1.17 THE EFFECT ON SOUTHERN HEMISPHERE CIRCULATION AND ANTARCTIC COASTAL CLIMATE OF CHANGING BAROCLINICITY

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1. INTRODUCTION

The mid-latitudes of the Southern Hemisphere are very active with the movement of tropospheric extra-tropical cyclones (ETC). These systems generally track eastward and tend to move southward toward the Antarctic coast, and they provide the primary mechanism for horizontal heat and moisture transport to the southern polar regions from lower latitudes (van Loon 1979). They therefore play a major role in the weather and climate of Antarctica. The systems owe their existence to the baroclinic instability provided by the strong meridional temperature gradient (MTG) across the southern oceans (Held 1993). In the mean, the ETCs produce a circumpolar trough (CPT) at around 62°S, the depth and position of which is mostly influenced by the MTG.

As the MTG exhibits a strong semi-annual oscillation (SAO) in response to the different rates of cooling and warming of the Antarctic continent and the oceans to the north throughout the year, so too does the strength and structure of the CPT (van Loon 1967). Studies have shown that the SAO in surface pressure has weakened considerably since the mid-1970s (van Loon et al. 1993), and this may be linked to other circulation changes that have been identified, such as decreasing ETC numbers (Simmonds and Keay 2000). The MTG is strongest in colder climates and therefore so too are the baroclinic eddies and heat transport (Rind 1986). The observed circulation changes could therefore be explained by warmer tropospheric temperatures and a weaker MTG.

In this study we investigate the impact of changing mid-latitude temperatures and the mid-tropospheric MTG on the circulation of the southern extratropics. We use an atmospheric model to which we impose temperature changes to alter the MTG and then examine the response of the circulation and climate of the Antarctic regions. We present the model and the experiments in the next section, then show the results in section 3.

2. MODEL AND EXPERIMENTS

We have used the ARPEGE atmospheric general circulation model for the experiments in this study. Version I of the model has been found to simulate the main features of the climate of Antarctica reasonably well (Murphy 1996), and is thus the version that we use here. In the horizontal the model uses a spectral harmonic representation of the prognostic variables, and in the configuration used here they are triangularly-truncated at wave number 42 (T42), which gives a resolution equivalent to 2.8°. In the vertical, the model has 30 hybrid levels, 10 of which are in the troposphere. The model time step in this configuration is 15 minutes. ARPEGE is described in detail in Déqué et al. (1994). Of interest for study of the high southern latitudes is that sea surface temperatures and sea ice are prescribed and non-interactive, and sea is concentration is 100% wherever it is present. We are performing 5-year AMIP-type experiments beginning in January 1979.

We wish to study the effect of internal modifications of the meridional temperature gradient between 50° and 65°S within the model. To do this we have imposed a 'nudging' term to the mid-tropospheric temperature in the model, with a maximum magnitude at 50°S. The temperature calculated by the model at the 500 hPa level is altered at the end of a model time step, the imposed anomaly taking the form given in Figure 1. This temperature anomaly is therefore seen by the model at the next time step. It has a maximum magnitude of 0.1°C per time step, and is thus equivalent to a heating term of 0.4°C hr^{-1}. We have performed two simulations wherein we apply a positive anomaly, therefore increasing the temperature at 50°S and hence strengthening the MTG (we refer to this as the MTG+ experiment),

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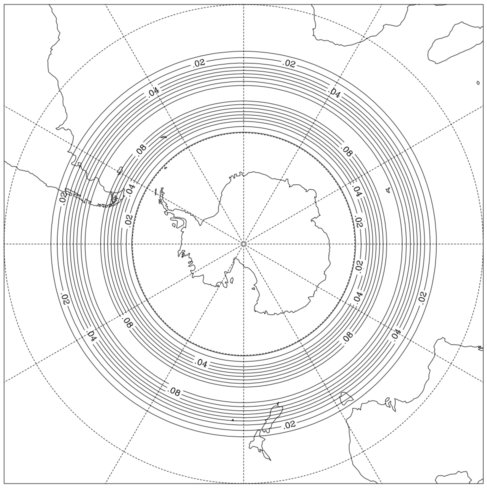


Figure 1: *The horizontal distribution of the nudging term with a maximum at 50°S, positive so that the temperature at 50°S is increased and the temperature gradient to the south is augmented. Contour interval is 0.01°C / time step.*

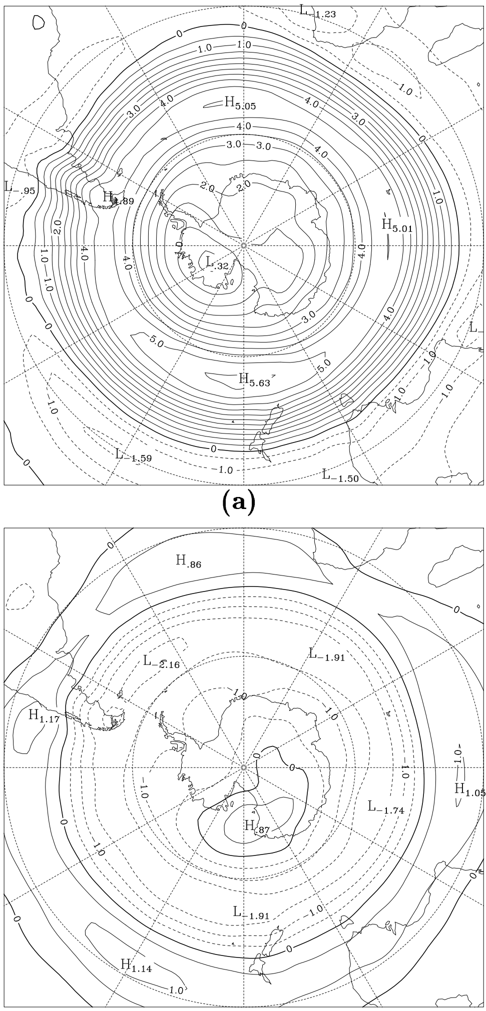
and a second where we apply a negative nudging term, thus decreasing the 50°S temperature and weakening the MTG (experiment MTG-). Each simulation ran for 5 years after a 4 month 'spin-up' period. The unperturbed (or 'control' simulation (CON))' was run for 10 years, but here we consider only the 5 years of the two perturbation experiments (January 1979 to December 1983).

3. RESULTS

3.1 500 hPa temperature response

With the introduction of the nudging term, we wish to increase and decrease the 500 hPa temperature at 50°S and thus strengthen and weaken the MTG in the MTG+ and MTG- experiments respectively. To determine whether this has been achieved with the nudging term chosen, we show the five-year mean temperature anomalies (differences from the control simulation) at 500 hPa in the two perturbation experiments in Figure 2. In this anomaly plots, differences that are significantly different from zero at the 95% level according to Student's t-test are stippled.

It can be seen that the maximum temperature anomalies that result from the imposed nudging occur at 50°S and they are of the correct sign. However, it appears that the response to the positive nudging term is greater than that to the negative nudging term in MTG-, as the maximum anomalies in MTG+ are much greater (up to 5.6°C) than those in MTG-. Despite introducing heating terms of the same magnitude in the two experiments, it appears that the warming at 50°S is amplified in MTG+ while the cooling at 50°S in MTG- is reduced. Therefore, although the strength of the MTG is altered in the desired way, the strengthening of the MTG in MTG+ is of the order of 2.0–3.0°C while the weakening in MTG- is only about 0.5–1.0°C in the mean. There are also some changes to the first and second harmonics of the annual cycle of the temperature gradient. The annual component strengthens (weakens) when the MTG is strengthened (weakened), while a weaker MTG produces a stronger semi-annual component.



(a)

(b)

Figure 2: *Five year average temperature anomalies in the (a) MTG+ and (b) MTG- simulations from the model control. Contour interval is 0.5°C and regions significantly different from zero are stippled.*

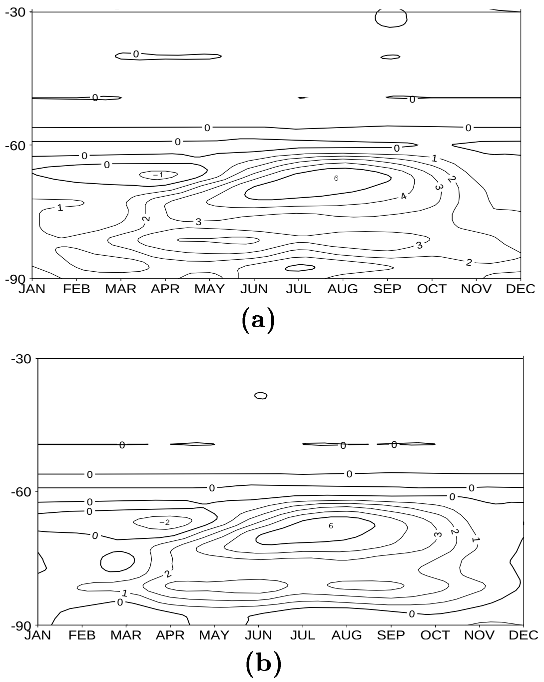


Figure 3: *Annual cycles of the anomalous (from the control) zonally-averaged mean-monthly surface temperatures in the (a) MTG+ and (b) MTG− experiments.*

3.2 Surface temperature response

The asymmetry of the anomalies in the 500 hPa temperature to the imposed temperature nudging in the two experiments suggests that the response to the MTG changes are non-linear. This is seen to a greater extent when we consider the changes in surface temperature that result. Figure 3 shows the mean changes in the annual cycles of the zonally averaged surface temperatures in the two experiments.

We can see that despite the opposite changes at 500 hPa, the two perturbation experiments show very similar temperature responses at the surface. Very strong warming is evident in winter along the Antarctic coast whether the MTG at 500 hPa is stronger or weaker. Weaker cooling occurs in summer/autumn, and large changes occur only south of 60°S.

That the two simulations experience essentially the same patterns of temperature change at the surface appears counter-intuitive. We expected that the strengthening of the 500 hPa MTG would lead to greater baroclinic instability in the region and thus an intensification of the CPT and greater southward heat transport over Antarctica. This appears to be the case, but we see the same warming when the 500 hPa MTG is weakened, and the opposite surface temperature change may have been expected.

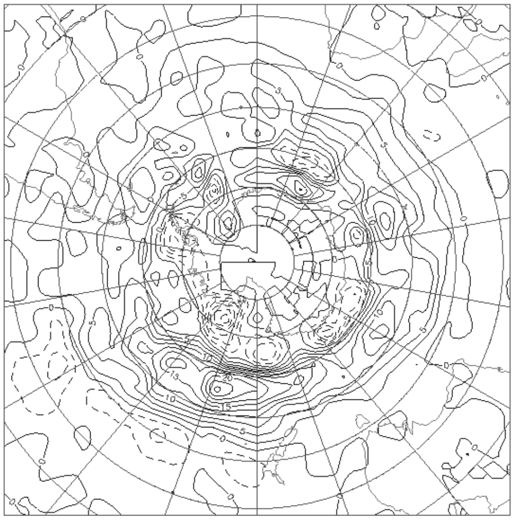


Figure 4: *The difference in wintertime cyclone track number between experiments T50− and T50+. Contour interval is 2.5 tracks per 2.5°x 2.5° grid.*

The temperature changes are not the same around the entire Antarctic coast. In winter, warming of up to 20°C (in the monthly mean temperature) occurs over or offshore of the Ross, Weddell and Amery ice shelves and off Dronning Maud Land, while almost no warming occurs along the Antarctic peninsula nor over the Budd coast and Adélie Lands.

3.3 Atmospheric circulation changes

We look now at the response of the atmospheric circulation to the imposed MTG changes and which may be responsible for the surface temperature changes. The wintertime mean sea level (MSL) pressure changes that occur in the experiments (not shown) indicate that the response is greatest in the MTG+ where the CPT appears to shrink and move southward closer to the Antarctic coast. However, in order to better investigate the change in the circulation, we have used an automatic cyclone tracking scheme to look at the change in ETC behavior. We have used the scheme of Murray and Simmonds (1993) that has been shown to perform very well in the extratropical regions (Leonard et al. 1998).

In figure 4 we show the difference between the MTG- and MTG+ simulations of the density of cyclone tracks analyzed over the 5 winters of the simulations. It can be seen that the cyclone track density around most of the Antarctic coast is greater in the MTG+ experiment, while north of about 60°S there are more tracks in MTG-. When the MTG is strengthened, the total number of cyclones decreases, but they tend to move further south and are more concentrated around the Antarctic coast. When the MTG weakens the total number of cyclones actually increases, but they are more disperse. These results show that the winter warming that was seen in both experiments is due to different mechanisms. In MTG+ the CPT shifts further south and there is more warm air advected to the coast in winter. In MTG- the CPT becomes broader and the same warming comes about because although there are fewer systems near the coast, there are more systems in the southern extratropics overall.

In addition to the changes in the cyclone track density, the regions of cyclone creation and destruction have also changed. When the MTG is strengthened there appear to be more cyclones forming in the region to the north of the Ross Sea that move eastward and die in the Bellinghausen Sea, thus intensifying this storm track.

There is also evidence of a change in the strength of the wintertime surface winds over the Antarctic continent. With a stronger MTG and greater cyclone track densities close to the Antarctic coast, the katabatic wind on the East Antarctic coast in enhanced, while with weaker MTG the katabatic flow is weakened.

4. CONCLUSIONS

This work has been motivated by the many studies that show that the climate of the high southern latitudes has changed over the last three decades. As the strength of the meridional temperature gradient in the mid-troposphere between 50° and 65°S strongly influences extratropical cyclone numbers and behavior through its effect on baroclinic instability, changes in it may well have lead to the circulation changes identified. We have therefore performed two numerical experiments whereby we impose a strengthening and weakening of this temperature gradient and examine the response of the atmosphere.

A stronger MTG leads to warming along the Antarctic coast in winter as extratropical cyclones tend to move further south close to the coast and transport more warm air there. This is achieved through an enhancement of the baroclinic instability of the southern extratropics. However, when the MTG is weakened and baroclinic instability reduced, the cyclones stay further north, although their numbers increase. Coastal surface warming therefore occurs in both cases but for different reasons. The impact of MTG on the circulation is therefore as expected, but the climate of Antarctica is modified depending on the exact nature of these circulation changes.

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