it, the prevalence of eddies in the Mozambique Channel would disappear. Intra-thermocline eddies were observed and described (Nauw et al., 2006) east of Madagascar for the first time. Even more dramatic was the establishment (Siedler et al., 2006) of the presence of a countercurrent in the subtropics of the South Indian Ocean that has only come to light recently. Other activities in the South Indian Ocean have extended over a wide range.

The predictability of sea surface temperatures (Collins et al., 2004), the influence of ambient currents on the marine and coastal ecosystems of Madagascar (Cooke et al., 2004), the movement of sea turtles by currents (Luschi et al., 2006) and the prevalence of Red Sea Intermediate Water (Roman and Lutjeharms, 2006) have all received attention. A coupled physical-biological model has been used (Machu et al., 2005) to investigate the production of chlorophyll-a in the South-West Indian Ocean. A key aspect in understanding the recruitment of the pelagic fish on the continental shelves of South Africa has been the manner in which the eggs and larvae of these fish travel from their spawning grounds to the Benguela upwelling regime. It was thought that this was by way of a shelf edge jet on the western side of the Agulhas Bank. Using the tracks of surface drifters (Lutjeharms et al., 2006) it was shown that the movement along this shelf edge is controlled by products of the Agulhas Current, making it predictable how successful this transport will be by studying products of satellite remote sensing such as altimetry.

All these results, and more, are put in context in the recent book *The Agulhas Current* (Lutjeharms, 2006d) that is based on more than 800 publications on the subject since the 1770s.

South-East Atlantic Ocean

Because of its relevance to the economically important fisheries, the Benguela upwelling regime has usually been the region that has received most research attention in the South-East Atlantic (Schumann et al., 1991; Gründlingh et al., 1999; Reason et al., 2006a). During the period 2004-2006 this had not changed.

The Benguela upwelling system extends from the western edge of the Agulhas Bank to the Angola-Benguela Frontal Zone to the north. Colberg and Reason (2006) using a regional ocean model have investigated the sensitivity of the intensity and position of the Angola Benguela Frontal Zone. Their results suggest that the windstress *curl* plays a major role in altering the position and strength of the Angola Benguela Frontal Zone, as it controls the southeastward flow of the South Equatorial Counter Current.

This zone was intensely studied (Mohrholz et al., 2004; John et al., 2004) during a period when it was disrupted by a Benguela Niño. It was shown that the intrusions of Angola Current water were mirrored in the biology of the region. These Benguela Niños can be extremely disruptive to the local upwelling and thus to the fisheries of the region. The forcing behind this phenomenon has now been identified (Florenchie et al., 2004) and has been shown to be predictable in principle. Indeed, (Florenchie et al., 2003) have shown that Benguela Niños tend not to occur in unison with their Pacific counterpart and may thus have unrelated forcing mechanisms. Using an ocean general circulation model, forced by real winds and verified with satellite data, it is shown that Benguela Niños are generated by specific wind stress events in the west-central equatorial Atlantic, and progress from there as subsurface temperature anomalies that eventually outcropped only at the south-west African coast.The variability of the velocity structure in the Atlantic tropics has also received attention (Bunge et al., 2006).

The relationship of the South Atlantic with climate has been a topic that is of increasing interest. Colberg et al. (2004) have modelled the response of this ocean region to ENSO (El Niño/Southern Oscillation) whereas others (Reason et al., in press) have investigated the predictability of southern African climate and its links with the variability of the Atlantic Ocean. Reason and Jagadheesha (2005) have shown the relationship between sea surface temperatures over the South Atlantic and the atmospheric circulation over the southern African subcontinent. NCEP reanalysis of outgoing longwave radiation data indicates that the winter intensification of wind stress off the Angolan coast is linked with convective activity over equatorial West Africa (Risien et al., 2006). The summer activity appears to be linked with the intensification of the Angolan heat low. Furthermore Rouault et al., (2003) have shown that intrusions of warm equatorial water in the South East Atlantic Ocean off Angola and Namibia may be linked with above average rainfall along the coast of those countries but sometimes also with inland areas of southern Africa. Rainfall over western Angola/Namibia is greatest for those events for which the local circulation anomalies act to strengthen the climatological westwards flux of Indian Ocean sourced moisture across low latitude southern Africa. Better understanding of these warm events is necessary for assessing impacts on regional rainfall, agriculture and fisheries and for improving seasonal forecasting in this region.

Conclusions

From the above the impression might be gained that there is much activity in the field of physical oceanography in South Africa and that it therefore is healthy and flourishing.

Regrettably this is not the case. Over the past decade the productivity of this scientific enterprise in South Africa has been reduced enormously, while in most comparable countries it has increased. This diminishment has been a function of poor policy decisions (Lutjeharms and Thomson, 1993), severe reduction in funding and destructive attempts at social engineering (Lutjeharms, 2006e). Many challenges need to be addressed if South African research efforts in Physical Oceanography are to be maintained. For example, the availability of research funds within the country remains poor by comparison to some other countries with similar gross domestic product per capita. Many of these funds are becoming increasingly prescribed, thereby reducing local expertise in fundamental curiosity-driven science. Some research areas appear over-funded and others grossly under-funded. Local universities struggle to fund and attract post-doctoral fellows, who play a pivotal role in the success of research-oriented universities overseas. Curricula at local universities need to keep abreast of international developments, be more diverse and cross-disciplinary in their offerings and attract students with good quantitative skills.

In the last decade or so, increased collaboration between various institutions within South Africa and also with international groups has contributed immensely to the development of South African expertise in areas such as climate change, seasonal forecasting, numerical modelling and regional oceanography. Prominent examples include the KAPEX project relating to exchange of waters south of Africa, the MARE experiment on the fate of Agulhas rings and the ACSEX programme on the Mozambique Channel transport. This collaboration offsets to some extent the lack of a critical mass of workers at most local institutions and has helped expose local scientists and students to a range of international expertise and opportunities.

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