A review of South African research in atmospheric science and physical oceanography during 2000–2005

C.J.C. Reason[a*], F. Engelbrecht[b], W.A. Landman[b,c], J.R.E. Lutjeharms[a], S. Piketh[d], C.J. de W.Rautenbach[b] and B.C. Hewitson[e]

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 5 years. Research published by South African scientists working abroad is not included. Most published research in these fields falls within the broad areas of climate variability, climate change, aerosols and atmospheric pollution, seasonal forecasting, numerical modelling (both atmospheric and oceanic), and the physical oceanography of the Agulhas and Benguela current systems. Most but not all of the atmospheric science papers relate to South Africa or southern Africa; however, some work pertaining to the southern hemisphere as a whole or to other regions has been done. We note that funding and institutional support for atmospheric science and physical oceanography research in South Africa remains poor and this situation significantly hampers local efforts.

Introduction

Over the last decade or so, various changes have occurred in the atmospheric science and physical oceanography (AO) community in South Africa. New areas of research interest and expertise have emerged while others have evolved. In this article, we attempt to review progress in the broad AO field made by workers based at South African institutions since about 2000. To keep the task manageable, we exclude work on South African problems by researchers based abroad and research done by South Africans if they were resident outside the country. However, the AO community is characterized by many diverse and rich collaborations with a range of overseas institutions and this work is included if at least one author on the paper is based in South Africa.

Several developments have had significant impacts on the nature of AO research conducted within South Africa in recent times. The huge expansion of readily available re-analysis data from the U.S. National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) and the European Centre for Medium Range Weather Forecasting (ECMWF) and in computing power has resulted in the growth of South African research into modelling and climate analysis, for example. Additionally, seasonal forecasting has developed substantially, with much more effort going into dynamical model-based forecasting than hitherto. Less positively, reductions in available funding from both the public and private sectors and in institutional support has posed great challenges for conducting certain types of research such as field programmes.

This article is divided into sections that deal with the main areas of AO research evident within the South African community. These are regional physical oceanography, climate variability, climate change, seasonal forecasting, numerical modelling, severe weather, and aerosols and atmospheric pollution. It does not cover all fields that are researched by members of the AO community — a glance at any recent conference proceedings of the South African Society for Atmospheric Science (SASAS) will show that there is also considerable research activity taking place in other fields such as agro-meteorology, land–surface interactions, and upper air meteorology, for example.

Regional physical oceanography

The field of physical oceanography in South Africa has continued its general downward trend of the past decade.[1,2] This drift may be seen as part of the general tendency in this regard for South African science as a whole,[3,4] but also has some of its own characteristics. This decline is reflected in the number of published papers in physical oceanography by the various institutions during the period,[5,6] although the number of papers produced by the University of Cape Town (UCT) has remained fairly steady. The causes of this decline in publication output relate to changes in policy by some organizations and the relocation of several key scientists to positions abroad.

Physical oceanography in South Africa during this period has involved several regional and international research programmes. In the Benguela upwelling region, there were the BENEFIT (Benguela Environment Fishery Interaction and Training)[7–9] and the French–South African IDYLE (Interactions and Spatial Dynamics of renewable resources in upwelling Ecosystems) programmes and the Benguela Current Large Marine Ecosystem (BCLME) programme was successfully initiated. In the southern Agulhas system, the multi-national programme KAPEX (Cape of Good Hope Experiment)[10,11] was concluded with many papers published in a special edition of *Deep-Sea Research II*.[12] A collaborative Dutch–South African observational programme oversaw the MARE (Mixing in Agulhas Rings Experiment)[13] and the ACSEX (Agulhas Current Sources Experiment).[14] In the Southern Ocean, Rhodes University and UCT collaborated on the DEIMEC (Dynamics of Eddy Impacts on Marion Island's Ecosystem) project.[15–18] South African physical oceanographers also took part in the German ANDEX project on the R.V. *Poseidon*[19] and a new international project to monitor the flow between Africa and Antarctica, called GoodHope, has just started.[20] Increasing collaborations between South African and foreign oceanographers have enabled local workers to overcome limitations in ship time and instrumentation. The synergy

[a]Department of Oceanography, University of Cape Town, Private Bag, Rondebosch 7701, South Africa.
[b]Department of Geography, Geomatics and Meteorology, University of Pretoria, Pretoria 0002, South Africa.
[c]South African Weather Service, Pretoria.
[d]Climatology Research Group, University of the Witwatersrand, Private Bag 3, WITS 2050, South Africa.
[e]Department of Environmental & Geographical Science, University of Cape Town.
*Author for correspondence. E-mail: cjr@egs.uct.ac.za

between local knowledge and foreign expertise has led to substantial advances in a number of cases, as will be evident from the descriptions below.

During this period, several new discoveries on the circulation were made in the Southern Ocean, in the greater Agulhas Current system, in the Benguela system and in various shelf regions.

Southern Ocean research

South African research in the Southern Ocean has concentrated on the environment of the Prince Edward Islands, although some theoretical work has been conducted on the Antarctic Circumpolar Wave,[21] a mode of variability manifest throughout the Southern Ocean during certain decades and involving large-scale atmosphere–ocean interaction. Some investigations have also been carried out on the fronts and water masses between Africa and Antarctica.[22,23] Much of the physical research near the Prince Edward Islands has been in support of biological studies, demonstrating the role of biological–physical interactions on pelagic productivity[24] and describing the spatial and temporal variability of these interactions.[25,26] It was shown[27] that both cyclonic and anticyclonic eddies are present in ever-changing numbers and shapes near the islands. Since the islands lie at the equatorward edge of a highly turbulent region in the Southern Ocean, downstream of where the Antarctic Circumpolar Current is forced through a narrow fracture zone in the South-West Indian Ocean, an unusual region of enhanced mesoscale turbulence is created with eddies shed that then drift past the islands.[28] Some bird species on the islands feed predominantly at the eddy edges, thus implicating these eddies in the terrestrial ecosystem.[29] Further expeditions in the region have been planned and executed on the basis of this new information.[17–19]

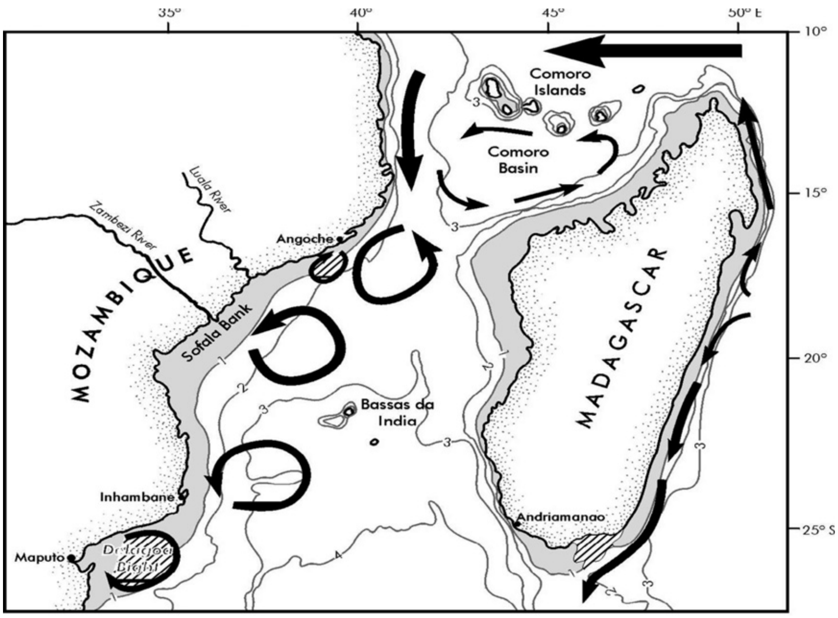

Fig. 1. Schematic illustration of the nature of the flow in the Mozambique Channel.

This multi-decadal study[16] of the oceanic environment of the Prince Edward Islands has been influenced by the logistical constraints of the South African National Antarctic Programme, limiting ocean-going research in this programme largely to the vicinity of the islands. This has led to this particular ocean region being one of the most thoroughly investigated of its kind in the Southern Ocean, but it has restricted in an unhealthy way the research interest of South African oceanographers. There is an urgent need for a geographically expanded interest in the Southern Ocean south of Africa that is driven more by curiosity than purely by logistical constraints.

It is not only the passing eddies that have a marked effect on the climatic conditions on the Prince Edward Islands. The climate of the islands seems to be changing noticeably,[30] with large areas previously permanently covered by snow or ice now free of such cover.[31] Analysis of sea-surface temperatures taken at Marion Island over the past 50 years[32] has shown that these temperatures have increased by 1.4°C over this period. A further analysis of wind and weather conditions[33] has demonstrated that this climate change is due to alterations in the semi-annual oscillation. Establishing this mechanism reflects important progress in understanding the climate variability of these islands.

Agulhas Current system

The Agulhas Current system may be considered to consist of four parts: the source regions, the Agulhas Current proper along the east coast of South Africa, the Agulhas retroflection south of Africa, and the rings and currents that move outward from the retroflection. In the last few years, important results have been obtained that have substantially changed previous concepts of the circulation in this system.

The source regions of the Agulhas Current have been described using ship's drift[34] that has defined the locations of the currents around Madagascar and in the Mozambique Channel. Of great importance has been the discovery that the concept of a Mozambique Current is false and that the predominant flow in the channel consists of a train of mesoscale eddies[35] moving poleward from the narrows of the channel (Fig. 1). An ACSEX cruise demonstrated that the termination of the southern limb of the East Madagascar Current produces vortex dipoles[36] that drift towards the coast of South Africa. These eddies may have substantial impacts on the behaviour of the Agulhas Current by triggering Natal pulses at the Natal Bight north of Durban. Based on observations from sub-surface floats as well as current meter moorings, it was shown for the first time[37,38] that Natal pulses extend all the way to the sea floor. These perturbations may also strongly influence the behaviour of the current downstream at the Agulhas retroflection.[39] Here Agulhas rings are shed that move off into the South Atlantic Ocean, carrying their anomalous loads of heat and salt. These rings rapidly lose their heat and salt in the Cape Basin,[40] and very few succeed in subsequently crossing the Walvis Ridge. It has become clear that Agulhas rings undergo dramatic changes during their early life history[41,42] by mixing with other rings, splitting and recombining, leading to that part of the Cape Basin being named the *Cape Cauldron*.[43] Some of the cyclones have been shown to be generated as lee eddies along the western side of the Agulhas Bank.[44] These lee eddies may be fed by cyclonic vorticity from shear edge eddies on the seaward side of the southern Agulhas Current along the eastern side of the Agulhas Bank.[45] It is interesting to note that these processes have been operating for at least 450 000 years,[46] with greater or lesser intensity, but never totally ceasing. This rich harvest of new research results concerning many of the components of the greater Agulhas Current system has fundamentally changed our thinking on many aspects of the system. International interest in the system is growing, so that many more results may be expected in the coming decade.

Concepts of how much water, salt and heat is exchanged between the South Indian and the South Atlantic oceans through the process of ring shedding at the Agulhas retroflection remains a perennial problem and estimates vary considerably. During the reporting period, two estimates have been made, one with an eddy-permitting ocean model,[47] and one using all hydrographic data currently available,[48] the latter to quantify the exchange of intermediate waters. A secondary source of water masses that may considerably complicate the melange of water types in the region is Subantarctic Surface Water that leaks equatorward across the Subtropical Convergence whenever an Agulhas ring is shed. This process is geographically quite localized, but involves water masses much deeper than only the surface waters.[49]

That part of the Agulhas Current which negotiates the Agulhas retroflection without becoming part of a ring shedding event proceeds eastwards along the Subtropical Convergence as the Agulhas Return Current. An analysis of this current's structure and flux, using all existing hydrographic data,[50] has shown that the Agulhas contribution is exhausted by a longitude of 60–70°E. The initial part of the Agulhas Return Current is very unstable, but strongly controlled by the bathymetry,[51] even at depth.

As can be expected from such a dominant western boundary current, it has a marked influence on the distribution of biota such as siphonophores,[52,53] coelacanths[54] and leatherback turtles.[55] These turtles were found to use the current and its eddies to move around, thus conserving energy, with some even ending up in the Benguela system.

The Benguela system

The Benguela system may be considered to consist of two components: the offshore drift constituting the Benguela Current proper — with embedded Agulhas rings — and the coastal, wind-driven Benguela upwelling. The extent of the Benguela Current has been established by a detailed analysis of ship's drift,[56] while the upper layer circulation has recently been described[57] using the best hydrographic data currently available. Furthermore, the equatorward extent of the Benguela upwelling system has been studied at sea[58] to show the structure of the Angola–Benguela Frontal Zone (ABFZ). Intrusions of water across this zone are reflected in the biogeography of fish and fish larvae.[59] Of particular value in these investigations has been the availability of remote sensing products[60] to delineate water masses by their sea-surface temperatures, wind stress patterns and phytoplankton distributions.

Remote sensing products have in fact played an increasingly important role in investigations on the overall upwelling system. This has included studies on the wind systems, their variability,[61] their secular variations[62] as well as the climatology and variability of sea-surface temperatures (SST) and surface chlorophyll.[63] It can be expected that the ever improving quality of such products[64] will increase their frequency of use in investigating the Benguela upwelling system.

As part of the BENEFIT training programme, several observational projects have been carried out at sea in the Benguela system. These include near-surface currents and hydrography[65–67] as well as the movement of surface drifters.[68] Studies have been conducted to establish the seasonal[69] and inter-annual changes in upwelling as well as considered extreme events that may lead to a much larger anchovy year class than normal.[70] A high-resolution regional model has been developed[71] and employed in a number of studies, many of a biological nature and therefore not discussed here. It has been successfully used in linking wind and inter-annual variability in the southern Benguela upwelling system.[72]

Analysis of the mechanisms associated with the Benguela Niño[73] has shed further light on this major mode of variability in the South-East Atlantic. This event is a spasmodic flow of warm surface water poleward along the west coast of Africa that breaches the ABFZ and affects the intensity and extent of the coastal upwelling farther south. This event also affects the local coastal rainfall as well as the ecosystem and thus the fisheries.[74] Using model simulations and satellite remote sensing,[73] it has been demonstrated that a tilting in the tropical thermocline brought about by local wind stress variations can induce a sub-surface pulse of anomalously warm water that travels across the equatorial Atlantic and along the west coast of southern Africa until it outcrops at the ABFZ. Further studies on this phenomenon[75] have shown that Benguela Niño events vary in strength and that analogous cold events also occur. The ocean anomalies associated with this phenomenon are mainly felt on the continental shelf. A number of other studies on the shelves of southern Africa have also been carried out in the last five years and are discussed in the next section.

Continental shelf research

One of the shelf regions of South Africa that is conceivably of great climatological as well as ecological importance is the Natal Bight between Durban and Cape St Lucia. This semi-enclosed region has now been hydrographically surveyed as a whole in a quasi-synoptic fashion for the first time and its physical hydrography[76] and nutrient distribution[77] described. A perennial upwelling cell at St Lucia is responsible for lifting water with high nutrient concentrations onto the shelf from where it is dispersed in the bottom layer of the larger part of the bight. It has been assumed that this upwelling cell is driven by the passing Agulhas Current. A similar upwelling cell has been found off the southeastern tip of Madagascar.[78,79] This is a major advance in knowledge of an otherwise poorly known part of the shelf off eastern Africa. The same process has now also been observed[80] where the Agulhas Current passes from a narrow shelf along southeastern Africa to the wider Agulhas Bank south of Africa. This particular upwelling cell, off Port Alfred, probably has a determining influence on the seasonal thermocline of the greater part of the Agulhas Bank and thus on the spawning habitat of economically important invertebrate and fish species.[81,82] Observations of similar physical processes have also been made on the western shelf,[83] to learn how these contribute to harmful algal blooms and impact on fish abundance.

Air–sea interaction

As could be expected, a current such as the Agulhas with temperatures so much greater than that of the ambient waters influences the overlying atmosphere. An example is cumulus cloud formation above the current.[84] It has been shown[85] that the effect of the current is felt not only directly above it, but it may also influence regional atmospheric circulation patterns.

The effect of the Agulhas Current has been studied with remote sensing[86] and it has been shown that weather forecasting models[87] underestimate the influence of the current on the overlying atmosphere. *In situ* investigations have shown that the atmospheric boundary above the current is strongly modified during along-current winds,[88] leading to conditions favourable to cumulus cloud formation. In at least one case study,[89] the influx of air so modified over the current led to the dramatic enhancement of the intensity of an extreme weather event over the southern Cape. Even air passing over warm Agulhas eddies at the Subtropical Convergence to the south have exhibited significant increases in speed.[90]

Ocean remote sensing

In addition to advances in regional oceanography, new remote sensing products and analysis techniques have shed further light on the variability of the neighbouring oceans. This work includes an assessment of the variability of thermal fronts in the central and eastern South Atlantic,[91] research into the optical properties of particulate matter suspended in the southern Benguela, which has implications for water quality and harmful algal blooms,[92] monitoring the seasonal and inter-annual variability of the ABFZ,[93] detection of hydrogen sulphide emissions off Namibia,[94,95] and the application of self-organizing map techniques to classify temperature patterns and species distribution in the Benguela upwelling system.[96–98]

Climate variability

Subsequent to NCEP re-analyses[99] becoming available, significant advances have been made in climate variability studies over South Africa. A review[100] of early work, largely at the University of the Witwatersrand (Wits), and restricted to station data over southern Africa and neighbouring islands, discussed some of the important atmospheric circulation anomalies associated with El Niño-Southern Oscillation (ENSO) effects over the region and the existence of inter-annual to interdecadal signals in summer rainfall.[101] On the near-decadal scale, evidence has been presented that the quasi-decadal signal in winter rainfall over the SW Cape and the quasi-bidecadal signal in summer rainfall over South Africa is related to the superposition of various ENSO-like patterns evolving on different low-frequency bands.[102] This idea was further extended to show how rainfall variability over southern Africa could be statistically modelled using a combination of signals on various time scales.[103]

More recent work based on the NCEP re-analyses and various historical data sets, confirmed and extended the early work on ENSO and showed how the signal was transmitted in preferred temporal bands.[104,105] In addition, this and other work[103,106,107] suggested that the ENSO impact over southern Africa varies through the record and that other climate modes are also important.

These modes include the recently proposed South Indian Ocean subtropical dipole,[108–110] which may be linked via hemispheric scale forcing to a similar sea-surface temperature (SST) pattern in the South Atlantic[111] and to ENSO and the Antarctic Oscillation.[112] A link between the Antarctic Oscillation, the semi-annual oscillation and changes in the summer climate of Marion Island (particularly reduced rainfall) has been found,[33] whereas the Antarctic Oscillation has been linked to winter rainfall over western South Africa.[113,114]

The ENSO influence over the South Atlantic region occurs via Rossby wave propagation in the so-called Pacific South America pattern.[115,116] The interaction of this propagation over South Africa with that emanating from the Indian Ocean[117] is yet to be clarified. Recent modelling work[118] suggests that the way that the Angola low and neighbouring SST is modulated during ENSO events helps determine the rainfall impact of a particular event over southern Africa. Links between ENSO and the African monsoons have also been examined.[119]

Although interest in southern African climate links with the Indian and Pacific oceans remains strong, more recently attention has returned to the South Atlantic. Early work[120] showed that warm SST anomalies off Angola could influence regional rainfall during summer. Recent analysis of four Benguela Niño events showed that the rainfall effects are related to the interaction between local anomaly and the mean easterly moisture flux over southern Africa.[74] Further south, subtropical-mid-latitude SST anomalies in the South Atlantic and anomalies in sea–ice extent were shown to influence winter rainfall over the SW Cape region of South Africa.[113,121,122] Circulation anomalies developing south and southwest of South Africa have also been implicated in several non-ENSO droughts over South Africa, since they act to increase the advection of relatively cool, stable and dry air from the South Atlantic over the landmass.[123,124]

Re-analysis data have also been used to build on early studies at Wits of moisture flux over southern Africa. Although on seasonal scales the inflow from the subtropical and tropical Indian Ocean is important, recent work has shown how a stronger (weaker) Angola low acts to enhance (reduce) intraseasonal and synoptic rainy spells over the country.[125] In addition, intraseasonal pulses of easterly wind in the Madagascan region may be linked with summer convection over South Africa.[126]

Climate change

Climate change research has focused on three aspects: historical change, development of dynamical modelling capacity, and projections of future change. In assessing historical change, much work in South Africa has traditionally focused on palaeo-environments. While this is of significant value in understanding the geological time scales, it is the recent historical analysis that is perhaps most informative of the current situation, which is arguably unique in the character of how global change is being forced. While there have been a range of studies on regional change,[127, 128] the most recent cohesive activity assessing historical change has been on behalf of the CLIVAR Expert Team on Climate Change Detection (ETCCDMI). An ETCCDMI workshop was hosted in 2004 to assess robust trends in historical data across southern Africa. Using long-term records from key observing stations across the subcontinent, extending to Zambia in the north, the results corroborate earlier conclusions that temperatures are increasing over the long term. In particular, there are clear indications of positive trends in temperature, especially minimum temperature. In conjunction with the temperature changes are regionally specific variations in rainfall. Most notable are spatially extensive patterns of a progressive increase in the duration of dry spells. Using a high-resolution gridded precipitation data set for South Africa, recent work[129,130] has found similar trends, with the most distinctive change being manifest as an increase in the length of dry spells.

A significant growth in the capacity to implement and use climate models for assessing the regional climate system has been made, particularly at the University of Pretoria (UP) and UCT, and efforts are now being made to address climate change issues. For example, the present and future mid-summer and mid-winter climate over southern Africa was simulated for two 10-year periods with the CSIRO's limited-area model DARLAM at UP. The model projected a general rise in temperature over South Africa with an increase of rainfall over the western and central interior of the country. These projections are related to an increase in atmospheric pressure over the eastern parts of the country. The projected climate was used as input into a predictive species model to simulate changes in tick distributions and East Coast fever over southern Africa.[131] A study[132] of land-surface responses under different climate change scenarios noted a strong potential for soil moisture variations to play a positive feedback role in exacerbating any climate trend towards drying.

Progress made with developing powerful computing facilities at UP and UCT has enabled more extensive and higher-resolution climate simulations to be made. For projecting future regional climate change, either regional climate models (RCMs) forced by boundary conditions from general circulation models (GCMs), or GCM fields empirically downscaled to high spatial resolutions are used, because both approaches are deemed to be of similar skill.[133] Empirical techniques have been used to develop multi-model projections for Africa, whereas the application of RCMs is limited, due to the computational demands, although there is a concerted effort in this regard at the two universities. Recently, two high-resolution 30-year simulations of present and future southern African climate have been performed at UP with the Conformal-Cubic Atmospheric Model (C-CAM) developed by the CSIRO in Australia.[134] Similar experiments with the MM5 and PRECIS RCMs have been performed at UCT[135] to assess changes in future summer temperature, rainfall and rain days.

Both the RCM and empirical approaches for deriving regional climate change information have developed largely under the auspices of Water Research Commission projects, and this has established a skills base within South Africa that is beginning to meet the needs of policy and resource management for climate change information. Projections of daily precipitation across South Africa have been developed[136] from a broad range of GCMs, characterizing to some degree the envelope of future change. Most notable in these projections is the convergence of projected change between the different driving GCMs. The general patterns of projected change suggest a wetter east coast, drier west coast, and a characteristic trend toward longer dry spells and increased precipitation intensity. By comparison, statistically significant negative (positive) trends in observed rainfall were found over the past 40 years over the summer rainfall region during April and May (over the west coast and adjacent interior during July and September).[137]

Taken as a whole, the assessment of the recent historical changes, the projections of future change, and the growing understanding of how the regional climate system and related feedbacks operate provide strong evidence that climate has changed over the last century, and will continue to do so in a manner that could place increasing stress on societal structures.

Seasonal forecasting

From the early 1990s, a number of institutions in South Africa started to issue seasonal forecasts for southern African summer rainfall.[138–141] The predictors were primarily global-scale SSTs, cloud depth and upper zonal winds. However, changes in the association between rainfall over parts of the subcontinent and sea-surface temperature variability in the tropical western Indian Ocean may produce a small decrease in potential predictability from statistical models.[142] GCMs may be able to simulate these changes, at least qualitatively.[143]

Estimation of the evolution of SST anomalies, which are often relatively predictable and which are known to influence regional rainfall variability, potentially provides a way to generate forecasts of seasonal-average weather.[144] When forced with observed global SSTs, a GCM was able to capture the main austral summer seasonal rainfall variability over southern Africa.[107,118,145] This result suggests that a GCM may be the most appropriate means to use in summer seasonal rainfall forecasting for the subcontinent.[143] GCM skill was also demonstrated in simulating inter-annual austral winter rainfall variability over southwestern South Africa.[146] In this country, most research and operations using GCMs are based on a two-tiered approach where global SSTs are either persisted or forecast[147–149] over the model integration period and subsequently used to force the GCM.[145,149]

The possibility of predicting the intra-seasonal variability over the region has started to be investigated[124,125,150,151] as well as dry-spell frequencies[152,153] and onset dates.[124,154,155] Both the dry-spell and onset dates predictability appear to be linked to ENSO. Correctly using seasonal forecasts to predict these seasonal characteristics over the region can be beneficial, since forecasts can potentially save the region up to US$1 billion annually.[156] Most of this prediction work concerns relationships with ENSO or the Indian Ocean; however, recently more attention is being paid to the influence of the Atlantic Ocean on southern African climate variability and its prediction.[73–75,122,154]

GCMs are unable to represent local sub-grid features, and tend to overestimate rainfall over southern Africa.[157] Also, the representation of rainfall at mid-latitudes is complex and often not well estimated.[144,145] Such systematic biases have created the need to downscale or recalibrate GCM simulations to regional level. Semi-empirical relationships exist between observed large-scale circulation and rainfall; assuming that these relationships are valid under future climate conditions and also that the large-scale structure and variability is well characterized by GCMs, equations can be constructed to predict local precipitation from the simulated large-scale circulation.[158] Recently, empirical remapping of GCM fields to regional rainfall has been demonstrated successfully over southern Africa.[144,159,160,161] The statistical approaches used to develop equations relating the GCM quantities to a forecast quantity are called perfect prognosis[144] and model output statistics (MOS).[162] The MOS approach is normally preferred[162] because it can directly include any influence of specific characteristics, such as systematic errors. These errors can be included because MOS uses predictor values in both the development and forecast stages. Using a MOS approach to recalibrate GCM output may not only improve GCM forecast skill over southern Africa, but can be of some value for operational applications.[160,163] Recently, it has been demonstrated that the attributes of the perfect prognosis and MOS can be combined to make December–February forecasts for southern Africa.[164]

RCMs have also been used to address the seasonal predictability problem. Seasonal biases in the MM5 simulations over southern Africa have been related to those in the diurnal cycle and rainfall frequency, with the choice of convection scheme shown to be important.[165] Currently, RCMs are not used operationally in South Africa to make forecasts except on weather scales. One potential application is to forecasting the seasonal characteristics of tropical cyclones over the southwestern Indian Ocean. The predictability of these cyclones has been investigated using dynamical[166,167] and statistical models.[168] However, keeping track of evolving climate signals over the tropical Indian Ocean could help forecasters of tropical cyclones over this ocean.[169] The coarse resolution of GCMs results in the lack of an eye or associated eye wall in the simulated cyclone-like vortex and has a strong impact on the intensity of the model tropical storms and on their tracks. An approach to improve on model resolution is by nesting a regional climate model within a GCM. These regional models have been demonstrated to produce cyclones that are weaker than observed, but more realistic than the vortices generated by a GCM.[170,171] Evidence has been presented[172] that there are potential benefits in using regional climate models to simulate tropical cyclone-like vortex tracks and the development over the southwestern Indian Ocean.

The inherent variability of the atmosphere requires seasonal climate simulations to be expressed probabilistically.[173] Probabilistic forecasts are made possible through the proper use of GCM ensembles, since ensemble forecasting is a feasible method to estimate the probability distribution of atmospheric states.[174] In addition, errors in the initial conditions as well as deficiencies in the parameterizations and systematic or regime-dependent model errors can largely be accounted for through ensemble forecasting.[175] Information contained in the distribution of the ensemble members can subsequently be used to represent forecast probabilities by calculating the percentage of ensemble members that fall within a particular category (e.g. below-normal, near-normal and above-normal). The national forecasts issued by the South African Weather Service (SAWS) represent forecast probabilities for these three equi-probable categories. These forecasts are a result of SAWS skilled expert interpretation and combination of probabilistic and deterministic forecasts produced by a variety of forecast models, both statistical and dynamical, and are verified using a standard verification system. The contributing institutions are SAWS, UCT, the International Research Institute for Climate and Society (IRI), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the U.K. Meteorological Office (UKMO). Consensus probability forecast maps of temperature and rainfall are produced each month and available at www.weathersa.co.za Although skill in predicting the three categories mentioned above has been demonstrated for the region, the South African Weather Service has recently invested in the predictability of extreme rainfall seasons.[176] High skill was found in the simulation of extreme rainfall seasons during December–February and March–May. Such investigations result from the high user demand for predictions of extreme seasonal rainfall.[177]

Combining multi-model forecasts has been shown to improve skill compared to individual model forecasts for southern African summer rainfall.[178] An analysis[179] of energy conversion rates over the South Atlantic during anomalously wet or dry South African summers and winters suggests that there are important feedbacks over this basin that prediction schemes do not take account of and which may reduce forecast skill. Multi-model ensembles have also been found to improve forecast performance of tropical cyclones,[180] something that needs to be further investigated for the southwestern Indian Ocean. Multi-model forecasting endeavours in southern Africa are illustrated through the Global Forecasting Centre for Southern Africa (GFCSA). The prime function of GFCSA is to operate a global seasonal forecasting system from where national meteorological and hydrological services within the Southern African Development Community (SADC) can obtain relevant seasonal forecast products. Global forecast fields are available online at www.gfcsa.net. Currently, the University of Pretoria, SAWS and the University of Cape Town contribute to GFCSA.

Numerical model developments

In collaboration with scientists from Australia, major improvements have been made in simulating rainfall over South Africa using the Australian CSIRO's Division of Atmospheric Research Limited Area Model (DARLAM) and the Conformal-Cubic Atmospheric Model at the University of Pretoria.[181–183] C-CAM is a new global model that employs a variable (stretched) grid to allow for fine-resolution simulations over particular regions of interest within the global grid.. Experimental daily weather forecasting results from this model are available routinely at www.up.ac.za/academic/geog/meteo

A unique, non-hydrostatic dynamic kernel has been introduced[182,183] for southern African applications and a split semi-Lagrangian integration scheme developed to solve a non-hydrostatic terrain-following coordinate equation set at high computational efficiency and accuracy. The equation set retains the advantages offered by the terrain-following coordinates of the widely used hydrostatic models, and is able to handle the meteorologically significant aspects of non-hydrostatic dynamics. Also, the set is free of vertically propagating sound waves, which implies a computational advantage over many of the recently developed nonhydrostatic models that make use of the fully compressible (unapproximated) atmospheric equations. The energy conservation properties of the equation set allows its application at scales larger than the mesoscale, thus it may potentially also be used for operational weather prediction over South Africa. It should be noted that much of the numerical modelling research at UP is performed in close collaboration with the CSIRO, illustrating the importance of international links for developing South African modelling capacity.

In terms of ocean model developments, collaboration with Australian scientists has led to the development of a curvilinear global model based on the GFDL Modular Ocean Model code.[184] This model allows a grid to be chosen such that there is much higher resolution over a particular area of interest, while maintaining a global configuration at coarser resolution, leading to relatively inexpensive computation. Applications of the model to the Agulhas Return Current/South Indian Ocean current region[185] and to the polar oceans[186] have shown the viability and advantages of this approach. The Regional Ocean Modelling System is also a curvilinear model but is intended for coastal to basin-scale applications and has been applied to the west coast region.[71] This model has been used to study the ocean response to inter-annual variability over the Benguela upwelling system,[72] the variability of the Angola–Benguela Frontal Zone[187] and the Agulhas Bank.

Numerical modelling of severe weather events

Southern Africa is prone to severe weather events and, in recent times, mesoscale numerical models such as Eta at SAWS, and MM5 at SAWS and UCT, have been used to simulate particular case studies of interest. For example, the Eta model was used[188] to simulate the February 2000 heavy rains over northeastern South Africa associated with two tropical storms, one being ex-tropical cyclone Eline, which led to devastating flooding in southern Mozambique and neighbouring areas. Although the simulations had some success with the spatial distribution of the rainfall, they underestimated the amount.

Cut-off lows are another weather system that may produce intense rainfall and flooding on occasion, particularly over the south and east coasts and adjacent interior. The evolution of two recent cases (East London, August 2002; Montagu, March 2003) has been modelled using MM5.[189,190] Both the model and satellite scatterometer winds showed that a low-level wind jet incident on the coastal mountains played a crucial role in generating the local flooding. Sensitivity and factor separation studies were used to show the relative contribution of latent heat fluxes from the neighbouring Agulhas Current region as well as the topography to the development of these storms.

Aerosols and atmospheric pollution

Understanding the composition characteristics of atmospheric transport patterns over southern Africa has advanced significantly over the past five years. In the late 1980s, much of the work undertaken in South Africa was concentrated over the industrialized highveld. After the Southern African Fire–Atmosphere Research Initiative (SAFARI-92), it was realized that it was important to evaluate atmospheric transport of constituents on much larger scales. The Southern African Regional Science Initiative (SAFARI 2000) was undertaken between 1999 and 2000 in order to investigate the nature of the regional atmosphere.[191] This section highlights the important findings over the past five years in terms of atmospheric transport, composition and distribution, deposition to the biosphere and hydrosphere, and the climate forcing potential of the atmosphere over southern Africa.

Sub-continental scale transport is the most important feature of the southern African atmospheric circulation. SAFARI-92 and SAFARI 2000 established average air transport patterns over the region (Fig. 2), and it is notable that the transport pathways are restricted to south of Zambia.[192] Satellite images obtained as part of SAFARI 2000 showed that air masses from Zambia transported visible quantities of aerosols and trace gases from biomass burning southward over the northeastern parts of South Africa and neighbouring areas.

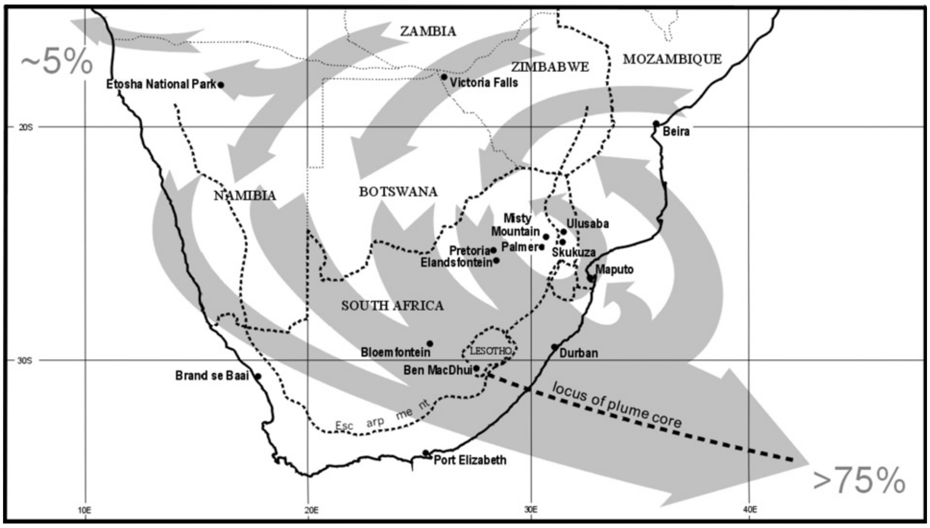

Fig. 2. Average atmospheric transport pathways over southern Africa.[202]

The 'River of Smoke' is an important feature of the southern African atmospheric circulation, linking emissions from as far north as 10°S to the rest of southern Africa[193,194] (Fig. 2). The recirculated transport pathway from Zambia to the Indian Ocean occurs most frequently during the spring (approximately 56% of the time).

The dominant sources contributing to the aerosol load over southern Africa were found to be industry, aeolian dust, biomass burning and emissions from the ocean. During the intensive field campaign of August and September 2000, a significant effort was made to characterize the composition of atmospheric aerosols found in the regional haze.[193,195–199] The findings confirmed the principal sources of atmospheric aerosols. Some advances have been made in understanding the morphology of aerosols both in the regional haze as well as within fresh smoke plumes from biomass burning. The specific composition is always associated with the dominant source. The main aerosol constituents included organic aerosols with inorganic inclusions, tar ball particles, soot, ammonium sulphate particles and components that included sea salt and biogenic particles.[196,197]

Given the fairly short lifetime of aerosols in the atmosphere, it is important to understand their spatial distribution, which is known to show significant seasonal variability. The aerosol gradient over southern Africa has been observed[200] to reverse between spring and autumn. SAFARI 2000 confirmed these findings, with the highest loading of aerosols occurring in the northern parts of southern Africa and being associated with emissions from biomass burning.[201] Vertical distributions of aerosols were also studied using *in situ* measurements and remote sensing. The regional atmosphere is highly structured in the vertical.[202–204] So-called clean air slots, associated with anticyclonic subsidence[205] and characterized by polluted air below and above an extremely clean layer of air, were found. The mechanisms for the formation of clean air slots and their persistence in the atmosphere are not well understood and need further study.

Aerosols have an important effect on the formation of clouds in the atmosphere. Cloud condensation nuclei (CCN) form the basis of every cloud droplet formed in the atmosphere. CCN concentrations and distributions have been successfully quantified for large regions of the subcontinent during both summer and spring months.[206] Both industrial and biomass burning emissions contribute significantly to the number of CCN available in the atmosphere. The highest concentrations of CCN are found over the industrialized highveld of South Africa and close to the most intense biomass burning regions to the north. The high concentrations of CCN impact directly on microphysical processes in clouds. High concentrations of accumulation mode CCN in continental air masses result in the formation of inefficient rain clouds.[206] Organic aerosols have also been shown to be significant, since they also act as CCN in the atmosphere. In addition, atmospheric aerosols interact directly with solar and terrestrial radiation to force the overall radiation budget. Once aerosols are deposited in the biosphere or hydrosphere, they also play a critical role by influencing the flux of minerals and nutrients into terrestrial and marine ecosystems.

Acid deposition due to wet and dry precipitation has been a cause for concern for many years in South Africa. A 13-year data set from two remote sites in South Africa (Louis Trichardt, Limpopo province, and Amersfoort, eastern Mpumalanga) shows that in general the rainfall at both sites is acidic with pH values of 4.91 and 4.35, respectively.[207] At Amersfoort, most of the acidity in the rainfall can be ascribed to sulphuric acid. At Louis Trichardt, the acidity is caused by organic (50%), nitric (25%) and sulphuric (25%) acids.[207]

Atmospheric aerosols have also been shown to play an important role in depositing nutrients to various ecosystems over the subcontinent and adjacent oceans. The deposition of aerosols from the atmosphere onto the Okavango Delta in Botswana has been calculated[208] as accounting for as much as 52% of the required phosphates and 30% of the nitrates of the ecosystem. The atmosphere acts as a link between the continent and the adjacent oceans. As much as 0.99 μg m^{-3} of fine aerosol iron per day has been estimated to be deposited on the Indian Ocean between 60° and 85°E during an episode of peak atmospheric aerosol transport,[209] leading to frequent phytoplankton blooms in the region. This deposition is likely to occur on at least 100 days per year. The presence of phytoplankton blooms in this part of the Indian Ocean seems to suggest that the iron that is deposited from the atmosphere is soluble and therefore available to the marine ecosystem.[209]

SAFARI 2000 provided much data that made it possible to estimate the radiative forcing potential of aerosols over the subcontinent during the spring. A radiative transfer model and *in situ* measurements were used[210] to calculate the radiative forcing resulting from aerosols emitted mainly from biomass burning. The model showed that, over land, the radiative impact is mostly negative. Over the ocean, the sign of the radiative forcing was influenced significantly by the presence of clouds and their position in the atmosphere relative to the aerosol layers. Clouds with haze layers situated above them result in a positive forcing. Recently, this model result was confirmed by observations.[211] The daily variation in radiative forcing over the subcontinent varied between –50 and –90 W m^{-2}, with the maximum forcing occurring at 09:00 and 15:00. The mean monthly radiative impact showed an average monthly forcing over the model domain of –1.7 W m^{-2} under cloud and –4.3 W m^{-2} under clear sky conditions.[210] The positive forcing off the west coast found by the radiative model and the *in situ* measurements appears to be caused by clouds overlaid by an aerosol layer.[212]

Summary

We have reviewed progress in the main fields of South African research in atmospheric science and physical oceanography. Space prevents mention of several other areas investigated — upper-air meteorology, ozone, agro-meteorology and land–surface interactions being important examples.

Many challenges need to be addressed if South African research efforts in atmospheric science and physical oceanography are to be maintained. For example, the availability of research funds remains poor by comparison with some other countries with a 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 such as the impact of human-induced climate change appear over-funded and others are grossly under-funded, leading to unhealthy distortions in local research expertise and training. Our universities struggle to fund and attract post-doctoral fellows, who play a pivotal role in the success of research-orientated universities abroad. Curricula at local universities need to keep abreast of international developments, be more diverse and cross-disciplinary in their offerings, and must attract students with good quantitative skills.

In the last decade or so, increased collaboration between various institutions within South Africa and also with groups abroad has contributed immensely to the development of South African expertise in areas such as aerosols and atmospheric chemistry, climate change, seasonal forecasting, numerical modelling and regional oceanography. Prominent examples include the SAFARI-92 and 2000[191] projects relating to aerosol transport pathways over the region, the KAPEX[11–13] project on the exchange of waters south of Africa, the MARE[42] experiment on the fate of Agulhas rings, and the ACSEX[15] 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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