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Antarctic winter tropospheric warming – the potential role of polar stratospheric clouds, a sensitivity study

T. A. Lachlan-Cope,[1]* W. M. Connolley,[1] J. Turner,[1] H. Roscoe,[1] G. J. Marshall,[1] S. R. Colwell,[1] M. Höpfner[2] and W. Ingram[3†]

[1] *British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, UK*
[2] *Forschungszentrum Karlsruhe, Institut für Meteorologie und Klimaforschung, Karlsruhe, Germany*
[3] *Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford and Hadley Centre, Met Office, Exeter, UK*

**Correspondence to: T. A. Lachlan-Cope, British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, UK. E-mail: tlc@bas.ac.uk*

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Abstract

Over the last 30 years, Antarctic mid-tropospheric temperatures in winter have increased by 0.5 K per decade, the largest regional tropospheric warming observed. Over this period, amounts of polar stratospheric cloud(PSC) have also increased, as rising CO_2 concentrations cooled the stratosphere. By imposing an idealisation of these increases in PSC within the radiation scheme of an atmosphere-only general circulation model, we find that they could have contributed to the observed warming. The present generation of global climate models do not properly represent PSCs, and so these results demonstrate the need to improve the representation of PSCs. Copyright © 2009 Royal Meteorological Society and Crown Copyright

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1. Introduction

Analysis of the balloon-launched radiosonde data for the Antarctic has revealed that the winter warming of the mid-troposphere over Antarctica during the last 30 years is larger than anywhere else on Earth (Turner *et al*., 2006). Data from nine Antarctic stations were used in that study to show that a warming had taken place across the 400–600-hPa layer of 0.5–0.7 °C per decade over the period 1971–2003. The warming was also present in the 40-year European Centre for Medium-range Weather Forecasts Re-Analysis (ERA-40) (Uppala *et al*., 2005), into which the radiosonde ascents, along with satellite sounder data and other observations, had been assimilated. However, the warming was not reproduced in the climate of the 20th Century (Folland *et al*., 2002) experiments conducted with the present generation of climate models, so the effect of the present, and possible future, warming, for example on the precipitation over the continent, will not be represented. It is, therefore, important to understand why this warming has occurred so that the processes involved can be incorporated into global climate models.

Inspection of the monthly trends in 500-hPa temperatures from the radiosonde data for the period 1971–2003 indicates that the largest warming has taken place in June. This is particularly the case around the coast of East Antarctica from Syowa (69°00′S, 39°35′E) to Casey (66°17′S, 110°32′E), where the warming trend has been between 0.5 and 1.0 °C per decade in June. In the second half of the year, there is a progressive decrease in the warming trend with all stations around East Antarctica having a cooling trend in December. At the South Pole, there is also a maximum warming in June. Our analysis therefore concentrates on June.

2. Polar stratospheric clouds

One of the most pronounced features of the Antarctic stratosphere is the polar vortex. This is strongest during the Antarctic winter and spring when the Equator-to-South Pole temperature difference is largest. When the sun sets on the polar stratosphere in early winter, the layer between 8 and 30 km (the lower stratosphere) cools radiatively to space, and, by June, temperatures have dropped low enough for polar stratospheric clouds (PSCs) to form despite the low specific humidities typical of the stratosphere. The stratospheric temperatures continue to drop until a minimum is reached during August. It is in June, when the temperatures are close to those at which PSCs form, when small changes in stratospheric temperatures will have the largest effect on PSC amounts. Later in the season when temperatures in the stratosphere are already low and PSCs are ubiquitous, further lowering of the temperature will only have a small effect on PSC amounts. The average winter temperature of the Antarctic stratosphere has been dropping by about 0.5 °C per decade over the last 30 years (Turner *et al.*, 2006).

PSC particles are found to exist in both liquid and solid phase depending on the composition and temperature. Below about 195 K, thin clouds of solid nitric acid trihydrate (NAT) or liquid supercooled ternary solution (STS, $H_2SO_4/HNO_3/H_2O$) droplets form. Around 5–10 K colder, the air becomes saturated with respect to ice. The presence of NAT facilitates the easy nucleation of ice onto NAT particles at typical ice saturation ratios of 1.05–1.1 (Benson *et al.*, 2006). This results in ice clouds forming at temperatures only just below the frost point. This is in contrast to tropospheric clouds, which often require much larger saturation ratios with the ice nuclei available at the higher temperature in the troposphere. The lower stratospheric temperatures should lead to an increase in the number or density of PSCs and in particular the ice PSCs, which contain more condensate and so have a stronger radiative effect.

In the core of the Antarctic stratospheric vortex, temperatures from meteorological analyses combined with observations of humidity predict that ice PSCs should be ubiquitous from June to September, between altitudes of about 10 and 25 km, and may exist in May and October. The prediction is confirmed by lidar measurements of PSCs (Cacciani *et al.*, 1997). Unfortunately, there are no measurements of sufficient duration to determine a trend. For example, although PSCs were measured by a lidar at McMurdo station from 1993 to 2001 (Adriani *et al.*, 2004), the first 2 years of data were contaminated by volcanic aerosol from the Mount Pinatubo eruption, and the last 7 years are too short a period and had too few good measurements (being ground-based and so screened by lower cloud) to determine a trend.

However, assuming that ice PSCs form at the frost point, it is possible to calculate the volume of air in which they are likely to be present and how this changes with time, from the temperature and water content of the stratosphere (Figure 1). We have used temperatures from the ECMWF reanalysis and the average water content for the winter stratosphere obtained from observations (Nedoluha *et al.*, 2000). This is reasonable in June when the water content is 4–5 ppmv, dependent on height, but is less reliable in the later months when the water content can be very variable as dehydration by sedimentation of ice particles can cause the water content to drop. It should be noted that the estimated volume and coverage are dependent on the estimation of water content and so, although the relative shape of the graphs will be correct, the absolute values may be in error.

PSCs affect the radiative balance of the atmosphere like any other cloud. In daylight, they reflect shortwave radiation (solar radiation) and so act to cool the surface. However, over Antarctic in June there is no sunlight. The effect of clouds on longwave radiation (terrestrial thermal) is to warm the surface and the atmosphere below the cloud, like any 'greenhouse' absorber. Most of the warming occurs in the first few kilometres below the cloud, where most of the longwave radiation from the cloud is absorbed.

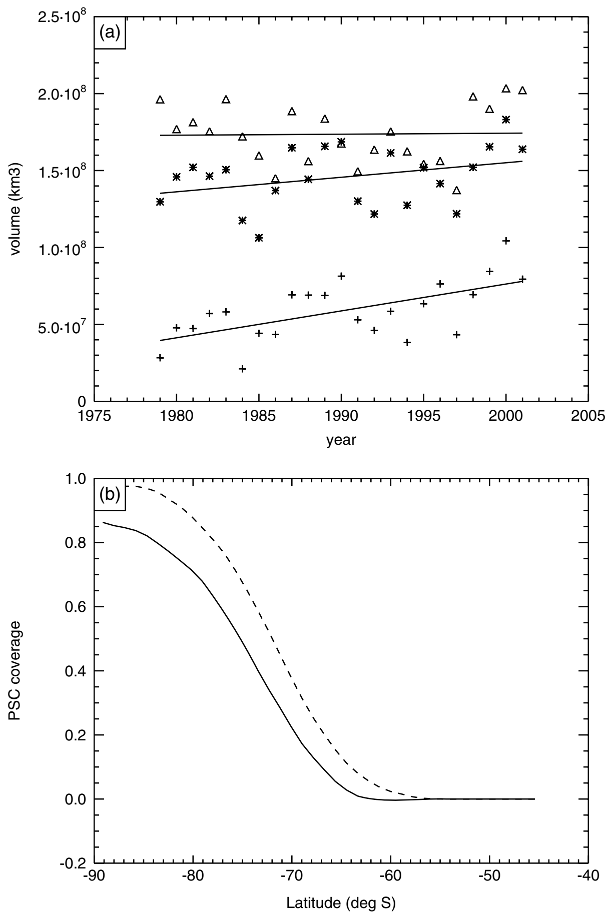

Figure 1. (a) The volume of air above the Antarctic where the ERA-40 temperature is below the ice point. This represents the volume of air potentially containing ice PSCs. The crosses are for June, the stars for July and the triangles for August. (b) The zonal average of the potential coverage of an ice PSC cloud for June at 100 hPa in 1979 (solid) and 2001 (dashed) similarly calculated.

The determination of the infrared (IR) optical depth of Antarctic PSCs presents several problems. Most measurements are of visible backscatter from airborne lidars, or of visible or near-IR extinctions from satellite-borne limb-sounding sensors observing the sun. Many airborne lidars have observed PSCs in the Arctic where they are usually NAT or STS types, but there are few airborne observations of ice PSCs in the Antarctic. Limb-sounding instruments only provide a lower bound for the optical depth unless it is unusually low (<0.03) (Höpfner *et al.*, 2006). Hence, the only way to determine the optical depth of thick PSCs is to use models that agree with such IR measurements when optical depths are small. We have developed a model

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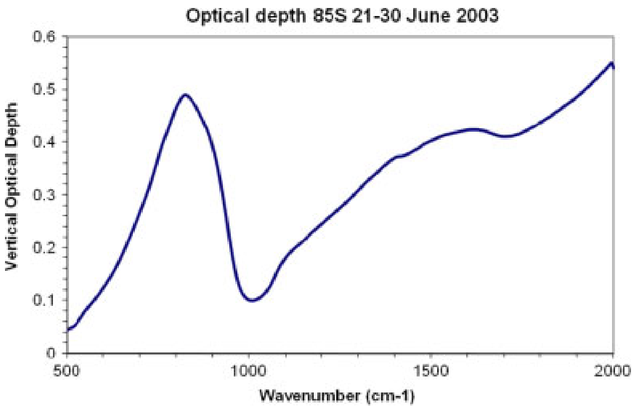

Figure 2. The mean optical depth spectrum for the last 10 days of June 2003 based on the model of Höpfner *et al.* (2006) using ECMWF analyses. The spectrum is dominated by absorption due to ice PSCs.

(Höpfner *et al.*, 2006) to calculate the spectral variation of vertical optical depth for the equilibrium mixture of NAT and ice clouds from ECMWF analyses. This model gives values for the optical depth, in the atmospheric window region around 12 μm (700–900 cm^{-1}), that vary between <0.1 at the start of June to around 1.0 by the middle of July. Figure 2 shows a typical calculated spectrum for the last 10 days of June 2003. For the atmospheric modelling work in this paper we have assumed an average optical depth of 0.5, ignoring the fine structure seen in Figure 2.

3. Climate model

Climate models forced with observed changes in greenhouse gases can be used to investigate changes in the 20th Century climate. However, the IPCC 4th Assessment Report (4AR) (http://www.ipcc.ch/activity/ar.htm) simulations show that the Antarctic mid-tropospheric warming is not represented by the average of the 19 models for which mid-tropospheric temperatures are available, and there is no consistency in the mid-tropospheric temperature trends between models. None of the 4AR models have a proper representation of NAT or STS PSCs. The cloud physics schemes used in all these climate models are designed and tuned to represent tropospheric cloud and if they allow stratospheric cloud it is often badly represented.

In this study, we conduct a sensitivity study to investigate whether PSCs can have an effect on the mid-tropospheric temperature. The satellite observations of PSCs reported above (Höpfner *et al.*, 2006) are uncertain; so the modelling study reported here is only intended to show that the mid-tropospheric temperature is sensitive to PSCs, and that, with PSC concentrations that are within the range calculated to be possible (Höpfner *et al.*, 2006), a typical climate model will show mid-tropospheric warming close to that observed. Although the climate model is run for the whole year, we will concentrate on June when the increase in PSCs over the last 30 years is greatest and mid-tropospheric warming is largest. Rather than including the full physics and chemistry of PSCs within a model, we have included a representation of the radiative effect of a PSC, with an idealised distribution, in an atmosphere-only version of the Met Office Hadley Centre General Circulation Model, HadAM3 (Pope *et al.*, 2000). The model has 19 levels in the vertical and a 2.5° × 3.75° horizontal grid. It has been forced at the lower boundary by imposing same annually repeating sea surface temperature and sea ice concentration in both the model runs (see below). The version of HadAM3 used in this study has a limited representation of the stratosphere. However, we are not interested here in the effect of PSCs on the dynamics of the stratosphere, but rather on the radiative effects on the troposphere. The radiative effect of the stratospheric cloud was included by imposing a cloud of given optical depth at a single level (100 hPa) in the model's radiation code within a circle centred on the South Pole. The optical depth of this single cloud layer is the same as a real cloud that may be spread over several layers in the stratosphere. Hence, the PSCs within these model runs are not controlled by the model cloud physics scheme and so they neither change as the temperature changes nor produce precipitation.

Uncertainties in ECMWF temperatures and our understanding of PSC formation mean that the coverage of PSCs calculated from ECMWF temperatures is uncertain. Here we have defined a simple change in the area of an idealised PSC to illustrate model sensitivity to changes in PSCs. We believe that the changes we have imposed in this study approximate those that may have taken place over the last 20–30 years. However, as the imposed PSCs are idealised and our knowledge of the real PSCs is limited, it is unlikely that the result will exactly match reality. Of course this is a simplification as the real clouds will have a more complex structure, but here we are only trying to show that PSCs can produce the correct magnitude of tropospheric warming and not reproduce the spatial details.

We have not included the effect of ozone loss in this study as in June ozone depletion is small and is unlikely to play a major role in the June tropospheric warming.

We consider two model runs, both of which had a PSC imposed during June, July and August in one model level at 100 hPa with an optical depth of 0.5. In these model runs, CO_2 has been kept constant and each individual model run does not show any significant change in 500-hPa temperature over Antarctica for the period of the run. The first run had the layer extending from the pole to 80 °S to simulate earlier conditions. The second had a layer from the pole to 70 °S to simulate more recent conditions, with the edge of the PSCs closer to coastal stations. These two runs are not intended to exactly represent the real conditions before and after the observed cooling in the stratosphere or the conditions shown in Figure 1. The model runs are intended to show the sensitivity of atmosphere

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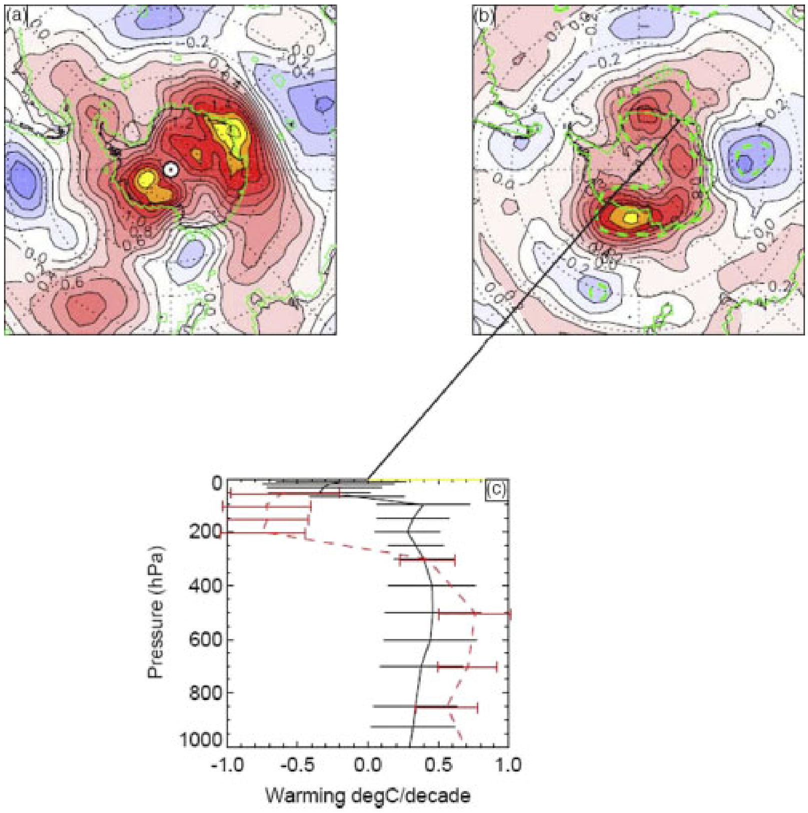

Figure 3. (a) The warming in June in ERA-40 at 500 hPa between 1979 and 2001. The maximum warming is greater in ERA-40 than in our climate model runs and the radiosonde ascents. (b) The warming in June observed between the two runs of HadAM3, the first with a 0.5 optical depth PSC layer at 100 hPa polewards of 80 °S and the second with a similar layer extending to 70 °S. The area of significant change at the 95% level (calculated using the student's *t*-test) is enclosed within the dashed green contour. Assuming the two runs represent conditions in 1980 and 2000, the warming between the runs has been divided by two to give a decadal change. (c) The observed vertical profile of the warming in June at Syowa from radiosonde data (red dashed) and from an average of an area around Syowa (65–75 °S, 0–45 °E) in the model runs (black).

to change in PSC extent. The models included PSCs for June, July and August although we only consider the June results here as it is in June that there is the biggest change in PSCs and in the mid-troposphere temperature. Both model runs were 30 years' equilibrium runs. In these runs, greenhouse gas concentrations, sea surface temperatures, sea ice extent, aerosols and stratospheric ozone amounts were kept fixed.

4. Results

When the radiative effects of a PSC are included in the model, the layer that includes the PSC, and those below, warm, while the layer immediately above cools. The exact pattern of this tropospheric warming depends on the shape and depth of the imposed PSC and on the circulation of the troposphere, which will distribute the warming. The runs considered here show a tropospheric warming that extends northwards from the edge of increased stratospheric cloud, particularly around the coast of East Antarctica, and also in an area centred over the Ross Sea (Figure 3b). The spatial pattern of the warming in the model is similar to that observed in the ECMWF reanalysis with two maxima separated by about 180° longitude and equatorward of the cloud change imposed (Figure 3a) with the pattern slightly rotated between the two models. The differences between the ECMWF reanalysis (Figure 3a) and the HadAM3 runs (Figure 3b) may be due to the different mean climates of the two models. The East Antarctic warming is spread over several radiosonde stations. Around Syowa (Figure 3c) the modelled warming is smaller than the observed warming, although the shape is similar with a peak at 500 hPa. The stratospheric cooling in the model does not represent the observed cooling well, but as the model does not include changes in stratospheric ozone or greenhouse gasses and has a limited resolution in the stratosphere, this is not surprising. Including greenhouse gasses will increase the cooling above 200 hPa as well as warming the troposphere; however, as Turner *et al.* (2006) pointed out, this extra warming is not sufficient to explain the observed warming. Although the climate model runs reported here reproduce the general pattern of the warming observed in ERA-40, the exact position and size of the peaks differ. However, the agreement between the measurements and model is qualitatively good.

Similar results were obtained with optical depths ranging from 0.3 to 0.7 (not shown here) and although the pattern of warming observed in the different runs

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showed a large variability, the warming does not seem to be very sensitive to the value of the optical depth.

5. Conclusions

This work reported here shows that changes in PSC extent, consistent with the observed changes in stratospheric temperatures, can have a significant effect on mid-tropospheric temperatures, which, although smaller, is similar to that observed in the radiosonde record. Unfortunately, measurements of PSCs over Antarctica during winter are sparse and those that exist are for recent years or have a limited duration and so cannot show how amounts of PSCs have changed. Especially the spatial extent of optically thicker ice PSC is a crucial parameter for the present study. More information on this subject is desirable and will in future be available from composition analysis of multi-annual satellite observations like CALIPSO (Pitts *et al.*, 2007) or MIPAS. This study suggests that there are significant challenges to overcome in the modelling and observation of PSCs if changes in the Antarctic troposphere are to be correctly represented within climate models. We do not, however, suggest that changes in PSCs will explain the whole mid-tropospheric warming rather that they are likely to play a significant part in any explanation.

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