Meteorologische Zeitschrift, Vol. 25, No. 1, 71–77 (published online October 21, 2015)

Atmospheric Dynamics

Remote impact of the Antarctic atmosphere on the southern mid-latitudes

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(Manuscript received April 9, 2015; in revised form July 15, 2015; accepted July 23, 2015)

Abstract

Would improved prediction capabilities over the Antarctic lead to improved forecast skill in southern mid-latitudes? Or more generally speaking, how large is the influence of the Antarctic atmosphere on the weather and climate of the southern mid-latitudes? To answer these questions we assess the skill of two sets of 14-day forecasts with the Integrated Forecast System of the European Centre for Medium-Range Weather Forecasts with and without relaxation towards the Interim reanalysis of the ECMWF over the Antarctic south of 75 ° S. Due to the relaxation both the mean absolute error and the root mean square error decrease by 2 to 5 % averaged over the southern mid-latitudes with the larger values in winter. Over southern South America and the South Atlantic error reductions are slightly larger and amount to around 5 to 6 %. No dependency of the error reductions of the El Niño Southern Oscillation or the Antarctic Oscillation could be found although error reductions averaged over the whole southern mid-latitudes tend to be larger in situations with decreased westerly flow in the mid-latitudes. In weather situations with anomalous meridional flow from Antarctica to southern South America improvements are most pronounced in the latter area which implies that this is the major pathway for Antarctic influence on southern mid-latitude weather and climate.

Keywords: Antarctic, southern mid-latitudes, NWP, higher-lower-latitude linkages

1 Introduction

Due to the harsh conditions over Antarctica and the surrounding ocean, the observation density is very sparse. Numerical Weather Prediction (NWP) models are usually poorly validated over Antarctica due to the lack of sufficient observations. Model parameterizations are not well tested and often originally made for tropical regions. In addition to inaccurate initialization fields, model shortcomings are responsible for forecast errors. Here we ask the question by how much forecasts in the southern mid-latitudes may be improved if we had a perfect knowledge of the Antarctic atmosphere during the entire forecast.

We would also like to answer the question of how the Antarctic conditions in the entire atmospheric column can influence the southern mid-latitudes and under which large-scale circulation conditions the influence is strongest in various mid-latitude areas. While for the Northern Hemisphere a multitude of studies regarding the influence of the polar region on the mid-latitudes exist (e.g. Jung et al., 2014; Peings and Magnusdottir, 2014; Semmler et al., 2012; Deser et al., 2010), this is not the case for the Southern Hemisphere. Over the Southern Hemisphere the focus has been on the influence of Antarctic ozone depletion on the high- and mid-latitude large-scale circulation (e.g. Manatsa et al., 2013; Polvani et al., 2011).

In the present study the influence of perfect weather forecasts over Antarctica on the weather forecast quality in the southern mid-latitudes is investigated in a systematic way using a relaxation technique proposed by Jung et al. (2010). In that study the technique has been applied successfully to investigate the impact of the tropics on the northern mid-latitudes while Jung et al. (2014) and Kasper et al. (in prep.) use it to study the impact of the Arctic on the northern mid-latitudes. An ensemble of pairs of simulations is conducted with one experiment of each pair being a control hindcast and the other one a hindcast relaxed to reanalysed data over the Antarctic. For simplicity, in the following hindcasts are referred to as forecasts. Note that the relaxation approach can not be used to actually make forecasts. The idea is not to present an improved forecast technique but solely to answer the question if we had perfect weather forecasts over Antarctica how weather forecasts could be improved over the southern mid-latitudes. Since we will never have perfect weather forecasts over Antarctica, the achieved error reductions over the southern mid-latitudes are an upper boundary of what could be achieved in reality. Furthermore, the achieved error reductions may be model dependent.

The remainder of this paper is organized as following: Section 2 describes the experiment set-up including the relaxation method and Section 3 the results. We discuss the results and draw conclusions in Section 4.

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DOI 10.1127/metz/2015/0685
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

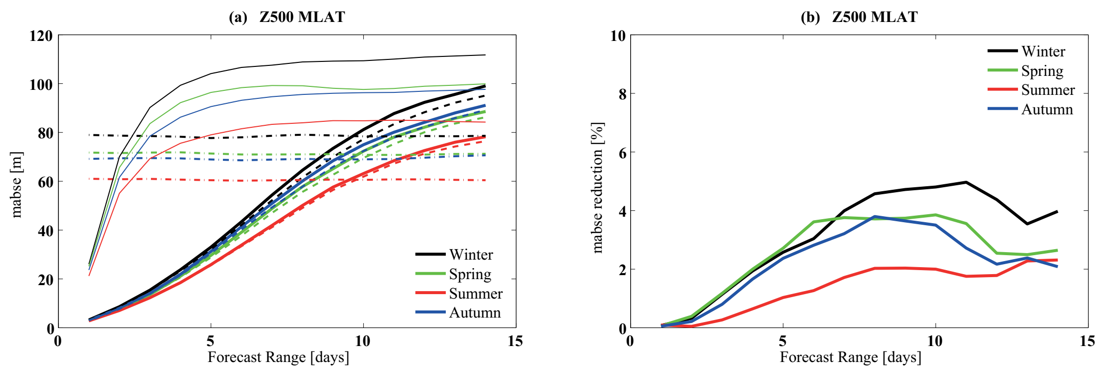

Figure 1: (a) Mean absolute error (mabse) of Z500 (m) averaged over all control forecasts of each season (solid thick lines) and averaged over all relaxed forecasts of each season (dashed lines), area averaged over the southern mid-latitudes (MLAT) between 20 ° S and 60 ° S, dependent on the forecast lead time in days. The thin lines give the corresponding mean absolute error of the persistence forecasts and the light-coloured dotted-dashed lines of the climatology forecasts. (b) Z500 mean absolute error reduction (%) of the average of relaxed forecasts compared to the average of control forecasts from (a).

2 Methods

In the present study we used the same method and set of experiments with the Integrated Forecast System (IFS) cycle 38r1 from the European Centre for Medium-Range Weather Forecasts (ECMWF) as in Kasper et al. (in prep.). Set-up of experiments, relaxation method and definition of composites are briefly summarized here. We initialized pairs of experiments on the 1st and 15th of each month of the time period 1979 to 2012 with the Interim reanalysis data (ERA-Interim, see Dee et al. (2011)) of the European Centre for Medium-Range Weather Forecasts (ECMWF) yielding 204 pairs for each season. Within each pair of 14-day IFS forecasts with prescribed sea surface temperature (SST) and sea-ice concentration (SIC), we ran one control forecast and the other relaxed to the ERA-Interim data throughout the atmosphere from 75 ° N to 90 ° N and from 75 ° S to 90 ° S. For the present study, only the relaxation of the Antarctic atmosphere is relevant, because the impacts of both the Arctic and the Antarctic atmosphere become negligible in the tropics. In a separate study (Kasper et al., in prep.) we investigate the influence of the Arctic atmosphere on the northern mid-latitudes using the same model data. The relaxation method is described in detail in Jung et al. (2010). The idea is to draw the IFS model toward the ERA-Interim reanalysis data, i.e. to correct the IFS model state, by adding an extra term of the following form to the IFS model state in the given relaxation area at each time step of 45 min:

$$-\lambda(x - x_{\mathrm{ref}}) \tag{2.1}$$

with x being the model state vector and x_{ref} the reference field, in our case the ERA-Interim reanalysis data. Between 10 ° north and south of the relaxation boundaries, a smooth transition of λ from 0 to λ_0 using a hyperbolic tangent function as described in Jung et al. (2010) is used. We set λ_0 to 0.1 per time step, equivalent to 0.133 h^{-1}.

To examine under which conditions the weather forecasts are improved strongest in a Southern Hemisphere target area, we carried out composite analyses. One composite consists of all the forecasts which are for a particular target area and for a given forecast lead time in days exceptionally improved taking the ERA-Interim reanalysis data as a reference. We defined an exceptionally improved forecast by a reduction of the mean absolute error of more than the mean reduction of this error plus one standard deviation for the given target area and for the given forecast lead time in days. For each season, a given target area and a given forecast lead time we get around 30 to 40 exceptionally improved forecasts, around a sixth of the 204 forecasts. The other composite consists of all the remaining forecasts. We call this the composite of neutral forecasts. We investigated the forecast parameters 500 hPa geopotential height (Z500), 850 hPa temperature (T850) and mean sea level pressure (MSLP). Differences between the composite of exceptionally improved and neutral forecasts can therefore be interpreted as anomalous conditions in the atmosphere under which the forecasts tend to be improved strongest. In other words, the anomalous conditions indicate in which situations the Antarctic has the strongest influence on the entire mid-latitudes or on a particular region, depending on the definition of the target area.

3 Results

Figure 1a shows the development of the mean absolute error over the 14 days from the control and the relaxed forecasts averaged over the southern mid-latitudes between 20 ° S and 60 ° S for each season separately. In addition, mean absolute errors of two commonly used reference forecasts, persistence and climatology forecasts, are presented. Figure 1b depicts the reduction of the mean absolute error due to the relaxation in the same region. We also investigated the commonly used root

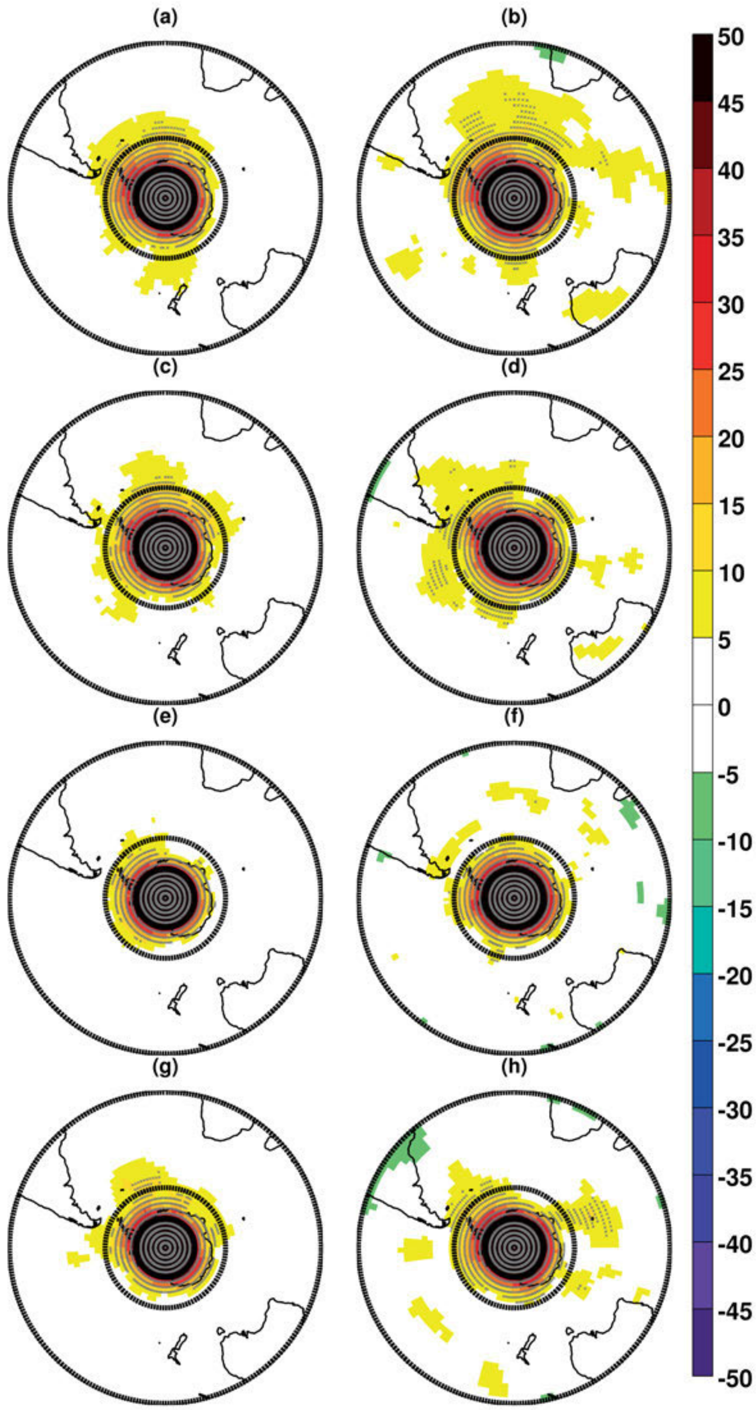

Figure 2: Z500 mean absolute error (mabse) reduction (%) due to relaxation south of 75 ° S in winter (JJA) averaged over (a) days 4–7, (b) days 8–14. (c) and (d) as (a) and (b) but for spring (SON), (e) and (f) for summer (DJF), and (g) and (h) for autumn (MAM). The dashed circles indicate the southern mid-latitudes between 20 ° S and 60 ° S. Stippled areas are significant at the 95 % level according to a Wilcoxon test.

mean square error which turned out to be systematically about 25 % higher than the mean absolute error. Relative error reductions are very similar between mean absolute error and root mean square error. All the statements made in the rest of the paper are valid both for the mean absolute error and the root mean square error. We divided the year into seasons according to the meteorological definition: June, July and August (JJA) as winter; September, October and November (SON) as spring; December, January and February (DJF) as summer; and March, April and May (MAM) as autumn. It should be noted that the error reduction is dominated by the higher mid-latitudes in which the variability and also the errors are higher compared to the lower mid-latitudes.

In all seasons and in both the control and the relaxed forecast experiments the error increases over time and

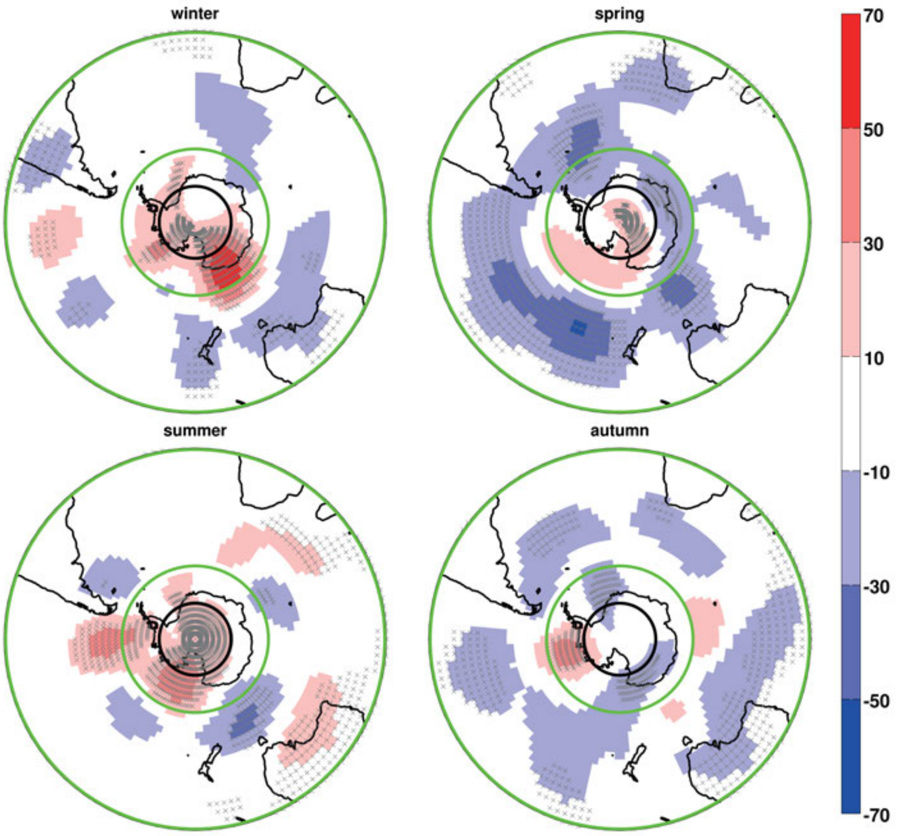

Figure 3: Difference between Z500 composites (m) of exceptionally improved minus neutral forecasts over the southern mid-latitudes (20 ° S–60 ° S) for forecast days 1–7 for each season. Areas marked with crosses are significant at the 95 % level according to a Wilcoxon test. The black circle indicates the relaxation area and the green circles the target area: the southern mid-latitudes between 20 ° S and 60 ° S.

starts to saturate after around 10 days. This is because the error is getting close to the climatological standard deviation. When compared to the reference forecasts for all forecast lead times, IFS forecasts can be regarded as useful, i.e. they show a smaller error than the better of the two reference forecasts, up to forecast lead times of 8 to 9 days. The relaxed forecast shows a slight improvement over the control forecast, making the forecast useful by 6 to 12 hours longer compared to the control forecast. Winter shows the largest error, followed by spring and autumn. Summer errors are smallest, presumably due to small variability. Strongest improvements are achieved for winter, followed by spring, autumn, and summer. The error reduction grows during the first week and remains between around 2 and 5 % during the second week. This is to be expected as during the first few days there is still a considerable forecast skill and therefore the relaxation does not impact the forecasts as much as for longer forecast lead times.

Regarding the evolution of the spatial distribution (Figure 2), for days 4 to 7 the error reduction is still quite restricted to the vicinity of the relaxation area, especially for summer. While for days 8 to 14 in winter, spring, and autumn significant error reductions spread out and can be found in some mid-latitude areas south of 40 ° S, in summer the perfect knowledge of the Antarctic atmosphere does not have any significant impact on the forecast quality in the mid-latitudes. There is a tendency towards stronger improved forecasts over the southern South Atlantic as well as over southern South America and its surroundings. Furthermore, over some parts of the southern Indian Ocean error reductions can be seen in autumn and winter and over some parts of the southern South Pacific in spring. Error reductions over Australia in winter and spring which would be of interest are not significant.

It is relevant to investigate under which atmospheric large-scale circulation conditions the improvement of weather forecasts is most pronounced. For this we focus on the first seven days of the forecasts – a time frame in which the forecasts can be regarded as useful. Figure 3 shows differences of composites of Z500 when forecasts are exceptionally improved between 20 and 60 ° S compared to the neutral forecasts. Generally, positive Z500 anomalies can be seen over parts of Antarctica and in the surroundings and negative ones in the mid-latitudes although there are exceptions of this rule. This means that when the zonal westerly flow in the mid- and high-latitudes is weaker than normal and more interaction between the high and mid-latitudes can take place, the improvement of the quality of the Z500 forecasts tends to be strongest. Qualitatively similar anomalies for exceptionally improved forecasts can be seen for MSLP (not shown).

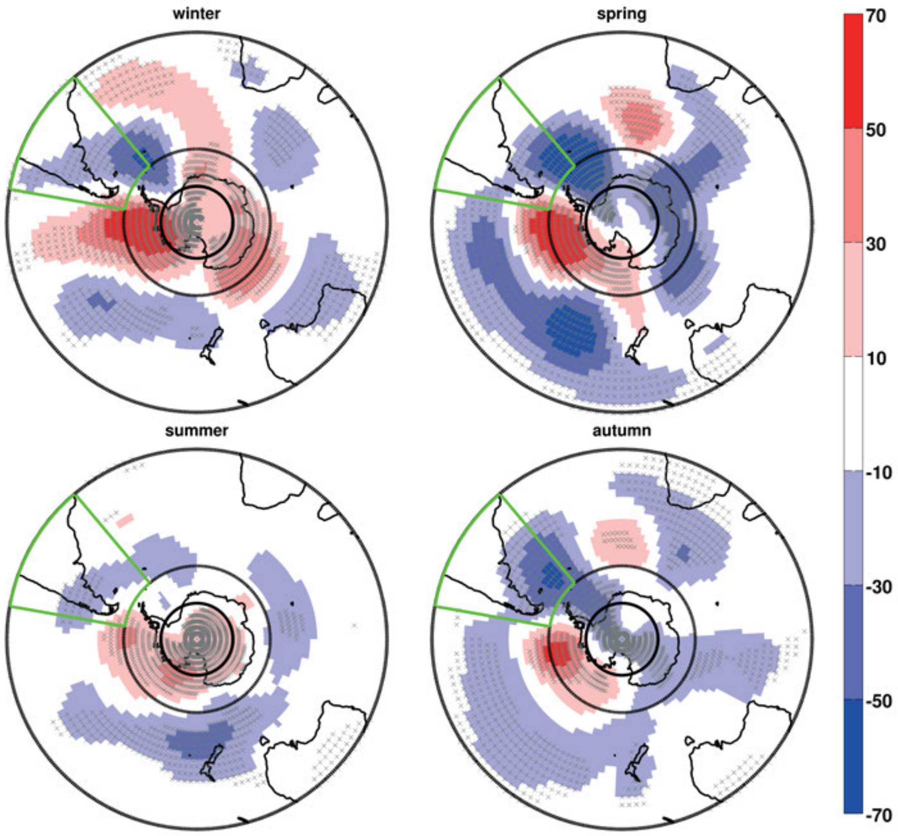

Figure 4: Difference between Z500 composites (m) of exceptionally improved minus neutral forecasts over southern South America (20 ° S–60 ° S, 80 ° W–40 ° W) for forecast days 1–7 for each season. Areas marked with crosses are significant at the 95 % level according to a Wilcoxon test. The inner black circle indicates the relaxation area, the outer black circles the southern mid-latitudes between 20 ° S and 60 ° S and the green box the target area: southern South America.

From a user perspective it is more important to investigate under which circumstances specific land areas such as southern South America, southern South Africa or Australia rather than the very extensive area of 20 to 60 ° S get the strongest forecast error reductions through the perfect knowledge of the Antarctic atmosphere. Figure 4 shows that forecasts are especially improved over southern South America and surroundings in all seasons when there is anomalously low Z500 east of the target area and anomalously high Z500 west of the target area implying an anomalous southerly flow from Antarctica into the target area. The effect is strongest in spring and weakest in summer. Similar anomaly patterns can also been seen for the surface, i.e. the MSLP (not shown). This makes sense as in such situations there is an anomalous transport of air masses from the relaxation area to southern South America and the benefit of the perfect knowledge over Antarctica can be felt. For southern South Africa a pattern of an anomalous southerly flow from Antarctica into the Atlantic upstream of the target area can be seen, but only for winter (not shown). Anomalies are weaker compared to southern South America. For the target area of Australia anomalies are weakest. Only in winter there might be a tendency to stronger improvements with an anomalous southerly flow from Antarctica to Australia (not shown). For the other seasons Z500 anomalies are only small and generally do not exceed 30 m.

When there is an anomalous airflow from Antarctica into southern South America, in winter and spring a clear cold anomaly of more than 2 K in 850 hPa can be seen northeast of the Antarctic peninsula (Figure 5). Considering the climatological westerly air flow in the mid-latitudes this is downstream of the anomalous southerly flow and is therefore consistent. In autumn a similar but weaker signal of up to 1.5 K can be seen while in summer only small anomalies of less than 1 K can be detected. In situations with cold conditions east of the southern tip of South America as well as over the Antarctic peninsula and east of it, and warm conditions west of the Antarctic peninsula, forecasts tend to be stronger improved compared to average conditions.

4 Discussion and conclusions

Forecast experiments with and without Antarctic atmosphere relaxation towards the ERA-Interim data show that the mean absolute error and the root mean square error of weather forecasts for the southern mid-latitudes

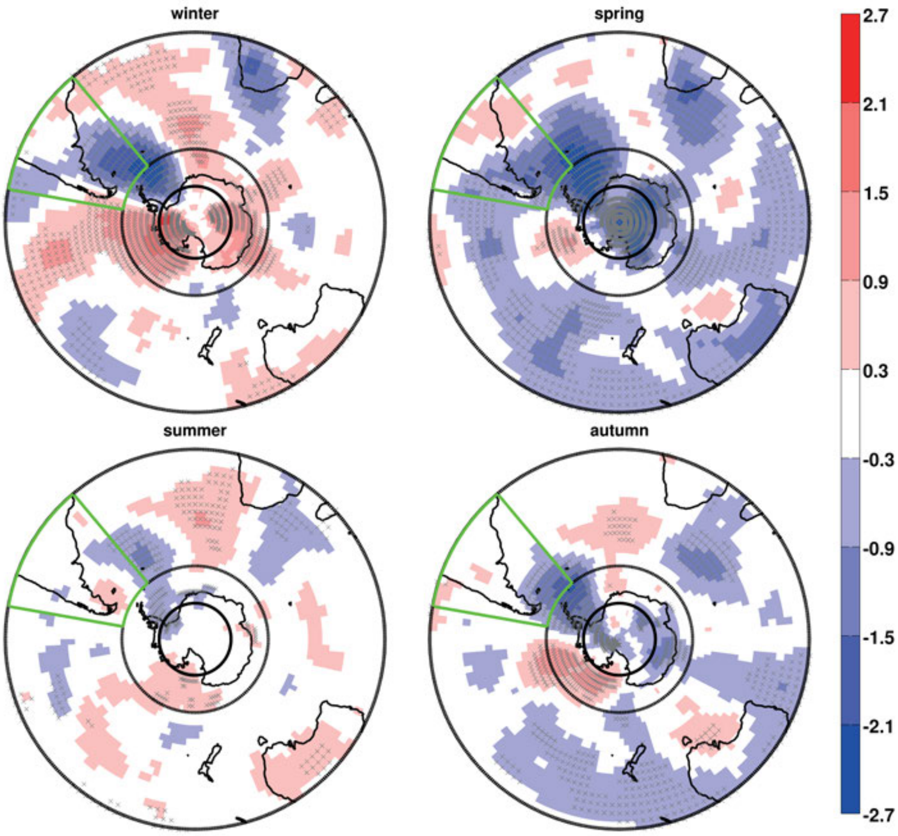

Figure 5: Difference between T850 composites (K) of exceptionally improved minus neutral forecasts over southern South America (20 ° S - 60 ° S, 80 ° W - 40 ° W) for forecast days 1–7 for each season. Areas marked with crosses are significant at the 95 % level according to a Wilcoxon test. The inner black circle indicates the relaxation area, the outer black circles the southern mid-latitudes between 20 ° S and 60 ° S and the green box the target area: southern South America.

could be reduced by 2 to 5 % in the case of perfect weather forecasts for Antarctica with the stronger reductions in winter and the weaker reductions in summer. This increases the forecast lead time of useful forecasts (better than predicting the climatology or a persistence of the circulation) by about 6 to 12 hours. Given that perfect Antarctic weather forecasts can never be achieved even with a strongly enhanced observation network and improved model formulations, such an increase in the forecast lead time is relatively little. Also compared to recent improvements in NWP this increase is only little. For example, Rodwell et al. (2010) found that the precipitation forecast lead times in the operational IFS system have increased by about 2 days in just 14 years.

Compared to the influence of the Arctic on the northern mid-latitudes where the error could be reduced by 4 to 6 % (Kasper et al., in prep.), the improvement for the southern mid-latitudes due to Antarctic relaxation is slightly smaller. Furthermore, in the more homogeneous southern mid-latitude environment which is dominated by the ocean, error reductions are relatively homogeneously spatially distributed over the entire southern mid-latitudes compared to the northern mid-latitudes. The relatively small error reductions could be due to the generally stronger zonal flow in the southern mid-latitudes compared to the northern mid-latitudes isolating the Antarctic more from the mid-latitudes compared to the Arctic. Indeed, in situations with anomalously high Z500 over Antarctica and anomalously low Z500 over the Southern Ocean resulting in a weaker-than-average westerly flow in the southern mid-latitudes, weather forecast improvements are most pronounced averaged over the whole southern mid-latitudes. However, it should be noted that the anomaly patterns for exceptionally improved weather forecasts due to the relaxation do not project on the Antarctic Oscillation and no systematic influence of the Antarctic Oscillation has been found, probably because the locations of the strongest anomalies are different between our composites and the loading pattern of the Antarctic Oscillation.

Investigating the regional distribution of improvements, downstream of and over southern South America there is the greatest potential. In southern South America the strongest improvements can be achieved in situations with an anomalous southerly flow from Antarctica to southern South America, cold conditions east of southern South America as well as over the Antarctic peninsula and east of it, and warm conditions west of the Antarctic peninsula. The high pressure anomaly southwest of southern South America in Figure 4 is similar to the composite of El Niño years in Turner (2004). This motivated us to explore if there are systematically stronger improvements of southern South American forecasts in El Niño years compared to La Niña years. However, we could not find any significant difference in the error reductions for southern South America between El Niño and La Niña cases.

We argue that our method to investigate improvements in the skill of weather forecasts due to relaxation enables us to identify major pathways of Antarctic influence not only on the weather but also on the climate of the southern mid-latitudes. The major pathway appears to stretch from the Antarctic peninsula to the southern tip of South America.

One could argue that the observation density over Antarctica is sparse due to difficult environmental conditions and therefore weather forecasts for Antarctica tend to be rather poor due to sparse initialization information. Generally the loss of mid-latitude weather forecast quality due to this is not that important in present-day climate. However, if the circulation would change towards a weakened westerly flow in the southern mid-latitudes in a future climate or if the pattern of a stronger meridional flow from the Antarctic peninsula to southern South America would occur more often, the situation may change.

Acknowledgments

The authors acknowledge ECMWF for providing the supercomputing resources under ECMWF special project SPDEJUNG2 as well as the Integrated Forecast System (IFS). S. S. benefited from funding through the Helmholtz Climate Initiative REKLIM.

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