On the Influence of the Andes on the General Circulation of the Southern Hemisphere

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5 April 1993 and 15 December 1993

ABSTRACT

An experiment is described in which the Andean topography in a general circulation model is replaced by an envelope topography and a new model climatology is produced. The resulting simulation is compared to the model climatology of an experiment in which the topography of the Andean region is completely removed. Apart from dramatic local effects, the Andean mountain range appears to exert little influence on the general circulation of the Southern Hemisphere. The experiments are assessed in the context of the geologically recent uplift of the Andes.

1. Introduction

The influence of the Andes on the general circulation of the Southern Hemisphere has been a subject of some controversy. Kalnay et al. (1986) used a general circulation model (GCM) with a resolution of 4 deg × 5 deg, nine vertical levels, and sophisticated physics to investigate, among other things, the role of the topographic forcing of the Andes. A 15-day forecast showed that observed large amplitude, short-wavelength stationary waves could be reproduced in the GCM simulation even if the Andes were removed, thus demonstrating the possibility that the Andes essentially affected the climate only locally and did not have a large impact on the general circulation. This experiment nevertheless is incomplete because the shortness of the simulations may mean that this result would apply only to the particular synoptic situations simulated.

The influence of the Andean region on the climate of the Southern Hemisphere has implications for the study of climates of the past. Considerable uplift has occurred in this region in the past few million years (Benjamin et al. 1987). This mountain building would be expected to have a dramatic impact on the climate of the surrounding regions, but the effect on the climate of the rest of the Southern Hemisphere is unknown. In a series of papers, Ruddiman et al. (1989), Ruddiman and Kutzbach (1989), and Kutzbach et al. (1989) demonstrated with GCM experiments that the similarly recent uplift of the Tibetan Plateau could have forced climate changes elsewhere in the Northern Hemisphere by changing the planetary wave patterns. Broccoli and Manabe (1992) performed a GCM experiment in which all topography was removed and examined the connection between Northern Hemisphere midlatitude arid climates and topographic uplift. They found that uplift may have contributed to the formation of such climates. Thus it is reasonable to assume that the formation of the Andes might be attended by large local and possibly remote climate changes.

In order to investigate the magnitude of the impact of the specification of Andean topography on the Southern Hemisphere general circulation, a series of experiments have been performed using a GCM. The model and the experimental methodology are described briefly in section 2. Experimental results are discussed in section 3, and section 4 contains concluding remarks.

2. Model and methodology

The model used in the topographic experiments described in this chapter was version 10A of the Australian Bureau of Meteorology Research Centre (BMRC) GCM. The details of this model are published in Hart et al. (1990), but the model will be described briefly in this section. It is a nine-sigma-level spectral model; a resolution of R21 was used in these experiments. The model incorporates stability-dependent surface fluxes based upon Monin–Obukhov similarity theory; the surface soil moisture is calculated using the “bucket” method, while the surface temperature is calculated using a Newton–Raphson iterative procedure on the heat balance equation. Fixed climatological sea surface temperatures were used (Alexander and Mobley 1976). A modified version of the Kuo (1974) convection scheme is used to calculate precipitation along with the Tiedtke (1984a,b; 1988) shallow convection scheme. Radiative fluxes are calculated using the Fels–Schwarzkopf (1975) radiation code, while cloud
amounts and surface albedos are specified from climatology. In these experiments, diurnally averaged incoming solar radiation was imposed, and the model was run in "perpetual" July mode for 390 days; the first 90 days of the simulation were discarded and a climatology produced from the average of the last 300 days.

Because of the lack of seasonal variation in these simulations, it is probably not appropriate to expect the same experiment to produce a similar result in other seasons. It might be expected, for instance, that the removal of topography would cause a bigger local response in the Andean region in January than in July, because of the stronger transient heating at upper levels in January (Gandu and Geisler 1991). Since this paper is predominantly concerned with the ability or lack thereof of the Andes to deflect the large-scale flow, and because wind speeds in the lower levels of the atmosphere in this region are higher in July than in January (Oort 1983), a July simulation seemed more appropriate here.

Two simulations were performed. The control experiment is one in which the topography used in Hart et al. (1990) was replaced over the Andean region alone by an envelope topography of one standard deviation (Wallace et al. 1983; Tibaldi 1986; Miller et al. 1989). This technique provides a better representation of Andean topography over regions of high topography. The envelope topography is shown in Fig. 1 and has a peak height of almost 4 km, which is close to reality. For the purposes of this experiment, the Andean region is defined as being bounded by longitudes 78.7°W and 61.9°W, and latitudes 49.3°S and 4.5°S. The topography was changed for those Gaussian grid points inside this area: gridpoint values were changed and then the spherical harmonic representation of the topography was recomputed. Slight but climatically insignificant changes in topographic heights therefore occur in locations outside the region of modified topography. A further simulation was performed in which the topography of the Andean region was removed; the two simulations were then compared to examine the impact of removing the topography of the Andean region. For the purpose of analysis, the surface pressure fields of both simulations were corrected slightly to account for the atmospheric mass displaced or created by the addition or removal of topography (M. Dix 1992, personal communication); such changes in topography would otherwise cause changes in surface pressures unrelated to the purely dynamical effects that we wish to examine.

3. Results

Figure 2a shows the control climatology of mean sea level pressure for 300 days of perpetual July simulation. Figure 2b shows the difference field between this run and the experiment in which the Andean topography was completely removed, while Fig. 2c gives the results of the Student's t-test calculated using ten 30-day averages of each run, with the statistic calculated at each Gaussian grid point. Shaded areas are significant at the 95% level. The results show that significant changes to the circulation occur only in the region of the Andean mountain range itself. At upper levels (Fig. 3), large areas of statistical significance in the equatorial regions are seen at 500 hPa, while pockets of significance are seen at 200 hPa. In both cases, however, the actual magnitudes of the differences are small compared to variations in the midlatitudes. Certainly the impact of the removal of the Andes on the 500- and 200-hPa zonal wind fields (not shown), while statistically significant locally, appears hemispherically and globally to be small.

The effect on the surface climate also appears in general not to be statistically significant at large distances from South America. Both the precipitation (Fig. 4) and the lowest sigma-level temperature (Fig. 5) show large statistically significant differences over and near South America associated with the change in topography, but such changes elsewhere are patchy and inconsistent. Significant changes in low-level temper-
ature appear to propagate weakly across the Pacific, with an area of significant decrease near Japan. The stability of this teleconnection is doubtful, however, given the possibility of sampling errors.

The effect on the surface climate of South America is, however, dramatic. Figure 6 shows results for surface temperature. Differences are large and statistically significant in most regions of the continent. There is naturally an increase in temperature over the regions where topography is removed, but there is also a decrease in temperature over the eastern coast from about 25°S to 40°S. This is probably caused by the fact that downslope winds warmed by latent heat release over the peaks of the Andes no longer occur when the topography is removed. There is also an area of significant increase over central Brazil, caused by the expansion

**Fig. 2.** Mean sea level pressure in hPa for (a) climatological simulation; (b) simulation with no Andean topography minus climatological simulation; and (c) Student's t-test results for the two simulations. Light shaded areas are increases significant at the 95% level, while dark shaded areas are similarly significant decreases.

**Fig. 3.** Difference in geopotential height field for zero Andean topography simulation minus envelope topography simulation for (a) 500 hPa; (b) the corresponding t test field; (c) 200 hPa; and (d) the corresponding t test field. Contour intervals for (a) and (c) are 10 m.
of the region of high temperatures over Amazonia associated with lower topography.

As expected, when the topography is removed, statistically significant increases in precipitation occur over Patagonia, which at present is in the rain shadow of the Andes (Fig. 7). Similarly significant decreases in rainfall occur near the topographic peak region and on the west side of the Andes near 40°S, a result that was also shown by Broccoli and Manabe (1992) in their experiment in which they removed all topography. Significant increases in precipitation appear to occur over southeastern Brazil, possibly associated with increased northward transport of moisture from the midlatitudes. Removing the Andes also increases precipitation in the presently dry west coast region between 0° and 10°S, probably because the removal of the mountains allows increased moisture transport by the prevailing easterlies into this region from Amazonia.

4. Discussion and conclusions

Experiments have been performed in which the impact on the climatology of a GCM of the removal of the Andes has been assessed. The general circulation of the Southern Hemisphere and elsewhere appears little changed by the removal of the Andes, even when an envelope topography is imposed upon the Andean region alone and the results of that simulation are compared to the case of no Andean topography. The results suggest that changes in climate caused by the uplift of the Andes through geological time would have had a dramatic effect over and near South America but little or no effect elsewhere.

The explanation of this result may be related to several factors. As noted by several workers, easterly flow cannot induce planetary wave patterns downstream (Frederiksen 1982; Kashara 1966; Bolin 1950). Thus any consideration of the large-scale downstream effects of topography must be restricted to regions where westerlies are predominant. Over the Andean region in July, westerly winds are on average observed south of about 30°S at 850 hPa, while at 500 hPa, westerlies are observed south of about 10°S (Oort 1983). Considerations of the conservation of vorticity (e.g., Barry 1992) suggest that large-scale flow deflection should occur downstream of the Andes. Certainly large-scale flow deflection occurs downstream of the Rocky Mountains (Oort 1993), although recent modeling results (K. Walsh 1994 personal communication) suggest that a large portion of this deflection is remotely forced by the Tibetan Plateau. The Andes mountain range and plateau system has a considerable meridional extent and is lower on average than the Tibetan Plateau. Calculations have been performed using the theoretical arguments of Trenberth and Chen (1988), which suggest that large-scale flow is not meridionally deflected by the Andes. Trenberth and Chen derived a theoretical criterion \( h_c \) for a critical height of large-scale topography such that if a topographic feature is higher than \( h_c \), flow should tend to travel around it, and if it is lower, then flow should tend to travel over it. The critical height \( h_c \) is defined:

\[
h_c = \beta L_v H / f,
\]

where \( f \) is the Coriolis parameter, \( \beta = \partial f / \partial y \), \( H \) is the scale height, and \( L_v \) is the meridional scale of the topography. Trenberth and Chen calculated \( h_c \) for the Tibetan Plateau, assuming \( L_v \approx 1000 \) km and choosing values of \( f \) and \( \beta \) typical for 35°N, and found \( h_c \approx 1.5 \) km. Since large areas of the Tibetan Plateau are higher than 4 km above sea level, flow should therefore be strongly deflected around it. Performing the same analysis for the Andean experiments described in this paper, we assume \( L_v \approx 2500 \) km, this being half the meridional extent of the region of topography modified in the experiments. We also assume values of \( f \) and \( \beta \) at a latitude of 27°S, which is near the midpoint of the latitudinal extent of the modified domain. We then calculate a value of \( h_c \approx 5 \) km. Since only the highest portions of the Andes are close to this height, according to this argument flow should still predominantly travel.
over the mountain range and should not be greatly deflected around it at the large scale. Performing a similar calculation for the Rocky Mountains also suggests that flow should not be substantially deflected by them—a result, however, that is at variance with a number of modeling studies (Boyer and Chen 1987; Ruddiman and Kutzbach 1989). The earlier theoretical results of Rooney and Janowitz (1979) suggested that in the case of the Andes, high upstream vertical shear is associated with a much reduced planetary wave amplitude compared to that induced by the Rocky Mountains.

Whatever the explanation, it is likely from the results presented here that the Andes do not have the potential...
to make changes in the planetary wave pattern through large-scale meridional deflections of the mean flow, whereas the Tibetan Plateau does. Thus, changes of climate distant from South America caused by removal of the Andes of the kind demonstrated in Ruddiman and Kutzbach (1989) for the Tibetan Plateau are unlikely.

As mentioned earlier, one limitation of these experiments is that they were performed for July only, and different responses may be generated for other seasons. In addition, the model contained no correction for the artificial horizontal diffusion of temperature and moisture along sloping surfaces, although it is doubtful whether this would be a major concern given the size

FIG. 7. The same as Fig. 6 except for precipitation; contour intervals for (a) and (c) are variable in mm per day, and for (c), 1 mm per day.
of the topography changes. Another limitation of these experiments is that sea surface temperatures are fixed and do not respond to changes in the climate of the atmosphere. In reality significant changes in wind patterns off the west coast of South America near Peru caused by changes in topography could cause changes in the strength of upwelling in this region, thus significantly altering the local sea surface temperatures. Locally significant changes in sea surface temperature patterns in this climatically important region might affect the trans-Pacific gradient of surface temperatures, which might force larger remote changes than are shown in the current experiments. Such teleconnections related to the El Niño–Southern Oscillation phenomenon are significant and can cause dramatic changes in precipitation patterns throughout the Pacific region and elsewhere (e.g., Philander 1990). In the absence of results from an experiment performed with an interactive ocean, it is difficult to speculate what differences there might be between the results of such an experiment and those presented in this paper. It would be instructive to perform such an experiment.

Acknowledgments. The author thanks the Australian Bureau of Meteorology for granting permission to use their GCM. The author would like to thank Barrie Hunt, Jozef Syktus, Leon Rotstayn, and Graeme Pearman for helpful comments. This work represents part of the author’s Ph.D. thesis under the supervision of Prof. Ian Simmonds at the University of Melbourne, and of Dr. Jorgen Frederiksen at CSIRO.

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