33rd Annual Conference of the South African Society for Atmospheric Sciences

21-22 September 2017

Hosts: University of Venda
Protea Hotel Ranch Resort, Polokwane

CONFERENCE PROCEEDINGS

SPONSORS:
MESSAGE FROM THE PRESIDENT

Dear Delegates,

After the successful 32\textsuperscript{nd} annual conference held in Cape Town last year, I would like to welcome you to the 33\textsuperscript{rd} conference of the South African Society for Atmospheric Sciences. We are delighted by the host as University of Venda and conference chair Dr. Hector Chikoore as it is the first time that the conference has been hosted in this region. The local organizer has done an excellent job organizing the conference and familiarizing us with the venue. I would like to extend my special appreciation to all the participants including international delegates from the USA and Australia. I believe that all delegates will be able to share their knowledge widely during the conference as well as benefit from the key note speakers and invited lectures.

The goal of SASAS as a society is to promote and develop atmospheric sciences in the broader Southern African context. Major topics presented SASAS annual conferences are not only confined to atmospheric structure and dynamics but also include meteorology, agro-meteorology, climatology, air quality, hydrology, atmospheric interactions, remote sensing techniques, numerical modelling and oceanography.

We in the SASAS committee, believe that the introduction of peer reviewed conference proceedings over the past 7 years has improved the quality of South African atmospheric science research. It might have also enhanced number of our young researchers to write a quality research output and thus their research career.

There are approximately 100 delegates at this conference and they are drawn from around the country from various higher educational institutions and research councils/organizations. I am happy to note that 70\% of the delegates are students or young researchers who will go on to play a major role in the future of the society. We hope that all students will take the opportunity to discuss their research with their peers and enhance their overall knowledge.

The SASAS committee has invested a substantial amount of time and energy to enhance the value of the society, however, I would like to personally ask all members to actively participate in as many ways as possible to augment the value and exposure of SASAS. To this end, our new council members have significant contribution to facilitate the efficient running of the society. SASAS therefore encourages all society members to voice their opinions, ideas, concerns and constructive comments to further improve the society. Let us move forward and work together to make SASAS grow from strength to strength.

Prof. Sivakumar Venkataraman
\textbf{SASAS President}
\textit{(Atmospheric Research Group – UKZN : atmres.ukzn.ac.za)}
COMMITTEES

EVENT ORGANIZING COMMITTEE
Dr Hector Chikoore, University of Venda (Conference Chair)
Ms Sharon Mashau, University of Venda
Dr Lufuno Kone, University of Venda
Dr Nkanyiso Mbatha, University of Zululand
Prof John Odiyo, University of Venda
Dr Nthaduleni Nethengwe, University of Venda
Mr Mulalo Masisi, University of Venda
Mr Matjutla Mokgoebo, University of Venda
Mr Edmore Kori, University of Venda
Mr Tinyiko Nkuna, University of Venda
Mr Rendani Munyai, University of Venda
Mr Tisang Ncube, University of Venda
Mr Mishumo Nengwekhulu, University of Venda
Ms Vhukhudo Ramufufhi, University of Venda
Mr Nkosinathi Xulu, University of Venda
Ms Todani Phuluwa, University of Venda
Ms Nohlahla Dlamini, University of Venda
Mr Percy Muofhe, University of Venda
Mr Thendo Sikhwari, University of Venda
Mr Ndamulelo Nembilwi, University of Venda

Conference proceedings edited by Dr. Hector Chikoore and Prof. Willem Landman

REVIEW PROCESS
The South African Society for Atmospheric Sciences annual meeting provides the opportunity for scientists to publish their work in the conference proceedings. All the papers in the proceedings underwent a blind review process to improve quality, performance and provide credibility to the research. Each paper was independently reviewed by two reviewers on the review panel. The reviewers were tasked to categorize the paper into; accept as is; accept with minor/major revisions; or reject. Based on the reviewers’ comments, the convenor made the final decision on acceptance. The reviewers’ comments and decision on acceptance were sent to lead authors. Following this, corrections were made by authors for final acceptance. A total of 27 conference proceedings were submitted, with only one paper withdrawn by the authors.
REVIEW COMMITTEE
Prof Willem Landman, University of Pretoria (Convenor)
Prof Mathieu Rouault, University of Cape Town
Prof Bruce Hewitson, University of Cape Town
Dr Thando Ndarana, University of Pretoria
Dr Christien Engelbrecht, Agricultural Research Council
Dr Mary-Jane Bopape, South African Weather Service
Dr Warren Tennant, Met Office, UK
Dr Hector Chikoore, University of Venda
Dr Chris Lennard, University of Cape Town
Dr Joel Botai, South African Weather Service
Dr Asmerom Beraki, Council for Scientific and Industrial Research
Dr Rebecca Garland, Council for Scientific and Industrial Research
Dr Piotr Wolski, University of Cape Town
Dr Nkanyiso Mbatha, University of Zululand
Dr Gregor Feig, Council for Scientific and Industrial Research
Dr Juliet Hermes, South African Environmental Observation Network
Ms Lerato Mpheshea, Council for Scientific and Industrial Research
Mr Robert Maisha, Council for Scientific and Industrial Research
Ms Stephanie Landman, South African Weather Service
Mr Steven Phakula, South African Weather Service

SASAS MEDAL COMMITTEE
Prof Willem Landman (University of Pretoria, SA) - Chairman
Dr Babatunde Abiodun (University of Cape Town, SA)
Prof Hassan Bencherif (Universite de La Reunion, Reunion, France)
Dr Simon Mason (International Research Institute for Climate and Society, USA)
Dr Thando Ndarana (Council for Scientific and Industrial Research, SA)
Prof Stuart Piketh (School of Geo and Spatial Science, University of North-West, SA)
Associate Prof Marcello Vichi (Department of Oceanography, University of Cape Town, SA)

STANLEY JACKSON AWARD REVIEWERS
Dr Björn Backeberg, Natural Resources and the Environment, CSIR
Dr Thando Ndarana, University of Pretoria
Dr Mary-Jane Bopape, South African Weather Service
Prof Mike Harrison, Oxford University, UK
KEYNOTE SPEAKER

Professor Francois Engelbrecht
Council for Scientific and Industrial Research,
Natural Resources and Environment
South Africa
fengelbrecht@csir.co.za

Prof. Francois Engelbrecht is a Chief Researcher in the Natural Resources and the Environment Unit (NRE) of the Council for Scientific and Industrial Research (CSIR) in South Africa. He specializes in the fields of numerical climate model development and regional climate modelling over Africa. His research is focused on the projection of future climate change and the simulation of present-day climate variability over Africa, and has led to new insights into the changing rainfall and circulation patterns over the continent under enhanced anthropogenic forcing. His research papers on climate change over Africa have been referred to in both Assessment Report Four (AR4) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC). He contributes actively to the Africa group within the Coordinated Regional Downscaling Experiment (CORDEX) of the World Climate Research Programme (WCRP) and currently leads the development of the first Earth System Model based in Africa, towards Assessment Report Six (AR6) of the IPCC.

Prof. Engelbrecht’s research is finding wide application in South Africa and Africa, within the context of the impacts of climate change on the continent, and the formulation of climate change adaptation strategies. He is actively involved in multi-disciplinary research efforts related to the potential impacts of climate change on the African continent. In recent years he has co-authored publications related to climate change impacts on agriculture, hydrology and biodiversity in Africa. Most recently, he was invited to serve as Lead Author of Chapter 3 of the IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.

Prof. Engelbrecht has graduated two PhD and five MSc students, and currently supervises or co-supervises the research of ten PhD and one MSc students at four universities in South Africa: the University of the Witwatersrand, University of Cape Town, North West University and Nelson Mandela Metropolitan University.
KEYNOTE SPEAKER

Professor Chris J.C. Reason
Department of Oceanography, University of Cape Town, South Africa
chris.reason@uct.ac.za

Professor Chris Reason completed his MSc and PhD degrees at the University of British Columbia, Canada before working in Australia (CSIRO and then the University of Melbourne) for a number of years. He joined the University of Cape Town in 1998. His research interests include Southern Hemisphere climate variability and change, ocean and atmosphere modelling, mesoscale meteorology and severe weather, and the physical oceanography of the South Atlantic and Indian Oceans.
Professor Geoff Pegram
Professor Emeritus in Engineering
Senior Research Associate Civil Engineering,
University of KwaZulu-Natal, South Africa
pegram@ukzn.ac.za

Professor Geoff Pegram is an emeritus professor in engineering and senior research associate at the University of KwaZulu-Natal. He has authored 235 publications which include book chapters, scientific papers, reports, and articles. Of these, 81 papers in journals and book chapters were peer-reviewed. He has made 135 presentations in South Africa and overseas. Amongst other publications he was the lead on 19 reports for the Water Research Commission and the Department of Water Affairs. He is a leading expert in stochastic hydrology, water resources simulation, space-time modelling of rainfall and remote sensing of soil moisture, with experience in systems development and applications in the southern African region.
Dr. Natalie Burls joined the Atmospheric, Oceanic and Earth Sciences Department at George Mason University as an assistant professor in January 2015. Her research focuses on improving our understanding of the key processes determining Earth’s climate and climate variability on a variety of timescales ranging from seasonal to decadal to much longer geological scales. In particular, she is interested in the climatic role of ocean general circulation, ocean-atmosphere interactions, and cloud dynamics. Dr. Burls, a South African, completed her PhD in the Department of Oceanography at the University of Cape Town where her research examined, from an energetics perspective, the part played by the ocean within the generation and evolution of coupled ocean-atmosphere variability in the tropical Atlantic Ocean - a region of great importance for African and South American climate. Before joining George Mason University, Dr. Burls was a postdoctoral associate in the department of Geology and Geophysics at Yale University where she worked on both fundamental and Pliocene climate research.
# PROGRAMME

**DAY 1: 21 SEPTEMBER 2017**

Session Chair: Dr Hector Chikoore

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<td>OPENING AND WELCOME</td>
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<td><strong>Professor Peter Mbati</strong></td>
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<td><strong>Vice-Chancellor and Principal, University of Venda</strong></td>
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<td><strong>Professor Francois Engelbrecht</strong></td>
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<td><em>Can the 2-degree global temperature goal save Africa from dangerous climate change?</em></td>
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<td>0930 - 1000</td>
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<td><strong>Professor Geoff Pegram</strong></td>
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<td><strong>Stochastic Hydrological Modelling: a 50-year Personal Perspective</strong></td>
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<tr>
<td>1000-1015</td>
<td>DISCUSSION</td>
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<td>1015 – 1045</td>
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## 1045 - 1230 SESSION 1

### 1A Climate Modelling and Development (Chair: Prof Willem Landman)

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<td>1</td>
<td>1045 - 1100</td>
<td>Mary-Jane Bopape</td>
<td>Sensitivity of midlatitude cyclone clouds to parameterization schemes</td>
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<td>2</td>
<td>1100 - 1115</td>
<td>John McGregor</td>
<td>Atmospheric modelling on the equal-area cubed-sphere</td>
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<td>3</td>
<td>1115 - 1130</td>
<td>Asmerom Beraki</td>
<td>Midlatitude SH storm tracks and implications to the WRZ of South Africa</td>
</tr>
<tr>
<td>4</td>
<td>1130 - 1145</td>
<td>Christien Engelbrecht</td>
<td>Exploring sub seasonal dynamic predictability of extreme events: a case study of the January and February 2016 heat waves</td>
</tr>
<tr>
<td>5</td>
<td>1145 - 1200</td>
<td>Steven Phakula</td>
<td>Evaluation of the SAWS multi-model system in predicting DJF rainfall frequency over southern Africa</td>
</tr>
<tr>
<td>6</td>
<td>1200 - 1215</td>
<td>Thabo Makgoale*</td>
<td>Downscaling of projected changes in the South African hydro-climate domain</td>
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### 1B Aerosols and Atmospheric Chemistry (Chair: Dr Nkanyiso Mbatha)

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<th>Title</th>
<th>Speaker</th>
<th>Abstract</th>
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<tbody>
<tr>
<td>1</td>
<td>1045 - 1100</td>
<td>Siva Venkataraman</td>
<td>A short review on NO₂, SO₂ pollution studies over Durban</td>
</tr>
<tr>
<td>2</td>
<td>1100 - 1115</td>
<td>Thumeke Mkololo</td>
<td>Stratosphere-troposphere exchange over Irene as observed by ozonesonde, satellites and models</td>
</tr>
</tbody>
</table>
3 1115 - 1130  Rebecca Garland  Representation of aerosol particles and clouds in southwestern Africa in CCAM and their impact on climate
4 1130 - 1145  Lesetja Lekololane*  Evaluation of planetary boundary layer mixing height in South Africa
5 1145 - 1200  Gift Rambuwani  The impacts of aerosols on forecasting short range temperature over South Africa
6 1200 - 1215  Lerato Shikwambana*  Study on NO$_2$ and aerosol interactions over South Africa using space-borne observations

15 MIN DISCUSSIONS

1230-1330  LUNCH

1330-1400  POSTER PRESENTATIONS

1400-1550  SESSION 2

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<th>Time</th>
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<th>Title</th>
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<tr>
<td></td>
<td>1400 - 1415</td>
<td>Willem Landman</td>
<td>Attributes of predicted rainfall patterns over the Southern Hemisphere associated with the El Nino-Southern Oscillation</td>
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<tr>
<td></td>
<td>1415 - 1430</td>
<td>Johan Malherbe</td>
<td>Simulated responses of the Southern Annular Mode to high latitude tidal mixing</td>
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<tr>
<td></td>
<td>1430 - 1445</td>
<td>Kirodh Boodhraj*</td>
<td>Investigating the turbulence response of a 1-D idealized water column located in the sub-Antarctic zone with focus on the upper ocean dynamics</td>
</tr>
<tr>
<td></td>
<td>1445 - 1500</td>
<td>Stefaan Conradie*</td>
<td>Assessing the co-variability of modes of variability and southern African climate in the 20$^{th}$ century reanalysis using various metrics</td>
</tr>
<tr>
<td></td>
<td>1500 - 1515</td>
<td>Robert Maisha</td>
<td>Simulations of present and future climate over Ethekwini using CCAM model</td>
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<td></td>
<td>1515 - 1530</td>
<td>Nkosinathi Xulu*</td>
<td>Present and future variability in the Indian Ocean Mascarene High</td>
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2B  Atmospheric chemistry and wave dynamics (Chair: Dr Rebecca Garland)

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<tr>
<th></th>
<th>Time</th>
<th>Presenter</th>
<th>Title</th>
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<tbody>
<tr>
<td></td>
<td>1400 - 1415</td>
<td>Rebecca King*</td>
<td>Impact of a volcanic eruption on sulphur dioxide, ozone and surface solar UV radiation at a secondary site 7658 km away</td>
</tr>
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<td></td>
<td>1415 - 1430</td>
<td>Sewela Malaka*</td>
<td>Contribution of crop residues to climate change through nitrous oxide emissions</td>
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<td></td>
<td>1430 - 1445</td>
<td>Siva Venkataraman</td>
<td>Seasonal vertical variation in SO$_2$ over South Africa as observed by the Ozone Monitoring Instrument (OMI)</td>
</tr>
<tr>
<td></td>
<td>1445 - 1500</td>
<td>Rirhandzu Novela*</td>
<td>Quantification of fine particulate matter, soot in ambient air and the geographical origin of the air masses passing through Thohoyandou</td>
</tr>
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<td></td>
<td>1500 - 1515</td>
<td>Axinia Sethabela*</td>
<td>Micrometeorological measurements and vapor pressure deficit estimates in wheat field under pivot irrigation</td>
</tr>
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<td></td>
<td>1515 - 1530</td>
<td>Deon van der Merscht</td>
<td>Mountain waves observed in the lee of the Tsitsikamma Mountains</td>
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20 MIN DISCUSSIONS
### 1550-1610  TEA/COFFEE
### 1610-1730  SESSION 3

#### PARALLEL

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<tr>
<th>Session</th>
<th>Topic</th>
<th>Speaker</th>
<th>Details</th>
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</thead>
</table>
| 3A      | Rainfall Variability (Chair: Thulebona Mbhamali) | 1 1610 – 1625 | Willard Zvarevashe*  
Timeseries analysis of rainfall data at Cape Point using Empirical Mode Decomposition |
| 3A      | Rainfall Variability (Chair: Thulebona Mbhamali) | 2 1625 – 1640 | Zwidofhelangani Tshiwandalani*  
The anomalously wet 2016/17 rainfall season over southern Africa |
| 3A      | Rainfall Variability (Chair: Thulebona Mbhamali) | 3 1640 – 1655 | Thendo Sikhwari*  
Modelling of extreme maximum rainfall using generalized extreme value distribution over Limpopo province: 1960-2014 |

<table>
<thead>
<tr>
<th>Session</th>
<th>Topic</th>
<th>Speaker</th>
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</table>
| 3B      | Rainfall and surface hydrology (Chair: Dr Johan Malherbe) | 1 1610 – 1625 | Jaco de Wit  
Trend characteristics of rainfall and streamflow in the Vaal River Catchment |
| 3B      | Rainfall and surface hydrology (Chair: Dr Johan Malherbe) | 2 1625 – 1640 | Shereen Maluleke*  
Simulating soil moisture storage in flood water management for arid tropical regions |
| 3B      | Rainfall and surface hydrology (Chair: Dr Johan Malherbe) | 3 1640 – 1655 | Ntanganedzeni Ramugondo  
Modelling rainfall and temperature variations in the Limpopo |

20 MIN DISCUSSIONS

#### 1730-1830  POSTER SESSION
#### 1730-1830  SASAS COUNCIL MEETING (Excalibur Room)

#### 1900  GALA DINNER (SAFARI Room)

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### DAY 2: 22 SEPTEMBER 2017

**Chair:** Dr Mary-Jane Bopape

#### PLENARY

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| 0830-0900 | Professor Natalie Burls  
*Wetter subtropics in a warmer world: contrasting past and future hydrological cycles* |

10 MINS DISCUSSIONS

#### 0910-1030  SESSION 4

**Climate Services and Research Opportunities (Chair: Dr Nthaduleni Nethengwe)**

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| 4       | Climate Services and Research Opportunities (Chair: Dr Nthaduleni Nethengwe) | 1 0910 - 0925 | Neville Sweijd  
The ACCESS Annual Cycle and Seasonality (ACyS) Project |
| 4       | Climate Services and Research Opportunities (Chair: Dr Nthaduleni Nethengwe) | 2 0925 – 0940 | Brilliant Petja  
Research Focal Areas and Funding Opportunities at the Water Research Commission |

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<th>0940 - 0955</th>
<th>Joel Chabata</th>
<th>Challenges in Communicating Climate Change and Global Warming: A Broadcast Meteorology Perspective</th>
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<td>4</td>
<td>0955 - 1010</td>
<td>Adriana Marais</td>
<td>Innovation by exploration: SAP Africa</td>
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20 MIN DISCUSSIONS

**1030-1050 TEA/COFFEE**

Chair: Professor Natalie Burls

**PLENARY**

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<td></td>
<td>Professor Chris Reason</td>
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<td></td>
<td>What is unique about the oceans around southern Africa and how does it influence our climate?</td>
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10 MINS DISCUSSION

**1130-1300 SESSION 5**

**PARALLEL**

### 5A Weather Systems (Chair: Ramontsheng Rapolaki)

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<th>1130 – 1145</th>
<th>Dedricks Morake*</th>
<th>Modelling variability in the Angola Low and Botswana High</th>
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<td>2</td>
<td>1145 – 1200</td>
<td>Matshidiso Mogale*</td>
<td>Continental tropical low-pressure systems and their associated rainfall over the Highveld of South Africa using self-organizing maps</td>
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<td>3</td>
<td>1200 - 1215</td>
<td>Lulama Nhlapho*</td>
<td>Evolution of wave activity in a cut-off low system and a tropical-temperate trough system</td>
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<tr>
<td>4</td>
<td>1215 - 1230</td>
<td>Mark Fourie*</td>
<td>The role of cyclogenesis in stimulating vertical propagation of wave activity associated with a cut-off low and tropical-temperate trough</td>
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<td>5</td>
<td>1230-1245</td>
<td>Tisang Ncube*</td>
<td>Tropical cyclone tracks and the occurrence of extreme rainfall over southern Africa: 1983-2013</td>
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### 5B Applications for Agriculture and Water Resources (Chair: Lerato Mpheshea)

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<th>1</th>
<th>1130 – 1145</th>
<th>Fhulufhelo Tshililo*</th>
<th>Rainfall variability over the Luvuvhu River Catchment during the growing season</th>
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<td>1145 – 1200</td>
<td>Teboho Masupha*</td>
<td>Observed extreme widespread drought during the growing season of maize in the Luvuvhu River catchment of South Africa</td>
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<td>3</td>
<td>1200 - 1215</td>
<td>Mulalo Thavhana*</td>
<td>Runoff simulation using the SWAT model for flood frequency analysis and design flood estimations in the Luvuvhu River catchment, South Africa</td>
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</table>
4 1215 - 1230  Sabelo Mazibuko*  Spatio-temporal assessment of agricultural drought and floods in the Luvuvhu River Catchment

5 1230 - 1245  Thulebona Mbhhamali*  Climate impacts on sugarcane yield in the eastern part of southern Africa

15 MIN DISCUSSIONS

1300-1400  LUNCH

1400-1530  SESSION 6  PARALLEL

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<th>Climate trends and Weather Forecasting (Chair: Nkosinathi Xulu)</th>
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<td>1400 – 1415  Patience Mulovhedzi*  Heat wave forecasting over short-medium range timescale at SAWS</td>
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<td>2</td>
<td>1415 – 1430  Lerato Mpheshea*  Forecast verification: do different observed data sets matter?</td>
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<td>3</td>
<td>1430 – 1445  Ramontsheng Rapolaki*  Variability and trends in extreme precipitation events over north eastern South Africa</td>
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<td>4</td>
<td>1445 – 1500  Belinda Monyela*  A two-year long drought in summers of 2014/15 and 2015/16 over South Africa</td>
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<th>6B</th>
<th>Impacts of Climate Variability and Change (Chair: Tebelelo Mashego)</th>
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<td>1</td>
<td>1400 – 1415  Matome Masehela*  Assessing the role of grassland across different land management units as atmospheric carbon sequester using new generation multispectral sensors</td>
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<td>2</td>
<td>1415 – 1430  Mpho Gegana*  Evaluation of the relationship between land surface temperature and land use/cover changes as contributors to an urban heat island over the city of Polokwane using Landsat 7 and 8 data</td>
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<td>3</td>
<td>1430 – 1445  Terence Sepuru*  Assessing the influence of climate change on land degradation in Sekhukhune using earth observation data</td>
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<td>4</td>
<td>1445 – 1500  Humphrey Thamaga*  Investigating climate change impacts on the spatial distribution of the invasive water hyacinth (Eichhornia crassipes) in the Greater Letaba River system</td>
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15 MIN DISCUSSIONS

1515-1530  TEA/COFFEE
1530-1540  AWARDS AND CLOSING (Prof Siva Venkataraman)
1540-1600  SOCIETY ANNUAL GENERAL MEETING (Chair: Prof Siva Venkataraman)

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<tr>
<td>Boodhraj</td>
<td>Kirodh</td>
<td>Investigating the turbulence response of a 1-D idealized water column located in the sub-Antarctic zone with focus on the upper ocean dynamics</td>
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Midlatitude SH storm tracks trends and implications to the WRZ of South Africa

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Abstract
The dynamical behaviour and time evolution of the SH eddy-driven jet stream are analysed within the numerical experimentation framework that uses an ESM on seasonal to interannual timescales. The model simulation shows a great deal of improvement from the previous attempts that used coupled ocean-atmosphere climate models that compromised a number of climate forcings notably influences arising from anthropogenic and ozone states. The jet stream dynamical characteristics are consistent with the observed, and the modelled intensification and poleward expansion of the storm-track activities is realistic. Furthermore, the analysis is able to probe the ESM’s systematic errors in terms of meridional and vertical positions of the jet stream. Key aspects of the seasonal behaviour of the jet is found to occur much later of the year compared to the reanalysis. The cause of the displacement deserves further investigation.

Keywords: ESMs, Eddy-driven jet stream, Systematic errors, Jet position and strength.

Introduction
The need to understand the contribution of various climate forcings and their intricate interactions is of key importance in climate predictability studies. This objective may be better accomplished with the use of Earth System Models (ESMs) that interactively couple the ocean-atmosphere-land-cryosphere despite that the use of ESMs is not widely practiced at seasonal to inter-annual climate timescales due mainly to computational considerations. The concept of complete climate system deployment is expedited through the Climate-System Historical Forecast Project (CHFP5) coordinated by the CLIVAR (Climate Variability and Predictability) Working Group on Seasonal to Interannual Prediction (WGSIP; Kirtman and Pirani, 2009; Butler et al., 2016). The current work, therefore, attempts to present an early developmental phase of a Variable-resolution Earth System Model (VRESM) within the context of the sub-seasonal to inter-annual climate timescales and predictability studies which are currently underway. The VRESM development is a joint effort of the Council for Scientific and Industrial Research (CSIR) in South Africa and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia.

Southern Hemisphere (SH) climate variability is characterized by the dominance of quasistationary and zonally propagating waves in the atmospheric circulation (e.g., Wallace and Hsu, 1983; Schoeberl and Krueger, 1983). On the intraseasonal timescale, the SH atmosphere is dominated by stationary or eastward-propagating wave trains in the meridional belt between 40°S and 60°S where the polar jet acts as a waveguide (Berbery et al. 1992).

The study investigates the midlatitud storm tracks activities using the 3D structure of the SH eddy-driven (polar) jet stream and transient eddy statistics to elucidate the synoptic dynamical behaviour and time evolution both in the ESM and the NCEP (National Centers for Environmental Prediction) Reanalysis (R2; Kanamitsu et al., 2002; used as proxy for observation). The jet stream (notably its meridional) position has significant effect on extratropics weather and storm track variability on both hemispheres, and has become a centre of attention over recent years. From the paleoclimate perspective, for instance, the wettest episode of the Holocene in the winter rainfall zone (WRZ) of South Africa occurred during the “Little Ice Age” (700–1000 cal years BP) most likely in response to a northward shift of the jet stream (westerlies; e.g. Weldeab et al. 2013). Many studies also noted that the mean latitude of extratropical cyclones migrated poleward and cyclones have become fewer and more intense, over the last half of the 20th century (e.g., McCabe et al., 2001).

Data and method
The ESM applied here may be regarded as a computational prototype of the Variable-resolution Earth System Model (VRESM) currently under development at the CSIR, through a collaboration with the CSIRO. The atmospheric component is the conformal-cubic atmospheric model (CCAM) of CSIRO (McGregor, 2005a). CCAM is a σ-coordinate model that uses a semi-implicit semi-Lagrangian method to solve the hydrostatic
primitive equations (a nonhydrostatic version also exists). It uses an R-grid (reversible staggering for the wind components) for good gravity wave dispersion behaviour (McGregor, 2005b). The GFDL parameterizations for long-wave and short-wave radiation are used, with interactive cloud distributions determined by the liquid and ice-water scheme of Rotstyn (1997). A stability-dependent boundary layer scheme based on Monin Obukhov similarity theory is used (McGregor et al., 1993), together with the non-local treatment of Holtslag and Boville (1993). The cumulus convection scheme uses a mass-flux closure, as described by McGregor (2003), and includes downdrafts, entrainment and detrainment. CCAM includes a prognostic aerosol scheme, and can be applied consistently with the emission inventories and radiative forcing specifications of the Coupled Model Intercomparison Project Phase Five (CMIP5).

The dynamic land-surface model used is the CSIRO Atmosphere Biosphere Land Exchange model (CABLE). CABLE includes a dynamic river routing scheme adapted from the CSIRO Mk3.5 CGCM. In the experiments performed here the model uses a CSIRO developed ocean model on the conformal-cubic grid, which also uses a semi-implicit semi-Lagrangian time discretization. VRESM is based on the above prototype system, with the difference that the ocean component is the Variable-resolution Ocean Model (VCOM) currently under development at the CSIR. VCOM solves the Boussinesq hydrostatic equations in a z-coordinate in momentum-conservation form, using a split-explicit procedure applied on the R-grid. VCOM is in turn coupled to the PISCES ocean biochemistry model. Coupling of the ocean, atmospheric and land-surface components takes place every time-step. It is envisaged that VRESM will be applied on a 100 km horizontal resolution grid within the Coupled Model Intercomparison Project Phase Six (CMIP6), with a longer-term plan of performing global eddy-resolving (10 km resolution) simulations depending on the availability of supercomputing resources at the CSIR.

The experiment consists of two set of model integrations. The first simulation is an AMIP type experiment, performed for the period 1870-2015, using the AMIP sea-surface temperatures (SSTs) and sea-ice concentrations (SICs) provided through CMIP6 as lower boundary forcing. That is, the first simulation performed is an atmosphere-only simulation, with the CCAM-CABLE system being forced at its lower boundary by the AMIP SSTs and SICs. In the second simulation performed, a fully coupled climate model (ESM) is used except that ocean model is nudged at its surface to the AMIP SSTs, using the spectral nudging method of Thatcher and McGregor (2010). The nudging (depending on its strength) presumably compels the simulation to resemble the AMIP SSTs at the large scale, although regional ocean currents and related atmosphere-ocean fluxes are capable to develop freely. Both experiments are additionally forced by the time-varying CO₂ and ozone fields provided through the CMIP5 archive for the period 1870-2100.

Figure 1: The daily climatology SH zonal average eddy-driven jet attributes (meridional position (a), vertical position (b) and strength (c) of the ESM (red)/ AMIP (black) simulations and NCEP reanalysis (blue). The amplitude represents the jet stream attributes in each longitude grid point of NCEP (light-blue) and ESM (light-pink). Similarly, the time evolution of the jet stream attributes are presented in 1yr (d-f) and 5yrs (g-i) running mean daily anomalies for the period of 1979-2015. NCAR Command Language software (NCL, 2017) was used for the analysis.

The eddy-driven polar jet stream position is detected using a cubic spline interpolant as in Gallego et al. (2005) except that our algorithm also considers the vertical movement of the jet stream. The strength of the jet stream is therefore assumedly associated with the value of the 3D position of the jet stream core. The wintertime storm-track activities are represented by various transient eddy statistics, as noted earlier, based on the Eulerian approach which applies bandpass-filtered daily data to retain 2–8 days synoptic time-scales variability (Blackmon et al., 1977). These include standard deviation of filtered geopotential height (\(\sqrt{\overline{x^2}}\)), eddy kinetic energy (EKE) and meridional eddy heat flux (\(\sqrt{\overline{PT}}\)) averaged from June to August (JJA; Gan and Wu, 2013). The overbar and prime denote seasonal average and departure from the mean respectively.
Figure 2: Observed trends (per season) of transient 850mb (left panel), 250mb (right panel) 2–8 days bandpass-filtered standard deviation geopotential height (a,b), eddy kinetic energy (EKE'; c,d), and meridional eddy heat flux (e,f) during the austral winter (JJA). The respective climatology is also shown with contour lines. The statistics were computed using the NCL (2017).

Results and discussions

The daily climatology SH zonal average of the three jet attributes (strength, meridional and vertical positions) of the ESM (red)/ AMIP (black) simulations and NCEP reanalysis (blue) is shown in Fig. 1 (see caption for details). The amplitude of the jet attributes simulated by the model (light-pink) is relatively wider than the NCEP (light-blue). Despite the general agreement between the model and the NCEP in the seasonality of the jet variation, the result finds a noticeable systematic error in the model. Relative to the reanalysis, the time when the jet stream moves upward/poleward and intensify in its strength displaced toward the austral summer in the model. The consistency in the time evolution vacillation and trend of the jet stream is encouraging particularly in its meridional and vertical movement (Fig. 1d-f). This dynamical behaviour is consistent with the findings of Yin (2005) for the 21st century SH midlatitude storm tracks using 15 coupled climate models. Furthermore, the similarity of the AMIP and ESM representation is presumable attributed to the spectral nudging method applied and is worth investigating under different strength of relaxation.

The poleward expansion and intensification of the storm tracks activities are noticeable, measured by the bandpass-filtered transient EKE and filtered standard deviation geopotential height (Fig. 2). Notwithstanding, meridional eddy heat flux is largely weakened which may suggest a probable weakening of extratropical cyclone activity. The model representation of the storm-tracks activities is in good agreement with observed trends (not shown).

Conclusions

The dynamical behaviour and time evolution of the eddy-driven jet stream are analysed within the numerical experimentation framework that uses an ESM on season to interannual climate timescales. The ESM simulation demonstrates a great deal of improvements from the previous attempts that used coupled ocean-atmosphere climate models (CGCMs) that compromise a number of climate forcings such as anthropogenic influence and use climatological ozone (e.g. Mathole et al., 2015). The jet stream poleward displacement and intensification are consistent with the observed intensification and the poleward expansion of the storm tracks activities and probable weakening of the extratropical cyclone activity.

The finding supports the notion that using complete climate systems may be a game changer approach in overcoming the models’ weaknesses in simulating midlatitude climate variability on the seasonal to interannual timescales. The analysis provides an important insight into the model’s systematic error notably on the daily climatological jet strength, meridional and vertical position of the eddy-driven jet stream for which seasonal changes are simulated to occur much later in the year compared to the reanalysis. The cause of the displacement is not clear and deserves further investigation.

Acknowledgement

The authors are thankful to the Center for High Performance Computing (CHPC) for providing
computational facility and two anonymous reviewers for their valuable comments.

References


Investigating the turbulence response of a 1-D idealized water column located in the sub-Antarctic zone with focus on the upper ocean dynamics

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Marcello Vichi, UCT and Marine Research Institute, Cape Town
Jacoba E. Smit, CSIR Modelling and Digital Science, Pretoria

Abstract

A one-dimensional ocean physical model was implemented in the sub-Antarctic Southern Ocean using the Nucleus for the European Modelling of the Ocean (NEMO) model. It was used to examine the effects of the turbulence response of the simulation of vertical mixing in the water column structure in the Southern Ocean (SO), using the available scattered data as comparison. The Brunt Väisälä frequency, turbulent diffusivity and turbocline provided valuable information regarding the turbulence response of the water column and the effect of an entrapped warm water parcel below cool waters was observed.

Keywords: NEMO, Sub-Mesoscale Parameterizations, Turbulence Scheme, Vertical Mixing, Southern Ocean

Introduction

Currently, the development of the first African based Variable Resolution Earth Systems Model (VRESM) is being carried out by the Council for Scientific and Industrial Research (CSIR) and will enhance the regional understanding and implications of climate change. Resolving eddies is an integral component of VRESM involving the use of sub-grid scale parameterizations (Gent and McWilliams 1990). Initial steps for understanding these parameterizations relies on oceanic vertical mixing processes which are essential for understanding surface stratification during the austral summer and deep mixing during winter. Ocean turbulence is a dominating physical process involving the distribution of momentum and energy and is modelled numerically using a turbulence scheme (Thorpe 2007). In this study, NEMO was used to simulate a 1D fluid column. The governing equations consist of a 1D version of the Navier-Stokes (Primitive) Equations. The objective of this paper is the use of turbulence schemes to model vertical mixing processes and to analyse various turbulence indicators. Furthermore, a warm water parcel was found trapped beneath cooler upper waters and is discussed.

Data and Method

This study focussed on the sub-Antarctic zone of the Southern Ocean region off the coast of South Africa (47ºS 4.5ºE), chosen due to the availability of in situ glider data. A configuration (named SAZ1D) was created in NEMO (based upon the work of Reffray et al. (2015) who modelled a 1D column in the Northern Pacific ocean), to model the turbulence response of a vertical 1D idealized fluid column at the chosen location. SAZ1D uses an Arakawa A grid with z-coordinates for numerical efficiency. The vertical grid had a variable number of levels (31, 51, 75, 101 and 151) for different simulations. Bathymetry (4500 m) was obtained from the General Bathymetric Charts of the Oceans (GEBCO 2016). Vertical levels were distributed into the bathymetry via a scaled hyperbolic tangent function due to it being smooth and creating tight spacing in the upper fluid column (which is integral to resolving atmosphere-ocean interactions).

This paper focusses on 101 vertical levels as this is an achievable future goal for global ocean models due to continuous improvements in computational power. Current global models generally employ 50-75 vertical levels (MERCATOR 2008). All simulations were performed for 15 June 2010 to 14 June 2011 with time step of 360 s. Various reanalysis products namely, the European Centre for Medium-Range Weather Forecasts ERA-Interim (Dee et al., 2011), Japanese Reanalysis (JRA55) (JMA 2016), National Aeronautics and Space Administration (NASA) (NASA 2016) and National Centres for Environmental Prediction (NCEP) (NCEP 2016) provided surface forcing data (wind
speed, specific humidity, solar and thermal fluxes, total precipitation and air temperature) for the simulations. Chlorophyll data from the European Space Agency (ESA) (ESA 2017) was used in conjunction with reanalysis data for all simulations. Initial conditions were obtained from the World Ocean Atlas (Locarnini et al. 2013) consisting of temperature and salinity profiles. Vertical mixing in the water column was simulated using the k-ε, k-o, k-kl, GLS (Umlauf 2003), TKE0, TKE10, TKE30 (Blanke 1993) and Pacanowski-Philander (PP) (Pacanowski 1981) turbulence schemes. Simulations were run for all possible combinations of turbulence schemes and reanalysis data (8×4=32 simulations in total).

Turbulence indicators include the Brunt Väisälä frequency, turbulent diffusivity, turbocline and Mixed Layer Depth (MLD). The Brunt Väisälä frequency was calculated using

\[ N^2 = \left( \frac{g}{\rho_0} \right) \frac{dp}{dz}, \]

where \( g = 9.8 \text{ m/s}^2 \), \( \rho_0 = 1034 \text{ kg/m}^3 \) (reference density), \( z \) the vertical depth from mean sea level and \( \rho \) the density. Density was calculated using TEOS10 (McDougall 2012) and MLD calculated using a density criterion of 0.1 \( \text{kg/m}^3 \). The turbocline is the depth where the upper turbulent layer is separated from the (less turbulent) fluid below, calculated by finding the minimum depth for where turbulent diffusivity (which indicates the turbulent strength) falls below \( 5 \times 10^{-4} \text{ m}^2\text{s}^{-1} \).

Results and Discussion

Figures 1 and 2 display the water column temperature and salinity time evolution. There is a distinct inter-annual variability and temperatures reached a maximum (minimum) of 12 (3) °C in the upper 300 m while salinities vary within a small band of 33.9-34.2 PSU. These temperature and salinity values lie within the bounds of glider data (Swart et al. 2015) obtained from the region. The winter deep mixing penetrates down to 150 m (above the permanent pycnocline) while during the summer stratification, high temperatures penetrate down to 100 m.

The temperature, salinity and density profiles (Fig. 3) indicate an entrapped warm water parcel around 150 m. This warm parcel is also present for combinations of other turbulence schemes and reanalyses. The warm parcel presence during deep mixing (September 2010), beginning of stratification (November 2010) and start of deep mixing (April 2011) is shown in Table 1. Regarding turbulence schemes, only NASA resulted in an entrapped warm parcel using k-ε. For all reanalyses, the PP scheme always produces a warm parcel. Regarding reanalysis, NASA always produced a warm parcel for all turbulence schemes. NCEP only produces a warm parcel using the PP scheme. ERA-Interim and JRA55 tend to have persistent warm parcels that are still visible at the beginning of the deep mixing period (April 2011). The exact cause of the entrapped warm water parcel is still unclear. It is believed the cold convection of water during the winter does not penetrate deep enough to fully mix the upper layer i.e., the warm parcel is an impression from the previous season. The monotonically increasing density, made stable due to salinity, is a possible reason for the warm water parcel (Fig. 3). The absence of density instabilities implies no need for mixing, suggesting erosion (or entrainment) of the layer above or below does not happen.

The Brunt Väisälä frequency (Fig. 4) indicates the strength of stratification. The permanent pycnocline is observed at 150 m. Multiple stratification events occur (seen from spike in the average Brunt Väisälä frequency) before the permanent onset of the seasonal pycnocline (50 m). The stratification events filter from the upper water column and terminate on the seasonal pycnocline because for stratification to occur, surface effects must be convected into the water column. The descent of the seasonal pycnocline indicated cooling of surface waters. Fig. 5 displays the turbulent diffusivity, turbocline depth and MLD. During austral winter/spring there are high diffusivities down to 180 m but shallows to 50 m in summer and slowly descends to 100 m in June 2011.
Figure 1: Water column temperature evolution plotted for annual period June 2010 to June 2011 using ERA-Interim data and the k-kl turbulence scheme.

Figure 2: Water column salinity evolution plotted for annual period June 2010 to June 2011 using ERA-Interim data and the k-kl turbulence scheme.

Figure 3: Water column temperature, salinity and density profiles using Interim data and the k-kl turbulence scheme during the deep mixing period (September 2010). Note the entrapped warm parcel at 150 m.

Figure 4: Brunt Väisälä frequency plotted for annual period June 2010 to June 2011 using Interim data and the k-kl turbulence scheme. The column average is shown for comparison.

Figure 5: Turbulent diffusivity (with MLD and turbocline) plotted for annual period June 2010 to June 2011 using Interim data and the k-kl turbulence scheme.

Table 1: The presence of the warm particle is shown for a combination of turbulence schemes and reanalysis products. † indicates the entrapped warm parcel’s presence during deep mixing (September 2010), ‡ at start of stratification (November 2010) and * at beginning of deep mixing (April 2011). Empty cells indicate absence of the warm parcel.

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<td>TKE30</td>
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<td>Pacanowski-Philander</td>
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This implies turbulence acts deeply during winter and diminishes during the summer stratification. The turbocline borders the diffusivity and is more sensitive to stratification events than the MLD. This is observed during winter, where the turbocline spikes while the MLD does not. Future work
includes investigating the effects of the warm parcel by simulating the water column beyond June 2011 and assessing whether a 1D model is accurate enough to provide guidance on turbulence scheme choice for global models.

Conclusions
In conclusion a warm water parcel was present for different combinations of reanalysis and turbulence schemes. Reasons for why this parcel formed were possibly due to lack of deep penetration of cold water convection due to a stable density profile. The turbocline was found to show higher sensitivity to the turbulent response of the water column compared to the MLD. The turbulent diffusivity correctly indicated the seasonal turbulent behaviour for an ideal vertical ocean model i.e., higher (diminished) turbulence during the austral winter (summer).

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Trend characteristics of rainfall and streamflow in the Vaal River Catchment

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Abstract
This contribution assesses annual and seasonal characteristics of rainfall and streamflow from 1985 to 2016 across 13 rainfall and streamflow stations distributed within the Vaal River Catchment. The nonlinear Mann-Kendall (MK) statistical test was applied to the monthly aggregated rainfall and streamflow time series to assess the inherent trends. The results indicate that seasonal and annual rainfall amounts have significantly decreased, with most of the negative trends observed during SON and DJF seasons. The observed trends across the seasons are statistically insignificant except during the SON season. Though the changes in rainfall patterns shows subtle effect in the seasonal and annual accumulated streamflow patterns, persistence decreases in rainfall and other factors such temperature, evapotranspiration and land use and land cover may result in reduction water resources within the Vaal catchment. This study therefore contributes towards understanding the status of water resources in the Vaal River Catchment vital for informing policy, successful planning and management for future water use in the region.

Keywords: Mann-Kendal test, Trends, Vaal catchment

Introduction
The Vaal River is one of the biggest rivers in South Africa, supplying water to approximately 12 million homes and industries through the Vaal River Integrated System, with the Vaal Dam forming part of this system. Persistent drought conditions exacerbated by increased temperatures and low rainfall has caused significant stress to the Vaal River System. According to the Department of Water and Sanitation, the Vaal Dam recently reached its lowest water percentage level (approximately 27%), see Fig. 1, although the dam has since recovered as a result of the rainfall received during the summer season. Global climate models and predictions project widespread occurrences of extreme events in most significant areas of South Africa (Shongwe et al. 2009; Shongwe et al. 2015). Significant impacts often manifest across populace with poorly resourced livelihoods.

Understanding past trends of climatic variables such as precipitation, temperature, streamflow, etc. contribute towards formulating appropriate adaptation, resilience and mitigation measures. In particular, analysis of precipitation trends plays an essential role in studying the influences of climate change and variability on water resources planning and management (Haigh, 2004). Historical trends in climate variables over South Africa have been extensively studied by various authors (Kruger 2006; New et al. 2006; Kruger and Sekele 2013). Most of these studies have reported on trends analysis focusing on precipitation and temperature variables. The current study focuses on analysing trends characteristics of precipitation and streamflow data within the Vaal River Catchment.

Study Area
The Vaal catchment is situated on the Central North and Eastern part of South Africa, (Fig. 2). The catchment area is divided into the Upper Vaal, Middle Vaal and Lower Vaal management areas, with a total catchment area of about 240 130 km². The Vaal catchment contains four major dams (e.g. The Vaal, Grootdraai, Sterkfontein and Bloemhof). The Vaal Dam is the primary supplier of potable water to more than 25% of the people of South Africa, for various purposes (e.g. industrial, mining, urban, rural, irrigation, power generation). The Vaal is characterized by highly variable rainfall as well as high evaporation, coupled with human activities (e.g. agriculture, forestry, mining, urbanization, power generation, etc.), all posing a significant threat to water resources. The Vaal catchment is selected in this study because of the central role that the Vaal dam plays to the socio-economic development of South Africa.
Figure 2. Map depicting South African Water Management Areas and the study area, the Vaal region. The red triangles correspond to the rain gauge stations selected for the analyses.

Data
Historical time series of daily (aggregated to monthly) precipitation from 13 automated weather stations operated by the Department of Water and Sanitation (http://www.dwa.gov.za/Hydrology/Verified/hymain.aspx) were analysed for the period spanning 1985 – 2016, see Table 1 for their characteristics. In addition, streamflow data from 13 gauge stations that were in close proximity to the rain-gauged stations were selected for analysis. All rainfall and streamflow stations considered had continuous records for 31 years. These selected stations were relatively evenly distributed throughout the study region, although coverage in the lower Vaal region is relatively sparse. The rate of missing data across the selected stations was less than 2%, per station.

Table 1. Characteristics of selected rainfall stations

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Location</th>
<th>MAP (mm)</th>
<th>C. Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1E001</td>
<td>Deneyesville at Vaal Dam</td>
<td>664</td>
<td>38620</td>
</tr>
<tr>
<td>C1E007</td>
<td>Riversdale at Grootdraai Dam</td>
<td>796</td>
<td>7928</td>
</tr>
<tr>
<td>C2E001</td>
<td>Vaalplaats at Vaal River Barrage</td>
<td>704</td>
<td>1121</td>
</tr>
<tr>
<td>C2E009</td>
<td>Naauppoort at Boskop Dam</td>
<td>588</td>
<td>3595</td>
</tr>
<tr>
<td>C2E015</td>
<td>Klipdrift at Klipdrift Dam</td>
<td>648</td>
<td></td>
</tr>
</tbody>
</table>

Methodology
Time series of the observed rainfall and streamflow data were analysed in order to understand the spatio-temporal characteristics of each climatic variable at seasonal and annual time scales. In particular, the daily time series data were analysed to assess the variation and trends of precipitation and streamflow variables during the selected period of study. The spatio-temporal characteristics of the climatic variables were described using the mean, standard deviation, coefficient of variation, skewness coefficient and kurtosis coefficient as a measure of variability. In addition, trends in rainfall and streamflow time series were analysed and detected using the nonlinear Mann-Kendall (MK) statistical test method (Yue et al. 2002). The main advantage of MK is that it is non-parametric, i.e. it does not require the data to be normally-distributed (Karpouzos et al. 2010). The MK test method is endorsed by the World Meteorological Organization for the assessment of trends in meteorological data (Mitchell et al. 1966).

Results
Precipitation and streamflow time series characteristics
Table 2 gives a summary of precipitation and streamflow time series characteristics within the Vaal River Catchment across different seasons. The results indicate that the mean seasonal rainfall is high during DJF, MAM and SON seasons. Similarly, the mean seasonal streamflow is higher in DJF, MAM and SON. Seasonal and annual streamflow exhibits higher variance across the Vaal region as compared to the precipitation, see Table 2. The distribution of precipitation is extremely skewed at an annual time scale and during MAM and JJA seasons (>1), moderately skewed in DJF (skew coefficient between
0.5 and 1) and fairly symmetric in SON (<0.5). On the other hand, the distribution of streamflow is extremely skewed, annually and across the seasons, within the Vaal region. In addition, precipitation time series exhibits light to heavy tailed distribution at intra-annual time scales while streamflow time series exhibits thick-tailed distribution (e.g. positive coefficient of kurtosis) at all time scales.

Table 2. Rainfall and streamflow statistical characteristics across different seasons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>289.28</td>
<td>140.78</td>
<td>23.59</td>
<td>164.21</td>
<td>617.86</td>
</tr>
<tr>
<td>STD</td>
<td>103.03</td>
<td>70.30</td>
<td>22.63</td>
<td>78.91</td>
<td>155.29</td>
</tr>
<tr>
<td>CV</td>
<td>0.37</td>
<td>0.50</td>
<td>1.00</td>
<td>0.45</td>
<td>0.26</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0.30</td>
<td>1.26</td>
<td>1.08</td>
<td>-0.09</td>
<td>-0.48</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.50</td>
<td>1.01</td>
<td>1.18</td>
<td>0.46</td>
<td>0.28</td>
</tr>
</tbody>
</table>

| Streamflow |      |      |      |      |        |
| Mean       | 9.89 | 5.20 | 2.41 | 3.20 | 5.15   |
| STD        | 15.81 | 8.24 | 3.03 | 3.64 | 6.41   |
| CV         | 1.75 | 1.76 | 1.69 | 1.71 | 1.35   |
| Kurtosis   | 5.51 | 5.35 | 8.95 | 7.88 | 4.74   |
| Skewness   | 1.99 | 1.98 | 2.33 | 2.10 | 1.62   |

Trends of seasonal rainfall and streamflow

Fig. 3 depicts seasonal rainfall (a) and streamflow (b) trends (Sen’s slope estimate) obtained using the MK test method across the selected weather stations within the Vaal River Catchment. The results indicate that SON rainfall has decreased overall except one station within the Vaal River Catchment. In DJF season, rainfall time series exhibit negative trends in more than 60% of the stations. The observed rainfall trends are however statistically insignificant. Positive but insignificant trends in rainfall are observed in the vast majority of the meteorological stations during the MAM and JJA seasons. As depicted in Fig. 3, vast majority of the Vaal River Catchment exhibits weak to moderate streamflow trends across the seasons, which mostly are statistically insignificant (except JJA). The trends observed during JJA are mostly statistically significant (8 of the stations) at 95% confidence level.

Trends in annual rainfall and streamflow

Annual trends in rainfall and streamflow are depicted in Figs. 4(a) and (b), respectively. Most of the stations exhibit negative rainfall trends, with 4 of the stations exhibiting statistically significant trends. About 30% of the stations exhibit positive trends that are statistically insignificant. On the other hand, annual streamflow time series exhibit weak positive trends overall except two stations within the Vaal region. Only two of the stations showing positive trends are statistically significant. Of the two stations showing a negative trend in annual streamflow, one is statistically significant while the other is insignificant.

Discussion

Analysis of 31 years of observed rainfall and streamflow data indicates that the rainfall has decreased during the study period, across the selected regions within the Vaal River Catchment. The changes in rainfall seem to be localized with a strong seasonal cycle. At annual time-scales, the observed changes in rainfall patterns seem not to influence the streamflow changes. Furthermore, the observed trend in streamflow is subtle implying that other factors such as temperature and evaporation also play a significant role. Although the results indicate that the rainfall has decreased over the study period, the impact of this decrease on the accumulated streamflow within the region cannot accounted for by the rainfall changes alone. In order to determine degree of rainfall influence to changes in streamflow,
cover changes, and evapotranspiration be factored in the equation. This is not considered in this contribution and currently being investigated.

**Figure 4.** Annual precipitation (a) and streamflow (b) trends across the selected stations within the Vaal River Catchment

**Conclusion**

This contribution provides important insights on the annual and seasonal characteristics of rainfall and streamflow in the Vaal River Catchment. The results indicate that Vaal River Catchment experienced a decrease in rainfall during the study period. The seasonal rainfall time series depict an overall negative trend, particularly during SON and DJF seasons, with the vast majority of the Vaal region showing significant trends in SON at 95% confidence level. The seasonal streamflow series also show a weak positive trend across the study area and the seasons. During the JJA season, most stations exhibit statistically significant trends. Annually, approximately 70% of the stations show a negative trend in the rainfall time series, with ~45% of the stations exhibiting significant trends. On contrary, a larger area of the Vaal River Catchment (~85% of the stations) exhibits weak positive trends in the annual streamflow time series, of which only two of the stations exhibit statistically significant trends. In order to determine the impact of changing rainfall patterns to changes in streamflow, additional factors such as temperature, evapotranspiration and land use and land cover changes ought to be introduced into the equation.

**References**


Anti-correlation between spring time ozone and ultraviolet radiation levels at Cape Point, South Africa: An exploratory analysis

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2Environment and Health Research Unit, South African Medical Research Council

Abstract

An anti-correlation exists between total column ozone and surface levels of solar ultraviolet radiation (UVR). Here, we use a simplified approach to explore the strength of that anti-correlation at Cape Point, South Africa for a 10-year period (2006-2015) and any distinct outcomes from four significant Antarctic ozone hole events in 2007, 2008, 2009 and 2015. Only days that were cloud-free were considered during the austral spring and summer months after the breakup of the ozone hole. A linear anti-correlation between UVR and ozone of -0.435 was found for 2009 which was statistically significant at a 95% confidence interval. The strongest anti-correlations were found during spring and summer months. The relatively low correlation coefficients that were found may be due to additional factors that influence UVR at the surface of the Earth. Future research should take these factors, such as fixed solar zenith angle, aerosols, and improved clear-sky versus cloud differences, into consideration.

Keywords - Ozone, Anti-correlation, Ozone hole, South Africa.

Introduction

The sun emits energy in the form of electromagnetic radiation. Part of the spectrum is ultraviolet (UVR) with a wavelength of 100-400 nm. UVR is divided into three different bands, i.e. UV-C, UV-B and UV-A, depending on the wavelength. UV-A and UV-B rays pass through the atmosphere but more than 90% of UV-B can be absorbed by atmospheric ozone. Cloud cover, ozone, aerosols, solar zenith angle (SZA) and latitude all impact the amount of solar UVR measured at the surface (Bai, 2011). Skin cancer and immune suppression are some of the harmful side effects associated with excess personal exposure to solar UVR. Therefore, solar UVR has significant implications for public health (Lucas, et al., 2006).

Ozone (O₃) is a naturally occurring gas that is found in various concentrations throughout the atmosphere. About 90% of total ozone is found in the stratosphere (18-50 km) leading to the "ozone layer" which absorbs UV-B radiation (Peethani, et al., 2014). There is a distinct ozone cycle that occurs every year (Diab, et al., 1992). During the Austral spring, Antarctic ozone depletion reaches a maximum, leading to the formation of the ozone hole. The ozone hole breaks up during late November and early December as a result of atmospheric dynamics (Varotos, 2004). Ozone poor air is transported to southern midlatitudes with the break-up of ozone hole. The Antarctic polar vortex air masses over the midlatitudes result in a decrease in ozone concentrations. A relation between spring time ozone depletion in the Antarctic polar vortex and decreasing ozone concentration in the midlatitudes of the Southern Hemisphere has been reported in e.g., (Ajtić, et al., 2004). Over South Africa, TOC increases from May to October and decreases over the summer months of each year (Diab, et al., 1992). Research on the decrease in ozone concentration helps to improve the understanding of increased ground-based solar UVR (Bialek, 2006).

The aim of this study was to perform an exploratory investigation of the anti-correlation between solar UV-B radiation and total ozone column (TOC) in the atmosphere above Cape Point, South Africa during spring that possibly follows ozone hole events over Antarctica. This study is the first phase of a series of investigations into the influence of ozone concentrations on ground-based UV-B radiation levels in South Africa; each phase will apply more sophisticated tools and analysis techniques based on findings reported here.

Data and methods

The hourly solar UV-B radiation data were obtained from the South African Weather Service (SAWS) for the Cape Point weather station for 2006-2015. The weather station at Cape Point (-34.35 °S, 18.50°E) is at 230 m above sea level (GAWSIS, 2015) (Brunke, et al., 2011).

The Solar Light Model Biometer 501 radiometer used and measures UVR with a wavelength band of 290-320 nm. The measured solar UVR is proportional to the analogue voltage output from the radiometer given in minimal erythema dose (MED) (Solar Light, 2014). The MED values were converted to UV Index (UVI) where 1 MED = 2.33 UVI (see Eq. 2 below).
Daily satellite TOC measurements were used as ground-based TOC was not available for Cape Point. The Ozone Monitoring Instrument (OMI) on the Aura satellite monitors the recovery of the ozone layer. OMI has a spatial resolution of 0.25° in latitude and longitude. Measurements are given in Dobson Units (DU) (Bhartia, 2012). Since the swath width of the satellite is greater than the station, it was assumed that the TOC concentrations above the station are uniform throughout the selected grid box (18.375°(West), -34.475°(South), 18.625(East), -34.225°(North)).

The SZAs were calculated using an online tool, Sunearthtools. The algorithm uses the date, time and location on the Earth and is accurate to +/-0.0003° (Reda & Andreas, 2008). The clear-sky UVI values were calculated to identify cloud-free days. The formula for clear-sky UVI (Eq. 1) values applies for cloud-free conditions, low surface albedo and low pollution levels (Madronich, 2007) and is given as:

$$UVI \sim 12.5 \mu^2 \left( \frac{TOC}{300} \right)^{-1.23}$$  \hspace{1cm} (1)

where $\mu$ is cosine of SZA, and TOC is total column ozone (in DU).

Only mostly cloud-free days were considered in this study in an attempt to eliminate cloud cover as an influencing factor. The UV-B data were converted from MED to UVI values (Eq. 2) as follows:

$$\left( \frac{MED \times 210}{3600} \right) \times 40 = UVI$$  \hspace{1cm} (2)

UVI is a scale used to represent the strength of UVR, particularly referring to the erythema strength of the UVR (Liley & McKenzie, 2006).

First, the climatology of the UVI and TOC was described for the four years with the lowest Antarctic ozone concentrations. During 2006-2015, the values of the average minimum TOC over Antarctica between 21 September and 16 October were considered to determine which years to analyse. They were 2007, 2008, 2009 and 2015. Each year was divided into four three-month intervals: January, February, March (JFM); April, May, June (AMJ); July, August, September (JAS); and October, November, December (OND). This deviation from the usual seasonal grouping was chosen as large data gaps were often at the end of a year. The daily 12h00 UTC+2 UVI values were extracted as 12h00UTC+2 is closest to the time of solar noon throughout the year when incoming solar radiation is at a maximum.

The difference between the calculated clear sky UVI value (Eq. 1) and the observed UVI value at 12h00 UTC+2 ($U_{VI} = U_{VI_{calc}} - U_{VI_{obs}}$) was obtained to determine which days were mostly cloud-free. The UVI difference values were then sorted in ascending order. Satellite images were studied to determine at which point there were clouds over Cape Point. Once clouds were found to be present at a point. A specific value could be assigned to remove cloudy days from each season

The correlation was tested between TOC and the daily UVI 12h00 UTC+2 values on mostly cloud-free days. The linear correlation coefficient ($R$) was used to test the strength of the correlation between TOC and UVI. Apart from the correlation calculations for the data covering each year, the OND and JFM period was also considered as it represents the spring and summer months.

To investigate whether ozone-poor air on specific days over Cape Point was associated with the Antarctic ozone hole, days with low TOC were selected to perform back-trajectories (Ajtić, et al., 2004). The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model programme was used to run the back-trajectories (Stein, et al., 2016) (Rolph, 2016). HYSPLIT uses meteorological data from the Global Data Assimilation System (GDAS) with a 1° global resolution to create back-trajectories. Each of the back-trajectories was run for a period of 10 days. Days with TOC values below 300 DU in the OND period were used as the initial (start) dates. The ensemble trajectories were run at 18 km above ground level, thus focussing on the level at which stratospheric ozone is found.

**Results and discussion**

The UV-B radiation yearly average obtained at Cape Point over the four investigated years was 3.7 UVI and the maximum values occurred during the summer months of December (8.1 UVI) and January (8.3 UVI). The minimum UVI values occurred in June (2.0 UVI). Even though only mostly cloud-free days were considered, other factors such as aerosols caused a variation in UVI measurements.

The TOC values observed over Cape Point for 2007, 2008, 2009 and 2015 had a yearly mean of 284.4 DU. Total ozone column was particularly low during 2008 when the lowest recorded value of 224.6 DU (28 June 2008 *) was very close to the critical 220.0 DU ‘low’ level. The general trend in the TOC data showed at least one peak value in September of each year (Fig. 1) and a decrease
during summer months. The TOC minimums occurred during the autumn months. There is some evidence of a lag effect between TCO and UVI but this requires further investigation.

Comparison of the UVI and TOC trends implied an anti-correlation between the two data sets (Fig. 1), particularly over the spring and summer months. Correlation calculations for individual years showed that 2007 and 2009 had statistically significant correlation coefficients. The stronger correlation of -0.435 was obtained for 2009.

![Figure 1 Time series of total ozone column and UVI for 2007, 2008, 2009 and 2015 for mostly cloud-free days. The scale of the x-axis only represents mostly cloud-free days.](image)

The correlation was tested over the spring (OND) and summer (JFM) months for each of the four years. Only the OND period showed statistically significant negative (inverse) correlations. The OND period of 2009 and 2015 had similar significant correlations of -0.458 and -0.456, respectively. The OND period of 2007 was found to have the highest significant inverse correlation of -0.721.

To eliminate the effect of the sun angle on the correlation, data points with the lowest daily SZA over the OND period with its corresponding UVI and daily TOC were chosen. There was a noticeable difference in the correlation values when only the lowest daily SZA data points was used. There was a moderately negative statistically significant correlation of -0.429 during 2009.

Using the findings from this study, future work on the relationship between and UVI should aim to eliminate any presence of clouds and to focus on the stratospheric ozone rather than TOC as stratospheric ozone absorbs UV-B radiation. A Radiation amplification factor (RAF) could be used along with correlation coefficients to describe the relationship, since this relationship is non-linear. These improvements should reduce the number of uncertainties and influencing factors in the analyses, and thus raise confidence in the obtained results.

At Cape Point over the OND period of the four investigated years there were 79 days of TCO below 300 DU. Here, only some illustrative examples are given of the HYSPLIT back-trajectories.

During the OND period in 2007, the strongest negative correlation was obtained for TOC and UVI. The back-trajectories during this period offered no conclusive evidence that ozone-poor air masses originated from the Antarctic ozone hole. During October and November, there is a possibility that some of the air masses originated from the edge of the ozone hole (Fig. not shown). In December, ozone-poor air could have been contained in small-scale ozone hole remnants which could have been transported northwards after the ozone hole breakup.

A common feature of the back trajectories at 18 km for the OND period of 2007 was their compactness: the trajectories were contained within the mid-latitudes, between 30 °S and 60 °S (Fig. 2). The horizontal transport in the zonal direction was not seen in all of the investigated days with low TOC. For example, on 26 December 2008, most of the calculated back trajectories originated from the north (Fig. 2) implying that in some instances, ozone-poor air reaching Cape Point comes from the tropics.

Improvements on the identification of the source of ozone-poor air can be made through using potential vorticity as a dynamic tracer and encompassing more initial heights.

**Conclusion**

This exploratory investigation of the anti-correlation between solar UV-B radiation and total ozone column above Cape Point, South Africa, during 2007, 2008, 2009 and 2015, showed a slightly negative (-0.188) but still statistically significant correlation over all four-years. This anti-correlation was pronounced during the months of October, November and December, with 2007 OND having a statistically significant correlation of -0.721. Limiting the correlation calculations to the UVI records only for the minimum daily SZA did not generate stronger correlations.

Considering the possible association of spring-time low TOC cases over Cape Point with the Antarctic ozone hole, preliminary results did not conclusively show that ozone-poor air was transported from the ozone hole. Instead, ozone-poor air could originate from the vortex edge or from another source. Some of the investigated cases showed that it was transported over Cape Point by the westerly winds. However, other
instances implied that ozone-poor air from the tropics could reach Cape Point during spring and summer.

References


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A short review on NO$_2$, SO$_2$ pollution monitoring studies over Durban

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Abstract

Air pollution is a major problem of the new millennium and it has become increasingly clear that human activities are playing an important role in the cycling of trace gases in the atmosphere. Poor air quality can affect health and the wider environment, particularly in urban areas where the majority of people live and work. Due to their abundance and substantial health impacts, pollutants chosen with direct relevance to this review are nitrogen dioxide (NO$_2$) and sulphur dioxide (SO$_2$). Their health and environmental impacts are briefly outlined together with a discussion on factors directly affecting air quality in Durban. A short review of air pollution studies in Durban is then presented for these target species. This review illustrates the fact that a detailed, long term study of all significant pollutants in the greater Durban area is both important and highly relevant.

Keywords: Air pollution, NO$_2$, SO$_2$, Durban

Introduction

A number of factors influence air quality in urban areas. The levels of pollutants released into the atmosphere are directly related to the number of emission sources, distribution of emission sources and volume of pollutants released by each source (Masiol et al. 2014). Air quality is also affected by the rate at which pollutants disperse as dispersion is dependent on both wind direction and strength. Strong winds result in rapid dispersal of air pollution whereas little or no wind results in the accumulation and in some cases, high concentration of air pollution. Local factors such as topography and proximity to coast, building height and time of year all affect local wind conditions and can play a role in increasing air pollution levels (Diab et al. 2002, Thambiran and Diab 2010). Atmospheric residence times reflect the length of time a chemical species remains in the atmosphere before chemical processing to another species occurs. As a result, residence times of a chemical species determine the effect of a specific pollutant on air quality. Air pollutants with very short residence times affect indoor and outdoor air quality as they do not undergo substantial atmospheric mixing before chemical modification takes place. However, species with very long residence times result in transport on a continental scale with corresponding global impacts (Carslaw and Carslaw 2001, DEA report 2012, Fiore et al. 2012).

There are multiple emission sources of NO$_2$ including sources of both natural and anthropogenic origin. Natural emission sources include biomass burning, lightning and microbial activity in soils (Thambiran and Diab 2010). Anthropogenic sources include motor vehicles and combustion sources that burn fossil fuels (Masiol et al. 2014). In tropical regions the primary source of NO$_2$ is human-induced biomass burning. However, in the northern hemisphere and mid-latitudes, the dominant emission sources are combustion of fossil fuels (Thambiran and Diab 2010). Brown haze which inhibits visibility in ambient air in areas of high air pollution is directly related to high concentrations of NO$_2$ (Moodley et al. 2011).

Sulphur dioxide (SO$_2$) has multiple emission sources both natural and anthropogenic in origin. Natural emission sources of SO$_2$ include volcanoes, grassland and forest fires. Coal and petroleum often contains sulphur compounds and their combustion generates SO$_2$. Anthropogenic SO$_2$ emission sources therefore include combustion of fossil fuels / crude oil and coal transformation processes. It is also produced as a by-product of metal smelting (of sulphur containing ores) and other industrial processes (Masiol et al. 2014). Approximately 90% of sulphur present in fossil fuels enters the gas phase in the form of SO$_2$ during combustion, unless it is deliberately removed from flue gas (Hewitt 2001).

Air quality in Durban

South Africa has been identified as a source of industrial pollution significant on a global scale (Josipovic et al. 2010). The problem of air pollution in Durban has a long history, particularly in relation to the Durban South Industrial Basin (DSIB). The DSIB is an approximately 4 km wide area on the eastern seaboard of South Africa, extending south from the Durban Central Business District (CBD) for 24 km to Umbogintwini. This area includes the CBD and Port of Durban, which is the busiest port in Africa. Poor historical land-use planning has resulted in juxtaposition of residential and industrial areas in South Durban.

At present, some 600 industries are reportedly located in South Durban Industrial Basin (South Durban Basin Multi-point plan case study report 2007). Principle emission sources include refineries Sapref, and Engen and the paper manufacturing plant, Mondi. A number of the major facilities have low stack heights (50 – 100 m) and this facilitates the increase of pollutants close to the ground. The DSIB is the focal point of many of the city’s major transport routes and this adds a further contribution to emissions from vehicular traffic and shipping (South Durban Basin Multi-point plan case study report 2007).

Winds in Durban basin blow predominantly from the south-south-west to south-west and north-north-east to north-east
in approximately equal proportions. Winds from north-north-east / north-east are associated with high atmospheric pressure and fine weather. However, winds from south-south-west / south-west are associated with the passage of coastal low pressure systems and cold fronts and hence accompany unfavourable weather. The direction of the predominant winds parallel to the coast, together with the DSIB topography results in the channeling of pollutants within the basin. Wind speeds are generally higher during the day due to the effect of sea breeze. This results in better dispersion conditions during the day than at night. Seasonally, wind speeds are higher in spring (September – November) while low wind speeds are typically recorded in autumn / winter (April – June). High levels of pollutants are generally connected to low wind speed conditions in winter and at night / early morning. This is because of poor vertical mixing and low horizontal transport out of the source area (South Durban Basin Multi-point plan case study report 2007).

The effect of temperature inversion conditions on pollutant levels should be noted. Inversions are common overnight during periods of calm weather and are generally strongest in the early morning hours. This inversion phenomenon acts like the ‘lid’ on a containment vessel that traps pollutants close to the ground and prevents upward air movement. Temperature inversions coupled with low wind speed can result in high levels of pollutants near the surface. A brown haze is a common feature of air quality in the Durban area in winter and can be attributed to the photochemical action of NO\textsubscript{2}, O\textsubscript{3}, SO\textsubscript{2}, PM and volatile organic compounds (VOCs). Finally, pollutants may also be increased through the transport of pollutants from inland areas down to the coast by north-westerly land breezes at night, particularly during winter.

The effect of rainfall on air pollution is significant. Annual average rainfall in Durban is 1009 mm with most of this rain falling in summer. This period of high rainfall is associated with periods of improved air quality as the net effect of rainfall is to remove dust and pollutant gases from the atmosphere. During summer, humidity is high (sometimes approaching 100% although the average humidity in March is 83%) while winter is characterised by low humidity (as low as 20% although the average humidity in June is 73%). This high humidity in summer implies that chemical reactions requiring water vapour are accomplished more efficiently and hence airborne pollutants are removed more effectively than during the dry winter conditions (South Durban Basin Multi-point plan case study report 2007), (Naidoo et al. 2007). Overall, dispersion conditions in summer improve due to less stable air conditions, higher wind speed and the effect of rainfall. As a result of the contributing factors discussed above, DSIB one of the most heavily polluted industrial areas in South Africa.

**Air pollution studies for target pollutant species:**

An extensive survey of the literature revealed the dearth of research on air quality monitoring for the greater Durban area. In the case of NO\textsubscript{2} and SO\textsubscript{2} studies, papers mentioned in this review are those that contain the longest and most up to date trend data. Smaller studies whose study periods overlap with more extensive and longer surveys are omitted. Figure 1 shows the locations of monitoring sites that will be referred to in this review.

**NO\textsubscript{2} studies:** A total of 3 papers relevant to this review were found and their principle findings are presented below.

**Naidoo et al. (2007): Study period 2004 – 2005.** A comprehensive study of air pollution exposure and associated health risk assessment was completed by Naidoo et al. (2007). Sampling of NO\textsubscript{2} was undertaken continuously at 8 sites (May 2004 – February 2005). These sites can be grouped into 3 categories: Lower DSIB / Southern sites (3 locations): Southern Works, Jacobs, Wentworth, Central DSIB / traffic sites (4 locations): Warwick, City Hall, King Edward, Ganges – these reflect primarily vehicular sources and Northern sites: (1 location): Ferndale – which is some distance from major roads and industry. In all the Monitoring of NO\textsubscript{2} was accomplished through conventional continuous gas-phase chemiluminescence detection methods (Monitor Europe, model ML 9841 B). Data were initially collected at 5 minute intervals and processed to 1 hourly averages if at least half of the data for that hour were available. These 1 hourly averages were then further processed to 24 hr averages if at least half of the hourly data were available for the 24 hr period.

Daily average NO\textsubscript{2} levels were calculated and used to deduce trends in NO\textsubscript{2} concentrations at the chosen sites. The principle findings from campaign averages were: Concentrations across the 8 monitoring sites show that the lowest levels are in the north (11 ppb) at Ferndale. The highest concentrations (19-24 ppb) are recorded in the city centre and industrial areas namely City hall, Warwick, King Edward and Jacobs. Moderate levels (12-14 ppb) were recorded at the southern sites Southern works and Wentworth. In line with principle emission sources for NO\textsubscript{2}, concentrations were generally highest at heavily traffic-impacted locations. At all sites, concentrations show a very strong seasonality with the highest levels in autumn / winter (March – August corresponding to 20-25 ppb). The authors state that given NO\textsubscript{2} emissions are likely relatively uniform over the year, this variation is likely to result from poor

![Figure 1: Locations of monitoring sites referred to in this review (Ethekwini air quality monitoring network – Annual report 2009).](image-url)
dispersion conditions in winter. However, it should be emphasised that this study had a duration of just under a year and such a conclusion is subjective and inconclusive.

Ethekwini air quality monitoring network - Annual report 2009: Study period 2004 – 2009. The air quality report released in 2009 by the Ethekwini air quality monitoring network contains NO₂ trend data for the period 2004 – 2009 as recorded by instrumentation in the network. These annual average trend data are presented for 8 monitoring stations and can be classified as: Northern sites: Ferndale, Central sites: Warwick, City Hall and Southern sites: Ganges, Jacobs, Southern Works and Wentworth. The authors state that the data shows no well-defined trend in annual average NO₂ levels over the period 2004 – 2009. However, due to the short duration of this study (5 years), this conclusion could be viewed as subjective and inconclusive. The national guideline for average annual NO₂ exposure is exceeded by a number of stations during the study period, namely: Ganges (2004, 2006, 2009), Jacobs (2007), Warwick (2004, 2008), City Hall (2006). Such exceedances occur for southern and central sites and therefore indicate that the origin of this pollutant is related to traffic emissions.

Moodley et al. (2011): Study period 2000 – 2001. Since vehicles stop or move slowly through intersections, concentrations of NO₂ are expected to be relatively high at these sites. In this study, inexpensive Ogawa passive samplers were placed at selected traffic intersections in the Durban metropolitan to trap NO₂ which was then analysed by an appropriate laboratory-based method. Data were recorded by passive samplers using a seven day collection period. Selected locations included Ethekwini municipality monitoring stations Wentworth and Settlers School (southern sites) and a number of busy intersections in Durban including Victoria embankment, Warwick Avenue, Argyle road and Spaghetti Junction. Sampling was done over a 12-month period to cover all seasons (2000 / 2001). For Settlers School and Wentworth, active sampling using a chemiluminescence detector was used in parallel to data collected by passive sampling. Active sampling was undertaken using a Teledyne API Model 200A NO₂ Analyser SN: 1570). Analysis showed that there was no statistical difference between the two methods of NO₂ measurement. The findings of this investigation can be summarized as follows: Concentration of NO₂ decreases with distance from kerbside, indicating that traffic is the principle emission source of NO₂ at these sites. A strong correlation between NO₂ levels and rainfall was found. Highest concentrations of NO₂ coincided with periods of low rainfall. Furthermore, the inversion layer which is quite pronounced during winter traps pollutants in the ambient air. The relatively calm conditions due to an increased number of windless days favours the accumulation of pollutants.

SO₂ studies: Air quality monitoring in Durban was initiated in 1958 at Wentworth. As a result, SO₂ is therefore the pollutant with the longest record of near continuous monitoring. As SO₂ is a principle by-product of many industrial processes it is often used as an ‘indicator pollutant’ that is, it is seen as a general indicator of overall air quality. Results of three studies with relevance to this pollutant will be discussed.

Diab and Motha (2007): Study period 1958 – 2005. Data was continuously monitored at Wentworth in DSIB for the period 1958 - 2005. Mean monthly SO₂ data (μg m⁻³) were derived from SO₂ bubbler records based on the hydrogen peroxide method of collection. Data were averaged over a 2 - 3 day period in order to investigate long term trends in SO₂ levels. Significant changes in ambient air quality are noted over the period 1958 – 2005, namely extended periods of increasing trends in SO₂ interspersed with shorter periods of decreasing trends. The following points should be noted: 1958 – early 1960’s: Steady increase in SO₂ to a peak annual concentration of 88 μg m⁻³ (34 ppb) in 1962. Late 1960’s – early 1970’s: Rise in SO₂ levels followed by a decline after 1971. The 1980’s and early 1990’s: Increasing trend in SO₂ with levels exceeding 80 μg m⁻³ (30 ppb) in 1989 and 1991 and approximating maximum levels recorded for study period (1962). After 1991: SO₂ concentrations decline and levels stabilize between 50 – 60 μg m⁻³ (19 – 23 ppb) over the following few years. Since 1998 there has been a further decline to a mean annual value of ≈ 40 μg m⁻³ (15 ppb). When ambient air quality levels are compared with global and local air quality standards, it is apparent that until relatively recently exceedances are a common occurrence in South Africa.

Mdluli (2015): Study period 2005 – 2014: A presentation containing data recorded by Ethekwini air quality monitoring stations illustrates trends for the period 2005 – 2014. Annual average SO₂ data for Ferndale, Ganges, Grosvenor, Jacobs, Prospecton, Settlers School, Southern Works, Wentworth sites are presented. For the period 2005 – 2014, all sites record levels below the South African annual average exposure limit of 19 ppb. Southern sites (Wentworth, Settlers School, Southern Works, Jacobs) generally record higher levels than northern sites (Ferndale). This is a direct consequence of proximity to SO₂ sources. There appears to be an approximate decreasing trend in SO₂ levels recorded for the study period 2005 – 2014 over most sites.

Diab et al. (2002): Study period 1997 – 1999. This study investigated variations of SO₂ in SDIB for the period 1997 – 1999. A network of monitoring stations was set up at four sites: AEIC, Athlone, Wentworth and Southern Works. Data was collected hourly using a UV fluorescence method to quantify SO₂. Spectral analysis of the data set shows that the dominant feature of the data is the diurnal cycle – this is very well developed in winter at the two stations (Southern Works, Wentworth) closest to an industrial source (Engen refinery). Diurnal variation of SO₂ at Wentworth reveals that diurnal curves have an amplitude of approx. 10 ppbv (or less) with the highest levels recorded in winter. For all seasons, peak levels are recorded at 8:00 am. Authors cannot provide a definite explanation for this observation but suggest it could be related to a traffic peak or industrial cycle. Minimum SO₂ values occurred in mid/late afternoons. In winter, SO₂ levels remained elevated throughout the night relative to other seasons. Concentrations in evening hours rise from 20:00 and reach a maximum at midnight. Authors suggest that Wentworth is exposed to a nocturnal source of pollution in evening hours not seen at other stations. For AEIC, little diurnal variation is apparent. Levels recorded in winter are slightly higher than those recorded in other seasons (approx 5 ppbv). One maximum (at 11 am) is observed for all seasons.

Conclusion
Chemical reactions in a polluted atmosphere are only one
aspect of a complex system as observed pollutant concentrations are also influenced by the distribution of emission sources, meteorology, complex local scale mixing and topography. Pollutants need to be monitored extensively and for long periods in order to clarify the complex relationships that exist between species, photo-chemistry and meteorological factors. To date, no comprehensive long term study of all significant atmospheric pollutants in the greater Durban area has been undertaken. A long term study of air pollutant behaviour (and their complex inter-relationships) in Durban is therefore proposed. This will be undertaken using data collected from Ethekwini air quality monitoring stations from 2003 to the present.

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Exploring subseasonal dynamic predictability of extreme events: a case study of the January and February 2016 heat waves

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Abstract

By following a case study approach, the subseasonal predictability of heat waves over South Africa has been explored by making use of the January and February 2016 UKMO maximum temperature ensemble forecasts that was initialised on 1 January 2016. The UKMO forecasts are integrated for 60 days, allowing 8 individual weekly forecast periods with lead-times of 0, 7, 14, 21, 28, 35, 42 and 49 days respectively. The amplitude of the weekly maximum temperature anomalies for all the lead-times are underestimated, but there is some evidence that changes, such as the number of heat wave days are predictable at lead-times beyond 14 days.

Keywords: Heat waves, Predictability, South Africa

Introduction

The 2015-16 summer season over South Africa was exceptionally hot with the relatively frequent occurrence of heat waves over the country compared to previous summer seasons. Apart from the heat waves being frequent, in particular during the October to December period, the spatial extent of the heat waves was wide spread, covering multiple provinces during a single heat wave event. One of the heat wave events that had large societal and agricultural impact developed during the last few days of December 2015 and lasted into the second week of January, where after two relatively cooler weeks occurred before increased maximum temperatures and a heat wave event occurred again in the first to second week of February (Fig. 1) (Engelbrecht and Landman 2017).

Knowledge prior to the likely occurrence of an extreme weather event can have value (e.g. Vitart 2014). For effective decision making and the implementation of alleviation measures, knowledge on the likely occurrence of an extreme event is needed a few weeks in advance of the occurrence of the event. To stand a chance for useful subseasonal predictions, some source of predictability needs to exist. In this study, a case study approach is followed to explore the predictability of the occurrence of heat waves during January and February 2016.

Figure 1: ERA-Interim maximum temperature weekly anomalies for the period 1 January 2016 to 25 February 2016 relative to the long-term mean for the corresponding weeks for the years 1998 to 2009.

Data and Method

Daily maximum temperature data from the Met Office’s UKMO model was downloaded from the S2S database that
resides at the European Centre for Medium-Range Weather Forecasts (at http://apps.ecmwf.int/datasets/data/s2s). The atmospheric component of the UKMO is coupled to an ocean model, whilst an active dynamical sea ice model is included as well. The UKMO S2S hindcasts and real-time forecasts are integrated for 60-days. The real-time forecasts (1 control and 3 perturbed forecasts) are produced daily since December 2015 and the hindcasts (1 control and 2 perturbed forecasts) are produced 4 times a month (1st, 9th, 17th and 25th) for the period 1996 to 2009.

As the subseasonal time scale is of interest, forecasts for week 3 and onwards are explored. Forecasts initialized on 1 January 2016 are used and calibrated by using the 1996 to 2009 hindcasts for the corresponding time of the year. Before exploring the predictability of heat waves, the weekly maximum temperature changes are explored. The weekly maximum temperature anomaly forecasts over the 60-day integration period are shown and compared to the observed weekly maximum temperature anomalies as derived from ERA-Interim data. There are 8 weeks within the 60-day integration period. For each week, the corresponding week’s maximum temperature climatology was calculated to obtain that week’s anomaly. The ERA-Interim weekly climatology of the maximum temperature was derived over the period 1996 to 2009, similar to that of the UKMO hindcast climatology.

The definition of heat waves as employed by Lyon (2009) are used in this study. The daily maximum temperature needs to exceed the climatological 90th percentile of the summer season’s maximum temperature for at least 3 consecutive days. The heat wave definition used in this study deviates slightly from that of Lyon (2009) as the summer season in this study is defined as January and February, whilst December, January and February was used as the summer season in Lyon (2009).

Results and Discussion
The observed weekly maximum temperature anomalies and the forecast weekly maximum temperature anomalies are shown in Figs. 1 and 2 respectively. The negative maximum temperature anomaly observed in week 3 has not been captured in the week 3 forecast. Surprisingly, the week 4 forecast has an indication of the observed negative maximum temperature anomalies over the southwestern parts of the country observed in week 4, although the amplitude and spatial extent are underestimated. During week 4, a cut-off low system that developed during week 3, caused good rainfall over the western interior regions and brought relief to the extreme hot and dry conditions that persisted throughout the summer up till then. There are some evidence that cut-off lows show some predictability on the seasonal time scale (Engelbrecht et al. 2017).

The amplitude of the forecast maximum temperature anomalies, irrespective the sign of the anomaly, is underestimated for all the weekly forecasts. The observed negative maximum temperature anomalies over the southwestern parts of the country in week 7 and 8 were missed in the week 7 and 8 forecasts.

The cooler conditions observed during week 3 and 4 (Fig. 1) was associated with an abrupt temporarily absence of widespread heat waves before a heat wave occurred again in February (Engelbrecht and Landman 2017). In Fig. 3, it can be seen that a decrease in heat wave days are predicted relative to the week 2 forecast. Here the ensemble average of heat wave days are accumulated over the relevant weekly periods, before a simple difference is calculated to indicate whether a decrease or increase in heat wave days are predicted.
UKMO forecasts of maximum temperature weekly anomalies for the period 1 January 2016 to 25 February 2016 relative to the long-term mean for the corresponding weeks of the hindcasts for the years 1998 to 2009.

The observed change from week 4 to week 5 after which another heat wave occurred again are also evaluated. From Fig. 4 it can be seen that fewer heat wave days are predicted over the western and southern parts of the country in week 4 relative to week 5. This occurred indeed with heat waves observed during week 5 at Willowmore, East London, Vredendal and Van Wyksvlei (Engelbrecht and Landman 2017).

Conclusions

By following a case study approach, the subseasonal predictability of heat waves over South Africa has been explored by making use of the January and February 2016 UKMO maximum temperature ensemble forecasts that was initialised on 1 January 2016. The UKMO forecasts are integrated for 60 days, allowing 8 individual weekly forecast periods with lead-times of 0, 7, 14, 21, 28, 35, 42 and 49 days respectively. The week 3 and beyond forecasts are of interest in this study.

Although the amplitude of the ensemble mean forecasts of the weekly maximum temperature anomalies for all the lead-times are underestimated, the observed transitions between week 2 and 3 and again between week 4 and 5 are to some extent suggested by the ensemble mean forecasts.
Both these transitions coincided with large scale atmospheric circulation patterns that can in turn be linked to certain long-wave characteristics, providing thus hope for useful predictions on this time scale or at least to identify times of higher predictability. However, the prediction of numerous more heat wave events need to be evaluated, over multiple seasons and by applying different prediction methodologies. Here, a basic deterministic approach (using only 3 ensemble members) was applied to a single model, initialised at a single time, to explore the predictability of an extreme event.

References


The role of cyclogenesis in stimulating vertical propagation of wave activity associated with the Cut Off Low and Tropical Temperature Trough

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Abstract

In South Africa the weather is affected by synoptic systems such as cut off lows (COLs) and tropical temperature troughs (TTTs). Cyclogenesis and wave activity are two important processes in the development of weather systems. This study attempts to explain the relationship between cyclogenesis and vertical propagation of wave activity and how this relationship is established. Geostrophic winds, basic state, perturbations and quasi-geostrophic relative vorticity equations were used to calculate cyclogenesis and wave propagation. For both a COL and a TTT the onset of cyclogenesis and wave activity occur at the same time.

Keywords: Cut off low, Tropical temperature trough, Cyclogenesis, Wave activity, South Africa

Introduction

A significant amount of resources has been invested in understanding how the weather impacts the South African population and its economy (Rong, 2010). These resources include the use of dynamical methods, such as numerical weather prediction (Singleton and Reason, 2007), to predict high impact weather systems such as cut off lows (COLs) and tropical temperate troughs (TTTs) (Dyson and van Heerden, 2002). These are important systems to predict accurately because they produce large amount of rainfall (Dyson and van Heerden, 2002). In addition to numerical weather prediction (NWP), South African scientist has many years of experience in synoptic meteorology, which has contributed to the current weather forecasting expertise in the country (Mallory, 2015). However, the understanding of these systems from a dynamical processes perspective is largely lagging behind other countries (Simmons and Hollingsworth, 2002), which have taken advantage of the advent of dynamical analysis during the last few decades.

One of the advantages of dynamical analysis is that it enables the quantitative study of baroclinic life cycles (Thorncroft et al., 1993), which begin with cyclogenesis. Several studies in the Southern Hemisphere have demonstrated that cyclogenesis is a mid-latitudeal process with preferred regions of occurrence, with some of the centers located in the Southern Ocean west and east of South Africa (Sinclair, 1995, Gan and Rao, 1990). The link between these centers of cyclogenesis and weather systems affecting South Africa has to be established. This link may be informed by the influence of cyclogenesis on the vertical propagation of wave activity.

Wave activity is a conserved quantity that all evolving baroclinic waves possess (e.g. Danielson et al., 2006). Baroclinic life cycle studies (Thorncroft et al., 1993) have shown that a baroclinic wave develops when wave activity starts propagating vertically upward, which, to a large extent, is informed by the poleward transport of heat. This suggests that the meridional heat fluxes involved here play a critical role in the early development of baroclinic waves. This, in fact, is supported by the fact that these heat fluxes facilitate the conversion of mean available potential energy to eddy kinetic energy, provided that the basic state atmosphere is baroclinically unstable (Holton and Hakim, 2014).

In order to link South African weather systems to any of the centers of cyclogenesis in the Southern ocean, there is a need to understand the relationship of the latter with the vertical propagation of wave activity at the beginning of baroclinic life cycles. Therefore the research question to be answered in this research is the influence of cyclogenesis on the onset of wave activity associated with a COL and a TTT.
Data and Methods

The study was conducted over the Southern African region from 22°S to 50°S and 15°E to 40°E. The two case studies chosen were a COL pressure system that occurred from 24 to 26 July 2016 and a TTT that occurred from the 16th to the 19th of January 2013.

National Centres of Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996) was used because it covers large areas including the oceans at a 2.5° x 2.5° horizontal resolution. The geopotential height fields from 1000 hPa to 500 hPa at every 100 hPa were used to derive the geostrophic wind fields, for which the derivatives involved were calculated using second order finite differencing. The potential temperature fields were derived using the Poisson’s equation (Holton and Hakim, 2014).

The calculation of the relevant component of the wave activity flux vector required a suitably defined basic state flow, the deviations from which produced the associated perturbations. To define the basic state flow, a central day (day 0) was identified as the day on which the cyclogenesis began. Based on this, the basic state flow was then calculated as the 31 day mean centered on this day 0.

Cyclogenesis is said to have occurred when there has been a decrease in relative vorticity by $2 \times 10^{-5} \text{s}^{-1}$ per day in a developing cyclone (Sinclair, 1994). To detect this process the geostrophic relative vorticity expression was used. To exclude matured systems, cyclone grid points in excess of $-5 \times 10^{-5} \text{s}^{-1}$ were ignored.

The vertical propagation of wave activity is described using the vertical components of the wave activity flux vector given by

$$W_v = \frac{\cos \varphi}{2f} \left\{ \left( \frac{f}{d\varphi} \right) (\overline{U_v v} \vartheta - \overline{U_v \varphi}) \frac{1}{a \cos \varphi} \frac{\partial \vartheta / f}{\partial \lambda} - \overline{V_v u} \vartheta - \overline{V_v \varphi} \frac{1}{a} \frac{\partial \vartheta / f}{\partial \varphi} \right\} \right. \tag{1}$$

The overbars represent basic state variables and the small letters (without the overbar) representing the perturbations. The variables $\Theta$ and $\Phi$ showed the perturbation of potential temperature and geopotential respectively. Also, $\varphi$ and $\lambda$ is the latitude and longitude and $f$ and $a$ are the Coriolis parameter and radius of the earth.

Results and Discussion

For the TTT the vertical propagation of wave activity occurred at the same time as cyclogenesis as shown in Figure 1. A visual inspection of the combined evolution of the relative vorticity and wave activity fields suggested that cyclogenesis was necessary for wave activity to start propagating upward. This hypothesis is supported by the observation that before cyclogenesis, the wave activity field exhibited negative values. The occurrence of cyclogenesis is immediately associated with a change in sign in wave activity to positive.

Figure 1: a) show cyclogenesis and b) wave activity on a latitude-longitude grid from -20°S to -40°S and 0 to 30°E, at 1000 hPa associated with a TTT on 17 January 2013 at 00h00UCT. In (a) the light to dark conversion shows decrease in relative vorticity, whereas, in (b) the dark to light conversion shows increase in vertical propagation of wave activity.
Similarly to the TTT case, the cyclogenesis associated with the COL appeared to be necessary for the vertical component to change sign from negative to positive, thus suggesting the vertical propagation of the latter. However, the wave activity associated with the COL is weaker than that associated with the TTT, with the wave associated with the latter stronger than the former.

**Conclusion**

In both cases it was found that for wave activity to propagate vertically upward, the relative vorticity field needs to comply with the cyclogenesis requirement. Since the vertical component of wave activity is associated with meridional heat fluxes, and also the fact that circulation in surface cyclones facilitate meridional heat fluxes, this preliminary conclusion is supported.

However, there are significant differences between the COL and TTT, which suggest that the propagation of wave activity of the former might last longer than that of the latter.

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**References**


Determining the efficiency of empirical downscaling against raw model seasonal forecasts for the Zambezi and Okavango catchment areas

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Abstract

The skill of a fully coupled ocean-atmosphere model predicting seasonal rainfall over the Zambezi and Okavango catchment areas has been tested through the evaluation of “raw” rainfall model hindcasts and statistically downscaled hindcasts. The model output statistics downscaling approach was considered. For the purpose of this study, geopotential height at 850 hPa, vertical thickness (i.e. geopotential heights averaged between 850-500 hPa) and rainfall were used as predictor variables and downscaled by applying Canonical correlation Analysis (CCA) for each using Climate Prediction Tool (CPT). CPT was also executed in a GCM-validation mode to correct bias in the simulated rainfall. Altogether, there are four downscaling methods analyzed here. Relative Operating Characteristics (ROC) scores were used to determine which of the downsampling method performs best. The results showed that using an 850 hPa geopotential heights as predictors gave the best ROC skill for forecasting seasonal rainfall over the Zambezi and Okavango catchment area. The use of different training periods also gave different ROC score for above normal and below normal.

Keywords: Model output statistics, Relative Operating Characteristic, canonical correlation analysis

Introduction

Estimated SSTs can be employed into atmospheric general circulation models (GCMs) to generate a forecast of seasonal-averaged weather (Graham et al. 2000). GCMs have good skill at global and continental scales but have trouble at a local sub-grid scale, subsequently overestimating the rainfall over southern Africa (Joubert and Hewitson. 1997). Systematic biases have created the need for downscaling GCM simulations over southern Africa (Landman and Beraki. 2012).

A long-range forecast has a certain amount of statistical errors due to the atmosphere not being perfectly predictable (Wilks. 2011). This chaotic nature of the atmosphere requires that forecasts are made through ensemble forecasting and should be expressed probabilistically (Brankovic and Palmer. 2000). When GCMs differ in their parameterizations, their performances differ under different conditions (Hagedorn et al. 2005). It is an advantage to combine ensembles of a number of different GCMs into a multi-model ensemble to take into account model error and uncertainties of initial conditions (Harrison et al. 1995). Model initialization is the process by which observations are processed as model dependent variables, from which the model integration begins (Wilks. 2011). There are noticeable differences in the forecasts when different initial conditions are used, giving a range of possible solutions (Tracton and Kalnay. 1993).

Statistical downscaling (SD) can help to determine the best forecast, where the model output corrects for the model’s systematic errors (Warner, 2010). Downscaling is done in the post processing of a data set. It uses the assumption that large-scale weather and climate strongly influences local-scale weather and climate (Rostkier-Edelstein, et al. 2016). SD uses the statistical links between large-scale climates and observed local-scale climates (Fowler. 2007). A predictor influences the changes in the forecasted climate. Circulation-related predictors, such as sea-level pressure, are a good choice since long observations are available and the GCMs simulations have good skill (Cavazos and Hewitson. 2005).

Data and Method

Hindcast data of ECHAM4.5-MOM3-DC2 (ECMD; Landman et al. 2012) – a fully coupled ocean-atmosphere model was used for this research project’. (ECHAM4.5, Roeckner et al. 1996) directly coupled to an ocean model (MOM3; Pacanowski and Griffies 1998). The data used from this model were: i) an 850 hPa level; ii) an 850-500 hPa vertical profile; and iii) the “raw” rainfall data. The hindcast data was obtained from the Data Library of the IRI and cover the period from 1982 to 2012. Forecast lead-times up to 5 months are also available, including a range of forecast output variables such as rainfall, geopotential heights, etc.

The ECMD data was downscaled and corrected to gridded rainfall data of the Climatic Research Unit (CRU, Harris et al. 2014) and the Climate Anomaly Monitoring System and OLR Precipitation Index (CAMS_OPI, Janowiak and Xie. 1999) sets. The reason why two different rainfall data sets were selected (different in terms of compilation and horizontal resolution) is to determine whether the forecast made with one data set corresponds to observed data from
another data set. The CRU is data comprised of station anomalies (1961 to 1990 means). The data was interpolated onto a 0.5° x 0.5° latitude and longitude grid. It covers the global land surface that excludes Antarctica (Harris et al. 2014). These anomalies were combined with existing climatology that obtains absolute monthly values. CAMS_OPI is a precipitation estimation technique (CAMS_OPI, Janowiak and Xie. 1999). Observations from rain gauges are merged together with precipitation estimates from a satellite algorithm that produces real-time monthly analyses of global precipitation. The analysis is on a 2.5° x 2.5° latitude and longitude grid.

The Climate Predictability Tool (CPT) was used for the correction and downscaling. Since the CPT uses the model output statistics (MOS) approach, it compensates directly for systematic deficits in the global models within the regression equations. Predictors were used in MOS equations to reduce model errors. The ECMD data used as the predictors are as follows: i) an 850 hPa level; ii) an 850-500hPa vertical profile (thickness); and iii) the “raw” rainfall data. The CRU data was set as the predictand. The predictands and predictor was run through a canonical correlation analysis (CCA). The forth approach was done through a GCM validation using the “raw” data as a predictor.

The following process was done for all four downscaling approaches. The predictor was set for the area of the Equator to 45° S and the Greenwich Meridian to 60° E (Fig. 1). The predictand was set for the area of 13° S to 20° S and 18° E to 35° E (Fig. 2). The tailoring was done through standardized anomalies; and the 25th percentile of above and below for probabilities was considered. The training period was 26 years (1982/83 to 2007/08) with an independent forecast in an operational environment for four years from 2008/09 to 2011/12. A retroactive process was done with an initial training period of 10 and 16 years to investigate the impact training periods had on the performance of downscaling models. Retroactive processing is the recalculation of prior periods due to the changes in data resulting in new results for that period. It was used to assess the quality of past probabilistic forecasts made (Mason, 2015).

The skill produced by the different downscaling approaches was determined through discrimination by the relative operating characteristic (ROC) scores and reliability by considering resolution slopes in reliability diagrams. A ROC score is the result of the hit rate corresponding to the false-alarm rate from the probability of forecasts (Kharin and Zwiers. 2003). Reliability is the confidence in the systematic biases of forecast probabilities (Landman and Beraki. 2012). These skills produced were used to determine the best downscaling method.

The best downscaling method was then used to determine a forecast for the four independent test years. The forecasted was then verified using the CAMPS_OPI rainfall data. The cumulative profits were also determined for this downscaling method to determine whether there was an investment risk associated with the forecast. This was done by using the CPT verification tool by calculating the cumulative profits.

**Results and Discussion**

The ROC scores produced by the four different downscaling methods gave noticeable differences (Fig. 3 and Fig. 4). We can see from the graphs that a 16 year training period gives better ROC scores than a 10 year training period. It can also been seen that the 850 hPa level had significant better results. However, the 10 year training period gave a better below normal score and the 16 year training period gave a better above normal score.
A Spearman’s Correlation map was created for each downscale done (Fig. 5 and Fig. 6). The yellow to red colour show a positive correlation and the light blue to dark blue shows a negative correlation. Fig. 5 shows the correlation for a 10 year training period. Fig. 6 shows the correlation for a 16 year training period. By analysing the maps created, it clearly shows that the 850 hPa level in Fig. 5(b) and Fig. 6(b) had significantly the best correlations for both training periods.

The ROC scores and Spearman’s Correlation maps show that the 850 hPa level as predictor would give the best probabilistic forecasts. The probabilistic forecast was done for the December-January-February (DJF) period in the years 2008/09, 2009/10, 2010/11, and 2011/12 (Fig. 7). The maps created were compared to the DJF average precipitation for each of the corresponding years (Fig. 8).

The 2008/09 forecast in Fig. 7(a) shows a normal rainfall season which corresponds to the observed average precipitation in Fig. 8(a). In the 2009/10 season in Fig. 7(b) the forecast was for a below normal rainfall. This 2010/11 forecast in Fig. 7(c) shows an above normal rainfall season for the whole study area. The observed precipitation in Fig. 8(c) only had above normal rainfall for the western part (18° E to 28° E) with below normal rainfall for the eastern part (28° E to 35° E). The 2011/12 forecast in Fig. 7(d) gave a normal rainfall season, but the drought observed was not captured. The observed precipitation in Fig. 8(c and d) only had above normal rainfall for the western part (18° E to 25° E) with below normal rainfall for the eastern part (25° E to 35° E).

The cumulative profits in Fig. 9 show that the investment risk was relatively strong associated with the forecast. If the forecast held for 2008/09 DJF season the effective interest rate would have stayed the same and the cumulative profit would not change. The forecast for 2009/10 was very important. The interest rate would decrease. The cumulative profits would have decreased if farmers did not plan ahead. For the 2010/11 and 2011/12, the investment risk would have increased. The forecast for both years were less accurate, therefore the cumulative profits would have decreased.
Figure 9 – Graph showing the cumulative profits of the DJF seasons from 1991/92 to 2007/08.

Conclusions
Both the ROC scores and the Spearman’s Correlation showed that the 850 hPa level downscaling created the best skill for rainfall over the Zambezi and Okavango catchment areas. The forecast done from this downscaling method was relatively good when compared to the “raw” rainfall model data. The first two DJF seasons where good forecasts. However, the third and the fourth showed some forecast errors. This leads to the conclusion that the agricultural industry may have benefitted from investing in the forecasts for the first two years, but may have obtained less benefit for the last two years.

References
Impact of a volcanic eruption on sulphur dioxide, ozone and surface solar UV radiation at a secondary site 7658 km away

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Abstract

The 2011 Chilean Puyehue-Cordón Caulle volcanic eruption resulted in widespread dispersion of volcanic aerosols across the Southern Hemisphere. Large-scale volcanic eruptions can cause an increase in solar ultraviolet radiation (UVR) absorption and short-term ozone depletion. Here, the relationships between (1) sulphur dioxide and solar UVR, and (2) sulphur dioxide and total column ozone are explored by considering the volcanic eruption impact on these relationships at the volcanic eruption site and at a secondary location, namely, Cape Point, South Africa. When comparing the relations sulphur dioxide and solar UVR, and sulphur dioxide and total column ozone at both locations, the correlation results were relatively weak. However, stronger correlations were found for higher levels of sulphur dioxide at the eruption site compared to Cape Point.

Keywords: Puyehue-Cordón, aerosols, atmospheric science

Introduction

When the Puyehue-Cordón Caulle volcanic complex (PCCVC) erupted on the 4 June 2011, it caused thick tephra deposits in Chile and Argentina. Due to the westerly winds in the mid-latitudes, widespread dispersion of aerosols and fine particles occurred across the Southern Hemisphere (Silva Parejas \textit{et al.}, 2012). These aerosols were transported to South Africa, Australia and even New Zealand, disrupting flights across the three continents (Bonadonna \textit{et al.}, 2015).

Sulphur dioxide (SO\textsubscript{2}) is one of the main gases associated with volcanic activity (Daug \textit{et al.}, 1999). SO\textsubscript{2} absorbs solar ultraviolet radiation (UVR), in the 300 nm to 325 nm wavelength range, 2.5 times more effectively than ozone. Due to its relatively low content in the normal atmosphere, it has minimal effect on the total UVR absorption. However, during a volcanic eruption, SO\textsubscript{2} levels at the site can reach up to 600 times their usual levels (Fioletov \textit{et al.}, 1998). This drastic increase in SO\textsubscript{2} can have an inverse effect on the amount of solar UVR reaching the surface of the Earth.

Intense volcanic eruptions can also cause short-term ozone depletion. The SO\textsubscript{2} from the eruption enters the stratosphere where it becomes sulphuric acid (H\textsubscript{2}SO\textsubscript{4}). The H\textsubscript{2}SO\textsubscript{4} then becomes a platform for the activation of stratospheric chlorine which is a catalyst for the depletion of ozone. The aerosol loading further decreases ozone concentrations by altering the stratospheric temperature and radiative fields, which affect photo-dissociation rate constants (Vogelmann \textit{et al.}, 1992).

Volcanic eruptions occur in various levels of intensity. Larger eruptions can inject volcanic aerosols into the stratosphere while smaller, less intense eruptions only inject aerosols into the troposphere. In the troposphere, volcanic SO\textsubscript{2} is flushed out of the atmosphere quite quickly. However, when volcanoes inject SO\textsubscript{2} into the stratosphere, the sulphate aerosols can remain present for up to three years. (Halmer \textit{et al.}, 2002). With a large scale volcanic eruption such as the PCCVC 2011, changes in total column ozone levels as well as surface solar UVR may have occurred and should be investigated, since the prolonged existence of sulphate aerosols in the upper atmosphere can contribute towards climate change (Halmer \textit{et al.}, 2002).

In this study, the effect of the increase in SO\textsubscript{2} on these variables will be considered at the eruption site, as well as at a secondary, mid-latitude location (Cape Point, South Africa). The secondary site is included to consider the extent of the impact over distance of the PCCVC 2011 eruption. This project has two aims. The first is to detect changes in SO\textsubscript{2}, total column ozone (TCO) and surface solar UVR after a volcanic eruption, at the volcanic eruption site and the second is to do the same but at a secondary site. This is done by observing seasonal variations in SO\textsubscript{2}, TCO and surface solar UVR over ten years. Then by comparing the seasonal variations with the observed changes in SO\textsubscript{2}, TCO and surface solar UVR during the year of interest (1 June 2011 to 31 May 2012). Lastly by demonstrating by association whether or not the PCCVC 2011 volcanic eruption had an influence on SO\textsubscript{2}, TCO and surface solar UVR at Cape Point.
Methodology

Data acquisition

For control purposes and in order to make accurate comparisons, data for each site have been obtained from the same source for each variable. The data for each site was obtained for a period of ten years, starting on 1 January 2007 and ending on 31 December 2016. Since satellite data were used for analysis, the point location of the sites were altered to define a bounding box in order to retrieve the data for the locations. The grid points of the bounding boxes were derived by adding and subtracting 0.125 degrees from the co-ordinates of the two sites.

![Figure 1: A map showing the geographical locations of the two sites. The eruption site is on the left while Cape Point is on the right.](image)

Sulphur dioxide

The SO₂ column mass density data were obtained through NASA’s Giovanni data portal and is a Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) product. It has an hourly temporal scale and has units of kg.m⁻².

Ozone

The total column ozone data used in this project were obtained through NASA’s Giovanni data portal and are a product of the Ozone Monitoring Instrument (OMI). It has a daily temporal scale.

Method

The data for each site have been analysed separately, however, with the same analysis techniques. For the SO₂, TCO and UVR datasets, similar techniques have been used to establish the seasonal variations. An average value was calculated over the ten year period. Then the standard deviation of each dataset was calculated. The standard deviation was added and subtracted from the average to consider the seasonal variation of the three variables over the ten year period.

Since SO₂ can be present in the upper atmosphere for up to 3 years (Halmer et al., 2002), the observed changes have been considered over a period of one year from 1 June 2011 to 31 May 2012. In the SO₂ dataset, any values greater than the mean plus the standard deviation have been considered as a result from the volcanic eruption. In the UVR and TCO datasets, any values which are less than the mean minus the standard deviation have been considered as a result from the volcanic eruption.

A correlation analysis has been applied to determine whether or not there was an association between the SO₂ and the other two variables considered, namely TCO and solar UVR. The correlation was run over the ten year period to establish the general correlation of the variables. A second correlation was then executed over the year of interest to determine the correlation of the variables during the effects of the volcanic eruption. The correlation results were then compared.

Results

The seasonal variation was established at two levels for each variable. The first level of standard deviation (SD1) was created by adding or subtracting the standard deviation and the mean. The second level of standard deviation (SD2) was created by adding or subtracting two times the standard deviation and the mean. Therefore, values outlying SD1 or SD2 have been considered to be outside of seasonal variation and indicative of anomalous conditions, such as the volcanic eruption.

The highest SO₂ value over the year of interest at the eruption site was recorded on 5 June 2011, the day following the volcanic eruption. This can be seen by the triangular point in Fig. 2. This is also the maximum recording of SO₂ during the ten year period. As shown by Fig. 2, there are observed values during the year of interest which are above SD2. This is an indication of higher levels of SO₂ content in the atmosphere at the eruption site.

![Figure 2: The representation of SO₂ levels at the volcanic eruption site. The year of interest is highlighted in dark grey. The SD1 and SD2 lines represent the first and second levels of standard deviation respectively. The triangular point is the largest value of SO₂ within the year of interest. The “X” marks the eruption date.](image)

Although there is only one ozone value below SD2 at PCCVC during the study year, there are more which are below SD1. This indicates that there are days with lower TCO after the eruption, however, with the difference in pre- and post-event ozone levels are not as large as seen for the SO₂ data.

At the site of the volcanic eruption, there are no UVR values below SD2 during the year of interest, or within the larger ten year period. There are however, values below
SD1 indicating days with lower UVR during the year of interest. This is shown in Fig. 3.

Figure 3: The representation of UVR levels at the volcanic eruption site. The year of interest is highlighted in dark grey. The SD1 line represents the first level of standard deviation.

The highest value of SO$_2$ at Cape Point during the year of interest was recorded on 17 August 2011, as observed by the triangular point in Fig. 4. Also seen by Fig. 4, there are values above SD2 during the study year, indicating higher SO$_2$ levels at Cape Point at times other than directly after the PCCVC 2011 event.

At Cape Point, there are no ozone values below SD2 from 1 June 2011 to 31 May 2012, but there are values below SD1. This indicates days with lower TCO.

Similarly to the eruption site, there are no UVR values which are beyond SD2 at Cape Point during the year of interest or the ten year period. As shown in Fig. 5, there are values which lie outside of SD1 at Cape Point, following the eruption.

As seen in Table 1, at the eruption site, there is a weak negative correlation between SO$_2$ and TCO. There is a slightly stronger positive correlation between SO$_2$ and UVR. This is contradictory to what was hypothesized for the SO$_2$-UVR correlation and further investigation of this is necessary.

At the secondary location, the correlation between SO$_2$ and TCO is negative and weaker than that at the eruption site. The SO$_2$ and UVR correlation is weaker than at the eruption site but negative. This can be seen in Table 1.

Table 1: The representation of the correlation coefficients between SO$_2$ and TCO, and SO$_2$ and UVR at the eruption site and at the secondary location, Cape Point. A Pearson R-test statistic was used over the ten year period.

<table>
<thead>
<tr>
<th>Correlation results over the ten year period</th>
<th>PCCVC</th>
<th>Cape Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>r-value</td>
<td>p-value</td>
<td>r-value</td>
</tr>
<tr>
<td>SO$_2$-TCO</td>
<td>-0.1782</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>SO$_2$-UVR</td>
<td>0.28264</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

* $r$ - values equal to 0 indicate no association between variables
* $p$ - values < 0.05 indicate significance in correlation

**Discussion and Conclusion**

Since the absolute values of all of the correlation coefficients are closer to 0 than they are to 1, these results suggest that the SO$_2$ has a low correlation to TCO and UVR. Although there were higher levels of SO$_2$ content in the atmosphere (especially at the eruption site), a strong correlative relationship between SO$_2$ and the other two variables could not be detected in this study. Several limitations could be the reason for this, including other factors that influence surface solar UVR levels, such as cloud cover.

Since SO$_2$ has to convert to H$_2$SO$_4$ (which becomes the platform for ozone breakdown) (Vogelmann et al., 1992), it could produce a delayed response from the ozone, meaning a correlation would not be easily detectable. Also, it is the activated chlorine that is responsible for the depletion of ozone in the process, the sulphur is only the platform (Vogelmann et al., 1992). Since the majority of stratospheric chlorine is present in the atmosphere due to anthropogenic forces (Vogelmann et al., 1992), not detecting a clear relationship between SO$_2$ and ozone could be an indication of decreased chlorine emissions.

Despite the overall low correlation between SO$_2$ and the other two variables, the $p$-values indicate that the correlations were nonetheless statistically significant. When comparing the results at the eruption site to those at Cape Point, there is a stronger correlation between SO$_2$ and TCO, as well as SO$_2$ and UVR at the volcanic site. Since the eruption site has higher levels of SO$_2$, this comparison...
suggests that high SO$_2$ levels tend to produce a stronger correlation with the other two variables, compared to when SO$_2$ levels are lower.

**Acknowledgements**

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**References**


Attributes of predicted rainfall patterns over the Southern Hemisphere associated with the El Niño–Southern Oscillation

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Abstract

Output from three coupled ocean-atmosphere models of the North American Multi-Model Ensemble (NMME) are combined and evaluated over the Southern Hemisphere to assess their ability to replicate “traditional” rainfall patterns associated with the El Niño–Southern Oscillation (ENSO). The season of interest is the austral summer period of December through February (DJF). Probabilistic rainfall forecasts, obtained from three NMME models initialised in early November, are evaluated over 21 DJF seasons. These seasons comprise of 7 El Niño, 7 La Niña and 7 ENSO-neutral events. Three rainfall categories are considered, which include a representation of seasons in the lowest or highest historical quartile. The NMME models are able to replicate ENSO-related probabilistic precipitation patterns which are reliable, but the same models are not skilful in reliably predicting opposing rainfall extremes. This result leads to the question why models fail when they do, which is beyond the scope of what is presented here.

Keywords: El Niño and La Niña, coupled ocean-atmosphere models, probabilistic forecasts, reliability

Introduction

El Niño–Southern Oscillation (ENSO) cold (La Niña) and warm (El Niño) phases are strongly associated with the shifting of rainfall patterns over many different parts of the world (e.g. Bradley et al., 1987). The resulting shifts during a particular ENSO phase (i.e., El Niño or La Niña) may cause the likelihood of above-normal rainfall totals to increase over some areas, while at the same time increase the chance of below-normal rainfall totals over other areas. The seminal papers of Ropelewski and Halpert (1987, 1989; from here on referred to as RH8789) identified changes in median precipitation globally conditional upon ENSO phases. Later on the analysis was extended and consequently provided useful indication of the global impacts of ENSO in probabilistic terms (Mason and Goddard, 2001). In this paper we will evaluate probabilistic rainfall forecasts from a multimodel consisting of three state-of-the-art ocean-atmosphere coupled global climate models. Evaluation is done in terms of the models’ ability to reproduce RH8789 and Mason and Goddard (2001) rainfall patterns (Fig. 1) and also determine to what extent these rainfall forecasts are reliable. Furthermore, the analysis will focus on the Southern Hemisphere only, since there is the notion in South Africa to learn from South American countries such as Uruguay, which has similar political and socio-economic challenges, about their agricultural information networks that include the provision of reliable seasonal forecast output for effective uptake (Landman et al., 2015). Moreover, South African modellers have in their established network of collaborators, First World country partners such as from Australia with whom advanced collaborative modelling has been taking place over a sustained time (Engelbrecht et al., 2011).

Figure 1. El Niño and La Niña influence on global rainfall patterns. The map is a result of the analysis described in RH8789 and in Mason and Goddard (2001). (Source: http://iri.columbia.edu)

Data and Methodology

a. Data

Two types of data sets are used in the modelling and analysis. The first type is a collection of hindcasts (or re-forecasts) from coupled models of the easily
accessibile North American Multi-Model Ensemble (NMME, Kirtman et al., 2014), while the second type is a gridded observed rainfall product against which hindcasts are verified. Results from three fully coupled models are used (COLA-RSMAS-CSM4, GFDL-CM2.5-FLOR-B01 and NASA-GMAO-062012) and their rainfall forecast are given equal weights in a multi-model configuration (Landman and Beraki, 2012). The hindcasts from each model are for monthly data from the early 1980s to present and are available at a 1°x1° latitude-longitude resolution for 12 ensemble members and for lead-times up to 11 months. We are using only 1-month lead-times for December to February (DJF) rainfall forecasts. The observed gridded (over land only) rainfall data are the WCRP GCOS GPCC FDP version 7 (0.5° lat-lon resolution.) (Becker et al., 2013) from which seasonal total rainfall for DJF is derived. The regional analysis is done for three land areas in the Southern Hemisphere, and they are SADC (12.25°S to 35.75°S; 11.5°E to 41.5°E), Australia (10.25°S to 40.25°S; 113°E to 154.5°E) and southeast South America (29.25°S to 39.25°S; 48°W to 63°W).

a. Methods
The “raw” ensemble mean (over 12 members) DJF rainfall forecasts from each coupled model are interpolated to the nearest GPCC grid-point after which the mean and variance biases of each model’s data are corrected with the IRI’s Climate Predictability Tool (CPT). Each model’s corrected hindcasts are produced over a common test period of 21 years from 1991/92 to 2011/12. This period contains seven El Niño (91/92, 94/95, 97/98, 02/03, 04/05, 06/07, 09/10), seven La Niña (95/96, 98/99, 99/00, 00/01, 07/08, 10/11, 11/12), and seven ENSO-neutral years (according to the Oceanic Niño Index for cold and warm episodes). Probabilistic rainfall forecasts over this period for the continental Southern Hemisphere are subsequently created for three categories with thresholds defined by respectively the 25th (dry category) and 75th (wet category) percentile values of the climatological record (Landman et al., 2012). Here, we refer to the wet or dry categories as rainfall extremes.

Results
The results are based on three types of analysis. The first shows averaged probabilistic DJF rainfall forecasts over the Southern Hemisphere for the 14 seasons associated with 7 El Niño and 7 La Niña phases in order to check if the multi-model can replicate the patterns of Figure 1. The second type presents scatter plots for the selected regions (e.g. SADC) between their observed frequencies and predicted probabilities, and finally so-called tendency diagrams are presented to determine the reliability of the regional forecasts. Take note that we did not attempt to categorise results in terms of the strength of ENSO events, but instead performed an analysis of how well the multi-model is able to predict extremes in DJF rainfall seasons during certain ENSO phases.

a. Averaged probabilistic forecasts
According to Fig. 1, for the three regions of interest, SADC and Australia should be anomalously dry (wet) during El Niño (La Niña) years, while southeast South America should be wet (dry) during El Niño (La Niña) phases. The top (bottom) panel of Fig. 2 shows the number (frequency) of DJF seasons during which below-normal (above-normal) rainfall totals were observed during the 7 El Niño years.

Figure 2. The number of times the observed DJF rainfall totals were less than the below-normal threshold (top panel) and the number of times DJF totals exceeded the above-normal threshold (bottom panel) during the 7 El Niño years.

Figure 3. Predicted rainfall probabilities averaged over the 7 El Niño seasons used in the analysis. The three panels respectively represent probabilities associated with the below-normal (top), near-normal (middle) and above-normal (bottom) categories as defined in the text.

Fig. 2 shows that during El Niño seasons the SADC and Australian regions are associated with increased counts of dry DJF seasons, while southeast South America is associated with an increased occurrence of wet DJF seasons. The opposite is found for the 7 La Niña years (not shown). This part of the analysis shows that for the 14 ENSO seasons considered here, the observations are in strong agreement with Fig. 1.

Fig. 3 shows the predicted rainfall probabilities for DJF rainfall, averaged over the 7 El Niño years, and Fig. 4 shows the result from averaging over the 7 La Niña years. Increased probabilities for below-normal
(above-normal) rainfall totals are found over SADC and Australia during El Niño (La Niña) years, with increased probabilities for above-normal (below-normal) rainfall totals over southeast South America during El Niño (La Niña) events. These results suggest that the multi-model is able to capture the typical ENSO patterns of Fig. 1 and 2.

![Predicted Rainfall Probabilities for SEVEN La Nina Seasons](image)

Figure 4. As for Fig. 3, but for 7 La Niña years.

Take note that the probabilities predicted for the middle category/panel indicate that the multi-model generally gives low probabilities for the middle category during ENSO seasons, even though the middle category is wider than that of the tercile-based, equi-probable categories often used in operational seasonal climate forecasting.

b. Reliability of probabilistic forecasts

In this section we compare observed frequencies of exceeding wet and dry season thresholds with their associated forecast probabilities for the three regions. Scatter plots of all the land grid-points that show the linear relationship between the discret count (maximum of 7) exceeding the predetermined thresholds and the associated predicted probabilities indicate that, as in the SADC example presented in Fig. 5, enhanced predicted probabilities are associated with increased observed frequencies. These plots can therefore be interpreted as an indication of the probabilistic reliability of the forecasts. For a more direct calculation of reliability, we next present results for each region as presented in tendency diagrams (Mason, 2011). Such diagrams can be used as a visualization tool through the comparison of average forecast probabilities of the (extreme) wet and dry categories with their observed relative frequencies. For the case of reliable forecasts, the observed relative frequencies are expected to be approximately equal to the average probabilities.

![Tendency Diagrams](image)

Figure 5. Scatter plot and histograms for all SADC land grid-points of observed frequencies vs. predicted probabilities during El Niño years when DJF rainfall totals were below-normal. The red line is the least-squares line of the scatter plot.

The tendency diagrams are also used here to present reliability estimates for those cases where forecast probabilities are for outcomes opposite to those presented in Fig.1, e.g., prediction vs. observation for wet (dry) El Niño (La Niña) seasons over SADC. Fig. 6 (a) and (b) are the tendency diagrams for SADC and it can be seen that the observed relative frequencies (blue bars) and average forecast probabilities (yellow bars) are approximately equal for the dry season outcomes during El Niño events and wet season outcomes during La Niña events (cf. Fig. 1). However, the same equality is not found for the prediction of wet El Niño and dry La Niña seasons. In fact, the forecast probabilities far exceed the relative frequencies for these outcomes. Similar results are found for Australia and for southeast South America (Fig. 6 (c) and (d)), except that for the latter case, wet (dry) conditions are much more likely during El Niño (La Niña) years. These results suggest good reliability to be restricted only to the category having an ENSO-related enhanced probability (as indicated in Fig. 1).

Summary and Conclusions

The main objective of this study was to assess to what extent state-of-the-art seasonal forecast models are able to capture extreme DJF rainfall seasons over the Southern Hemisphere during ENSO events. In fact, it was found that models can replicate these rainfall extremes, and that the probabilistic forecasts for such cases are reliable as demonstrated for three regions over three continents separated by major ocean basins. However, there is little evidence that the models can capture the observed marked reduction in probability of the opposing rainfall extremes. This model weakness may be related to an apparent bias towards under-forecasting the middle rainfall category and displacing probability to the least likely extreme, whose probability is then over-forecast.
Figure 6. Tendency diagrams for DJF rainfall over SADC [(a) and (b)] and southeast South America [(c) and (d)] for wet and dry cases, and El Niño and La Niña seasons. Observed: relative frequencies exceeding wet/dry thresholds, averaged over land points; Forecast: Forecast probabilities, also averaged over land points.

Acknowledgements
We thank ENSO for having a predictable impact on Southern Hemisphere seasonal-to-interannual rainfall variability. We acknowledge the agencies that support the NMME-Phase II system, and thank the climate modelling groups (Environment Canada, NASA, NCAR, NOAA/GFDL, NOAA/NCEP, and University of Miami) for producing and making available their model output. NOAA/NCEP, NOAA/CTB, and NOAA/CPO jointly provided coordinating support and led development of the NMME-Phase II system.

References


Evaluation of the planetary boundary layer mixing height in South Africa

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Abstract
The characteristics of the mixing height in South Africa are not well studied despite its importance in air quality assessments. Two methods of determining the mixing height, the use of The Air Pollution Model (TAPM) and the use of analytical formulae, were examined in order to recommend the best method to be used in South Africa. The Monin-Obukhov length was used to analyse the stability conditions of the planetary boundary layer. There is a clear diurnal and seasonal variability of the mixing height in both inland and coastal regions. There was no correlation found between the use of TAPM and analytical formulae. TAPM is preferred, but a testing for bias is recommended when it comes to the output of parameters important for computing the mixing height.

Keywords: Stability conditions, Monin-Obukhov length, Pollution studies, TAPM, Mixing height

Introduction
Boundary layer meteorology has increasingly become an important field in the atmospheric studies. Many human activities are concentrated in this part of the atmosphere. Over the past several decades, issues of pollution and climate change have gained interest from the general public, private sectors and governments. It is therefore important to understand this layer which is directly linked with the pollution and climate issues.

The planetary boundary layer (PBL) is the lowest part of the troposphere that is directly affected by the Earth’s surface. When substances are emitted into this layer, they steadily disperse through different transport and turbulent diffusion processes (Stull, 1988). A completely mixed layer is not always reached under stable conditions. To emphasise the process, it is therefore preferable to refer to this part of the atmosphere as the mixing layer (Seibert et al, 2000). The depth of the mixing layer is called mixing height (MH).

In this research project, MH was defined as the height of the mixing layer that is directly influenced by the Earth’s surface and where emitted substances become vertically dispersed by different processes within a period of one hour.

Understanding the characteristics and the structure of the MH is important, but research into this has largely been neglected in South Africa. This despite the MH being required for air quality assessments and monitoring (Garcia et al., 2007). MH is also required for air pollution predictions and as a parameter for describing vertical profiles and concentrations, including by atmospheric pollution models (Beyrich, 1997; Baklanov & Kuchin, 2004). MH is not measured by standard meteorological operations. It is rather derived from observations and modelling.

This research project is seeking to evaluate the MH data from The Air Pollution Model (TAPM) and three frequently used analytical formulae. In the process the Monin-Obukhov length is used to analyse the MH stability conditions over South Africa’s inland and coastal regions. The Monin-Obukhov length refers to that height at which buoyancy, as compared to wind shear, is more responsible for the production of turbulence (Stull, 1988). The diurnal and seasonal variation of the MH in the study areas is also analysed. All of this is done in order to recommend the best method of determining the MH in South Africa.

Data and Methodology
TAPM is the numerical model that was evaluated in this study. It is a PC-based prognostic meteorological and air pollution model. The model uses fundamental atmospheric equations including the momentum equations, the continuity equation, and some meteorological prognostic equations (Hurley, 2002). Table 1 summarises some of the properties of TAPM as configured in the current study.

Table 1: Some properties of TAPM.

<table>
<thead>
<tr>
<th>Description of properties</th>
<th>Temporal resolution</th>
<th>Vertical range</th>
<th>Type of the PBL computed</th>
<th>Method of determining the MH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 hour</td>
<td>0-4 km</td>
<td>Convective and stable boundary layer</td>
<td>Convective updraft strength</td>
</tr>
</tbody>
</table>

The inland area chosen for this study was Tembisa (26.0106°S, 28.2219°E). With an average elevation of about 1578m above sea level, Tembisa is a semi-urban township located in the north-east of Johannesburg. The coastal study area was Alexander Bay (28.5700°S, 16.5280°E). Alexander Bay is a town that is located at the extreme north-west of South Africa in the Northern Cape Province, and has an elevation of about 34 m above sea level. These two study areas are indicated in Fig. 1.

Since the temporal resolution of TAPM is 1 hour (Table 1), data examined contained 8760 hours for each study.
The stability parameter ζ was interpreted according to Table 2.

Table 2: The interpretation of ζ values.

<table>
<thead>
<tr>
<th>Values</th>
<th>PBL stability condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ζ &lt; 0</td>
<td>then we have a convective boundary layer (CBL)</td>
</tr>
<tr>
<td>ζ ≈ 0</td>
<td>then we have a near neutral boundary layer (NBL)</td>
</tr>
<tr>
<td>ζ &gt; 0</td>
<td>then we have a stable boundary layer (SBL)</td>
</tr>
</tbody>
</table>

Statistical methods were used to compare the results from TAPM and the three frequently used analytical formulae listed below. For a neutral boundary layer (NBL) we have

\[
z = \frac{c_n u_*}{|f|} \approx \frac{z}{L},
\]

where \(c_n\) is a constant given by \(c_n = 0.40\) and \(f = 2\Omega \sin \phi\) is the Coriolis parameter. \(\phi\) is the latitude and \(\Omega = 7.292 \times 10^{-5}\) rad/s.

For the stable boundary layer (SBL) conditions, Eq. (2) was used as proposed by Arya (1981).

\[
z = c_s \left(\frac{u_* L}{|f|}\right)^{1/2},
\]

where \(c_s\) is a constant given by \(c_s = 0.74\). For the convective boundary layer (CBL), an equation that considers the Monin-Obukhov similarity theory was used as derived by Zilitinkevich (1972).

\[
z = \left(\frac{c_u}{c_n}\right)^{3/2} \times \frac{u_*}{|f|} \sqrt[3]{\zeta},
\]

where \(c_u\) is a constant given by \(c_u = 1.2\).

**Results and Discussion**

Statistical analyses were conducted and it was found that according to TAPM, Tembisa has a clear diurnal variability of the PBL’s stability conditions as compared to Alexander Bay (Fig. 2). It was also found that in Tembisa, the CBL generally develops in the morning between 6am and 8am during the Austral summer months (October to March), and between 8am and 10am during the Austral winter months (April to September). As indicated in Fig. 3, the CBL develops earliest from December to February, and latest from April to August.

On the contrary, the SBL generally develops in the evening between 5pm and 7pm during the Austral summer, and between 3pm and 5pm during the Austral winter. It can also be seen from Fig. 3 that the SBL develops earliest during winter months, and latest during summer months.
It was determined that the NBL conditions are not usually sustained in Tembisa, and slightly occur either during the transition between CBL and SBL conditions or between SBL and CBL conditions. As shown in Fig. 2b, the PBL in Alexander Bay is generally either stable or neutral, and rarely convective.

Extreme CBL conditions (which imply daily maximum CBL conditions in spite of whether the PBL is fully mixed or not) are normally reached between 1pm and 2pm. They are mostly reached earlier than that during mid-winter (July), and later than that during late-spring (between October and November), mid-summer (January) and during late-autumn (May).

The diurnal extreme CBL conditions for Tembisa, as indicated in Fig. 4, appear to follow the pattern of the observed daily maximum temperatures. When daily maximum temperatures are higher than the annual average (January), the extreme CBL is reached at around 2pm. On the contrary, when they are lower than the annual average (July), the extreme CBL is reached at 12pm.

Analysis indicates a clear seasonal and diurnal variability of the MH, especially for Tembisa (Fig. 5a and Fig. 6). In Tembisa, Austral summer months have a deeper MH as compared to Austral winter months. In Alexander Bay, TAPM indicates a generally shallow and a less varying MH throughout the year (Fig. 5b). On the contrary, the analytical formulae indicates higher and varying MH values.
Fig. 6 indicates a clear diurnal change in the depth of the MH in Tembisa. In January it is deeper than in July. The same figure also indicates a seemingly unvaried MH depth in Alexander Bay for the same period.

Fig. 7 indicates that there is no diurnally strong correlation between the use of TAPM and analytical formulae. The correlation coefficient in Tembisa is +0.35 and in Alexander Bay is -0.15.

Considering the unique South African climate, including between coastal and inland regions, it can be highlighted that the use of TAPM is preferable compared to analytical formulae. It has been shown by Korhonen et al. (2014), however, that TAPM tends to underestimate the depth of the MH in South Africa. It is recommended that before the use of numerical models, observational data should be used to test for biases when it comes to the output of parameters important for determining the MH.

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Reference
Simulations of present and future climate over Ethekwini using the CCAM model

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Abstract

The study evaluates high-resolution model simulations of the urban heat islands (UHI) over Ethekwini, South Africa. The Conformal Cubic Atmospheric Model (CCAM) is forced with European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis data. An Urban Canopy Model (UCM), called Town Energy Budget (TEB) is coupled within the CCAM, and downscalings are produced at 8km and 1km resolution, respectively. The UHI is well-developed at night following the period of radiative cooling, but mixing by sea-breezes and synoptic-scale system weaken the UHI during the afternoon. Future projections are produced for high and low mitigation scenarios. Present and future projections indicate the existence of UHI which is more visible in minimum temperatures.

Keywords: Greenhouse gases, Urban heat island, Urban climate model, Ethekwini, Mitigation scenarios

1. Introduction

By 2014, approximately 54% of the world’s population resided in cities, and this number will increase to at least 66% by 2050 (United Nation; UN, 2014). The higher rate of urbanization result in increased human activities, and the concentration of greenhouse gases in the atmosphere (Garland et al. 2015), leading to an increased global warming. The increase in temperature is expected to have adverse effects on human health (Garland et al. 2015), with high vulnerability and risk in cities due to extreme events such as heat waves and flooding. These effects are expected to be even larger in cities due to a high proportion of the population and the additional stress of the urban heat island (UHI) (Blake et al. 2011; Chen et al. 2015). UHI occurs as a result of increased urban activities such as changes in land surface features, tarred roads, increased emissions as well as temperatures in cities which result in altered city microclimates (Blake et al. 2011). Air pollution also lead to the absorption of longwave radiation and further worsen the UHI conditions (Kim and Baik, 2002). Higher temperatures will impact human directly since they will lead to physical disorders such as fatigue and heat strokes as well as death (Chen et al. 2015; Garland, et al. 2015). This aim of the project is to study UHI over the city of Ethekwini, South Africa under present-day and future climates. Ethekwini is a medium size coastal city, with between 1 to 5 million inhabitants. The population of Ethekwini increased from 3.09 million in 2001 to 3.44 million in 2011, and is projected to have an estimated population of 3.82 million by 2021 (Ethekwini, 2015), and 5.8 million by 2030 (UN, 2014).

2. Data and Method

2.1 Data

The global atmospheric model, the Conformal Cubic Atmospheric Model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia is applied for this project (McGregor, 2005; Engelbrecht et al. 2009). The CCAM solve non-hydrostatic primitive equations applying semi-implicit, semi-Lagrangian equations using both dynamical and physical parametrization scheme (Engelbrecht, 2009; Engelbrecht et al. 2011; Garland et al. 2015). The CCAM model is coupled to an urban canopy model (UCM) called the Town Energy Budget (TEB) model, originally developed by Masson (2000) and implemented in CCAM by Thatcher and Hurley (2012). The UCM applied comprise intersections, as well as
buildings which have orientation, and applies the “canyon model” (Thatcher and Hurley, 2012). The TEB model calculates the turbulent fluxes that are fed to the CCAM at the surface covered by buildings, roads and artificial material, and therefore it is coupled to the planetary boundary layer scheme of the CCAM (Chen et al. 2015). The CCAM has been setup to run at a quasi-uniform resolution of about 50km over Africa. The CCAM is forced with the European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis (ERA) Interim data including sea-surface temperatures (SST), sea-ice and land surface data at six hourly intervals. Important parameters used for urban climate modeling includes: fraction and height of buildings, roads, building aspect ratio, canyon aspect ratio, thickness of roof, roads and walls, anthropogenic sensible and latent heat flux released in the canyon from traffic and also from industries as described in Thatcher and Hurley (2012).

2.2 Methods

Firstly, the CSIRO Atmosphere Biosphere Land Exchange (CABLE), developed by Thatcher and Hurley, (2012) was setup at 50km, 8km and 1km respectively to provide the land surface and topographic features for the CCAM boundary conditions. The Schmidt stretch factor was applied at approximately 0.95, 0.15 and 0.017 respectively for each grid resolutions. Then the CCAM was initially run at 50km over Africa, secondly the 50km output was nudged to the 8km resolution run over South Africa, and lastly to 1km run over Ethekwini area (over an area of about 160 x 160 km²). At both 8km and 1km resolution, the urban scheme is switched on. The TEB (Thatcher and Hurley, 2012) is coupled to the CCAM every 300s and the two models exchange radiation, both sensible and latent heat and also momentum fluxes. TEB provides eight urban types ranging from urban generic to industrial high. Each of the urban types is associated with its own specific characteristics. e.g. building height and vegetation fraction. The TEB model also considers the radiative heat transfer inside the canyon between buildings and road surfaces (Masson, 2000). The TEB uses three surface temperatures, which are representative of roofs, roads and walls. The model also has air conditioning to close the building energy budgets (Thatcher and Hurley, 2012).

Future climate projections were performed using both low mitigation (RCP8.5) and high mitigation (RCP4.5) scenarios data. These climate change simulations were performed for 1km and 8km resolutions nudged within the 50km simulations forced with CABLE boundary conditions data.

3. Results and Discussion

The results of this study explore the suitability of the CCAM model at high resolution in simulating the UHI over Ethekwini, when applied at a high resolution of 1km, nudged within the 8km grid spacing simulations produced at a stretched grid.

3.1 Current climate simulations

Fig. 1 depicts the urban fraction as well as the vegetation fraction over Ethekwini, as determined by CCAM using satellite input data.

![Figure 1: The urban fraction (a) and the vegetation fraction (b) (in percentage) over Ethekwini when the aTEB scheme is turned on at 1km.](image)

The structure of the urban fraction is more realistic in the 1km grid (Fig. 1a) simulations than 8km grid (not shown). The vegetation fraction represented by the 1km simulations (Fig. 1b) is much more variable than for the case of the 8km simulations (not shown). Fig. 2 depicts the surface temperatures over Ethekwini. When the urban scheme is turned on, the island is simulated over the interior of the domain (Fig. 2a) similar to an urban area in Fig. 1a. However, when the urban scheme is turned off, the island is reduced (Fig. 2b).
The most dominant wind patterns are south easterlies (Figures 2a and b), indicating the role of the Indian Ocean in reducing the intensity of the island. The minimum screen temperature (not shown) follows both the topography and is also indicative of the urban area. The minimum temperatures are smaller over higher altitudes than close to the coast, with higher values over the area identified as urban, resulting in the UHI being more clearly visible. The maximum temperature simulation at 1km resolution (not shown) also reflects its dependence on the topography than it is on the landuse type. In higher altitudes, maximum temperatures are lower, with higher temperatures in lower altitudes. The UHI is not observed in day-time maximum temperatures over Ethekwini. During the day sea-breezes (Fig. 2) and synoptic-scale winds mixes the urban, rural, coast and interior air masses, diluting the UHI.

3.2 Future climate projections
The projected changes in temperatures, including projected changes in the UHI, are displayed in Fig. 3 for January under a low mitigation for the 2030s and 2050s with respect to the present-day climate of the 2000s. These simulations provide a portrayal of how the Ethekwini UHI may change under enhanced anthropogenic forcing, including changes in the greenhouse effect and land-use.

For the near-future period (2030s; top), the projected increase in minimum temperatures is relatively small, in the order of 0.5 to 1°C. By the mid-future of the 2050s (bottom), these changes become relatively large, are in the order of 2°C or more, reaching 3°C over the far northern interior. By the far-future of 2060s (not shown), temperature increases of 3°C are common over the entire Ethekwini area, reaching 4°C over much of the interior areas. It may be noted that significant, but relative small increases in temperature are projected for the present-day Ethekwini area relative to the surrounding rural areas. Maximum temperatures are projected to increase less than minimum temperatures, which is a clear signal of an increase in cloud cover over Ethekwini under climate change. Nevertheless, for the far-future (2060s; not shown) these increases reach 2°C over the urban areas, and in fact indicate a strengthening of the mid-day UHI.

4. Conclusions
The CCAM modelling system applied at the Council for Scientific and Industrial Research (CSIR) to study the UHI effect over Ethekwini has shown that the UHI is quite prominent relative to the surrounding rural areas within the KwaZulu-Natal Province. The benefit of using the urban scheme was clearly demonstrated in the study. The surface variables analysed at 8km and 1km simulations were found to correspond well, which indicates that there is some
usefulness in the 8km simulations if applied over the entire province of KwaZulu Natal. For projections of future climate scenario for the future up to 2060’s using both low mitigation (RCP8.5) and high mitigation (RCP4.5) scenarios, results indicate the benefit of high mitigation scenario which will reduce temperatures considerably and therefore reduce the occurrence of UHI over the city. This report demonstrates that an UHI model, the first of its kind to be configures in South Africa has been configured for Ethekwini. The urban surface can be modified for a realistic representation of any city under investigation. Further work is underway to populate CCAM with point data for Ethekwini such that the quantified UHI intensity is made even more representative of the study area.

5. Acknowledgements
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6. References

Simulated responses of the Southern Annular Mode to high-latitude tidal mixing

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We consider possible atmospheric effects related to the 18.6-year variation in tidal mixing. Preliminary results show a response of atmospheric circulation patterns that has a similar signal as noted in an earlier observational study. The simulated forcing may at least partially explain variability at the decadal time scale over certain parts of the Southern Hemisphere, including southern Africa. Consistent with observations, the signal is evident during late summer.

Keywords: Tidal forcing, decadal variability, Southern Annular Mode, Antarctic Oscillation, OMIX

Introduction
The northeastern parts of South Africa experience a characteristic 18.6-year variability (Tyson et al. 2002). At this time scale, variability in the northern Pacific, specifically the Pacific Decadal Oscillation, has been demonstrated to potentially be associated with the 18.6 -year oscillation in the lunar tide, associated with the lunar nodal cycle (Tanaka et al. 2012). The decadal signal in rainfall over the northeastern parts of South Africa, and particularly over the Limpopo River Basin, is related to variability in the southwestern Indian Ocean in the strength of the anticyclone which in turn varies in association with the Antarctic Oscillation/So uthern Annular Mode (SAM) during late Austral summer (Malherbe et al. 2014a). The variability of the SAM during late/Austral Summer from January to March (JFM) has in turn also been observed to vary with high -latitude tidal forcing, with stronger forcing shown to be associated with a lower SAM, and weaker high latitude potential associated with a higher SAM during this time of the year (Malherbe et al. 2014b).

This paper reports on the first findings of atmospheric responses over the Southern Hemisphere as simulated in a high-resolution coupled ocean-atmosphere model, focusing on the simulated and observed climate signal with respect to varying tidal forcing at high latitudes and associated climate anomalies in the southern African region.

Data and Methodology
As part of the OMIX project, the coupled model MIROC5.2 (Watanabe et al. 2010) was used to create two 500-year simulations, one with constant prescribed internal oceanic tidal energy dissipation (the control experiment) and the other with the 18.6 -year oscillation included, where high -latitude tidal potential varies in accordance to the oscillation. The ocean component of the model entails a horizontal resolution of 1° north/south x 0.5 – 1° east/west and 63 levels in the vertical. The atmospheric component has a T42 resolution with 40 levels in the vertical. For this paper, we analyze the 850 hPa heights and precipitation, focusing on the latter parts of the two 500-year simulations.

Following earlier research that showed an observed association between the SAM and high -latitude tidal forcing, we focus specifically on the JFM period. We apply a trend analysis to identify multiyear cycles in the Southern Hemisphere that may be associated with the 18.6 -year oscillation. The analysis is performed per grid point for the 850 hPa geopotential and high -latitude tidal forcing over the Southern Hemisphere using the median of pairwise slopes method (Hoaglin et al. 1983; Lanzante, 1996).

The monthly SAM is calculated by subtracting the normalized 850 hPa height at 65°S from that at 40°S (Gong and Wang 1999). We perform a Fourier analysis on the yearly JFM SAM for the latter part of the 500-year simulations. We also consider the simulated rainfall over the southern African area.

Results and Discussion
Figure 1 shows the Spearman rank trend based on the method of pairwise slopes for the Southern Hemisphere during JFM.
based on 850 hPa geopotential and tidal potential at high latitudes as associated with the 18.6 year oscillation. Positive (negative) values are shown in areas where the height of the 850 hPa level shows an increasing (decreasing) trend with increasing high-latitude tidal mixing.

Figure 1 Spearman rank trend for JFM as calculated for the last 200 years of the control experiment (top), the experiment with 18.6-year oscillation included (middle) and observed in NCEP reanalysis data for 1948 – 2012 (bottom)

The observed 850 hPa heights as well as the simulation that includes the 18.6 year oscillation both show a trend towards a pattern indicating a lower SAM with increasing high-latitude tidal mixing associated with the 18.6 year oscillation (Figure 1). This is illustrated by the positive (negative) trend at high (low) latitudes with increasing high-latitude tidal potential. This pattern is absent in the control experiment. Focussing on the SAM (at 850 hPa), a Fourier analysis shows a significant oscillation around 18.6 years and around 9 years (Figure 2).

Figure 2 Fourier analysis results for 5-year smoothed JFM SAM (Bars) with 90% significance levels indicated (solid line) for the last 300 years of the experiment including the 18.6-year oscillation.

Results of the Fourier analysis (Figure 2) and trends associated with varying tidal mixing (Figure 1) suggest an oscillation in the SAM, associated with the 18.6 year oscillation. Trends in the 850 hPa heights in JFM (Figure 3), as represented by the Spearman rank correlation with increasing high-latitude tidal mixing associated with the 18.6 year oscillation, show a tendency for relatively unfavorable conditions for rainfall during periods of stronger high-latitude tidal mixing.

Figure 3 Spearman rank trend for 850 hPa geopotential during JFM as calculated for the last 200 years of the experiment with 18.6-year oscillation included.

Negative correlations to the east of southern Africa, with increasing trends over the interior of the subcontinent, are generally associated with drier conditions over South Africa. Ranking the rainfall data from the control experiment and the experiment with the 18.6 year oscillation included with increasing tidal mixing at high latitudes show a general trend for drier conditions, particularly around northeastern South Africa (Figure 4).
Figure 4 Difference with average rainfall during JFM, grouped into 4 equally sized groups according to increasing high-latitude tidal mixing (Q1 – Q4) according to the 18.6 year oscillation, for the experiment including the 18.6 year oscillation (left) and the control experiment (right).

Figure 4 shows a tendency for dry (wet) conditions to develop over the northeastern parts of South Africa and into the Limpopo River Basin (Mozambique Channel) with increasing high-latitude tidal mixing associated with the 18.6 year oscillation. These findings are in accordance with earlier observations (Malherbe et al. 2014b) based on 104 years of observed rainfall and tidal data. The trend is absent in the control experiment.

**Conclusion**

Results obtained from the 500 year simulations support earlier observations, relating the late summer SAM to high-latitude tidal potential and showing the association with rainfall over the northeastern parts of South Africa. While only the association between the SAM and high latitude tidal mixing has been shown to be significant in the model study, other trends (in the 850 hPa heights and also the rainfall signal around southern Africa) are qualitatively similar to that reported in earlier observational work. The simulation experiment therefore indicates, along with previous observational studies, that there is further need to understand the effect of tides on climate variability in the southern Hemisphere.

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STRATOSPHERE-TROPOSPHERE EXCHANGE OVER IRENE AS OBSERVED BY OZONESONDE, SATELLITES AND MODELS

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Abstract
This paper presents preliminary results from the stratosphere-troposphere exchange events over Irene stations (25.9°S; 28.2°E), South Africa. The study uses data measured by Irene ozonesonde, National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis data and Atmospheric Infrared Sounder (AIRS) instrument onboard NASA’s EOS-Aqua satellite, to investigate different aspects of the stratosphere-troposphere exchange over Irene. Results shows a strong signature of stratosphere-troposphere exchange events taking place over Irene. In a case study of the 17 August 2012, ozone mole fraction increased by a factor of approximately 3-4. October

Keywords: Ozone, Irene, Stratosphere-troposphere exchange, Ozonesonde

Introduction
A continuous weekly launch of ozonesondes in Irene station (25.9°S; 28.2°E), South Africa started in 1998 when the site joined the Southern Hemisphere Additional ozonesondes (SHADOZ) network (Thompson et al. 2003). Prior to the Irene station joining the SHADOZ network, the station’s ozonesonde measurements were done under Southern African Fire-Atmosphere Research Initiative/Transport and Atmospheric Chemistry near the Equator-Atlantic (SAFARI-92/TRACE) (campaigns for June 1990 to August 1994).

The growth of ozone concentrations in the troposphere either through stratospheric ozone intrusion or chemical reaction of compounds such as nitrogen oxides (NO\textsubscript{x}), carbon monoxide (CO) and volatile organic compounds (VOC) has a toxic effect on humans and vegetation. Though there has been an a lot of studies which are dedicated to the understanding of stratospheric ozone concentrations in the recent years, the focus has shifted to the investigations of the increase of ozone concentrations in the troposphere (e.g. Galani et al. 2003; Clain et al. 2016 and others). While most of these tropospheric ozone studies focus on the near-surface ozone concentrations, which are reported to be primarily due to human influence, only a few studies investigate the role of the stratosphere-troposphere exchange to the tropospheric ozone budget.

In addition to the Irene ozonesonde measurements, this study also uses data retrieved from the Atmospheric Infrared Sounder (AIRS) (www.giovanni.sci.gsfc.nasa.gov) instrument, which is onboard the NASA’s EOS-Aqua satellite, taken as the satellite overpasses the closest to Irene. Also, the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis data was used to investigate the vertical circulation patterns over Irene.

Data and method
This research used ozone data measured at Irene station, South Africa. Regarding the Irene ozonesonde, the integration of ozone concentration was done from the surface to about 16 km. The data was averaged for each altitude height (1 km, 2 km to 16 km) which the balloon passes as it rises from the ground to 16 km. Monthly average composites were calculated for all balloon ozonesondes and used to construct monthly troposphere profiles. The analytical procedure and launching of Irene ozonesondes is discussed extensively in studies by i.e. Thompson et al. (2003) and Diab et al. (2004).

Furthermore, the AIRS satellite data for the period 2003-2015 was retrieved and used to investigate troposphere and lower stratosphere ozone profiles. AIRS is aboard the NASA satellite, and it gives vertical measurements of atmospheric dynamics and atmospheric chemistry from 1000 hPa to 0.1 hPa. The elevated ozone events were identified with ozonesondes data by using monthly composite troposphere-lower stratosphere profiles from satellite and balloon ozonesondes as the guideline on expected profile maximum and minimum values. In order to eliminate the possible ground pollution and events, only episodes occurring at the upper troposphere are considered for the current study. A similar approach to identify stratosphere-troposphere ozone exchange was
also reported by Greenslade et al. (2017) in their study on the stratospheric ozone intrusion and their impacts on tropospheric ozone concentration. Therefore, it is important to only look at the ozone content of the upper troposphere because the main focus is to investigate the events that concern the exchange of particles between the stratosphere and the troposphere.

It is also always important to look at both horizontal and vertical mean wind circulation in order to identify the air mass direction of motions in the atmosphere. For this purpose, zonally averaged wind vectors were calculated using zonal wind \((u)\) and meridional wind \((v)\) from the NCEP/NCAR reanalysis data archive.

The AIRS ozone mole fraction data used in this study was used as an input to the wavelet analysis technique (Torrence and Compo, 1998) in order to detect the major frequency of oscillation in the ozone mole fraction data at the tropopause height over Irene. A study by Grinsted et al. (2004) showed how the Morlet wavelet with the dimensionless frequency \((\omega_0=6)\) could be recommended for identifying features of geographical time series, which provides a balance between time and frequency localization. Thus, for the wavelet power spectrum for a time series \(X_n, n=1, 2, 3... N\) such as the Irene ozone mole fraction data, one could calculate the wavelet transform of the time series by using the formula defines as:

\[
W^x_n = \sqrt{s} \sum_{n'} x_{n'} \psi_0[n' - n] \frac{\delta t}{s} \]

(1)

where, \(\psi_0\) is the Morlet wavelet, and \(s\) is the scale.

Results and discussion

Fig. 1 shows climatological profile of both Irene ozonesonde (black line) and AIRS mean (blue line), and the 17th August 2012 ozonesonde vertical ozone mole fraction (red dashed line) profiles (all plotted in parts per millions in volume (ppmv) units). The AIRS data was taken as the satellite overpasses at \(\pm 1^\circ\) for both latitude and longitude of the Irene site. Both the ozonesonde and AIRS climatological profiles are for the period from January 2003 to December 2015. However, it should be mentioned that there was a data gap in the Irene data from 2008 to 2011, presumably due to unavailability of funding for ozonesonde launch. In general, there is a noticeable difference between the AIRS and ozonesonde data, especially in the troposphere. This difference could be associated with the difference in data sampling between the satellite and ozonesonde data, and also the difference in ozone mole fraction retrieval algorithms. A better agreement is observed at the lower stratosphere.

In order to identify stratosphere-troposphere exchange events, a daily profile (red dashed line) measured by Irene ozonesonde was plotted together with the climatological profile observed by both the ozonesonde and the AIRS instruments. An example of this is a daily mean profile measured on the 17th of August 2012 (see Fig. 1). The dashed red line clearly indicates that there is an increase (by a factor of 3-4) of ozone mole fraction at the height between 8 and 12 km, which easily reach approximately 0.14 ppmv. Considering the criterion of the stratosphere-troposphere exchange, this is an intrusion of stratospheric ozone in the troposphere.

Fig. 2 shows the vertical cross-section circulation pattern averaged for 27-29\(^\circ\)E longitude for August 2012 month. There is clear indication of a downturn of wind vectors at 450-250 mb at latitudes between 22 and 26.4\(^\circ\)S. This could be the main reason of the increase of ozone mole fraction at the tropopause. These results are also consistent with a study by Diab et al. (2004) where they reported an increase of stratosphere-troposphere exchange event during winter and late winter months over Irene.
Figure 2: NCEP/NCAR composite vertical cross-section of atmospheric circulation, averaged for 27-29°E longitudes for the August 2012 month.

The day-time mean time-series anomalies of ozone mole fraction in ppv measured by the AIRS instrument taken for the 250 hPa for data from 2003 to 2015 is shown in Fig. 3. There is a clear variation in ozone mole fraction of the tropopause over Irene, with some days reaching mole fractions of approximately $6.5 \times 10^8$ ppv (e.g. the year 2012). The indication is that from time-to-time, there is an intrusion of particles from lower stratosphere to the troposphere.

Figure 3: Daily mean AIRS ozone mole fraction data taken at 250 hPa over Irene for 2003 to 2015.

Fig. 4 shows the circular/spiral graph of years from 2003 to 2015 monthly means for the AIRS measured ozone mole fractions over Irene (at 250 hPa). The graph indicates that there is somewhat increase of ozone mole fraction during the period between May and October.

Figure 4: Spiralling ozone mole fraction (ppv) monthly mean for the period from 2003 to 2015 over Irene site.

The maximum monthly ozone mole fraction is observed to be approximately $4 \times 10^9$ ppv during August 2012. These observations are somewhat consistent with observations by Diab et al. (2004) on their study on tropospheric ozone climatology over Irene, South Africa, from 1990 to 1994 and 1998 to 2002. Raghunandan et al. (2007) also reported some elevated ozone events over Johannesburg based on analysis of tropospheric ozone partial columns. In their study, they showed in a case study that in September 1998 there was penetration of ozone-rich air from the stratosphere to the troposphere. Fig. 4 seems to show that there is an inter-annual variability in the tropopause ozone mole fraction. The ozone variability in the tropopause seems to follow that of the stratosphere, which has an inter-annual variability (e.g. Toihir et al. 2015).

Fig. 5 shows the results of wavelet analyses of the ozone mole fraction anomalies daily data for the period from 2003 to 2015. The thick black line contours indicate the 5% confidence level against red noise. The lighter shades indicate the cone of influence where edge effects might distort the picture. There is a high power in the 365-1024 band for the period from 2005-2013.

Figure 5: Wavelet analysis of daily ozone mole fraction anomalies from 2003 to 2015.
There is also a maximum power observed in the band between 24-64 days period from 2003-2004, 2008-2009 and 2011-2012; and lastly for the band between 96-128 days for the period 2005-2006. The high power bands clearly indicates (in frequency domain) the periods where there are sudden increase of ozone mole fraction in the tropopause over Irene.

**Conclusion**

There are several episodes of enhancement of ozone concentrations observed over Irene. During the 17 August 2012, a strong stratosphere-mesosphere exchange was observed over Irene using the SHADOZ ozonesonde data. This was also verified by strong downwards turn of the wind circulation vectors between the lower stratosphere and higher troposphere during August 2012 (see Fig. 2). Winter and late winter months seem to be period where stratosphere-troposphere exchange dominate. One of the reasons for this could be that the Southern Hemisphere polar vortex is very active during winter months, and hence this could also change the dynamics of the atmosphere all the way to the subtropics. A detail study of the stratosphere-troposphere exchange over Southern Africa is ongoing, which includes the depth of the intrusion and the statistics of occurrence of this important event.

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**References**


Climate impacts on sugarcane yield in the eastern part of southern Africa

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Abstract
This current study has investigated climate impacts on the yield. Rainfall and temperature datasets were used to compute the annual time series of sugarcane index against rainfall and temperature in the sugar-area. The study explored the relationship between climate and the yield via regression and pair-wise correlation analysis in climate explorer. Climate shows significant correlations from Dec-May of harvest year. There is a significant positive correlation (+0.5) between sugarcane yield and rainfall, while a negative correlation (-0.4) between yield and temperature has been envisaged. This implies that, climate is responsible for 40-60% of sugarcane reduction over southeastern southern Africa.

Keywords: - Climate impacts, Precipitation, Temperature and Sugarcane yield

Introduction
Warming of the Earth surface has increased, the global air temperature anomaly of 2016 has been reported as the warmest in record (NOAA 2017). The surface air temperature increase depletes soil moisture via enhanced evaporation (Engelbrecht et al. 2015). When the evaporation (output) exceeds precipitation (input), that condition might induce drought (Chikoore 2017), which negatively affect agricultural yields. There is a reduction in sugarcane growers who submit cane for milling (Dubb, 2015a), because of low commodity prices and drought to some extent (Gbetibouo and Hassan 2005). Previous studies on sugarcane production and climate show desperate trends, some suggested increased sugarcane yield (Marin et al. 2013; Jones et al. 2015) owing to future climate changes, whereas others reported a decline (Deressa et al. 2005; Knox et al. 2010; Chandiposha 2013).

The main aim of the study is to investigate the influence of meteorological conditions on sugar yield over southeastern southern Africa (South Africa and Swaziland). The study concentrated on exploring the degree of association and the extent to which past climate affects yield.

Data and Methods
The study used empirical models which are statistical and descriptive in nature based on long-term observations derived from climate websites. Data used...
in the study is obtained from KNMI climate explorer, and include ECMWF, MERRA and station-based products (e.g. GPCC and TS3.23).

Monthly Global Precipitation Climatology Centre Version 7 monthly rainfall data at 1 degree and the Climatic Research Unit at University of East Anglia TS3.23 air temperatures (Harris et al. 2014) were the key climatic datasets used to compute annual time series for sugar index against rainfall and temperature in the area-averaged.

South Africa and Swaziland sugarcane yields data was extracted from the Food and Agriculture Organisation of the United Nations website. The yields were merged into one sugar index using the total mean yield from 1970-2013 based on their production. Thus, South Africa contributed 84% influence on the sugar index, and Swaziland contributed 16%.

Statistical correlation analysis was done in a lagged pair-wise manner to determine the degree of association between climate variables and sugarcane yield from 1970-2013. A sample size of 44 years was selected. Thus, a correlation >0.5 was required to get statistical significance at 90% confidence.

**Results and Discussion**

<table>
<thead>
<tr>
<th>Months</th>
<th>Rain r Lag -3</th>
<th>Temp r Lag -3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.496</td>
<td>-0.476</td>
</tr>
<tr>
<td>Feb</td>
<td>0.253</td>
<td>-0.288</td>
</tr>
<tr>
<td>Mar</td>
<td>0.270</td>
<td>-0.145</td>
</tr>
<tr>
<td>Apr</td>
<td>0.292</td>
<td>-0.295</td>
</tr>
<tr>
<td>May</td>
<td>0.424</td>
<td>-0.483</td>
</tr>
<tr>
<td>Jun</td>
<td>0.110</td>
<td>-0.042</td>
</tr>
<tr>
<td>Jul</td>
<td>0.186</td>
<td>-0.207</td>
</tr>
<tr>
<td>Aug</td>
<td>-0.043</td>
<td>0.061</td>
</tr>
<tr>
<td>Sep</td>
<td>0.099</td>
<td>-0.317</td>
</tr>
<tr>
<td>Oct</td>
<td>-0.060</td>
<td>-0.125</td>
</tr>
<tr>
<td>Nov</td>
<td>0.345</td>
<td>0.033</td>
</tr>
<tr>
<td>Dec</td>
<td>0.264</td>
<td>-0.189</td>
</tr>
</tbody>
</table>

Table 1: correlation for each month from 1970-2014 of sugar yield with detrended rain and temperature in the sugar growing area, leading by 3 months. Bold and black numbers indicate significant correlations.

Figure 2: The inter-comparison of annual area-average a) GPCC V7 rainfall against the detrended sugarcane index b) annual area-average CRU TS3.23 surface temperatures anomalies against the detrended sugarcane index over South Africa and Swaziland for the period 1970 to 2013.
The results showed a strong correlation between climatic conditions and the yield during December of the preceding year up to May of the harvest year (Table 1). The study revealed that there is a significant positive correlation \( (r \geq +0.5) \) between rainfall and sugarcane (Fig. 3(a) and (b)).

Sugarcane \((Saccharum officinarum)\) requires large amount of rainfall greater than 1000 mm per year to give high yield. There is a downward trend in sugarcane yield annual time series from 1970 to 2013 (Fig. 2(a) and (b)), partially because of altered characteristics of the rainy season and alternating of rainfall from dry to wet.

A negative correlation \( (r \leq -0.5) \) between temperature and the yield was envisaged in the area-averaged (Fig. 4(a) and (b)), and meteorological conditions (drought) that inhibit rainfall also cause a decline in annual sugarcane yield, which detrimentally affects the local economy.

**Conclusions**

Introduction of new technologies, mitigation and adaptation strategies such as improving the variety of sugarcane and increased irrigation did not yield the maximum expected benefits to sugar industry. Hence, they are found to be not always viable options. The key findings show that climate affect sugar up to 40 - 60% (Figs. 3(a) and (b); Figs. 4(a) and (b)), which signals that reduction in sugarcane production cannot be attributed to climate only. Bezuidenhout et al. (2008) found that there is other non-climatic forcing such
agronomic practices, pests and diseases that also depress cane.

Acknowledgements
The KNMI climate explorer is given the acknowledgement it deserves for providing easy platform to facilitate research and open-public data used in this paper, which is available from this website (https://climexp.knmi.nl/start.cgi?id). Also a sincere gratitude to Prof. Mark R. Jury of the University of Puerto Rico (supervisor), Dr. Nkanyiso B. Mbatha and Dr. Nozipho M. Motsa of the University of Zululand (co-supervisors), for assisting and guiding me during the study.

References


Abbreviations and Acronyms
CE - Climate Explorer
CRU - Climate Research Unit
ECMWF - European Center for Medium range Weather Forecasting
GPCC - Global Precipitation Climatology Centre
KNMI - Royal Netherlands Meteorological Institute
MERRA-Modernd Era Retrospective-Analysis for Research and Applications
NOAA - National Oceanic and Atmospheric Administration
r - Correlation Coefficient
TS3.23 - Gridded CRU Time Series (TS) 3.23
UEA - University of East Anglia
V7 - Version Seven (7)
Abstract

Remarkable heavy rainfall events resulting in floods over South Africa have been associated with continental tropical low-pressure systems (CTLs). The study of CTLs climatology shows an increasing trend of the occurrence of CTLs over Southern Africa. Very little is known about the contribution of CTLs to South African rainfall. Therefore daily synoptic circulation patterns over Southern Africa associated with CTLs were identified using self-organising maps (SOMs). SOM output nodes were used to compute the frequency of occurrence of CTLs. Rainfall data was also used to calculate the average maximum rainfall for all mapped days and for days when CTLs occurred. The results show that as the frequency of CTLs is higher, the average rainfall is also higher. The results quantify the contribution of CTLs to South African rainfall.

Keywords: continental tropical low-pressure systems, self-organizing maps, synoptic circulation patterns, average rainfall, South Africa

1. Introduction

A Continental Tropical low-pressure system (CTL) is a low pressure system that stands upright (low extends from the surface to upper levels) and has a warm core at the upper level. It is a slow-moving weather system that can cause widespread heavy rainfall associated with floods (Dyson and Van Heerden, 2002). CTLs occur infrequently and not every summer (October to March) in South Africa (S.A), however notable flood events experienced have been associated with these systems. For example, a flood event over the Free State in 1988 was responsible for a couple of dam failures, damage to roads and property and people were evacuated (Trieegaardt et al., 1991). Dyson and Webster (2017) studied the climatology of CTLs over southern Africa over a period of 37 years and found an increasing trend in the occurrence of CTLs.

Considering the increasing trend of CTLs, very little is still known about their variability and effect on South African rainfall. In this study, daily synoptic circulation patterns over a period of 37 years were described using self-organizing maps (SOMs). Synoptic circulation patterns associated with CTLs were thereby identified. Thereafter average rainfall for each SOM node was computed to quantify the effect of CTLs to rainfall.

SOMs are clustering and pattern recognition maps which were introduced to meteorological and climatic sciences in the late 1990s (Liu and Weisberg, 2011). SOMs are used in fields which deal with high dimensional data. In the medical field for example, SOMs are used to study the clustering of genes (Liu and Weisberg, 2011). Their applications in meteorology have been extensively used since the start of the 21st century (Dyson, 2015). SOMs have been applied in several synoptic circulation investigations. Among them are circulation patterns associated with snow (Stander et al., 2016), fog (van Schalkwyk and Dyson, 2013), rainfall (Lennard and Hegerl, 2014) and tropical cyclones (Malherbe et al., 2013).

The advantage of using SOMs is that they preserve non-linear characteristic data between the atmosphere and surface variables (Lennard and Hegerl, 2014). The SOMs technique chooses an output neuron (winner) that best matches the input...
data patterns, and then determines all the neighbourin

This paper focuses on the Highveld of South Africa confined to the highlighted region in Fig.1 (25° S to 27.5° S and 25° E to 30° E). The Highveld is a densely populated area of S.A as it covers Gauteng and the rest of the Witwatersrand. It falls in the summer rainfall region and some parts of it were affected by floods associated with CTLs. There are informal settlements within the Highveld of which some are located near floodplains.

The main technique of this study was to generate synoptic archetypes (nodes) in the SOM_PAK VERSION 3.1 software using NCEP data. These nodes were used to identify synoptic circulation patterns associated with CTLs. A SOM with 28 nodes was decided on after some experimentation as it adequately resolves synoptic circulation patterns associated with CTLs. The use of fewer nodes would result in more generalization making it inadequate to capture the CTL.

Daily maximum rainfall for all the months DJFM was associated with all the dates in the nodes and thereby used to compute the average rainfall for each node. The same procedure was performed only this time with the incorporation of CTL dates (as determined by Dyson and Webster). The methodology ends by associating CTLs with rainfall thereby quantifying their contribution to South African summer rainfall.

3. Results and discussions

Fig 2 is a SOM output of the archetype maps (nodes) that describes daily synoptic circulation patterns over a period of 37 years. The SOM output maps nodes with similar characteristics close to each other and dissimilar nodes are mapped further apart (Stander at el, 2016). Fig 2 depicts that for example, the highlighted nodes have similar circulation patterns hence are mapped close together while node 7 and 22 are Synoptic circulation patterns associated with high pressure system located south and east of Africa. The high extends its ridge into northern of South Africa.

An added advantage of using SOMs is the ability to relate each day to one of the 28 nodes. This makes the calculation of the frequency of the CTLs to the total number of days with similar circulation patterns in each node possible. Fig 3 shows the frequency of occurrence of CTLs in each node represented in percentages. Node 1 has the highest frequency (16.1%) of CTLs while node 26 and 28 shows no occurrence of CTLs. Noting that nodes with similar characteristics are mapped close

Fig. 1 Location map of the study area (highlighted area) within the Highveld of South Africa.

2. Data and methods

Daily synoptic circulation patterns over southern Africa during summer were described using the 1200UTC, 850 hPa geopotential heights from the National Centre for Environmental Prediction (NCEP) reanalysis which has a grid spacing of 2.5° (Kalnay et al, 1996). Tropical systems occur during late summer over Botswana and contribute to the summer rainfall (Dyson and Van Heerden, 2002.) and hence the focus of this study is on a 4-month summer period defined as December to March (DJFM). Daily maximum rainfall data from the South African Weather Service (SAWS) was obtained for all the months DFJM, from January 1979 to December 2016. On each day, the maximum rainfall in the study area was identified and this maximum daily value was used in the calculation of averages.
together, a similar trend is found with the frequency of CTLs. Not only node 1 has the highest frequency but also the close by highlighted nodes. Node 21 has the lowest frequency of the occurrence of CTLs and the nodes close by also have low frequencies.

Fig 4 shows the average daily maximum rainfall in millimeters (mm) over the study area. The averages were computed for all the days with similar circulation patterns (mapped days) in each node and also for all the days when CTLs occurred. Generally the highest average maximum rainfall is found in the upper left portion of the SOM with the highest average rainfall in node 9 (105 mm). The average rainfall of all the days when CTLs occurred is generally higher than the average rainfall of all the mapped days in each node.

The results in fig 2 and fig 3 shows that as the frequency of the occurrence of CTLs is higher, the average rainfall is also higher. The upper left quadrant has the highest frequency of CTLs; this is associated with the highest average rainfall. The frequency of CTLs in node 2 is 6.2% increasing to 7.2% in node 3, average rainfall increases from 84.3 mm (node 2) to 94.2 mm (node 3). It is noticeable that nodes 26 and 28 show no occurrence of CTLs and they have the lowest average rainfall.

Node 9 has the highest average rainfall (105 mm) when CTLs occurred yet the frequency of occurrence is low. Most of the CTL dates in this node are associated with the wet seasons. According to the climatology of CTLs, location of CTL during the very wet 1999/2000 was further south (Dyson and Webster, 2017).

Nodes 3 and 16 show that high average rainfall occurred when there was a connection between tropical and extra-tropical systems while Node 24 shows that there is no need for that connection for high rainfalls to occur. However high rainfall does not confine to CTL only, other systems such as the ridging high in node 21 cause high rainfalls.
4. Conclusions

The results show a directly proportional relationship between the frequency of occurrence of CTLs and the average rainfall. The highest maximum rainfall occurs in the nodes with synoptic circulation patterns associated with CTLs. An average rainfall when CTLs occurred is generally higher than an average rainfall of all days that are not associated with CTLs. It was also found that in 2000, a very high average rainfall was associated with a CTL located further south. I recommend that an effect of the location of a CTL to rainfall must be further investigated.

Acknowledgements

I would like to greatly thank the South African Weather Service for the data provided.

References


A two-year long drought in the summers of 2014/2015 and 2015/2016 over South Africa

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2 Nansen-Tutu Center for Marine Environmental Research, University of Cape Town, South Africa.

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Abstract

Droughts occurred over South Africa during the summer seasons of 2014/2015 and 2015/2016. At the same time, the Pacific Ocean was warmer than normal starting in 2014 and leading to the very strong 2015/2016 El Niño. The objective of the study was to use the Standard Precipitation Index at different time scales (3 months duration, 5 months duration and 17 months duration) to assess the severity of 2015/2016 summer drought compared to the other droughts of the 20th and 21st century (1921 to 2016) and to analyse the relationship between droughts and ENSO. The South African Weather Service rainfall data shows that KwaZulu-Natal was the only region within South Africa, to have the 2015/2016 as the strongest summer drought since 1921 but 2015/2016 was still one of the worst droughts on record in South Africa, especially at the 2 consecutive seasonal scales. For South Africa, the summer rainfall 2015/2016 season had the fifth worst drought after the El Niño related drought of 1982/1983 and 1991/1992 and the non El Niño-related droughts of 1967/1968 and 1944/1945.

Introduction

Drought is one of the natural hazards that are endemic to South Africa. Negative departures in the seasonal rainfall anomalies have regional and national socio-economic impacts (Meque and Abiodun, 2015). Southern Africa was affected by a severe drought during the summers of 2014/2015 and 2015/2016, generally, lasting for two years. At the same time, warm anomalies developed in 2014 in the Pacific Ocean and conditions in austral summer 2014/2015 was nearly El Niño-like while one of the strongest El Niños developed in 2015. The two year drought has resulted in crop failure, leaving 2.5 million people in Malawi, Mozambique, Zimbabwe, Lesotho and Madagascar seeking a quick humanitarian response, while South Africa’s maize production dropped to 25% during the summer of 2014/2015 (AgriSA, 2016).

It has been established that the El Niño Southern Oscillation (ENSO) plays a significant role in the inter-annual rainfall variability in South Africa. Even though the relationship between ENSO and rainfall is not totally linear, droughts in this region were found to be favoured by El Niño events (Rouault and Richard 2003; Cretat et al., 2010; Meque and Abiodun, 2015). El Niño events impacts over South Africa are the strongest during the summer peak rainfall months, from December-March (Dieppois et al., 2015), over the south-eastern and northern parts of South Africa (Richard et al., 2001). During El Niño droughts, anomalous low-level divergence occurs over Southern Africa due to changes in the Walker circulation (Mason, 1994) and Hadley Circulation. This also prevents the moisture transport into southern Africa from the Indian Ocean contributing to the reduction of the seasonal rainfall. Moreover, abnormal high pressure anomalies prevent rain to occur (Dieppois et al., 2015).

The objective of the study is to use the Standard Precipitation Index (SPI) used previously by Rouault and Richard (2003) to quantify whether the droughts of 2014/2015 and 2015/2016 were the strongest on record in South Africa compared to other droughts since 1921/1922.

Methods

Nino 3.4 Index

To calculate the El Niño Index over the Pacific Ocean, Sea Surface Temperature (SST) was extracted between (5°N-5°S,120°W-170°W) in the Niño 3.4 domain using the Extended Reconstructed Sea Surface Temperature (ERSST) v4 that is obtained online from the Earth System Research Laboratory (ESRL) at NOAA (http://www.esrl.noaa.gov/data/gridded/data.noaa.ersst.html ). The data is available on a 2 x 2° regular grid and extends from 1854 until present. To compute the Niño 3.4 index, we average summer SST (December, January and February, DJF) in the
defined region above, subtract the corresponding climatology and further standardize the results by dividing by the standard deviation of that same period (DJF) over the climatological period from 1921 to 2016.

**SPI data**

The study uses monthly precipitation provided by the South African Weather Service (SAWS) from January 1921 to December 2016 to calculate the SPI. The SAWS categorises the country into the 94 rainfall districts (Figure 1), of which each rainfall district at least combines the mean of 5 to 15 rain gauges (Rouault and Richard, 2003). The 94 districts are further subdivided into 8 climatic rainfall areas (Figure 1). This study only calculate the SPI for the austral summer rainfall regions (region 4-8) from 1921 to 2016 and for the average of region 4 to 8 (Figure 2). The SPI was calculated for 3 time scales: 3 month duration SPI until the end of February for the heart of the summer rainfall season, 5 months duration SPI until the end of March for all summer season and 17 months duration SPI until the end of March for a nearly two year long summer season index. Further details on how to compute the SPI can be obtained from Hayes et al. (1999). The SPI program only requires rainfall data in ASCII format and was downloaded from http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx).

**Results and Discussion**

Figure 3 shows the time series of droughts at 3 different monthly time scales. The timescales are 3 months at the end of February, 5 months at the end of March and 17 month. At a 3-month timescale, the values of the SPI reflect short term drought index at the heart of the rainy season, usually used to monitor agricultural drought. At a 5-month timescale the SPI values rather reflect most of the rainy summer. The 17 month SPI values reflect longer term precipitation anomalies, which affect hydrological systems, particularly dams. Rainfall shortage and SPI values from this 17 month timescale can further be associated with deviation from the mean in reservoir level. Table 1 categorises the SPI into different classes, for instance, if a SPI falls within a positive category it indicates that the rainfall is greater than normal, while negative SPI value will indicate that rainfall is less than normal.

Furthermore, the negative class of which this paper is dedicated to has a different hierarchy of dryness. SPI value of -2.00 or lesser value classify a drought as extreme; while between -1 and -1.5 a drought will be classified as moderately dry (Table 1).

Figure 2 further represents the time series of SPI over the summer rainfall region of South Africa, which was averaged over all the summer rainfall sub-regions (Central Interior, Kwazulu-Natal, Northern Interior, Western Interior and Southern Interior). At the 3 and 5-month timescales, South Africa experienced its most extreme drought during the El Niño summer of 1982/1983, while at the 17-month timescale, the driest summer was at 1991/1992 summer. During the strongest El Niño event of 2015/2016, the country experienced its third strongest drought of the century (from 1921 to 2016) at the 17 month timescale. It should be further highlighted that after 1970, the relationship between ENSO and southern African rainfall strengthened (Fauchereau et al., 2003 and Richard et al., 2001).

[Figure 1. Location of the 94 rainfall districts of the SAWS. The 94 district are further categorised into 8 climatic rainfall areas defined by SAWS, namely: North-Western Cape (1), South-Western Cape (2), South Coast (3), Southern Interior (4), Western Interior (5), Central Interior (6), Kwa-Zulu Natal (7) and North-Eastern Interior (8). Source from :( Rouault and Richard, 2003).]

In the central interior (Figure 3) the worst dry year at a 3-month timescale occurred during the La Niña summer of 1967/1968. During the same year, wetter conditions were found over the area at a 17-month time scale, which represent two consecutive seasons. At a 5 month timescale, the central interior received its worst drought(> -2) during the El Niño summer of 1991/1992, while at the 17 month timescale the most severe drought at this scale followed a summer after the El Niño event of 1991/1992. The summers
of 2014/2015 and 2015/2016, were moderately dry at the 5 and 17 month timescales.

Figure 2. SPI at 3, 5 and 17 month timescales at the end of February for the 3 month period and March for the 5 and 17 month periods for the summer rainfall region. Red and blue bars represent El Niño and La Niña respectively, while the black bars represent normal years.

Table 1. Classification of the SPI values

<table>
<thead>
<tr>
<th>SPI Class</th>
<th>Drought Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPI &gt; 2</td>
<td>Extremely Wet</td>
</tr>
<tr>
<td>1.50 &lt; SPI ≤ 1.99</td>
<td>Very Wet</td>
</tr>
<tr>
<td>1 &lt; SPI ≤ 1.49</td>
<td>Moderately Wet</td>
</tr>
<tr>
<td>-0.99 &lt; SPI ≤ 0.99</td>
<td>Near Normal</td>
</tr>
<tr>
<td>-1.49 &lt; SPI ≤ -1.00</td>
<td>Moderately dry</td>
</tr>
<tr>
<td>-1.99 &lt; SPI ≤ -1.50</td>
<td>Severely dry</td>
</tr>
<tr>
<td>SPI ≤ -2.00</td>
<td>Extremely dry</td>
</tr>
</tbody>
</table>

Figure 3. SPI at 3, 5 and 17 month timescales at the end of February for the 3 month period and March for the 5 and 17 month periods for the Central Interior. Red and blue bars represent El Niño and La Niña respectively, while the black bars represent normal years.

The worst drought at the 3 and 5 month timescales over KwaZulu-Natal (Figure 4) occurred during the El Niño event of 1982/1983 while the strongest drought at a 17 month timescale occurred during the strongest El Niño year of the century in 2015/2016. It is interesting to note that at the 17 month timescale, the two strongest wettest events were recorded during the El Niño years of 1977/1978 and 1987/1988. This is because 1976/1977 was slightly above normal but the preceding year was a very wet La Niña year. Over the north-eastern (Figure 5) interior of South Africa the driest summer since 1920/1921 on a 3 and 17-month timescales was recorded during the El Niño event of 1982/1983 while at a 5-month timescale is recorded during the weak warm Pacific event of 2002/2003. It should be further noted that after 1970s at this region, the frequency and the magnitude of the drought at this region is more pronounced than any sub-region within the South African subdomain.

In the southern interior area (Figure 6) of South Africa, the pattern is very distinctive from the other summer rainfall regions of South Africa, for instance the intensity and frequency of drought has decreased since the 1970s, especially at a 17-month timescale which is opposite from what has happened in southern Africa (Fauchereau et al., 2003, Rouault and Richard, 2003). However, the worst drought since 1921/1922 in this region at the 3 and 5-month timescale occurred after the 1970s during the 1982/1983 El Niño event. At a 17-month timescale, it is notable that a severe drought occurred during the normal year of 1945/1946 following two below normal but not exceptionally below normal season summer season while the wettest summer is recorded during the El Niño year of 1976/1977. Furthermore, it is also very interesting to note that during the strongest El Niño event of the century 2015/2016, the area had normal to near normal SPI values at all scales.

Figure 4. Same as figure 2, but for KwaZulu-Natal.
Conclusion

The main objective of the study was to investigate whether the summer of 2015/2016 was the strongest compared to the other summer droughts of the 20th and 21st (1921 to 2016) century. During this strongest El Niño event of 2015/2016, KwaZulu-Natal was the only region within the South African domain to experience the strongest drought of the 94 year period since 1921 but at a longer timescale (17 months). The shorter time scales (3 months and 5 months) shows little difference. To conclude, for South Africa the dry summer rainfall season of 2015/2016 was the fifth worst drought after the El Niño related droughts of 1982/1983 and 1991/1992 and the non El Niño related droughts of 1967/1968 and 1944/1945 at the seasonal scale. At the 17 month timescale, an index that encompasses two summer seasons, 2015/2016 was the third worst drought since summer 1921/1922 after 1982/1983 (1st) and 1964/1966 (2nd), which could have been influenced by dry conditions during the two El Niño summers of 2014/2015 and 2015/2016.

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References


Forecast Verification: does different observed data sets matter?

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Abstract

The 8-km CCAM forecast for summer seasons (December to February) of 2013/2014; 2014/2015 and 2015/2016 were verified against TRMM and CHIRPS datasets. The analysis of typical forecast verification metrics revealed somewhat different results. The measure of forecast quality is sensitive to the observed data set used.

Key words: Verification, CHIRP, TRMM, CCAM

1. Introduction

In the recent years, there has been significant improvement in the accuracy and skill of weather forecasts. For instance, the forecast that is produced today for the next 6 days is as accurate as the 5-day forecast ten years ago (Bauer, et al., 2015). This advancement in forecast skill can be attributed to factors such as an increased global observational data that provide more accurate initial states of the atmosphere (Simmons & Hollingsworth, 2002). The improvement of computational architectures over the years also played an integral part in numerical weather forecasting (Simmons & Hollingsworth, 2002). Currently, numerical models can simulate the future state of the atmosphere at spatial resolution up to ~1 km (e.g. Schwartz, et al., 2017), albeit over relatively small domains and/or short lead times. This method of increasing the spatial resolution of a numerical model is therefore common practice when observations have lower resolution than forecasts for forecasts to be up-scaled to the grid resolution of the observed data (Bougeault, 2003). The aim of this study is to assess the value that the use of different verification data sets, with different grid spacing add to the measure of forecast quality.

Here Conformal Cubic Atmosphere Model (CCAM) is verified against Tropical Rainfall Measuring Mission (TRMM) and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data sets. The following section provides a description of these datasets and verification techniques. In section 3, results are presented and discussed. Concluding remarks are presented in section 4.

2. Data and Method

Model data

The CCAM hindcasts were performed for summer seasons (December to February) of 2013/14; 2014/15 and 2015/16 using the atmospheric conditions at 00 UTC provided by the Global Forecasting System (GFS). After initialisation, the CCAM runs globally at 50 km spatial resolution and it is integrated temporally for up to 14 days into the future. The high-resolution simulations are obtained by dynamically downscaling the 50 km global forecast output to 8km horizontal resolution over southern Africa.
Verification analysis was only done on the 24-hr rainfall CCAM forecasts simulated at 8km resolution. CCAM forecasts were re-scaled to grid resolution (~5 km and ~25 km) of observed datasets before applying verification matrices described in the method subsection below.

**Verification data**

**TRMM**

TRMM 3B42 is one of the available type precipitation product that can be obtained from Tropical Rainfall Measuring Mission (TRMM) satellite (Duan, et al., 2016). The data is made available by National Aeronautics and Space Administration (NASA) of the United States of America. The thorough details of physical structure and calibration procedures of TRMM satellite are described by (Kummerow, et al., 1998). Data has a time resolution of hourly and it has a global coverage with spatial resolution of 0.25° (~25 km). For the purpose of this study, the regional data covering southern Africa [15–33°E; 21–35°S] was extracted.

**CHIRPS**

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a rainfall dataset in the domain [50°N - 50°S; 180°W – 180°E]. CHIRPS data has a spatial resolution of 0.05° (~5 km) and spans from 1981 to near present (Funk, et al., 2015). As with TRMM data, CHIRPS was also extracted over southern African region.

**Verification Methods**

**Bias**

The forecast bias is calculated in order to determine whether the model has a wet (positive) or a dry (negative) bias. Bias is a measure of forecast accuracy and it is computed following equation 1 below. The perfect forecast would have a bias of 0.

\[
Bias = \frac{1}{N} \sum_{i=1}^{N} (Fi - Oi)
\] (1)

Here \(N\) represents the total number of forecasts issued for the period considered and \(Fi\) and \(Oi\) represent forecast and observed values respectively.

**Root mean square error (RMSE)**

RMSE (eq.2) is typically used to measure the accuracy of the forecast. On each grid point the RMSE value is computed by taking the difference between values predicted by the model and the values observed, then added and average the forecast-observation pair to produce the Mean Square Error. The square root of this is taken to produce the RMSE. The more accurate the forecast, the closer to zero the RMSE values should be.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Fi - Oi)^2}{n}}
\] (2)

In eq.2, \(O\) is the forecast value and \(O\) is the corresponding observed value and \(n\) is the number of forecast-observation pairs.

**3. Results**

Fig. 1 shows a bias in predicted 24-hr accumulated rainfall based on TRMM and CHIRPS data. The bias spatial map indicates location of areas with positive and negative bias represented by green and blue shades respectively. These maps show somewhat different bias pattern. CCAM compared with TRMM seem to have a wet bias over the central interior of South Africa and low lying areas along the south and east coasts. A dry bias is seen over most parts in the peripheral region of South Africa. Bias analysis based on CHIRPS data shows a generally wet bias over the whole country except over some parts in the north-eastern region of South Africa where a dry bias is detected. Important qualitative correspondences between the different calculated biases are the large positive biases the model display over the Lesotho escarpment, and the negative biases detected over the northern Drakensberg of Mpumalanga and Limpopo.
Figure 1: Spatial distributions of bias of 24-hr rainfall simulated by CCAM compared to TRMM (top) and CHIRPS (bottom) data for DJF seasons of 2013/2014; 2014/2015 and 2015/2016.

The RMSE score maps shown in Fig. 2 depict different results. The CHIRPS-based RMSE values range between 0 and 7 mm/d over the country excluding the region surrounding the Drakensberg escarpment where RMSE scores range from 10 to 20 mm/d. The TRMM analysis on the other hand show these large RMSE (i.e. 10-20 mm/d) values to be widely spread across the eastern part of South Africa.

Figure 2: Spatial distributions of root-mean squared error of 24-hr rainfall forecasts compared to TRMM (top) and CHIRPS (bottom) data for DJF seasons of 2013/2014; 2014/2015 and 2015/2016.

In order to measure the quality of CCAM forest system, an anomaly correlation coefficient between forecasts and observations were computed and the results are presented in Fig. 3 where darker shades of blue and green indicate areas of strong correlation. Considering the Highveld region, where there is high frequency of heavy rainfall bearing systems typically during the December to February period; TRMM-based analysis indicate a relatively weak relationship whereas a stronger relationship is seen between forecast and CHIRPS data set.
Figure 3: Spatial distributions anomaly correlation coefficients between 24-hr rainfall forecasts and TRMM (top) and CHIRPS (bottom) observed data for DJF seasons of 2013/2014; 2014/2015 and 2015/2016.

4. Conclusion

The 24-hr rainfall forecasts for the summer (Dec-Feb) seasons of 2013/2014; 2014/2015 and 2015/2016 were verified against TRMM and CHIRPS datasets. The verification techniques applied measured accuracy and skill of forecasts. Overall, the results obtained from TRMM-based and CHIRPS-based analysis are somewhat different. This implies that the degree of perceived forecast quality is highly sensitive to the type of gridded data chosen to represent the observed atmospheric state.

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References


The evolution of wave activity in the cut-off low system and the tropical temperate trough system

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Abstract
Cut-off lows and tropical temperate troughs are both baroclinically unstable systems which bring about rainfall. This paper studies how the wave activity evolution differs between these two weather systems. Geostrophic wind basic states and perturbations, heat perturbations and the Coriolis parameters were used at different latitudes and longitudes to calculate the wave activity evolution components. Contour and quiver functions display the differences between the two systems using three dimensional wave activity flux diagnostics. The results show that the evolution of wave activity associated with the investigated tropical temperate trough and cut off low differ. One of the differences is that the cut off low appears to evolve slower than the tropical temperate trough.

Keywords: cut-off lows, tropical temperate troughs, wave activity evolution, three dimensional wave activity flux diagnostics

Introduction
A cut-off low (COL) is a closed upper-level low which has been cut off from its basic westerly current and moves independently of that current. This type of system moves slowly and therefore could stay stationary for a few days. COLs are baroclinically unstable systems that may also be associated with synoptic scale Rossby wave breaking events (Ndarana and Waugh, 2010) and with the equatorward flux of wave activity (Elser and Haynes, 1999). An example of this system over South Africa occurred on the 22nd of July 2015.

In baroclinically unstable weather systems, such as COLs, warm air rises east of the trough axis, whilst cold air sinks west of the axis. At the same time, heat is transported poleward and cold temperatures are adVeXed towards the equator (Holton and Hakim, 2014). This process facilitates meridional heat fluxes by the small meridional wind perturbations. In a baroclinically unstable atmosphere, where the meridional temperature gradient (or vertical shear in the zonal flow) is nonzero, the meridional heat fluxes are responsible for converting mean available potential energy to eddy available potential energy, whilst the vertical circulation in the system facilitates the conversion from the latter to eddy kinetic energy (Holton and Hakim, 2014; Schneider, 1996). The transformation of potential energy to kinetic energy causes the weather systems to grow (Schneider, 1960). This describes the evolution of weather systems, which can also be interpreted from a wave activity flux view point (Thorncroft et al. 1993).

A tropical temperate trough (TTT) is a system that is associated with an upper air westerly wave in the temperate latitudes and a high pressure system, for example over the Zimbabwean region. The systems transport high energy tropical air into the South African region along the periphery of the high pressure system thereby causing the well-known long cloud bands that can stretch from Botswana to the midlatitudes. TTTs are mostly responsible for summer rainfall (Ratna et al. 2012). These systems transport energy and momentum toward the poles (Todd and Washington, 1999). These fluxes are an important factor for the formation of precipitation (Tyson and Preston-Whyte, 2000). An example of a TTT occurred on the 27th of January 2009. Similarly to COLs, TTT are baroclinic systems because baroclinic waves are necessary (but not sufficient) for them to develop (Macron et al. 2014). This suggests that the evolution of TTTs can also be analysed by making use of wave activity flux diagnostics.

Wave activity is a conserved quantity in the atmosphere that complies with the conservation law, namely,

$$\frac{\partial A}{\partial t} + \nabla \cdot \mathbf{W} = 0 \, ,$$

(1)

where \(A\) and \(\mathbf{W}\) are the wave activity density and flux, respectively (Takaya and Nakamura, 2001; Danielson et al. 2006). Wave activity flux can be used to study baroclinic wave life cycles of a TTT and a COL because of this conservation property. This approach to understanding baroclinic life cycles has long been established (Thorncroft et al. 1993), but the two dimensional Eliassen-Plam flux was used. In this paper, the three dimensional wave activity diagnostics
(e.g. Danielson et al. 2006) will be used to study the COL and TTT referred to above.

The hypothesis is that the life cycle characteristics of the COL and the TTT differ, with the wave activity associated with the COL taking longer to dissipate than that associated with a TTT. This is based on the fact that the former last longer than the latter.

Data and methodology

National Centre for Environmental Prediction (NCEP)/National Centre for Atmospheric research (NCAR) reanalysis data (Kalnay et al. 1996) was used to calculate the components wave activity flux vector for the two case studies mentioned in the introduction section.

To calculate the basic state flow variables, a central day (day 0) during the evolution of any of the two systems was defined as the day on which the negative geopotential anomalies first appeared (see Figs. 1 and 2). Then a 31 day mean, centred on day zero was calculated. The perturbations were the deviations from the basic state.

\[
W_z = \bar{U}_g(v^2_g - \phi \frac{1}{a \cos \phi} \frac{\partial v_g}{\partial \lambda}) +
\]

\[
\bar{V}_g(u_g + \phi \frac{1}{a \cos \phi} \frac{\partial u_g}{\partial \lambda})
\]

\[
W_x = \bar{V}_g(v^2_g - \phi \frac{1}{a \cos \phi} \frac{\partial v_g}{\partial \lambda}) +
\]

\[
\bar{U}_g(u_g + \phi \frac{1}{a \cos \phi} \frac{\partial u_g}{\partial \lambda})
\]

\[
W_y = \frac{f}{d \theta/d p} (\bar{U}_g v_g - \bar{V}_g \phi \frac{1}{a \cos \phi} \frac{\partial \theta_1}{f})
\]

where the overbars represent basic state variables (the mean state) and the small letters (without the overbar) representing the perturbations. To calculate the derivatives in the definition of the geostrophic wind as well as those that appear in the wave activity flux diagnostics, a second order finite differencing method was used. \(\bar{U}_g, \bar{V}_g, v_g, u_g, \phi, \lambda\) and \(d \theta_1/d p\) are basic state of the horizontal component, the perturbation of the horizontal, basic state of the vertical component, perturbation for the vertical component for the geostrophic winds, latitude, longitude and reference state respectively.

Based on established life cycle studies (e.g. Thorncroft et al. 1993), the vertical component of the wave activity flux vector applies the early stages of the development of baroclinic waves, where the meridional heat fluxes dominate at the lower levels in the mid-latitudes. For wave activity to propagate vertically upwards, this component should be positive. The zonal and meridional components, combined, apply at the later stages of development. At these later stages, the wave activity fluxes are characterised by momentum fluxes.

For analysis, the three components for the wave activity flux vector are plotted for every level and every day. These plots are then analysed to see the similarities and differences between the two systems’ wave activity evolution.

Results and discussions

Figs 3 and 4 show the strongest wave activity flux in the vertical direction (i.e. Wz) on the 17th of January 2009 and on the 29th of June 2015 for the TTT and COL, respectively. The strongest wave activity flux is determined by the most positive value calculated within the 31 day period, for which the basic state was calculated. This component was plotted for 850 hPa because meridional heat fluxes are more dominant close to the surface (Holton and Hakim, 2014). The regions marked with black boxes in the figures show the region of interest (South Africa and the oceans and bordering countries), for ease of comparison.
Conclusions

The evolution of wave activity associated with the investigated TTT and COL differ. One of the differences is that the COL appears to evolve slower than the TTT. The evolution of wave activity of the COL it takes 8 days whilst that of the TTT takes 5 days from day 0. This means that the COL takes longer to dissipate compared to the TTT. However, the COL has a stronger horizontal wave activity flux at 200 hPa. This is consistent with the fact that COLs may be associated with Rossby wave breaking events (Ndarana and Waugh, 2010). From the above result, it is concluded that the hypothesis stated is supported. This research demonstrates that the three dimensional wave activity flux diagnostics can be used to track the life cycle of these two systems.

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Evaluation of SAWS multi-model system in predicting DJF rainfall frequency over southern Africa

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Abstract

South African Weather Service (SAWS) multi-model system is evaluated in predicting the December to February (DJF) seasons rainfall frequency forecasts over Southern Africa. The skill of the forecasting system in predicting rainfall days exceeding 10mm is also assessed. Observations show that dry (wet) conditions during DJF seasons are associated with low (high) rainfall frequency over southern Africa. Using canonical correlation analysis as statistical downscaling tool the forecast skill levels of the model is determined through retro-actively generated hindcasts. ROC scores is used a measure of skill and it shows here that the forecasting system is skillful in predicting the rainfall frequency. The multi-model rainfall frequency forecasts for recent DJF seasons correspond very well with observations, indicating the usefulness of this forecast system.

Keywords: Retro-active validation, Forecast skill, ROC scores, Multi-model forecasts.

Introduction

Southern Africa is a region of significant rainfall variability on a range of temporal and spatial scales and is prone to extreme droughts and floods events (Usman & Reason, 2004). Examples include, the devastating floods in northeast South Africa and southern Mozambique during February/March 2000 and severe droughts of 1991/92, 2002/03 and 2003/04 over northern South Africa and surrounding areas (Cook et al., 2004). Most of African countries depend significantly on rain fed agriculture, which is highly vulnerable to the amount and distribution of rainfall (Kijazi & Reason, 2005). According to Usman and Reason (2004) the occurrence of extreme dry (wet) conditions over southern Africa during the austral summer have been associated with high dry spell frequency (wet spell frequency). Climate studies demonstrated that seasonal rainfall totals are predictable over South Africa (e.g. Landman et al. 2012). Recently, Phakula et al. (2017) found that both coupled ocean-atmosphere and atmospheric global climate models (GCMs) have skill in predicting rainfall frequency within summer rainfall seasons over South Africa. This study is a follow-up to Phakula et al. (2017) and its purpose is to evaluate the SAWS operational multi-model system (MMS) in predicting rainfall days exceeding 10mm within December to February (DJF) seasons over Southern Africa. This threshold is of interest because is a significant amount and predictable over the region (e.g. Phakula et al., 2017).

Data and Methodology

Observed high resolution (0.1°X0.1”) gridded daily rainfall dataset of African Rainfall Climatology version 2 (ARCv2) are used to calculate number of rainfall days exceeding 10mm threshold within DJF summer rainy seasons over Southern Africa from 1983/84 to 2016/17. The predicted large-scale 850hPa geopotential heights (1 -month lead) for DJF seasons, which are taken from the hindcasts and forecasts of the SAWS MMS are also used. The MMS is a result of averaging the hindcasts of the SAWS Coupled Model (SCM; Beraki et al., 2014), the ECHAM4.5 (Roeckner et al., 1996; Beraki et al., 2015) and the NCEP Climate Forecast System (CFS; Saha et al., 2014) global climate models (GCMs). Using open source Climate Predictability Tool (CPT)
developed at the International Research Institute for Climate and Society (IRI) (http://iri.columbia.edu/climate/tools/cpt) the 850hPa heights hindcast outputs of the SAWS MM are first statistically recalibrated and downscaled to number of rainfall days exceeding 10mm within DJF seasons over South Africa by using model output statistics (MOS). The 850hPa geopotential heights are used here since they are found to be the best predictor of summer rainfall over southern Africa (e.g. Landman et al., 2012). Forecast skill levels are evaluated using retroactively generated hindcasts through canonical correlation analysis (CCA). Retroactive forecast validation is found to be a robust method to assess forecast model performance and give unbiased skill levels (Landman et al., 2001). The model forecast skill levels is assessed using relative operating characteristics (ROC). A high ROC score (>0.5) indicates the models’ ability to discriminate event from non-events.

Results and Discussion

Firstly, an eyeball verification is performed for the observed rainfall days exceeding 10mm for the previous DJF rainy seasons, namely, 2014/15, 2015/16 and 2016/17, respectively and are compared with DJF climatology of rainfall days exceeding 10mm from 1983/84 to 2016/17. Figure 1 show that during 2014/15 and 2015/16 seasons most of southern Africa dominated by low number of rainfall days, except the northern part of Mozambique during 2014/15. The low frequency of rainfall days corresponds very well with extremely below-normal rainfall conditions experienced, particularly during 2015/16, which resulted in what is regarded as the most severe drought in recent decades. During 2016/17 DJF season high rainfall frequency were observed and associated with above-normal rainfall and flooding in some areas. This result agree with findings in Phakula et al. (2017), that dry (wet) seasons are mostly associated with low (high) rainfall frequency during DJF seasons.

Secondly, before evaluating the forecasts, the predictability of the MMS is tested using ROC scores. Figure 2 indicate that the 850hPa geopotential heights hindcast outputs of the SAWS MMS have skill (ROC scores > 0.5) in predicting low and high rainfall frequency (rainfall days > 10mm) within DJF seasons over southern Africa. The forecast skill is high and well distributed to the east of sub-continent with highest scores up to 0.9 over Limpopo province of South Africa.

Lastly, forecasts produced by the SAWS MMS are compared with the observed. The forecasting system predicted low number of rainfall days exceeding 10mm over most parts of southern Africa during 2014/15 and 2015/16 DJF seasons, while the 2016/17 season was dominated by high rainfall frequency (Figure 3). This forecasts correspond well with the observed (cf. Figure 1). It must be noted that these forecasts are in agreement with DJF seasonal rainfall totals produced by the same system (not shown).
Observations show that the droughts of 2014/15 and 2015/16 over southern Africa were associated with low number of rainfall days exceeding 10mm within DJF, while above-normal rainfall conditions during 2016/17 season was dominated by high rainfall frequency. It is shown that the SAWS MMS have skill in predicting number rainfall days exceeding 10mm within DJF summer seasons over southern Africa. It is demonstrated that rainfall frequency forecasts for 2014/15, 2015/16 and 2016/17 DJF seasons correspond well with the observed. Therefore, it can be concluded that the SAWS MMS is capable of predicting rainfall frequency within DJF seasons.

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Seasonal vertical variation in SO$_2$ over South Africa as observed by the Ozone Monitoring Instrument (OMI)

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Abstract

This study investigated the seasonal variation of Sulphur dioxide (SO$_2$) at different height levels over South Africa from 2004-2013 through the analysis of data recorded by the Ozone Monitoring Instrument (OMI). Results indicate that most of the SO$_2$ was confined to the Planetary Boundary Layer (PBL) layer with relatively high SO$_2$ plumes observed near industrial regions in Mpumalanga irrespective of all the vertical columns. Besides this, the spatial maps confirmed that, there was not much seasonal variation in their ranges as PBL had ~2 Dobson Unit (DU), followed by Lower Tropospheric Layer (TRL) (0.5 to 0.75 DU), whereas the Middle Tropospheric Layer (TRM) and Upper Tropospheric and Stratospheric Layer (STL) had smaller amounts of SO$_2$ (nearly 0.4 DU). The seasonal variations illustrated that winter was characterized by the most dispersed SO$_2$ plumes. This was in direct contrast to summer, which had the most confined plumes. In spring, relatively small amounts of SO$_2$ were seen in TRL, TRM and STL over the southern parts of the country. PBL and STL showed negligible SO$_2$ concentrations in all seasons over the regions except those falling inside the industrial Highveld.

Keywords: SO$_2$, OMI, height levels, spatial maps and seasonal variation

Introduction

Sulphur dioxide (SO$_2$) is considered a critical pollutant because of its numerous detrimental effects on human health. It is released into the atmosphere through both anthropogenic (fossil fuel combustion, smelting) and natural emissions (volcanic activity). In a study on global SO$_2$ emissions (2000-2011), it has been calculated that there has been a significant decrease in SO$_2$ emissions in the United States (~6000 Gg) and European Union (~3700 Gg) between 2005 and 2010. However, China made a substantial contribution of 30% to global SO$_2$ emissions in 2010. In India, SO$_2$ emissions are increasing rapidly due to lack of strict emission reduction strategies (Klimont et al., 2013). Emissions of SO$_2$ average ~1550 kt per year over South Africa (2005-2011) has been estimated by satellite based Ozone Monitoring Instrument (OMI), despite there was no appreciable increase in the percentage of SO$_2$ emissions over this time period (Fioletov et al., 2016). Global SO$_2$ maps of OMI (Theys et al., 2015), Global Ozone Monitoring Experiment-2 (GOME-2) (Hörmann et al., 2013) and Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) (Richter et al., 2006) have located SO$_2$ hot spot regions in South Africa among other countries like China, Bulgaria.

The behaviour of SO$_2$ differs in the troposphere (it is reactive with a short residence time of a few days) compared to the stratosphere (residence time of approx a month). The main aim of this study is therefore to investigate the seasonal variations of SO$_2$ over South Africa (2004 to 2013) for different altitude levels namely, Planetary Boundary Layer (PBL - centred at 0.9 km), Lower Tropospheric Layer (TRL - centred at 2.5 km), Middle Tropospheric Layer (TRM - centred at 7.5 km), Upper Tropospheric and Stratospheric Layer (STL - centred at 17 km).

Satellite data

The satellite data used in this study are products from OMI which is located on board NASA’s Earth Observing System’s (EOS) Aura satellite. OMI was launched on 15 July 2004 from Vandenberg Air Force base in California (Levett et al., 2006). This study uses the daily level 2 OMI SO$_2$ data product version 003 (2004 to 2013) and was downloaded from the National Aeronautics and Space Administration (NASA) Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml). OMI has a high spatial resolution of ~13 x 24 km$^2$ in comparison to any other satellite data. OMI measurements are based on a Principal Component Analysis (PCA) algorithm such that the SO$_2$ retrieval quality is substantially improved (OMS02 README File 2008). Data are filtered when the radiative cloud fraction is greater than 0.2 and the solar zenith angle exceeds 50° (OMI data User’s Guide).

Results and Discussion

As described previously, 10 years of recorded OMI data were used to investigate seasonal variations of SO$_2$. The seasonal measurements were separated
and corresponding mean values were calculated. The spatial mapping of SO2 vertical columns over South Africa for each season and for different vertical levels (PBL, TRL, TRM and STL) are plotted in Figures 1, 2, 3 & 4. The results are as follows:

**PBL:** Figure 1 shows SO2 concentration in the PBL layer for different seasons. It is apparent from the figure that a distinctive pattern of high SO2 levels was located over the central hub of Mpumalanga and its neighbouring regions. By comparison, remote parts of South Africa recorded negligible amounts of SO2. In spring, SO2 levels equivalent to 2 DU and slightly dispersed around the location of power stations and the Highveld region were observed. A small amount of 1-1.5 DU near northern KwaZulu-Natal (KZN) and the adjacent Indian Ocean was seen. A similar seasonality was observed in summer. However, the PBL were more localized around the Highveld region in the vicinity of electrical power plants in Mpumalanga province and the major portion of Gauteng covering the Johannesburg, Pretoria megacities, Sasolburg and part of the Vaal Triangle region. More specifically, the movement of air masses towards the north west was visible in summer. This could be due to the effect of easterly waves that occur ~55% of the time exclusively in summer (Tyson et al., 1996a; Tyson et al., 1996b). Autumn and winter followed a similar pattern where the SO2 air masses ranged from 1.5-2 DU and were more dispersed in Mpumalanga and Gauteng provinces compared to summer and spring. Furthermore, the movement of air masses from north west to south east towards the Indian ocean was clearly apparent in Figure 1 for all the seasons. This could be due to direct transport from the Highveld region towards the central Indian Ocean as observed by Freiman and Piketh (2003). In their study, they specified the transport pathways from the Highveld only in the lower troposphere at 800-700 hpa. However, in the present study, movement was seen exclusively in the PBL column, which might be due to the low SO2 levels in the TRL. Winter had the largest number of scattered plumes. This might be due to the existence of prominent anticyclonic conditions in this period. Subtropical anticyclones (which are the predominant phenomenon in winter with 70% occurrence in mid-winter) along with the transient ridging anticyclones, contribute 80% of anti-cyclonic circulation in June and July (Tyson 1996b). The occurrence of low SO2 levels in the outskirts of the Mpumalanga region could be the resultant of ageing of plume masses as they move out from the source region.

**TRL, TRM & STL:** Seasonal variations of TRL, TRM and STL are shown in Figures 2, 3 and 4. A similar trend was observed to that seen in PBL. The major difference was that overall SO2 levels were lower namely, the industrialised Highveld region recorded 0.75-0.5 DU, 0.3-0.5 DU and 0.3 DU for TRL, TRM and STL respectively. The three layers had an identical pattern in spring, where parts of eastern, western and northern cape had slightly higher SO2 values (TRL 0.4 DU, TRM 0.2-0.3 DU, STL 0.2 DU). In winter, the SO2 levels in these three layers showed a scattered and different mixed trend similar to PBL. Both TRL and TRM showed minimum SO2 concentrations in remote areas in all seasons. However, the STL layer resembled PBL in that respect where the outlying regions from the industrial hub recorded negligible SO2 values irrespective of season. It was seen that TRM in the vicinity of the Highveld region showed slightly higher SO2 values in summer. This was consistent with a study by Höpfner et al. (2015) based on Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) measurements. He observed a high mixing ratio of SO2 in summer over northern (mid to high latitudes) and southern (mid latitudes) at an altitude ~10 km and negligible global SO2 variations at an altitude ~18 km irrespective of all seasons, except over Antarctica in austral winter.

The seasonal spatial maps of SO2 data revealed some major findings: Firstly, very low seasonal variation was seen in the vicinity of the highly industrialised region. Here SO2 levels were 1.5 DU at the PBL in almost all the seasons in this area. Lee et al. (2011) showed similar results in their study on global SO2 emissions in 2006 using OMI and SCIAMACHY data. They found that there was not much appreciable seasonal variation over high SO2 point source regions in the world. Secondly, the results of this study showed that the transport of SO2 plumes from neighbouring South African regions and the recirculation of air over the industrial plateau occurred in all seasons and at all the altitude regions (but more clearly seen in the PBL maps due to high SO2 columns) except summer. This observation was in accordance with the results studied by Freiman and Piketh (2003), in their seasonal variation of transport pathways to the Highveld region, where these two types of transport occur in combination ~ 35% in winter, spring and autumn, except in summer where they were less than ~ 12% at lower troposphere. Finally, the spatial distribution of SO2 exhibited differently in winter at all altitudes, where the climatology of the wind clearly plays a vital role. This needs to be
investigated further in detail and will be the subject of future work.

Acknowledgements
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Reference


Figure 1. Seasonal variation of SO$_2$ for PBL over South Africa

Figure 2. Same as Figure-1, but for TRL

Figure 3. Same as Figure-1, but for TRM

Figure 4. Same as Figure-1, but for STL
Study on NO$_2$ and aerosol interactions over the Republic of South Africa using Space-borne observation

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Abstract

Five year climatology of NO$_2$ Vertical Column Density was carried out in South Africa using the Ozone Monitoring Instrument (OMI). The highest values of NO$_2$ are observed in the months of July, August or September while the lowest values were observed in January and December. The highest NO$_2$ column density was observed in late winter and spring. The major reasons for the high rate in these seasons were found to be: (1) the high presence of O$_3$ which increases the conversion rate of NO$_x$ to NO$_2$; and (2) biomass burning that begins in late winter. The major source of NO$_2$ is in the north eastern parts of RSA (Mpumalanga) due to industrial activities that occur in that region. NO$_2$ observed in Cape Town was as a result of transport of NO$_2$ from the Mpumalanga Highveld.

Keywords: NO$_2$, OMI, CALIPSO, Extinction coefficient

Introduction

Tropospheric nitrogen oxides (NO$_x$) are important pollutants affecting ozone, acid deposition, and climate (Lin et al, 2015; Chimot et al, 2016). There are several reasons why we need to improve our knowledge of NO$_x$: (1) nitrogen oxides are the precursors of (ammonium) nitrate, an important component of particulate matter, and contribute to acidification and eutrophication of soils and surface waters; and (2) exposure to nitrogen dioxide leads to adverse health impacts (Chimot et al, 2016).

NO$_2$ studies have been carried out in the Republic of South Africa (RSA) using a variety of techniques. Lourens et al (2012) used the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) data for 2003-2009. They observed that NO$_2$ concentration was mainly at the Highveld. They also reported that megacities (i.e. Johannesburg and Pretoria) showed maximum atmospheric NO$_2$ levels during peak traffic periods in the early morning and late afternoon. Vertical column densities (VCDs) of tropospheric nitrogen dioxide (NO$_2$) retrieved from the Ozone Monitoring Instrument (OMI) in the Republic of South Africa (RSA) has been reported by Sundström et al (2015). Although the study was not entirely focused on using OMI, the instrument was used to show the distribution and density of NO$_2$ in RSA for a 4-year period from January 2007 to December 2010.

Most of the NO$_2$ work that has been reported has mainly focused on the use of ground based instruments in the Highveld of South Africa. In this paper we use satellite data to study NO$_2$ country wide. The aim of this paper is to study: (1) the climatology of NO$_2$ over RSA from January 2011 to December 2015 using OMI and (2) the seasonal variation of NO$_2$ from January 2014 to December 2014 using OMI.

Data and Method

A map of the Republic of South Africa is shown in Fig. 1. The map further shows the towns (Bethal, Pretoria and Cape Town) were OMI measurements were carried out. Bethal and Pretoria are located in the Highveld of RSA.

Figure 1: A map of the Republic of South Africa showing the towns were measurements were carried out.
Several coal-fired power stations and industrialised sites are located in this region. Cape Town is in coastal area of RSA with dominance in marine aerosols.

The Ozone Monitoring Instrument (OMI) is the result of a partnership between NASA and the Dutch and Finnish meteorological institutes and space agencies. OMI flies onboard the NASA EOS-Aura satellite (Krotkov et al, 2016) and can distinguish between aerosol types (such as smoke, dust, and sulphates) and measure cloud pressure and coverage, which provide data from which tropospheric ozone levels may be derived. The retrieval technique of the OMI tropospheric NO$_2$ Vertical Column Density (VCD) is common to all the other similar satellite missions. The backscattered solar radiation is captured in daylight in the visible spectral domain by the instrument at the Top Of the Atmosphere (TOA) and then processed through the Differential Optical Absorption Spectroscopy (DOAS) retrieval approach. The DOAS method is based on radiative transfer modelling of tropospheric NO$_2$ Air Mass Factor (Chimot et al, 2016). For this work the Aura OMI NO$_2$ Data Product-OMNO2 (Version-3) was downloaded from the web-based application developed by the Goddard Earth Sciences Data and Information Services Center (GES DISC), Giovanni (Geospatial Interactive Online Visualization ANdaNalysis) (https://giovanni.sci.gsfc.nasa.gov/giovanni/).

Results and Discussion

Five year NO$_2$ Vertical Column Density climatology of RSA is shown in Fig. 2. The red dots show the mean monthly value of NO$_2$ Vertical Column Density of RSA for 2011-2015. The highest values of NO$_2$ are observed in the months of July, August or September (winter and spring) while the lowest values of NO$_2$ are observed either in January or December (summer). The highest NO$_2$ column density was observed at a value of $\sim 1.2 \times 10^{15}$ cm$^{-2}$ in September 2014 while the lowest value was observed at a value $\sim 0.6 \times 10^{15}$ cm$^{-2}$ in December 2015. The reasons and sources for this are explained as part of Figure 3 since they occur seasonally.

A further analysis of this data reveals overall that RSA has the highest NO$_2$ column density ($\sim 10 \times 10^{14}$ cm$^{-2}$) in the winter season and the lowest NO$_2$ column density ($\sim 7 \times 10^{14}$ cm$^{-2}$) in the summer season (see Fig. 3).

Nitric oxide (NO) oxidizes in the atmosphere to NO$_2$. The conversion rate depends on the ambient concentrations of NO and ground-level ozone (O$_3$). If O$_3$ is present, the conversion is very rapid. Laban et al (2015) showed that the maximum mean surface O$_3$ concentration over Southern Africa occurs in late winter and spring (August to October) but this does not apply to the whole country. Some regions have less concentrations of O$_3$ during these seasons. But since O$_3$ is dominant throughout the country in these seasons, this explains the high concentration of NO$_2$ in winter and spring. Lourens et al (2011) also showed that sites with high NO$_2$ concentrations exhibited the lowest O$_3$ levels, while higher O$_3$ concentration coincided with lower SO$_2$ and NO$_2$ levels. Moreover, the contribution from biomass burning in spring could also add to the concentration of NO$_2$. 

The seasonal vertical column density of NO$_2$ retrieved for the year 2014 is shown in Figure 4. This result further confirms
that NO$_2$ concentration is higher in the late winter and spring season. Figure 4 also shows that NO$_2$ concentration is more prone in the north eastern parts of RSA. This has been shown by several researchers in the past, Laakso et al (2012) and Josipovic et al, (2010). These authors have shown that in winter the Highveld in RSA has a high concentration of NO$_2$ resulting from various factors such as: (1) stable atmospheric conditions and (2) biomass burning which begins in August. Maenhaut et al. (2002) also identified biomass burning as the major contributor during dry season campaign of the SAFARI 2000. The lack of NO$_2$ being detected in the interior of the country suggests that NO$_2$ could be so minimal that OMI cannot measure it. Therefore ground based instruments would be better placed to carry out measurements in those areas. Traces of NO$_2$ were observed in the south western parts of RSA i.e. Cape Town. NO$_2$ is observed in the spring, summer and autumn season while winter has minimal NO$_2$ concentrations. This NO$_2$ concentration is referred to as “brown haze” which is formed as a result of sunlight acting on petrol driven vehicle emissions (Popkiss, 1992). Although the contribution of NO$_2$ from vehicle emission is true, recent studies have shown that transport of NO$_2$ from Mpumalanga has major contributions. Studies by Abiodun et al (2014) using the regional climate model (RegCM) showed that at the low level (surface–850 hPa) the easterly and north easterly flows transport the Mpumalanga Highveld’s pollutants westward toward Cape Town, and during the extreme events, the north easterly flow transports NO$_x$ directly from the Mpumalanga Highveld to Cape Town. NO$_2$ has a short lifetime ranging from hours near the surface and 1 to 2 weeks in upper troposphere. At the surface vehicle emissions will be dominate since NO$_2$ has a short lifetime. However, in the upper troposphere transport will be dominant.

From Figure 4(c) three towns (see Fig. 1) were chosen in autumn and their NO$_2$ concentration were compared, see Fig. 5. Bethal shows the highest NO$_2$ concentration (~1.3x10$^{16}$ cm$^{-2}$) followed by Pretoria with a concentration of (~0.6x10$^{16}$ cm$^{-2}$). Cape Town has the least concentration of (~0.3x10$^{16}$ cm$^{-2}$). Bethal has the highest concentration of NO$_2$ because it is close to the surroundings of power stations which are the main sources of NO$_2$ production. NO$_2$ is then transported to various areas. Although Pretoria and Cape Town might have sources of NO$_2$ the major contribution to the overall concentration might be due to transport. The long distance transport of NO$_2$ could results in less concentrations being detected.

![Figure 4: Seasonal vertical column density of NO$_2$ from January 2014 to December 2014 retrieved from OMI. (a) Spring, (b) summer, (c) autumn and (d) winter.](image)

![Figure 5: Averaged autumn 2014 NO$_2$ Vertical Column Density in Pretoria, Bethal and Pretoria.](image)
Conclusions

The highest NO\textsubscript{2} column density was observed in late winter and spring. The major reasons for the high rate in these seasons are: (1) the high presence of O\textsubscript{3} which increases the conversion rate of NO\textsubscript{x} to NO\textsubscript{2} and (2) biomass burning that begins in late winter. The major source of NO\textsubscript{2} is in the north eastern parts of RSA. This is due to industrial activities that take place there. NO\textsubscript{2} observed in Cape Town was as a result of transport of NO\textsubscript{2} from Mpumalanga.

References

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Analysis of Meteorological Variables Influencing Photovoltaic Energy Output over Upington

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Abstract

Variation in maximum (T\text{max}) and minimum (T\text{min}) temperature, average temperature (T\text{Avg}) relative humidity (RH), cloud cover (CC) and wind speed (WS) have been studied over Upington using in situ data (1950s to 2016). The aim of this study was to analyse meteorological variables influencing photovoltaic energy output over Upington. T\text{max}, T\text{min}, and CC have shown similar behavior (maximum in summer and minimum in winter). RH has shown different variation (minimum in summer and maximum in winter). The climatological mean of T\text{max}, T\text{min}, CC, RH, and WS suggested that Upington is a good site for solar energy projects. However, increasing trend of temperature due to an increase in atmospheric concentration of carbon dioxide (CO\textsubscript{2}) is a matter of concern as it affects the performance of photovoltaic cells.

Keywords: Temperature, Relative humidity, Cloud cover, Wind speed, Photovoltaic energy output

1. Introduction

An increase in the atmospheric concentration of carbon dioxide (CO\textsubscript{2}) and other greenhouse gases since pre-industrial times have increased global temperatures, Hartman \textit{et al.} (2013), and are predicted to cause further warming shortly, Stocker \textit{et al.} (2013). Our warming planet earth is facing many challenges (like floods, drought, heat waves and decreasing biodiversity) due to the global warming. With the change in climate, the livelihood of people is at stake. Many climate mitigation plans are discussed across the world, and the use of renewable energy came up as a very effective way to decrease the carbon footprint. The South African government aims to cut greenhouse gases emissions by 42% by 2025 by implementing a range of climate change mitigation strategies, including the renewable energy of which solar and wind resources are highly dependent on climate, Herbst and Rautenbach (2015). In South Africa a lot of research is being done to increase the understanding of the use of solar energy from Photovoltaics (PV) like Singh \textit{et al.} (2017) and Pan and Dinter (2017). Properly designed PV system can decrease the carbon footprint. Energy production on an annual scale from the PV system is the main basis for designing PV system. Annual energy output depends upon so many meteorological factors like incoming solar radiation, temperature and relative humidity. Considerable investment is required in solar projects, so it is advisable to understand the prevailing meteorological condition over any prospective site. In previous literature, the importance of solar radiation for PV output has been discussed e.g. Singh \textit{et al.} (2017). The main focus of the present work is to study the variation of temperature, relative humidity, cloud cover and WS using observational data over Upington.

2. Data and Methodology

Upington is located on the banks of the Orange River in the Northern Cape Province of South Africa, (Fig. 1). The Northern Cape is drier (arid climate) than the rest of South Africa (Singh and Kruger, 2017).

![Figure 1. Google earth image of study area Upington (shown in yellow circle) Source: http://www.earth.google.com, Imagery date-December 14, 2015.](image-url)
According to Singh (2016), out of nine provinces, the Northern Cape Province has the highest incoming solar radiation. The South African Weather Service (SAWS) Automated Weather Station (AWS) data for Upington has been used in the present study. Datasets include daily maximum ($T_{max}$) and minimum ($T_{min}$) temperature (1952-2016), daily RH (1952-2016), CC (1958-2016) and WS (1953-2016) for three times a day 8 AM, 2 PM, and 8 PM were also used.

The above selected years were those where data availability was more than 90%. Daily observation of $T$, RH and CC has been used for calculating the monthly averages. Variation of WS has been observed after taking the daily mean for the available data period. Monthly averages were used for studying monthly variation and trends.

3. Results and Discussion

3.1 Variation in $T_{max}$, $T_{min}$, RH, WS and CC

Fig. 2 illustrates monthly variations of average $T_{max}$, $T_{min}$, RH and CC over Upington. It can be seen that Upington has high temperatures during austral summer months (December to February). In January the highest mean $T_{max}$ (35.85°C) and $T_{min}$ (19.95°C) were observed. In June, the lowest $T_{max}$ was (21.05°C) and in July, the lowest $T_{min}$ was (3.99°C) were observed in Upington for the period (1952-2016). Meanwhile the RH in June was at its highest peak (47.12%).

![Figure 2](image-url)

**Figure 2.** Monthly Variation of $T_{max}$ (°C), $T_{min}$ (°C), $T_{Avg}$ (°C), RH (%) and CC (%) over Upington.

With the increase in temperature, evaporation increases that cause the decrease in RH. Over Upington also, when temperature was highest during summer, RH was lower, Fig. 2. Monthly variation of $T_{max}$ (°C), $T_{min}$ (°C), $T_{Avg}$ (°C), RH (%) and CC (%) over Upington The average CC was also highest in summer (February, 34.2°C). Monthly variation of CC for the period 1958-2016 matched with $T_{max}$ and $T_{min}$. Over Upington, $T_{Avg}$, never crossed 28°C, RH was also less than 50%, and CC was below 35% most of the time. Lesser value of $T_{Avg}$, RH and CC make this station a good site for solar power projects. The efficiency of solar panels depends on $T_{Avg}$. In each case the efficiency of solar panel decreases as the temperature increases. RH was also less than 47%, which is also quite good for PV installation as degradation rate of PV modules decreases with an increase in RH.

![Figure 3](image-url)

**Figure 3.** Monthly variation of CC (%) and RH (%) over Upington (8 AM, 2PM, 8PM, Avg-Average of all three times)

Fig. 3 (a) and 3 (b) is a monthly variation of CC and RH over Upington at 8 AM, 2 PM, 8 PM and an average of all. Observation of RH and CC at three times (8 AM, 2 PM and 8 PM) have also shown monthly variation. The RH in Upington is highest in the morning (8 AM), at this time, air is closer to saturation. Again at night, RH is relatively high because at night temperatures drop. At 2 PM, RH is at its lowest because of rising temperature in afternoon. Relative humidity values were highest at 8 AM and lowest at 2 PM. This could be due to the average humidity was highest for 8 AM in all the months. The rate of evaporation increases with an increase in temperature. In Upington, the rate of evaporation from waterbodies, land and vegetation increases in the afternoon (high temperature and low RH), and the reverse is true during morning and night times. RH variation is also associated with rising/convergence (higher RH) and sinking/divergence (lower RH) of air.
The average cloud cover was always less than 3 oktas, Fig. 4 (a), for all months. Values of CC at 2 PM was higher than values at 8 AM and 8 PM. After sunrise, convective activity starts and in the afternoon more convection occurs as a result of high temperatures are experienced at the surface. At all times, CC was higher in summer and lower in winter (Fig. 3). Likewise the mean WS values are also higher for 2 PM than both 8 AM and 8 PM, Fig 4(a). Except for RH (RH is divided by 10 for the sake of comparison with WS and CC), the mean values for CC and WS reach maximum at 2 PM, Fig 4(b). Mean WS never crossed 6 m s\(^{-1}\) at 2 PM, and it rarely crosses 4 at 8 AM, and 8 PM. Mean WS for Upington is low, this lowers the possibility of the problem associated with the soiling of solar panels.

**Figure 4.** Variation of daily mean WS (ms\(^{-1}\)) (a, left) and bar graph for average of daily means of WS, RH, and CC (%) (b, right) over Upington (8 AM, 2 PM, 8 PM, Avg-Average of all three times)

### 3.2 Trend in Temperature Average, Relative Humidity and Cloud Cover

Time-series of \(T_{\text{Avg}}\), RH and CC over Upington is shown in Fig. 5. It is clear from the figure that over the years Upington has experienced substantial inter-annual variations in \(T_{\text{Avg}}\), RH and CC. Long term linear trend shows that \(T_{\text{Avg}}\) is increasing at the rate of 0.02\(^\circ\)C/\(\text{yr}\). This warming trend is significant and is evident that the climate is changing and that the planet is getting warmer and warmer. However, CC and RH have shown the declining trend with approx. 0.01% per year, Fig. 5. Over South Africa, the decline in CC has been reported previously (Kruger, 2007).

The increase in temperature is not good for a location like Upington due to its arid climatic condition. On the other hand, decreasing trend in CC and RH is good for incoming solar radiation and evaporation, respectively. High incoming solar radiation is good for electricity production from the solar panels. However, incoming solar radiation is not only dependent on cloud cover. Other factors like aerosols also play a very important role. Evaporation increases in lower relative humidity. Evaporative cooling helps in reducing the overheating of solar panels due to high temperature. The efficiency of solar panels is affected by the overheating of panels (Akbarzadeh and Wadowski, 1996).

**Figure 5.** Trends of \(T_{\text{Avg}}\) (\(^\circ\)C), RH (%) and CC (%) over Upington (m=slope)

### 4. Conclusions

The present work deals with the analysis of SAWS in situ observations of \(T_{\text{max}}, T_{\text{min}}, \text{RH}, \text{CC}\) and WS over Upington from 1950s to 2016. The mean monthly variation of temperature and CC have shown higher values in summer months and lower values in winter months. However, RH has shown opposite behaviour with maxima in winter and minima in summer. Observation of RH, CC and WS at three times (8 AM, 2 PM and 8 PM) have shown diurnal variation. RH was maximum at 8 AM and minimum at 8 PM. CC and WS values were higher in the afternoon. The significant findings from this study are that climate in Upington has evolved through the years. The change in climate is due to increase in average temperatures because of the greenhouse gas build up in the atmosphere since pre industrial times. The decrease in relative humidity is good for the evaporative cooling process. However, there is a need to study aerosols and other atmospheric constituents to understand the availability of solar radiation at the surface. In Upington, higher temperatures in the afternoon cause lower RH while lower temperatures in the morning
cause high RH. CC is at its highest in the afternoon because of the convection which occurs due to warm temperatures. The average temperature never crossed 28°C, RH was also less than 47%, and CC was below 2.7o/1as most of the time. Mean WS for this site never crossed 6 ms\(^{-1}\). Lesser values of \(T_{avg}\), RH, CC and WS make this site suitable for solar energy projects, although it needs further research. It can be concluded that the decrease in cloud cover through the years might be good for incoming solar radiation.

5. Acknowledgments

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6. References


Understanding the Variation in Meteorological Parameters over Cape Point for Renewable Energy Applications

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Abstract

The main objective of this study is to analyse the longer time series of meteorological parameters, maximum (Tmax) and minimum (Tmin), average temperature (Tavg), relative humidity (RH), wind speed (WS) and direction (WD) and carbon dioxide (CO2) for Cape Point. Total solar radiation (TSR) for Cape Town was also analysed. These parameters were analysed to see their inter and intra annual variation. Monthly variation of Tmax, Tmin, Tavg and RH at the following times (8 AM, 2 PM and 8 PM) were analysed. Frequency distribution analysis of WD and WS were also analysed. From the results Tavg and CO2 trends were increasing while RH trend was decreasing. Monthly variation of RH revealed an increase at 8 AM and 8 PM in summer and spring and a decrease in winter and autumn while 2 PM showed an increase during winter and a decrease in summer. Frequency distribution analysis of WD revealed a prevailing southerly WD while WS frequency was maximum speed between 8 and 9.5 ms⁻¹. Based on the high WS and RH this location is not very suitable for solar energy project. However, present study also stresses on the need of further detailed analysis of meteorological and topographical parameters for wind as well as solar energy applications.

Keywords-Temperature, Relative humidity, Wind speed, Wind direction

1. Introduction

The greenhouse effect is making our planet liveable by increasing its temperature to ~33 °C (with an existing average temperature of 15 °C, Ma (1998). According to Papakostas et.al (2014) and Frank (2015), global temperature is increasing with an increase in time (years) and it is one of the indicators of global warming. There is an increased intensity of heat waves, disease occurrence and also malnutrition because of drought and floods. The increase in temperature also increases the energy demand; most common example is the increased usage of Air Conditioners. Greenhouse gases such as CO₂ and methane are responsible for global warming. Fossil fuel burning in power plants is mainly responsible for carbon emissions. To minimise these carbon emissions, use of renewables is often recommended. In recent years across the world use of renewable energy has increased, Shahiduzzaman and Layton (2017); Singh et al. (2017), to combat the effect of increasing temperature. The use of PV (photovoltaic) is very popular among other solar energy applications. The main variable of PV power generation is incoming solar radiation. It determines the amount of power generation from the solar panels. Along with solar radiation, there are some other meteorological factors which are also responsible for deciding the efficiency of power generation, panel lifecycles like humidity and temperature. Based on the study conducted by Singh (2016), out of nine provinces the ranking of Western Cape is 7 (annual), 5 (seasonal), 7 (monthly). The main criterion for this ranking is surface incident shortwave flux. The analysis of other factors like temperature, RH, and WS and WD would give more insight about the local meteorological conditions prevailing over the test site for solar PV plants installation. In this work, Cape Point station of Western Cape has been selected to study the variation of T, RH, WS, WD and CO₂.

1. Study Area and Datasets

The study area for the present work is Cape Point (-34°S, 18°E) Western Cape, South Africa as shown in Fig.1.

Figure 1. Google earth image of study area Cape Point (shown in yellow circle) in South Africa (a), enlarged view of study area (A- SAWS’s sites for historical total solar radiation, B- site for AWS and CO2 observations) (b). Source: http://www.earth.google.com, Imagery date-December 14, 2015.
Cape Point is located just few kilometres from both Atlantic and Indian Ocean. \(\text{CO}_2\) is measured at the Cape Point Global Atmospheric Watch (GAW) station (established in 1977), Brunke et al. (1990). South African Weather Service (SAWS) Automated Weather Station (AWS) data for Cape Point has been used in the present study.

Meteorological variables used in the present study are \(T_{\text{max}}\) and \(T_{\text{min}}\) (1918-2016), RH (1978-2016), WS and WD are available for three times a day 8 AM, 2 PM and 8 PM. WS and WD data available for 8 AM (1940-2016), 2 PM (1949-2016) and 8 PM (1960-2016). Total solar radiation (TSR) data (12:00 hrs.) from Cape town (approximately 50km from Cape Point station) (1957-1994) were also considered for the trend analysis.

3. Methodology

For calculating the monthly and annual average of \(T_{\text{max}}\), \(T_{\text{min}}\), RH, TSR and \(\text{CO}_2\) only those years where the percentage (\%) of data availability was more than 90% were selected for analysis. Monthly averages of \(T_{\text{max}}\), \(T_{\text{min}}\), RH, TSR and \(\text{CO}_2\) have been calculated using daily data. Trends of RH, average temperature (\(T_{\text{Avg}}\)), TSR and \(\text{CO}_2\) were also studied. Frequency distribution of WS and WD have been plotted over the available time period.

4. Results and Discussion

Whenever there is any energy assessment, either selection of proper site for PV installation or checking the energy performance of PV modules, the most fundamental step is to look into the existing meteorological condition to have a better understanding of weather variables. Monthly variations and past trends are important analysis methods

4.1 Monthly Variation of \(T_{\text{max}}\), \(T_{\text{min}}\), \(T_{\text{Avg}}\) and RH

The monthly average of daily \(T_{\text{max}}\), \(T_{\text{min}}\) and \(T_{\text{Avg}}\) shows that values of temperatures were highest in February (summer month), 21.7°C (\(T_{\text{max}}\)), 15.9 °C (\(T_{\text{min}}\)), and 18.8 °C (\(T_{\text{Avg}}\)), Fig. 2(a). As expected the lowest values for temperature were observed during winter 10.5°C, July and August (\(T_{\text{Avg}}\) 13.1°C). Here the range of temperature difference is not very high (<6°C) as it is a coastal station. Temperature difference range between \(T_{\text{max}}\) and \(T_{\text{min}}\) is generally less over coastal station compared to continental station. Monthly average of daily RH dataset at 8 AM, 2 PM and 8 PM for Cape Point were calculated and plotted as shown in Fig. 1(b). RH is low during the day at 2 PM in summer and peaks in winter (August 71.7 %) while in the morning, 8 AM and at night, 8 PM it follows an opposite trend it is higher in summer and lower in winter. Overall RH values were high in the morning (8 AM) followed by night (8 PM) and least in the afternoon (2 PM). RH changes with the change in temperature. In afternoon hours air temperature increases. Warm air can hold more moisture and decreases RH the afternoon (2 PM). RH changes with the change in temperature. In afternoon hours air temperature increases. Warm air can hold more moisture and decreases RH.

![Monthy Variation of Tmax (°C), Tmin (°C), T_avg (°C) and RH (%) over Cape Point.](image)

4.2 Histograms of WS and WD

The histograms of WS and WD are shown in Figs 3(a) and 3(b). They were plotted using long term daily average data for three observational time 8 AM, 2 PM and 8 PM (1960-2016). Histograms of WS and WD indicates that it is unimodal. WS is slightly skewed and the most dominant WS frequency is between 9 -9.5 ms\(^{-1}\) followed by 8.5 - 9 ms\(^{-1}\). The prevailing wind direction is between (170 to 180 degrees) that is in between few degrees from the south and the south direction Fig. 3(b). This is followed closely by wind blowing just a few degrees before SSW with a frequency of 95. We can conclude that the most dominant WD is between SSE and SSW, with S prevailing. High speed wind will bring moisture to this area.

![Histograms of WS and WD over Cape Point.](image)
4.3 Trends in $T_{\text{Avg}}$, CO$_2$, RH and TSR

Humidity is one of the factors that influences climate of any place. Global scale theoretical and modelling studies predict that with the increase in temperature, RH will remain constant (Approx.), Held and Soden (2000); Sherwood and Meyer (2006). The increase in temperature is one of the indicators of global warming Papakostas et al. (2014); Frank (2015). Increase in temperature has been reported in many studies across the world like Almazroui et al. (2012) for Saudi Arabia, and Brunetti et al. (2000) for Italy. The results of $T_{\text{avg}}$ for Cape point (1918 to 2016) were plotted in Fig 4. There is a slight linear increase in $T_{\text{avg}}$ trend as shown in the Fig 4 (a) represented by a gradient of 0.011$^\circ$C y$^{-1}$. For Cape Point also $T_{\text{avg}}$ trend agrees with the above mentioned previous study. Trend in CO$_2$ data set (1996-2015) for Cape Point is shown in Fig 4(d). The gradient for this linear trendline is 1.95 ppm y$^{-1}$. This is in agreement to a study by Gurjar et al. (2011) that there is an increase in CO$_2$ emissions from the consumption of fossil fuels as a result economic development of a country. Cape Point station is considered as a pristine site. However, increasing trend in CO$_2$ indicated that the location is also under the influence of carbon emissions. So it is clear that CO$_2$ is increasing with each year and it’s also one of the important factors that drives climate change. Annual average for TSR data (12 noon) for Cape Town over the years has shown declining trend with gradient 0.12 Wm$^{-2}$y$^{-1}$.

5. Conclusions

In the present work in situ observation of meteorological variables- $T_{\text{max}}$, $T_{\text{min}}$, RH, WS, WD and greenhouse gas- CO$_2$ for the Cape Point were analysed. The mean monthly $T_{\text{max}}$ was always (<21.7$^\circ$C), which is good for any PV solar projects, however high RH (>70%) is not good for solar panels. Increasing trend in CO$_2$ (1996-2015) has explained the increasing trend in $T_{\text{avg}}$ (1918-2016) over this station. RH is also decreasing at the rate of 0.11% y$^{-1}$ (1978-2016), however in all the years RH is still higher than 75%. TSR data for 12 noon (1957-1994) for Cape Town has shown declining trend (-0.12 Wm$^{-2}$ y$^{-1}$). There is a need to understand other factors like topographical features before we suggest
anything for this site. Here WS and RH is high, which are not good for solar panels as high WS is responsible for soiling and high RH is responsible for the degradation of solar panels. Decline in TSR and RH have been also observed from the results. Occurrence of high WS is good for Wind Energy applications. However, there is a need of extensive study over this location to understand its potential for renewable energy applications (wind and solar).

6. Acknowledgments

The authors acknowledge South African Weather Service, Pretoria for support during the entire work.

7. References


Mountain waves observed in the lee of the Tsitsikamma Mountains
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Abstract
At the time of a fatal aircraft crash, mountain waves were observed with three features: they appeared to the north of the main Tsitsikamma Mountains ridge, contained interference patterns and were partially generated by terrain features upwind from the main ridge.

In this study, similar features were identified for an additional twenty events in order to determine which geographical features of the Tsitsikamma Mountains may influence the shape of the mountain waves. These events originated in the low-level westerly to south westerly flow of passing cold fronts, upper air cut-off lows and ridging high pressures. Three geographical regions were identified where interference regularly occurred, either from converging or crossing waves.

Formosa, the highest mountain peak, generated two distinct lee wave shapes.

Keywords: Interference, Converging, Crossing, Formosa

Introduction
Mountain lee wave development requires an upwind wind direction within 30° of perpendicular to a mountain ridge, with a summit wind speed of at least 7ms⁻¹ (Barry, 1981). Lindsay (1962) added a further requirement - a decrease in the Scorer Parameter with increased height. In South Africa, mountain waves typically form in the presence of stable prefrontal north westerly winds over the Atlantic coastline or by westerly to north westerly Föhn-type airflow over the interior of South Africa (van der Mescht and Ellof, 2013).

On 16 December 2015, a Cessna 182Q crashed in the Kareedouw Mountains, approximately 20km east of the adjacent Tsitsikamma Mountains. On this occasion, mountain waves had not formed in Föhn-type flow, but rather in the presence of westerly to southwesterly winds, equatorward from a nearby passing cold front.

Ellrod (1986) mentions that small scale mountain waves are best viewed using high-resolution visible channel imagery. In the case of 16 December, mountain wave details were not clearly observable in the IR channels. By using Eumetsat Visible channel satellite imagery around the time of the crash, three main features were identified. These are indicated in Figure 1. Firstly, it was observed that mountain waves were formed to the north of the coastal mountains, propagating north eastwards. The angle indicates that the direction of the wave propagation on this occasion was 61° east of the typical propagation direction observed for waves parallel to the main ridge. Secondly, complex wave patterns were observed in the lee of the mountains. Both Uhlenbrock et al. (2006) and Feltz et al. (2008) found that complex shape lee waves were associated with more severe turbulence, as reported by aviators, while linear patterns parallel to mountain ridges were associated with milder turbulence. Lastly, it was observed that smaller ridges, upwind and perpendicular to the west-east orientated main ridge of the Tsitsikamma Mountains, appeared to generate wave features. Witelskop and Storms River peak are indicated by 1 and 2 in Figure 1, respectively. Lee waves have formed east of both peaks. The crash site is marked by a star. The dotted line shows two points along the planned route, between points A and T. The Peak indicated by 3, is Formosa, the highest point in the Tsitsikamma Mountains. Some mountain waves were also generated by terrain in the adjacent Outeniqua Mountains and are observed west of Formosa. Using the method of Fritz (1964), the wavelength of lee waves were determined to be approximately 8km.

The three mountain wave features observed, formed the basis for identifying twenty similar westerly to southwesterly wind events over the period 2008 to 2016. These events were classified according to the weather systems which generated the low-level flow. The presence of waves implies that the wind speed, wind direction and stability parameters according to Barry (1981) and Lindsay (1962) were met. This study aims to highlight the shape and geographical position of mountain waves observed on visible channel satellite imagery in dominant westerly to south westerly flow.
By using surface data from the Port Elizabeth airport, all the westerly to south westerly wind events were identified along the Cape South Coast for the period 2008-2016. The 1km resolution visible channel satellite imagery on the NEODAAS/University of Dundee satellite database for these dates were checked to see whether mountain waves were visible to the north of the Tsitsikamma Mountains. The satellite database is restricted to six-hourly images during the first few years of the period. For later dates, the frequency improved to three-hourly images and eventually hourly images from 2015. A set of 72 mountain waves were identified. From these events, 21 events, including 16 December 2015, were identified having evidence of interference as well as wave features to the south of the main Tsitsikamma ridge.

Prominent mountain peaks and ridges were identified upwind from mountain waves. In Figure 2 (a), the Tsitsikamma Mountains are shown at 500m height intervals above mean sea level. The numbers 1, 2 and 3 represent the positions of Witelskop, Storms River Peak and Formosa, respectively. The Adjacent Outeniqua Mountains, to the west of the Tsitsikamma Range, are shown in Figure 2 (c). The Karatara ridge is marked with the number 4.

It was assumed that the presence visible mountain waves implied that all necessary wind speed, wind direction and stability data criteria for mountain wave development were met. This study only focused on the observed mountain wave position and shape.

The 16 events were classes according to the prominent synoptic scale features which generated the west or south westerly winds. Satellite imagery, together with NCEP-DOE reanalysis data was used to identify cold fronts, upper air cut-off lows and ridging surface high pressures as the tree synoptic scale features associated with the events.

Results and Discussion

In Table 1, the events are classified according to weather systems. The eight cold fronts which lead to mountain wave formation included primary cold fronts which pass near the coast, as well as secondary cold fronts which formed in the cold air behind primary fronts, similar to Conover (1964); which mentions the observations of mountain waves equatorward of a cyclone in 1962 TIROS imagery.

Two cut-off lows were found to have generated winds which created the desired mountain waves. One system was located to the southwest and one to the southeast of the Tsitsikamma area. There were eleven ridging surface high pressures observed which generated favourable low-level flow for mountain wave development. In a few cases, post-frontal cold air cumulus clouds were observed very close to the Tsitsikamma coast.

When considering the possible influence of terrain on the shape and position of mountain waves, it was observed that an area in the Outeniqua Mountains frequently generated complex downstream waves. The terrain in question is a prominent ridge near the settlement of Karatara. Two peaks along this ridge have elevations in excess of 1400m. Table 1 lists sixteen cases where interference is observed downwind of Karatara. The interference frequently manifested itself as waves generated by the Karatara ridge converged with waves downwind from Formosa; distorting the linear patterns in the lee of the mountains.
Table 1: Summary of mountain wave events. W and F refer to Witelskop and Formosa, respectively. CF, COL and H refer to the synoptic weather systems: cold front, cut-off low and ridging high, respectively.

<table>
<thead>
<tr>
<th>DATE</th>
<th>WX</th>
<th>INTERFERENCE</th>
<th>Crossing</th>
<th>Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/12/16</td>
<td>CF</td>
<td>Y Y Y Y</td>
<td>E of W</td>
<td></td>
</tr>
<tr>
<td>2016/05/03</td>
<td>CF</td>
<td>Y Y W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014/07/12</td>
<td>CF</td>
<td>Y Y Y</td>
<td>Y F</td>
<td></td>
</tr>
<tr>
<td>2014/10/19</td>
<td>CF</td>
<td>Y Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014/02/21</td>
<td>CF</td>
<td>Y Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014/03/19</td>
<td>CF</td>
<td>Y Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009/09/19</td>
<td>CF</td>
<td>Y Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008/07/11</td>
<td>COL</td>
<td>Y Y Y Y Y Y</td>
<td>F W</td>
<td></td>
</tr>
<tr>
<td>2008/08/23</td>
<td>COL</td>
<td>Y Y Y Y Y Y</td>
<td>F W</td>
<td></td>
</tr>
<tr>
<td>2012/02/11</td>
<td>COL</td>
<td>Y Y Y Y Y Y</td>
<td>E of...</td>
<td></td>
</tr>
<tr>
<td>2010/09/16</td>
<td>H</td>
<td>Y Y Y Y Y Y</td>
<td>E of...</td>
<td></td>
</tr>
<tr>
<td>2011/05/31</td>
<td>H</td>
<td>Y Y</td>
<td>E of...</td>
<td></td>
</tr>
<tr>
<td>2008/08/23</td>
<td>H</td>
<td>Y Y</td>
<td>E of...</td>
<td></td>
</tr>
</tbody>
</table>

Interference is most frequently viewed to the north of Formosa – in fact, in all but two cases. The shape of waves in the lee of Formosa generally follow the contours of the ridges around the mountain. Formosa forms part of two ridges, highlighted in Figure 3. The longer ridge in Figure 3(b) includes a part of the main ridge of the range, indicated by M. The summit wind directions could be determined from the wind direction through lee waves, using Conover (1964) and Feltz et al. (2008). The majority of events showed a primary wave resembling the shape of the N-S oriented ridge in Figure 3(a). Along this ridge, the summit wind direction varied between 207° and 250°. Six events had a primary wave resembling the shape of the longer ridge in Figure 3(b). The average wind direction at ridge height varied between 189° and 234°. In these cases, the summit winds were more perpendicular to the main ridge section (M) of the longer ridge.

There were five events during which lee waves travelled in different directions and altitudes; indicative of severe turbulence (Feltz et al., 2008). Their positions are listed in Table 1 under the column, marked ‘crossing’. In 80% of these cases, the phenomenon occurred in the lee of Formosa. The crossing of low-level waves was observed to the northeast and to the south of the main ridge. In two cases the phenomenon of crossing waves was also observed to the east of Witelskop. Thus, both these isolated peaks generated this phenomenon.

There were three cases where a clear slot was observed between wave trains to the northeast of Witelskop. These cases are shown in Table 1 under the heading ‘gaps’. Feltz et al. (2008) noted that these areas of suppressed mountain wave formation occur in the lee of isolated peaks where a drop in wind speed occurs downwind of the peak as air flows around the peak, rather than over the top. The same phenomenon was not observed in the lee of Formosa. Hence the break in mountain waves in the lee of Witelskop may have a different origin than the case with wind speed wakes.

Conclusions

All the mountain wave shapes observed in this study displayed evidence of interference to the north of the Tsitsikamma Mountains. In addition to, interference patterns being associated with a higher level of turbulence (Uhlenbrock et al. (2006) and Feltz et al., 2008), the fatal crash on 16 December 2015 serves as evidence of severe turbulence due to loss of control over the aircraft. Interference patterns were most frequently viewed downwind from Formosa and the Karatara ridge. On occasion, waves from these mountain features would converge to the north of the Tsitsikamma Mountains. Formosa appeared to produce two distinct lee wave shapes; depending on the summit wind direction. The crossing of mountain waves at different altitudes was observed downwind from two isolated peaks (Formosa and Witelskop).

In January 2017 a study of mountain waves and gap flow in the lee of Witelskop was started, using surface weather stations and balloon soundings. A similar study is planned for research into the turbulence downwind of the Karatara and Formosa areas, with the aim to obtain data during the convergence of interference patterns generated by these two mountain features.

Due to the incomplete set of satellite data, this study was unable to identify all mountain wave events resulting from westerly to south westerly flow. It was also not possible to determine the duration of
the events with accuracy. The latter problem should be solved by the current and future studies.

References


Empirical Mode Decomposition (EMD) is a data adaptive method, which is best suited to analyse nonlinear and non-stationary data. The original data is decomposed into several intrinsic mode functions(IMFS) which represent different time scales.

A 31-years of monthly rainfall data is measured at Cape Point weather station is decomposed into 10 IMFs and residual. The residual shows a general pattern of the expected rainfall variations over the site. The inter-annual variability (2-8 years) is identified which is known to be primarily influenced by El-Niño Southern Oscillation (ENSO). The Southern Oscillation Index (SOI), which is one of the indices used to measure the strength of ENSO, is further used to find the correlation with rainfall.

We found a high correlation between IMFs from SOI and rainfall, which evidences the influence of ENSO on the rainfall pattern through the EMD method. The identified IMFs are orthogonal to each other and their sum approximates the original data, which shows that it is a lossless decomposition and there is less amount of information leakage. Based on the results obtained, the EMD method is found to be suitable to identify different oscillations in the rainfall data.

Keywords: Rainfall, EMD, ENSO, Time series analysis
period from the 1980 to 2011. The Southern Oscillation Index (SOI) represents fluctuations in sea level pressure between Tahiti and Darwin, Australia. It is one of the key atmospheric indices used to gauge the strength of El Niño. The data for SOI is publicly available on National Center for Environmental Information (NCEI) (https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/).

2.2 Empirical Mode Decomposition
Empirical Mode Decomposition (EMD) is an adaptive time-frequency data analysis method, which requires only that the data must consist of simple intrinsic mode of oscillations (Huang et al., 1998). It is most suitable for nonlinear and non-stationary data. The EMD methodology is based on a sifting process, which identifies local extrema (maxima and minima) which results in the formation of intrinsic mode functions (IMFs). The first IMF will contain the highest fluctuations and this is subtracted from the original data and subsequent IMFs are then derived from the subtracted data. The IMFs and residual data approximate the original data when they are summed together (Huang et al., 1998). The rainfall time series is decomposed into local orthogonal modes. A given series \( x(t) \) is decomposed into IMFs, \( c_i(t) \), and residual \( r(t) \) so that the original data is approximated by the sum of IMFs and residual.

\[
x(t) \approx \sum_{i=1}^{n} c_i(t) + r(t) \tag{2.1}
\]

The IMFs and residual were added together to reconstruct the original data. Root Mean Square (RMSE) was used to evaluate the original data and reconstructed decomposed data.

The IMFs must be mutually orthogonal to each other. Higher orthogonality corresponds to less amount of information leakage. Index of orthogonality (IO) is used which is given by

\[
IO = \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{i=1}^{n} c_i^2(t) \right) \cdot \frac{c_i(t) \cdot c_j(t)}{c_i^2(t) + c_j^2(t)} \tag{2.2}
\]

where \( i \) and \( j \) represents the \( i^{th} \) and \( j^{th} \) IMFs.

Orthogonality between two IMFs is given by

\[
IO_{ij} = \frac{1}{T} \sum_{t=1}^{T} \frac{c_i(t) \cdot c_j(t)}{c_i^2(t) + c_j^2(t)} \tag{2.3}
\]

The orthogonality between two IMFs must be less than 0.100 for it to be acceptable (Molla et al., 2005).

3. Results and Discussion
The average monthly rainfall at CapePoint was standardized for easy computation and comparison. The data was decomposed until when there is at most one maximum and one minimum in the residual. From the standardized rainfall data 10 IMFs were found and 8 for SOI. The decomposed rainfall and SOI showed a higher correlation in some of the IMFs as shown in figure 3.1. It is noted that IMF 4 (rainfall) against IMF 3 (SOI) is having positive correlation of 0.285 and -0.193 against IMF 4 (SOI). IMF 3 is annual oscillation whilst IMF 4 has average cycle of about 18.2 months.

Figure 3.2 shows the general pattern and oscillation of IMF 4 for rainfall and SOI. Seven-year oscillation represented by IMF 6 and 7 (rainfall) also have significant correlations with IMF 6 and 7 from SOI.

The rainfall data for May, June and July period was decomposed into 7 IMFs and residual. On figure 3.2 Annual oscillation (IMF 1), quai-biannual oscillation (IMF 2) and ENSO like oscillation (IMF 6) are identified in the rainfall. The probability density function for each IMF is approximately normally distributed. The IMFs and residual are added together to reconstruct the data. The reconstructed data approximates the original data with Root
The correlation coefficients of the SOI and Cape Point Monthly Rainfall and their corresponding IMF-like components for a 12 month period. IMF 0 here represents original signal.

Figure 3.2 Rainfall IMFs for May, June and July at Cape Point station.

Mean Square Error of order $10^{-14}$. This clearly shows that EMD is lossless decomposition with minimal data being lost in the decomposition and managing to capture most of the oscillations in the data.

The overall index of orthogonality (IO) for decomposed rainfall is $0.594 \times 10^{-4}$ and SOI $0.154 \times 10^{-4}$. It is noted that the maximum value of orthogonality between the IMFs is found to be $\approx 0.001$ and it is way below the acceptable value of less than 0.1. It confirms that there is less amount of information leakage.

4. Conclusions

The effectiveness of EMD to analyse nonlinear and
non-stationary data was demonstrated. The rainfall data was decomposed into IMFs and residual data, which summed up to the original data. EMD was effective in isolating the data into different timescales and therefore the variability of the rainfall pattern was identified, in the end evidence of the effect of ENSO was provided. This is consistent with what was found by Phillippon et al. (2012)

References


