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Bachelor Thesis

B. Sc. Physics of the Earth System:
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Southern hemisphere sudden stratospheric warmings in the ECHAM6 model

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Abstract

On rare occasions, a sudden stratospheric warming (SSW) occurs in the Southern Hemisphere (SH), drastically weakening or even reversing the strong winter polar vortex. During SSW events, circulation changes occur that can have significant effects from the upper stratosphere down to the surface. ECHAM6 model data are used to study these impacts. In the atmosphere-only experiment with a perpetual 2018 conditions setup, 13 SSWs are found in 142 simulated years. Since these events coincide with a negative phase of the southern annular mode (SAM), SAM and temperature indexes are created to better track the downward propagating SSW anomalies. The anomalies in the SAM index also make it possible to divide the SSWs into two groups: those followed by significant, long-lasting effects on the tropospheric circulation and those where this is not the case, although the latter are a minority.

As soon as the anomalies reach the surface, a change in the regional climate of the SH can be found. The Antarctic, for example, experiences significantly higher temperatures and pressures than average. This condition shifts the storm tracks on the SH to the north, resulting in significantly drier and warmer conditions than usual in western South Africa and Australia, whereas an increase in precipitation in southern Australia and New Zealand is simulated. Apart from South America, where no significant results were found, ECHAM6 generally simulates SSW effects on near-surface climate in the SH very well, consistent with literature on observed negative SAM phases or weak vortex years.

Zusammenfassung

In seltenen Fällen kommt es auf der Südhemisphäre (SH) zu einer plötzlichen Stratosphärenerwärmung (auf Englisch 'sudden stratospheric warming', SSW) wobei sich der im Winter stark ausgeprägte Polarwirbel drastisch abschwächt oder sogar komplett umkehrt. Wann immer ein SSW Ereignis auftritt, kommt es zu Zirkulationsänderungen, die signifikante Auswirkungen von der oberen Stratosphäre bis hinunter zur Oberfläche haben können. ECHAM6-Modelldaten werden verwendet, um diese Einflüsse zu untersuchen. In dem Modell mit freier Atmosphäre und gleichbleibender Oberflächenbedingungen des Jahres 2018 wurden in 142 simulierten Jahren 13 SSWs festgestellt. Da diese Ereignisse mit einer negativen Phase der antarktischen Oszillation (auf Englisch 'southern annular mode', SAM) einhergehen, werden SAM- und Temperatur-Indizes geschaffen, um die nach unten propagierenden Anomalien besser nachverfolgen zu können. Durch die Anomalien im SAM Index ist es auch möglich, die SSWs in zwei Gruppen zu unterteilen: in solche, denen signifikante, lang anhaltende Auswirkungen auf die troposphärische Zirkulation folgen und jenen, wo dies nicht der Fall ist, obwohl letztere eine Minderheit sind.

Sobald die Anomalien die Oberfläche erreichen, kann eine Veränderung des regionalen Klimas der SH festgestellt werden. So kommt es in der Antarktis zu deutlich höheren Temperaturen und Druckwerten als im Mittel. Dadurch verschieben sich die Sturmbahnen auf der SH nach Norden, was im westlichen Südafrika und Australien zu deutlich trockeneren und wärmeren Bedingungen als üblich führt, während im südlichen Australien und Neuseeland eine Zunahme der Niederschläge simuliert wird. Abgesehen von Südamerika, wo es keine signifikanten Ergebnisse gab, simuliert ECHAM6 die Auswirkungen des SSW auf das oberflächennahe Klima in der SH im Allgemeinen sehr gut und übereinstimmend mit Literatur über beobachtete negative SAM-Phasen oder schwache Wirbeljahre.

Contents

1 Introduction

The stratosphere is the second layer of the atmosphere and reaches from about 10 (depending on latitude) to 50 km high. At these altitudes, intense circumpolar vortices occur every winter as a result of the large-scale temperature differences between the poles and the lower latitudes. They are characterized by strong westerly winds that have their maximum at around 60° latitude in midwinter. The stratospheric polar vortices form in autumn as the solar radiation decreases, intensify in the respective hemispheric winter and collapse in spring as the sunlight returns, transitioning to summer easterlies (Waugh and Polvani, 2010).

The polar vortices can suddenly weaken during the strong westerly wind phase. Planetary Rossby waves initiated in the troposphere propagate upward and break in the stratosphere (McIntyre and Palmer, 1983). This can lead to strong and rapid temperature rises in the polar stratosphere in winter, so-called sudden stratospheric warmings (SSWs) that can weaken or even reverse the westerly winds of the vortex. Since in the northern hemisphere (NH) there are larger topographic as well as land-sea differences which act as planetary wave sources, the NH vortex is weaker and more disturbed than in the southern hemisphere (SH) (Waugh et al., 2017). Therefore NH SSWs occur more often with a frequency of approximately six per decade. Because the SH polar vortex is more stable, average wind speeds are about twice as high as on the NH and SSWs occur only about once every 25 years (Shen et al., 2020, Wang et al., 2020). SH SSWs and resulting surface impacts are therefore less studied than their NH counterpart.

But no matter in which frequency, such events can have significant effects on surface weather in e.g. temperature and precipitation anomalies (Wang et al., 2020). Both reanalyses and climate model runs show that especially SSWs characterized by a more negative index of the so-called Northern Annular Mode (NAM) have a greater likelihood of being followed by tropospheric impacts (Baldwin and Dunkerton, 2001). Analogous to a NAM, there is also the Southern Annual Mode (SAM, also known as the Antarctic Oscillation) which describes a climate variability on the SH. It considers the opposing pressure, or geopotential height (gph) anomalies over Antarctica and the mid-latitudes (Fogt and Marshall, 2020). A positive phase is associated with negative gph anomalies over the high latitudes and an increase in gph in the mid-latitudes, opposite for a negative phase. The SAM is thereby related to changes in the strength and position of the jet stream and thus significantly related to SH weather (Gillett et al., 2006). Therefore, along with a SSW leading to a negative shift of the SAM, the SH jet stream weakens, shifting the storm's track equatorward (Lim et al., 2019).

The literature explicitly examining the regional climate impacts of SSWs on the SH is not abundant, but there are studies on the effect of SAM phases in general. For example, temperatures in New Zealand are higher than normal during a positive phase and precipitation is lower than normal throughout western parts of the North and South Islands. During a negative SAM phase, the opposite is observed with cooler and wetter weather in the western part of the country (Thompson and Renwick, 2006). East of the Andes between 10°S and 40°S during negative SAM phases precipitation also intensifies (Silvestri and Vera, 2003) as well as in the far south of Australia. There, the stronger westerly winds lead to above-average winter precipitation in western Tasmania while the opposite is true during the positive phase (Meneghini et al., 2007). Another study has come to the same conclusion for western South Africa. Here, wet winters are associated with an equatorward shift of the subtropical jet and thereby a negative SAM phase as dry winters are associated with a positive phase. After such a wet (dry) winter, the SAM-induced anomalies continue into the austral spring, which also tends to be wet (dry) (Reason and Rouault, 2005).

One of the few regional studies which does not only deal with the SAM but also draws the connection to SH SSWs was conducted for Australia. Lim et al. (2019) examined nine years where the vortex was weak within 1979 – 2016 for influences on the Australian climate. For this, anomalies in e.g. temperature and precipitation averaged over October-January in the nine weak vortex years were computed relative to all other years. They found maximum temperatures up to 2°C higher than normal in central-eastern Australia and a reduction in precipitation over most of the eastern part of the continent. These anomalously hot and dry conditions can have large impacts on human health, energy and water supplies, agriculture and can increase wildfire risk in this region (Lim et al., 2019).

In this study, data from the ECHAM6 atmospheric model are used (Stevens et al., 2013). It has a perpetual 2018 year setup with a free atmosphere but prescribed surface conditions. As a result, trends such as global warming are not present. 2018 was also an ENSO-neutral year so there is no influence on the Southern Ocean from this variability. 142 simulated years are examined.

The aim of the thesis is to find out when and how many SSWs the atmospheric model represents and what influences are observed in the troposphere after such an event. Following the observations of Karpechko et al. (2017), this study looks at gph averaged over the polar cap at all pressure levels to create a simple approximation of a SAM. Using this, signal propagation from the stratosphere into the troposphere can be seen and the SSWs that occur can be divided into downward propagating and non-propagating SSWs. In the same way, temperature data are examined to see if and how anomalies extend to the lowest level of the atmosphere. Similar to Lim et al. (2019), this thesis then looks at the austral spring through summer to examine anomalies in the regional climate of the weak vortex years by analyzing temperature extremes, as well as changes in precipitation distribution and sea level pressure changes. The results are compared to analyses of real observed SSW or negative SAM impacts to see how well ECHAM6 represents the consequences on the near-surface climate in years with weak SH polar stratospheric vortex.

2 Model and data

The basis for this study is the ECHAM6 atmospheric general circulation model, developed at the Max Planck Institute for Meteorology (MPI-M). Details on the dynamics, the physical and radiation parameterizations as well as the land model (JSBACH) can be found in Stevens et al. (2013). A T63 grid is used in the simulation, which corresponds to a horizontal resolution of roughly 1.8° by 1.8°. Vertically, 95 levels are used up to 0.01 hPa or roughly 80 km.

The ECHAM6 simulation used in this study has an experimental design similar to the Atmospheric Model Intercomparison Project (AMIP), with free atmosphere but prescribed sea surface temperature and sea ice (Eyring et al., 2016). For this simulation, they were taken from daily ERA5 reanalysis data (Hersbach et al., 2020). It is a perpetual 2018 year setup, so each calculated year uses the same external forcing. Since there were neutral ENSO conditions in 2018 this large-scale circulation pattern is not present. Due to the fixed surface conditions, this also applies to trends such as global warming. 142 years are calculated.

Previous experiments show that the stratosphere is well represented in ECHAM6. For instance, it is the atmospheric component in the Flexible Ocean and Climate Infrastructure (FOCI) Earth system model. Matthes et al. (2020) show that aspects such as the winter polar vortex in the upper stratosphere as well as the tropospheric jets are very well captured. ECHAM6 also achieves good results in simulating SSWs. In FOCI, the total frequency of SSWs on the NH in the period 1958-2017 is very well computed. However, there are significant discrepancies in the seasonal distribution. Thus, ECHAM6 has a tendency to simulate SSWs too early in the year on the NH (Matthes et al., 2020), but the exact distribution of SSWs is a common problem in climate models (e.g. Charlton et al., 2007)

In this thesis, daily zonal-mean zonal winds (U), geopotential height (gph) and temperature at each pressure level are analyzed from the atmospheric model, as well as sea level pressure (slp), precipitation, maximum (Tmax) and minimum (Tmin) temperature at two meters above sea surface.

3 Methods

The following section provides an overview of the methods and definitions used to investigate changes in the atmosphere due to SSWs. Where applicable, a two-sided t-test at the 95% significance level is used.

3.1 SSW event definition

In the SH a SSW event is defined according to Rao et al. (2020) who state that an event occurs when the zonal-mean zonal winds at 60°S and 10 hPa decrease to ≤ 20 m/s. The central date when zonal mean winds drop below this threshold is referred to as day 0. Based on this criteria, 13 SSW events in the atmospheric model data in which the winds weaken to this extent have been identified as seen in Figure 1.

3.2 SAM Index

To better understand circulation changes and downward propagation of SSW anomalies, a SAM index is created. For the sake of simplicity, the criteria of Karpechko et al. (2017) are used, where an approximation of a NAM was developed. Thus it is also possible to divide the occurring events into those followed by significant anomalies in the troposphere and those not followed by significant effects in the annular mode to better examine the impact of SSW events on the troposphere.

As a simple approach for a SAM the mean gph averaged over the polar cap (60-90°S) is calculated after the values are multiplied by the cosine of the respective latitude so that gph is approximately area-weighted, without dominance of the higher latitude values. The gph anomalies are calculated with reference to the climatology, meaning the mean values for each calendar day over the entire 142 year period. This is done at each pressure level and then normalized by standard deviations. Analogous to the NAM where the phase is usually defined as negative if the polar cap gph anomalies are positive, all polar cap gph anomalies are multiplied by minus 1.

In order to investigate whether a SSW signal propagates into the troposphere, the SAM index is examined for three criteria defined by Karpechko et al. (2017):

(1) The mean SAM index at 1000 hPa (SAM1000) over the period of 45 days (days 8-52 after day 0) must be negative

(2) the proportion of days within this 45-day period on which the daily SAM1000 is negative shall be at least 50%

(3) the proportion of days within that 45-day period on which the daily SAM indices in the lower stratosphere (SAM150) are negative shall be at least 70%

If one or more of the above criteria are not fulfilled, a SSW event is defined as having little impact on the troposphere and thus being non-propagating (nSSW) otherwise as downward propagating (dSSW). Since studies have found a delay in stratospheric impacts on the troposphere (Baldwin and Dunkerton, 1999), the first week after day 0 is not considered. A period of 45 days (days 8-52) is considered to provide a sufficiently long period to account for the impact on the surface. Further details on the method are described in Karpechko et al. (2017).

It is important to point out, that Karpechko et al. (2017) tuned the criteria to agree with a subjective analysis of downward propagation in ERA-Interim reanalysis data (Dee et al., 2011) and were applied for this study without additional adjustment. Criterion (1) is used to ensure, in general, that the sign of the circulation anomaly is consistent with the expected SSW impact. Since there are cases where the SAM1000 is strongly negative for only a short period of time, but there is no corresponding anomaly in the lower stratosphere, which is expected in a stratosphere-troposphere coupling event, this criterion alone is not sufficient (Maycock and Hitchcock, 2015). To ensure only coupled stratosphere-troposphere events are considered, the additional criteria (2) and (3) were introduced by Karpechko et al. (2017).

After applying the criteria, 11 of the 13 SSWs in the model data could be identified as dSSW and two as nSSW (Table 1). However, since dSSWs dominate the composite of all events the SAM differences between all SSWs and only the dSSWs were not substantial (Figure 2, top and middle). Therefore all years with weak vortices are considered in the following.

3.3 Temperature Index

In analogy to the SAM, a standardized temperature index is created. The values are also weighted by the cosine of the latitude, and then the anomalies are calculated with respect to the daily climatology. As no predefined convention exists for the temperature index, no change of sign as for the SAM index is applied.

3.4 Surface impact of SSWs

In addition to the time-height evolution of the SAM and temperature indexes, the surface impacts on slp, precipitation and Tmax and Tmin are analysed, regarding significant differences in the 13 vortex weak years in the ECHAM6 data. The majority of events (10 of 13) occur in the austral winter, therefore most of the austral spring and the beginning of the austral summer are examined for impacts. For comparability, a similar method was used as by Lim et al. (2019), although in their study the data was averaged from October to January. Here, January is not included because no significant anomalies are found that month. Anomalies are calculated at each grid point by subtracting the climatology based on all simulated years. This is also slightly different from Lim et al. (2019), who calculated differences with respect to years without SSWs.

4 Results

In the ECHAM6 data, 13 SSW events can be identified in the 142 modeled SH winters. The zonally averaged winds at 60°S all weaken to at least 20 m/s during these 13 events, as shown in Figure 1. The earliest event occurs on July 17th and the latest on September 3rd (Table 1). Weak easterlies are found in two of the SSWs events.

4.1 Downward propagating anomalies

Based on the SAM selection criteria defined in Section 3, 11 dSSWs (85%) and two nSSWs (15%) can be categorized. The nSSWs differ from the dSSWs by the fact that in both events the mean SAM1000 in the 45 day period within 8 – 52 days after the central date is not negative (Table 1).

The composited time evolution of the SAM index relative to the SSW central dates is shown in Figure 2. Even before the central date, a prominent and significant negative anomaly can be seen throughout the stratosphere in the composite of all SSWs (Figure 2, top). The negative SAM values indicate strong positive gph anomalies in the SH polar cap. These anomalies then propagate downward over the next few days. In the troposphere, significant negative anomalies are triggered from around day 10. The lowest extreme value of below -3 standard deviations (std) occurs on day 3 at 20 hPa. While there is a smoother evolution of the SAM through the stratosphere, the coupling of lower-stratospheric anomalies with the surface is more sporadic. At 1000 hPa, stronger negative anomalies reach the surface about 25 days after the central date with the lowest value of -1.2 std on day 27. Positive SAM anomalies indicating vortex recovery appear about a month after the central date in the upper stratosphere. However, the significant fraction does not propagate downward that much and the positive anomalies are less pronounced than the negative ones and remain below 1 std.

Almost the same results are obtained for the dSSW composited SAM (Figure 2, middle). In the troposphere, more negative values below -1 std are found between day 20 – 60 compared to all SSWs. Again, a positive anomaly can be seen in the upper stratosphere as the vortex recovers in the later stages.

Central date (Day 0)	dSSW/nSSW	SAM1000 (days 8–52)	Daily SAM1000 (%)	Daily SAM150 (%)
14.08.2068	dSSW	-0.32	73	100
21.08.2072	dSSW	-1.67	100	100
24.08.2073	nSSW	0.07	42	84
16.08.2074	dSSW	-1.56	100	100
05.08.2097	dSSW	-0.56	78	100
16.08.2100	dSSW	-2.01	100	100
08.08.2104	dSSW	-1.24	96	100
17.08.2119	dSSW	-0.50	84	100
01.09.2131	dSSW	-2.23	100	100
13.08.2134	dSSW	-0.69	89	100
17.07.2142	dSSW	-0.87	89	96
03.09.2154	nSSW	0.02	51	100
02.09.2158	dSSW	-0.64	82	98

Table 1: List of SSWs in ECHAM6 model data and their classification into d/nSSW according to the three criteria following Karpechko et al. (2017)

In nSSWs, the SAM is more variable (Figure 2, bottom), due to the fact that only two events are in this composite. Negative anomalies of over -2.2 std are found, but these are smaller in both temporal and spatial extent. Less pronounced negative anomalies propagate into the troposphere and some positive anomalies occur in the period up to 52 days after day 0, which both do not occur in the dSSWs nor in the mean of all events. However, negative tropospheric SAM anomalies of more than -1.4 std can be seen after day 100. No substantial anomalies are observed in the dSSWs this late. It is also noticeable that in this composition the vortex further up in the stratosphere seems to recover stronger and longer than in the dSSW group. However, it is questionable how meaningful these observations are, since very little of the nSSW SAM is significant.

As mentioned in Section 3, all SSWs are used for further analysis, since dSSWs dominate the composite of all events. Compared to the SAM, a similar picture emerges for the standardized temperature index (Figure 3). As expected by the definition, a strong warming of the stratosphere can be seen. After roughly 40 days, positive temperature anomalies reach the surface. In comparison, the temperature anomalies during SSW events are similar to the circulation anomalies indicated by the SAM as the maximum value is also more than 3 std occurring around the central date in the stratosphere. A negative anomaly is also noticeable occurring around day 0 above 1 hPa. Negative temperature anomalies propagate from there into the middle stratosphere over the next 100 days, indicating a recovery of the vortex.

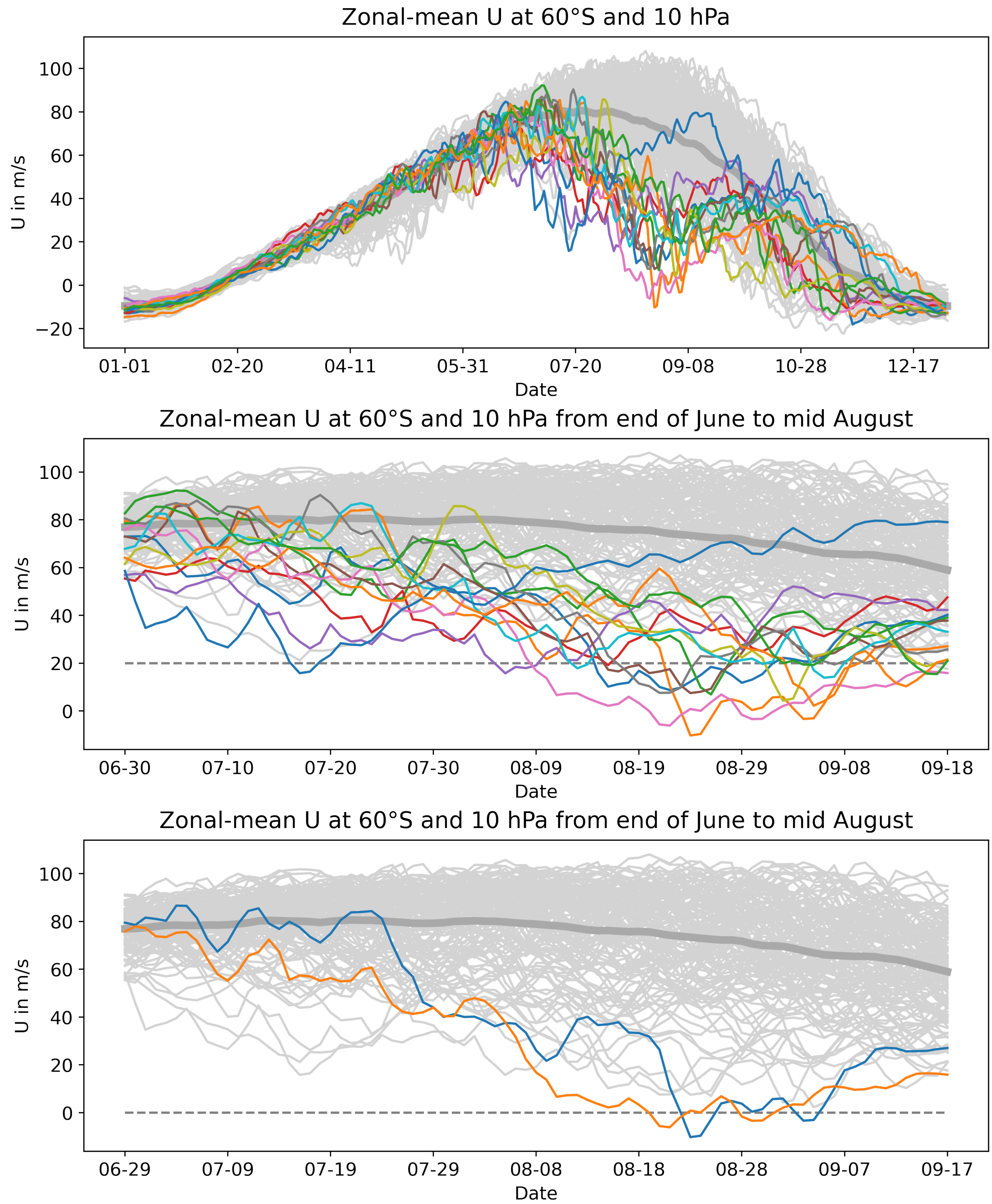

Figure 1: Day-by-day evolutions of the zonal-mean U in m/s at 10 hPa and 60°S for each year. The light gray curves indicate years without SSW events, the thick dark gray curve denotes the climatology. All SSW events are highlighted in colors (top and middle) or only those which turn into easterly winds (bottom) The dotted line indicates the 20 m/s or 0 m/s threshold.

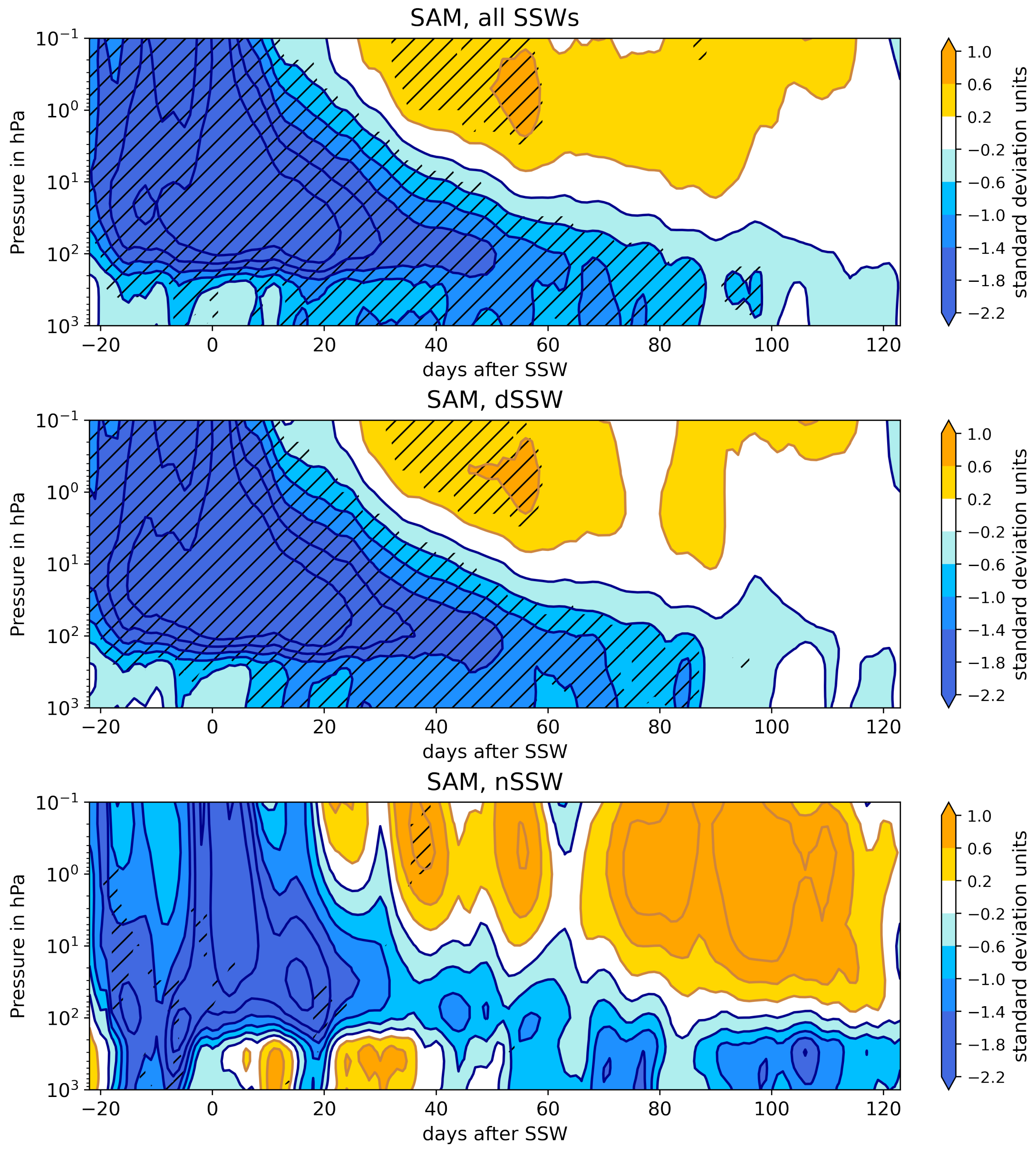

Figure 2: Evolution of the SAM Index (in standard deviation units) around the central SSW date (day 0) in total SSW composite (top), downward propagating composite (middle) and non-propagating composite (bottom). The contour interval is 0.4. Striped indicates significance.

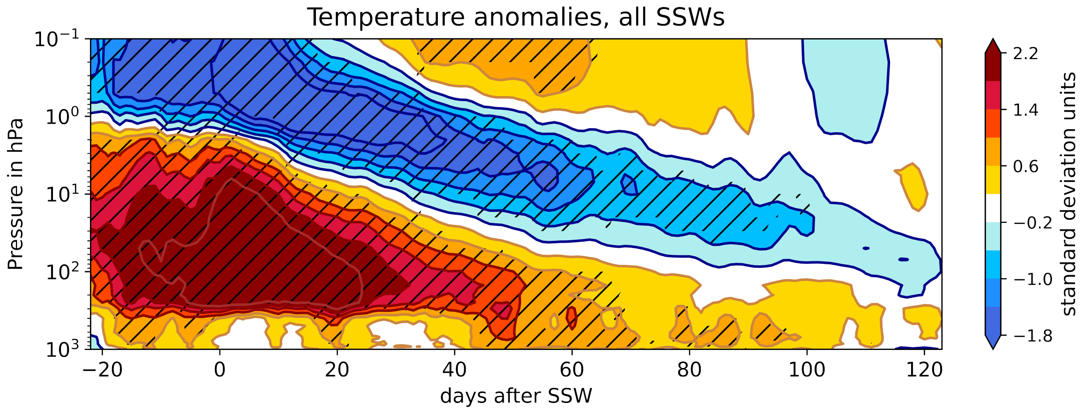

Figure 3: Evolution of the Temperature Index (in standard deviation units) around the central SSW date (day 0) in total SSW composite. The contour interval is 0.4. Striped indicates significance.

4.2 Surface anomalies

The composite precipitation, slp and temperature anomalies averaged from October to December for the 13 years with SSWs on the entire SH is shown in Figure 4. A ring-shaped precipitation deficit around Antarctica roughly at 60°S can be seen in the upper left of Figure 4, followed by positive precipitation anomalies at about 45°S which are significant over large areas. This pattern in the change in precipitation indicates a northward shift in precipitation around Antarctica. Looking at the entire SH, the largest anomalies are in the western equatorial Pacific around 140°E with 1.5 mm/day, and in the Indian Ocean around 10°S 70°E with -1.3 mm/day. However, these regions have smaller significance because near the equator total rain and its variability are much higher than in the extratropics. Since both extremes are very far north, these anomalies are unlikely to be related to a SSW.

The slp anomalies also show clearly a ring-shaped pattern in Figure 4 in the upper right. Strong positive anomalies are over Antarctica, including more than 6 hPa deviation from the mean around 80°S and 75°E. These slp anomalies are totally in agreement with the SAM index from Figure 2. The strong pressure increase over Antarctica pushes the low-pressure systems around Antarctica further north. The lowest value is -3.7 hPa around 45°S and 65°E on this band of slightly weaker but clearly significant negative anomalies. This also explains the shift of the precipitation on the SH, which causes more rain than usual in the latitudes just mentioned.

In the temperature data, a similar but weaker annular pattern is found as shown in Figure 4 (bottom panel). Two regions with warmer conditions than average can be seen, one in Antarctica and the other at about 30°S. In between at about 60°S is a band of negative anomalies. The largest temperature anomaly on the SH is near the

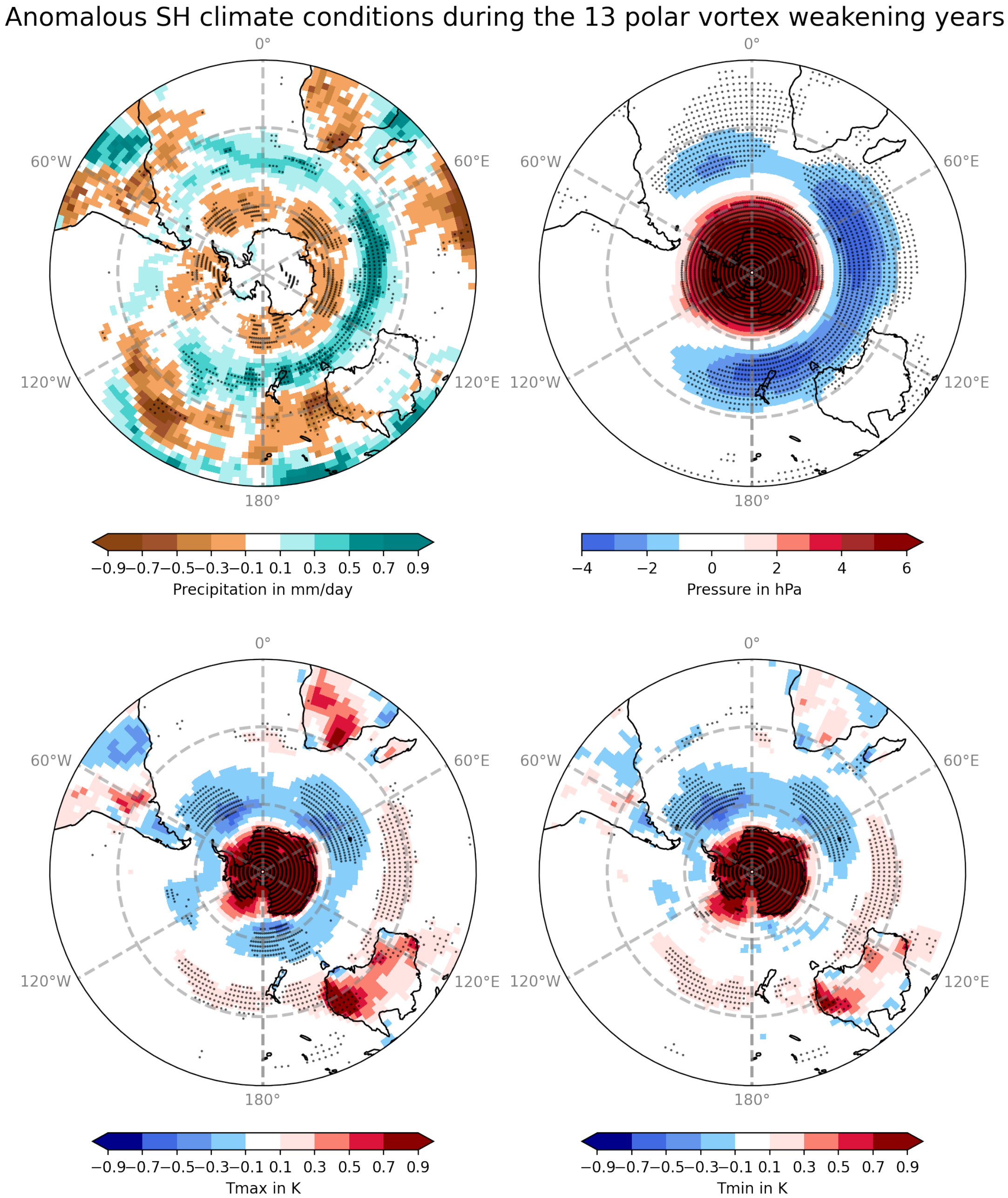

Figure 4: Anomalous climate conditions during the 13 polar vortex weakening years from October–December compared to the climatology in the Southern Hemisphere. The parameters shown are precipitation (upper left), slp (upper right), Tmax (lower left) and Tmin (lower right). The contour interval is 0.2 mm/day for precipitation, 1 hPa for slp and 0.2 K for Tmax and Tmin. Black dots indicate significance.

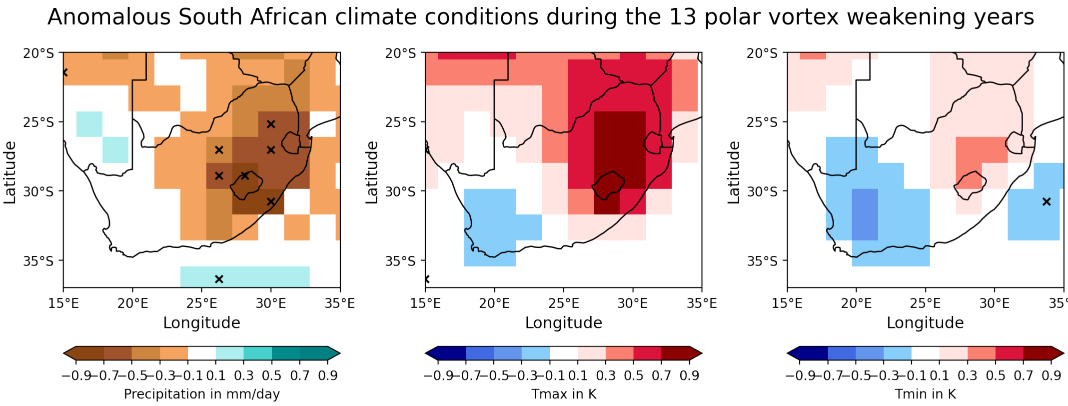

Figure 5: Anomalous South African climate conditions during the 13 polar vortex weakening years from October–December compared to the climatology. The parameters shown are precipitation (left), Tmax (middle) and Tmin (right). The contour interval is 0.2 mm/day for precipitation and 0.2 K for Tmax and Tmin. Black crosses indicate significance.

South Pole with 1.5 K in Tmax which is consistent with the downward propagating stratospheric temperature anomalies (Figure 3). The strongest negative anomaly is -0.6 K in the south Atlantic around 60°S and 30°W.

In the following, the regional impact of surface parameters such as temperature and precipitation over South Africa, Australia, New Zealand and South America are looked at in further detail.

South Africa

Dry and warm conditions can be seen in large parts of eastern South Africa in Figure 5. Most remarkable is the area of negative precipitation anomaly with its low of -0.9 mm/day at the southeast coast. Positive rainfall changes have their maximum only at 0.25 mm/day off the coast of South Africa at about 30°S. Warmer temperatures of nearly 1 K more than average are also found in the east compared to negative anomalies below 0.3 K in the southwest. However, unlike the precipitation data, these are of little significance.

Australia

Stronger rainfall is observed both north and south of the continent with anomalies of more than 0.7 mm/day, which mainly affects Tasmania as the southernmost point as shown in Figure 6 on the left. Analogous to South Africa, drier and warmer conditions are observed in the east of the country. The strongest negative precipitation anomalies are over eastern Australia with as low as -0.7 mm/day just off the east coast. The highest temperature anomalies for Tmax and Tmin are also found in the east with up to 1.5 K higher than usual (Figure 6, middle and right). These warm conditions

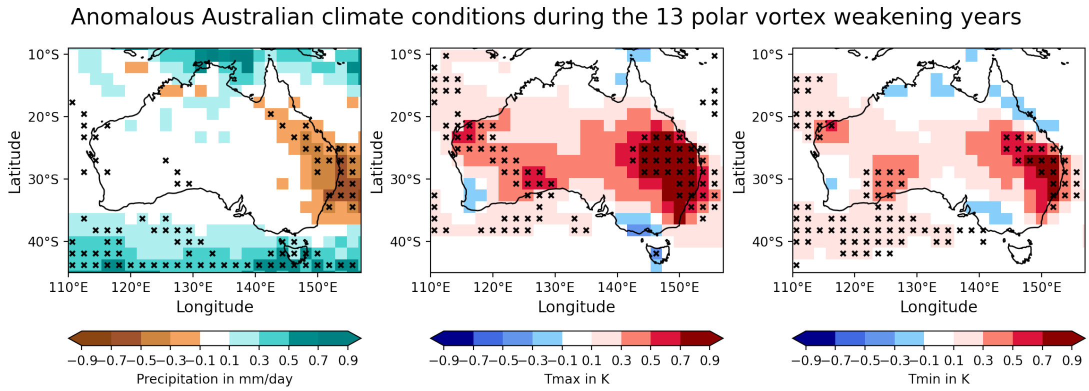

Figure 6: Anomalous Australian climate conditions during the 13 polar vortex weakening years from October–December compared to the climatology. The parameters shown are precipitation (left), Tmax (middle) and Tmin (right). The contour interval is 0.2 mm/day for precipitation and 0.2 K for Tmax and Tmin. Black crosses indicate significance.

extend across the continent at around 30°S. Surrounding the positive anomalies are small regions of slightly cold and non-significant temperature anomalies. Of all the continents on the SH, Australia has the broadest regions with significance. In the pressure anomalies in Figure 4 (top right), it can already be seen that the circulation anomalies are strongest in this area. Therefore and probably because Australia has the most land mass at this latitude, the significance is this large here.

New Zealand

Similar to Tasmania, New Zealand extends into the band of positive precipitation anomalies at about 45°S resulting in a precipitation surplus of up to 1 mm/day on the south-western coast. The model also indicates insignificant negative anomalies of less than -0.3 mm/day off the northern tip of the country, on the same latitude as the deficits in eastern Australia. In contrast to the higher amounts of precipitation, the temperature extremes are rather low. They range from below 0.2 K in the north to -0.1 K in the south.

South America

Looking at South America from 10°S poleward, more precipitation than usual with more than 0.8 mm/day is calculated by the ECHAM6 model in the northeast, as can be seen in the left of Figure 8. It is noticeable that extensive negative precipitation anomalies are in the northwest of the continent and in front of the Andes and at about 30°S. However, only the east coast at about 27°S is significant, with deficits of less than -0.5 mm/day. At the same level are positive temperature anomalies with a maximum of 0.6 K in the north of Argentina (Figure 8, middle). The lowest temperature anomalies are below -0.3 K at 40°S on the east coast (Figure 8, right). It is

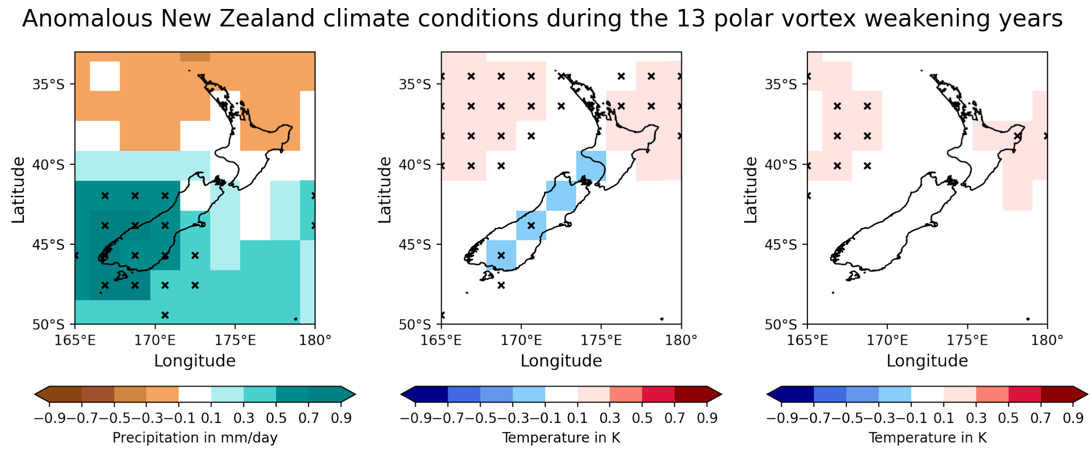

Figure 7: Anomalous New Zealand climate conditions during the 13 polar vortex weakening years from October–December compared to the climatology. The parameters shown are precipitation (left), Tmax (middle) and Tmin (right). The contour interval is 0.2 mm/day for precipitation and 0.2 K for Tmax and Tmin. Black crosses indicate significance.

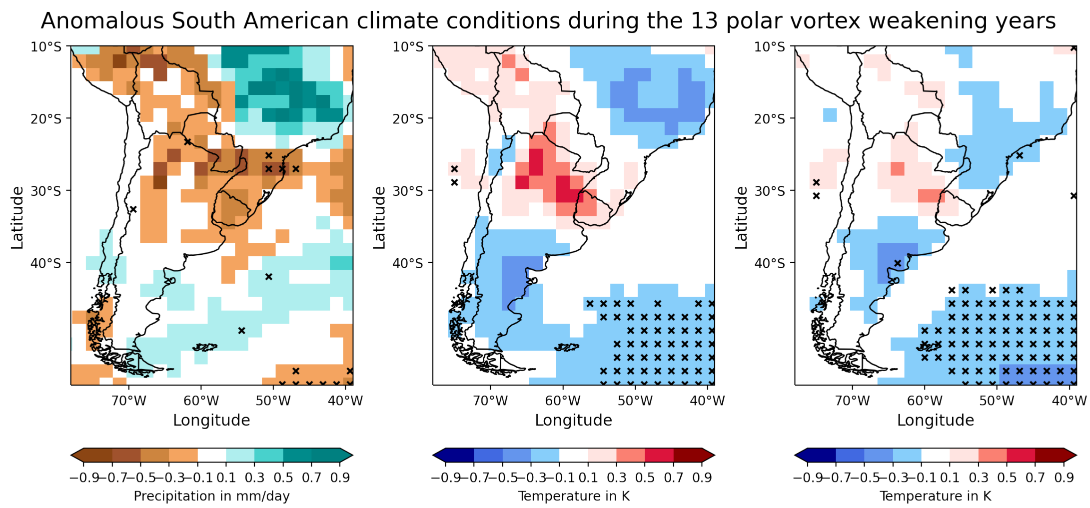

Figure 8: Anomalous South American climate conditions during the 13 polar vortex weakening years from October–December compared to the climatology. The parameters shown are precipitation (left), Tmax (middle) and Tmin (right). The contour interval is 0.2 mm/day for precipitation and 0.2 K for Tmax and Tmin. Black crosses indicate significance.

noticeable that few values on the continent show significance. Already in the circulation anomalies in Figure 4 (top right), there are no significant pressure differences in the East Pacific and South America. Among other things, this may be due to the influence of the Andes.

5 Discussion

In the ECHAM6 model, a SSW occurs on average in 9% of the simulated years which is about every 11 years. Wang et al. (2020) have estimated the probability of a SSW in the SH is about 4% but with a more restrictive definition of a SSW, considering only events in which the daily and zonal mean of the zonal wind at 10 hPa and 60°S reverse. The threshold of this thesis is already 20 m/s. Taking only the two SSWs with light easterly winds, the occurrence is 1.4% which is a lot smaller than the probability of 4%. However, Wang et al. used 2576 realizations of an ensemble model hindcast so their calculation is probably more accurate.

In the model data, 11 SSWs occur in austral winter and 2 in early spring. Since on the SH such events occur very rarely due to the stability of the vortex, there are only the two observed SSWs of 2002 and 2019 for comparison, where both had the central day in September (Rao et al., 2020).

The method of creating a simple approximation for a SAM index based on the paper by Karpechko et al. (2017) is a good way to represent the changes in the atmosphere and signal propagation from the upper stratosphere down to the troposphere shortly before and after the occurrence of the composite of SSWs. The SAM index shows a clear connection between the SSWs and a downward-propagating negative SAM phase, as described in publications like Baldwin and Dunkerton (2001) for the NH and Thompson et al. (2005) for the SH. Using the criteria described in section 3, the effects on the low altitudes can be quantified well, although the division into dSSWs and nSSWs was not decisive for this thesis. From the results in Figure 2 bottom row, one could also assume that the events categorized as nSSWs just propagate downward more slowly than the dSSWs, since only outside of the 8-52 days specified in the criteria, notable negative anomalies reach the troposphere. That the classification of Karpechko et al. (2017) does not fit perfectly was to be expected, since these criteria were created for observed SSWs on the NH while this study considers modeled SH events. The same methodology as for the SAM index is also well suited to show the progression of the positive temperature anomalies in the SSWs through the atmosphere.

Both the positive gph and temperature anomalies propagate downward where they significantly affect the climate in the southern hemisphere. In the ECHAM6 data, the annular anomalies at the surface can be seen very well, including the significantly higher temperature and pressure values in Antarctica that occur after a SSW event (Lim et al., 2020). A shift of the low-pressure systems equatorward during weak eddy years (Baldwin and Dunkerton, 2001, Waugh et al., 2017) can be recognized mainly by the pattern of precipitation anomalies.

In the following, regional impacts in the SH on the climate due to the SSWs are compared with existing literature. As mentioned in the introduction, there are mainly studies on the influence of SAM with no direct reference to SSWs with the exception of Australia (Lim et al., 2019).

Reason and Rouault (2005) investigated the relationship between SAM and dry and wet winters in South Africa. Looking at reanalysis data, they concluded that a negative phase and the accompanying shift of the subtropical jet stream towards the equator leads to wetter winters in the west of the country. No such effect is seen in the results of this study. However, according to Reason and Rouault (2005), there are positive thickness anomalies in the 1000 – 500 hPa layer over the northeast of the country. A higher thickness means a less dense, warmer atmosphere that is more capable of trapping water vapor. Accordingly, this could be an indicator of reduced precipitation there. However, since their study was primarily focused on the western part of South Africa, they do not discuss this further. In general, the comparison with their work also has several weaknesses. First, the data used are from 1948 – 2004, whereas the basis of the ECHAM6 calculations is much later from 2018. Second, they average over the austral winter while this study averages a much later period from spring to early summer.

The results of the model calculations for Australia fit very well with the observations of Lim et al. (2019) which is one of the rare studies of observational climate data in weak vortex years. Since this work followed their methods, the outputs are well comparable, although Lim et al. considered one month more (Oct – Jan instead of Oct – Dec). In both data sets, there are strong, significant warm and dry anomalies in the east of the continent. When analyzing the real conditions, the extreme values are slightly higher than in the model, with up to 2 °C and -1 mm/day. Positive temperature anomalies are also found in western Australia, although in both cases somewhat weaker than in the East. The above-average precipitation in southern Australia is also likely to result from the SSWs and the subsequent change in the SAM. This is confirmed by studies showing a correlation between a negative SAM phase and an intensification of precipitation in Tasmania (Meneghini et al., 2007).

In New Zealand, the model data show a significant increase in precipitation in the South. This is not entirely consistent with the study of Thompson and Renwick (2006), who found positive anomalies during a negative SAM phase throughout western New Zealand. However, as they examine the positive SAM phase, they remain quite vague about a negative phase without addressing where the largest anomalies are. In general, positive SAM phases are associated with decreasing rainfall, especially on the southern island (Thompson and Renwick, 2006, Sen Gupta and England, 2006), which suggests that it is the opposite in a negative phase.

In South America, a decrease of precipitation during a negative SAM phase east of the Andes and at about 30°S was calculated in this study, which is opposite to the results of Silvestri and Vera, 2003 in spring (Nov – Dec). However, as already noted in Section 3, the results of this thesis have little significance in this region.

6 Conclusion and outlook

The aim of this study was to investigate SH SSWs and their surface impacts, which are rarely studied in literature. In the ECHAM6 atmospheric model, 13 SSWs were detected in 142 simulated years. The majority occur in austral winter and two in early spring. Starting from the central date at which the mean zonal averaged wind speed of the polar vortex at 60°S in the stratosphere falls below 20 m/s, positive temperature and gph anomalies can be observed over the polar cap. The resulting occurrence of a negative SAM phase and the propagation of the anomalies into the troposphere is clearly visible in the data.

When comparing the conditions in the vortex weak years with the climatology, the model is able to give a good representation of the effects on the near-surface climate in large parts. For example, Antarctica experiences significantly higher temperatures and slp than average. This strong pressure anomaly shifts storm tracks northward on the SH resulting in positive precipitation anomalies at about 45°S and negative anomalies at about 60°S. The annular pattern of changes are very well seen in the ECHAM6 data and help to understand what effect a negative SAM has on the SH. The regional calculations are significant in Australia and in agreement with the existing literature. There are also parallels in New Zealand and in South Africa to previous studies on the impact of the SAM. The anomalies in South America, on the other hand, cannot be verified and the data are only sporadically significant in that continent.

Because SSWs occur so rarely in SH, existing studies have focused primarily on the influences of the (positive) SAM. For future research it would be interesting to know more about the regional influence on the continents of such extreme events. One way to do this is to look more closely at observational data to see what effect weak vortex years have on South Africa, New Zealand and South America, similar to what Lim et al. (2019) have done in Australia.

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