Impact of lower stratospheric dynamics on the predictability of summer rainfall over South Africa

By

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Declaration

I, Kelebogile Ruth Mathole declare that the dissertation, which I hereby submit for the MSc degree in Meteorology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: ………………………….. DATE: ………………………………….

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Abstract

Seasonal climate prediction of rainfall and temperature in South Africa (SA) during summer is mainly related to the variability of El Niño Southern Oscillation (ENSO) besides other forcings from local surrounding oceans. However, the predictive skill is low whenever ENSO is dormant; therefore rainfall and temperature forecast become uncertain over the region. The study then aims to investigate the possible importance of proper representation of stratospheric processes in climate prediction models. These stratospheric processes include mainly ozone and green-house gases. A comparison of trends in lower stratospheric temperatures and summer zonal wind fields in 27 years of the National Centre for Environmental Prediction (NCEP) of the Department of Energy (DOE) Reanalysis II data and output from hindcast simulations using an ocean-atmosphere general circulation model (OAGCM) is conducted. Lower stratospheric ozone in the OAGCM is relaxed towards the observed climatology and increasing greenhouse gas concentrations are neglected. In reanalysis lower stratospheric ozone fields are better represented than in the OAGCM. The lower stratospheric/upper tropospheric cooling in the polar cap during spring (shown by previous studies as a result of lower ozone depletion) appears in reanalysis but not in the OAGCM. The corresponding summer tropospheric response also differs between datasets. Moreover, in reanalysis a statistically significant poleward trend of the summer jet position is found. However, contrary to this, no such trend is found in OAGCM. Furthermore, the dynamics of the stratosphere is analyzed using wave activity. The lack of wave activity in the model as opposed to observations further suggests that the dynamical coupling which is essential for proper simulation of the stratosphere is compromised. Lastly, the statistical forecasting system using winds and temperature during spring when the stratosphere is actively coupled also suggest potential predictability of summer rainfall over South Africa, particularly wet conditions when the tropospheric eddy-driven jet is shifted towards the poles.

Preface

The stratosphere together with the troposphere in the past decade, have undergone significant alterations which contributed towards the current state of the climate. Scientific studies suggest that both natural and anthropogenic forcings are the main cause for these alterations. However, the stratosphere in particular, has been shown to be one of the main driving forces of the recent observed changes in the southern hemisphere circulation with the likes of the discovery of ozone changes two decades ago making it an exception. For this reason, interest in the research of the impact of these changing atmospheric layers (particularly the stratosphere) on climate has grown. The research is mainly steered by the need to understand the current atmospheric climate state as well as its relevant driving forces in order to predict its future state. Therefore **chapter 1** gives the research background regarding how the stratosphere interacts with tropospheric circulation on both longer (climate-change) and shorter (seasonal-annual) timescales. The relevance of different oceanic regions for summer rainfall over South Africa is also discussed with main emphasis given to ENSO as well as its limitations.

Chapter 2 describes all the datasets used as well the methodology followed in order to perform different analyses.

Chapter 3 gives attention to exploring the role of the stratosphere together with its processes for the benefit of South African climate predictions. Even though there has been extensive research on the impact of the stratosphere on climate circulations and predictability globally, it is also worth noting that no such study has been done in South Africa. Therefore the study investigates the relevance of stratospheric processes and their representation in seasonal climate models through the use of a South African Weather Service coupled ocean-atmosphere model. The model has recently been configured for operational seasonal forecast production. However, the stratospheric ozone field in this coupled model is relaxed towards observed climatology and the anthropogenic forcing is also neglected. It is learnt that this shortfall compromises the ability of the model to simulate some of the observed climate trends such as the well-known spring stratospheric cooling as well as the summer mid-latitudes tropospheric jet trends which occurred in the southern hemisphere. This result therefore leads to a hypothesis (which will be tested here) that the model that incorrectly simulates the jet position variability and climatology thereof will likely be unable to simulate summer rainfall variability correctly.

Furthermore, issues of the dynamics of the model's stratosphere are also at play and are being analyzed in **chapter 4**. The dynamics are to some extent a proxy for coupling between the stratosphere and the troposphere which manifests as a result of planetary wave forcing. In fact, the inter-annual variability of the stratosphere has been subjected to wave forcing rather than long-term changes of ozone. Therefore the inter-annual variability of the stratosphere requires proper wave forcing in order to enable coupling with the troposphere. Even though the dynamical mechanism that facilitates this coupling is still a research question, the study shows that wave forcing is also an essential element for coupling as well as proper simulation of the stratosphere by the model. The result shown by the model's wave forcing suggests inconsistencies with regards to wave-mean interaction theory in general. Meanwhile this is the case, it can be hypothesized that wave forcing is one of the main drivers for mechanisms that explain the model's shortcomings. To also extend and connect issues of the dynamics of the stratosphere to the surface, the study analyzes various model's capability of simulating the Southern Annular Mode as it's the leading mode of variability in the extra-tropical southern hemisphere climate.

The study in **chapter 5** also looks at whether stratospheric information can be useful in predicting summer rainfall over South Africa. Proxy variables of the stratosphere such as wind and temperature fields are used to demonstrate this possibility which involves a simple statistical model using canonical correlation analysis. In this particular case, NCEP-Reanalysis dataset are assumed to have at least a realistic stratosphere even though the datasets comprises other contributions which might not be associated with the stratosphere circulation itself. Even though there could also be some outstanding issues, it is also learnt that stratospheric fields (winds and temperature) may be potential predictors for summer rainfall over South Africa.

Lastly, **chapter 6** is mainly dedicated for summary, recommendations and conclusions.

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CONTENTS

List of tables

Lists of Figures

Lists of abbreviations

AC&C	Atmospheric Chemistry and Climate
AGCM	Atmospheric model general circulation models
AN	Above-normal
BN	Below-normal
CCM	Chemistry Climate models
CCMVal	Chemistry Climate Model Validation
CLIVAR	Climate Variability and Predictability
CERM	Community Earth System Model
DJF	December-January-February
DOE	Department of Energy
DynVar	Dynamics and Variability of the Stratosphere-Troposphere System
ENSO	El Niño Southern Oscillation
ESM	Earth System Model
GCM	Global Circulation Model
GHG	Green-House-Gases
JJA	June-July-August
MOS	Model Output Statistics
MPMD	Multiple Program Multiple Data
NCEP	National Centre for Environmental Prediction
OAGCM	Ocean-Atmosphere General Circulation Model
PSC	Polar Stratospheric Clouds
PV	Potential Vorticity
ROC	Relative Operating Characteristic

SA	South Africa
SAM	Southern Annular Mode
SAWS	South African Weather Service
SH	Southern hemisphere
SON	September-October-November
SPARC	Stratospheric Processes And their Role in Climate
SST	Sea-Surface Temperature
SSW	Sudden Stratospheric Warming
STE	Stratospheric-Tropospheric Exchange
WCRP	World Climate Research Programme

CHAPTER ONE

1.1 BACKGROUND

1.1.1 Lower Stratospheric Circulation during Winter/Spring

Southern hemisphere (SH) stratospheric circulation during austral winter is mostly characterized by strong westerly winds and very low temperatures that form over the high latitudes (Holton, 2004).

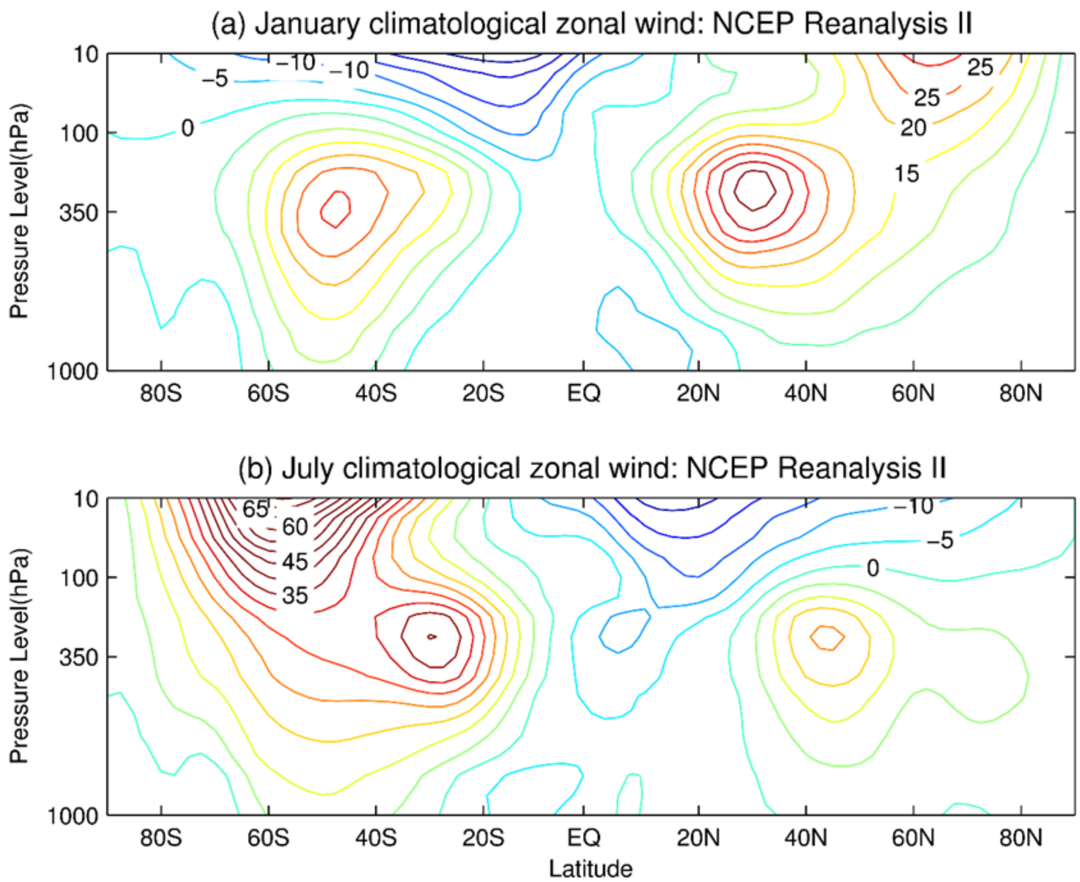

Figure 1.1: The climatological zonal wind structures during a). Mid-summer January and mid-winter b). July of the NCEP-Reanalysis II

The SH polar stratosphere in particular, gets much colder and stronger (wind circulation) than the northern one owing to their different wave-induced hemispheres. The cold stratosphere is largely due to the offset of sunlight heating over the poles during the winter-time which then result in very low temperatures. As a result, strong pole-to-equator temperature gradients form and thus lead to a strong westerly circulation (Waugh and Polvani, 2010) which dominates at least the winter stratosphere (see Fig. 1.1). For example, there seems to be less wave generation (which disturbs the stratosphere) in the SH because of absence of topographical features, such as mountains etc... as compared to the northern hemisphere (Haynes, 2005), and thus resulting in a more defined structure. Notwithstanding, this circulation could also persists into spring months and finally cease due to the onset of summer in the polar stratosphere. The circulation described above is what basically defines the stratosphere during winter and spring and therefore remains important to the stratospheric literature. In fact, the much popular strong cyclonic westerly jet termed the polar vortex or the polar night jet (Nakamura and Shimpo, 2004) in particular, defines this circulation. The importance of its structure, dynamics and variability has been widely studied (e.g. Randell and Newman, 1998; Waugh and Polvani, 2010; Haynes, 2005; Schoeberl and Newman, 2003), particularly as the component of stratosphere/troposphere dynamical coupling as well as determining the key role in the winter and spring stratospheric circulation such as ozone-depletion (Waugh and Polvani, 2010).

1.1.2 The Relationship between Stratospheric Variability and the Middle-Latitude Eddy-Driven Jet

Over the last two decades, SH tropospheric climate has undergone significant changes due to the effects of anthropogenic forcings (Son *et al,* 2008; 2009). The effects of ozone-depletion in particular (Shindel and Schmidt, 2004) has been shown to be responsible for this tropospheric alteration (Arblaster and Meehl, 2006; Miller *et al*, 2006). Observational (e.g. Thomson and Solomon, 2002) and modelling studies (Son *et al*., 2009, McLandress *et al.,* 2011) have demonstrated that the formation of the ozone-hole caused by photochemical ozone-depletion (Newman and Nash, 2005) has led to lower stratospheric and upper tropospheric cooling during the austral spring months. The destruction of ozone occurs mainly in spring months due to chemical reaction which activates ozone depleting substances as sunlight returns to the polar Stratosphere (Newman, 2010). Increasing GHG's concentration have also made a contribution to this problem as it has been shown that they too cool the lower stratosphere as opposed to warming the troposphere (Kushner *et al,* 2001; Perlwitz, 2011), thus complementing the effects of ozone-depletion.

The above discussion suggests that perturbation in the stratosphere imposes significant changes in the troposphere; however this is evident under robust coupling mechanisms (Gerber *et al,* 2012). Even though still unknown, the coupling between the stratosphere and the troposphere has been extensively reviewed in terms of the so-called annular modes (e.g. Baldwin *et al,* 1994; Baldwin and Dunkerton, 1999; Thompson *et al,* 2003). These annular modes are explained to be the dominant patterns of variability in the extra-tropical stratosphere and troposphere. They are characterized by the coupling of stratospheric variations and geopotential height anomalies in the troposphere (Thompson and Wallace, 2000). The stratospheric mode structure signifies the polar vortex variations (Baldwin and Dunkerton, 2001) while the tropospheric one signifies the time- lagged tropospheric response (Gillet and Thompson, 2003). Moreover, studies have also shown that on longer time scales, the cooling of the lower stratosphere and upper troposphere has led to a strengthened polar vortex (Waugh *et al*, 2009). Even though these changes are subjected to longer-climate change timescale, the changes in the strength of the polar vortex occur at a significant inter-annual variability and therefore could pose implications on intra-seasonal timescales.

1.1.3 Tropospheric Summer Eddy-Driven Jet and Rainfall over South Africa

Summer rainfall variability over South Africa (SA) has been shown to be influenced by the location of the middle-latitude tropospheric jet (Tyson and Preston-Whyte, 2000). This middle-latitude eddy-driven jet dominates the circulation over the SH during the summer (Hurrel *et al*, 1998) and the associated storm tracks. The mechanism by which the eddy-driven jet is associated with storm tracks is mostly explained by low-level baroclinicity (Trenberth, 1991). The jet occurs throughout the year, but becomes most intense during the austral summer at around 40S to 50S and dominates the austral summer circulation (e.g. Nakamura and Shimpo, 2004).

The convergence of eddy momentum fluxes (Kim and Lee, 2004) is associated with upper tropospheric baroclinic waves that break in the anticyclonic direction in the subtropics (Ndarana and Waugh, 2010; Ndarana and Waugh, 2011, Ndarana *et al*, 2012). This association links the eddy-driven jet to weather producing systems which are in turn, associated with poleward eddy momentum fluxes (Holton, 2004). The role played by the eddy-driven jet in southern African climate is characterized by regulating the location of the well-known cloud bands that are associated with tropical temperate troughs (Reason *et al*, 2006). These cloud bands usually extend from Angola, south east to the South Indian Ocean waters as they cross the southern African region (Hart *et al* 2010). The systems also contribute about 60% to South African annual rainfall (van den Heever, 1997). When the jet and storm tracks are anomalously poleward (equatorward) then SA experiences a wet (dry) summer season and it has also been shown to be associated with the El Niño Southern Oscillation (ENSO) phases (Tyson and Preston-Whyte, 2000).

1.1.4 The Role of Oceanic Regions over southern African Climate

Efforts of modelling oceanic regions that are important to the climate variability of southern Africa have gone a long way in the history of seasonal forecasting. This work has been documented to range from modelling of the well-known equatorial Pacific Ocean (Stockdale *et al*, 1998) to that one of other oceanic areas such as the equatorial Indian (Mason *et al,* 1999) and the Atlantic (Pezzi *et al,* 1998) Ocean. The role that these oceanic regions play on most of the SH climate and at the global scale at large is considered important since they offer means of predicting seasonal average weather. This comes about as the sea-surface temperature (SST) anomalies originating from these oceans become relatively predictable by models so that they can be used to force atmospheric general circulation models (AGCM's) via two-tier forecasting approach (Landman *et al*, 2001a). Moreover, the advent of fully-coupled ocean-atmosphere modelling capabilities (Saha *et al,* 2006; Stockdale *et al,* 1998; Beraki *et al,* 2014) has even offered a more sophisticated mechanism whereby a two-way feedback mechanism is established between both the ocean and the atmosphere and therefore outperforms AGCM's (Landman *et al*, 2012). Ocean models employed in these coupled one-tier systems also offer ways of predicting evolution of SST anomalies at comparable skill levels (Landman and Beraki, 2012).

1.1.5 Summer Rainfall Predictability over SA

Efforts to improve the predictability of summer rainfall over SA have advanced owing to the extensive research done over the region since the 1990s (e.g. Mason, 1995). These efforts range from determining those relevant climate drivers which give much predictability to the region as well as their limitations. With ENSO being described as generally the main climate driver of the Southern African climate (Goddard *et al*, 2001); SA rainfall predictability during the summer season December-January-February (DJF) is achievable. Predictability in general favors this season because of the dominance of the tropical circulation (Mason *et al,* 1996) that's enabling a more direct ocean-atmosphere coupling and thus enhancing predictive skill (Landman and Goddard, 2002). In fact, predictive skill during summer rainfall in particular becomes more enhanced during those years associated with ENSO events (Landman and Beraki, 2012).

Notwithstanding, other local climate drivers such as the Indian Ocean Dipole and SAM are still important for understanding climate variability over SA (Goddard *et al*, 2001). These atmosphere-ocean circulations mainly indicate the state of SST over the surrounding oceans for the upcoming months/season and can usually be used to estimate seasonal climate anomalies of rainfall and temperature. For example, studies have shown that below (above) rainfall anomalies over SA are usually associated with El Niño (La Niña) - ENSO state. However this is not always the case since the association between ENSO and rainfall over SA is not linear (Fauchereau *et al,* 2008; Landman and Beraki, 2012), therefore wet conditions can still occur outside La Niña state (e.g. Kruger *et al,* 1999), and the same goes for dry conditions and El Niño. All this association is however mostly dominant during the December-January-February (DJF)-summer season over SA due to the presence of a tropical circulation (Mason et al, 1996; Landman and Goddard, 2005).

1.2 RESEARCH MOTIVATION

While ENSO variability has gone a long way into providing skillful summer rainfall predictions, it is still limited during those years associated with non-ENSO or neutral-ENSO conditions and therefore diminishes predictability. Moreover, ENSO explains only about 20-30% of the climate variability in the SH, therefore this gives room to explore other sources of seasonal climate predictability. The changes in lower stratospheric winds as well as temperatures during winter and spring could serve to provide another source of predictability, particularly for rainfall during the summer over SA since there also seems to exist an association between the stratosphere and the troposphere. The relationship is that the strength of the stratospheric polar vortex during winter/spring has an impact on the position of the tropospheric middle-latitude eddy-driven jet during the summer (Polvani and Waugh, 2002) and therefore could influence summer rainfall over the country as demonstrated in (Tyson and Preston-Whyte, 2000)

1.3 STUDY OBJECTIVES

The main objective of this study is to show that the proper representation of stratospheric processes in seasonal climate models could be important for predicting summer rainfall changes over SA, and to this achieve this, the following sub-topics have been considered:

1.3.1 Objective One: To demonstrate the importance of representing stratospheric processes properly in seasonal prediction systems

Lately climate variability has been shown to be driven by the human-induced anthropogenic processes that are in the stratosphere such as ozone-depletion as well as the tropospheric GHG's concentrations. In fact they seem to have been the dominant driver for the recent changes that have been observed in the SH climate. These changes play a key role in determining the state of atmospheric conditions under anthropogenic forcings. Climate prediction models on the other hand would require information of the current state of atmospheric conditions (anthropogenic-forced) in order to predict into the future. Therefore it would be very important that prediction-models are able to respond to these changes so that they could simulate real-time surface variables (such as rainfall, temperatures, etc.) realistically. However, it is understood that such climate prediction models need to have a better resolved stratospheric chemistry; otherwise it would likely not be able to represent stratospheric processes realistically and therefore affect the model's performance.

To support these claims, the model output from the coupled ocean-atmosphere general circulation model (OAGCM) used for seasonal forecasting production at the South African Weather Service (SAWS) is being considered. In this model, GHG concentrations are kept at 1960 levels and lower stratospheric ozone fields are of monthly climatologies. Therefore, there is no ozone-depletion in the model. Also at hand, reanalysis data which has got a relative contribution of ozone-depletion and GHG's is used in order to demonstrate the possible impact of stratospheric processes on seasonal prediction for this objective.

1.3.2 Objective Two: To demonstrate the importance of proper representation of stratospheric processes for the dynamic coupling between the stratosphere and the troposphere

The way in which the dynamics of the stratosphere is represented in climate models is very important as it is one factor that helps to facilitate the communication or coupling, between the stratosphere and the troposphere. First and foremost, the proper coupling between these two atmospheric layers may only exist when their dynamics are represented realistically. To test this notion further, the study in this objective, aims to analyze the dynamics of the stratosphere with regards to the planetary wave forcing. In this way, vertical propagation of planetary waves which are assumed to be initiated from the troposphere to the stratosphere would be regarded as a proxy for suggesting the possible mechanism that is responsible for coupling in the upward direction. It is also envisaged that the results would suggest how successful the coupled model is in order to simulate the variability of the stratosphere and its associated dynamics.

1.3.3 Objective Three: To demonstrate the possible impact of stratospheric variability on summer rainfall over South Africa.

Stratospheric variability is also composed out of the NCEP-reanalysis data in order to accomplish this objective. The variables of interest in this case that represent changes in the stratosphere would mainly be those that describe prominent features (such as e.g. polar vortex, stratospheric cooling etc…) of the stratosphere such as winds and temperatures. As much as it is known that reanalysis data is considered a model data set, but it is also close to observations as much possible. For that reason, it comprises not only stratospheric processes alone as the main driver, but also other natural and internal variations. However, this data set is assumed to provide a better estimation of how an improved stratospheric winds and temperature fields may impact the summer rainfall predictability over SA. This objective would then aim to demonstrate the importance of considering stratospheric variability as another source of predictability.

1.3.4 Objective Four: To address limitations and discuss recommendations based on the research findings

The study here aims to address issues associated with the impact of stratospheric variability on seasonal prediction of summer rainfall based on the findings. This objective also serves to recommend of the important stratospheric processes which may play a role in seasonal prediction over SA.

CHAPTER TWO

2. DATA AND METHODS

2.1 Datasets Obtained

2.1.1 Observations

The data set used here as a proxy for observation is from the National Centre for Environmental Prediction (NCEP) of the Department of Energy (DOE) Reanalysis II (Kanamitsu *et al*, 2002) which is an updated version of the original NCEP data set (Kalnay *et al*, 1996). This dataset covers a much longer period but the study only focuses on the period from 1982 until 2009. This study period is chosen so as to match the period for the model datasets and also to by-passes problems associated with the quality of datasets during the pre-1979 era (Tennant, 2004). Fixed fields such as lower stratospheric ozone and carbon dioxide (CO_2) concentrations have been improved. Seasonal climatology ozone is used in the radiation calculations to better represent processes associated with it. Therefore ozone-depletion and increasing CO_2 are both presented more realistically than previously. NCEP-reanalysis is on a typical horizontal resolution of 73 latitude and 144 longitude grid (i.e 2.5º x 2.5º) and 17 vertical levels.

2.1.2 Model hindcasts

Hindcasts from the South African version of the coupled European Centre Hamburg Model, (version 4.5) – Modular Ocean Model, version 3 – South Africa, Ocean Atmosphere General Circulation Model (called the ECHAM 4.5-MOM3-SA OAGCM, Beraki *et al,* 2014) were also obtained. This model comprises an atmospheric model-ECHAM4.5 and an ocean model-MOM3 which uses multiple program multiple data (MPMD) as coupling software (Beraki *et al*, 2013). Integrations for the hindcasts were made for the first lead time (i.e. forecasts are made in early November for DJF). The model is mostly configured for operational seasonal forecast purposes, however daily averages of the zonal wind velocity and temperature fields over a period of 28 years (1982–2009) are computed to suit the purposes of the analysis. Its output is available at a T42 (triangular truncation at wave number 42) horizontal resolution which corresponds to a grid of 64 latitudes by 128 longitudes and 17 vertical levels. The ozone field in the coupled model is relaxed towards observed climatology and its anthropogenic forcing is neglected.

2.2 Methodology Used

2.2.1 Linear trends

2.2.1.1 Middle-Latitude Tropospheric Jet Location

Seasonal averages for summer (DJF) zonal wind are computed for this analysis. The location of the jet in the troposphere is obtained by first calculating the zonal average of the zonal wind fields. It is then followed by fitting cubic splines at all pressure levels in order to identify the maximum value of the zonal wind over the whole of the troposphere. This approach by-passes problems associated with variations in the level at which the maximum zonal wind value occurs. The latitude at which the maximum wind would occur is therefore defined as the location of the eddy-driven jet, which is obtained on an inter-annual basis. The summer climatological jet is calculated over the period of 27 years for DJF totals (i.e. DJF 1982/83 – DJF 2008/09). And lastly, the least squares regression curves are fitted onto the data sets (i.e. NCEP and OAGCM) in order to validate the comparisons.

2.2.1.2 Temperature Trends

To investigate the hypothesis that lower stratospheric cooling is influenced by short-term ozone variations and its depletion, linear trends of the polar cap temperatures are calculated on all pressure levels. The polar cap is defined here as the zonally-averaged field of the latitudinal range from 70°S-90°S, which is a common way for defining the polar cap (e.g. Waugh *et al,* 2009; Polvani *et al,* 2011). Lastly, the linear trends for monthly temperature climatologies (1983-2009) are calculated over the polar cap.

2.2.1.3 Middle-Latitude Tropospheric Jet Trends

Lastly, linear trends of the middle-latitude zonal wind are also calculated in order to demonstrate the response of the mid-latitude tropospheric winds/eddy-driven jet to the stratospheric cooling. Middle-latitude here is also defined as the latitude ranging from 50°S-70°S (e.g. Waugh *et al,* 2009). Similar to temperature trends, linear trends for monthly wind climatologies (1983-2009) are also calculated over the middle-latitudes.

2.2.2 Polar Vortex Identification in the SH

Stratospheric polar vortex is defined here using zonal-mean zonal wind at 10 hPa pressure level. This level is considered to be in the middle stratosphere (Waugh and Polvani, 2010). Latitude – height variations of the stratospheric zonally averaged wind shows the core of polar vortex occurring over middle-latitude at about 60ºS during winter (e.g. Polvani and Kushner, 2002; Haynes, 2005; Waugh and Polvani, 2010).

This structure can also sustain into early-late spring months. The strength of the polar vortex also varies with height and therefore may be different when defined on another pressure level. The polar night jet (Nash *et al*, 1996) can start to form as early as autumn and maintain its strength during winter to spring where it finally decays. However, polar vortices can also be defined using potential vorticity (PV) on isentropic levels (e.g. Randell and Newman, 1998; Waugh and Randell, 1999) whereby the core of the vortex is defined as a region of high PV values on isentropic surfaces (Nash *et al,* 1996). These high PV values are also associated with the maximum wind and coincide with the steep gradients of PV (Waugh *et al*, 1999).

As Wilcox *et al* (2013) stated, PV is not a standard output in models therefore, using it in order to determine the polar vortex could result in large inaccuracies. For example interpolating to isentropic surface requires good stratospheric resolution in order to estimate properly the surface on which processes may occur. Therefore to bypass these problems the polar vortex in this study is defined as the zonally-averaged zonal wind at 60ºS in the middle stratosphere (i.e. 60ºS/10hPa, see Fig. 2.2.2).

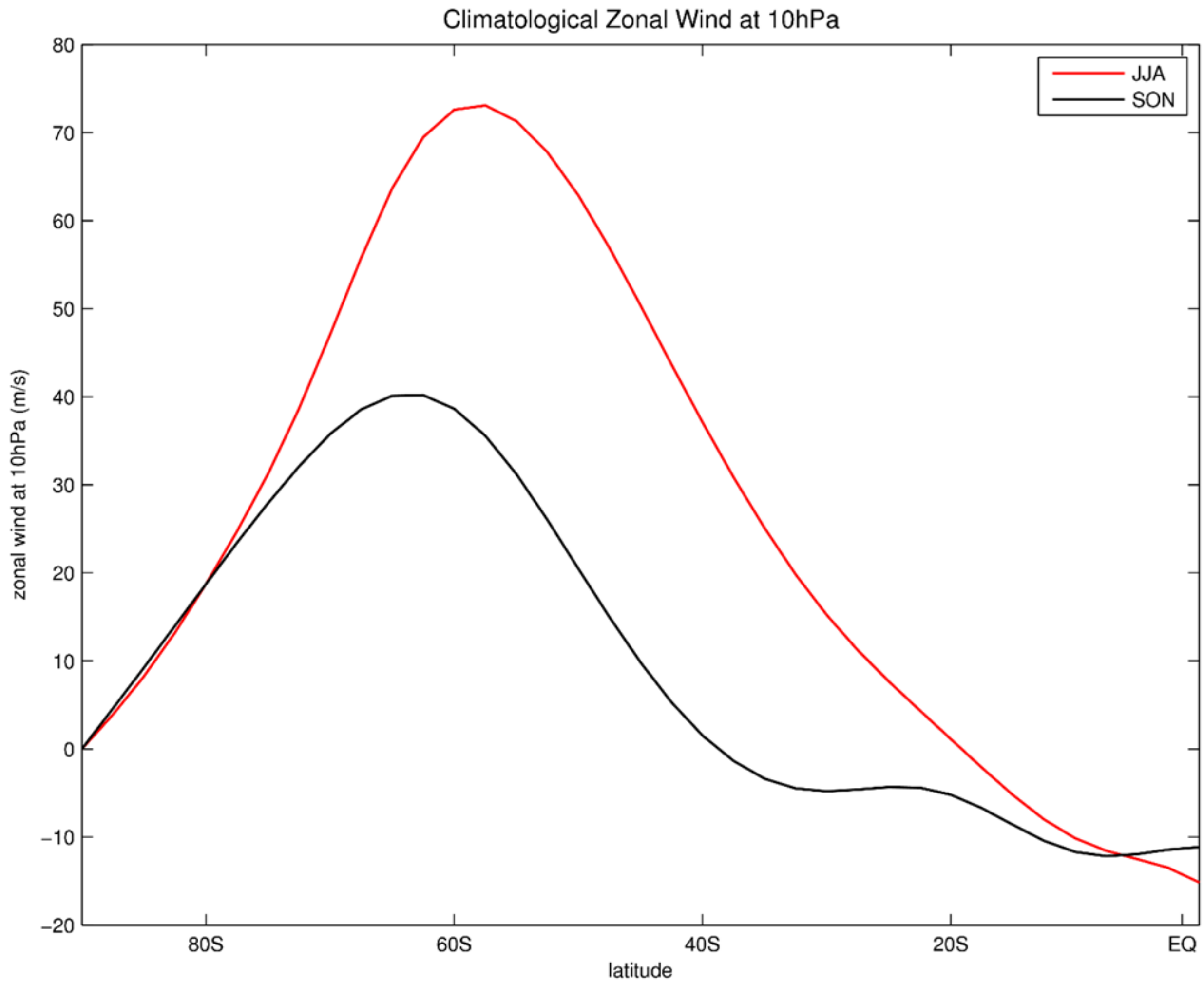

Figure 2.2.2: Climatological zonal-mean zonal wind at 10hPa during winter (JJA) and Spring (SON) in the SH over the period 1982-2009. NCEP-reanalysis II

2.2.3 Polar Vortex Break-up Diagnostics

In order to determine the demise of the polar vortex in the SH due to natural variability, the methodology that suits the usage of purely zonal winds to capture the stratospheric polar vortex (as seen above, Fig. 2.2.2) break-down date is established.

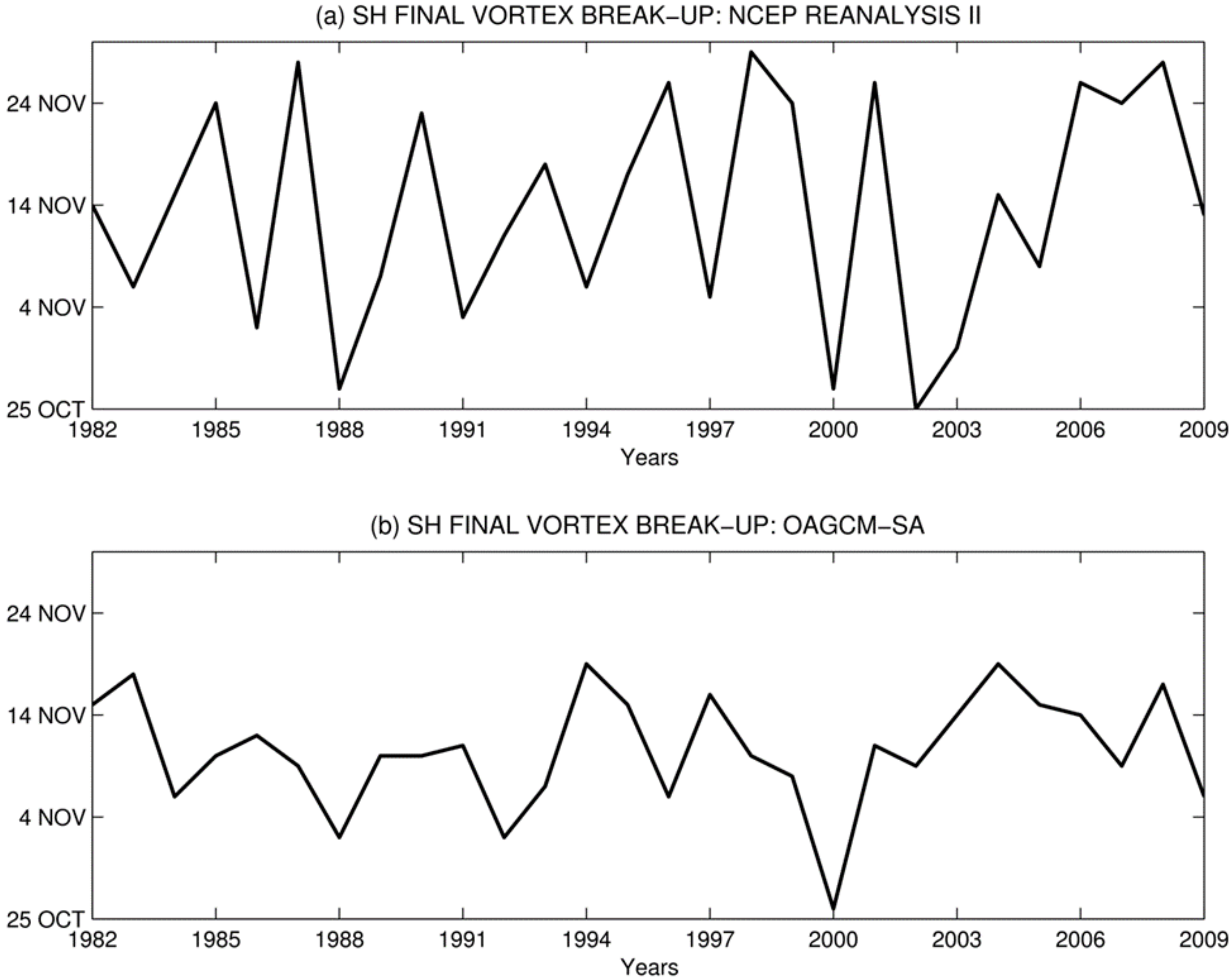

Figure 2.2.3: Inter-annual variability of the polar vortex break-down date in the SH for both NCEP-Reanalysis II and the OAGCM-SA Model. The period of analysis is from 1982-2009.

This method follows that one of Black and McDaniel (2007) even though a much lower (i.e. 50hPa) pressure level was used. The criterion used to determine the polar vortex break-up date was based on the wind speed threshold in order to identify the cut off days that are not associated with the polar vortex. Therefore the date on which the polar vortex breaks up is defined here as the final date when the wind speed falls below a critical threshold value of 10m/s, provided this condition remains satisfied until the following year's autumn. This criterion suffices the diagnostics for the break-up because the core of the polar vortex in the middle stratosphere (60ºS/10hPa) is characterized by wind speeds greater than 10m/s during winter and spring.

The diagnostic again renders an opportunity to establish individual break-down dates of the polar vortex for each year in both datasets (NCEP and OAGCM, see Fig 2.2.3). Note that these dates demonstrated will be used later in the study for selecting different sets of periods. However, the method is also understood to be purely subjective and therefore could be sensitive to parameters used to define the wind thresholds (Waugh *et al*, 1999). For example, one could probably get a slightly different break-up date if not using a wind threshold value of 10m/s.

Moreover, other studies (e.g. Manney *et al*, 1994; Waugh *et al,* 1999; Waugh and Randell, 1999) used diagnostics that involves dynamical PV distribution on isentropic surfaces, associated with winds on PV isolines (Nash *et al,* 1996). However, these studies were studying the dynamics of polar vortices in detail. Another recent study by Haigh and Roscoe (2009) used temperatures to identify break-up dates. But despite using different criteria/methodologies, a common agreement must be reached which shows that the polar vortex broke up much later in the 1990's than in the 1980's (Wilcox *et al*, 2013). Lastly, the pressure level chosen to represent the polar vortex could also affect the date due to the downward progression of break-down date from top to lower levels (e.g. Hardiman *et al,* 2010).

2.2.4 Variability of the Stratosphere

Periods in which the stratosphere is active or variable are defined using the dates established for the polar vortex break-down in section 2.2.3. This procedure ensures the exclusion of any stratospheric circulation that is simply not associated with the polar vortex and it is done on an inter-annual basis in order to produce sets of active stratospheric circulation. These sets are computed in such a way that a number of days are counted backwards from the day on which the polar vortex breaks down up to the targeted day number (e.g. count 30-days, 60-days, etc… backwards from the day of the break-up to the final day number), for every year. Since there is high variability in the vortex break-up dates (see Fig. 2.2.3), it is worth noting that these sets of periods would differ on a year-to-year basis (i.e. 30-days-period of 1982 would not consider the same dates as the ones in 1983, even though they are computed for the same number of days, see Table 1). However, a 30-day period here is estimated to make up a month, while 60-days constitute two months and so forth in multiples of 30. It is also worth noting that the days selected to make up these period(s) may overlap in between months, therefore a monthly average in this case may not necessarily comprises only a particular standard month (see Table 1). The datasets for these periods(s) are prepared in this way in order to try and simulate shorter timescale (high frequency) to longer timescale (low frequency) stratospheric variability.

Table 1: Example of the dates to show how different sets of period(s) have been created for the analysis. Only three years have been shown in this table; however the same criterion is applied over other remaining years

Period(s)/Year(s)	**30-day**	**60-day**	**90-day**
1982	1982**Nov**13–1982**Oct**15	1982**Nov**13–1982**Sep**15	1982**Nov**13–1982**Aug**15
1983	1983**Nov**05–1983**Oct**07	1983**Nov**05–1983**Sep**07	1983**Nov**05–1983**Aug**07
1984..,2009	1984**Nov**13–1984**Oct**15	1984**Nov**13–1984**Sep**15	1984**Nov**13–1984**Aug**15

2.2.5 Eddy Heat-Fluxes and Wave Driving in the Stratosphere

To diagnose stratospheric wave driving, the study makes use of eddy-heat fluxes as a quantity to estimate the propagation of wave activity into the stratosphere (Waugh *et al,* 1999; Randel *et al,* 2002; Polvani and Waugh, 2004). Defined by the vertical component of Eliassen–Palm flux (Andrews *et al*, 1987), the meridional eddy-heat fluxes are derived from the components of both eddy temperature (T') and meridional wind (v') so as to make up the product ($v'T'$). Newman and Nash (2000) analyzed the wave driving of the stratosphere by classifying it into its different wave types. The study shows that eddy-heat fluxes in the lower stratosphere during winter are dominated by large-scale waves such as Rossby-planetary waves (i.e. waves of type 1-3) over the middle-latitude regions. This revelation satisfies the Charney-Drazin theory in such a way that only large-scale waves are able to propagate into a stronger westerly flow (Newman and

Nash, 2000). Nonetheless, the medium-scale waves (i.e. waves of type 4-7) are also present during spring (in fact throughout all seasons) but mainly in the lower troposphere as they cannot propagate into a stronger westerly flow. The analysis here focuses thus on eddy heat-fluxes of the large planetary scale rather than the smaller scale ones. The wave driving of the stratosphere from the troposphere is defined as zonal-mean eddy-heat flux at 50hPa in the SH and averaged over 40° to 80° S.

2.2.6 Statistical Downscaling

Three sets of periods starting from 30-days (before the polar vortex break-up) to at least 90-days are created so as to employ them in a statistical forecasting system for summer rainfall prediction over SA. This work is aimed at testing a statistical forecasting system that uses stratospheric zonal winds (u) and temperatures (t) as predictors for summer rainfall over SA.

2.2.6.1 The Stratospheric Predictor Field

The predictor fields of the forecasting system to be used here are zonal winds and temperature in the middle stratosphere (i.e.10hPa). Both winds and temperature fields are computed for the three sets of periods mentioned above, i.e. 30, 60 and 90 (see Table. 1). An example of the climatological zonal wind fields considered in this analysis is shown for both reanalysis and the coupled model, respectively (Fig. 2.2.6.1a and b). However, note that the stratospheric zonal fields shown here (In Figs. 2.2.6.1 a and b) are for the 90-day average only.

The band of the winds concentrated in the SH is a clear indication of an active stratosphere during this 90-day period and therefore confirms the existence of the polar vortex. The core of the polar vortex coincides with wind speed greater than 60m/s as indicated by the NCEP-reanalysis (Fig 2.2.6.1 a). Since our main aim is to assess the impact of stratospheric variability together with its associated polar vortex variability on summer rainfall over SA, the domain that will be chosen for the predictor field in the analysis will be restricted over the region where stratospheric winds are active. The same methodology applies for stratospheric temperatures as well. Therefore, the domain here for the predictor is restricted over the area between the high latitudes 50S and 80S, and 0 to 135E

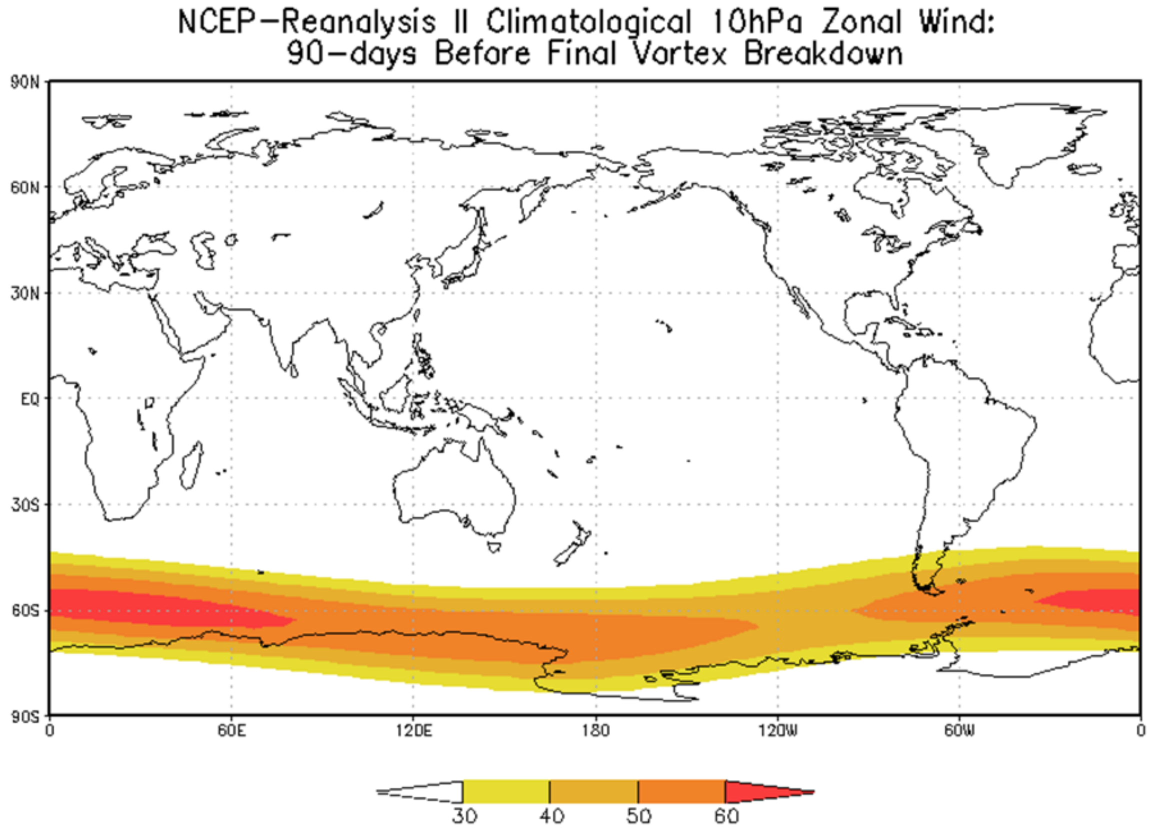

Figure 2.2.6.1a: Climatological zonal wind field at 10hPa and 60ºS. The zonal wind is averaged over 90-days before the final break-down of the polar vortex and over 28 years (1982-2009)

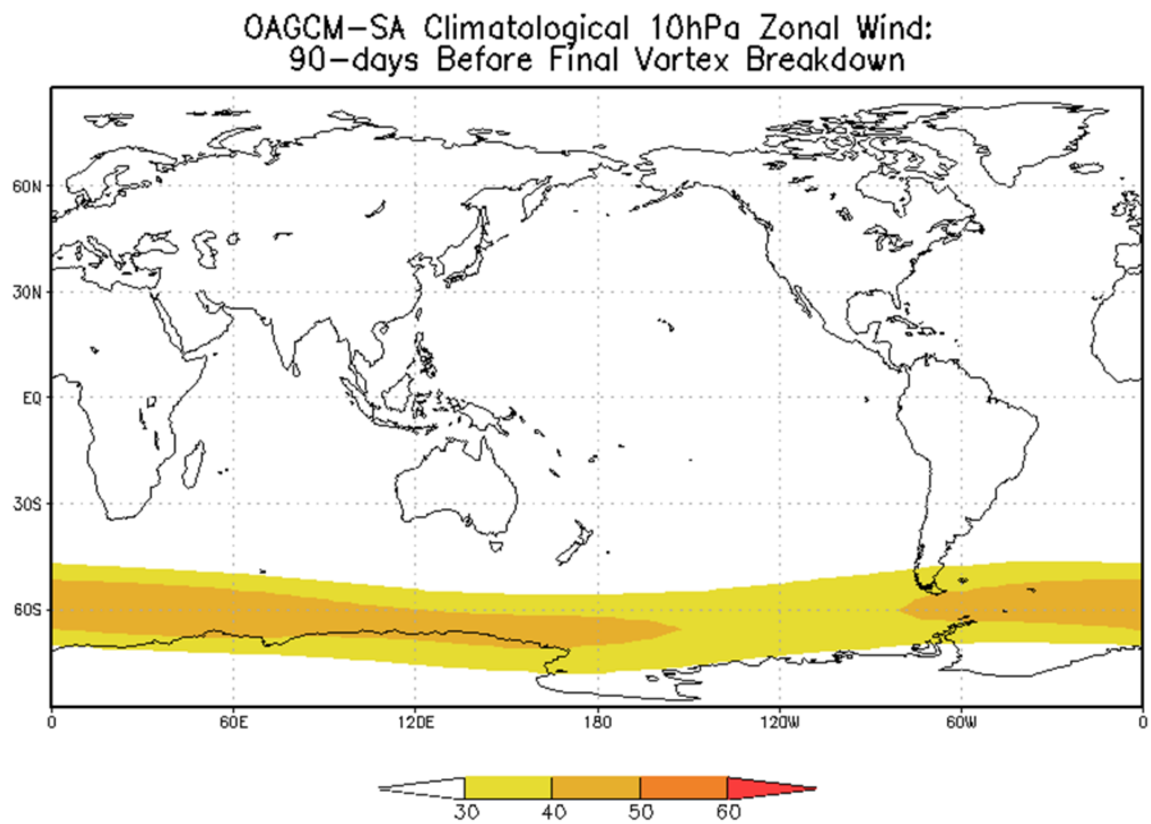

Figure 2.2.6.1b: Climatological zonal wind field at 10hPa and 60ºS. The zonal wind is averaged over 90-days before the final break-down of the polar vortex and over 28 years (1982-2009) climatological base period using OAGCM hindcasts.

2.2.6.2 Statistical Forecasting System.

Each set of the predictor field period described above are considered separately over a 27 year climatological period (i.e. 1982/83 – 2008/09). The forecasting system which uses stratospheric winds as a predictor field comprises three separate analyses for each period considered for the statistical system. Here, these assumed large-scale systems are downscaled into SA rainfall using the Model Output Statistics (MOS, Wilks, 2006) approach which uses the Canonical Correlation Analysis (CCA, Barnett and Preisendorfer, 1987). This approach seeks to find existence of the relationship between observed large scale circulation and predictand variable. Downscaling is performed onto South African gridded station data set. The same is done for the forecasting system when stratospheric temperatures are used as predictor fields.

2.2.6.3 Performance of the Forecasting System

The verification of the forecasts is done on a retro-active forecast setting environment in order to try and simulate the potential true forecast performance which does not inflate skill. The detailed procedure for this forecasting setting is stated in Landman and Beraki (2012). Since forecast are judged probabilistically, Relative Operating Characteristic (ROC) will be used here as one verification measure (Wilks, 2006) in order to determine the discrimination (are the forecasts discernibly different given different outcomes?). This verification method has been used extensively, especially in the field of atmospheric sciences as a way of estimating the quality of both deterministic and probabilistic forecasts (Mason and Graham, 1999). Therefore, ROC scores for both above-normal (AN) and below-normal (BN) categories will be used in order to assess whether the forecasting system is successful in discriminating high and low summer rainfall total events over SA or not. This discrimination will be represented by the ROC score which should be greater than 0.5 for the forecast to be skillful (Mason, 1982).

CHAPTER THREE

3. POSSIBLE IMPACT OF THE LOWER STRATOSPHERIC OZONE ON SEASONAL PREDICTION SYSTEMS?

3.1 Introduction

The El Niño Southern Oscillation (ENSO) phenomenon is the single biggest contributing factor to climate variability because of its large global impact (Goddard *et al,* 2001). Its effect on seasonal-summer rainfall over SA is well documented (Landman and Goddard, 2002; Landman and Goddard, 2005; Landman *et al*, 2009). These studies have shown that ENSO signals are usually associated with rainfall anomalies over the country, i.e. above (below) normal rainfall conditions are often associated with La Niña (El Niño) phases. ENSO-forced predictability becomes even more enhanced during the austral summer as a result of tropical circulation that becomes dominant during this season and thus increasing the predictability of seasonal rainfall at shorter lead time scales (Landman *et al*, 2001a). Moreover, as indicated earlier, numerous modelling studies (Landman *et al*, 2001a; Mason *et al*, 1999) have shown that variations of sea-surface temperatures (SST) from the equatorial Pacific and Indian Oceans provide skillful predictions over southern Africa because of the linear relationship that they have with the region's summer seasonal rainfall (Landman *et al*, 2001b). Therefore, ENSO serves as a source for seasonal predictability over southern Africa, particularly in the case of above average summer rainfall during La Niña years (Landman *et al,* 2012).

Although ENSO-based seasonal prediction systems have gone a long way to produce skillful summer rainfall forecasts during La Niña and El Niño events, they are constrained during neutral conditions over the equatorial Pacific Ocean as their skill diminishes (Landman and Beraki, 2012). Furthermore, ENSO explains only about 20 to 30% percent of the climate variability (Rocha and Simmonds, 1997) over southern Africa. Therefore adding to these efforts, stratosphere/troposphere coupling and stratospheric dynamics could therefore be explored and be added as another source of seasonal predictability for the region; this notion is to be explored in the coming chapters.The eddy-driven jet, which dominates the SH circulation during the summer (Hurrel *et al*, 1998) and the associated storm tracks, could affect summer rainfall over

SA (Tyson and Preston-Whyte, 2000). The mechanism which is responsible for this association is explained by low-level baroclinicity (Trenberth, 1991). In general, an anomalously poleward (equatorward) position of the jet as well as storm tracks are associated with anomalously wet (dry) conditions over SA. During anomalously dry conditions, the cloud bands that bring much of the country's summer rainfall are displaced from their usual position and are positioned east of the country as shown in Tyson and Preston-Whyte (2000). Because the position of the jet is influenced by the strength of the polar vortex (Polvani and Kushner, 2002; Kushner and Polvani, 2006) through robust stratospheric and tropospheric coupling mechanisms, the variability of winter and spring stratospheric winds, as well as temperatures, could be another source of summer rainfall predictability (Gerber *et al*, 2012). Moreover, Son *et al* (2010) have shown that for stratospheric variability to be useful in predicting tropospheric processes, the former has to be represented correctly in a model.

At longer time scales, observational (Thompson and Solomon, 2002) and modelling studies (Son *et al*, 2010; McLandress *et al*, 2011) have shown that the formation of the ozone-hole has led to lower stratospheric and upper tropospheric cooling during the austral spring months. This formation has also been responsible for the persistent poleward movement of the eddy-driven jet during the summer and a persistent positive phase of the Southern Annular Mode (SAM, Marshall, 2003). As would be expected, these changes in the tropospheric circulations have been accompanied by long-term changes in subtropical rainfall patterns (Kang *et al*, 2011; Feldstein, 2011). Note however, that these changes have not been caused by ozone-depletion alone. Increasing greenhouse gases (GHG) concentrations also have a cooling effect on the lower stratosphere (Perlwitz, 2011). During the 1970s to 2000, these two radiative forcings have complemented each other (Perlwitz *et al*, 2008).

Because summer rainfall over SA is influenced by the inter-annual variability of the position of the jet (e.g. Tyson and Preston-Whyte, 2000), it is reasonable to hypothesize that a model that incorrectly simulates the jet position variability and climatology thereof will likely be unable to simulate summer rainfall variability correctly. The effect may subsequently compromise the reliability of rainfall predictions at the seasonal time scale, but it is hypothesized that an improved representation of stratospheric processes, such as ozone and GHG concentrations in climate models used to predict climate variability might lead to improved seasonal forecasts. The representation of stratospheric processes in climate models has various facets and is important for realistic simulations. A recent study (Waugh *et al,* 2009) showed that if ozone variations in a model are zonally symmetrical as opposed to three dimensional, lower stratospheric and upper tropospheric temperature trends as well as changes in the zonal winds are under estimated. The proper representation of stratospheric ozone is achieved through the use of interactive stratospheric chemistry schemes such as the one described in McLandress *et al,* (2011). It is also possible that the atmospheric level at which the model top is located plays an important role in the accuracy of climate models in simulating stratospheric dynamics. The highest level in most models is 10 hPa, which is far too low to accurately capture the dynamics of the stratospheric polar vortex.

Information on stratospheric processes that occur at levels higher than 10 hPa is conveyed into the model vertical domain by specifying model top boundary conditions (Purser and Kar, 2002) However, these boundary conditions may not be equivalent to actually including the stratospheric processes, which can be achieved by raising the model top to 0.01 hPa. An idealized modelling study (Gerber and Polvani 2008) showed that stratospheric/tropospheric coupling is captured clearly in a model with the top as high as 0.1 hPa. High top models are also considered in the fifth phase of the Coupled Model Inter-comparison Project (CMIP5) experiments (Taylor *et al*, 2012). Increasing stratospheric resolution, in addition to the above, has the ability to improve seasonal climate predictions significantly (Scaife *et al*, 2012).

Studies such as Roff *et al* (2011) also indicate the importance of stratospheric resolution on extended forecasting skill. Even though all these issues are applicable at time scales longer than that of seasonal prediction, they could be relevant to this time scale too and therefore raise many questions with regards to the role of stratospheric processes and seasonal predictability. As such, in this chapter the climatological behavior of lower stratospheric and upper tropospheric circulation under realistic stratospheric chemistry will be demonstrated. NCEP-reanalysis data is used as it is considered to be realistic in this case. The coupled ocean-atmosphere general circulation model (OAGCM), in which the ozone representation is not realistic and has no GHG forcing is also considered for this demonstration. Moreover, the response of the mid-latitude tropospheric circulation for both NCEP and the model will be shown and both results will be compared. This effort aims to highlight and stress the importance of proper representation of stratospheric processes in seasonal prediction models.

3.2 Climatology of the Summer Zonal Wind

The zonal winds in Figures 3.2a and b show the climatological general structure of the zonal wind flow during austral summer (DJF) as a function of latitude and pressure for both observations and the coupled model, respectively. This structure is characterized by positive westerlies covering the tropospheric region (within the 850 and 100 hPa levels), and a strong wind maximum that is associated with the eddy-driven jet. However, the jet core in observations and the model occurs at different levels. It is located at 350 hPa in the reanalysis but above 350 hPa in the model OAGCM.

These zonal wind structures are caused by a strong meridional temperature gradient found in the middle-latitudes, as required by the thermal wind balance (Holton, 2004). The meridional temperature gradient is in turn caused by differential heating between the tropical and Polar Regions. Eddy momentum fluxes that converge in the middle-latitudes (Kim and Lee, 2004) are responsible for maintaining the jet after having been transported poleward by anti-cyclonically breaking upper tropospheric trough (Holton, 2004; Postel and Hitchman, 1999; Ndarana and Waugh, 2011) breaking waves convert eddy kinetic energy to mean kinetic energy (Holton, 2004). There are also significant differences between the NCEP and OAGCM tropospheric jet structures (Fig. 3.2a and b). The former shows a weaker jet core which is centered more poleward (at about 48˚S) than its OAGCM counterpart (at about 42˚S). However, the jet in the model appears to be at a higher level than in the reanalysis, which could also bear implications for moisture transport

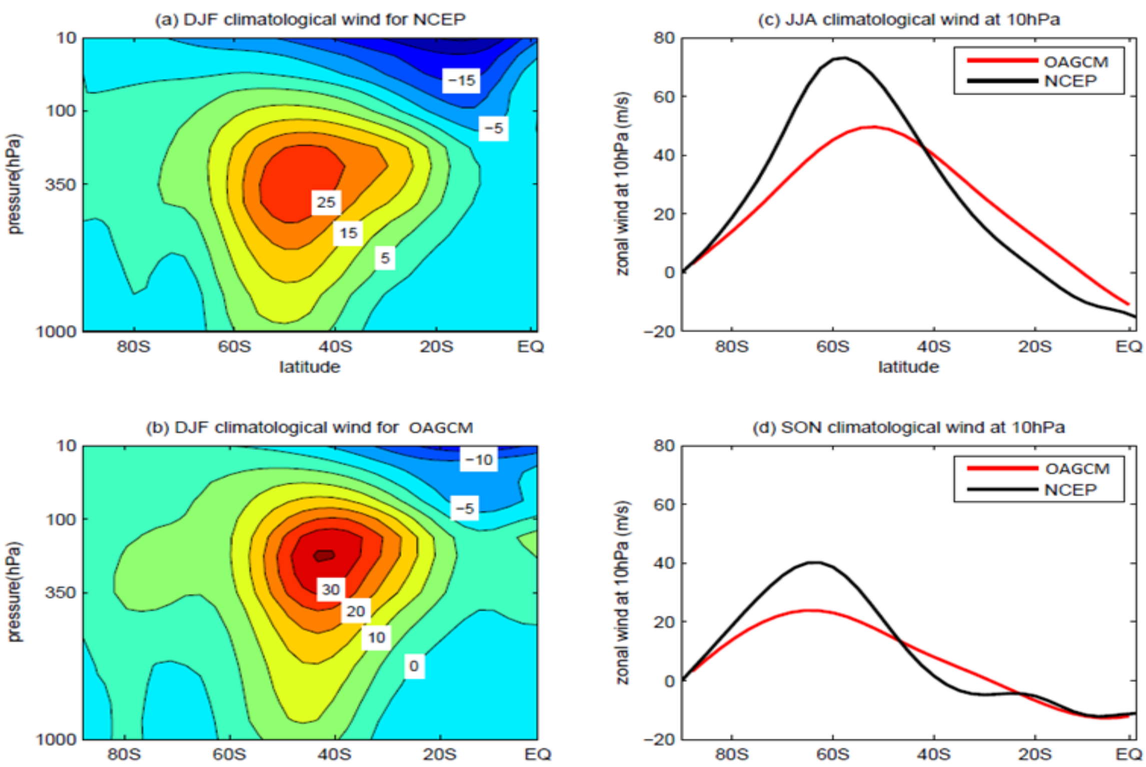

Figure 3.2: Zonal wind component averaged in the longitudinal direction for (a) NCEP and (b) OAGCM-SA at all isobaric levels during DJF and at 10 hPa during (c) JJA and (d) SON. Summer (DJF) tropospheric wind is in response to the strength of stratospheric polar vortex during winter (JJA) and spring (SON). Thick red (black) contours in (c) and (d) represent OAGCM (NCEP). Wind speed

As it was alluded to in the introduction and will be discussed further below, the climatological position of the jet should be an important consideration in seasonal prediction systems because it could determine the shorter term (inter-annual) variability of its position relative to SA. The position of the summer jet in different data sets also indicates that the storm tracks would be placed at different locations in the observations and in the model. The association between the eddy-driven jet and storm tracks occurs through baroclinic waves which influence the zonal-mean flow and hence storm tracks activity (Nakamura and Shimpo, 2004). Storm tracks are important because they transport heat, moisture and momentum (Hitchman and Huesmann, 2007).

Fig. 3.2c and d give an indication of a relative climatological stratospheric wind circulation during austral winter (JJA) and spring (SON), respectively. These figures show zonal winds (u) at 10 hPa, with black (red) lines representing the NCEP (OAGCM). The 10 hPa pressure level is the level which is considered to be in the middle stratosphere as it is above the 500K isentropic surface and therefore considered in both data sets. Various studies (Waugh and Polvani, 2010; Waugh and Rong, 2002) have used PV on isentropic levels to diagnose the dynamics of the polar vortex. A typical vortex comprises strong and cold winter westerly winds centered along the core replacing the summer and autumn easterlies (Andrews *et al*, 1987). Its lifespan is estimated to decay sometimes in late spring to summer and the timing of its break-up is highly variable (Waugh and Rong, 2002; Waugh and Polvani, 2010; Andrews *et al*, 1987).

The peaks of the zonal wind at 10 hPa that occur in the mid-latitudes in Fig. 3.2c and d is a good indication of the lower stratospheric polar night jet (Nash *et al,* 1996) in the data sets considered here, hence the associated polar vortex (Held and Suarez, 1994). NCEP climatological winds at 10 hPa are stronger than those in the OAGCM case during the winter and spring. As noted above, a persistent stronger (or weaker) polar vortex during the winter and, in particular, in spring, leads to a poleward (or equatorward) shift of the eddy-driven jet during the summer (e.g. Polvani and Kushner, 2002; Kushner and Polvani, 2006). Therefore, because the NCEP vortex is stronger than its OAGCM counterpart, one would expect that the summer eddy-driven jet of the former to be positioned more poleward than that of the OAGCM. This displacement is indeed found to be the case as discussed above. This effect is a purely dynamical phenomenon as it has been demonstrated by idealized modelling studies (Polvani and Kushner, 2002). Idealized models comprise only dynamical cores and other physical processes (Held and Suarez, 1994) to separate atmospheric dynamical phenomena from other processes. The above discussion suggests that the climatology of stratospheric zonal winds is consistent with the tropospheric circulation in both data sets despite the incorrect positioning of the tropospheric jet in the OAGCM.

3.3 Evolution of Polar Cap Temperatures

The climatological evolution of polar cap temperatures is now considered. They are defined as zonally averaged temperature fields that are also averaged from 70° to 90°S. The selection of this latitude ranges confirms the south polar cap and defining the polar cap in this way is common practice (Waugh *et al,* 2009; Polvani *et al*, 2011). Fig. 3.3a and b show the polar cap temperature for the NCEP and OAGCM, as a function of month and pressure level. The evolution of lower tropospheric polar cap temperatures is similar in NCEP and OAGCM, but both the lower stratosphere and upper troposphere are quite different. The structure of the changes in NCEP temperatures are consistent with those of ozone concentrations as seen in Atmospheric Chemistry and Climate (AC&C) and Stratospheric Processes And their Role in Climate (SPARC) data (see Fig. 1, Polvani *et al,* 2011). Because lower stratospheric ozone has not depleted in the OAGCM, as opposed to in the NCEP-reanalysis which has a better representation of ozone, it means that the lower stratosphere of the former is much warmer than that of the latter. By the thermal wind relation (Holton, 2004) one can see why the NCEP polar vortex is stronger than its OAGCM counterpart (Fig. 3.2).

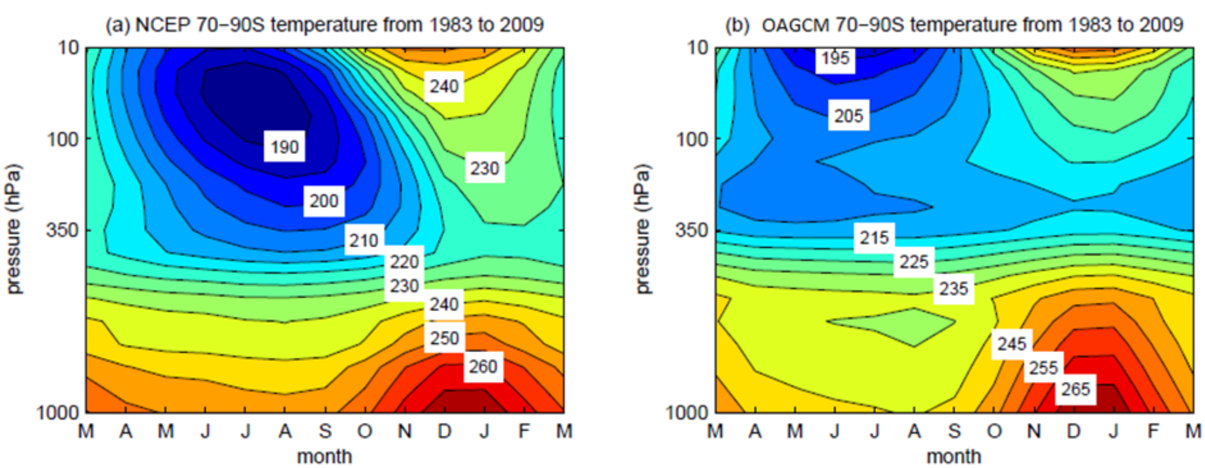

Figure 3.3: Polar cap temperatures evolution as a function of month and pressure for (a) NCEP and (b) OAGCM. The contour intervals are 5 K.

These results reveal that the NCEP climatological structure of the zonal wind distribution in the lower stratosphere during winter and the associated summer zonal wind distribution throughout the tropospheric mid-latitude regions are different from those of the OAGCM's. The relative strengths of the polar night jet in the respective data sets are also consistent with the climatological temperatures in the lower stratosphere and upper troposphere, which are in turn consistent with ozone representation in the data sets.

3.4 Seasonal Trends

In the discussion above it was demonstrated that there are significant differences between the mean stratospheric and tropospheric winds and temperatures during the winter, spring and summer seasons in NCEP and OAGCM datasets. It was further suggested that this finding might be linked to an inadequate radiative forcing in the OAGCM; in a sense caused by unrealistic ozone variations as noted in Section 3.3. In this section the study considers changes in the lower stratospheric temperatures during the spring season in the different data sets and their associated tropospheric response during the summer months, as also established in previous modelling and observation studies. This work is aimed at demonstrating the likely importance of proper radiative forcing and representation of stratospheric processes in seasonal prediction systems. The polar cap stratosphere is climatologically colder in the NCEP case than in the OAGCM, as noted above by thermal wind relations (Holton, 2004).

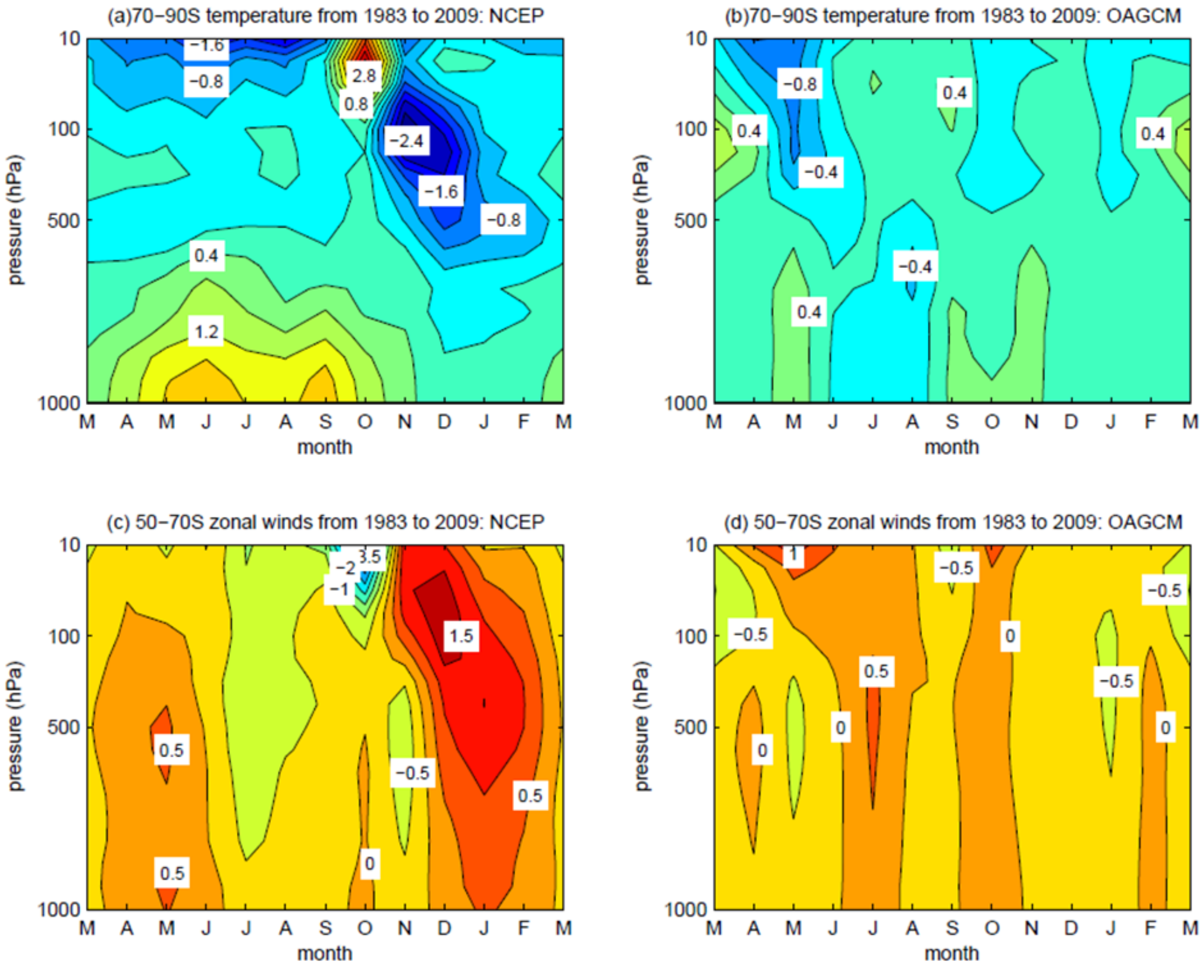

Figure 3.4: Top panels: Linear trends in polar cap (averaged over 70-90S) temperature measured in K.decade-1 from 1983 to 2009 in (a) NCEP and (b) OAGCM data sets. Bottom panels: Mid-latitude winds (averaged from 50 to 70S) linear trends measured in m.s-1.decade-1. The contour intervals in the top and bottom panels are 5K.decade-1 and 0.2m.s-1.decade-1 respectively.

These climatological thermal structures could be associated with changes in the temperatures. As shown in Fig. 3.3a, NCEP polar cap temperatures exhibits cooling in the lower stratosphere and upper troposphere during October to March. This result is consistent with observational studies (Thompson and Solomon, 2002) which used radiosonde data sets and model simulations (McLandress *et al,* 2011; Waugh *et al*, 2009) using Chemistry Climate models (CCM's) with state-of-the-art interactive stratospheric chemistry schemes. As shown in these studies and others, this cooling is a direct result of ozone-depletion with increasing GHG concentrations augmenting it (Son et al, 2010). There is no such cooling in the OAGCM polar cap (Fig. 3.4b). The reason for the absence of this cooling is that ozone does not deplete in the model because it is represented as monthly climatologies, as noted in the previous section.

Furthermore, the GHG concentrations do not increase in the OAGCM. Fig. 3.4c shows the corresponding linear trends in NCEP zonal winds averaged between 50˚S and 70˚S as a function of month at each pressure surface. The zonal wind response to the cooling begins during October in the lower stratosphere and upper troposphere. This response is shown by positive linear trends and it is mostly evident in the middle and lower troposphere during the summer months (Fig. 3.4c), – a phenomenon that is well documented. As expected, a similar response does not occur in the OAGCM. Instead, there is a negative trend in the zonal wind between 50°˚ and 70°˚S in the OAGCM (Fig. 3.4d). This result therefore suggests (as will be further elaborated on below) that the tropospheric response in the model, although consistent with the associated polar cap temperatures, is not realistic.

3.5 Possible Impact of Ozone Concentration in Seasonal Prediction Model(s)

It has been demonstrated in Fig. 3.4 that when ozone variations are represented in a realistic manner (meaning that ozone-depletion actually occurs in the NCEP data sets), then the stratospheric cooling that results from it has a positive tropospheric response and this is evident during austral summer months. If this is not the case, as shown by the coupled model, ozone does not deplete and thus leads to the opposite negative tropospheric response. Figure 3.5a and b is confirmation to such a response with features showing both positive and negative linear trends represented by thin black and red contours, respectively. Therefore in this case, the tropospheric response is actually an acceleration (or deceleration) of the eddy- driven jet on the poleward (or equatorward) side as is shown in the figure. Moreover, the response is also consistent with what is seen in (Fig.3.4c), which shows positive linear trends as a result of stratospheric cooling caused by ozone-depletion (Fig.3.4a). A response in DJF mainly occurs as a result of stratospheric anomalies that have a time lag of a few weeks to descend to the surface (Baldwin and Dunkerton, 2001; Thompson and Solomon, 2002; Gillet and Thompson, 2003).

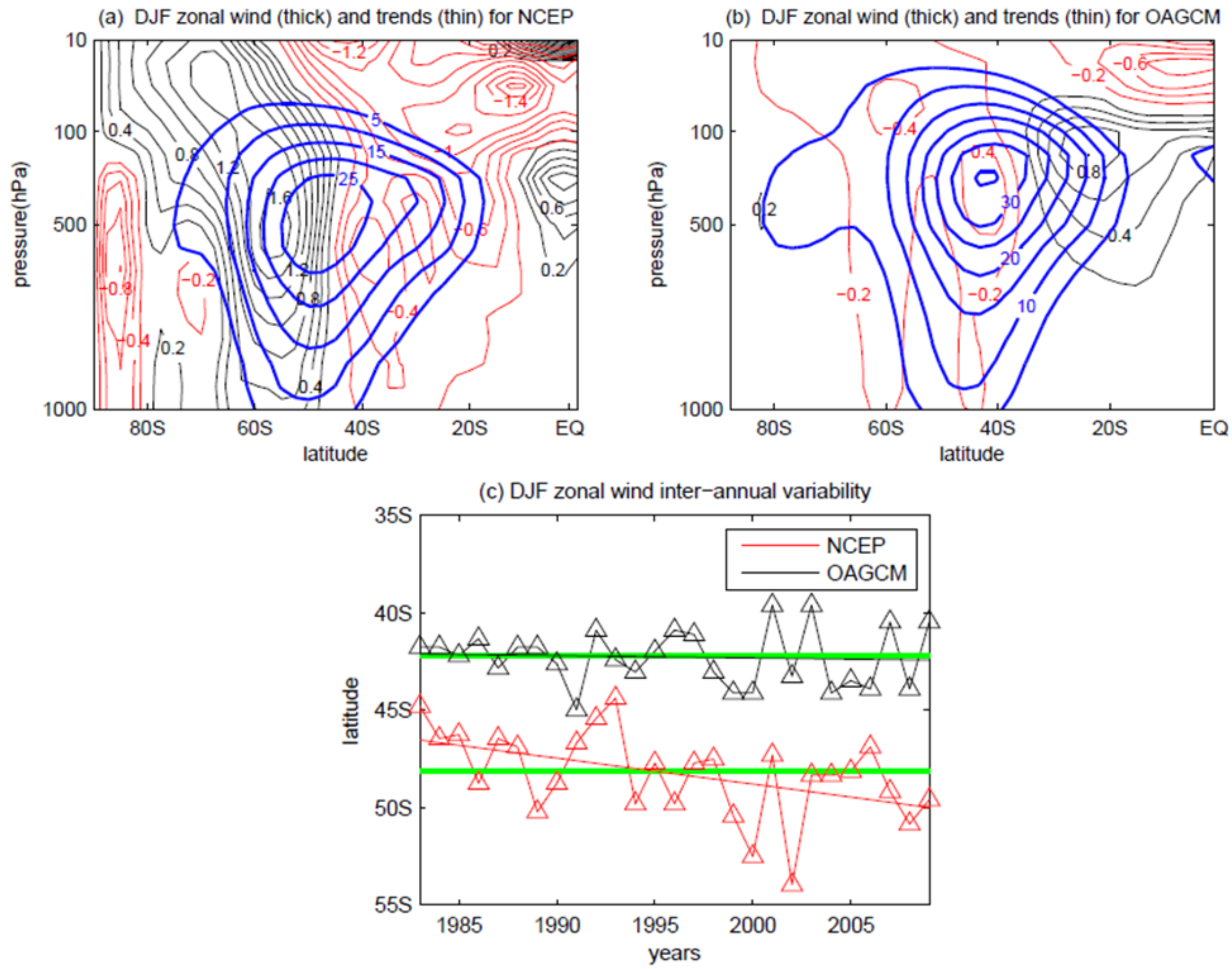

Figure 3.5: The eddy-driven jet (thick blues contours) with trends in the zonal winds super imposed for (a) NCEP and (b) OAGCM. Red (black) contours represent negative (positive) trends in m/s/decade. The zonal-mean isotachs and trends thereof are drawn in 5 m/s and 0.2 m/s/decade contour intervals, respectively. (c) Representation of the inter-annual variations with NCEP (red line) and OAGCM (black line) linear trends over the analyses period. Green line is the climatological position of the jet in both

The linear trends are a manifestation of the poleward movement of the eddy- driven jet as shown by the red linear trend line in Fig. 3.5c, which has moved from about 46°S to about 50°S during the analyzed period. As noted before, the shift in the jet is a result of a cooler ozone-induced polar stratosphere (Fig. 3.4a). Moreover, a Monte Carlo or re-randomization test (Wilks, 2006; Livezey and Chen, 1983) is performed on the Reanalysis data linear trend of Figure 3.5c to test for its statistical significance by randomly creating a time series from the original inter-annual NCEP variations. After each re-randomization, a least -squares regression line is fitted to the randomized data from which the trend is calculated, and the process was repeated 10 000 times. The number of times the original trend was larger than the re-randomized trends is noted. Less than 1% of the re-randomized trends are larger than the original trend. This sloping linear fit is therefore statistically significant at the 99% level of confidence.

The magnitude of the poleward shift can also be measured using the climatological position as a reference (green straight line in Fig. 3.4c). The initial sub-climatological jet position is equatorward of the climatological position and ended up on the poleward side of it at the end of the study period. Meanwhile this is the case, the OAGCM jet has tended to decelerate (accelerate) on the poleward (equatorward) side, even although this tendency was weak (Fig. 3.5b). This response is also consistent with the tropospheric response seen in (Fig. 3.4d), responding to the warm stratosphere which is as a result of the non-depletion of ozone. Moreover, this response has resulted in the lack of trends as shown by the black straight line coinciding with the climatological jet position in Fig 3.5c. Therefore, it is clear from the above discussion that there are notable differences between NCEP and OAGCM lower stratospheric cooling during the spring and the associated summer tropospheric response.

To conclude, the importance of a proper representation of the lower stratospheric ozone processes for seasonal prediction is pointed out by considering the inter-annual variability of the position of the middle-latitude tropospheric jet. As explained earlier, variations in the jet position relative to SA are important to the country's summer rainfall. Most of the summer rainfall results from long cloud bands that stretch diagonally across the main lands and connecting the tropical processes to the mid-latitudes through tropical temperate troughs (Harrison, 1984). When the eddy-driven jet is placed anomalously equatorward, these cloud bands become displaced and occur outside the eastern boundaries of SA, thus leading to a dry summer season (Tyson and Preston-Whyte, 2000).

3.6 Synopsis

It has been demonstrated that in an OAGCM that has a climatological representation of lower stratospheric ozone, the depletion thereof (as opposed to in the reanalysis data) does not occur. The non-depletion of ozone has led to a lack of stratospheric temperature cooling, which is not in support of previous findings (e.g. Thompson and Solomon, 2002; McLandress *et al*, 2011; Waugh *et al*, 2009). These studies have shown that ozone-depletion leads to the cooling of the lower stratosphere, particularly in spring months. The Reanalysis data shows a significant austral summer tropospheric response that manifests as an acceleration of the eddy-driven jet on the poleward side and its deceleration on the equatorward side. These features are caused by a gradual and persistent poleward migration of the sub-climatological jet core. Because of the lack of ozone-depletion in the OAGCM, the same is not observed. Instead, the sub-climatological jet remains largely stationary as indicated by the weak acceleration and deceleration of the climatological jet stream on the equatorward and poleward sides, respectively. However, the aim of this study was to demonstrate that the exclusion of long-term changes in stratospheric ozone (and GHGs) leads to an inaccurate position of the jet stream and the inter-annual vacillations of the zonal wind fields occur at about an inaccurate latitude in the OAGCM, – which is far more north than where it is supposed to be. However, the phases of the zonal wind anomalies observed in the NCEP-Reanalysis were correctly reproduced by the OAGCM, suggesting that the model simulated the ENSO signal correctly.

Other mechanisms such as Stratospheric-Tropospheric Exchange (STE) could also influence the movement of this jet because its chemical effect in turn influences the lower stratosphere (Holton *et al,* 1995). However, the exact mechanism by which the stratosphere influences the troposphere is unknown and therefore still remains research ongoing (Polvani and Kushner, 2002). In fact, the study, by Kang *et al* (2011) found a direct link between changes in summer rainfall in the subtropical belt and the ozone-hole, thus attesting to the importance of this forcing. Also in support of this, a recent study by Son *et al* (2013) has also found a significant relationship between ozone-depletion and surface variables such as rainfall and temperature in the SH.

CHAPTER FOUR

4. PHYSICAL MECHANISMS

4.1 Introduction

Broad issues of the possible implication of representing stratospheric processes poorly in prediction models are stipulated in the previous chapter. This came after it was realized that both the stratospheric and tropospheric circulation of the model (whose ozone and GHG concentration are poorly represented) could not manage to simulate the recent ozone and GHG-forced trends properly. These trends were mainly the cooled stratosphere as well as its associated poleward shift of the tropospheric summer eddy-driven jet over the middle-latitude. However, even though these trends are considered valid under long-term timescales, the migration of the middle-latitude eddy-driven jet position towards the poles was shown to occur at a noticeable inter-annual variation and hence it was hypothesized that it can impose implications on surface climate variables such as rainfall during the summer season over SA.

In fact, a study by Son *et al* (2013) has supported the relevance of the possible impact of stratospheric processes (Ozone concentrations, particularly in the SH) on the inter-annual timescale rather than on intra-seasonal. This possibility was confirmed by the existence of a significant relationship between the stratospheric ozone concentrations in spring and the dominant mode of variability (Simpson *et al*, 2011) in the SH, i.e. the Southern Annular Mode (SAM) as it affects surface climate variables such as rainfall and temperature. The association was shown to have a one-month lag in between, with stratospheric ozone concentrations in September affecting the October SAM and its associated surface variables. However,, even though little evidence has been found, the lack of a significant intra-seasonal variability in the SH has been explained to be mainly due to the nature of less/no extreme events of the polar vortex such as the Sudden Stratospheric Warming (SSW events, e.g. Baldwin and Dunkerton, 2001). Besides this setback, SSW events have also been explained to be not predictable on extended timescales (Marshall and Scaife, 2010). The scarcity of these events are subjected to a somewhat weaker tropospheric wave forcing in the SH (Gerber *et al*, 2012) as well as a much stronger stratospheric polar vortex (Son *et al*, 2013). However an exception has been given to the extreme event which occurred in September, 2002 (e.g. Newman and Nash, 2005; Thompson *et al*, 2005; Roscoe *et al*, 2005).

While this is the case, it is evident that on shorter to inter-annual timescale, variations in the stratospheric circulation can influence the troposphere as well as surface climate (Baldwin and Dunkerton, 2001; Charlton *et al,* 2004). This influence occurs as stratospheric anomalies propagate down into the troposphere by means of a dynamical mechanism, but as to how this coupling really occurs still remains a research question (Wallace, 2000; Plumb and Semeniuk, 2003; Waugh and Polvani, 2010). Notwithstanding, suggestions as to under which dynamical mechanism does this downward influence occur have been raised by several studies (e.g. Polvani and Kushner, 2002; Song and Robinson, 2004; Perlwitz and Harnik, 2004; Kushner and Polvani, 2006), with mainly wave propagation stated to be the main possible fundamental mechanism (Perlwitz and Harnik, 2004). However, not only is there a one-way downward influence, but a two-way interaction between the two atmospheres (i.e. from the troposphere to the stratosphere) is also possible. In fact, Perlwitz and Harnik (2004) stressed the troposphere to be the main source of this downward propagation as waves get generated first in the troposphere and then propagate upwards into the stratosphere where it perturb its circulation. These perturbed stratospheric anomalies also have a tendency of propagating slowly with time into the troposphere on time scales of a few weeks (Perlwitz and Harnik, 2004).

Studies have made use of annular modes of variability in order to demonstrate the coupling between the stratosphere and the troposphere, particularly in the NH (e.g. Baldwin and Dunkerton, 1999, Baldwin and Dunkerton, 2001; Kushner and Polvani, 2004; Polvani and Waugh, 2004). Simpson *et al* (2011) state that these modes are dominant modes of variability in both the stratosphere and troposphere and are mostly diagnosed by the leading/first Empirical Orthogonal Function (EOF) of a low frequency geopotential anomaly, defined at each pressure surface (Baldwin and Dunkerton, 1999; 2001). The above mentioned studies explain the signatures of these modes to have structural patterns, indicating a hemispheric pressure sign which may be associated with the strength of the polar vortex in the stratosphere or the position of the middle-latitude jet in the troposphere. A well-defined downward coupling in this case manifests as large anomalies appear first in the stratospheric upper levels and descend downward with time into the lower levels where they get coupled to the troposphere (Seviour *et al*, 2014). However, Polvani and Waugh (2004) also found that coupling in the opposite direction (i.e. where anomalies appear first in the troposphere then into the stratosphere) is possible. This result may be in agreement with Perlwitz and Harnik (2004)'s findings about the troposphere being the main source of this downward coupling.

The above discussions indicate that a proper coupling between the stratosphere and the troposphere may only exist when the stratosphere itself is represented properly as the two atmospheres change information. The downward exchange of information in this particular case (where the stratosphere acts as a source rather than a sink) may also be a priority for this coupling since the study is interested in exploring its effect on the surface climate. Also at play is the issue of a suitable timescale to look at in order to explore this notion. As explained earlier, a much convincing timescale for this coupling mainly occurs on inter-annual timescale rather than on a much shorter intra-seasonal due to the rarity of extreme events during spring months / season in the SH as opposed to the NH.

Studies such as Son *et al* (2013) and Seviour *et al* (2014) have demonstrated the possibility of using the stratosphere to predict surface variables during spring. All this effect was possible because of a time-lagged downward coupling which occurs as stratospheric anomalies are coupled with the troposphere. This coupling also renders skillful predictions of important phenomena such as the SAM which also in turn affect most the atmospheric variables in the extra-tropics. Therefore the study in this chapter wishes to further explore implications of a poor representation of stratospheric processes on the dynamics of the stratosphere as well as coupling between the stratosphere and troposphere.

This notion was highlighted in the previous chapter as a recommendation to also improve the resolution of the middle stratosphere in seasonal prediction models. Looking at how the model failed to simulate the recent stratospheric and tropospheric changes in the SH, it is not inconceivable that its dynamics could also be crippled. As alluded to earlier, the dynamics are very crucial for coupling during those periods of active stratosphere and of course this coupling occurs under special dynamical conditions which may depend heavily on the representation of the stratosphere itself. To be much precise, besides suggested different theories of possible dynamical mechanisms by previous studies (e.g. Waugh and Polvani, 2010), wave driving in the upper troposphere/lower stratosphere maintains the stratospheric circulation and therefore coupling. Therefore as a result, in this chapter, the study will try to quantify the current state of the model's stratospheric dynamics and link it to the findings in the previous chapter (i.e. chapter 3). Inspired by Hurwitz *et al* (2010); the study start by addressing the importance of the proper planetary wave forcing for determining the stratospheric circulation. This will then be followed by also assessing if there is any dynamical coupling existing in the coupled model. The findings may therefore suggest better ways to improve the model's stratosphere as well as its associated dynamics.

Moreover, the dynamical coupling of the stratosphere and the troposphere also plays an important role in the predictability of SAM (Seviour *et al*, 2014). Having being described as the dominant pattern of the tropospheric circulation (Reason and Roualt, 2005), SAM gets coupled to the stratosphere during months when the stratosphere is active particularly in spring (Thompson and Solomon, 2002). This coupling has even showed to render skillful prediction of the SAM during mid-spring especially in October. For example, studies such as Son *et al* (2013) and Seviour *et al* (2014) demonstrated the possibility of using stratospheric circulation such as ozone concentrations and stratospheric anomalies for skillful predictions of SAM at extended lead times, respectively. However, all these at the same time signify the possible downward connection between the stratosphere and the troposphere and as explained previously it occurs under special dynamical mechanisms.

Therefore it can also be hypothesized that the lack of dynamics also leads to an incorrect representation of the SAM. To try and demonstrate this, the study assessed whether the misrepresentation of the SAM is a general problem in other models which are configured in the same manner as the OAGCM used here. The priority is mainly given to tracking the much popular general increase of the SAM towards a high polarity index as it has been presented in observational studies (e.g. Thompson and Solomon, 2002; Marshall, 2003).

Using the methodology of Gong and Wang (1999), SAM is calculated using the mean sea level pressure for the individual austral summer month (i.e. December, January and February) in other models of the ECHAM-generation (Roeckner *et al*, 1996) with different configurations. The simulation of SAM by these models confirms that even though there is somewhat variability of the SAM, however there is no general pattern that is showing an increasing trend towards the positive phase in all the austral summer months as opposed to observations (Fig. 4.1) - with the mid-January month being the most pronounced. However, the ECHAM-Climate Forecasting System (ECHAM-CFS) model forced with observed SST seems to capture the December trend even though it doesn't sustain the whole three month analysis period.

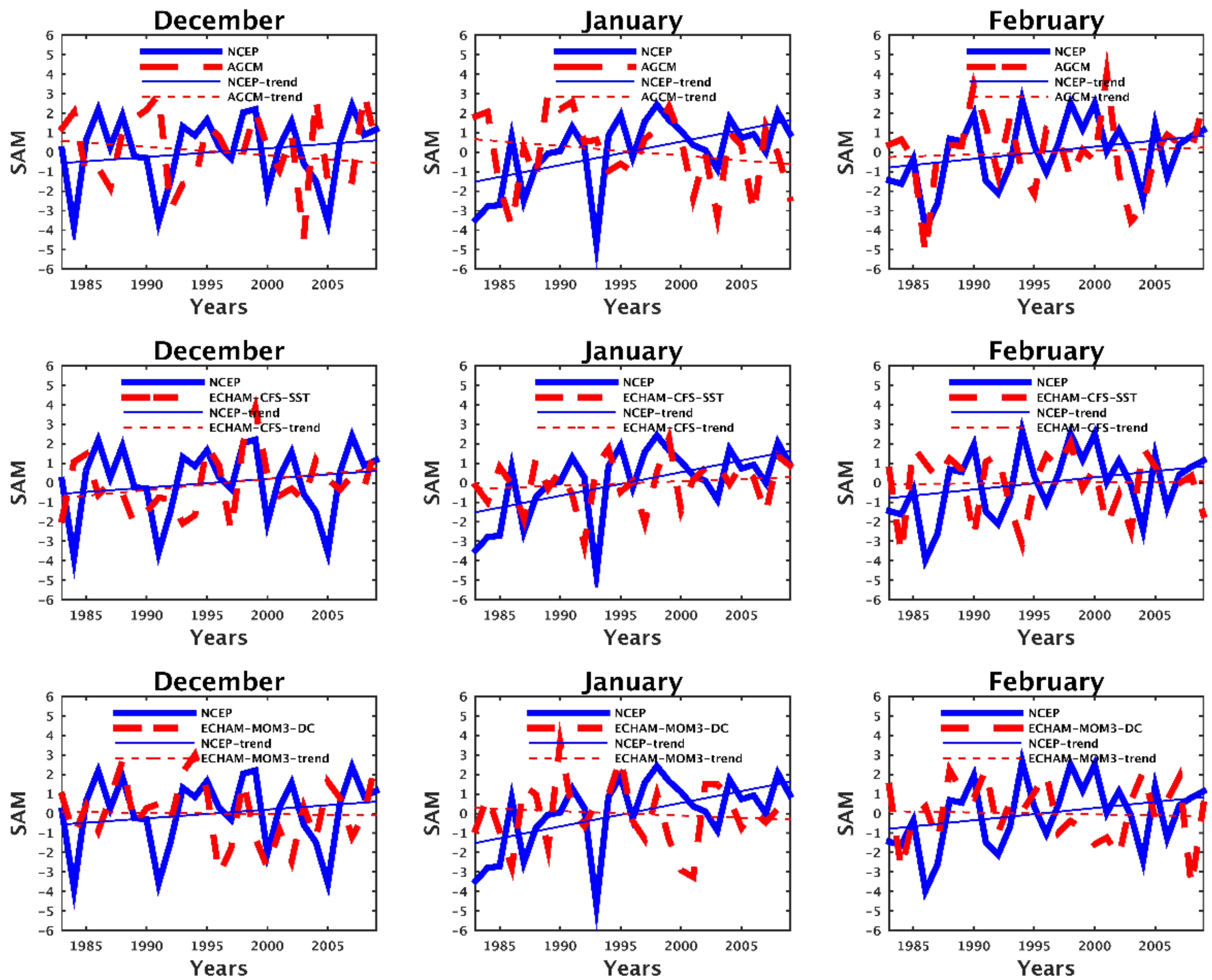

Figure 4.1: Simulation of the inter-annual variability of the SAM during the austral summer months (i.e. December, January and February) as presented in the three ECHAM-generation models and plotted against NCEP-Reanalysis observations.

This trend mainly quantifies the strengthening and the migration of the middle-latitude tropospheric jet towards the poles (Polvani *et al*, 2011), which in turn is responsible for the positioning of the mid-latitude storm tracks as explained earlier. Even though it still remains unclear as to what exactly causes this positive trend between ozone-depletion and GHG, ozone-depletion in particular (e.g. Thompson and Solomon, 2002; Son *et al*, 2009; Meehl, 2007) has been shown to have played the major role. Notwithstanding, the skill of predicting the SAM is more related to the ability of the model to have the stratosphere that is variable so that it can promote anomalies that would descend (in spring months) with time and couple with the troposphere (Seviour *et al*, 2014).

4.2 Climatology of the Zonal Wind and Wave Driving in the Stratosphere

4.2.1 Observations

The climatological structure of the middle stratospheric zonal wind as well as its wave driving is presented (Fig. 4.2). Here, observed stratospheric winds (Fig. 4.2a) and heat-fluxes in the lower stratosphere (Fig. 4.2b) are used as proxy for representing the relationship between stratospheric circulation and wave forcing, which is assumed to be under specialized dynamical mechanisms (Waugh and Polvani, 2010). This association is shown by the general structure of the stratospheric zonal wind as a function of months, together with its associated eddy-heat fluxes in the SH. The zonal wind structure (Fig. 4.2 a) as depicted by the reanalysis data agrees well with structures seen in other studies (e.g. Andrews *et al*, 1987; Randel and Newman, 1998 and Waugh and Polvani, 2010). A somewhat stronger westerly flow in the high latitudes, with wind speed reaching as high as 80m/s can be clearly seen, which on average confirms the strength of the polar vortex during winter/spring months.

This much strengthened stratospheric zonal flow in the SH has been tested by theories which explain hemispheric differences in terms of wave-mean interactions (e.g. Haynes, 2005, Waugh and Polvani, 2010). For example, the NH stratospheric zonal wind during winter is not expected to be as strong as the one in the SH as it generally experiences more wave disturbances caused by topographical features as well as land-sea contrasts found in the NH. Nevertheless, studies of wave-mean interaction theories give suggestions of how the stratospheric flow responds to tropospheric wave forcing during winter and spring (Randel *et al,* 1987). As seen in observations, the stratospheric zonal wind starts to form during fall and maintains its strength until late spring (Fig. 4.2a) where it coincides with a strong wave forcing (Fig 4.2b) and ensures its final break-down. Even though this wave activity is not as large as compared to the NH in magnitude, it is sufficient to maintain the proper zonal flow in the stratosphere (e.g. Holton, 2004).

4.2.2 OAGCM-Model Simulation

Even though the coupled model still manages to simulate the general structure of the zonal winds well, its vortex core is slightly weaker and smaller than observed. This is confirmed by the negative difference in the zonal wind which occurs during the winter-time months (Fig. 4.2c). Such modelled stratospheric polar winds usually lead to a much persistent vortex into summer as there would be no sufficient wave activity to end the polar wind circulation during spring (Hurwitz *et al,* 2010). However, on the contrary, this is not the case in the coupled model. Instead, associated with this weaker modelled vortex strength, there appears much weaker planetary wave forcing which occurs during mid-spring months (i.e. October, Fig. 4.2 d), however does not promote vortex persistence. Hurwitz *et al* (2010) also showed that the wave forcing which occurs in October can be used to quantify the time-lagged persistence of the vortex in the following month (i.e. November). Since there seem not to exist such a persistence in the model's polar vortex despite the weaker strength, the result may be suggestive of a poor representation of stratospheric chemistry and it's in association with dynamics.. The reason why stratospheric chemistry is thought to be the main culprit in this case is that the results which have been shown by previous studies to have vortex persistence in particular, have been captured by only the newly-introduced sophisticated Chemistry Climate models (CCM's) which include a well-resolved stratospheric chemistry (e.g Eyring *et al,* 2006, 2007). However, despite the biased-related deficiencies encountered by the CCM's such as higher ozone concentrations and too-much persistent vortices (Eyring *et al,* 2006, Garfinkel *et al*, 2013), their stratospheric dynamics are usually well simulated. To quantify this poorly modelled stratospheric circulation even further, there seem to exist not much variability in the model's wave activity (Fig. 4.2f, red line) and most importantly, the observed strongest heat-fluxes which occur over the middle-latitude in October (Fig. 4.2f, blue line).

This observed wave forcing during October has been described by numerous studies to be important especially in ensuring proper timing of the polar vortex break-up and its associated warming (e.g. Waugh *et al*, 1999; Rao *et al,* 2003). The break-down of the vortex would come about as meridional temperature gradient reduces due to the warming of the polar stratosphere (Hurwitz *et al*, 2011). This effect is promoted through thermal-wind relation (Holton, 2004). And also as expected, the model's simulation of the polar vortex does not seem to conform the time-lagged wave forcing response i.e. there is no clear indication of at least one month lag between the polar vortex break-down and heat-fluxes. Moreover, it can be seen that the vortex break-down which occurs few days later than observed (Fig. 4.2c) is somewhat a response from the weaker planetary wave driving in the model (Fig. 4.2d).

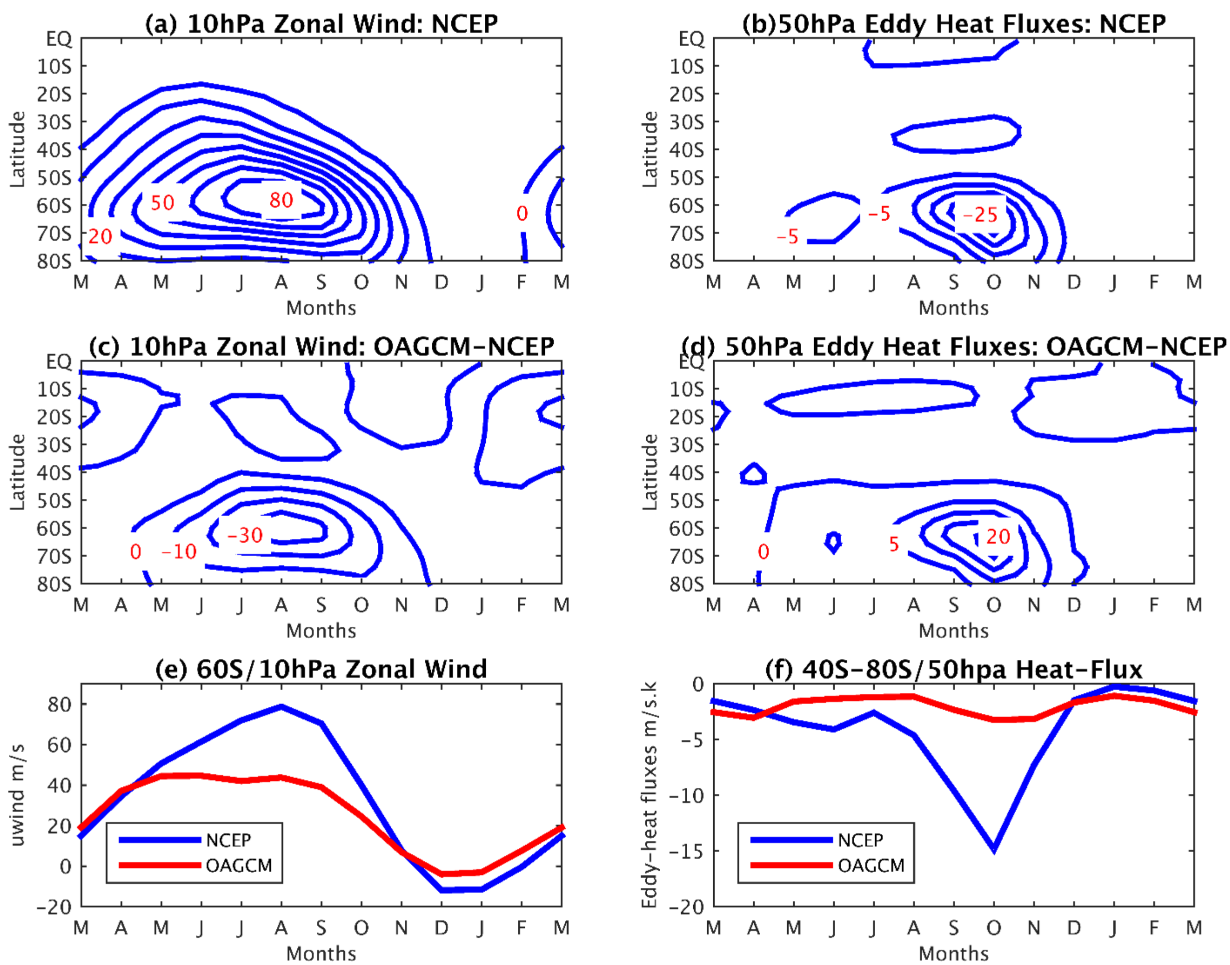

Figure 4.2: Monthly annual cycles of 10hPa zonal- mean zonal wind averaged over 27 year climatology period (1983-2009) as well as the corresponding Eddy-heat fluxes at 50hPa also averaged over the same period (a and b, respectively) for NCEP-Reanalysis. Differences between OAGCM and NCEP-Reanalysis climatological zonal wind and eddy-heat fluxes (c and d respectively). Lastly, the climatology of the stratospheric polar vortex and heat-fluxes averaged over the middle-latitudes (e and f, respectively). Contour intervals are 10m/s and 5K.m/s for zonal wind and heat-fluxes, respectively.

The observed enhanced heat-fluxes in October (Fig. 4f, blue line) is an indication of the upward propagation of planetary waves, which seem to be absent in the coupled model. This heat flux coincides with the time when the polar stratosphere is warmed enough so that the so-called Polar Stratospheric Clouds (PSC) does not form and as well as ozone-hole formation. To extend this analysis further, the study will now use the dynamics of a more specialized type of stratospheric event such as the so-called Sudden Stratospheric Warming (SSW, Newman and Nash, 2005) to demonstrate the coupling which may exist between the two atmospheric levels (i.e. stratosphere/troposphere) when the chemistry of the stratosphere is represented realistically. This stratospheric warming event is one of the major extreme events to ever occur in the SH and has been discussed extensively in the literature which attempt to quantify the dynamical connection between the troposphere and the stratosphere (e.g. Baldwin and Dunkerton, 2001; Polvani and Waugh, 2004; Gerber and Polvani, 2009). These studies explain that the year 2002 stratosphere in particular was very unusual as it was overwhelmed by large amounts of wave activity that entered the stratosphere and therefore preceded this major SSW extreme event. Therefore, since this event is considered to be one of the major dynamical source of stratospheric variability (Polvani and Waugh, 2004), its dynamics will be used to demonstrate how the stratosphere responds to the troposphere following planetary wave forcing and hence coupling in the upward direction.

4.3 Dynamical Coupling of the Troposphere and Stratosphere

4.3.1 Climatological Response of the Stratosphere to Wave Forcing

The observed stratospheric circulation which is integrated a certain number of days before the final polar vortex break-up indicates an association between temperatures and winds. This association is shown during the period of about 120 days before the stratosphere in the SH could become dormant. Take note that the period was carefully selected in order to capture the “somewhat” spring season, which is a good period to use in order to track down the variability of the stratosphere. Observations show that during this 120-days-period, eddy-heat fluxes (Fig. 4.3a, blue line) in the lower troposphere maintain both the variability of the polar stratospheric temperatures and winds. A typical warming of the polar stratosphere is observed which seem to occur immediately from 90th day(s) prior to the final vortex break-up (Fig. 4.3c, blue line). This noticeable warming period coincides with the period on which eddy-heat fluxes are becoming stronger. The relationship is consistent because wave activity modulates easterly momentum fluxes which are responsible for warming the cold polar stratosphere in spring (Newman, 2010). Moreover, an anomalous growth of heat-fluxes seems to occur during a 30-days-period prior to the final vortex break-up. This growth may be an indication of contributions from bursting planetary waves from the troposphere (Andrews *et al*, 1987), which is usually seen in October, as demonstrated previously (see Fig. 4.2f, blue line). Previous studies such as Hurwitz *et al* (2010) have also found this strong wave activity to occur in October.

The observed stratospheric polar vortex climatology also agrees well with the response of polar temperatures to heat-fluxes during this 120-days-period. It is noted that polar vortex maintains its strength during earlier days (i.e. from 120th day) than during later days (i.e. from 30th day) as it reaches final break-down (Fig. 4.3e, blue line). The deceleration of the wind which is noted during later days before the polar vortex break-up also coincides with the period in which the polar stratosphere was warm. And as explained earlier, the warming together with the deceleration is as a result of the stratospheric residual mean meridional circulation that is increased (Haynes *et al*, 1991).

The above description of observed stratospheric response to wave forcing during this particular period show some consistencies with regards to wave-mean interaction theory (Polvani and Waugh, 2004). On the contrary, the stratospheric response (polar temperature and winds) in the model is somewhat weaker than observed throughout the study period (Fig. 4.3c and e, red line respectively). Again, one of the reasons why this might be the case is because of weaker/no wave activity in the model. It can be seen that the modelled eddy-heat fluxes do not vary much and therefore remains constant throughout the 120-days-period (Fig. 4.3a, red line). Therefore this may be an indication that even though there seem to appear some stratospheric response in the model, it may still not be associated with this particular wave forcing as seen in observations.

4.3.2 The Importance of Stratospheric Variability: The 2002 Unusual Stratospheric Event

To try and quantify this dynamical response even further, the study now looks at an event of the year 2002 which could serve to be a clear indication of a proper dynamical response of the stratosphere to wave forcing. This so-called SSW extreme event in particular has been subjected to the anomalous dynamical wave activity that was experienced in the winter-spring season of the year 2002 (e.g. Kushner and Polvani, 2004; Newman and Nash, 2005). So the analysis period (i.e. 120 days before the final break-down) mostly cover the winter-spring season and also ensure that the SSW event is captured during that particular year (i.e. year 2002). Observed heat-fluxes confirm the anomalous condition of the wave forcing activity which took place during the year 2002. It is shown how heat-fluxes fluctuated from earlier days (from 120th day) prior to the large anomalous wave activity event.

This anomalous wave activity is indicated by heat-fluxes which reaches the value of about 80Km/s more than usual (Fig. 4.3b, blue line). It is also clear that the dramatic warming follows few days after this major wave forcing (Fig. 4.3c, blue line), and also associated with these shocks, is a major sudden drop in the polar vortex speed (Fig. 4.3f, blue line). Prior to the sudden drop in wind speed, the polar vortex seems to experience some anomalous variations which according to Scaife *et al* (2005) may be associated with the pre-conditioning of the vortex. It is also important to note that this temporarily reversal (Charlton and Polvani, 2007) of polar winds coincides exactly with the time when the major warming occurs, which is also a few days lag prior to the final break-down of the vortex. Literature studies have estimated this day to be just after the 22nd of September 2002 (Baldwin *et al*, 2003; von Savigny *et al*, 2005; Newman and Nash, 2005). This day is also reported to have been followed by an apparent split of the ozone-hole (Chalton *et al*, 2005; Roscoe *et al*, 2005) as a result of the warming. In this light nonetheless, this main extreme event to ever occur in the SH clearly suggests the major dynamical coupling through which the stratosphere can be influenced by the troposphere as well as determining the variability thereof. And that seem to be only through planetary wave driving.

Regarding the coupled model, it is clear that there seem not to exist such an extreme event as seen in observations. This is indicated by the absence of strong levels of heat-fluxes as it was observed few days before the final break-down of the vortex (Fig. 4.3b, red line). Instead the modelled eddy-heat fluxes seem to fluctuate around the mean. Consistent with this model result is a non-lag warming response to wave forcing as well as its associated decrease in polar vortex strength (Fig. 4.3d and f, red line, respectively).

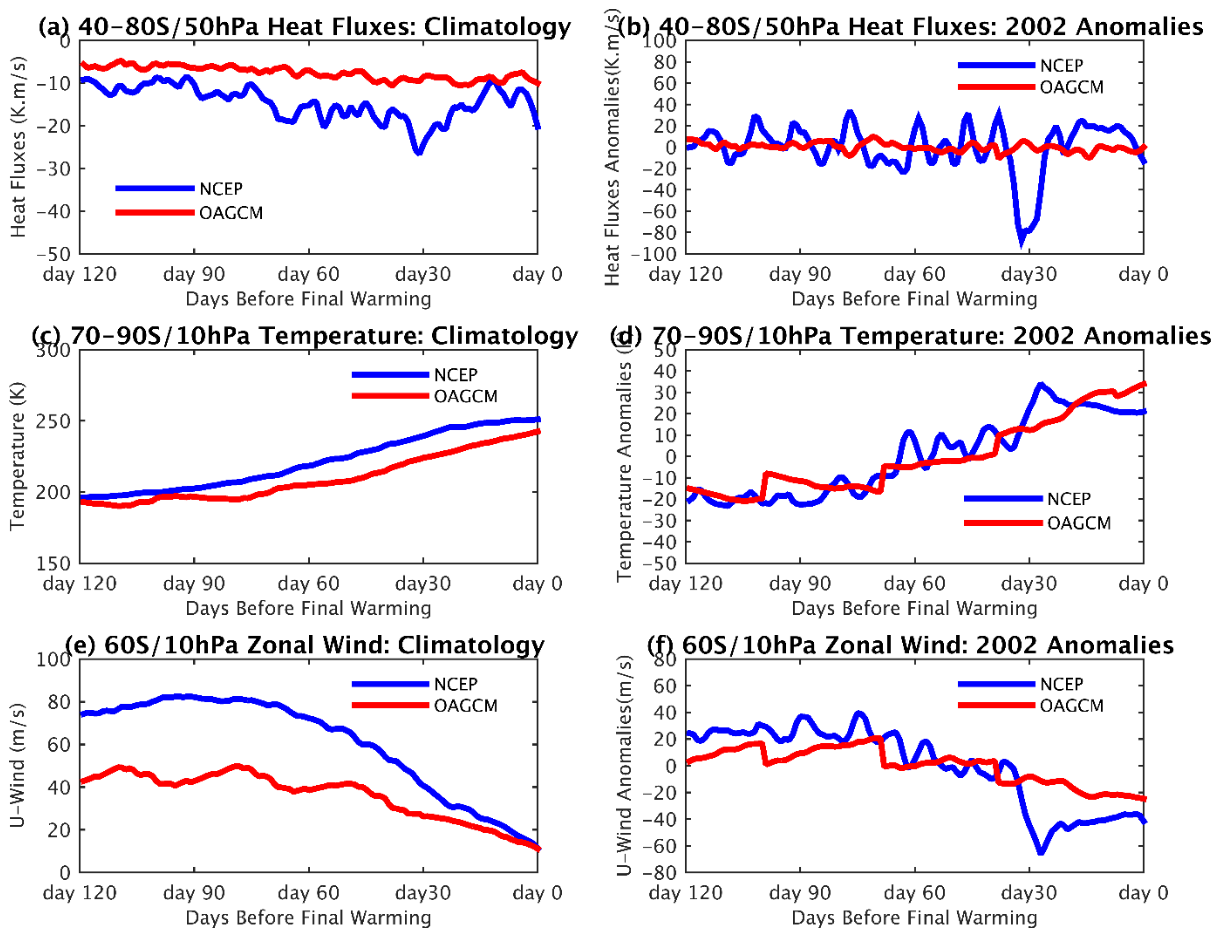

Figure 4.3: Daily values of 10hPa zonal-mean wind (at 60ºS) and the associated daily eddy-heat fluxes calculated 120 days before the final warming/breaking of polar vortex for both (a). NCEP and (b). Coupled model. Contour intervals are 10K.m/s and 50K.m/s for climatology and year 2002, respectively. Daily climatologies are determined form 1982-2009 period.

In fact, a recent study by Seviour *et al* (2014) has shown simulation of somewhat a realistic stratospheric variability even though not using the model with a much resolved stratospheric chemistry. However, the analysis showed that even though the modelled stratospheric winds were somehow biased towards weaker winds, but the model managed to capture the 2002 SSW event. Meanwhile this is the case, it is understood that despite the model's lack of interactive stratospheric chemistry, its vertical heat-fluxes relates very well to the models ozone quantity, hence the model managed to at least capture this SSW event.

4.4. Synopsis

The importance of proper representation of dynamics in climate models has been explored. This was motivated by the need to understand those underlying factors which could have contributed to the model's failure to simulate both stratospheric (cooling) and tropospheric (eddy-driven jet migration) changes as demonstrated in the previous chapter. Wave forcing in the upward direction in particular, was given main emphasis. It has been demonstrated that due to the lack of interactive chemistry in the model, its simulation of dynamics is not proper. The climatological wave forcing in the model's lower stratosphere is weaker than observed during the winter/spring months. Polar winds during winter in the upper stratosphere are also much weaker on the contrary despite the general structure which is simulated well. However, as alluded to earlier, such a simulation is in contrary to other models (which include interactive chemistry) whose wave forcing is also weaker than observed in such a way that it leads to the polar vortex which persists into the summer months. Such cases are evident in some of the CCMs with overestimated ozone concentrations (Eyring *et al*, 2006). Therefore the coupled model's inconsistencies may be suggestive of the lack of a resolved stratospheric chemistry amongst other factors.

Moreover, it has been shown that the lack of wave forcing in the model has also led to the lack of vertical wave propagation of planetary waves into the stratosphere. The timing of the polar vortex break down has been compromised too as a result of the absence of wave activity. The final break down of the polar vortex also plays a critical role in determining ozone distribution (Sun *et al,* 2014) by sustaining the cold polar temperatures which are conducive for ozone-depletion (Waugh and Polvani, 2010). As explained earlier, cold polar stratospheric temperatures are surrogates for ozone loss during spring (in the SH) as they promote the building-up of the PSC (McElroy *et al,* 1986; Newman, 2010, Salby *et al*, 2011) which through photochemical reaction (that takes place as the sun returns to the SH winter) causes depletion of ozone. This photochemical reaction process is detailed in both McElroy *et al* (1986) and Newman (2010). The ill-timed vortex break-up by the model could also be linked to the poorly-modelled planetary wave activity entering the stratosphere as the waves maintain easterly momentum which ensures the deceleration of the polar winds, particularly in spring (Newman, 2010). In this light nonetheless, it is clear that the results suggest the lack of vertical propagation in the model as a result of a much weaker or rather the absence of wave forcing. Vertical propagation of heat-fluxes may be considered to be crucial for coupling, especially in the upward direction. Evidence of the wave propagation into the stratospheric polar vortex during this particular time/season has also been explained by Haynes (2005) using the dynamical PV field of the stratospheric flow. The evidence served to provide a clear indication of the mechanism involved in the process of polar vortex breakup. However, even though the issue of mechanisms still remains one of the main research questions in the study of stratospheric dynamics, planetary wave forcing seems to suggest a way in which the stratosphere can respond to the troposphere (Perlwitz and Harnik, 2004).

Lastly, the dynamics of a more specialized type of the stratospheric event such as the SSW has been used in order to demonstrate the importance of wave activity in dynamical coupling between the troposphere and stratosphere. The result of the coupled model have confirmed that its stratosphere is not in any way communicating with the troposphere, even under major sources of dynamical variability. The year 2002 major stratospheric warning event is not evident in the coupled model which is indicative of the lack of the most important dynamical source (i.e. wave forcing). Therefore this in turn confirms the absence of coupling in the upward direction (i.e. from the troposphere to the stratosphere).

The coupled model simulation of the stratosphere in this case could be more related to variability of ENSO as it captures this phenomenon well (Beraki *et al*, 2014) than that associated with planetary wave mechanisms. However, even though this may still remain the case with the coupled model, the relationship between ENSO and the stratosphere may not also be expected to be realistic. The reason being that ENSO events (especially warm-phase such as El Niño) usually tend to have a particular signature in the stratosphere (Garfinkel and Hartmann, 2008; Hurwitz *et al*, 2011), which appears as a planetary wave response particularly in spring. Hurwitz *et al* (2011) however explain the relationship to be more robust during the so-called "warm" El Niño events rather than the "cold" ones. It is therefore not inconceivable that the model lacks planetary wave forcing even though its ENSO simulation is robust. Therefore the result above may suggest that the upward dynamical coupling of the model is likely crippled by the ill-representation of the planetary wave forcing. Even though it is still not clear as to what exactly controls eddy-heat fluxes/wave activity (Waugh *et al,* 1999), anthropogenic forcings (such as GHG and ozone) may also contribute towards alterations of the amount of heat-fluxes entering the stratosphere (Shindell *et al*, 1998).

In fact Waugh *et al* (1999) related the persistence of the polar vortex in the past decades to the amount of heat-fluxes in the lower stratosphere. Moreover, since dynamical coupling has to take place in order for the stratosphere to influence the troposphere, it is therefore not inconceivable that the lack of wave forcing in the model may cripple its ability to promote coupling. This coupling has to start in the upward direction then propagates downwards into the troposphere. The way in which perturbed stratospheric anomalies (as a result of wave forcing) progress downward into the troposphere has been subjected to the dynamics of wave-mean interaction theory (Christianson, 2001; Baldwin and Dunkerton, 2001; Plumb and Semeniuk, 2003; Polvani and Waugh, 2004). Therefore the results shown by the model also suggest inconsistencies with the wave-mean interaction theory.

CHAPTER FIVE

5. SEASONAL FORECASTING SYSTEM PERFORMANCE USING STRATOSPHERIC VARIABILITY

5.1 Introduction

The hypothesis that stratospheric wind and temperature anomalies could be used as another source of summer rainfall predictability under realistic ozone prescription and anthropogenic forcing will be investigated in this chapter. As previously stated the trends in the jet position associated with ozone-depletion apply to longer term stratospheric/tropospheric active dynamical coupling and therefore could also be important for seasonal prediction. The reason for this is that South African summer rainfall is regulated by the position of the eddy-driven jet and associated storm tracks, relative to the land (Tyson and Preston-Whyte, 2000). As stated before, if the jet is placed more poleward than normal, then the country experiences a wet summer season. Otherwise the cloud bands from which summer rainfall results are displaced eastward, leading to a dry summer. It is therefore hypothesized that ozone-depletion induced poleward trends of the jet position (as it was demonstrated in the previous chapter) would affect the inter-annual seasonal rainfall occurrence over SA. This effect may also cause the low frequency vacillations of the jet to be progressively poleward.

Notwithstanding, predictability of the mid-summer rainfall over SA has been assessed to almost its full capacity owing to the fact that it is predictable, especially during active phases of ENSO years. In fact, Landman and Beraki, (2012) has shown through the performance of state-of-the-art forecasting system(s) that ENSO constitutes most of the skillful predictions of SA rainfall anomalies during the summer. It was shown that enhanced predictability of dry conditions is achievable during warm episodes of ENSO (i.e. El Niño) as well as predictability for wet conditions during cold episodes (i.e. La Niña) of ENSO. However, it has also been shown that the predictability of the opposite anomalies of rainfall during El Niño and La Niña are evident and that there is less or no skill during non-ENSO years. This performance resulted from a statistical system which used ENSO-forced large-scale fields (such as the geopotential heights) since they are assumed to be accurately simulated by the GCM's and therefore remain suitable for downscaling purposes (Landman and Goddard, 2002). These large-scale fields are usually outputs from the GCM's and may be used as predictor fields in a statistical system in order to downscale them to the observed rainfall (e.g. Landman *et al*, 2012). Here an attempt to try and explore the possibility of considering stratospheric fields such as wind fields and temperatures in a statistical forecasting system is being conducted. These fields are presumed to be proxy for stratospheric circulation under chemically forced stratospheric circulation (such as ozone and GHG's). As alluded to earlier, NCEP-Reanalysis fields will be considered to demonstrate this possibility. However, even though the NCEP-reanalysis fields may not be the relevant dataset to use for this demonstration as it is observations, it may still give an indication as to whether or not the above mentioned stratospheric fields could be used as predictors for summer rainfall over SA. OAGCM model hindcasts stratospheric fields will be also used as input into a statistical forecast system. Since spring season is being explained to be generally the potential season to make possible the couplings between the stratosphere and the troposphere and therefore promotes extended predictability (Gerber *et al*, 2012), our main attention will then focus on using stratospheric fields during this season. These large-scale stratospheric fields have been computed using the polar vortex break-down date as a reference in order to capture the spring-stratosphere events.

5.2 Stratospheric Winds as Predictors

The potential predictive skill when large-scale stratospheric wind field are used as predictors are presented here using NCEP-reanalysis data. The verification results for the three systems tested here are presented showing both AN and BN categories. Fig. 5.2.1 shows the area-average ROC scores for each of the model used when different period(s) of large-scale stratospheric winds are used for the 14 year retro-active analyses period of 1995/96 to 2008/09. The three forecasting systems (i.e. 30-day, 60-day and 90-day average) generally shows the ROC scores of above 0.5 for AN category with the 90-day average being the highest with skill score reaching as high as 0.6. However, the two statistical models (i.e. 30-day and 60-day average), except for the 90-day one, and have not scored above 0.5 for the BN category. Therefore this suggests that the two above mentioned models (i.e. 30 and 60) could only stand a better chance of predicting AN rainfall category. However, the 90-day model stands a good chance of predicting for both categories at elevated skill levels (close to 0.6). Before any further conclusions can be made, the results demonstrated by the 90-day model may be a confirmation of a low frequency predictable signal rather than a high frequency (month or two month) average and therefore makes sense in seasonal forecasting.

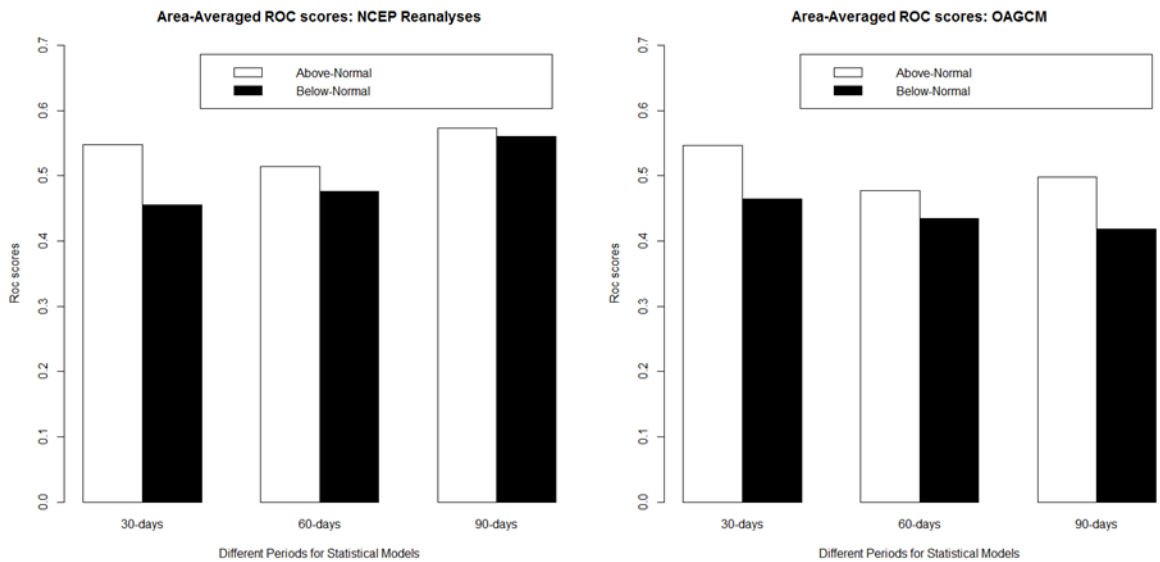

Figure 5.2.1: ROC Scores. Area averaged over SA. Above (white) and below (black) normal rainfall categories scores obtained for the 30-day, 60-day and 90-day models. The statistical models were constructed using stratospheric winds as predictors for rainfall.

Nonetheless, the purpose of considering the other two models which use a monthly (30-days) and two months (60-days) predictor averages respectively is to try and search for the period where the "active" stratosphere might hold much skill for predicting this summer rainfall. These periods are referred to as "active" mainly because they fall in the spring season when the Stratosphere is potentially coupled to the troposphere and therefore could provide extended predictability (Gerber *et al,* 2012). On the other hand, the OAGCM model also show a tendency of favoring the AN category in all the models considered but with ROC skill scores which are lower than that of the NCEP-Reanalysis. However, the 30-day average model seems to have much similar ROC scores as compared to NCEP for both categories. The other two models (i.e. 30 and 90) have marginal skill, however only for the AN category. This result therefore suggests that all the models constructed here would likely not be able to predict BN rainfall. However, they have a chance to predict the AN category, particularly for the 90-day model. The ROC skill distribution maps (Fig. 5.2.2) also confirms this result, with much of the skill favoring the AN category as is found with the NCEP-reanalysis. The patterns of ROC scores which are greater than 0.5 dominates both the central and north eastern parts of SA. This skill distribution also seems to be similar to the typical summer rainfall forecasting system skill during ENSO years (Landman and Beraki, 2012). Moreover, shades of skill levels greater than 0.9 are also evident over these regions, particularly for the AN category which may be further indicative of the ability of the forecasting system to discriminate wet and dry seasons from other seasons. The OAGCM results also confirms the low skill associated with the first two models, particularly the 60-day model which shows only few patches of ROC scores greater than 0.5 over the central coastal regions for both AN and BN category. However, the 90-day model shows skill distribution that is similar to the 30-day model over the central and east coastal regions with at least shades of skill greater than 0.9 in the east coastal region.

Therefore, the ROC skill distribution maps confirm that the system using NCEP stratospheric predictors outperforms that one of OAGCM predictors. By linking this observed skill to the dynamics of the stratosphere, the 90-day model generally coincides with the period on which the polar stratospheric winds (i.e. polar vortex) are starting to respond to the underlying wave forcing, as demonstrated in the previous chapter (cf. Fig. 4.3e, blue line). This may be a clear indication that the stratosphere is communicating with the troposphere and therefore coupling gets initiated. It also appears that the 30 and 60-day models also fall within the period when stratospheric winds are active as a result of propagating wave activity. However, these periods show some marginal skill, since they seem to be missing out on important periods which capture the initiation of the coupling which starts from the 90th day, hence the associated much-reduced skill as compared to the 90-days model.

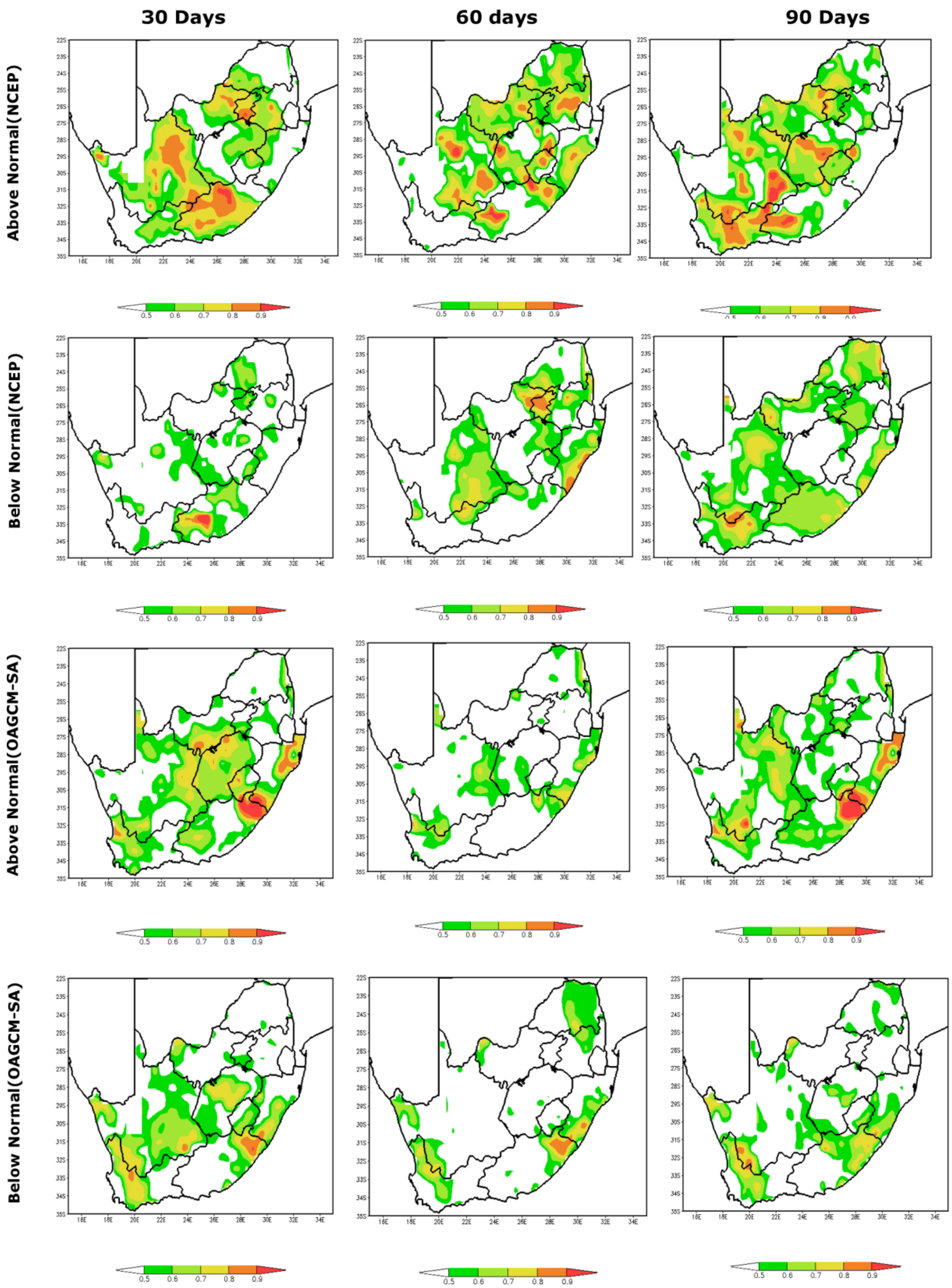

Figure 5.2.2: NCEP (top panel) and OAGCM (bottom panel) ROC Scores maps showing skill distribution when stratospheric winds are used as predictors for both above and below-normal categories, respectively

The above-mentioned association is not observed in the model. As indicated, only the 30-days model seems to have ROC scores which are above 0.5 for the AN category.

Polar stratospheric winds during this period in the model are not responding to the wave forcing (i.e. no sufficient wave activity, Fig. 4.3e, red line). This is an indication that there exists no coupling in the model as a result of the absence of wave forcing. Moreover, as suggested by observations, 30-days model is likely to miss out a lot of important stratospheric activities associated with wave dynamics as compared to the 90-days one even though it happens to show some skill. Also on the contrary, the much expected period(s) on which skill can be attained is not observed in the model (i.e. both 60 and 90 days), especially the 90-days model which is supposed to encompass all wave-induced stratospheric variability. Therefore the results shown by the model could be related to the absence of proper wave forcing.

5.3 Stratospheric Temperatures as Predictors

The three forecasting systems have also been tested using stratospheric temperatures as a predictor and their verification results are presented here. Again, both NCEP-Reanalysis and the OAGCM data sets have been used in statistical models. The NCEP results also seem to show a tendency for all the forecasting systems (i.e. 30, 60 and 90-day) favoring the AN category than the BN one (Fig. 5.3.1). However, there also seem to appear somewhat better skill in predicting for the BN category particularly in both the 60 and the 90-day model. The 90-day average model again generally appears to outscore other two models particularly with regards to the AN category. This result seems to agree with the previously demonstrated models (i.e. Figures in section 5.2) when stratospheric winds are used as predictors.

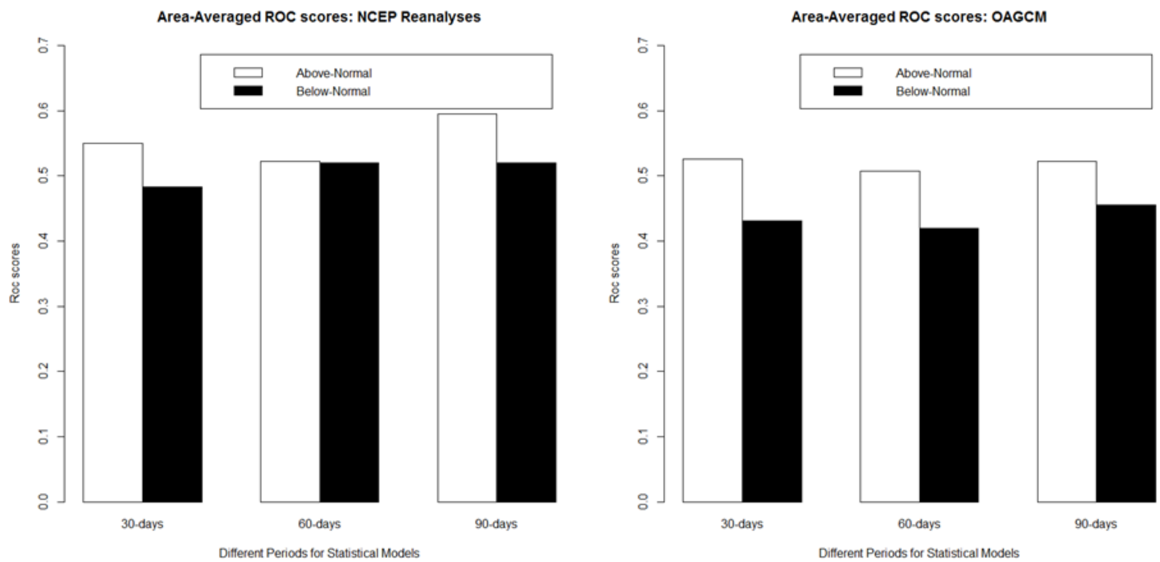

Figure 5.3.1: ROC Scores. Area averaged over SA. Above (white) and below (black) normal rainfall categories scores obtained for the 30-day, 60-day and 90-day models. The statistical models were constructed using stratospheric temperatures as predictors for rainfall

The OAGCM also show some consistency as it is still not able to capture skill for the BN category in all the three models. The AN category also shows low skill levels with ROC scores of nearly 0.5 and slightly above. Therefore the obtained result may also suggest that the three forecasting systems may barely predict BN rainfall category than AN one. The skill distribution shown by the ROC maps also confirms this skill for both NCEP and OAGCM (Fig. 5.3.2, a and b, respectively). However, the way in which the skill is distributed may be a suggestion that the forecast skill only benefits a specific region, rather than the whole country. Once more, the NCEP-Reanalysis shows that most of the skill is concentrated over most parts of both the central interior as well as over the eastern coastal regions. However, the skill is not distributed evenly as much in the three models except for the 30-day model of the AN category.

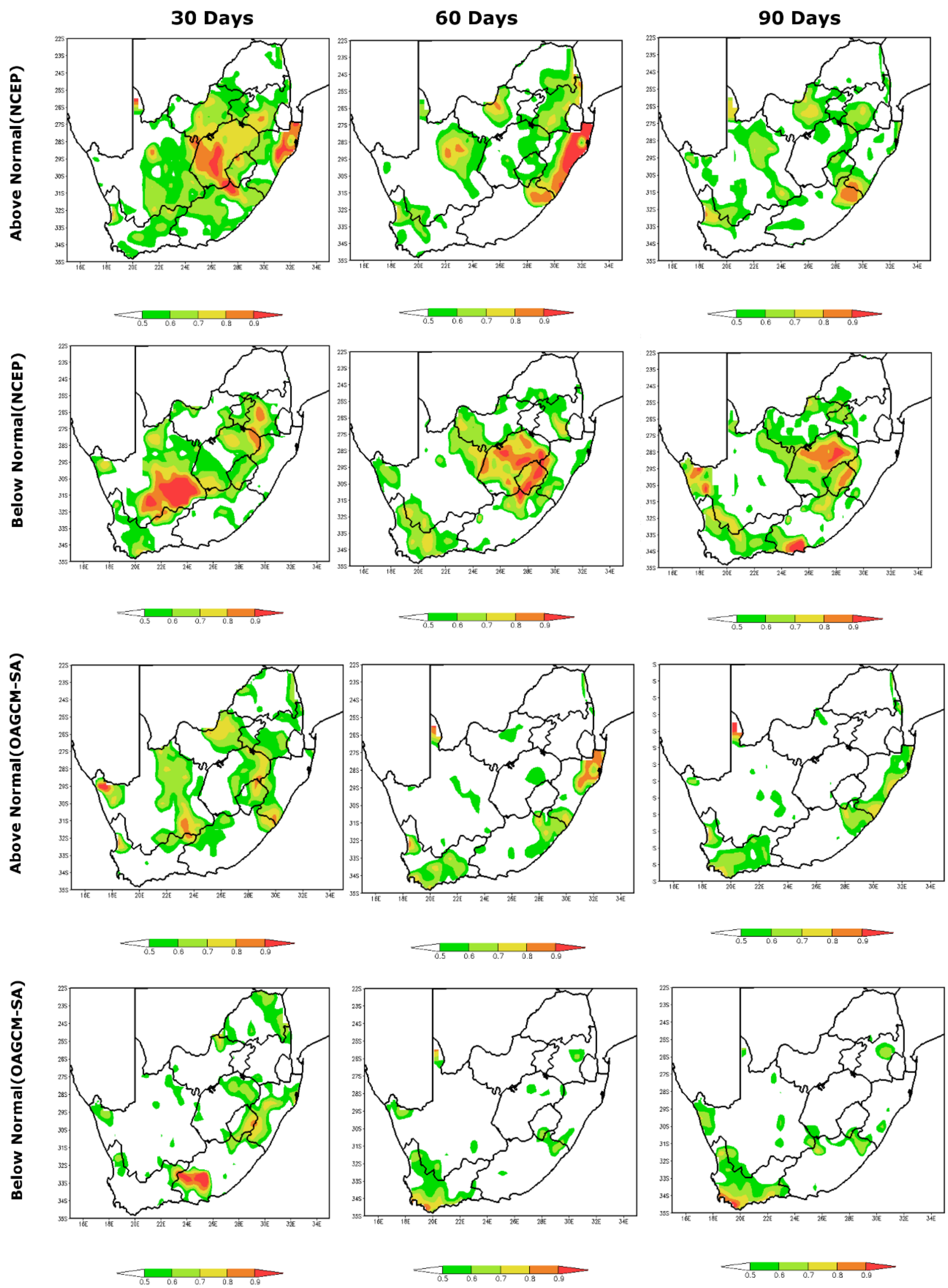

Figure 5.3.2: NCEP (top panel) and OAGCM (bottom panel) ROC Scores maps showing skill distribution when stratospheric temperatures are used as predictors for both above and below-normal categories

There also seem to appear large shades of areas with skill greater than 0.9 over the above mentioned regions except for the north eastern parts as seen earlier when stratospheric winds were used as predictors in the models. This skill pattern may also be similar to the one obtained during ENSO years as explained earlier. Contrary to this, the OAGCM model's skill distribution shows very few patches of skill levels greater than 0.5 over most parts of the country in general, except for the first 30-day model where small patches of skill can be seen over the central interior. The result depicted by the OAGCM model is however consistent with ROC graph shown in Fig. 5.3.1 which shows more skill dominating the 30-day-model than the other two. Also in trying to connect the dynamics associated with the skill when observed stratospheric temperatures are used as predictors, it can also be postulated that much of the skill obtained by all the three models may also be explained by the relationship between stratospheric temperatures and the underlying wave forcing as seen in Fig. 4.3 previously.

Stratospheric temperatures which are similar to polar winds also tend to respond to wave forcing from the 90th day. This may also be an indication that skills levels obtained by these models (particularly the 90-day) are aligned with the robust relationship that exist between temperatures and wave forcing. The fewer-days (i.e. 30 and 60 days) models have also improved as compared to when stratospheric winds were used as predictors. The reason behind this improved skill could be that stratospheric temperatures responds more directly to an enhanced wave forcing that usually occurs in the later days before the final break-down of the polar vortex. With regards to the OAGCM again, skills levels seem to have been reduced as compared to when winds were used. As explained earlier, there exists no relationship between the models stratosphere and wave forcing. However, even there seem to appear some temperature response in the model (Fig. 4.3e, red line), it may not be expected to be as a result of the wave forcing as it does not exist in the model.

5.4 Synopsis

Statistical forecasting systems which use stratospheric winds and temperature as predictor fields have been explored. It comprises of three periods which are believed to describe stratospheric circulation during the spring season i.e. the 30-day, 60-day and the 90-day period. As explained earlier, spring is believed to be generally the season that provides extended predictability because it is a period when the stratosphere is actively coupled with the troposphere (Gerber *et al*, 2012). The three forecasting systems, as indicated by the NCEP-Reanalysis, have shown the ability to predict AN rainfall over SA, with the 90-day model being most successful. These results also agree well with Landman *et al* (2012) which also found better predictability for wet seasons as opposed to dry season.

Notwithstanding, the forecasting system seem to indicate the highest potential for predictability of the expected rainfall anomalies when the middle-latitude eddy-driven jet is shifted poleward than normal (e.g. Tyson and Preston-Whyte, 2000). One would recall that such a response of the eddy-driven jet is usually due to a more strengthened polar vortex during winter and spring (e.g. Polvani and Kushner, 2002; Kushner and Polvani, 2004). Therefore the overall results indicated by the forecasting systems may be a confirmation of a response to such a winter/spring stratospheric circulation i.e. changes in the stratospheric polar vortex associated with ozone-depletion have impacted the SH surface climate (e.g. Garfinkel *et al*, 2013). Even though these changes have been observed on a longer-climate change timescale, polar vortex strength has been recorded to be changing with significant inter-annual variability, particularly in the 1980's (Waugh *et al*, 1999).

Stratospheric polar temperatures have also seemed to support these findings i.e. on average the forecasting systems still show the ability to predict AN rainfall better than BN rainfall. This result may also serve to confirm the relationship between the polar stratospheric winds and temperatures. As it is known, a persistent stratospheric polar vortex usually constitutes for lower-stratospheric temperatures (Waugh and Polvani, 2010) and thus setting a path for ozone-depletion (Newman *et al*, 2010). Therefore stratospheric temperatures and winds are very much related as they seem to show similar features (Randell and Newman, 1998), and this notion is also supported by thermal wind relation (Holton, 2004). However, the skill when stratospheric temperatures are used as predictor fields is generally higher than when winds were used, both in the NCEP and the OAGCM. The BN rainfall skill is also evident with marginal skill for NCEP-Reanalysis. Therefore this result suggests that temperature of the high latitude stratospheric circulation during spring may provide a more meaningful relationship with summer rainfall over SA than stratospheric wind.

Moreover, the results shown by the 90-day model could be an indication of the period when both the stratospheric winds and temperatures are robustly coupled with the troposphere. It also coincides with the period when ozone concentration is actively coupled with the troposphere (e.g. Son *et al,* 2013). The study demonstrated this coupling using ozone concentrations and the tropospheric fields. It has been shown that on longer timescale, the spring (September-October-November) ozone concentrations are strongly negatively correlated with the January tropospheric SAM. As the SAM index in the troposphere tracks down the position of the jet (Polvani and Waugh, 2004), the strong correlation found would then serve to relate ozone concentrations during spring and the shift in the position of the middle-latitude eddy-driven jet during the summer. Other studies have also attributed these tropospheric summer changes to ozone-depletion in particular (e.g. Thompson and Solomon, 2002; Son *et al*, 2008, 2009, 2010).

Therefore, this result suggests that the winds and temperature fields during this 90-day spring period may also be related to the stratospheric ozone concentration and the related wave dynamics found within this period. In fact, the extent at which the stratospheric circulation is (in terms of temperatures and wind strength) also determines the stratospheric ozone concentration. For example, a much cooled polar stratosphere usually leads to a powerful vortex (Gerber *et al*, 2012) which in turn determines the amount of ozone-depletion during spring (Solomon, 1999). And this inter-annual variability of stratospheric ozone concentration is very much related to wave dynamics (Salby *et al*, 2011). The 90-day model skill for AN rainfall shown here may also be related to information on stratosphere and its dynamics. Therefore this again may point back to showing the importance of representing stratospheric processes in prediction models.

The OAGCM model’s ROC scores for the AN rainfall category, when temperatures are used as predictor fields have also improved from the previously demonstrated models when stratospheric winds were used. However, here the 90-day model for AN category (of which according to NCEP is considered to be the best due to the above mentioned stratospheric processes and dynamics) could not attain skills levels as compared to its counterpart (i.e. NCEP). As mentioned earlier, polar stratospheric temperatures (together with their associated winds) which mainly occur during this 90-day period emulate an association with the spring ozone concentration as a result of wave forcing.

The OAGCM stratospheric wind field as seen in the analyses method (Fig. 2.2.6, 1b) showed a weaker circulation as compared to NCEP-Reanalysis. Therefore it is not unthinkable that the stratospheric temperature fields of the OAGCM are also the same by thermal wind relation (Holton, 2004). Since both stratospheric winds and temperatures may be associated with ozone changes and the planetary wave activity during this period, the results may confirm that the OAGCM stratospheric fields lack realistic representation of ozone concentration and associated GHG's thereof. Moreover, planetary wave forcing of the model is not realistic as a result of the lack of proper representation of these processes and therefore promotes no coupling between the stratosphere and troposphere.

CHAPTER 6

6. SUMMARY, RECOMMENDATION AND CONCLUSION

6.1 Summary

In an effort to search for better predictability of those climate variables which hold great societal importance, notably rainfall, the study investigated the importance of stratospheric dynamical processes in climate prediction models using a seasonal prediction model used at SAWS for operational forecasting. Since there was no significant difference between the coupled and uncoupled GCM's with regards to the stratosphere, the attention was focused on the more advanced coupled model. It has been shown that in an OAGCM that has a climatological representation of lower stratospheric ozone, the depletion thereof, as opposed to reanalysis data, does not occur. This result leads to a lack of lower stratospheric temperature cooling trends in the model, which is expected to be associated with the formation of the ozone-hole as demonstrated by other studies.

Moreover, reanalysis data shows a significant austral summer tropospheric response that manifests as an acceleration of the eddy-driven jet on the poleward side and its deceleration on the equatorward side. These features are caused by a gradual and persistent poleward migration of the sub-climatological jet core. Because of the lack of ozone-depletion in the model, the same features are not observed. Instead, the sub-climatological jet remains largely stationary as indicated by the weak acceleration and deceleration of the climatological jet stream on the equatorward and poleward sides, respectively. It may be postulated that should the model capture the observed trends of the poleward jet migration and stratospheric cooling, the average position about which the annual vacillation of the jet occurs can be expected to have a profound effect on rainfall hence improving rainfall predictability over southern Africa.

The other main objective of the study was to assess the dynamics of the OAGCM-coupled model stratosphere in order to try and quantify why the model was not able to capture the recent trends as observed. Nonetheless, the study was motivated by the need to understand the mechanisms which constitute stratosphere-troposphere coupling. Even though the exact mechanism for this coupling is still a research question, the study analyzed the importance of wave activity in the dynamics of the stratosphere. As the shorter time scale variability of the stratosphere is largely controlled by the wave dynamics than rather the long-term stratospheric processes such as ozone-depletion, propagation of planetary waves (particularly in the upward direction) appeared to be one of the fundamental mechanisms for the coupling. As known, these planetary waves are generated first in the troposphere by heat sources such as topography and land-sea contrasts where they propagate up into the stratosphere and therefore interact and perturb the stratospheric mean flow. The perturbed stratospheric conditions also in turn tend to influence the troposphere.

This result therefore shows that there could be a way in which the coupling between the two atmospheres can manifest itself. On the other hand, for many years it has always been known that stratospheric circulation only responds to, but do not impact the troposphere, hence the upward coupling (i.e. troposphere to stratosphere). But recent observations and modelling studies also confirmed the possibility of a downward coupling by the use of the so-called annular modes of variability (e.g. Baldwin and Dunkerton, 2001; Kushner and Polvani, 2004; Polvani and Waugh, 2004, Gerber and Polvani, 2008). This influence occurs as stratospheric anomalies propagate down into the troposphere by means of a dynamical mechanism, but as explained earlier this mechanism is still under investigations (Wallace, 2000; Plumb and Semeniuk, 2003; Waugh and Polvani, 2010). A well-defined downward coupling would manifest as large anomalies appear first in the stratospheric upper levels and descend downward with time into the lower levels where they get coupled to the troposphere (Seviour *et al,* 2014). This downward coupling can be regarded as important in such a way that it poses implications for tropospheric climate.

In this light nonetheless, the assessment of possible mechanisms for the stratosphere to be coupled to the troposphere partly clarifies some of the flaws in the OAGCM. The results mainly suggest that mechanisms that are supposed to be responsible for connecting the stratosphere and the troposphere are absent in the model. One of those mechanisms has been shown to be planetary wave forcing which seems to modulate coupling in the upward direction. The absence of this dynamical component therefore cripples the main source for stratospheric variability in the model, which on the other hand is supposed to impact the troposphere and therefore have practical implications for predictability. However, this variability is noted on the shorter time scale (i.e. inter-annual) rather than on longer timescales. This result is also a confirmation that the variability of the stratosphere may necessarily be related to shorter-time scaled wave dynamics than to long-term changes (such as ozone-depletion).

Whilst the proper coupling of the stratosphere-troposphere system is assumed to be one of the key elements for connecting the stratosphere to tropospheric climate (Gerber *et al,* 2012), the question whether variability of the stratosphere could also promote some sort of predictability for seasonal climate variables (such as rainfall and temperature) over SA remains important. Despite the overwhelming role of ENSO on predictability of rainfall over the country during the summer, the study also attempted to reveal the role that stratosphere can also play in the rainfall predictability. Stratospheric variables such as winds and temperatures also appeared to be useful when used during spring when the stratosphere is mainly variable. This is mostly the period when the stratosphere is highly active and therefore generally promotes time-lagged impact on the tropospheric climate. Observations have revealed that the skill which can be attained during this period when winds and temperatures are used as predictors for summer rainfall over SA is most likely related to the wave dynamics of the stratosphere. Dynamical wave propagation activity contributed to the variability of the stratosphere and therefore modulated predictive skill for the AN rainfall during the summer. This skill is similar to the one seen in studies such as Landman and Beraki (2012) showing predictability of wet conditions during the summer over SA.

6.2 Recommendations

Since the tropospheric and stratospheric trends in the model were not simulated properly, its simulation of rainfall cannot be expected to be completely realistic. One way of improving this state of affairs could be to improve representation of lower stratospheric ozone as well as GHG-concentrations in the model. The latter is important in this respect as it cools the lower stratosphere, albeit to a much lesser extent than the formation of the ozone-hole. Advanced modelling centers such as the Canadian Climate Modelling Centre (McLandress *et al,* 2011) and the National Aeronautics and Space Administration (NASA, e.g. Pawson *et al*, 2008) use models which employ interactive stratospheric chemistry. Such configurations may offer a better simulation than a mere climate model that is prescribed with monthly mean zonal-mean ozone because they calculate stratospheric ozone interactively (Perlwitz *et al,* 2008; Son *et al*, 2008).

Improvements of the chemistry in the coupled climate model could be facilitated through modelling endeavors such as the Stratospheric Processes and their Role in Climate (SPARC) and the Chemistry Climate Model Validation (CCMVal) efforts. As noted in the CMIP5 (e.g. Taylor *et al*, 2012) experiment design, a stratospheric ozone data set is also available for inclusion in models operated by centres which do not have capabilities of implementing sophisticated models which have got interactive stratospheric chemistry schemes. More details of how these programs are working on the how the atmospheric chemistry of the model could be improved especially for inclusion in a fully-coupled climate system such as an Earth System Model (ESM) will be given.

A second recommendation has to do with the way in which the stratospheric dynamics are captured in the OAGCM as well as the atmospheric chemistry of the coupled model. Stratospheric/tropospheric coupling is a robust dynamical phenomenon which can occur at all-time scales (Gerber *et al*, 2012). With the results depicted by the OAGCM (i.e. existence of coupling in the upward direction), it is not inconceivable that its dynamics are not properly captured and as such, it is also possible that operational seasonal forecasting could be adversely affected. The dynamics of the stratosphere play an important role in the coupling between the stratosphere and troposphere. Therefore in efforts to try and address these issues, Modelling the Dynamics and Variability of the Stratosphere-Troposphere System (DynVar) activity of the World Climate Research Programme's (WCRP) Stratospheric Processes and their Role in Climate (SPARC) has been initiated. As Gerber *et al* (2012) explained, the DynVar program mainly focuses on seeking to accurately represent the dynamics of the stratosphere and its processes, where multi-model datasets are used. Such model datasets have been seen in the fifth phase of the Couple Model Inter-comparison Project (CMIP5, Taylor *et al,* 2012) which involved numerous Earth System Models (ESM) participating. These ESM are usually configured in such a way that they ensure the incorporation of the chemical composition changes into the AGCM in order to constitute a more established dynamic–chemistry feedback mechanism.

What remains most important in stratosphere-resolved ESM development process is that a stand-alone module/model which comprises the full chemistry package is needed in order to describe stratospheric ozone chemistry and the tropospheric background in its entirety. Moreover, efforts of trying to evaluate how well the Chemistry Climate Models (CCM) simulates key processes of the stratosphere-troposphere system have been made by the CCMVal project which is also under the WCRP. Additionally on the other hand, the AC&C / SPARC has provided an ozone database for facilitating or forcing models that do not include interactive chemistry. These datasets are generated from separate stratospheric and tropospheric sources which include observations and Chemistry Climate models (CCM's) and spans the period from 1850 and projected into the future 2100. Examples of efforts of trying to improve the atmospheric chemistry of the AGCM have been seen in studies such as Jockel *et al* (2005, 2006) which used the so-called Modular Earth Sub-model System (MESSy) approach in order to make up a fully-coupled Atmospheric Chemistry (AC)-AGCM by connecting different sub-models to the base model, which is an AGCM. So far MESSy has been applied to a new generation of ECHAM5-AGCM i.e. ECHAM5/MESSy where it improved the simulation of the stratosphere-troposphere system to such an extent that it even managed to capture the much popular SSW event in the SH because of the improved wave dynamics.

Lamarque *et al* (2012) have also demonstrated the way in which a fully-interactive chemistry model-CHEM can be integrated into the AGCM (i.e. Community Atmospheric Model, CAM) in order to make up a complete ESM, Community Earth System Model (CERM). These experiments demonstrated that a fully-coupled system (i.e. with a well-resolved atmospheric chemistry) is likely to allow a proper stratospheric response to wave dynamics rather than when the model is run without chemistry, such as the one used in this study, i.e. the OAGCM. Also at play is the model's atmospheric top. It is recommended that the OAGCM model-top be increased to higher atmospheric levels in order to capture the above mentioned dynamics. Typical ESM comprises a very high model top which can be as high as 0.01hPa with a finer resolution of about 1° x 1.25° x L72 (e.g. Goddard Earth Observing System Model-version 5, GEOS-5, Pawson *et al*, 2008).

The recommendations stated above are efforts to try and improve our understanding of the coupled system through modelling and predictability studies which requires the knowledge of stratospheric circulation as well as chemical processes (e.g. CO_2 and ozone) and its dynamics. In this way the knowledge contributes to the so- called 'complete climate system'. This notion was endorsed by the WCRP's Climate Variability and Predictability (CLIVAR) in aiming to improve climate and intra-seasonal predictability. This complete climate system would however above all, require the advancement towards the direction of developing an ESM where each component of this climate system needs proper representation in order to make up a fully-coupled ESM. The issue of decadal prediction also requires better initialization of estimates of the current observed atmospheric states in coupled models (Hurrel *et al*, 2010). However, the advancement of decadal prediction also depends on the improvement of seasonal prediction (Goddard *et al,* 2012).

6.3 Concluding Remarks

Evidence that the stratosphere together with its processes play an important role on climate prediction systems was presented. Therefore the major conclusion from the study is that modelling efforts for seasonal climate prediction should include improvement on the representation of the stratosphere and its dynamics in models. South Africa, as in other countries is emerging a strong drive towards the development of ESMs (e.g. Beraki *et al*, 2014) and so such efforts should address possible problems regarding poor representation of stratospheric processes in order to optimize these models.

7. REFERENCES

Andrews DG, Holton JR., and Leovy, C.B, 1987. *Middle Atmosphere Dynamics.* Academic Press.

Arblaster, J. M., and Meehl, G.A, 2006. Contribution of external forcings to southern annular mode trends. *J. Climate,* Volume 19, pp. 2896-2905..

Arblaster, J. M., and Meehl,G. A, 2006. Contributions of External Forcings to Southern Annular Mode Trends. *J. Clim,* Volume 19, pp. 2896-2905.

Baldwin, M. P., and Dunkerton, T. J., 1999. Propagation of the Arctic Oscillation from the stratosphere to the troposphere.. *J.Geophys.Res,* Volume 104, pp. 30937-30946.

Baldwin, M. P., and Dunkerton, T. J, 2001. Stratospheric Harbingers of Anomalous Weather Regimes. *Science,* Volume 294, pp. 581-584.

Baldwin, M. P., Cheng, X., and Dunkerton, T. J, 1994. Observed correlations between winter-mean tropospheric and stratospheric circulation anomalies. *J. Geophys. Res,* Volume 21, pp. 1141-1144.

Barnett, T.P and Preisendorfer, R. W, 1987. Origins and levels of monthly and seasonal forecast skill for United States air temperature determined by canonical correlation analysis. *Mon. Wea. Rev,* Volume 115, pp. 1825-1850.

Beraki, A. F., Landman, W. A., DeWitt, D. G., Olivier, C., Mathole, K., and Ndarana, T., 2013. *Modelled sea-surface temperature scenario considerations and Southern African seasonal rainfall and temperature predictability,* Pretoria: Report to the Water Research Commission.

Beraki, A.F.,DeWitt, D.G., Landman, W.A., and Olivier, C, 2014. Dynamical seasonal climate prediction using an ocean-atmosphere coupled climate model developed in partnership between South Africa and the IRI. *J. Climate,* Volume 27, pp. 1719-1741.

Black, R. X., and McDaniel, B. A , 2007. Interannual Variability in the Southern Hemisphere Circulation Organized by Stratospheric Final Warming Events. *J. Atmos. Sci,* Volume 64, pp. 2968-2974.

Charlton, A. J., and Polvani, L. M., 2007. A New Look at Stratospheric Sudden Warmings. Part I: Climatology and Modeling Benchmarks. *J. Climate,* Volume 20, pp. 449-469.

Charlton, A. J., O'neill, A., Lahoz, W. A., and Massacand, A. C., 2004. Sensitivity of tropospheric forecasts to stratospheric initial conditions. *Quart. J. Roy. Meteor. Soc,* Volume 130, pp. 1771-1792.

Christiansen, B., 2001. Downward propagation of zonal mean zonal wind anomalies from the stratosphere to the troposphere: Model and reanalysis. *J. Geophys. Res,* Volume 106, pp. 27307-27322.

Darryn, W. W., and Rong, P-P, 2002. Interannual Variability in the Decay of Lower Stratospheric Arctic Vortices. *J. Meteorol. Soc. Jpn,* Volume 80, pp. 997-1012.

Eyring, V., and Coauthors, 2006. Assessment of temperature, trace species and ozone in chemistry-climate model simulations of the recent past. *J. Geophys. Res,* Volume 111, pp. D22308, doi:10.1029/2006JD007327.

Eyring, V., Waugh, D. W., Bodeker, G. E., Cordero, E., Akiyoshi, H., Austin, J., Beagley, S. R., ... Yoshiki, M, 2007. Multimodel projections of stratospheric ozone in the 21st century. *J. Geophys. Res,* Volume 112 .

Fauchereau, N., Pegram, G., and Sinclair, S, 2008. Recurrent daily OLR patterns in the southern African/southwestIndian Ocean region, implications for South African rainfall and teleconnection. *Clim. Dyn,* Volume DOI:10.1007/s00382-008-0426-2.

Feldstein, S. B, 2011. Subtropical rainfall and the antarctic ozone hole. *Science,* Volume 332, pp. 925-926.

Garfinkel, C. I., and Hartmann, D. L, 2008. Different ENSO teleconnections and their effects on the stratospheric polar vortex. *J. Geophys. Res,* Volume 113, pp. D18114, doi:10.1029/2008JD009920.

Garfinkel, C. I., Oman, L. D., Barnes, E. A., Waugh, D. W., Hurwitz, M. H., and Molod, A. M, 2013. Connections between the Spring Breakup of the Southern Hemisphere Polar Vortex, Stationary Waves, and Air–Sea Roughness. *J. Atmos. Sci,* Volume 70, pp. 2137-2151.

Garfinkel, C. I., Waugh, D. W., and Gerber, E. P, 2013. The effect of tropospheric jet latitude on coupling between the stratospheric polar vortex and the troposphere.. *J. Clim,* Volume 26, pp. 2077-2095.

Gerber, E. P., Butler, A., Calvo, N., Charlton-Perez, A., Giorgetta, M., Manzini, E., and Co authors, 2012. Assessing and Understanding the Impact of Stratospheric Dynamics and Variability on the Earth System.. *Bull. Amer. Meteor. Soc,* Volume 93, p. 845–859.

Gillet, N.P., and Thompson, D.W.J, 2003. Simulation of recent Southern Hemisphere climate change. *Science,* Volume 302, p. 273–275.

Goddard, L., Mason, S. J., Zebiak, S. E., Ropelewski, C. F., Basher, R., and Cane, M. A. , 2001. Current approaches to seasonal to interannual climate predictions.. *Int. J. Climatol,* Volume 21, pp. 1111-1152.

Haigh, J. D., and Roscoe, H. K, 2009. The final warming date of the Antarctic polar vortex and influences on its interannual variability. *J. Clim,* Volume 22, p. 5809–5819.

Hardiman, S. C., Butchart, N., Osprey, S. M., Gray, L. J., Bushell, A. C., and Hinton, T. J, 2010. The Climatology of the Middle Atmosphere in a Vertically Extended Version of the Met Office’s Climate Model. Part I: Mean State.. *J. Atmos. Sci,* Volume 67, pp. 1509-1525.

Harrison, M.S.J, 1984. A generalized classification of South African summer rain-bearing synoptic systems. Journal of Climatology. *J. Clim,* Volume 5, pp. 547-560.

Hart, N. C. G., Reason, C. J. C., and Fauchereau, N., 2010. Tropical–Extratropical Interactions over Southern Africa: Three Cases of Heavy Summer Season Rainfall. *Mon. Weather. Rev,* Volume 138, pp. 2608-2623. .

Haynes, P, 2005. STRATOSPHERIC DYNAMICS. *Annu. Rev. Fluid Mech,* Volume 37, p. 263.

Held, I. M., and Suarez, M. J, 1994. A Proposal for the Intercomparison of the Dynamical Cores of Atmospheric General Circulation Models. *Bull. Amer. Meteor. Soc,* Volume 75, p. 1825.

Hitchman, M. H., and Huesmann, A. S, 2007. A Seasonal Climatology of Rossby Wave Breaking in the 320–2000-K Layer. *J. Atmos. Sci,* Volume 64, pp. 1922-1940.

Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L, 1995. Stratosphere-troposphere exchange. *Reviews of Geophysics,* Volume 33, pp. 403-439.

Holton, J. R, 2004. *An introduction to dynamic meteorology.* Burlington, MA: Elsevier Academic Press. .

Hurrell, J. W., Delworth, T., Danabasoglu, G., Drange, H., Griffies, S., Holbrook, N., Kirtman, B., ... and Co authors, 2010. *Decadal climate prediction: opportunities and challenges.* doi:10.5270/OceanObs09.cwp.45., ESA Publ, p. 12.

Hurrell, J.W., van Loon, H., and Shea, D.J, 1998. The mean state of the troposphere. Meteorology of the Southern Hemisphere. *Meteor. Monogr. Amer. Meteor. Soc,* Volume 49, pp. 1-46.

Hurwitz, M. M., Newman, P. A., Li, F., Oman, L. D., Morgenstern, O., Braesicke, P., and Pyle, J. A., 2010. Assessment of the breakup of the Antarctic polar vortex in two new chemistry-climate models. *J. Geophys. Res,* Volume 115, p. doi:10.1029/2009JD012788.

Jöckel, P., Sander, R., Kerkweg, A., Tost, H. and Lelieveld, J, 2005. Technical Note: The Modular Earth Submodel System (MESSy) - a new approach towards Earth System Modeling.. *Atmos. Chem. Phys,* Volume 5, pp. 433-444.

Jöckel, P., Tost, H., Pozzer, A., Brülh, Ch., Buchholz, J., Ganzeveld, L.N., Hoor, P., ... Lelieveld, J., 2006. The atmospheric chemistry general circultation model ECHAM5/MESSy1: Consistent simulation of ozone from the surface to the mesosphere. *Atmos. Chem. Phys,* Volume 6, p. 5067–5104.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., ... Joseph, D, 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc. ,* Volume 77, pp. 437-471.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J. J., Fiorino, M., and Potter, G. L, 2002. NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc,* Volume 83, pp. 1631-1643.

Kang, S. M., Polvani, L. M., Fyfe, J. C., and Sigmond, M, 2011. Impact of polar ozone depletion on subtropical precipitation. *Science,* Volume 332, p. 951–954.

Kim, H., and Lee, S, 2004. The Wave-Zonal Mean Flow Interaction in the Southern Hemisphere. *J. Atmos. Sci,* Volume 61, pp. 1055-1067.

Kruger, A. C, 1999. The influence of the decadal-scale variability of summer rainfall on the impact of El Niño and La Niña events in South Africa. *Int. J. Climatol,* Volume 19, pp. 59-68.

Landman, W. A., and Goddard, L, 2002. Statistical recalibration of GCM forecasts over southern Africa using model output statistics. Journal of Climate. *J. Clim,* Volume 15, pp. 2038-2055.

Landman, W. A., and Goddard, L, 2005. Predicting southern African summer rainfall using a combination of MOS and perfect prognosis. *Geophys. Res Lett,* Volume 32, pp. L15809, DOI: 10.1029/2005GL022910..

Landman, W.A., and Beraki, A, 2012. Multi-model forecast skill for mid-summer rainfall over southern Africa. *Int. J. Climatol.,* Volume 32, p. 303–314.

Landman, W.A., DeWitt, D., Lee, D., Beraki A., Lotter, D, 2012. . Seasonal Rainfall Prediction Skill over South Africa: One- versus Two-Tiered Forecasting Systems. *Wea. Forecasting,* Volume 27, pp. 489-501.

Landman, W.A., Kgatuke, M.M., Mbedzi, M., Beraki, A., Bartman, A., du Piesanie, A, 2009. Performance comparison of some dynamical and empirical downscaling methods for South Africa from a seasonal climate modelling perspective. *J. Clim,* Volume 29, pp. 1535-1549.

Landman, W.A., Mason, S.J., Tyson, P.D and Tennant, W.J, 2001a. Retroactive skill of multi-tiered forecasts of summer rainfall over southern Africa.. *Int. J. Climatol,* Volume 21, pp. 1-19.

Landman, W.A., Mason, S.J., Tyson, P.D., Tennant, W.J, 2001b. Statistical downscaling of GCM simulations to stream flow. *J. Hydrology,* Volume 252, pp. 221-236.

Livezey, R.E., and Chen, W.Y, 1983. Statistical field significance and its determination by Monte Carlo techniques. *Mon. Wea. Rev,* Volume 111, pp. 46-59.

Manney, G.L., Zurek, Z.W., O'Neill, A., SwinbankJ, R., Kumer, B., Mergenthaler,J.L., and Roche, A.E, 1994. Stratospheric warmings during February and March 1993. *Geophys. Res. Lett,* Volume 21, pp. 813-816.

Marshall, A. G., and Scaife, A. A, 2010. Improved predictability of stratospheric sudden warming events in an atmospheric general circulation model with enhanced stratospheric resolution. *J. Geophys. Res,* Volume 115, pp. D16114, doi:10.1029/2009JD012643.

Marshall, G.J, 2003. Trends in the Southern Annular Mode from Observations and Reanalyses. *J. Clim,* Volume 16, pp. 4134-4143.

Mason, S. J., Cosijn., C., and Crimp, S.J , 1996. Review of seasonal forecasting techniques and their applicability to southern Africa.. *Water SA,* Volume 22, pp. 203-209.

Mason, S. J., Goddard, L., Graham, N. E., Yulaeva, E., Sun, L., and Arkin, P. A, 1999. The IRI Seasonal Climate Prediction System and the 1997/98 El Niño Event. *Bull. Amer. Meteor. Soc,* Volume 80, pp. 1853-1873.

Mason, S.J, 1995. Sea-surface temperature—South African rainfall associations, 1910–1989. *Int. J. Climatol,* Volume 15, pp. 119-135.

McElroy, M. B., Salawitch, R. J., Wofsy, S. C., and Logan, J. A , 1986. Reductions of Antarctic ozone due to synergistic interactions of chlorine and bromine.. *Nature,* Volume 321, pp. 759-762.

McLandress, C., Shepherd, T. G., Scinocca, J. F., Plummer, D. A., Sigmond, M., Jonsson, A. I., and Reader, M C., 2011. Separating the Dynamical Effects of Climate Change and Ozone Depletion. Part II: Southern Hemisphere Troposphere. *J. Clim,* Volume 24, pp. 1850-1868.

Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., Stouffer, R. J., ... Taylor, K. E, 2007. THE WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. *Bull. Amer. Meteor. Soc,* Volume 88, pp. 1383-1394.

Miller, R.L., Schmidt,G.A., and Shindell, D.T, 2006. Forced annular variations in the 20th century Intergovernmental Panel on Climate Change Fourth Assessment Report models. *J. Geophys. Res,* Volume 111, pp. D18101, doi:10.1029/2005JD006323.

Nakamura, H., and Shimpo, A, 2004. Seasonal variations in the Southern Hemisphere storm tracks and jet streams as revealed in a reanalysis data set. *J. Clim,* Volume 17, pp. 1828-1842.

Nash, E.R., Newman, P.A., Rosenfield, J.E., and Schoeberl, M.R, 1996. An objective determination of the polar vortex using Ertel's potential vorticity. *J. Geophys. Res,* Volume 101, pp. 9471-9478.

Ndarana, T., and Waugh, D. W., 2011. A Climatology of Rossby Wave Breaking on the Southern Hemisphere Tropopause. *J. Atmos. Sci,* Volume 68, pp. 798-811.

Ndarana, T., and Waugh, D.W, 2010. The link between cut-off lows and Rossby wave breaking in the Southern Hemisphere. *Q. J. R. Meteorol. Soc,* Volume 136, pp. 869-885.

Ndarana, T., Waugh, D. W., Polvani, L. M., Correa, G. J. P., and Gerber, E. P, 2012. Antarctic ozone depletion and trends in tropopause Rossby wave breaking.. *Atmos. Sci. Let,* Volume 13, pp. 164-168.

Newman, P. A., and Nash, E. R, 2000. Quantifying the wave driving of the stratosphere.. *J. Geophys. Res,* Volume 105, pp. 12485-12497.

Newman, P. A., and Nash, E. R, 2005. The Unusual Southern Hemisphere Stratosphere Winter of 2002. *J. Atmos. Sci,* Volume 62, pp. 614-628.

Pawson, S., Stolarski, R.S., Douglass, A.R., Newman, P.A., Nielsen, J.E., Frith, S.M., and Gupta, M.L., 2008. Goddard Earth Observing System chemistry-climate model simulations of stratospheric ozone-temperature coupling between 1950 and 2005. *J. Geophys. Res,* Volume 113, pp. doi: 10.1029/2007JD009511. issn: 0148-0227..

Perlwitz, J., and Harnik, N, 2004. Downward Coupling between the Stratosphere and Troposphere: The Relative Roles of Wave and Zonal Mean Processes. *J. Clim,* Volume 17, pp. 4902-4909.

Perlwitz, J., Pawson, S., Fogt, R. L., Nielsen, J. E., and Neff, W. D, 2008. Impact of stratospheric ozone hole recovery on Antarctic climate. *Geophys. Res. Lett,* Volume 35, p. doi:10.1029/2008GL033317.

Perlwitz, J, 2011. Tug of war on the jet stream. *Nat. Clim. Change,* Volume 1, pp. 29-31.

Pezzi, L.P.,Repelli, C.AP.,Nobre, P., Cavalcanti, I.F.A., and Sampaio,G, 1998. Forecasts of Tropical Atlantic SST Anomalies Using a Statistical Ocean Model at CPTEC/INPE - Brazil. *Experimental Long-Lead Forecast Bulletin,* Volume 7, pp. 28-31.

Plumb, R. A., and Semeniuk, K, 2003. Downward migration of extratropical zonal wind anomalies. *J. Geophys. Res,* Volume 108, pp. doi:10.1029/2002JD002773, D7.

Polvani, L. M., and Kushner, P. J, 2002. Tropospheric response to stratospheric perturbations in a relatively simple general circulation model.. *J. Geophys.Sci,* Volume 29, pp. 7-18.

Polvani, L. M., and Waugh, D. W, 2004. Upward Wave Activity Flux as aPrecursor to Extreme Stratospheric Events and Subsequent Anomalous Surface Weather Regimes. *J. Clim,* Volume 17, pp. 3548-3554.

Polvani, L. M., Waugh, D. W., Correa, G. J. P., and Son, S.-W, 2011. Stratospheric Ozone Depletion: The Main Driver of Twentieth-Century Atmospheric Circulation Changes in the Southern Hemisphere. *J. Clim,* Volume 24, pp. 795-812.

Postel, G. A., and Hitchman, M. H, 1999. A Climatology of Rossby Wave Breaking along the Subtropical Tropopause. *J. Atmos. Sci,* Volume 56, p. 359–373.

Purser, R. J., and Kar, S. K, 2002. Radiative upper-boundary conditions for a non-hydrostatic atmosphere. *Q.J.R. Meteorol. Soc,* Volume 582, pp. 1343-1366.

Randel, W., and Newman, P.A, 1998. The stratosphere in the Southern Hemisphere. In: *Meteorology of the Southern Hemisphere.* Washington, D. C: Meteorol. Monogr, p. 243–282.

Reason, C. J. C., Landman, W., and Tennant, W, 2006. Seasonal to Decadal Prediction of Southern African Climate and Its Links with Variability of the Atlantic Ocean.. *Bull Amer Meteor Soc,* Volume 87, pp. 941-955.

Reason, C. J. C. a. R. M., 2005. Links between the Antarctic Oscillation and winter rainfall over western South Africa. *Geophys. Res. Lett,* Volume 32, p. doi:10.1029/2005GL022419.

Rocha, A., and Simmonds, I, 1997. Interannual variability of south-eastern African summer rainfall. Part 1: relationships with air–sea interaction processes. *Int. J. Climatol,* Volume 17, pp. 235-265.

Roeckner and Co-authors, 1996. *Simulation of the present-day climate with the ECHAM4 model: Impact of model physics and resolution,* Hamburg, Germany: Max-Plank-Institut fur Meteorologie Rep. 218.

Roff, G., Thompson, D. W. J., and Hendon, H., 2011. Does increasing model stratospheric resolution improve extended-range forecast skill?. *Geophys. Res. Lett,* Volume 38, p. doi: 10.1029/2010GL046515.

Saha, S., Nadiga, S., Thiaw, C., Wang, J., Wang, W., Zhang, Q., Van, . D. H. M., ... Xie, P, 2006. The NCEP Climate Forecast System. *J. Clim,* Volume 19, pp. 3483-3517.

Schoeberl, M. R., and Newman, P. A, 2003. Middle atmosphere: Polar Vortex. In: *Encyclopedia of Atmospheric Sciences.* San Diego, Calif: Elsevier Science Ltd, pp. 1321-1327.

Seviour, W. J. M., Hardiman, S. C., Butchart, N., Maclachlan, C., Scaife, A. A., and Gray, L. J., 2014. Skillful seasonal prediction of the southern annular mode and Antarctic Ozone. *J. Clim,* Volume 27, pp. 7462-7474. .

Shindell, D. T., and Schmidt, G. A, 2004. Southern Hemisphere climate response to ozone changes and greenhouse gas increases.. *Geophys. Res. Lett,* Volume 31, p. doi:10.1029/2004GL020724..

Simpson, I. R., Hitchcock, P., Shepherd, T. G., and Scinocca, J. F, 2011. Stratospheric variability and tropospheric annular-mode timescales. *Geophys. Res. Lett,* Volume 38, p. doi:10.1029/2011GL049304.

Son, S.-W., Polvani, L. M., Waugh, D. W., Akiyoshi, H., Garcia, R., Kinnison, D., Pawson, S., ... Shibata, K., 2008. The Impact of Stratospheric Ozone Recovery on the Southern Hemisphere Westerly Jet. *Science,* Volume 320, pp. 1486-1489.

Son, S.-W., Polvani, L. M., Waugh, D. W., Birner, T., Akiyoshi, H., Garcia, R. R., Gettelman, A., ... Rozanov, E. , 2009. The Impact of Stratospheric Ozone Recovery on Tropopause Height Trends. *J. Clim,* Volume 22, pp. 429-445.

Son, S.-W., Purich, A., Hendon, H. H., Kim, B.-M., and Polvani, L. M, 2013. Improved seasonal forecast using ozone hole variability?. *Geophys. Res. Lett,* Volume 40, p. 6231–6235.

Son., S.-W., Gerber, E. P., Perlwitz, J., Polvani, L. M., Gillett, N. P., Seo, K.-H., Eyring, V.,Yamashita, Y., 2010. Impact of stratospheric ozone on Southern Hemisphere circulation change: A multimodel assessment. *J. Geophys. Res,* Volume 115, p. doi:10.1029/2010JD014271.

Song, Y., and Robinson, W. A, 2004. Dynamical Mechanisms for Stratospheric Influences on the Troposphere. *J. Atmos. Sci,* Volume 61, pp. 1711-1725.

Stockdale, T. N., Anderson, D. L. T., Alves, J. O. S., and Balmaseda, M. A, 1998. Global seasonal rainfall forecasts using a coupled ocean--atmosphere model. *Nature,* Volume 392, pp. 370-373.

Taylor, K.E, Stouffer, R.J and Meehl., G.A, 2012. Summary of the CMIP5 Experiment Design. *Bull. Amer. Meteor. Soc,* Volume 93, pp. 485-498.

Tennant, W, 2004. Considerations when using pre-1979 NCEP/NCAR reanalyses in the southern hemisphere. *Geo Res Let,* Volume 31, pp. L11112, doi:10.1029/2004GL019751.

Thompson, D. W. J., and Wallace, J. M, 2000. Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *J. Clim,* Volume 13, pp. 1000-1016.

Thompson, D. W. J., Lee, S., and Baldwin, M. P, 2003. Atmospheric Processes Governing the Northern Hemisphere Annular Mode/North Atlantic Oscillation.. *Geophys. Monogr,* Volume 134, pp. 81-112.

Thompson, D.W. J., and Solomon, S, 2002. Interpretation of recent Southern Hemisphere climate change. *Science,* Volume 296, pp. 895-899.

Trenberth, K.E, 1991. Storm tracks in the Southern Hemisphere. *J. Atmos. Sci,* Volume 48, pp. 2159-2178.

Tyson, P. D., Preston-Whyte, R. A., and Preston-Whyte, R. A, 2000. Climatic Change and Variability. In: *The weather and climate of southern Africa..* Cape Town: Oxford University Press, p. 332.

van den Heever, S. C., D'Abreton, P. C., and Tyson, P. D, 1997. Numerical simulation of tropical-temperate troughs over southern Africa using the CSU RAMS model. *S. Afr. J. Sci,* Volume 93, pp. 359-365.

von Savigny, C., Rozanov, A., Bovensmann, H., Eichmann, K.-U., Noël, S., Rozanov, V., Sinnhuber, B.-M., ... Kaiser, J. W, 2005. The Ozone Hole Breakup in September 2002 as Seen by SCIAMACHY on ENVISAT. *J. Atmos. Sci,* Volume 62, pp. 721-734.

Wallace, J. M, 2000. North atlantic oscillatiodannular mode: Two paradigms—one phenomenon. *Q. J. R. Meteorol. Soc,* Volume 126, pp. 791-805.

Waugh, D. W., and Polvani, L. M, 2010. Stratospheric Polar Vortices. *Geophys. Mon. Ser,* p. doi10.1029/2009GM000887.

Waugh, D. W., and Randel, W. J, 1999. Climatology of Arctic and Antarctic Polar Vortices Using Elliptical Diagnostics. *J. Atmos. Sci,* Volume 56, pp. 1594-1613.

Waugh, D. W., Oman, L., Newman, P. A., Stolarski, R. S., Pawson, S., Nielsen, J. E., and Perlwitz, J, 2009. Effect of zonal asymmetries in stratospheric ozone on simulated Southern Hemisphere climate trends. *Geophys. Res. Lett,* Volume 36, p. doi: 10.1029/2009GL040419.

Waugh, D. W., Randel, W. J., Pawson, S., Newman, P. A., and Nash, E. R. , 1999. Persistence of the lower stratospheric polar vortices. *J Geophys. Res,* Volume 104, pp. 27191-27201.