

# Transequatorial Effects of Sea-Surface Temperature Anomalies in a Global General Circulation Model<sup>1</sup>

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**ABSTRACT**—The global response of the atmosphere, as simulated by the Mintz-Arakawa, two-level, general circulation model, to a persistent anomalous pool of warm sea-surface temperatures (SST) in the extratropical Pacific Ocean is examined in this descriptive study in terms of the meridional pole-to-pole profile of the zonally averaged 600-mb surface for periods up to 90 days. Following an initial hydrostatic inflation of the isobaric surface in the latitude of the warm pool, effects spread poleward within the hemisphere, then begin to appear after about 2-3 weeks in high latitudes of the opposite hemisphere, but with little or no response in the Tropics. The same sea

temperature anomaly field generates a stronger response in winter than in summer and a very different reaction when located in the Southern Hemisphere than when in the Northern Hemisphere. After a month of thermal forcing, the response to an SST anomaly is at least as large in the opposite hemisphere as in the hemisphere of the anomaly. A winter hemisphere responds more rapidly to an SST anomaly in the opposite hemisphere than does a summer hemisphere. Vacillation between low and high meridional wave number patterns is observed in the computed reaction to the warm pool.

## 1. INTRODUCTION

Experiments with the Mintz-Arakawa, two-level, general circulation model have recently been carried out for the purpose of estimating the possible response of the atmosphere to persistent anomalies of sea-surface temperature (SST) over periods of the order of a season (Spar 1972, 1973). One of the conclusions derived from these experiments was that SST anomalies may induce a significant response in the sea-level pressures in the opposite hemisphere after several weeks, and that these reactions appear to occur with little or no disturbance of the equatorial region. It appeared from these computations as if the transequatorial propagation took place through a form of forced standing wave with an equatorial node. However, no attempt was made in the previous study to examine this interhemispheric transfer of influence in any detail. In the present paper, an effort is made to describe the development of the model atmosphere's response to these SST anomalies in terms of their effect on the pole-to-pole meridional profile of the zonal mean 600-mb surface, which represents approximately the middle level of the model. An earlier experiment similar to the one described here was carried out by Rowntree (1972), but with a hemispheric Geophysical Fluid Dynamics Laboratory (GFDL) model and an SST anomaly in the equatorial region. Since there are, of course, no interhemispheric effects in Rowntree's hemispheric experiment, his results cannot be compared with ours. Ramage and Murakami (1973) have recently argued that the equatorial wall in the hemispheric model is responsible for some of Rowntree's principal results.

A complete documentation of the Mintz-Arakawa two-level model has been provided by Gates et al. (1971), and a

brief description of the model can be found in Spar (1973). In the Northern Hemisphere SST anomaly experiments (designated NHTA), the climatological mean annual sea-surface temperatures, which are employed as fixed boundary conditions in the model computations, were altered by adding from 2° to 6°C to the SST over a "box" in the North Pacific Ocean bounded by latitudes 22° and 42°N and longitudes 140°W and 180°. For the Southern Hemisphere SST experiments (designated SHTA), the same anomaly field was added to the corresponding box in the South Pacific Ocean. In both cases, the maximum anomaly (+6°C) isotherm corresponds to a "rectangle" defined by longitudes 150° and 170°W and latitudes 30° and 34°, so that the center of the warm pool in the ocean is at latitude 32° and longitude 160°W. A Northern Hemisphere anomaly experiment was conducted for both the winter (NHTA-W) and summer (NHTA-S) seasons with the same SST fields, while the Southern Hemisphere anomaly experiment was carried out for northern summer (southern winter) only. Initial conditions for the three experiments were taken from history tapes provided by the UCLA group under Yale Mintz. (See Mintz et al. 1972 for examples of the climate simulations generated by the model.) The effect of the SST anomaly is measured by comparing the "anomaly" run with a "control" run that is identical in every respect except for the absence of the SST anomaly. Differences between anomaly and control runs presumably represent effects of the SST anomaly.

In each experiment, the expected initial effect of the positive SST anomaly is an augmented heat transfer from sea to air over the local anomaly region. It is impossible to anticipate a priori precisely how this increased heating effect will propagate away from the warm ocean area or what its ultimate dynamical consequences will be. However, one can expect that the immediate hydrostatic

<sup>1</sup> The research reported in this paper has been supported by the National Aeronautics and Space Administration, Goddard Space Flight Center, under Grant NGR 33-016-174.

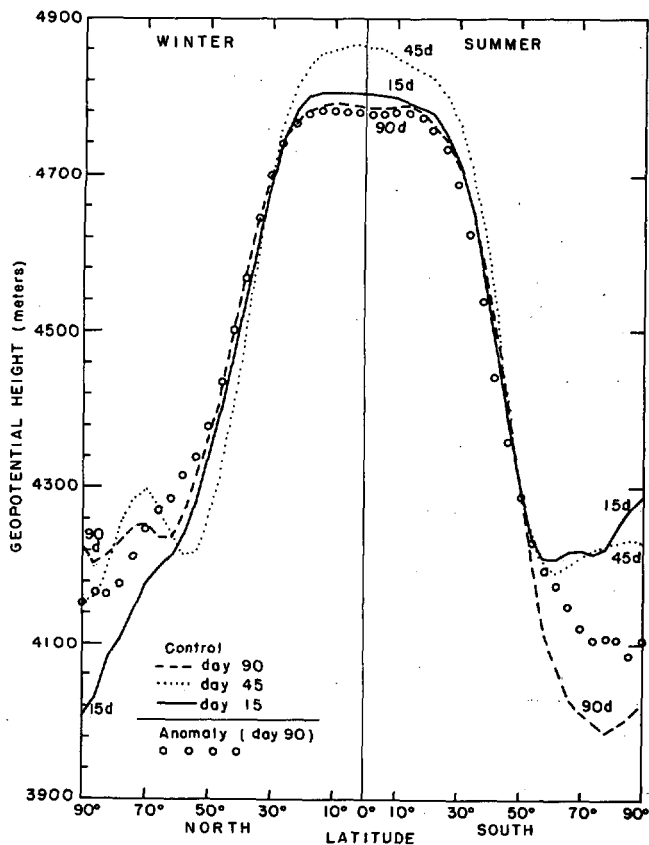


FIGURE 1.—Meridional profile of zonal mean 600-mb height for the winter control run, experiment NHTA-W, on days 15, 45, and 90. (Circles represent the profile on day 90 for the anomaly run.)

effect of the augmented heating will be an inflation of the isobaric surfaces aloft. Since the present study is concerned primarily with the meridional propagation of these effects, it is desirable to examine zonally averaged quantities. For our purpose, we have chosen the 600-mb level as a characteristic isobaric surface and have computed for each day of each 90-day run and for every  $4^\circ$  of latitude the zonal mean geopotential height of that surface. The initial effect of the SST anomaly on this quantity is expected to be a rise (relative to the corresponding control case) of the zonal mean height within the latitude band containing the warm pool. This initial reaction and the subsequent evolution of the 600-mb meridional height profile, including the response in the opposite hemisphere, are illustrated and discussed in the following sections.

## 2. EXPERIMENT NHTA-W

To illustrate the characteristic meridional 600-mb profiles generated by the model in the northern winter season, we have reproduced in figure 1 the profiles for the winter control run for days 15, 45, and 90, corresponding to early, middle, and late winter.<sup>2</sup> The large fluctuations in height found in the Arctic and Antarctic (where the maximum height ranges computed for the whole

<sup>2</sup> Because of the fact that initial conditions for the first day of each control run were selected at random from the history tapes for the appropriate season, whereas the model sun was reset to its proper solstitial position for the actual control run, the model appears to go through a transient adjustment period during the first few days. Therefore, day 15 rather than the first day (approximately the solstice) was selected as representative of early winter.

season were 501 and 377 m respectively) may be unrealistic. Similarly, the total range of heights at the Equator during the season (computed to be 85 m) also may be too large. Between latitudes  $50^\circ\text{N}$  and  $50^\circ\text{S}$ , the profiles are nearly symmetrical. The mean zonal geostrophic wind speeds corresponding to the mean height profiles at 600 mb between latitudes  $30^\circ$  and  $50^\circ$  in both hemispheres are approximately 20 m/s and are slightly higher in the Southern Hemisphere than in the Northern Hemisphere, despite the fact that figure 1 represents northern winter.<sup>3</sup> (The small circles in figure 1 represent the zonal mean 600-mb heights at 90 days for the anomaly run and will be discussed later). The large decrease in height in the Antarctic at the end of the season appears to indicate that the effect of radiative cooling is already becoming apparent there by the time of the equinox.

The reaction of the model atmosphere to the SST anomaly during the first month is illustrated in figure 2 in the form of a time-latitude cross section of height differences between the anomaly and control runs. Positive values represent an increase in the height of the 600-mb surface relative to the control case. Difference isopleths, including the zero isopleth, are drawn at an interval of  $\pm 20$  m up to 100 m, and  $\pm 40$  m at higher values. Hatching is used to indicate positive effects in excess of  $+20$  m. The latitude of the SST anomaly is indicated schematically by the bar graphs on either side of the figure, the length of the bar being proportional to the magnitude of the anomaly at each latitude. For the first 3 weeks, the response is largely confined to the Northern Hemisphere. The 600-mb surface is initially elevated within the latitude band of the SST anomaly and lowered to the north. The crest of this inflation wave migrates slightly poleward after about 2 weeks before vanishing. The maximum height difference within the latitude band of the SST anomaly, shown in figure 3 for the entire 90-day period, rises at an almost constant rate for the first 2–3 weeks. After that time, the inflation effect in the warm pool latitude band disappears briefly, and is replaced by a marked elevation of the 600-mb surface in the polar regions. At the North Pole, this effect, which is probably spurious, reaches a maximum value of 260 m on day 25. Almost simultaneously a dubious response appears in the Antarctic;<sup>4</sup> near the end of the month, large effects are seen in middle latitudes of the Southern Hemisphere. At the end of the 30 days, the inflation in the latitude band of the SST anomaly begins to reappear, and another period of inflation lasting about 3 weeks begins, as shown in figure 3.

During the first month, the largest height difference computed in the equatorial region was only 14 m; during the entire 90-day period, the equatorial response did not exceed 18 m. The small equatorial reaction is illustrated

<sup>3</sup> As shown, for example, by van Loon (1964, 1965), the geostrophic zonal westerlies at 500 mb in the Southern Hemisphere in southern summer are stronger than in southern winter, and at least as strong as the zonal westerlies at 500 mb in the Northern Hemisphere in northern winter. Thus, the symmetry of the profiles in figure 1 is probably realistic.

<sup>4</sup> A recently discovered coding error (Gates et al. 1971) in the computation of the albedo over snow and ice has been found (Gates 1972) to produce spurious results in the simulated climatology, especially in the Antarctic. This, together with certain computational problems in the vicinity of the poles, renders suspect all results poleward of about latitude  $70^\circ$ .

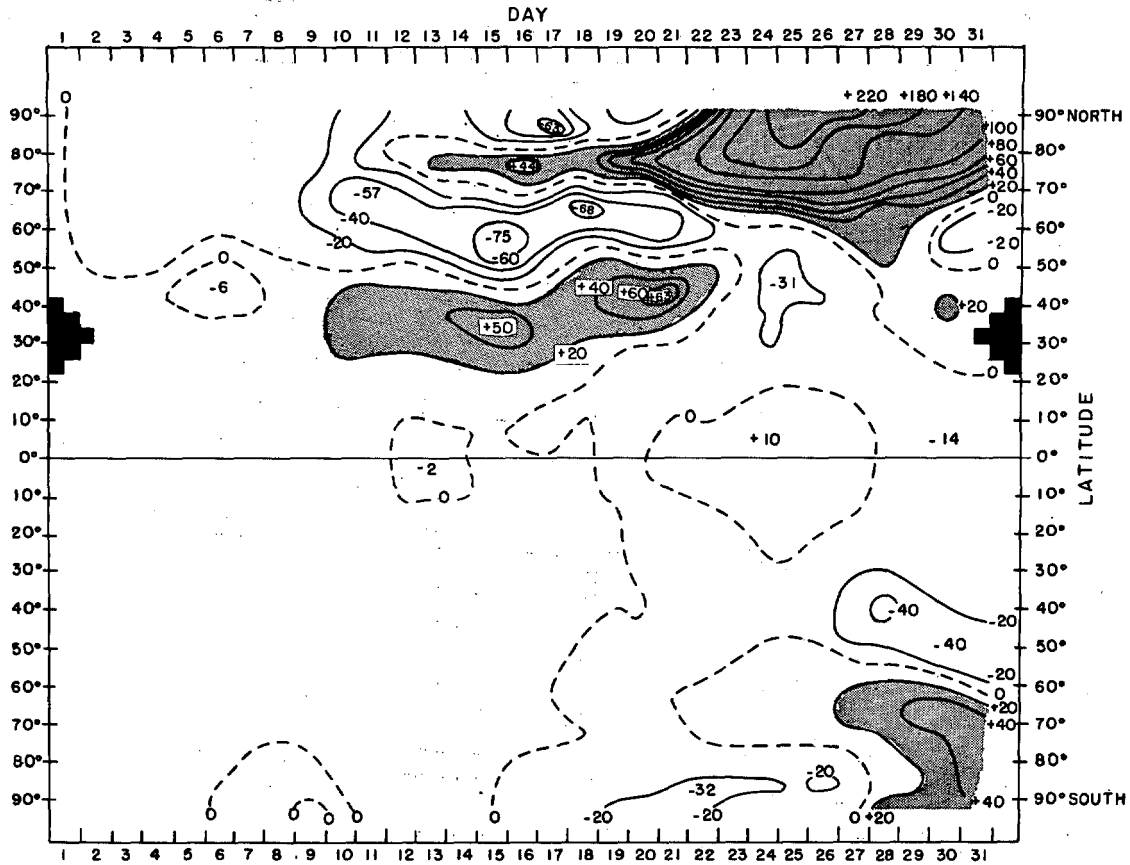


FIGURE 2.—Time-latitude cross section of anomaly-minus-control 600-mb height differences for the first month of experiment NHTA-W. Isopleths are drawn for an interval of 20 m up to 100 m, and 40 m above 100 m. Positive differences in excess of +20 m are indicated by hatching. The latitude band of the warm pool is indicated by the bar graphs.

for the whole season in figure 4, where we have plotted for each day the largest height difference (positive or negative) in the latitude band from 6°N to 6°S. Some disturbance of the equatorial region does in fact appear after about 3 weeks, suggesting a propagation of influence across the Equator. However, there is no evidence either in figure 2 or in the corresponding time-latitude sections for the following 60 days (not shown) of traveling meridional waves crossing the Equator. While the small-amplitude equatorial oscillation shown in figure 4 does apparently represent a response to the SST anomaly, it appears to have the character of a standing oscillation rather than a progressive wave.

The global response of the 600-mb surface to the SST anomaly is further illustrated in figure 5 showing daily meridional profiles of the anomaly-control height differences drawn at 10-day intervals beginning on day 20. Latitude is represented on a sine scale; therefore, the surface area of any latitude band is proportional to horizontal distance in the figure. No values are plotted or analyzed poleward of latitude 70°. The bar graphs in the figure indicate the latitude band of the SST anomaly. Days 20, 30, 40, and 50 are shown in figure 5A and days 60, 70, 80, and 90 appear in figure 5B. From figure 5, it is apparent that, with the possible exception of the shallow trough on days 20 and 30, no disturbances of significant amplitude crossed the Equator during the season. It can also be seen in figure 5 that, following the initial inflation of the 600-mb surface in the latitude band of the SST

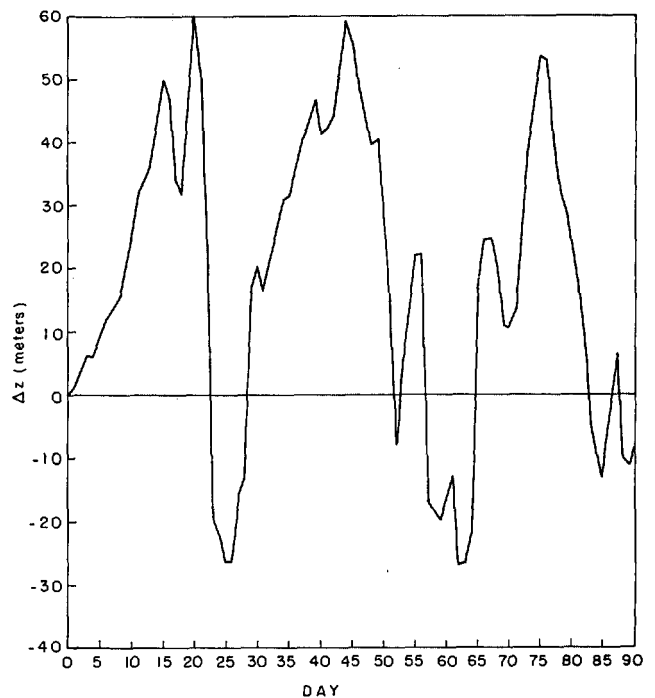


FIGURE 3.—Maximum (positive or negative) anomaly-minus-control 600-mb height differences,  $\Delta z$  (m), in the latitude band 22°-42°N for experiment NHTA-W.

anomaly, all subsequent inflations took place north of the center of the warm pool. The standing character of the oscillation induced in the Northern Hemisphere is indi-

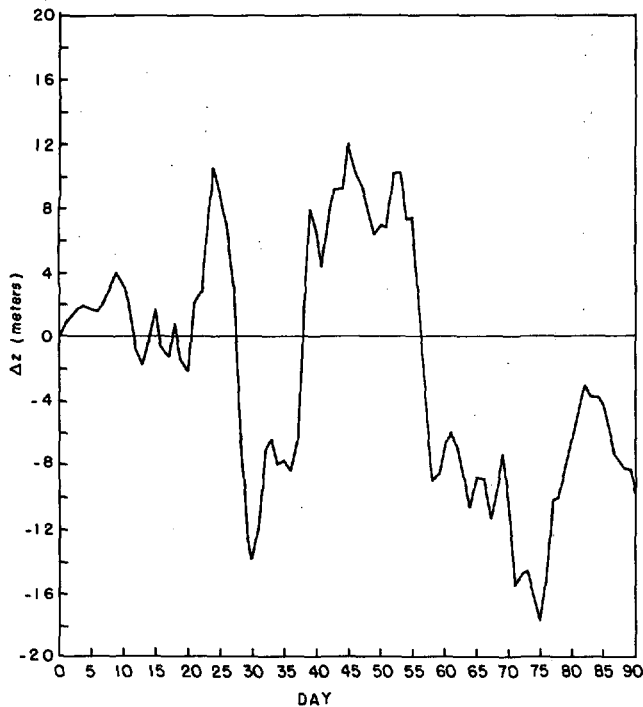


FIGURE 4.—Same as figure 3 for latitude band 6°N-6°S.

cated in figure 5, where the amplitude of the oscillation is seen to diminish with time in middle latitudes and increase in higher latitudes.

The Southern Hemisphere response first appears clearly at 30 days in figure 5A in middle and high latitudes, then shifts toward the Antarctic. However, after 60 days, as shown in figure 5B, the influence of the SST anomaly becomes "locked in" in the Southern Hemisphere, with a permanent anomaly in the slope of the 600-mb surface. This anomalous corrugation is characterized by relatively high geopotential in the Antarctic and low geopotential near latitude 40°S, as indicated also by the circles representing the anomaly profile on day 90 in figure 1. At latitude 50°S, the anomalous slope on day 90 corresponds to a decrease of about 7 m/s (equivalent to more than 30 percent) in the speed of the geostrophic westerlies. [A similar diminution of the surface Southern Hemisphere westerlies in the latter part of the season was also noted by Spar (1973), based on 30-day mean sea-level pressure fields]. On the other hand, at latitude 70°N on day 90, the anomaly profile shown in figure 1 represents a reversal of the geostrophic zonal flow from weak easterlies in the control case to westerlies in the anomaly run.

The response of the 600-mb surface to the SST anomaly can also be examined in terms of the day-to-day changes in the spectral characteristics of the height difference profile. A simple representation of this history is shown in figure 6, where the meridional wave number of maximum amplitude (the "dominant wave number") for each day is plotted against time with the relative amplitude of each dominant harmonic indicated by the length of a vertical spike. (In the Fourier analysis of the meridional height difference profiles, the domain was taken as twice

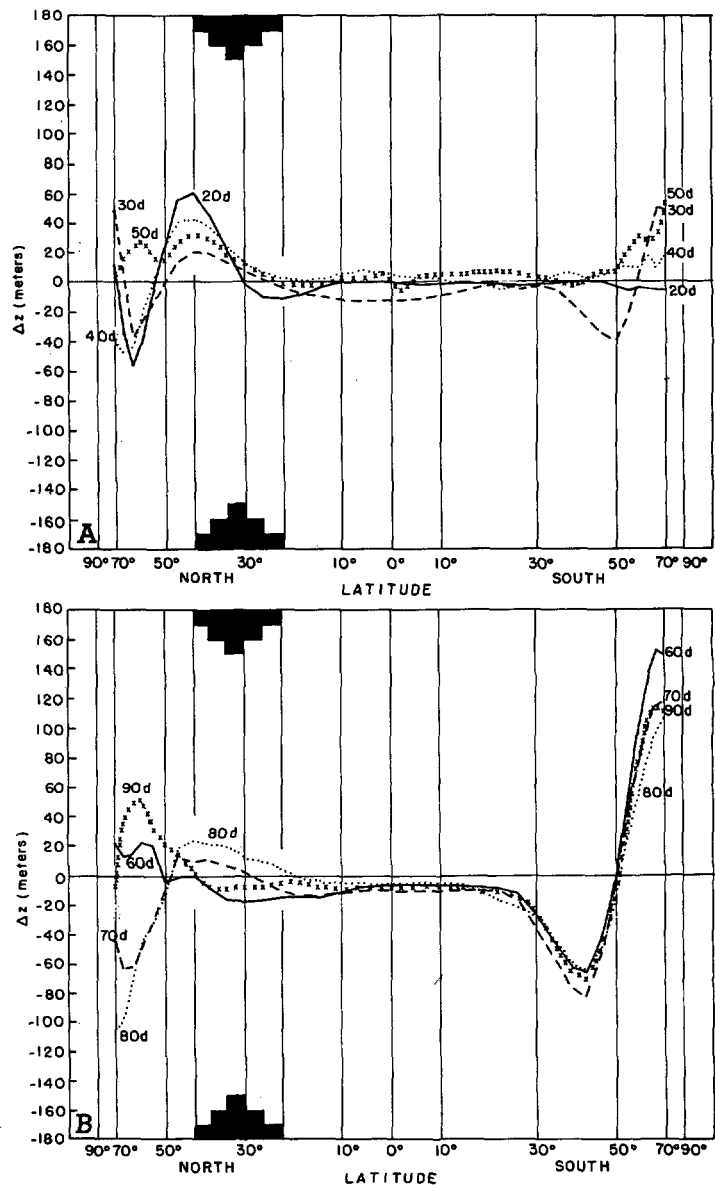


FIGURE 5.—Meridional profiles of anomaly-minus-control 600-mb height differences,  $\Delta z$  (m), for (A) days 20, 30, 40, 50, and (B) days 60, 70, 80, and 90, of experiment NHTA-W. The latitude of the SST anomaly is indicated by the bar graphs.

the distance from pole to pole, so that wave number 2 represents one wavelength from pole to pole, wave number 4 one wavelength from pole to Equator, etc.)

For the first 10 days, the profile is characterized by a low-wave-number (3) regime of small but increasing amplitude, corresponding to the initial hydrostatic inflation of the 600-mb surface. The meridional propagation of the anomaly effect within the Northern Hemisphere is represented by an abrupt transition to a high-wave-number (7-13) regime lasting 9 days. As the SST effect crosses the Equator between days 21 and 31, a second low-wave-number regime (2-4) is established. Then from days 32 to 39, the wave numbers fluctuate indecisively before settling into a high-wave-number (8) pattern between days 40 and 45. This latter period was characterized by the reappearance of inflation in the Northern Hemisphere latitude band of the SST anomaly (as shown

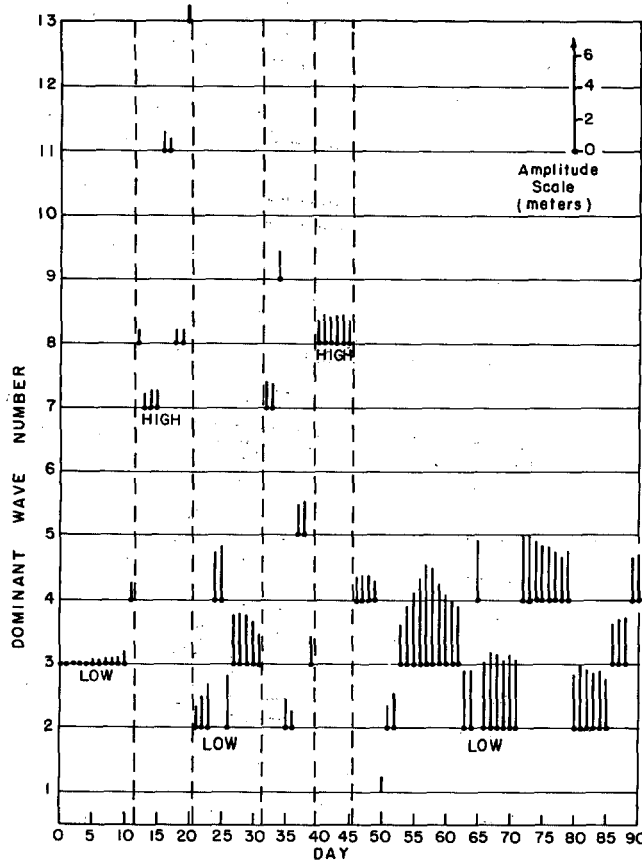


FIGURE 6.—Meridional wave number of maximum amplitude (dominant wave number) of the anomaly-minus-control 600-mb height difference profile for each day of experiment NHTA-W. Vertical spikes indicate the relative amplitude of each dominant harmonic.

in fig. 3), while at the same time the Southern Hemisphere reaction was increasing in magnitude.

From day 46 until the end of the season, the Southern Hemisphere response becomes "locked in," as noted previously, and dominates the profile. As a result, the anomaly-control height difference pattern is characterized by low wave numbers during all of the latter half of the season. Thus, in terms of the meridional 600-mb anomaly profile spectrum, the response to the northern winter SST anomaly is a vacillation between low- and high-wave-number regimes in the first half of the season, and a fixed low-wave-number anomaly pattern in the second half.

### 3. EXPERIMENT NHTA-S

Representative meridional 600-mb profiles generated by the model for the northern summer season are illustrated in figure 7 for days 15, 45, and 90 from the summer control run. (The circles in the figure represent the anomaly profile for day 45, which will be discussed. A comparison of figure 7 with figure 1 reveals both the small annual variation in middle latitudes of the Southern Hemisphere and the large annual variation in middle and high latitudes of the Northern Hemisphere, as well as the asymmetry between the hemispheres characteristic of northern summer. The profile for day 90 indicates that the effect of radiative cooling at high latitudes in the Northern Hemisphere may already be apparent in the

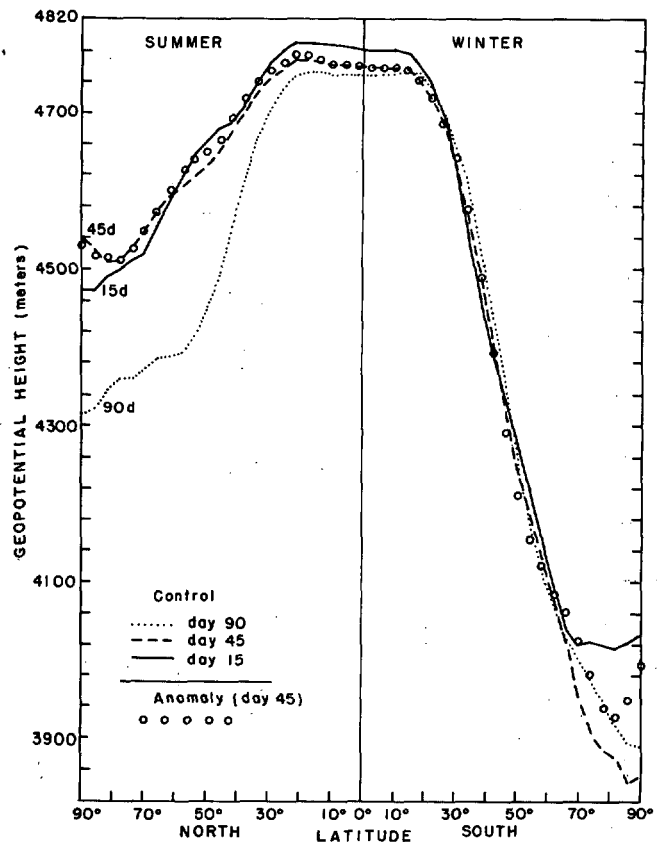


FIGURE 7.—Same as figure 1 for the summer control run, experiment NHTA-S. (Circles represent the profile on day 45 for the anomaly run.)

model in the increased slope of the 600-mb level by the time of the equinox.

The time-latitude cross section in figure 8 shows the response (anomaly-minus-control height differences) to the SST anomaly in northern summer for the first month. Compared with the northern winter experiment (fig. 2), the initial inflation in summer in the latitude band of the SST anomaly is both slower and smaller. This is also apparent from figure 9, where the maximum (positive or negative) anomaly-control height differences in the latitude band of the SST anomaly have been plotted for 87 days. During the first month, the maximum inflation effect is less than 20 m in summer compared with more than 60 m in winter (fig. 3). (Only at the end of the season, as shown in figure 9, does an inflation effect of 45m, comparable to that of the winter experiment, appear.) According to the bulk aerodynamic formula used in the model (Gates et al. 1971) to compute heat transfer from sea to air, the anomalous heating, and hence the inflation effect, should be proportional to the magnitude of the SST anomaly, which is the same in both the summer and winter experiments. However, the heat transfer is also assumed to be proportional to the surface wind speed, which is generally greater in winter than in summer in the region of the warm pool. This undoubtedly contributes to the difference between the two seasons. (The relatively large inflation effect at the end of the summer season noted in figure 9 is probably also due in part to stronger surface winds.) Other nonlinear factors, such as greater instability and stronger convective heat transfer over the ocean

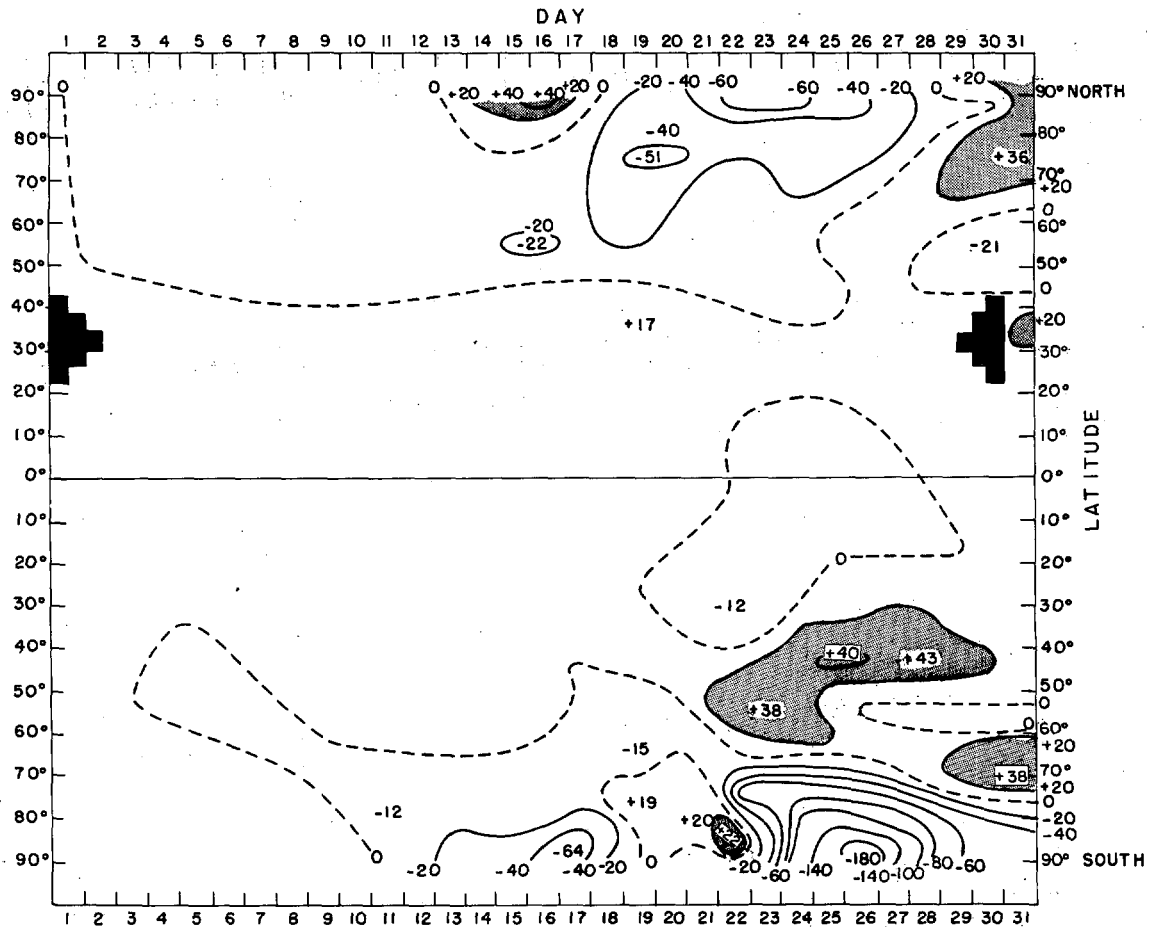


FIGURE 8.—Same as figure 2 for the first month of experiment NHTA-S.

in winter, also contribute to the seasonal difference between the inflation effects.

In the equatorial region, the height differences in experiment NHTA-S between anomaly and control runs are extremely small during the entire season with maximum absolute values of less than 7 m (compared with 18 m in NHTA-W). Despite this evidence that meridional wave propagation does not take place across the Equator, the response in the Southern Hemisphere to the SST anomaly in the opposite hemisphere appears earlier and is larger in southern winter (fig. 8) than in southern summer (fig. 2). It appears that the winter hemisphere is more responsive to SST anomalies in the opposite hemisphere than is the summer hemisphere.

The remaining history of experiment NHTA-S beyond the first month is illustrated in figure 10, which shows the meridional height difference profiles on days 40, 60, and 80. As in figure 5, latitude is plotted on a sine scale and no results are shown poleward of latitude 70°N and 70°S. In these curves, there is no evidence of the locked-in response noted in the Southern Hemisphere in figure 5. Instead, the reaction in the Southern Hemisphere to the thermal forcing in the north appears to be in the form of a standing oscillation. The inflation effect in the Northern Hemisphere at the end of northern summer noted in figure 9 also appears in the curve for day 80 in figure 10 accompanied by a response of even larger amplitude in the Southern Hemisphere.

Returning again to figure 7, we see that the anomaly profile at 600 mb, represented for day 45 by the circles, is not very different from the control profile on the same day. The effects shown in figures 8, 9, and 10 do not represent radical alterations of the zonal mean flow, but only relatively small-amplitude perturbations. However, these small effects on the zonally averaged profiles may be associated with synoptic effects of considerable magnitude (Spar 1973).

#### 4. EXPERIMENT SHTA

The possibility that unobserved events in the Southern Hemisphere may be transmitting significant signals to the Northern Hemisphere over periods of the order of a month to a season was the motivation for experiment SHTA. In this experiment, the SST anomaly in the South Pacific Ocean was introduced at the beginning of southern winter (northern summer). Hence, the control profiles for the SHTA experiment are also represented by the curves in figure 7.

The initial response in this experiment closely resembles that of the previous two. Maximum inflation begins in the latitude band of the SST anomaly and grows rapidly. However, as shown in figure 11, where the inflation curves for the SST anomaly belts are plotted for the first 10 days for all three experiments, the resemblance abruptly ends after 4 days. Up to day 4, the inflation effect is almost the same for NHTA-W and SHTA; that is, for both

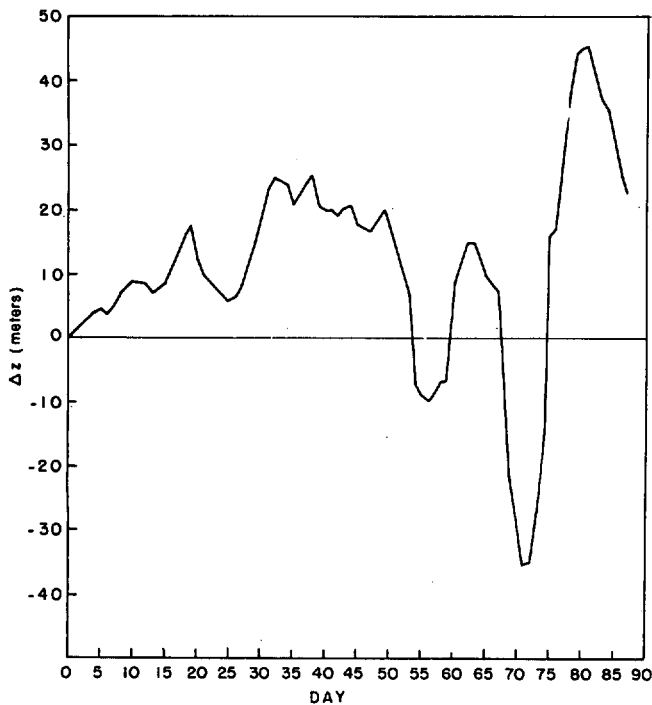


FIGURE 9.—Same as figure 3 for experiment NHTA-S.

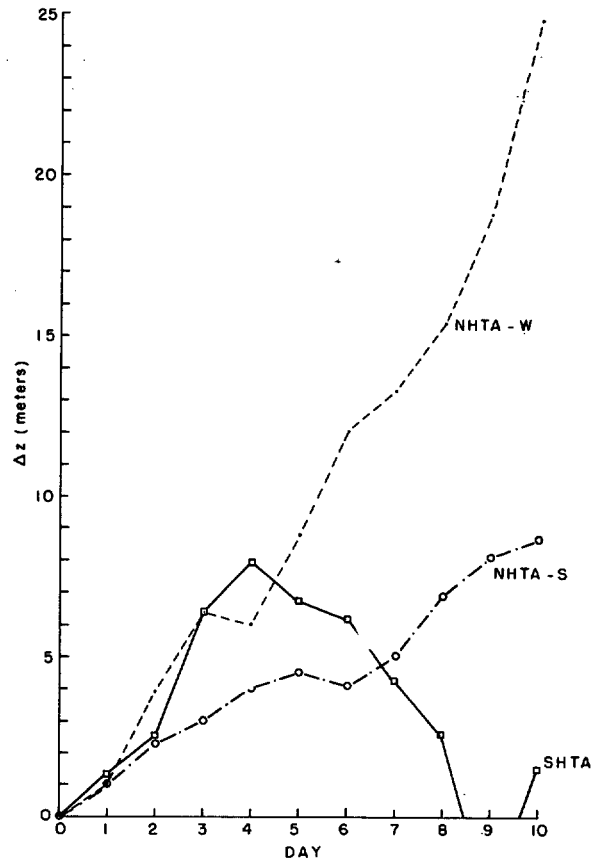


FIGURE 11.—Maximum anomaly-minus-control 600-mb height differences,  $\Delta z$  (m), in the latitude band of the SST anomaly for the first 10 days of experiments NHTA-W, NHTA-S, and SHTA.

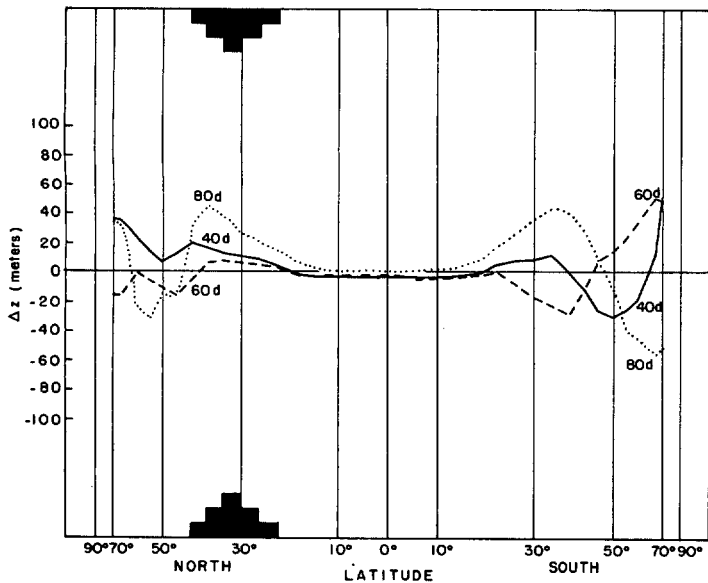


FIGURE 10.—Same as figure 5 for days 40, 60, and 80, of experiment NHTA-S.

winter hemisphere SST anomaly experiments. (The summer hemisphere inflation rate represented by NHTA-S is generally smaller.) After day 4, however, the initial inflation effect rapidly disappears in SHTA, whereas in NHTA-W the inflation continues for about three weeks (fig. 3). The subsequent response to the SHTA SST anomaly in the latitude band of the Southern Hemisphere warm pool is shown in figure 12, which may be compared with the corresponding figure 3 for NHTA-W. Both figures exhibit positive maxima at 40–45 days and 75–80 days, with minima (negative maxima) at 60–65 days. Except for these gross similarities however, the two curves bear little resemblance to each other.

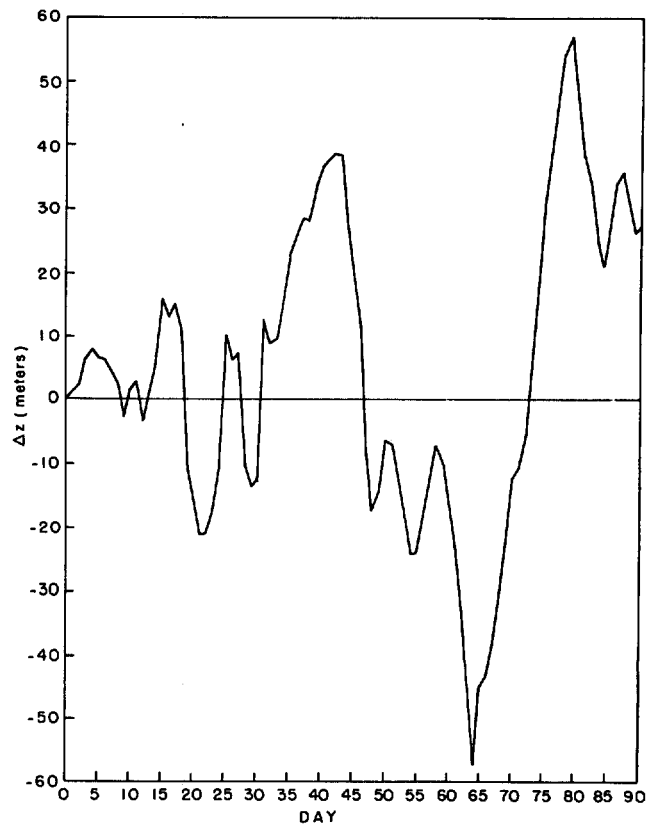


FIGURE 12.—Same as figure 3 for latitude band 22°–42°S for experiment SHTA.

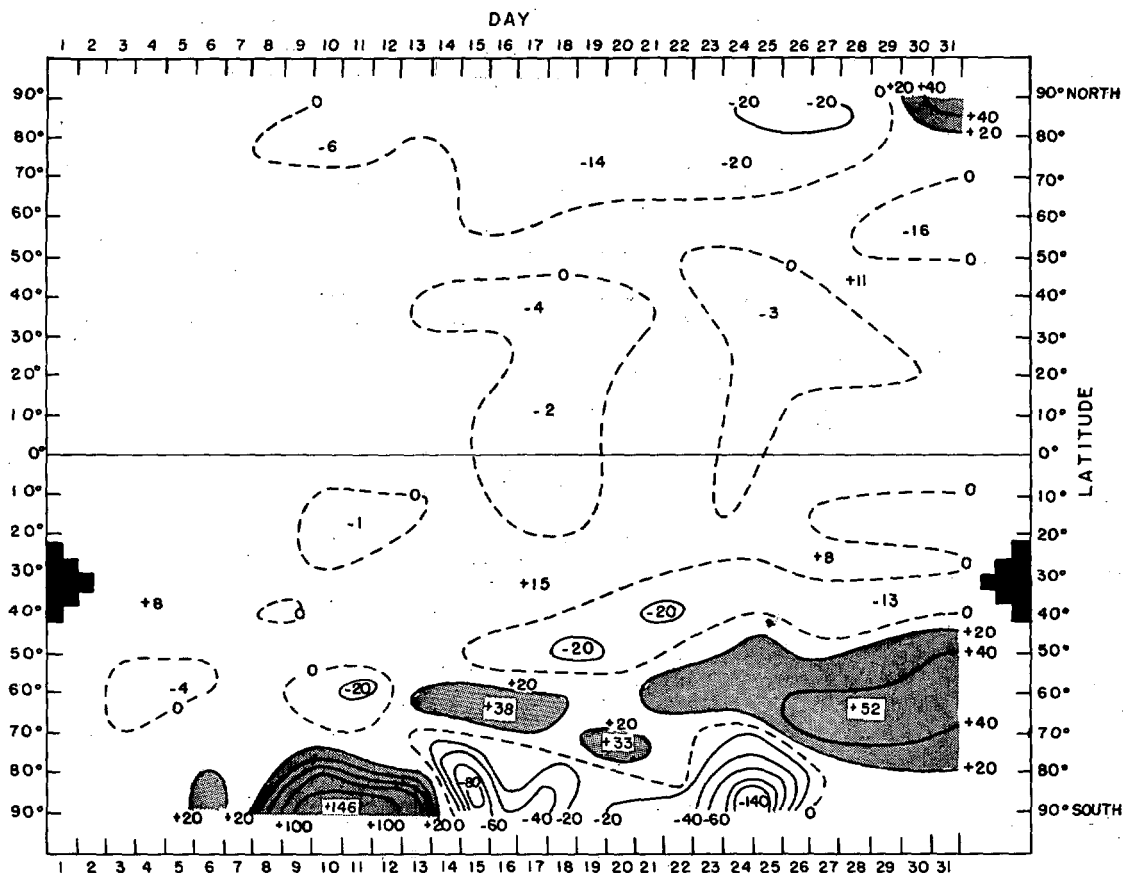


FIGURE 13.—Same as figure 2 for the first month of experiment SHTA.

As shown in the time-latitude cross section for the first month of SHTA (fig. 13), significant height effects do appear in the Southern Hemisphere within a few days, generally poleward of the latitude band of the SST anomaly. However, the response in the opposite hemisphere is minimal in the first month compared with that found in NHTA-W (fig. 2) or NHTA-S (fig. 8). This same lack of response in the Northern Hemisphere during the first month of SHTA was also noted by Spar (1973) in both the sea-level pressures and regional 600-mb circulation indices. One can only speculate about the reasons for both the cut-off of inflation and the slow transequatorial response in the SHTA experiment. Whatever the reasons (different initial conditions, effects of continentality, etc.), it is apparent that the response to SST anomalies is complex and not readily anticipated.

The history of the meridional response at 600 mb in the SHTA experiment is illustrated in figure 14 by the height difference profiles for days 40, 60, and 80. Again the response appears to take the form of a standing oscillation in both hemispheres but with a larger amplitude in the hemisphere opposite the SST anomaly. Relatively large height differences appear on day 80 in the equatorial region in this experiment compared with the previous two experiments (figs. 5, 10). This is further illustrated in figure 15, where the largest positive or negative height differences in the equatorial belt, 6°N-6°S, are plotted for each day. Here it can be seen that the equatorial

response, represented by a lowering of the isobaric surface relative to the control, began only after two months, but continued to the end of the season.

## 5. SUMMARY AND CONCLUSIONS

The global response of the model atmosphere to a positive SST anomaly located in extratropical latitudes of the Pacific Ocean has been studied in terms of the meridional profile of the 600-mb surface from pole to pole. The initial effect of the SST anomaly is an inflation of the isobaric surfaces, relative to a control run, within the latitude band of the warm pool. This is apparently a direct hydrostatic result of the augmented warming associated with increased sea-to-air heat transfer. The initial inflation rate is greater in winter than in summer. In experiments with a North Pacific warm pool, the inflation continued for about 3 weeks in both winter and summer. However, when the same SST anomaly was placed in the South Pacific Ocean, the initial inflation of the isobaric surface lasted only a few days.

During the first month of each experiment, the atmospheric reaction within the hemisphere of the SST anomaly appeared mainly poleward of the latitude band of the warm pool. This was true in all three experiments but was more apparent in the winter hemisphere experiments (NHTA-W and SHTA), as shown in figures 2 and 13, than in the summer hemisphere experiment (NHTA-S),



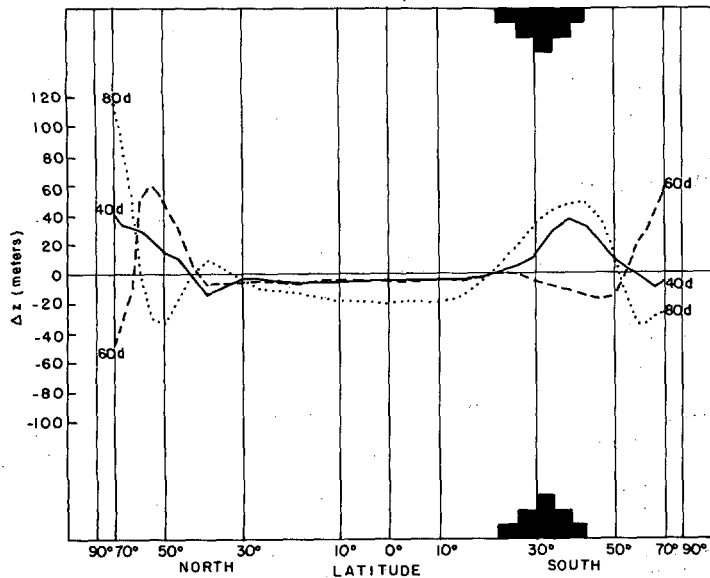


FIGURE 14.—Same as figure 5 for days 40, 60, and 80, of experiment SHTA.

illustrated in figure 8. Although, as shown in figure 11, the initial inflation persisted longer and grew ultimately larger in the Northern Hemisphere summer experiment (NHTA-S) than in the Southern Hemisphere winter experiment (SHTA), the reactions poleward of the inflation belt were stronger in the winter hemisphere than in the summer hemisphere.

Significant transequatorial effects first appeared at high latitudes in the hemisphere opposite the warm pool after about 2–3 weeks. After a month, the magnitude of the response was at least as large in the opposite hemisphere as in the hemisphere of the SST anomaly. The winter hemisphere appeared to respond more rapidly to SST anomalies in the opposite hemisphere than did the summer hemisphere. This can be seen by comparing the rapid transequatorial response in figure 8, where the opposite hemisphere is a winter hemisphere, with the slower transequatorial response in figures 2 and 13, where the opposite hemisphere is the summer hemisphere. Thus, it appears that the winter hemisphere appears to respond more sensitively than the summer hemisphere, not only to the effects of thermal forcing within the hemisphere of the warm oceanic pool, but also to the transequatorial signals transmitted by SST anomalies in the opposite hemisphere.<sup>5</sup>

The reactions in the Tropics were generally quite small, and at no time was there evidence of meridional wave propagation across the Equator. Instead, the transequatorial response appeared either as a permanent corrugation of the isobaric surface or as a standing oscillation in middle and high latitudes of the opposite hemisphere. The

<sup>5</sup> Had this unexpected result been anticipated, we would have planned at least two additional experiments, one with an SST anomaly in the Southern Hemisphere in northern winter and one with anomalous warm pools in both hemispheres. But then, there is no bound to the number of experiments one is tempted to perform with dynamical models

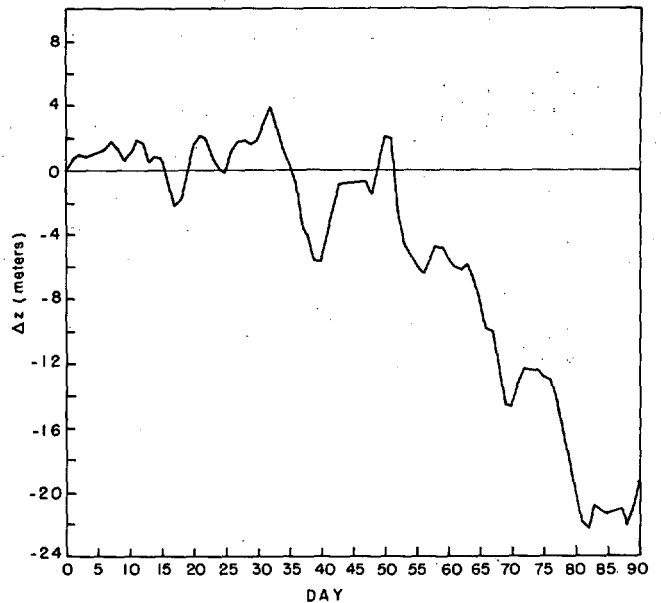


FIGURE 15.—Same as figure 3 for latitude band 6°N–6°S for experiment SHTA.

vacillation between high and low meridional wave number patterns in the response of the zonally averaged 600-mb height profile appears to represent an alternation between the dominance of direct thermal forcing (i.e. inflation), the migration of influences (largely poleward) within the hemisphere of the warm pool, and the transequatorial response.

During the 3-mo period of each experiment, the SST anomaly imposed a small but significant perturbation on the 600-mb height profile. The effect on the zonal circulation, represented roughly by the slope of the difference profile, was not computed as part of the experiment but was undoubtedly of even relatively larger magnitude. However, the character of the perturbation was quite different in each experiment despite the identical character of the SST anomaly. Clearly, the atmospheric response, as represented by the model computations, is a complex function of the initial state of the atmosphere and the hemispheric topography on which the anomaly is superimposed and could not have been anticipated from simplistic qualitative reasoning.

In this descriptive study, we have left unanswered the question of what *mechanism* is responsible for the propagation of influence across the Equator. Further diagnostic studies of the experiment, which are in progress, may provide a better understanding of that problem.

#### ACKNOWLEDGMENTS

This study was carried out in cooperation with the Goddard Institute for Space Studies (GISS) directed by Robert Jastrow, whose support is gratefully acknowledged. Among the GISS staff we especially acknowledge the assistance of Milton Halem, who arranged for computing services, and John Liu, who was responsible for all the programming and computations carried out for the project on the GISS IBM 360/95 computer. We also wish to thank

Yale Mintz and Akio Arakawa of the University of California, Los Angeles, for allowing us to use their model and programs for these experiments. To the National Academy of Sciences, we express our appreciation for the appointment as National Research Council Senior Research Associate at GISS during August 1972, when much of this paper was written. The 600-mb anomaly-control height difference profile computations were analyzed at New York University by Lawrence J. Lewis. Figures were drawn by Gertrude Fisher.

#### REFERENCES

- Gates, W. L., Batten, E. S., Kahle, A. B., and Nelson, A. B., "A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model," *Report R-877-ARPA*, The RAND Corporation, Santa Monica, Calif. Dec. 1971, 408 pp.
- Gates, W. L., "The January Global Climate Simulated by the Two-Level Mintz-Arakawa Model: A Comparison With Observation," *Report R-1005-ARPA*, The RAND Corporation, Santa Monica, Calif., Nov. 1972, 107 pp.
- Mintz, Yale, Katayama, A., and Arakawa, A., "Numerical Simulation of the Seasonally and Inter-Annually Varying Tropospheric Circulation," *Proceedings of the Survey Conference, February 15-16 1972, Climatic Impact Assessment Program, Cambridge, Mass.*, A. E. Barrington (Editor), U.S. Department of Transportation, DOT-TSC-OST-72-13, Washington, D.C., Sept. 1972, 281 pp. (see pp. 194-216.)
- Ramage, C. S., and Murakami, T., "Comment on the Paper by P. R. Rowntree: The Influence of Tropical East Pacific Ocean Temperatures on the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, Vol. 99, No. 420, London, England, Apr. 1973, pp. 393-394.
- Rowntree, P. R., "The Influence of Tropical East Pacific Ocean Temperatures on the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, Vol. 98, No. 416, London, England, Apr. 1972, pp. 290-321.
- Spar, Jerome, "Effects of Surface Anomalies on Certain Model-Generated Meteorological Histories," New York University, Geophysical Sciences Laboratory *Report No. GSL-TR-72-2*, NASA Grant NGR-33-016-174, Bronx, N. Y., Apr. 1972, 54 pp.
- Spar, Jerome, "Some Effects of Surface Anomalies in a Global General Circulation Model," *Monthly Weather Review*, Vol. 101, No. 2, Feb. 1973, pp. 91-100.
- van Loon, Harry, "Mid-Season Average Zonal Winds at Sea Level and at 500 mb South of 25 Degrees South, and a Brief Comparison with the Northern Hemisphere," *Journal of Applied Meteorology*, Vol. 3, No. 5, Oct. 1964, pp. 554-563.
- van Loon, Harry, "A Climatological Study of the Atmospheric Circulation in the Southern Hemisphere During the IGY, Part I: 1 July 1957-31 March 1958," *Journal of Applied Meteorology*, Vol. 4, No. 4, Aug. 1965, pp. 479-491.

[Received November 6, 1972; revised May 31, 1973]