EFFECT OF A PACIFIC SEA-SURFACE TEMPERATURE ANOMALY ON THE CIRCULATION OVER NORTH AMERICA: A NUMERICAL EXPERIMENT WITH THE GLAS MODEL

J. Shukla

Department of Meteorology
Massachusetts Institute of Technology
Cambridge, Massachusetts
and
NASA Goddard Space Flight Center
Laboratory for Atmospheric Sciences
Greenbelt, Maryland, USA

and

B. Bangaru

Sigma Data Services Corporation, Inc.
NASA Goodard Space Flight Center
Greenbelt, Maryland, USA

ABSTRACT

A numerical experiment with the GLAS model has been carried out to determine the effect of sea-surface temperature anomalies over the Pacific on the circulation over North America. The sea-surface temperature anomaly pattern chosen for this study was similar to the one observed during January 1977. It is shown that a cold sea-surface temperature anomaly over the Pacific produces a strong southward flow over the United States and colder temperature in eastern Canada and the United States, as it was observed during 1977 Winter. The results indicate, contrary to the published results of earlier numerical experiments, that the SST anomaly over the Pacific can produce a significant downstream effect over the continental United States.

1. Introduction

During the fall and winter 1976-77, SST in the north Pacific was characterized by abnormally cold temperatures in the central and western portions of the north Pacific with a warm pool located off the west coast of the U.S.A. (Fig. 1). Namias (1978) has suggested that the north Pacific sea surface temperature (SST) anomalies may have been one of the multiple causes of the abnormally cold temperatures in eastern North America during the 1976-77 winter. In this study we have attempted to test this hypothesis by conducting a numerical experiment with the General Circulation Model (GCM) of the Goddard Laboratory for Atmospheric Sciences (GLAS).

Voluminous meteorological literature exists on the subject of the effects of SST anomalies on the general circulation of the atmosphere. While there are no established rules of thumb to determine the specific effects of a given SST anomaly on the atmospheric circulation, it is reasonable to assume that the response of a given SST anomaly depends upon the following factors:

1. The magnitude and the spatial and temporal structure of the anomaly.
2. The latitude of the anomaly (because of the Coriolis force dependence in the thermal wind).
3. The location of the anomaly with respect to the most dominant dynamical regime. For example, a warm anomaly in the ascending branch of the Hadley or Walker circulation may be more efficient in accelerating the circulation than a cold anomaly in the descending branch of a thermally direct circulation.
4. The structure and dynamics of the circulation regime in which the anomaly is embedded. In tropical latitudes, where CISK may be the primary driving mechanism, a conditionally unstable atmosphere may respond rather quickly to a warm SST anomaly, whereas in mid-latitudes, where the primary driving mechanism is the baroclinic instability, a given SST anomaly field would affect the vertical shear and therefore the growth rates of the baroclinically unstable waves.

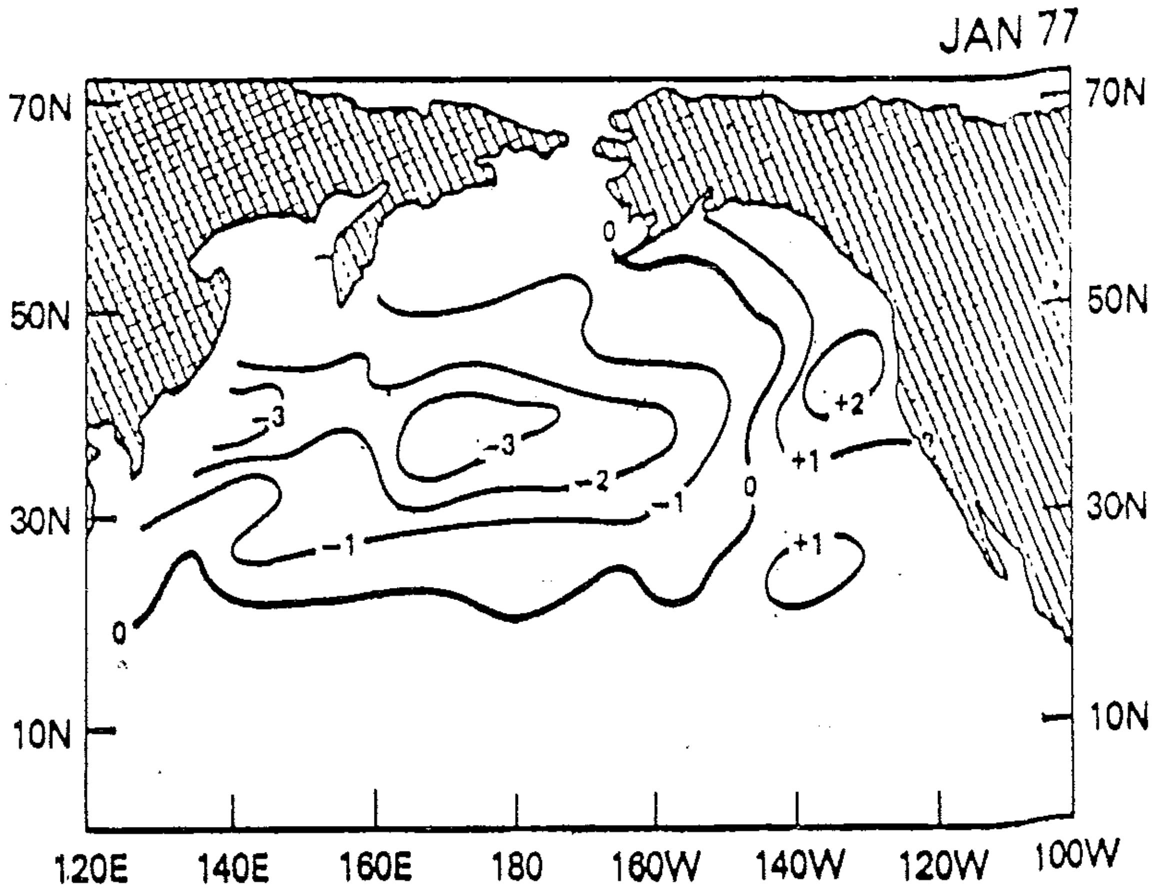

Fig. 1. Observed sea surface temperature anomaly (°F) during January 1977.

The importance of the magnitude and structure of the SST anomaly can easily be shown by the linear theories where the scale and magnitude of the response depends upon the scale and magnitude of the forcing. However, another important factor is the mean SST over which the anomaly is assumed to be superimposed. This is because of the highly nonlinear nature of the relationship between saturation vapor pressure and temperature.

In summary, therefore, in order to determine the response of a given SST anomaly one must consider the structure and dynamics of the prevailing atmospheric circulation in addition to the magnitude and structure of the anomaly field itself. Further, one must also include the orographic and diabatic effects realistically. It was, therefore, considered appropriate to use the GLAS GCM to conduct these numerical experiments.

2. Description of Experiments

The model used in the present study is the one described earlier by Somerville *et al.* (1974) and Stone *et al.* (1977). A modified version of the model has also been presented in these proceedings by Halem *et al.* (1979). The experiments were performed by first integrating the GLAS GCM for 45 days with the climatological mean SST and the observed initial conditions valid for January 1, 1975. We will refer to this integration as the Control Run (C). The climatological SST field was then changed by adding a time invariant anomaly field and therefore, although the climatological SST varied with season, the imposed anomaly field remained constant with time. The structure of the imposed SST anomaly was the same as shown in Fig. 1. but the numerical values were exaggerated by considering them in °C rather than °F. The model was integrated again for 45 days and we will refer to this run as the Anomaly Run (A).

Control Run C and Anomaly Run A were further repeated with their respective boundary conditions in SST but the initial conditions in u, v, T and surface pressure were randomly perturbed. The spatial variation of the random perturbations corresponded to Gaussian distributions with zero means and standard deviations of 1°C in temperature, 4 m/s in horizontal wind components and 3 mb in surface pressure over land points, and 2°C in temperature, 8 m/s in horizontal wind components and 6 mb in surface pressure over ocean points.

We will refer to these runs as Initial Condition Perturbation Runs C_1 and A_1 for Control (C) and Anomaly (A) respectively. Four additional Initial Condition Perturbation Runs were already made by Spar *et al.* (1978) which we will refer to as C_2, C_3, C_4 and C_5. We shall refer to the average of the atmospheric parameters for the six runs C, C_1, C_2, C_3, C_4, C_5 as the mean control (Cm) and the average of two anomaly runs A and A_1 as mean anomaly (Am). In order to assess the response of the imposed SST anomaly on the atmospheric circulation we will examine the differences between the mean control and the mean anomaly runs averaged for the period between day 15 through day 45, and compare the magnitude of the differences with respect to the standard deviation among the mean monthly values for the six control runs for this period.

3. Simulation of the Mean Field

Figure 2 shows the 500 mb geopotential height for the mean control (Cm). Mean control for the 500 mb geopotential height field is in reasonable agreement with the observed climatological mean winter circulation at 500 mb. Of particular interest or note is the ridge near the west coast of the U.S.A. It is the intensification and the persistence of this ridge during the winter 1976-77 which was the most conspicuous feature of the general circulation over North America, with which the very cold temperatures over the eastern U.S.A. were associated.

4. Results

Figure 3a shows the difference between the mean anomaly and the mean control runs for the 700 mb temperature. The largest differences are found along the International Date line which is the longitude of maximum negative anomaly in SST, and the eastern parts of Canada and northern U.S.A. A positive anomaly is found over Greenland. Occurrence of colder 700 mb temperatures over the cold anomaly and warmer

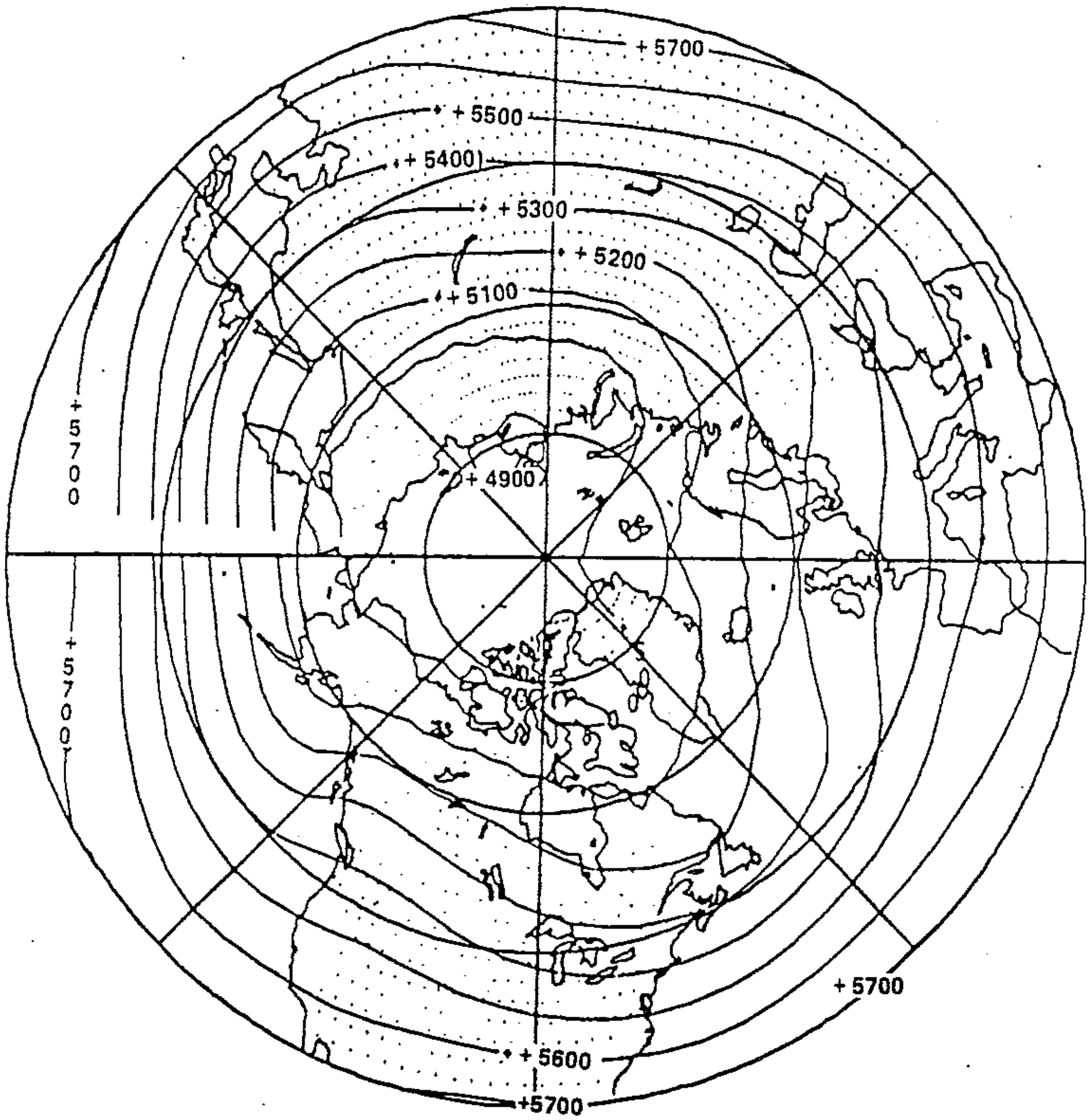

Fig. 2. Mean geopotential height at 500 mb (control), in m.

700 mb temperatures over the warm anomaly can be explained by considering the radiative, sensible and latent heat fluxes. A detailed examination of the model generated heat fluxes showed that the evaporation and convective cloudiness decreased over the cold anomaly. Reductions in the moisture and the sensible heat flux which reduce the convective clouds cause a reduction in the latent heat of condensation, and this can also cause cooling of the atmospheric temperatures. Consistent with the decrease in the convective cloudiness, it was also found that the solar flux at the surface increased but the long wave flux at the surface decreased. Since the sea-surface temperatures were prescribed, this feedback does not operate in the model. It should be noted, however, that the net effect of these diabatic heat sources and sinks is such that the heat source (sink), which was initially confined to the lower boundary, finally extends into the troposphere.

The most interesting feature in this figure is the coldest 700 mb temperatures centered around 50°N, 75°W. This is clear evidence of the downstream response of the model to the SST anomalies in the Pacific. Figure 3b shows the ratio of the differences and the standard deviations among the six control runs. We may refer to these ratios as the signal to noise ratio. Two areas of maximum signal to noise are found, one over the anomaly itself and the other centered around 50°N, 75°W. The positive temperature anomalies over Greenland were found to have a signal to noise ratio less than two.

Differences between the anomaly and control runs for 500 mb temperatures (Fig. 5a) and corresponding signal to noise ratio (Fig. 5b) show the same general features. This indicates that the influence is not confined to the lower layers only. Even 200 mb fields (not shown here) show similar effects.

Difference fields for the geopotential height field at 700 mb (Fig. 4a) and 500 mb (Fig. 6a) and their respective signal to noise ratio fields (Figs. 4b and 5b respectively) show that the anomalous geopotential field has maximum positive values along 145°W and maximum negative values along 45°W. This implies an anomalous southward flow over eastern Canada and northeast U.S.A. It is this anomalous southerly flow which advects cold air from the north and produces cold temperatures as shown in Figs. 3a and 5a.

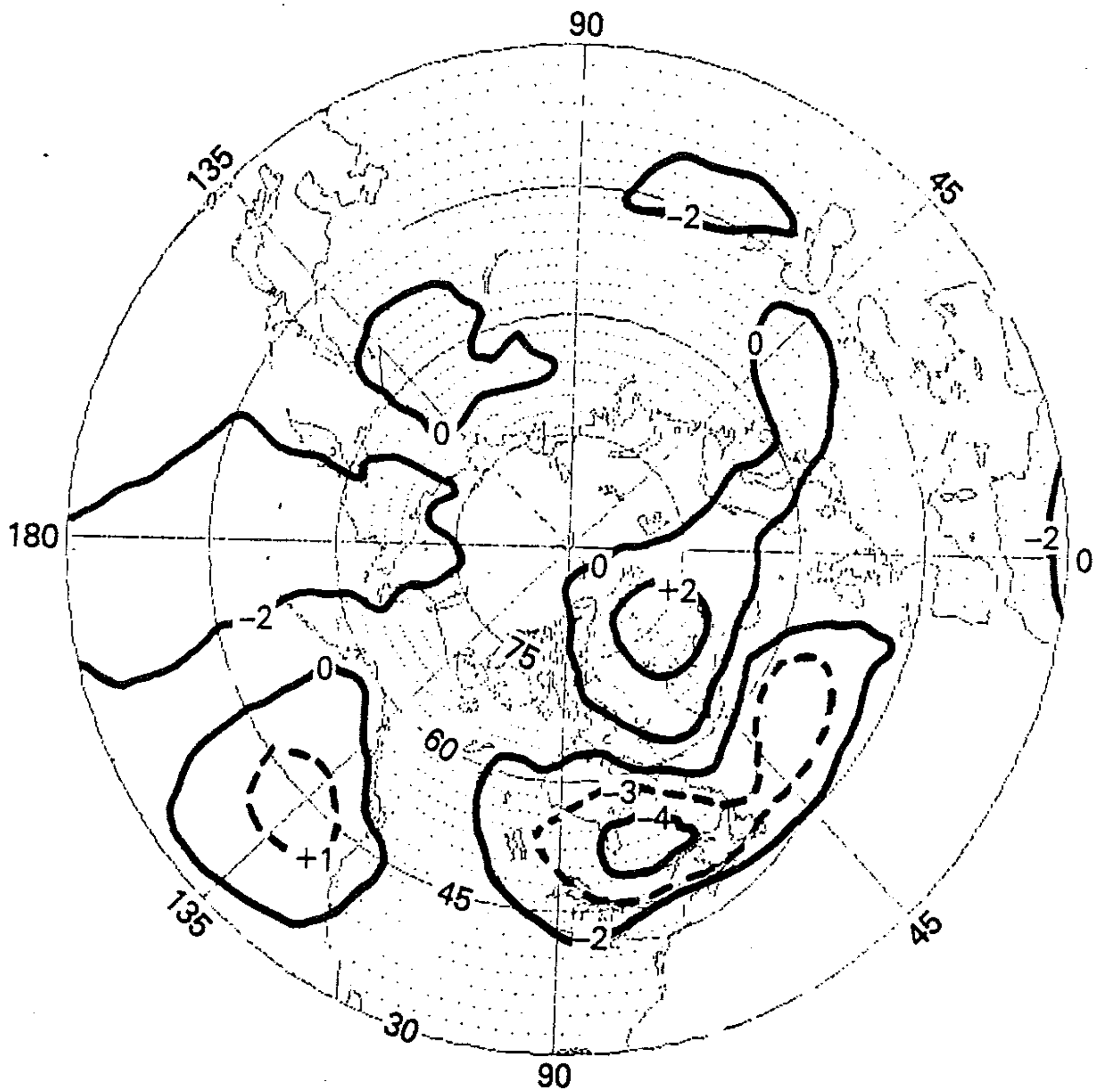

Fig. 3a. The temperature difference (°C) at 700 mb between the mean anomaly and mean control runs.

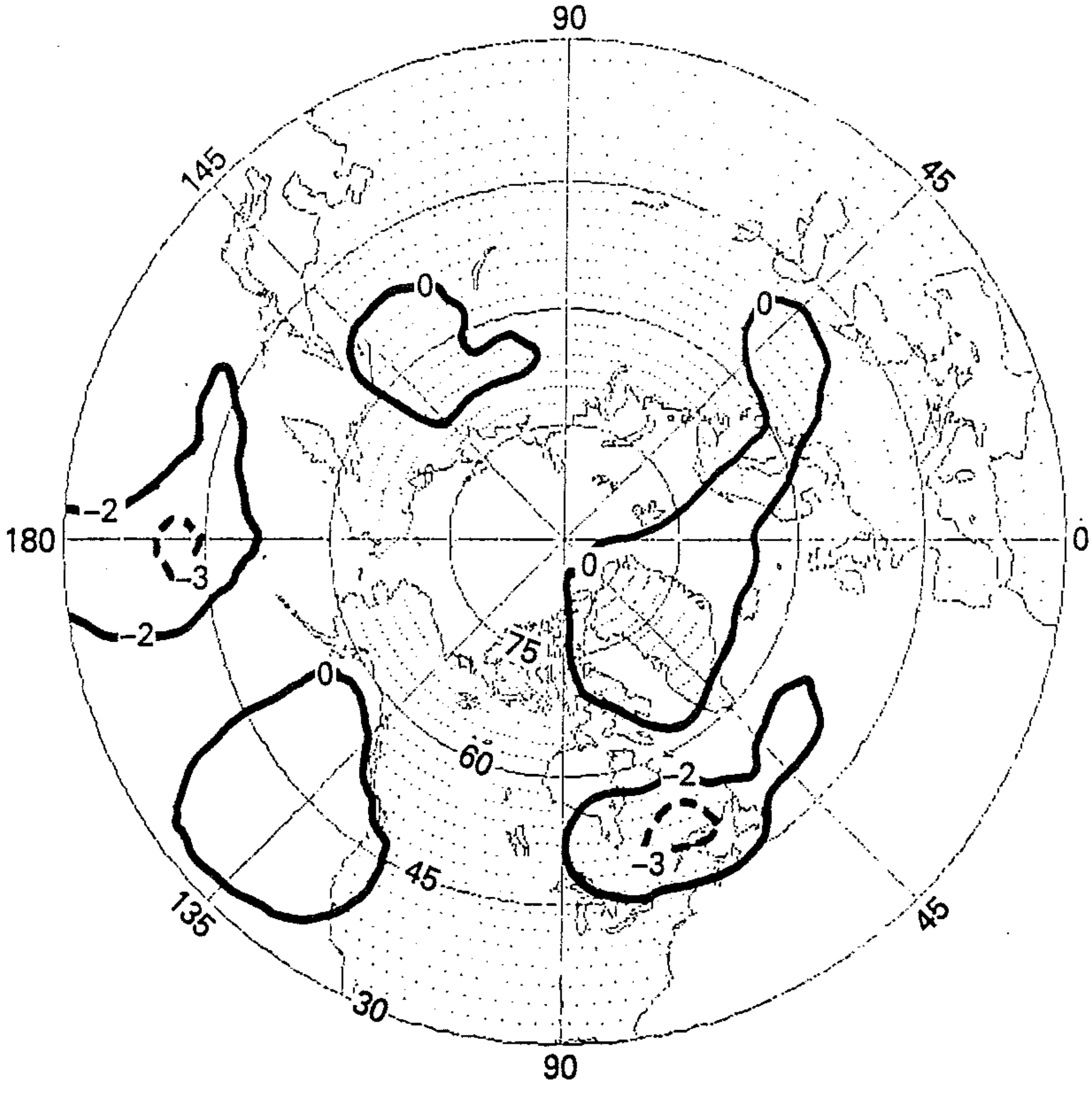

Fig. 3b. Ratio of the temperature difference at 700 mb to the standard deviation among the control runs.

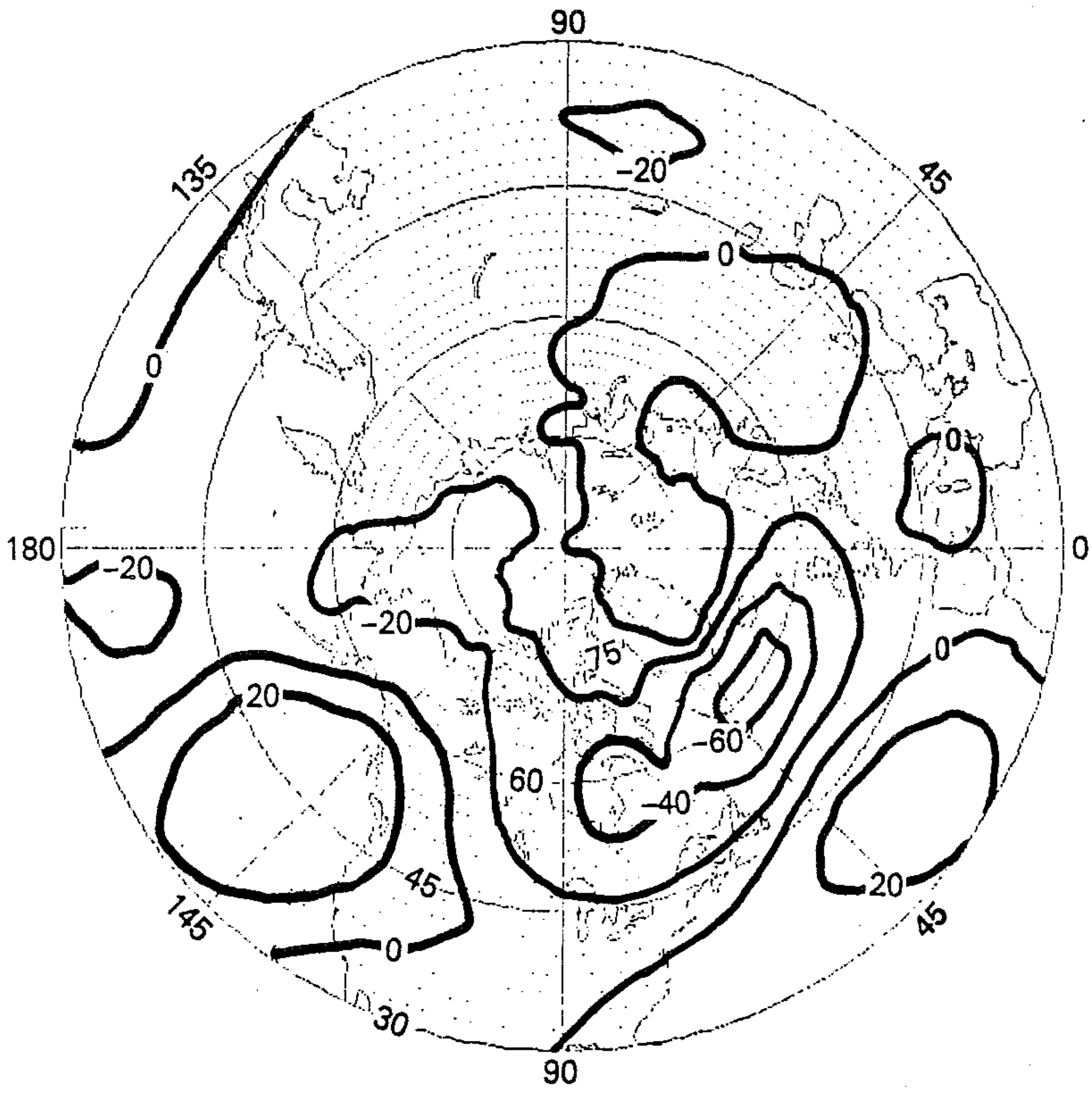

Fig. 4a. The geopotential height difference (m) at 700 mb between the mean anomaly and mean control runs.

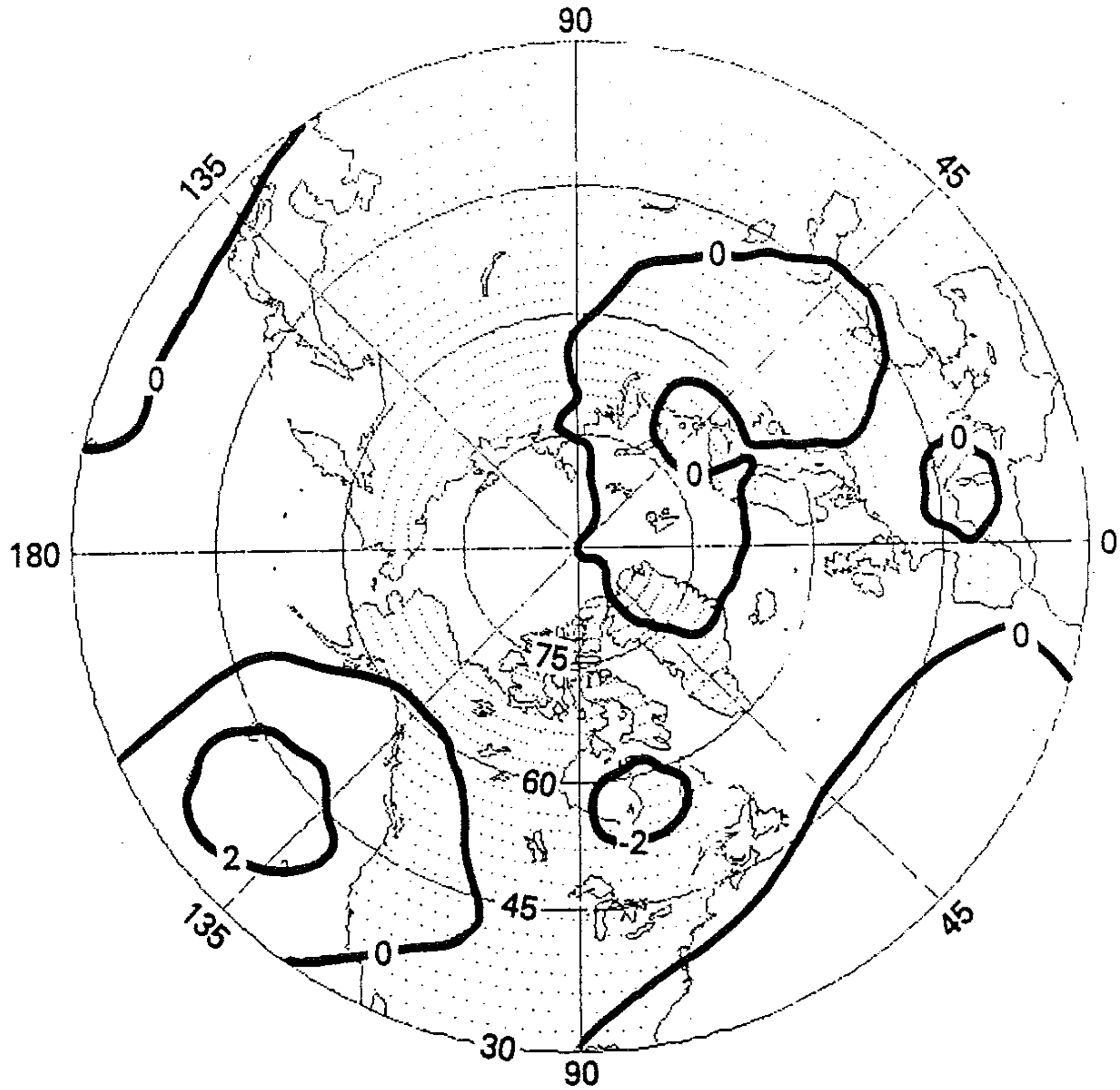

Fig. 4b. Ratio of the geopotential height difference at 700 mb to the standard deviation among the control runs.

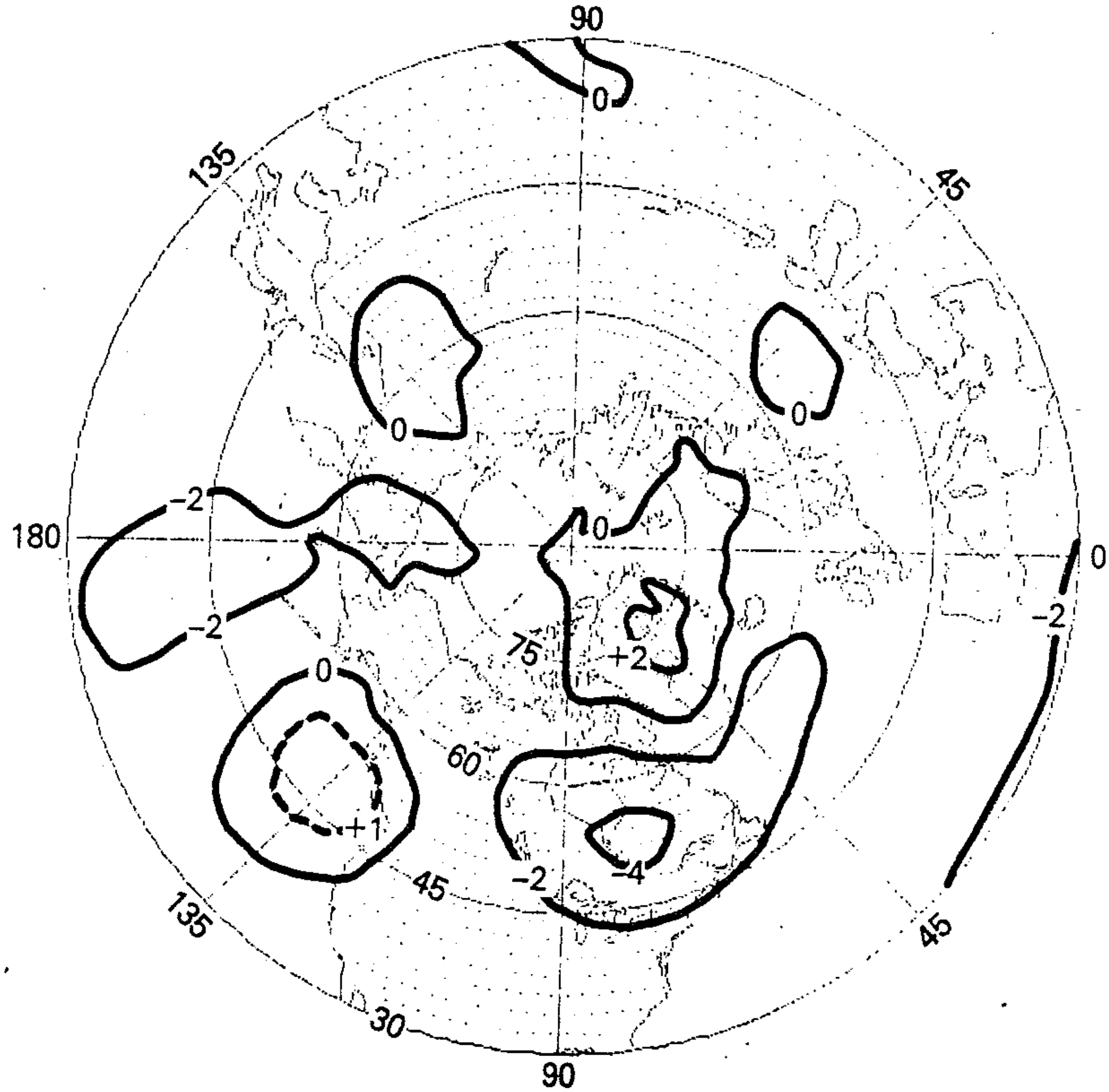

Fig. 5a. Same as Fig. 3a except for 500 mb.

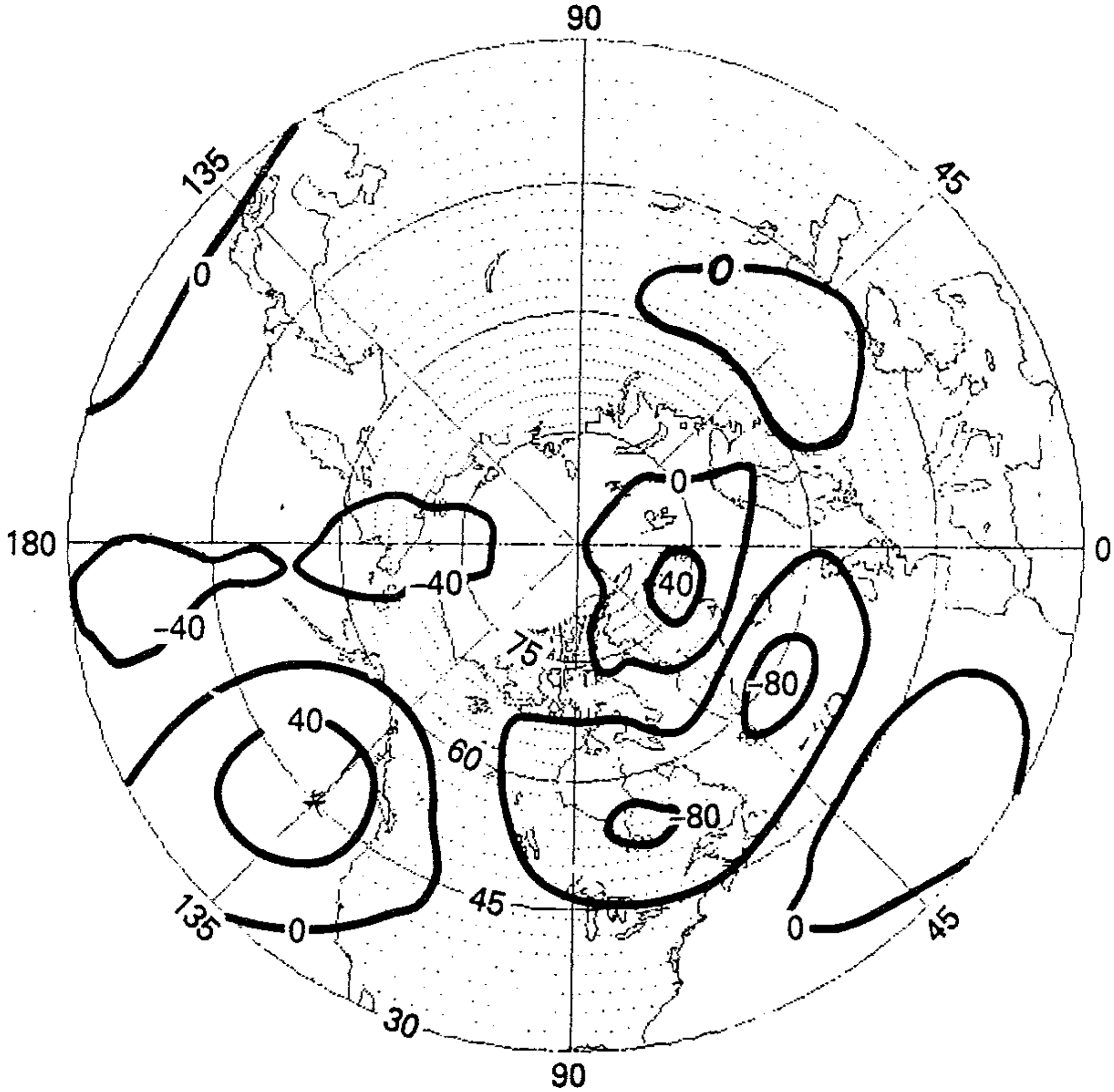

Fig. 6a. Same as Fig. 4a except for 500 mb.

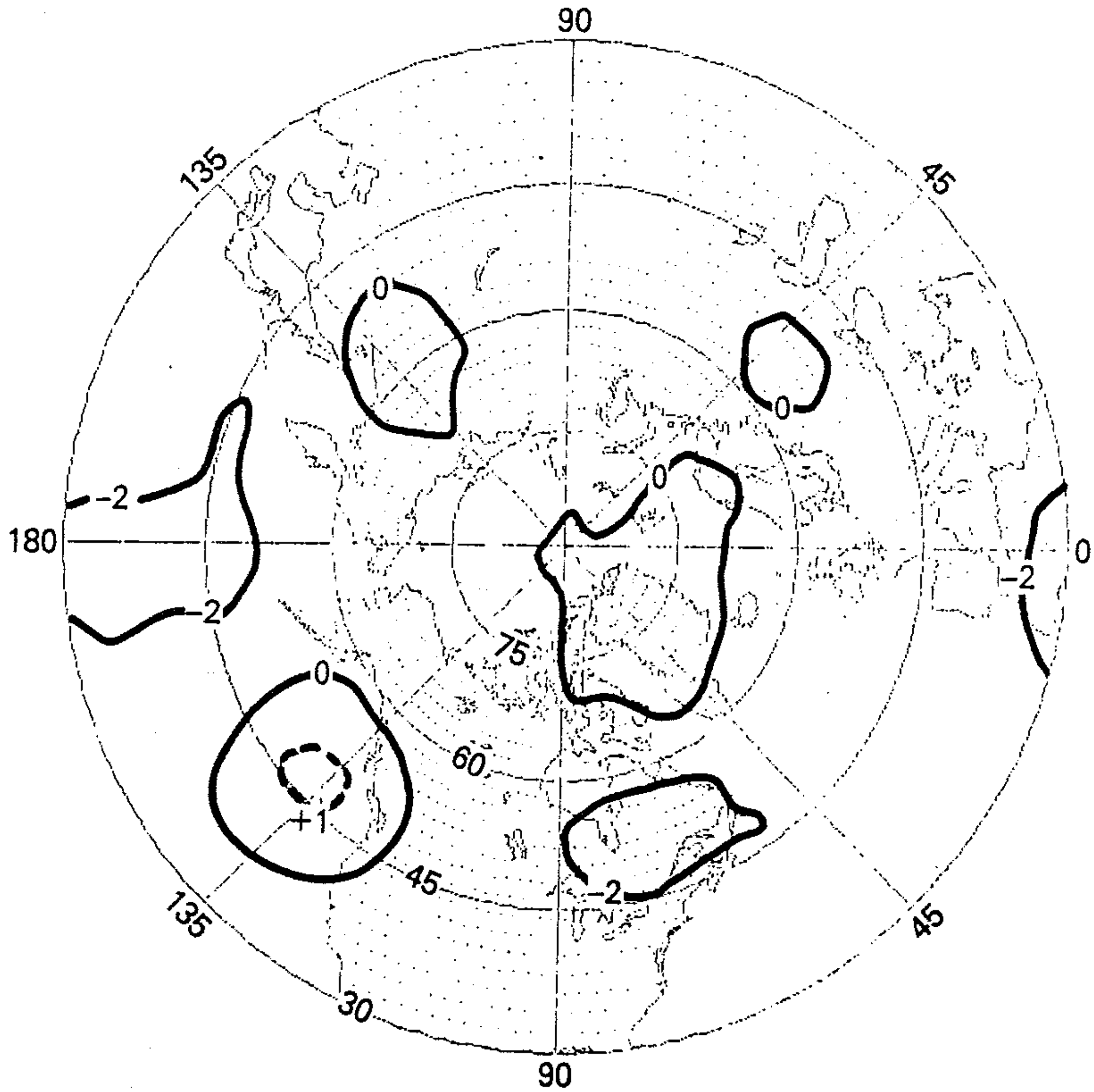

Fig. 5b. Same as Fig. 3b except for 500 mb.

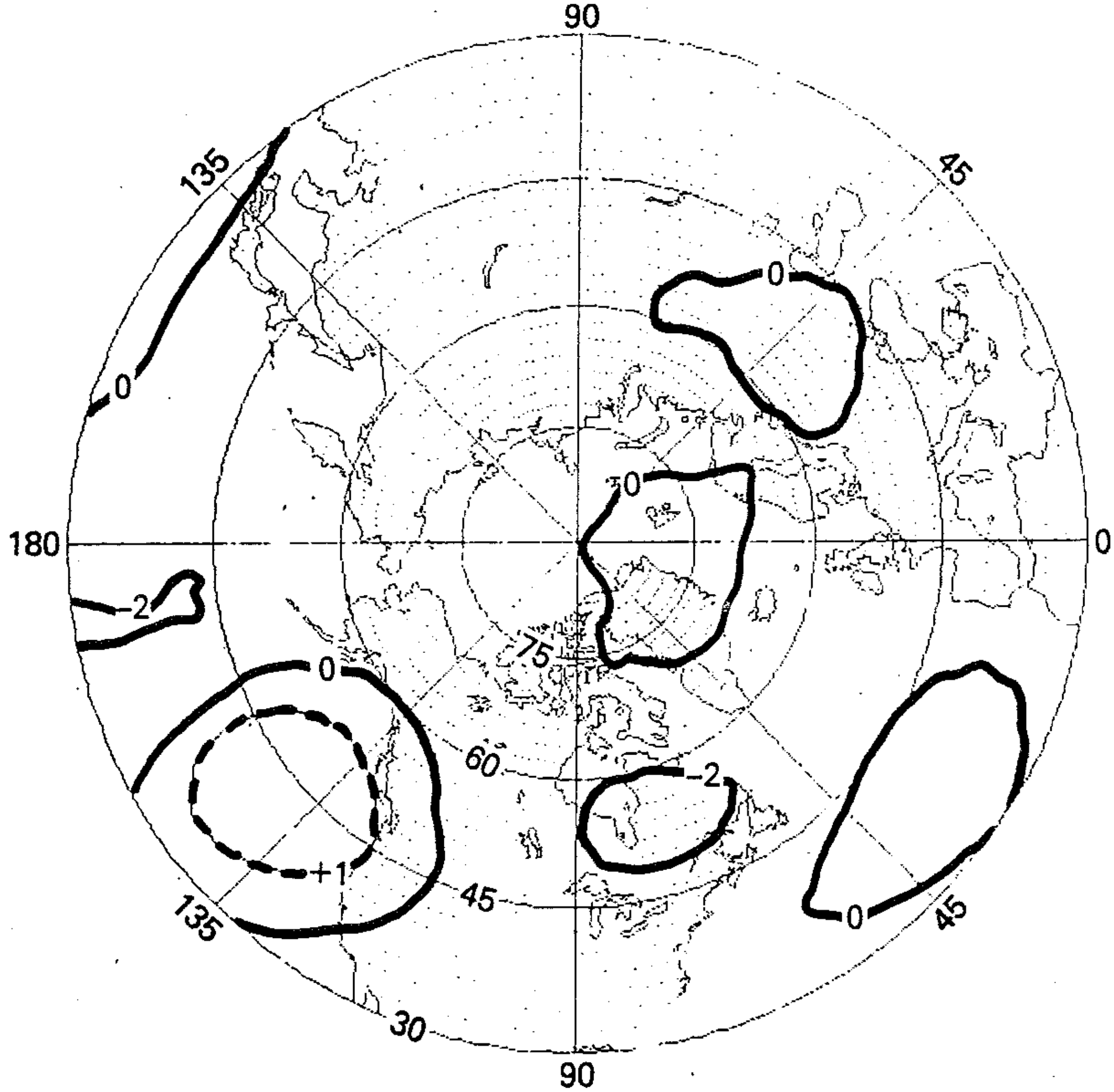

Fig. 6b. Same as Fig. 4b except for 500 mb.

In the earlier numerical experiments with the NCAR model (Kutzbach *et al.*, 1977; Chervin *et al.*, 1976) no significant downstream effect was noticed. Although the two general circulation models are not identical (especially with regard to their simulation of the transient eddies), in our opinion the primary reason a downstream effect was observed in the GLAS model was due to the nature of the spatial structure of the SST anomaly.

5. Conclusions and Discussion

The results of these numerical experiments support the hypothesis by Namias that the SST snomalies over the Pacific during 1976-77 winter may be one of the contributing factors towards very cold temperatures over northeast U.S.A. and warm temperatures over the Alaskan region. Since this was not a coupled ocean-atmosphere model, SST anomalies were assumed to persist for the whole period of integration. This assumption is justified by the observed fact that the SST anomalies did persist for a time period of several months.

These results show a clear evidence of downstream response of the model atmosphere to the imposed SST anomalies over the Pacific. It is interesting to note that for some levels the downstream effect away from the anomaly is more than the effect over the anomaly itself. Since the natural variability of the mid-latitude atmosphere is rather large, the standard deviation among six predictability runs was calculated and the ratios of the mean differences to the standard deviations indicated that the downstream effects are indeed significant.

The results of the present study suggest that the downstream orographic barriers may contribute to amplify the SST generated atmospheric perturbations. In other words, an orographically forced atmospheric flow regime may be more sensitive to further modification by the perturbations generated by the SST anomalies. This qualitative conjecture is suggested by these numerical experiments in which it is found that the effects of the north Pacific SST anomalies are most prominent on the western and the eastern sides of the North American continent. This is of special significance for the winter of 1976-77 because, as pointed out by Namias (1978), the anomalous flow pattern over North America was in phase with the normal winter flow pattern. Therefore, this was interpreted as an inphase amplification of the normal winter circulation which is orographically and thermally forced by the mountains and the mean heat sources and sinks. The purpose of the numerical experiment was not to simulate the actual events of the 1976-77 winter but only to examine the effects of similar SST anomalies on the model atmosphere. It should be noted that the atmospheric conditions in the mean control run corresponded to the winter of 1975.

Detailed examination of the model simulated daily charts indicated that in general the anomaly runs did not show a persistent blocking pattern near the west coast of the U.S.A. as observed during the 1976-77 winter. However, there were periods of 3-5 day duration in which the ridge over the west coast of the U.S.A. was highly intensified and such events were more frequent in the anomaly run compared to the control run. Blocking situations do occur but they do not last too long. It is not clear whether this is a manifestation of some model deficiency or if it is because the model integrations are not performed over several interannual cycles.

We do not have a dynamical explanation for blocking. Application of linear resonance theories is questionable because they do not explain the persistence of the blocking situation. Moreover, blocking appears to be mostly a regional phenomenon. Recently Charney and Devore (1978) have suggested that the blocking may be one of the multiple equilibrium states of the atmosphere. If this is so, even a weak thermal or orographic forcing can sustain a large amplitude change in the mean flow.

The results of these numerical experiments, as of any numerical experiments, do not give a full dynamical explanation for the computed response, but they do confirm or suggest reasonable hypotheses for which dynamical explanations could be sought.

Acknowledgements

We would like to thank Dr. M. Halem for his interest and support of this study and for making useful suggestions on an earlier version of the manuscript. We would also like to thank Dr. J. Namias and Dr. J. Roads for their valuable suggestions in the formulation of the experiments and providing us the SST anomaly fields.

REFERENCES

Charney, J. G., and J. G. Devore, 1978: Multiple flow equilibria in the atmosphere and blocking. (Submitted for publication.)

Chervin, R. M., W. M. Washington and S. H. Schneider, 1976: Testing the statistical significance of the response of the NCAR general circulation model to north Pacific Ocean surface temperature anomalies. *J. Atmos. Sci.*, *33*, 413-423.

Halem, M., J. Shukla, Y. Mintz, M. L. Wu, R. Godbole and Y. Sud, 1979: Climate comparisons of a winter and summer numerical simulation with the GLAS general circulation model. In *Proceedings of the JOC Study Conference on Climate Models: Performance, Intercomparison and Sensitivity Studies*, GARP Publications Series, World Meteorological Organization, Geneva (in press).

Kutzbach, J. E., R. M. Chervin and D. H. Houghton, 1977: Response of the NCAR general circulation model to prescribed changes in ocean surface temperature, Part 1: Mid-latitude changes. *J. Atmos. Sci.*, *34*, 1200-1213.

Namias, J., 1978: Multiple causes of the North American abnormal winter 1976-77. *Mon. Wea. Rev.*, *106*, 279-295.

Somerville, R.C.J., P. H. Stone, M. Halem, J. E. Hansen, J. S. Hogan, L. M. Druyan, G. Russell, A. A. Lacis, W. J. Quirk and J. Tenenbaum, 1974: The GISS model of the global atmosphere. *J. Atmos. Sci.*, *31*, 84-117.

Spar, J., J. J. Notario and W. J. Quirk, 1978: An initial state perturbation experiment with the GISS model. *Mon. Wea. Rev.*, *106*, 89-100.

Stone, P. H., S. Chow and W. J. Quirk, 1977: The July climate and a comparison of the January and July climates simulated by the GISS general circulation model. *Mon. Wea. Rev.*, *105*, 170-194.

GARP

JOINT ORGANIZING COMMITTEE

GARP
PUBLICATIONS
SERIES

No. 22

REPORT OF THE JOC STUDY CONFERENCE ON CLIMATE MODELS: PERFORMANCE, INTERCOMPARISON AND SENSITIVITY STUDIES

VOLUME I

INTERNATIONAL COUNCIL
OF SCIENTIFIC UNIONS

WORLD METEOROLOGICAL
ORGANIZATION