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SUPPLEMENTARY NOTES ON SEA SURFACE TEMPERATURE ANOMALIES AND MODEL-GENERATED METEOROLOGICAL HISTORIES

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Abstract

In seasonal computations, the Mintz-Arakawa two-level model is found to be sensitive to a minor alteration in the computational program. Effects of the program change on monthly mean sea level pressure fields are small in the first month, but large in the second and third months, although the meteorological histories generated by both the original and modified programs are equally credible.

The inherited effects of a transient (one month) sea surface temperature (SST) anomaly on the computed monthly mean sea level pressure fields over a period of a season are about as large in absolute magnitude as those generated in the model by a persistent (seasonal) SST anomaly.

The effects of a transient SST anomaly in the North Pacific Ocean on monthly and seasonal temperature and precipitation in the eastern United States may be large enough to produce a change of one or two class intervals in these predicted weather elements. The model-generated precipitation in the equatorial region is also found to be sensitive to the sea surface temperature field in the North Pacific.

Introduction

In three earlier reports (Spar, 1972, a, b, c) we have described some results of numerical experiments with the two-level Mintz-Arakawa global general circulation model (Gates, et al., 1971) in which a certain persistent positive anomaly pattern was superimposed on the sea surface temperature (SST) field for a period of three months. This note describes some further calculations which were carried out as part of the same experimental program, but which have not been previously reported. Like the experiments which have already been described, these new computations were also designed to estimate the influence of SST anomalies on the behavior of the atmosphere over periods of time from a month to a season, and to provide some background for studies in long range weather prediction. Although the new experiments were not entirely successful (for reasons which are discussed below), the results may nevertheless be of some interest.

One basic question which arises regarding the response of the atmosphere to an SST anomaly concerns the duration, or persistence, of the anomaly field. In the previously reported experiments, an SST anomaly pattern in the extratropical Pacific Ocean was held fixed for three months. The three-month model history corresponding to this so-called "anomaly run" was then compared with a three-month "control run", identical in every respect except for the absence of the SST anomaly pattern. In the new computations, the Northern Hemisphere winter experiment (one of the three original experiments conducted) was repeated with the same initial state, and with the same positive SST anomaly (maximum, 6°C) located in the same region of the North Pacific Ocean (centered on latitude 32°N, longitude 160°W). However, this time the warm oceanic pool was allowed to persist for only one month of the anomaly run, after which time the control SST field, represented by the climatological mean annual SST pattern, was restored. How would the atmosphere respond to only one month of anomalous thermal forcing compared with a season of the same SST anomaly? It was our intention to compare the two sets of meteorological histories in order to answer this question. Unfortunately this proved impossible due to an unanticipated minor change in the computational program at

GISS[1] between the two experiments. The program change[2], which was intended only as an optimization device, resulted in the separation of what should have been two identical model histories after about two weeks, a result very similar to that exhibited in various predictability experiments. Thus, the two sets of SST anomaly experiments were not comparable, and the question above could not be answered directly. Although the program modification eliminated the possibility of comparing a transient one-month anomaly with a persistent seasonal anomaly, it inadvertently provided an opportunity to examine the effect of a computational perturbation on extended time integrations with the model. In the first part of this note the solutions generated by the modified program, hereafter referred to as the "fast" program, are compared with the corresponding solutions computed with the original program. Furthermore, in the course of the one-month anomaly experiment with the fast program, certain new calculations were performed. These are presented in the latter part of this paper.

Effects of the Program Change

A comparison of the control histories generated by the original and fast programs should reveal the effects of the program change[2] over the total three-month period. A similar comparison of the corresponding original and fast anomaly runs is valid only for the first month, after which time the differences are due to both the program change and the differences between the SST fields. Hence, for the first thirty days we may use either the control or anomaly histories to determine the effect of the program change. However, beyond thirty days only the control runs can be employed for this purpose.

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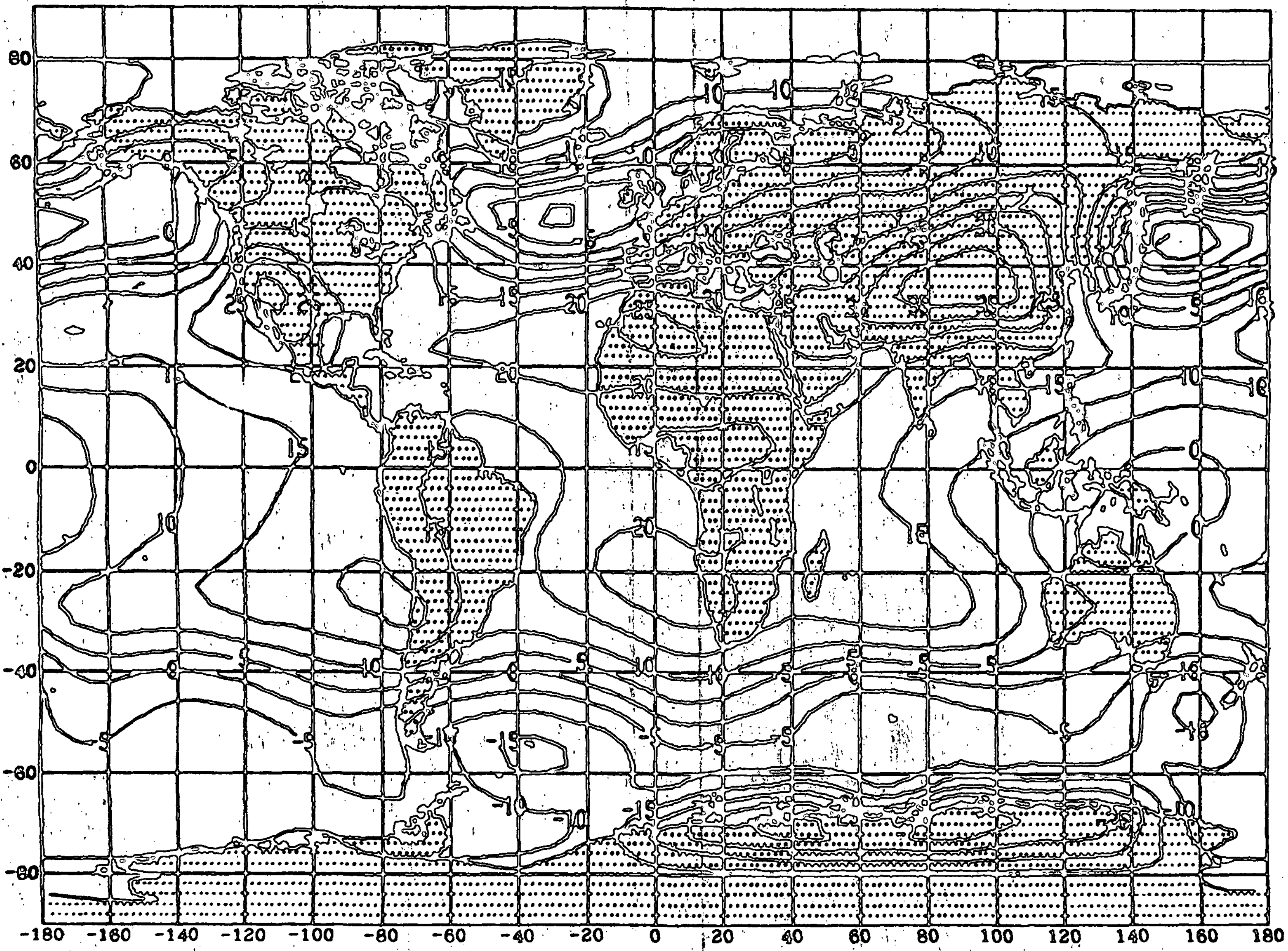
[1] The Goddard Institute for Space Studies (GISS) is located in New York City.

[2] The program change introduced was only a faster algorithm for computing the function p^{κ}, where p is pressure and κ (= R/c_p) is the Poisson constant. The two algorithms give identical results up to 4 to 6 digits over the range of p from 50 to 1050 mb.

In both the anomaly and control runs, there is virtually no detectable difference between the daily global sea level pressure fields generated by the original and fast programs for the first twelve days. Up to day 9 the maximum difference at any grid point is less than 2 mb. On day 12 the maximum difference exceeds 5 mb, but in general the differences are much smaller, and the pressure patterns are almost identical. However, on day 14 significant differences between the synoptic patterns begin to appear, with absolute differences of sea level pressure in excess of 8 mb. These differences continue to increase, especially in the Northern Hemisphere, and by the end of the month the differences between any two corresponding daily control (or daily anomaly) maps, computed respectively with the original and fast programs, are at least as large as the differences between an anomaly map and its corresponding control map. The cumulative effect of the computational differences between the original and fast programs on the daily sea level pressure fields is similar to that found in predictability experiments starting from two initial states which differ from each other by only some small random error distribution (see, e.g., National Academy of Sciences, 1966). After about two to three weeks, the two solutions diverge, becoming effectively as uncorrelated as any two randomly selected fields.

Despite the limit on predictability of daily patterns indicated above, time averaging may be expected to reduce the differences between the solutions computed by the two programs. This is illustrated in Figure 1 which shows the 30-day mean sea level pressure fields for the first 30 days of the control history as generated by the original and fast programs respectively. Although some quantitative differences between the monthly mean pressures can be seen, notably in the North Atlantic Ocean, the two patterns are virtually identical for the first month. However, after the first month, even 30-day averaging fails to smooth out the differences between the two control histories. As shown in Figure 2, the mean sea level pressure maps for the second month (days 31-60) of the control history, as computed with the original and fast program respectively, are quite different both in quantitative detail and in major pattern features. Except for the subtropical high pressure cells in the Southern

Figure 1(A). Monthly mean sea level pressure field for days 1-30 of northern winter control run. Original program. Isobar interval: 5 mb.



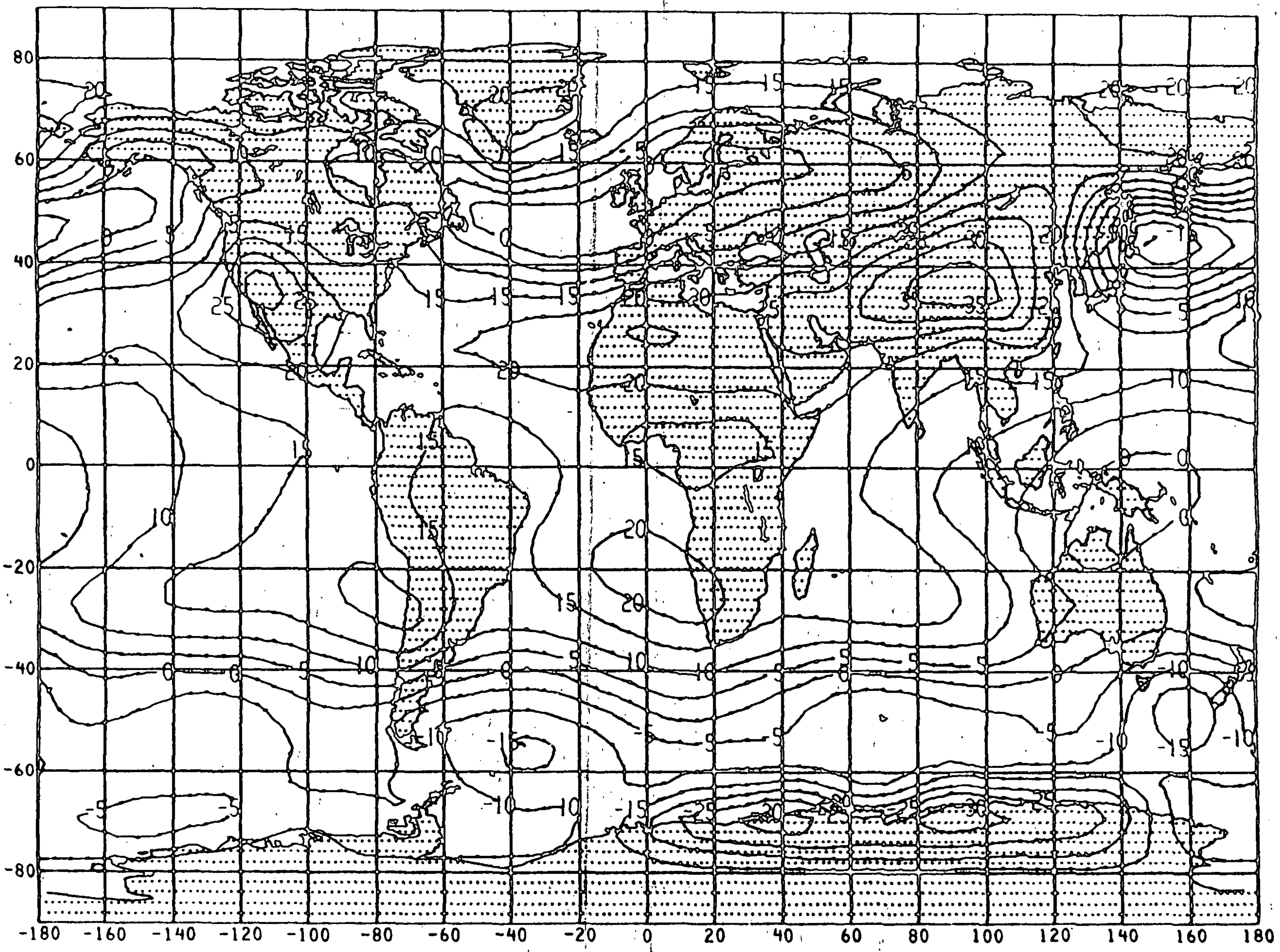
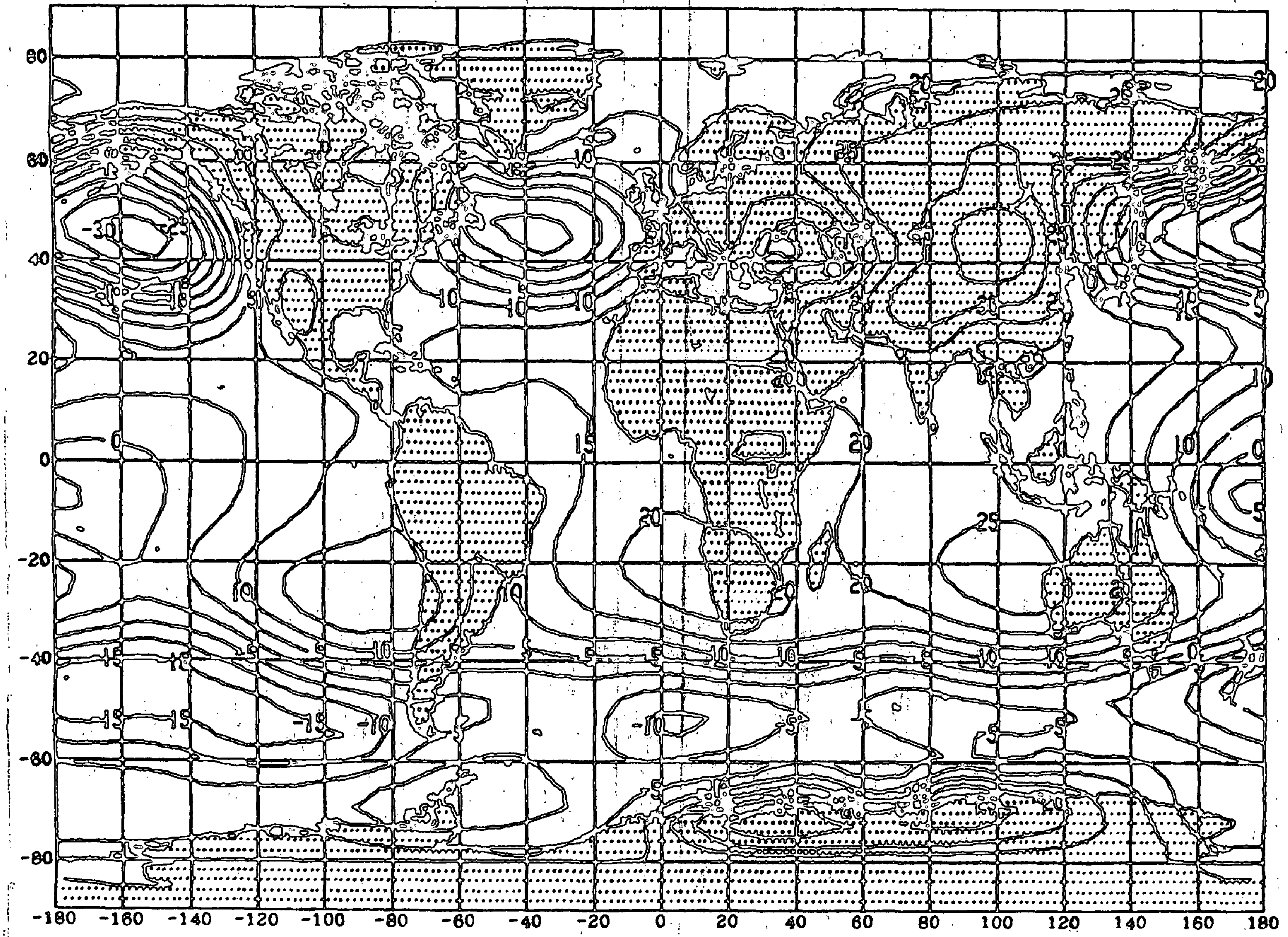


Figure 1(B). Monthly mean sea level pressure field for days 1-30 of northern winter control run. Fast program. Isobar interval: 5 mb.

Figure 2(A). Monthly mean sea level pressure field for days 31-60 of northern winter control run. Original program. Isobar interval: 5 mb.



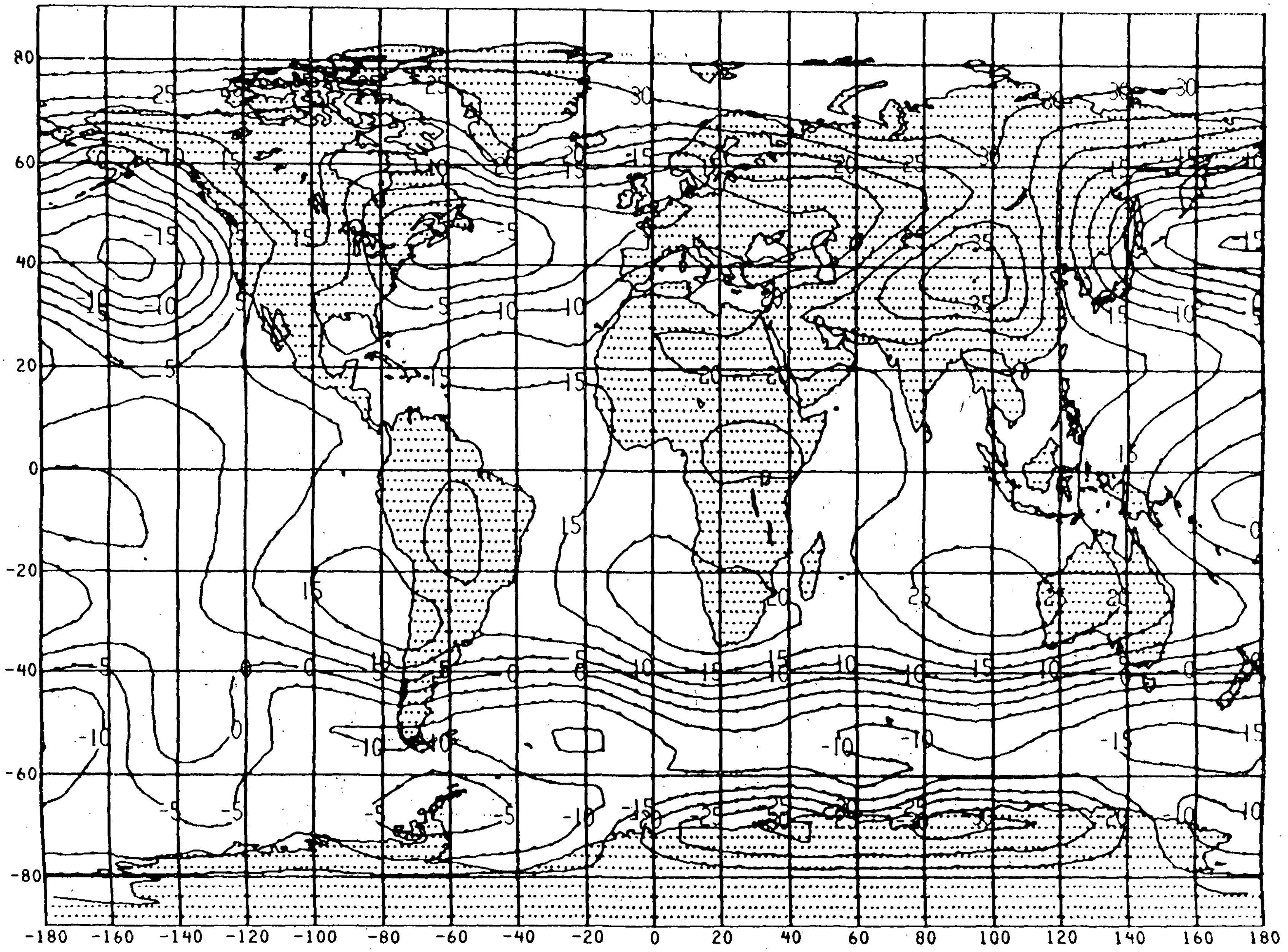


Figure 2(B). Monthly mean sea level pressure field for days 31-60 of northern winter control run. Fast program. Isobar interval: 5 mb.

Hemisphere, every major pressure system has been altered by the program change. Thus, the depth of the North Pacific cyclone is changed; the depth of the North Atlantic cyclone is changed and the position of the center is shifted as well; the Asiatic anticyclone is shifted; and in the South Pacific the pressure pattern is completely altered.

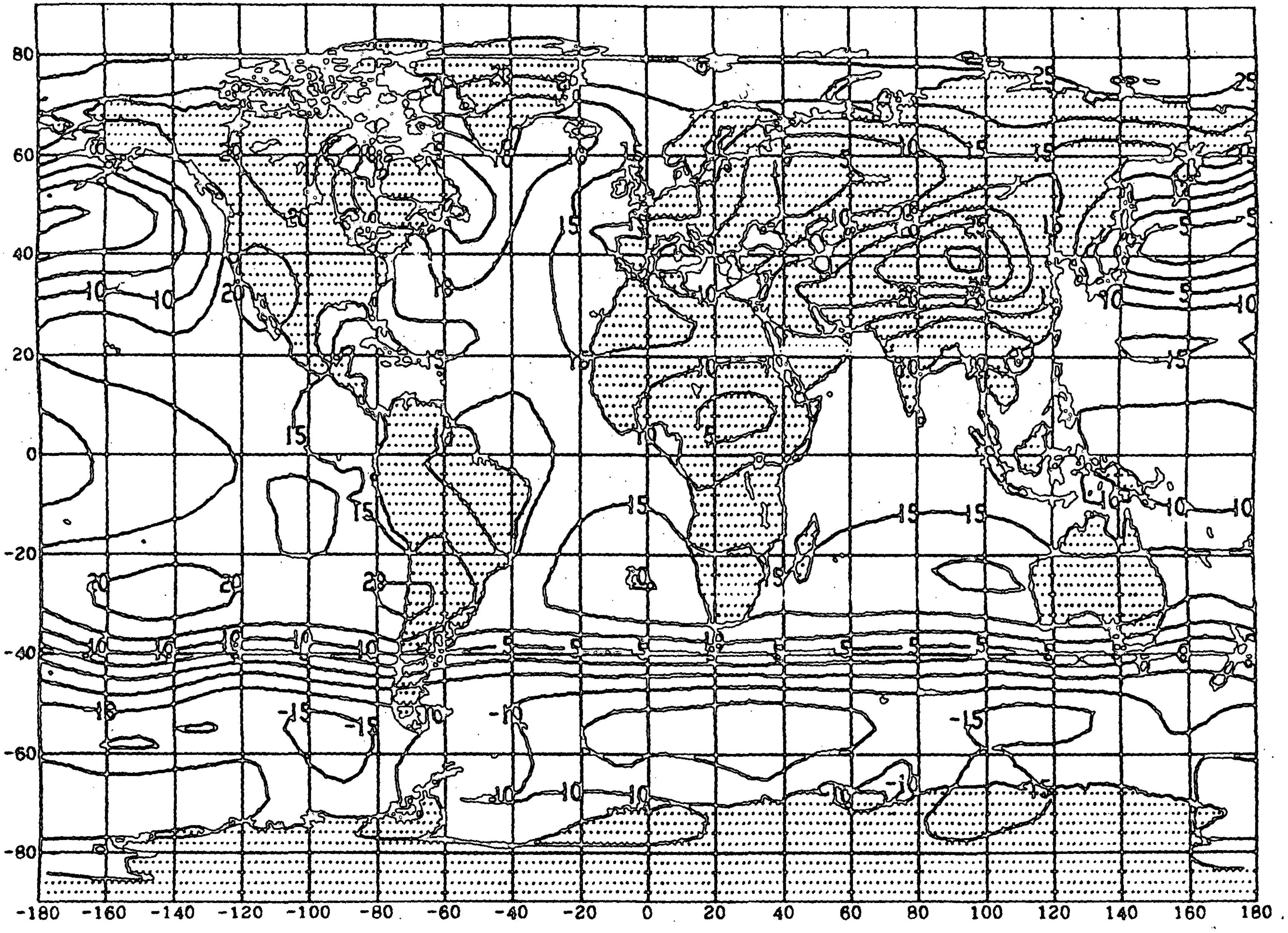
In the third month, represented in Figure 3 by the mean of days 61-90, pressure difference between the original and fast programs are apparent in the subtropical latitudes of the Southern Hemisphere as well as in the tropics. However, the most striking effect of the program change is seen in the North Atlantic where the fast program has generated a deep cyclone that is not in evidence in the original solution. This sensitivity of the model to a relatively minor program alteration is indicative of the difficulty of forecasting even the time-averaged monthly and seasonal pressure patterns with a dynamical model. Although both sets of solutions for the second and third months appear realistic and are equally credible, they obviously cannot both represent "correct" predictions. The combined effect of uncertainty in the initial state together with the "computational uncertainty" noted here places a severe limit at the present time on both the application of dynamical models to monthly and seasonal forecasting and the credibility of the results of anomaly experiments.

Qualitative Comparison of the Responses to Transient and Persistent SST Anomalies

Although the program change referred to above made it impossible to compare in quantitative detail the results of the two experiments (i. e., the transient one-month anomaly versus the persistent seasonal anomaly), it is nevertheless possible to extract some qualitative information from the computations. For example, one can determine whether the anomaly-control pressure differences two months after the SST anomaly was removed indicate a larger or smaller carry-over effect than that resulting from the persistent warm pool.

The transient and persistent SST anomaly experiments are compared in Figures 4, 5, and 6 for the first, second, and third months, respectively. Each figure shows the difference between the 30-day mean sea level pressure

Figure 3(A). Monthly mean sea level pressure field for days 61-90 of northern winter control run. Original program. Isobar interval: 5mb.



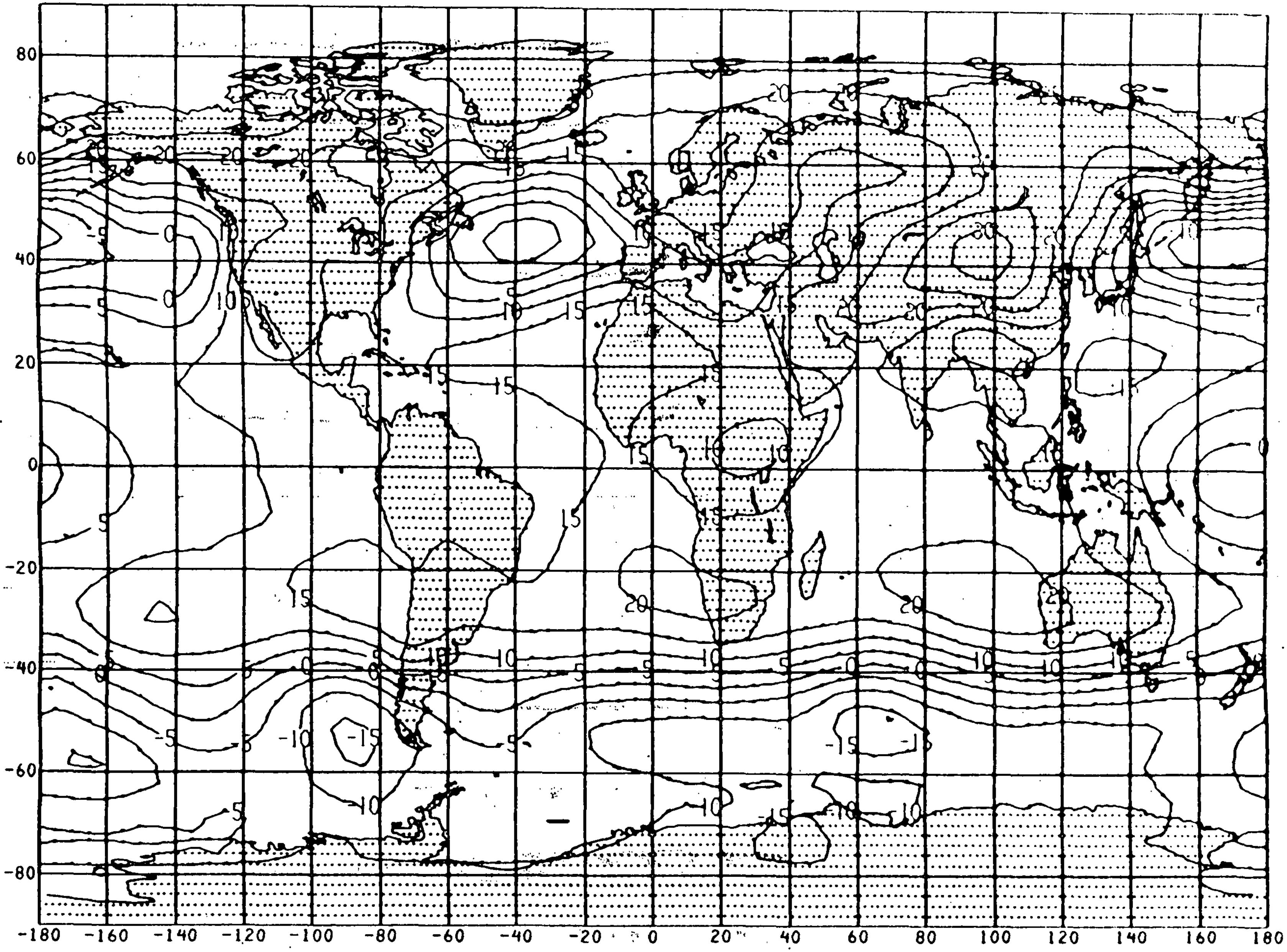
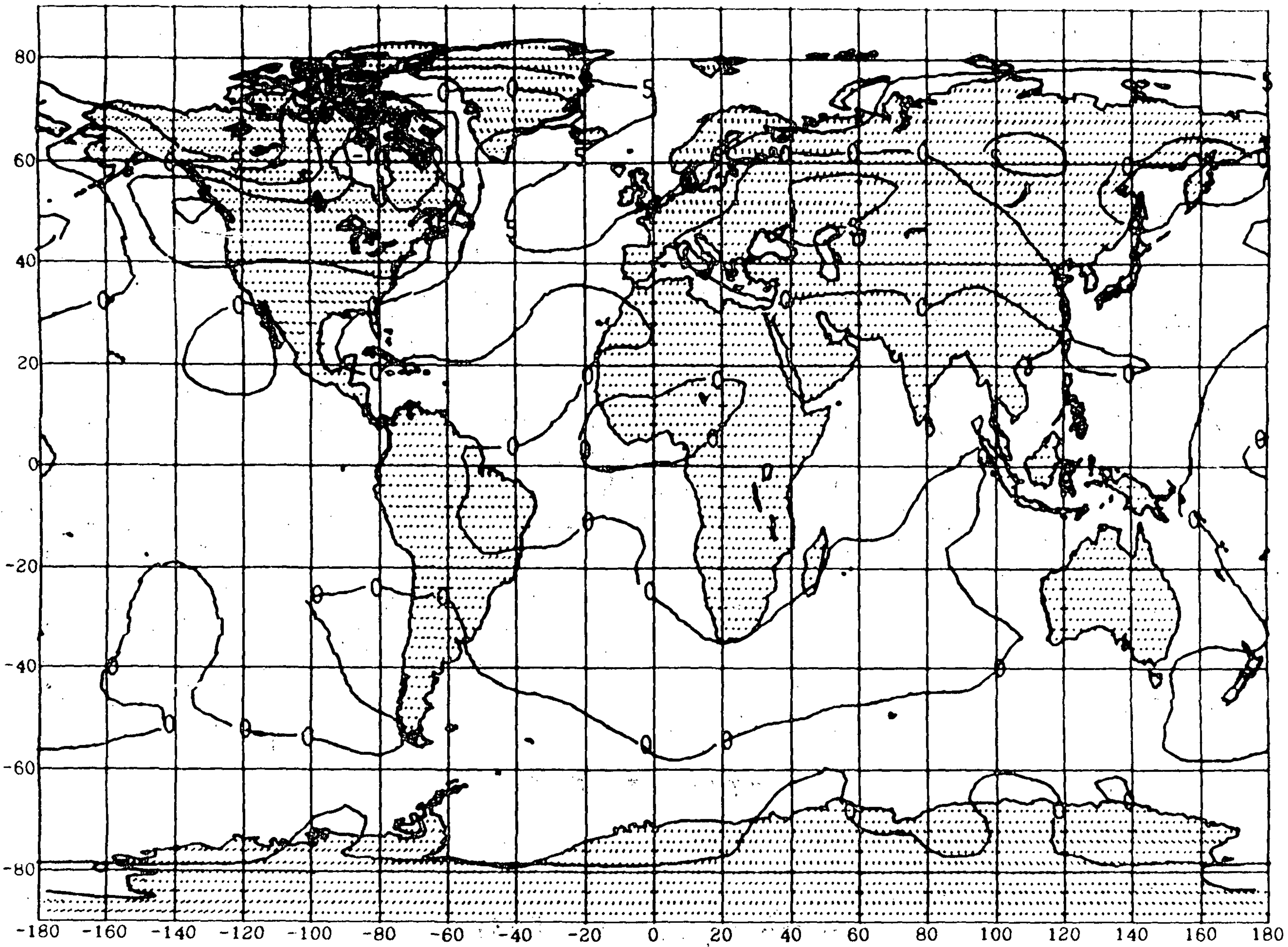


Figure 3(B). Monthly mean sea level pressure field for days 61-90 of northern winter control run. Fast program. Isobar interval: 5 mb.

Figure 4(A). Anomaly-minus-control sea level pressure differences for first month (days 1-30) of northern winter experiment with persistent SST anomaly and original program. Isobar interval: 5 mb.



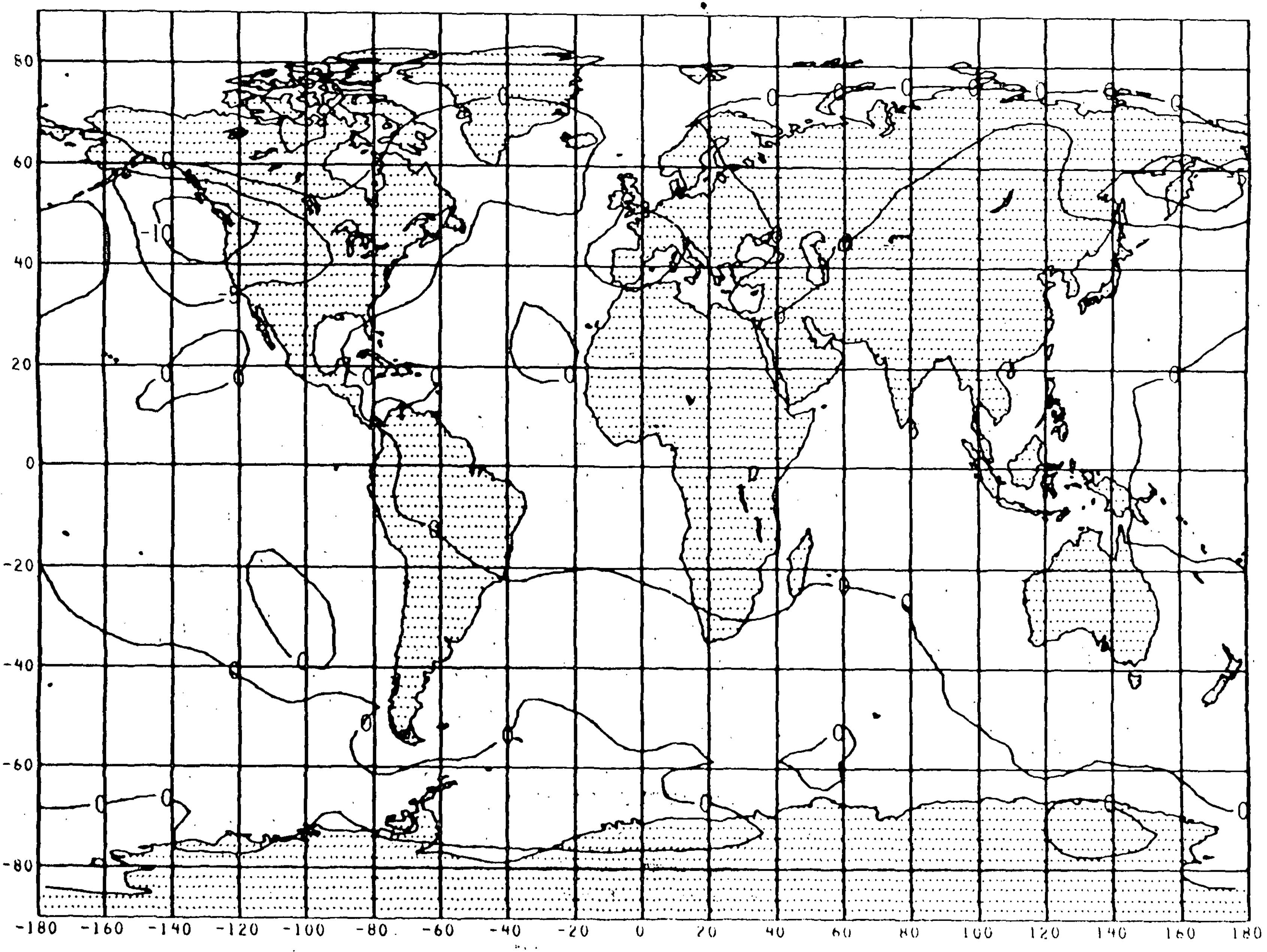
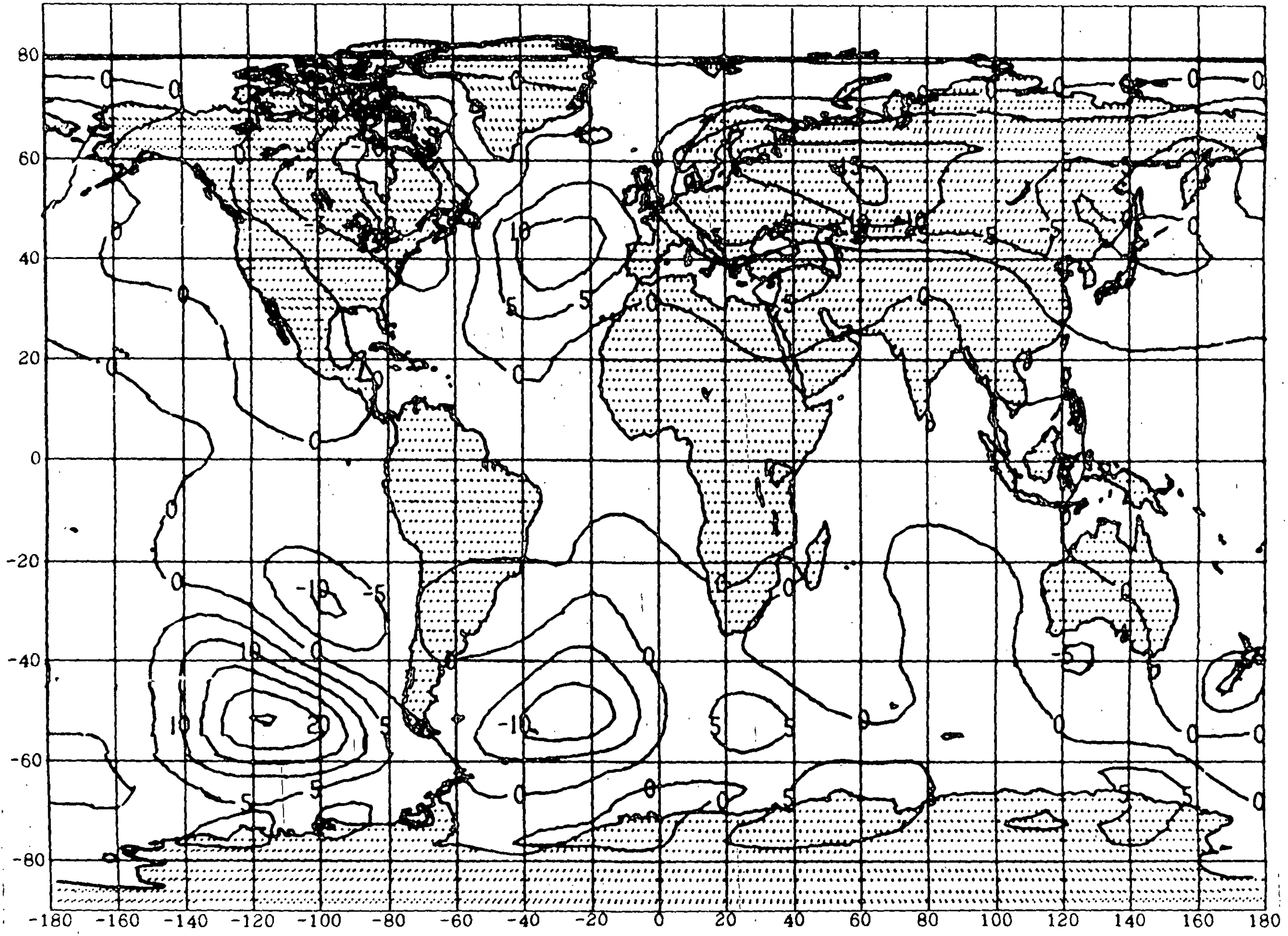


Figure 4(B). Anomaly-minus-control sea level pressure differences for first month (days 1-30) of northern winter experiment with transient SST anomaly and fast program. Isobar interval: 5 mb.

Figure 5(A). Anomaly-minus-control sea level pressure differences for second month (days 31-60) of northern winter experiment with persistent SST anomaly and original program. Isobar interval: 5 mb.



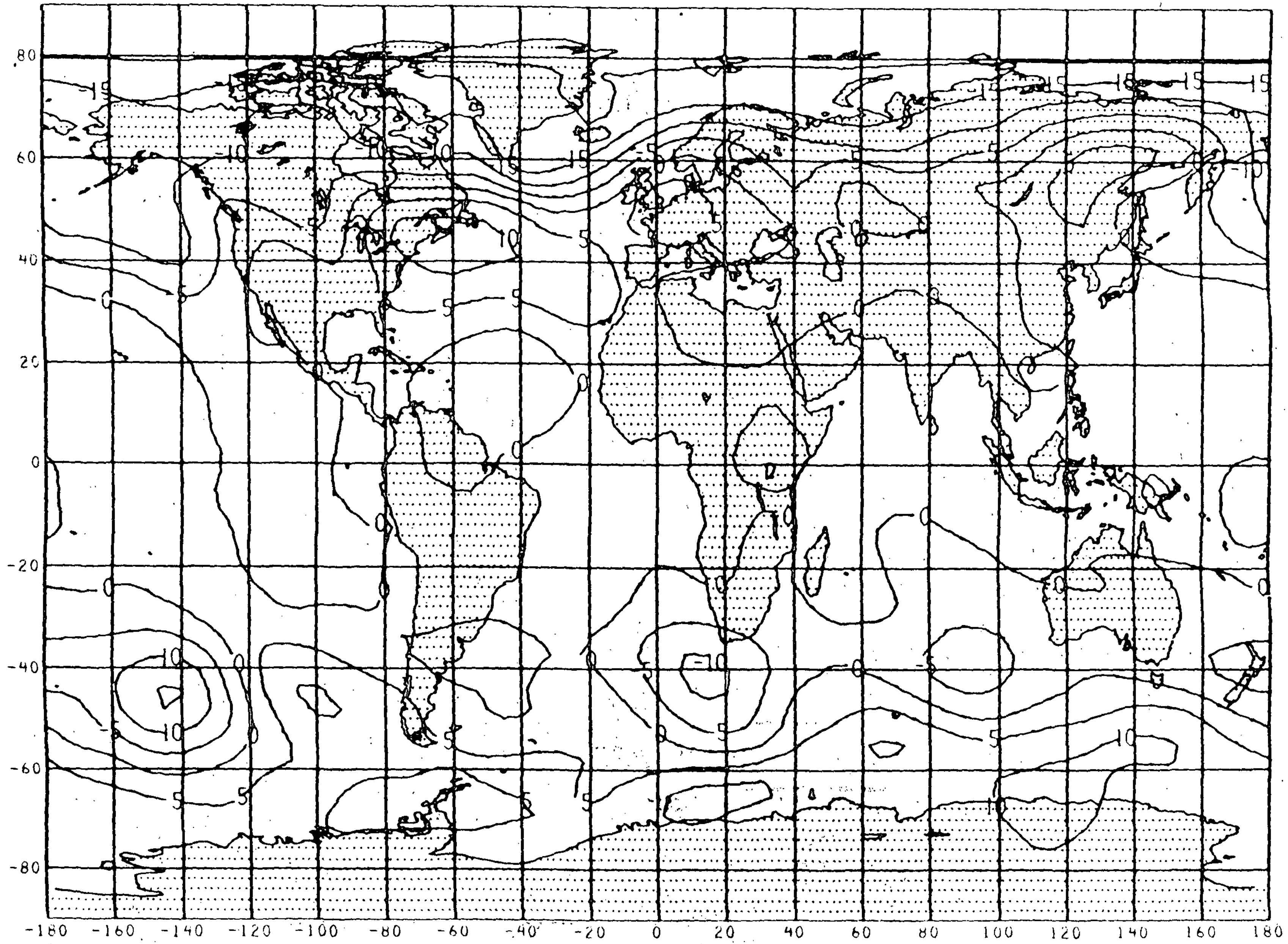
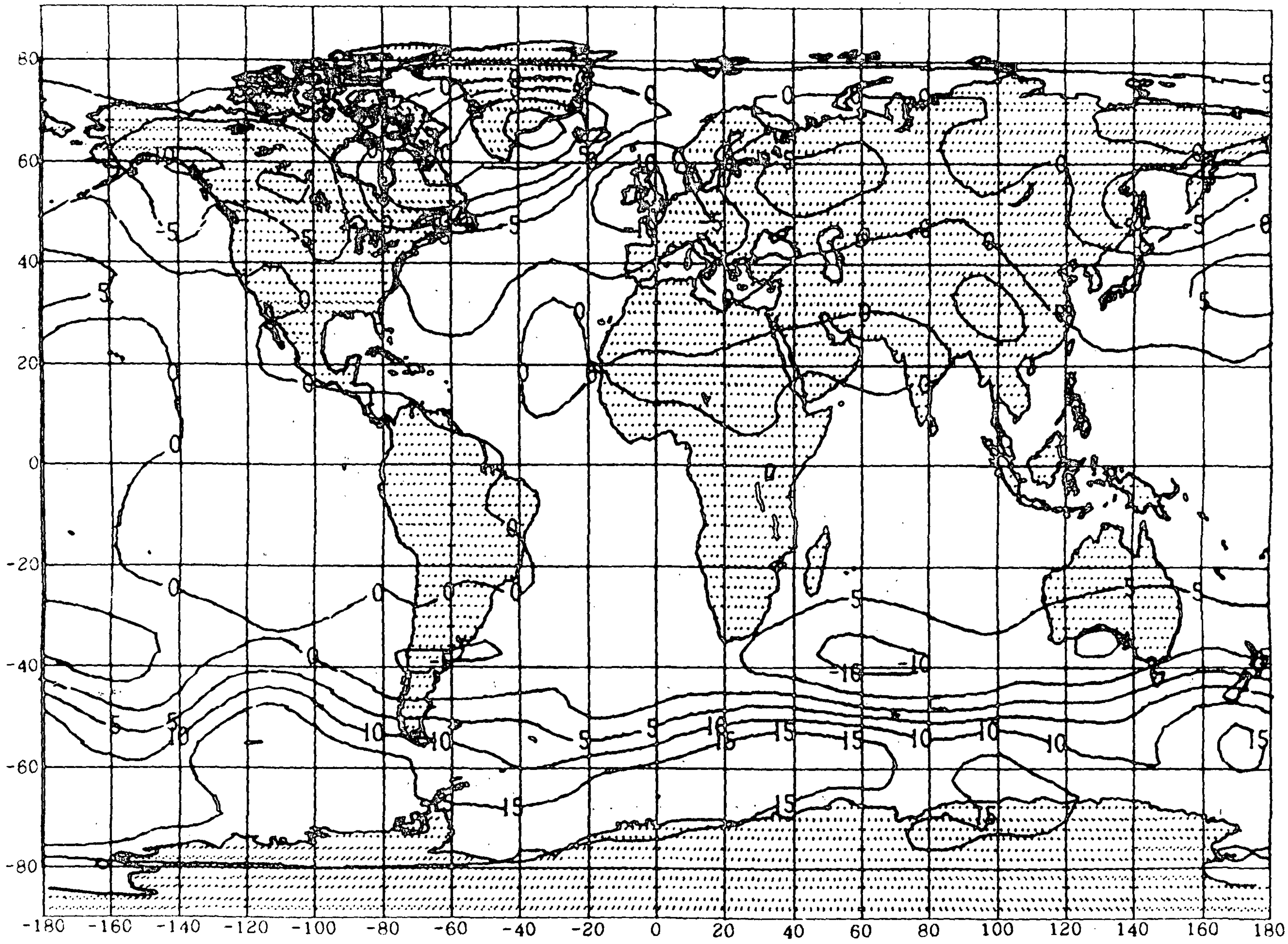


Figure 5(B). Anomaly-minus-control sea level pressure differences for second month (days 31-60) of northern winter experiment with transient SST anomaly and fast program. Isobar interval: 5 mb.

Figure 6(A). Anomaly-minus-control sea level pressure differences for third month (days 61-90) of northern winter experiment with persistent SST anomaly and original program. Isobar interval: 5 mb.



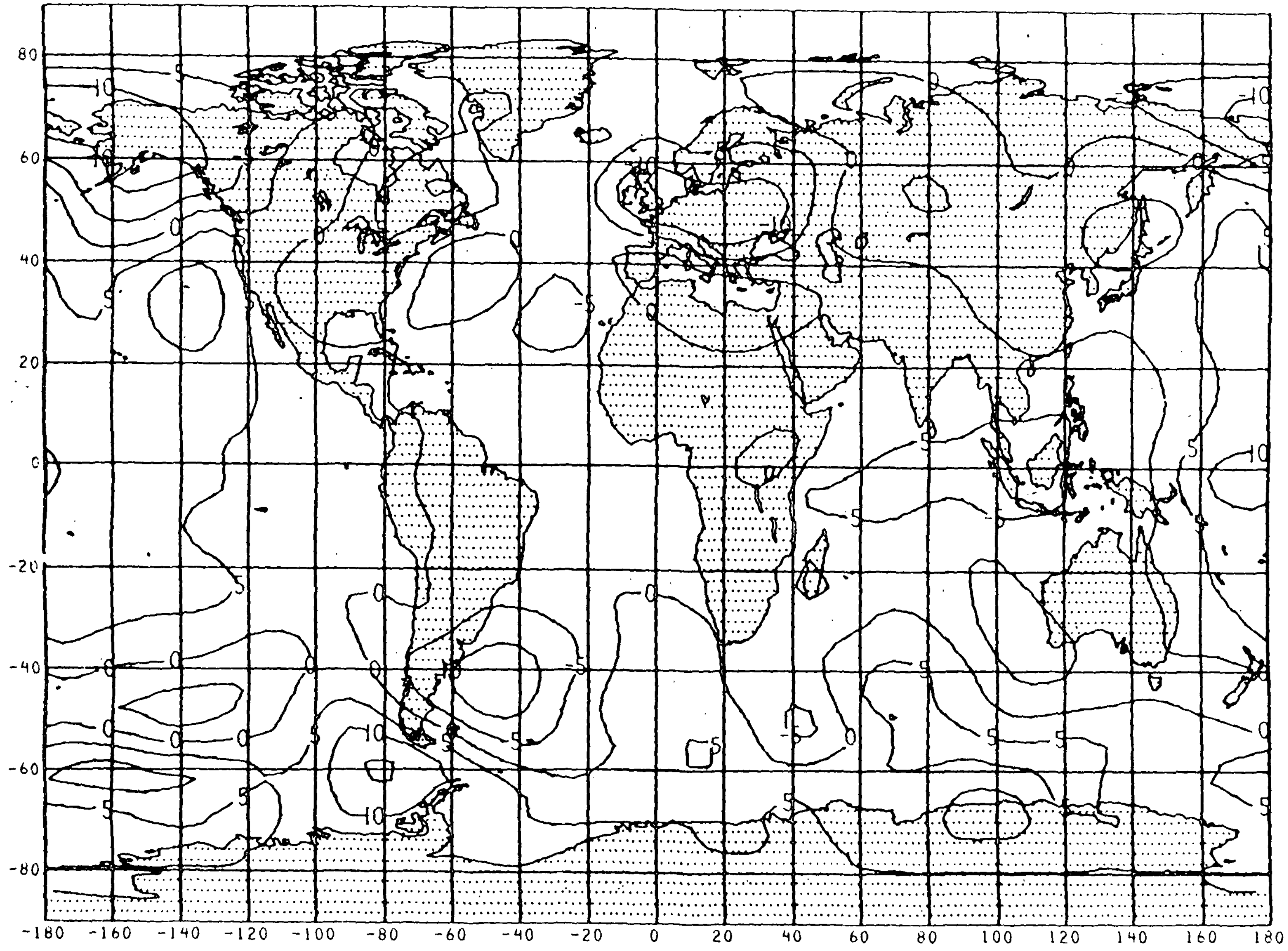


Figure 6(B). Anomaly-minus-control sea level pressure differences for third month (days 61-90) of northern winter experiment with transient SST anomaly and fast program. Isobar interval: 5 mb.

fields for the anomaly run and the corresponding control run. The upper map (A) in each figure represents the case of the persistent SST anomaly, and was computed with the original program, while the lower map (B) represents the case of the transient (first month only) SST anomaly, and was computed with the fast program.

In Figure 4, representing the first month, the two anomaly-minus-control pressure difference fields should be identical, if the computational program had not been altered. The two difference fields are indeed quite similar, with differences close to zero over most of the earth in both experiments. One major effect of the North Pacific SST anomaly, which appears in both Figure 4(A) and 4(B), is a negative difference in excess of 10 mb on the West Coast of North America. On the other hand, an equally large negative pressure effect, which appears over Labrador in the original computation [Figure 4(A)], is not found in the fast computation [Figure 4(B)], although qualitatively the patterns are similar on the two maps.

The anomaly-control pressure differences in the second month (shown in Figure 5) are, as might be expected, quite different for the two experiments represented by Figures 5(A) and 5(B). In view of the effect of the program change noted above, a detailed comparison of the two fields would be of little value. However, it is worth noting that the magnitude of the residual pressure effect left after removal of the transient warm pool, as represented by Figure 5(B), is no smaller in the Northern Hemisphere than that associated with the persistent warm pool, as shown in Figure 5(A). In the Southern Hemisphere, on the other hand, the magnitude of the response is weaker in the former case than in the latter. The range of mean sea level pressure differences over the globe in the second month is from -25 to +12 mb for the transient SST anomaly compared with -20 to +25 mb for the persistent anomaly.

From a visual comparison of the two maps in Figure 6 it is apparent that the major effects of the persistent anomalous thermal forcing, shown in Figure 6(A), are not reflected in the map [Figure 6(B)] representing the residual effect of the transient warm pool in the third month. The two major effects in the former case are the positive pressure difference in Greenland and the general meridional gradient of pressure differences in high latitudes of the

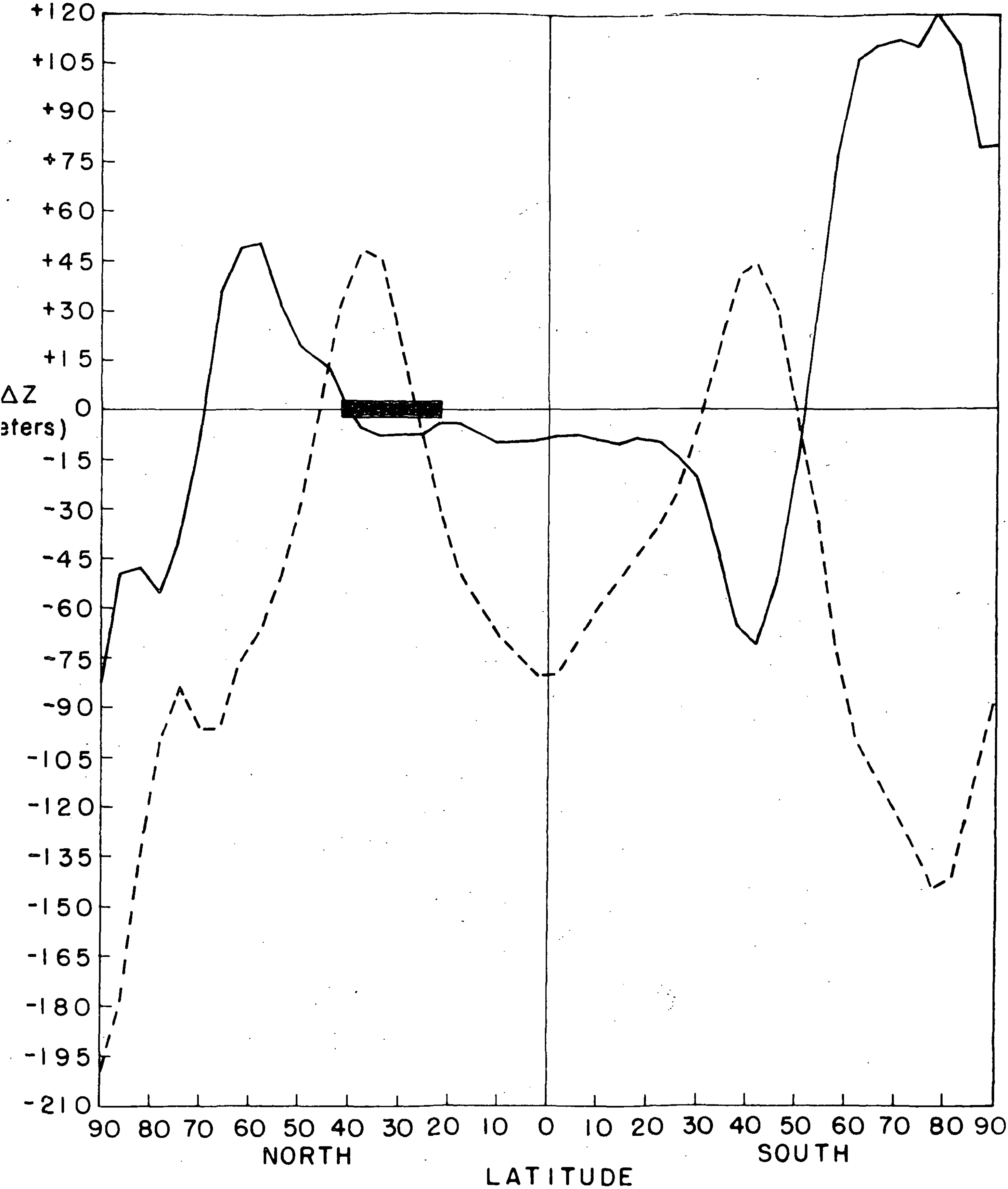


Figure 7. Meridional profiles of anomaly-minus-control 600 mb height differences on day 90 for northern winter SST anomaly experiments. Solid curve: persistent anomaly, original program. Dashed curve: transient anomaly, fast program.

Southern Hemisphere, neither of which appears in Figure 6(B). Thus, it appears at first glance as if the residual effect of the transient SST anomaly is diminishing with time. However, the range of pressure differences over the globe in the third month is from -15 to +15 mb for the transient case compared with -15 to +20 mb for the persistent case. Thus, the magnitude of the effect is again almost as large in the transient case, although the pattern of effects appears to be better organized on a large scale in the case of the persistent warm pool.

Another indication of the effect of the transient SST anomaly, as compared with the persistent anomaly, is illustrated in Figure 7, which shows the meridional profiles of the anomaly-minus-control differences between the zonally averaged 600 mb heights on day 90, the final day of each run, for the two experiments. The solid curve represents the case of the persistent SST anomaly, and was computed with the original program, while the dashed curve represents the case of the transient SST anomaly, which was computed with the fast program. Clearly the magnitude of the effect is the same in both cases, although the distributions are different. In both the persistent and transient anomaly cases there are large interdiurnal variations of the meridional difference profiles, so that the curves shown in Figure 7 are in no sense "typical". (For example, the large effect in the equatorial region indicated by the dashed curve appeared only in the last few days of the run with the transient anomaly.) However, the two curves are representative in the sense that they do indicate the relative magnitudes of the effects of transient and persistent SST anomalies.

The results above suggest that the magnitude of long-term (e.g., seasonal) effects of SST anomalies may be just as great for a transient (e.g., one month) anomaly as for a persistent one, even though the form of the atmospheric response may be quite different. In the transient anomaly experiment, only the new initial conditions at the beginning of the second month are different for the anomaly run than for the control run. Any anomaly-control pressure differences generated in this experiment after the first month are thus inherited effects of the anomalous thermal forcing that occurred in the first month. Although in time the atmosphere may "forget" its initial conditions, and the inherited effect may decay, the rate of decay is apparently slow enough for such effects to be found at least two months after the SST anomaly has been turned off. This apparent sensitivity of the model global atmosphere to local transient oceanic anomalies indicates that the problem of extended and long range prediction will probably not be solved until an interactive ocean-atmosphere model is successfully developed.

In view of the model's sensitivity to the computational perturbation noted above, as well as other evidence[3] of its extreme sensitivity to random perturbations in the initial state, one may question whether any conclusions at all can be drawn regarding the effects of persistent SST anomalies in the real atmosphere from the model experiments. Certainly the noise level of the numerical experiments is now much too high for any signal generated by the SST anomalies to be clearly detected. At this point (and until some way can be found to reduce the noise level of the experiments) one can only argue that the solutions generated represent possible atmospheric responses, and do give some indication of the possible magnitudes of the effects of the SST anomalies studied.

Effect of a Transient SST Anomaly on Temperature and Precipitation

In the course of the experiment with the transient SST anomaly, a number of global and regional diagnostic quantities were calculated. Among these were the daily average surface temperature and average daily precipitation over the eastern region of North America, as well as daily and seasonal averages of zonal and global precipitation. A comparison of the anomaly and control results in terms of these "weather" parameters is presented in this section to indicate the possible climatic influence of the oceanic anomaly. (As we did not compute these same quantities for the persistent anomaly experiment, it is not possible to compare the relative magnitudes of the effects of the two types of SST anomalies).

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[3] W. L. Gates of Rand Corporation has recently reported (in a Symposium on Climatic Change held at the Scripps Institution of Oceanography in LaJolla, California on 15-17 November 1972) the results of numerical experiments which clearly show that random perturbations of the initial state in the model lead to the generation of large amplitude "noise" in the 30-day mean pressure fields.

The "eastern region" is represented in the experiment by 30 grid points in the area bounded by latitudes 30°N and 50°N and longitudes 70°W and 90°W. A regional daily average is computed as the mean of 360 two-hourly grid point values, and a regional monthly average as the mean of 30 daily averages. The effect of the transient SST anomaly in the North Pacific Ocean on the computed eastern regional weather for the three month winter season is indicated in Table 1, in which are shown the regional average monthly and seasonal temperature, in degrees celsius, and total precipitation, in centimeters, for the anomaly and control runs.

Table 1. Computed monthly and seasonal mean temperatures (T) in °C and total precipitation (R) in cm. averaged over the eastern region for the anomaly (A) and control (C) runs. Differences (A-C) are also shown.

Month No.	1		2		3		Season	
	T(°C)	R(cm)	T	R	T	R	T	R
A	+6.1	7.15	+8.3	10.18	+5.0	7.03	+6.5	24.36
C	+4.6	8.34	+5.1	16.92	+6.7	11.36	+5.5	36.62
A-C	+1.5	-1.19	+3.2	-6.74	-1.7	-4.33	+1.0	-12.26

In view of the computational uncertainty noted earlier, no special significance should be attached to the numerical results in Table 1. However, the magnitudes are interesting. Effects of the order of 1 to 3°C in monthly and seasonal mean temperatures are indicated in the table by the differences, A-C. Over the eastern region of the United States in winter, the class limits used in monthly weather predictions by the National Weather Service (Namias, 1953)[4] to separate the monthly mean temperature class "normal" from "above" and "below" normal span a range of only about 2 to 3°F, or less than 2°C. The departure-from-normal class limits which define the temperature prediction classes "much above" and "much below" normal are approximately ± 3 to 6°F, or only about ±2 to 3°C. Thus, one effect of a transient SST anomaly in the North Pacific Ocean could possibly be to alter the monthly mean temperatures

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[4] See also the Average Monthly Weather Outlook issued twice a month by the National Weather Service.

over the eastern United States by as much as two class intervals, if the model computations are credible.

For the purposes of monthly precipitation forecasting in winter in the eastern United States, the class limits used to separate "moderate" precipitation from "heavy" and "light" respectively span a range of approximately 2 inches or less, i.e., no more than about 5 cm. As can be seen in Table 1, effects of this magnitude can apparently be produced by a transient SST anomaly in the North Pacific Ocean, if the model computations are to be believed. Indeed, in the present experiment, the SST anomaly appears to have caused a consistent deficit of precipitation amounting to 12 cm (almost 5 inches) for the season over the eastern region. Thus, it appears that the influence of even a transient North Pacific SST anomaly on regional weather, over periods of at least months and seasons, may be "significant" in the sense that monthly (as well as seasonal) temperatures and precipitation can possibly be altered by as much as one or two class intervals. From the viewpoint of monthly and seasonal weather prediction, this is clearly a matter of some practical importance.

The version of the two-level Mintz-Arakawa model used for this ex periment overpredicts global precipitation. This is primarily the result of an overprediction in the tropics resulting from the parameterization of convection, which leads to an excess in the convective component of the precipitation. The global average precipitation for the 90-day period is 4.6 mm day^{-1} for the control run and 4.4 mm day^{-1} for the anomaly run, indicating an apparent reduction of less than 5% in the global precipitation due to the SST anomaly. The zonal average precipitation for the season in both runs shows a maximum at latitude 6°S, with 24.6 mm day^{-1} in the control run and 22.9 mm day^{-1} in the anomaly run, indicating a modest decrease (about 7%). However, at latitude 2°S the anomaly run yields 9.2 mm day^{-1} compared with 19.0 mm day^{-1} for the control, a decline of about 50%. In view of the low level of credibility of the tropical precipitation values, no attempt has been made to trace the mechanism in the model which produced this startling remote effect of the North Pacific SST anomaly. Nevertheless, the computations again indicate the sensitivity of the model to relatively modest changes in sea surface temperatures.

Conclusions

The experiments in seasonal weather computation with the global two-level Mintz-Arakawa model have shown that the model is sensitive both to the numerical differences associated with different computational algorithms and to the physical influence, as represented in the model, of the sea surface temperatures. With a time step of six minutes, more than 2×10^4 steps are required to march out a 90-day forecast. The cumulative effect of the differences between alternative computational procedures over this many time steps results in a decorrelation of the alternative solutions, all other things being equal. Nor is the situation helped appreciably by time averaging. Monthly mean maps for the second and third months after the start of the computations are also decorrelated.

The sensitivity of the model to computational procedures raises serious questions regarding the credibility of the seasonal calculations. The SST anomaly experiments indicate that both persistent and transient sea temperature variations of reasonable magnitude are capable of generating marked differences in surface and upper level pressure patterns, as well as significant long-term weather effects at remote places. There is, as yet, no reason to doubt that this behaviour of the model may indeed reflect a similar sensitivity of the real atmosphere to the temperature of the sea surface. However, the computational sensitivity does suggest that the particular manner in which the model responds to an SST anomaly is probably not a credible reflection of nature. At this time one can conclude only that the interaction between the atmosphere and the ocean introduces a significant element of indeterminacy in monthly and seasonal weather prediction.

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