The Influence of Ocean Surface Temperature Gradient and Continentality on the Walker Circulation. Part II: Prescribed Global Changes

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(Manuscript received 16 December 1983, in final form 25 April 1984)

ABSTRACT

The mechanisms responsible for forcing the global Walker circulation are investigated with a series of experiments using an atmospheric model developed at the Goddard Institute for Space Studies. These experiments feature worldwide changes in ocean surface temperatures (OSTs), topography and/or continents. The results show that the primary factor affecting the circulation in the model is the global distribution of continents and oceans. The OST gradients are also important, but the topography is relatively unimportant. Both continentality and OST gradients by themselves force the model atmosphere by introducing zonal variations of surface heating, which give rise to vertical motions. These in turn give rise to variations in moisture convergence and condensation, which reinforce the vertical motions. The forcing by OST gradients is partly nonlocal in character, and the atmospheric response is affected by the continentality. In particular, in the south tropical Pacific the model response is greatly enhanced by the continentality, and is controlled by distant OST gradients more than by local OST gradients. In all cases the zonal variations of the vertical motions are highly correlated with condensation (i.e., precipitation) and this in turn is correlated more with moisture convergence than with local evaporation.

1. Introduction

Chervin and Druyan (1984, hereafter referred to as Part I) investigated the relative influence of changes in ocean surface temperature (OST) gradient and continentality in the south tropical Pacific on the Walker circulation. The vehicle used for their investigation was a global climate model developed at the Goddard Institute for Space Studies (GISS). In Part I, prescribed changes in OST and continent–ocean distribution were imposed in the model for the tropical Pacific sector only and the model's response was evaluated in terms of differences in zonal wind and vertical velocity from an average of five January means produced in an extended integration over several annual cycles. It was found that both continentality and OST gradients were important factors in establishing the overall structure of the Walker circulation.

In this paper, we report on experiments with the same model, in which massive prescribed changes in global surface conditions are imposed in an attempt to isolate the separate contributions of continentality and OST gradient to the global Walker circulation. The model used is the GISS Model II, a finite difference model with nine sigma layers in the vertical and a horizontal resolution of 10° in the zonal direction and approximately 8° in the meridional direction. The model is briefly described in terms of its simulation of the Walker circulation in the zonal plane in Part I. A complete documentation of the model's composition and performance may be found in Hansen *et al.* (1983). For the most part, we follow the analysis procedure used in Part I, but we also evaluate the relationships between the surface heat balance, surface evaporation, precipitation and vertical motion in the tropical atmosphere. These relationships are particularly valuable in identifying how surface conditions affect the atmospheric circulation, and the feedbacks between the surface and the atmosphere.

2. Experimental design

In this study, we analyzed the model's response to three different prescribed global changes in boundary or surface conditions. Where appropriate, we compared the response to the most nearly equivalent prescribed local change experiment from Part I. In three of those experiments the normal west-to-east OST gradient in the tropical Pacific band from 8°N–16°S was replaced with a uniform distribution in

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

which the temperatures were set, respectively, at the warmest, coldest or mean values in the band, and in one experiment, the South American continent was replaced by an ocean with OSTs linearly interpolated between Pacific and Atlantic values. In Part I, these experiments were referred to as Cases WTNG, CTNG, MTNG and NSAC, respectively.

Here, in our first experiment, we changed all OSTs worldwide to their zonal average values (with the annual cycle retained). This prescribed change removed all west-to-east OST gradients without altering the net heat input into the atmosphere (to first order). The continent–ocean distribution remained as in the control case. We designate this experiment with all continents and no OST gradients, Case ACNG. The second experiment, Case FCNG was the same as Case ACNG except that all continents were flattened to zero topographic height. In the third experiment, we retained the OST distribution (with all the gradients) but replaced *all* continents with oceans having surface temperatures equal to the normal zonal average ocean values. This experiment with no continents and all gradients will be referred to as Case NCAG.

As in Part I, we began each of these prescribed change experiments on 1 December and continued the integration through the end of January. Model statistics for the month of January were used to assess the impact of the different prescribed changes. (The model troposphere's characteristic time to adjust to changes in the boundary conditions is about one month.) For various fields and variables of interest, we determined a prescribed change response by subtracting the control January ensemble average from the January mean for the given experiment. If the magnitude of a prescribed change response exceeded the control standard deviation by a factor of 3 or more, then, for the sample sizes under consideration here, the difference is significantly different from zero at the 5% significance level. (See Chervin and Schneider, 1976, for further details.)

3. Tropical response

Paralleling the approach in Part I, we evaluate the response of the Walker circulation in the model's tropical atmosphere to the prescribed changes described in the previous section by means of longitude–height cross sections of zonal wind and vertical velocity averaged over the latitude band from 16°S–8°N. In this section, we present cross sections of both mean January fields and differences from the control for each prescribed change experiment. For the sake of ready comparison, we also include cross sections for the control ensemble averages and standard deviations. On the difference cross sections, statistically significant differences are shown stippled.

a. Zonal wind

Figures 1 and 2 show the mean and difference zonal wind cross sections for the three prescribed change experiments as well as the estimated ensemble average and standard deviation for the control population. As was noted in Part I, the Walker circulation in the control case features six cells in this zonal plane—three clockwise cells over the oceans and three counterclockwise cells over the continents. However, the cells over the Indian Ocean and East Indies (the maritime continent) are much weaker than the other four cells.

In Case ACNG, the six-cell structure is essentially reduced to two cells. The weak cells over the Indian Ocean and East Indies have been absorbed by the Pacific cell, which is now much broader, although significantly weaker over the Pacific sector. The Atlantic and African cells are weaker with the African cell only evident relative to the zonal average. The only remaining counterclockwise cell (i.e., over South America) is stronger and broadened considerably to the west. When compared to the responses in Part I, Case ACNG is most similar to Case MTNG—not a surprising observation since the prescribed change for this experiment in Part I is essentially a localized version of the global change in Case ACNG.

The additional impact of flattening the continents in Case FCNG is relatively small. The difference cross section closely matches that for Case ACNG.

The removal of all continents in Case NCAG serves to replace the six-cell structure with four cells. Now the South American cell has disappeared and the Pacific and Atlantic cells have merged into a dominant Western Hemisphere cell which is much stronger than any of the three narrow Eastern Hemisphere cells. As was to be expected, this response resembles that of Part I's Case NSAC in which the South American continent was removed.

b. Vertical velocity

The vertical velocity means and differences shown in Figs. 3 and 4 for the prescribed change experiments along with the control ensemble average and standard deviation are, for the most part, consistent with the quasi-two-dimensional nature of the Walker circulation. The ascending branches over the South American and African continents remain the dominant features in the cross sections for Cases ACNG and FCNG. Significant reductions in the upward motion over the western Pacific (and the maritime continent) and in the subsidence over the eastern Pacific are found in both of these cases. An upward displacement and intensification of the vertical motion maximum over the African continent also results from the removal of all OST gradients. This response was also found in Part I for Cases WTNG, CTNG and MTNG.

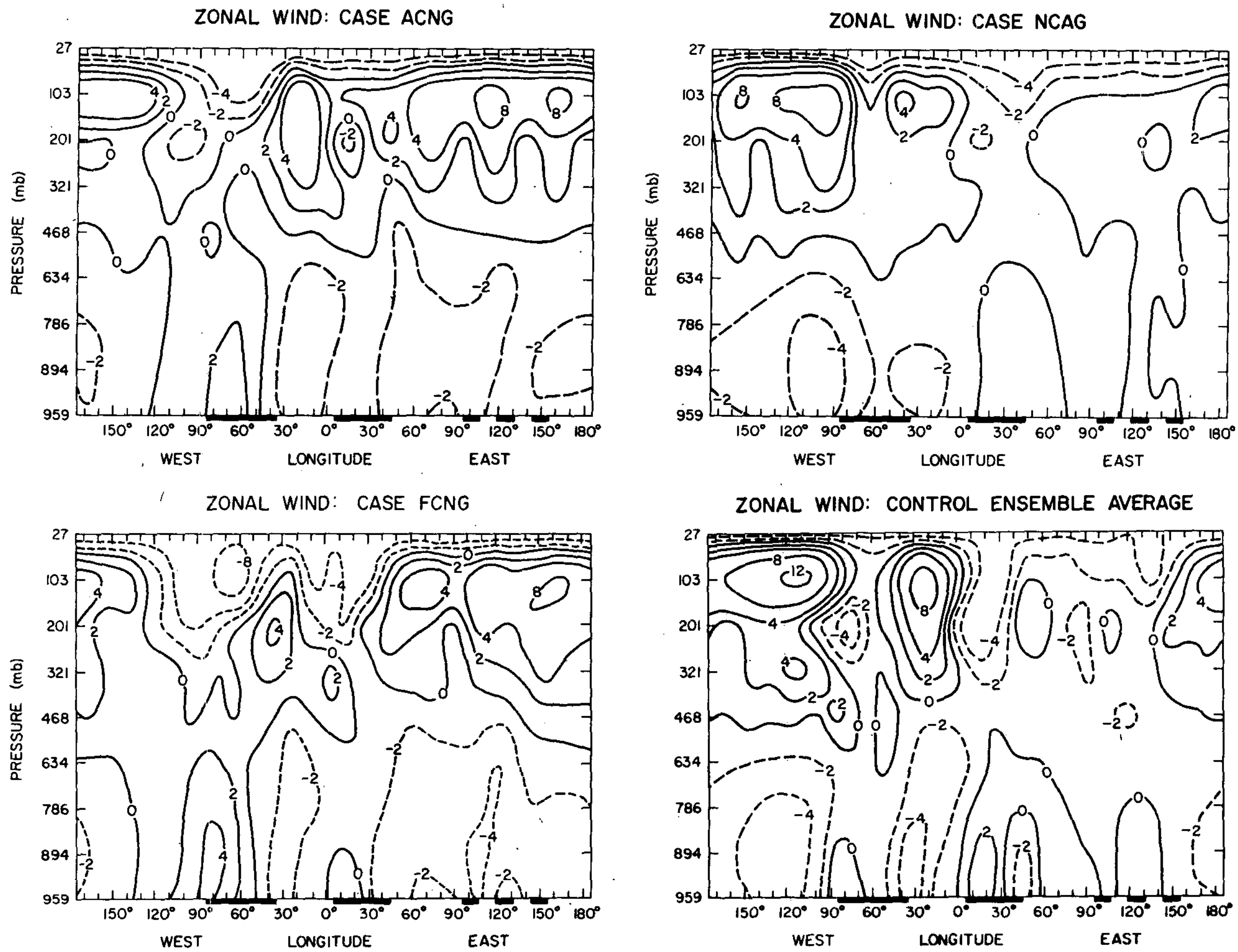

FIG. 1. Longitude–height January mean cross sections of the zonal wind averaged over the latitude band 8°N–16°S: upper left, case with all continents included but with no OST gradients (Case ACNG); lower left, case with flat continents and no OST gradients (Case FCNG); upper right, case with continents replaced by oceans with zonal average values of OST but with all OST gradients retained elsewhere (Case NCAG); lower right, control ensemble average as estimated from five independent simulated Januaries. The solid underbars indicate the South American and African continents and the broken underbar indicates the maritime continent formed by the Indonesian Archipelago and New Guinea. The nominal pressure levels at which the variables are computed in the model are given on the vertical axis. Units are m s^{-1}.

In Case NCAG, the upward motion over the regions previously occupied by South America and Africa is greatly reduced. The mean cross section indicates a broad (though nonuniform) ascending branch over the entire Eastern Hemisphere. However, the resemblance (in terms of vertical motion branches) between Case ACNG and the control is still greater than that between Case NCAG and the control. In particular, the strong rising motion over South America in the control is associated almost entirely with the continentality; that over Africa has contributions from both continentality and OST gradients, but the former appears to be larger. The ascending branch over the East Indies and western Pacific does appear to be dependent on both sources, but in a highly nonlinear fashion. As was to be expected, the response in Case NCAG resembles that in Case NSAC in Part I.

The experiments in Part I indicated that both continentality and OST gradients in the south tropical Pacific region were important in forcing the Pacific cell and the global Walker circulation. Our experiments here support these conclusions. However, no conclusions could be drawn in Part I on the effects of distant OST gradients on the Pacific Walker cell.

To help elucidate this issue, we examined a concise summary of the characteristics of the Pacific overturnings in the form of mean vertically averaged vertical velocity for two key, equally-sized regions within the Pacific basin (Table 1). These regions, designated central tropical and eastern tropical, correspond to the local maximum and minimum, re-

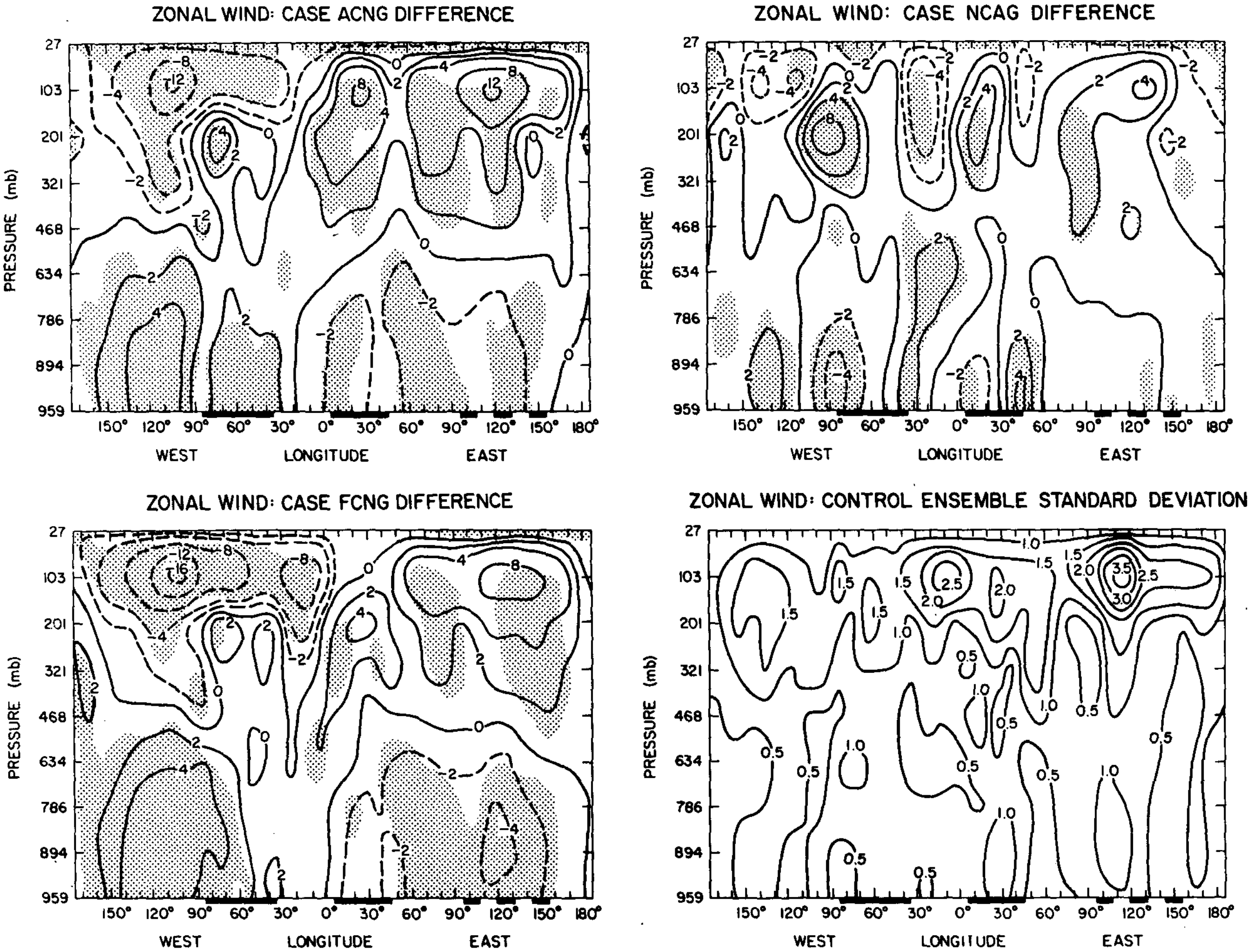

FIG. 2. As in Fig. 1 except for prescribed change responses (i.e., the control ensemble average as estimated from five simulated Januaries is subtracted from the January mean for each experiment) and control ensemble standard deviation. Stippled areas correspond to normalized responses $r \geqslant 3$ and indicate statistically significant differences at the 5% significance level. (r = ratio of the prescribed change response to the ensemble standard deviation.)

spectively, for the vertical motion in the control. For each experiment, the difference of the two vertical velocities can serve as a simple (though incomplete) measure of the "strength" of the Pacific cell (Table 2). The exact areas are defined in Tables 1 and 2 in which m_c represents the control ensemble average, σ_c is the control standard deviation, m_e is the January mean for each of the prescribed change experiments and Δ is the prescribed change response (i.e., $m_e - m_c$) for each experiment. A normalized response $\Delta/\sigma_c \geqslant 3$ implies a statistically significant difference at the 5% level. Removing either the continents (in Case NCAG) or the OST gradients (in Case ACNG) had a substantial and significant effect in the eastern region, with the effect of the OST gradients being slightly larger. In the central region, the upward motion was reduced in Case NCAG, but not significantly. Nevertheless, all three cases did significantly reduce the strength of the Pacific cell.

We also include in Table 1 the result for Case MTNG from Part I. This experiment removed the OST gradients in the south tropical Pacific, and replaced them by the mean OST in that region. Thus, Cases ACNG and MTNG both retain the continents and topography and have a zero zonal OST gradient in the south tropical Pacific. They only differ in that Case MTNG retains the observed OST gradients *outside* the south tropical Pacific, while Case ACNG does not. Nevertheless, the vertical motions in these regions differ substantially in these two cases. Thus, the *distant* OST gradients have a major effect on the circulations in the south tropical Pacific. In fact, comparing cases ACNG and MTNG with the control in Tables 1 and 2, we infer that in the model, distant

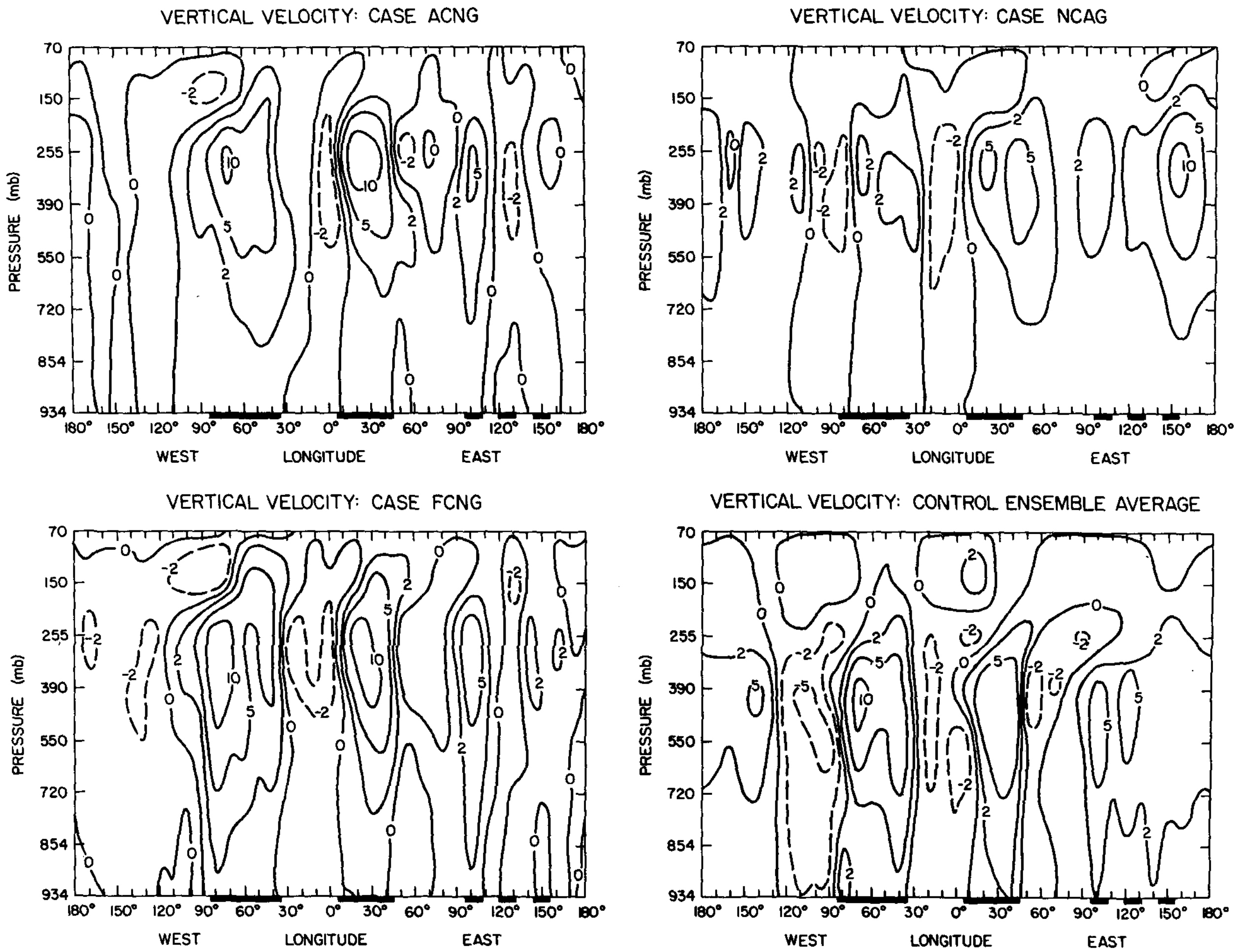

FIG. 3. As in Fig. 1 except for vertical velocity. Units are mm s^{-1}.

gradients are *more* important than the local gradients in producing the characteristic vertical motions in the south tropical Pacific. This effect is also apparent from a comparison of the vertical velocities in cases ACNG (Fig. 3) and MTNG (Part I, Fig. 5).

4. Analysis of forcing mechanisms

The results of Section 3 indicate that both the ocean–continent contrasts and the OST gradients play important roles in forcing the global Walker circulation. However, the continentality appears to dominate it setting the overall pattern, as anticipated by Ramage (1968) and Webster (1972). By contrast, the topography is relatively unimportant. More insight can be gained by analyzing the relationship between the surface heat and moisture balances and the resulting precipitation and vertical motion in the model's tropical atmosphere. These relationships should elucidate the feedbacks involved in forcing the Walker circulation in the model.

To determine these relations we computed the correlation and linear regression between different pairs of variables likely to be involved in the forcing mechanisms. The calculations were made from monthly mean model data averaged over the latitude band 16°S–8°N for the three prescribed change experiments and the control ensemble average. The longitudinal variations around the full latitudinal band were then correlated. Table 3 summarizes these calculations: $\rho(A, B)$ is the correlation of A with B; $\hat{w}$ is the vertical velocity averaged vertically; P is the precipitation rate; E is the surface evaporation rate; T_s is the ocean surface temperature; H is the net heating of the atmosphere by the underlying surface; S is the surface sensible heat flux; R is the net radiative flux into the surface; C is the net total moisture convergence into an atmospheric column; and L is the fraction of a grid point occupied by land.

The 36 model points around a latitude circle are not, in general, independent of each other. The

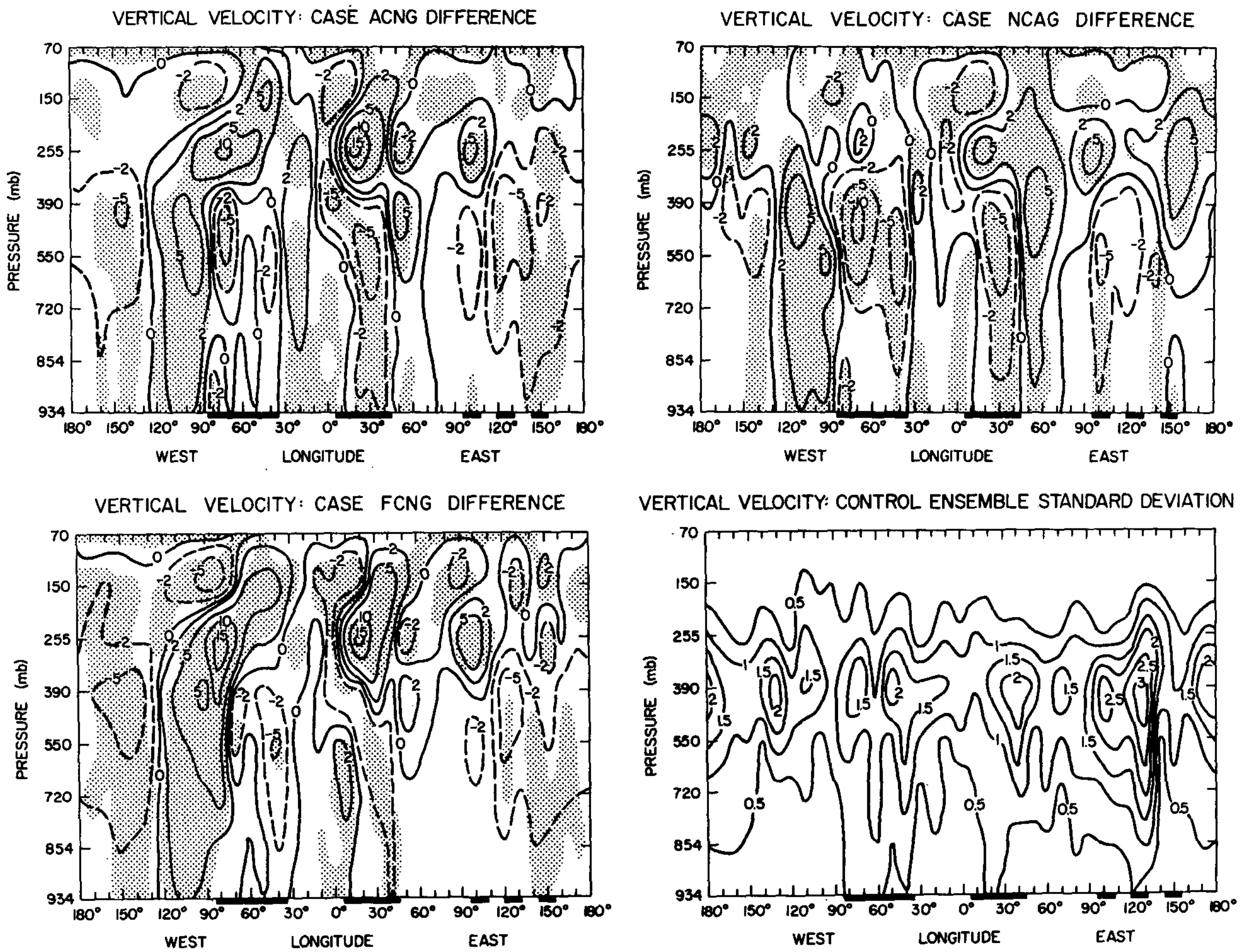

FIG. 4. As in Fig. 2 except for vertical velocity. Units are mm s^{-1}.

presence of short-scale variations in the vertical velocity pattern around a latitude circle in the control, with the distance from some maxima to adjacent minima being only about 30° (see Fig. 3), indicates that, in principle, there could be 12 independent values of this field around a latitude circle. However, as was demonstrated by the prescribed change responses in Part I, the aforementioned vertical motion branches do exhibit a reasonable degree of spatial correlation. Therefore, some estimate of effective independent sample size would be required for a formal assessment of the statistical significance of the cross correlations shown in Table 3. The relationship between (independent) sample size and significant

TABLE 1. January mean vertically averaged vertical velocity (0.1 mm s^{-1}).

Case	m_e	Δ	Δ/σ_c
Case $\hat{W}_{CT}$. Central tropical Pacific region (8°N–16°S, 175–135°W) Control m_c = 17.9, σ_c = 4.1			
ACNG	−10.0	−27.9	−6.8
FCNG	1.0	−16.9	−4.1
NCAG	14.0	−3.9	−0.9
MTNG	11.8	−6.1	−1.5
Case $\hat{W}_{ET}$. Eastern tropical Pacific region (8°N–16°S, 125–85°W) Control m_c = −24.8, σ_c = 1.6			
ACNG	4.0	28.8	18.0
FCNG	2.0	26.8	16.8
NCAG	−2.0	22.8	14.3
MTNG	−11.8	13.0	8.1

TABLE 2. January mean Pacific cell "strength" (0.1 mm s^{-1}). Case ($\hat{W}_{CT} - \hat{W}_{ET}$).

Case	m_e	Δ	Δ/σ_c
Control m_c = 42.7, σ_c = 4.5			
ACNG	−14.0	−56.7	−12.6
FCNG	−1.0	−43.7	−9.7
NCAG	16	−26.7	−5.9
MTNG	23.6	−19.1	−4.2

TABLE 3. Longitudinal correlations for January mean model data averaged over the latitude band 16°S to 8°N. The correlations were computed using all 36 longitude points within the band, except where otherwise noted. (See text for notation).

Correlation	Control	Case ACNG	Case FCNG	Case NCAG	Control minus Case ACNG
$\rho(\hat{w}, P)$	0.93	0.96	0.96	0.97	0.96
$\rho(\hat{w}, T_s)$	0.77*	—	—	0.74	0.64*
$\rho(\hat{w}, H)$	0.69	0.91	0.90	0.83	0.83
$\rho(\hat{w}, E)$	0.63	0.91	0.92	0.57	0.86
$\rho(H, T_s)$	0.12*	—	—	0.73	0.39*
$\rho(E, T_s)$	0.34*	—	—	0.18	0.35*
$\rho(H, E)$	0.60	0.89	0.89	0.74	0.94
$\rho(P, E)$	0.68	0.87	0.89	0.68	0.88
$\rho(P, C)$	0.85	0.94	0.88	0.95	0.92
$\rho(C, E)$	0.41	0.66	0.57	0.43	0.63
$\rho(C, T_s)$	0.71*	—	—	0.70	0.62*
$\rho(C, H)$	0.34	0.67	0.51	0.73	0.64
$\rho(H, L)$	0.89	0.87	0.93	—	—
$\tau(E, L)$	0.29	0.68	0.74	—	—
$\rho(H, S)$	0.73	0.39	0.52	0.66	−0.48
$\rho(H, R)$	0.73	0.95	0.93	0.66	0.47

* Calculation excludes points with fractional land areas exceeding 25%, i.e., 26 points in longitude were included.

correlations (at the 5% level) is shown in Table 4 for both one-sided and two-sided *t*-tests. Since only positive correlations are of interest, we have ample justification for considering only the one-sided test. A reasonably conservative estimate of independent sample size, likely to be valid for most fields of interest, is taken to be 6. Hence, a significant correlation is judged to be 0.73. Most of the larger correlations shown in Table 3 are significant when judged by this criterion.

In all the experiments, $\hat{w}$ and P are highly correlated. This same result was found by Webster (1972) and by Cornejo-Garrido and Stone (1977). The linear regressions between $\hat{w}$ and P showed that, on the average, zonal anomalies of 1 mm day^{-1} in the model's precipitation produced zonal anomalies of 1.0 to 1.3 mm s^{-1} (depending on the experiment) in the model's vertical motion.

The precipitation may arise either from local surface evaporation or from local convergence of moisture. The correlations of P with C are generally higher than those with E, indicating that the net convergence is more important than evaporation in supplying the precipitation. This again agrees with Cornejo-Garrido and Stone's (1977) conclusion, but their conclusion applied to only the south tropical Pacific, while ours applies to the tropics as a whole. The low correlation of C with E in the control indicates that the two mechanisms do not reinforce each other in analogous circumstances to the real world. In fact, in the control the linear regressions between P and C showed that, on average, the precipitation anomalies were almost equal to the moisture convergence anomalies.

TABLE 4. Significant correlations (5% level).

Independent sample size	One-sided t-test	Two-sided t-test
12	0.50	0.58
11	0.52	0.60
10	0.55	0.63
9	0.58	0.67
8	0.62	0.71
7	0.67	0.75
6	0.73	0.81

The mechanisms by which continentality and OST gradients separately force the atmosphere in the model are indicated by the correlations in the individual experiments. We note first that the correlations in Cases ACNG and FCNG are virtually identical, i.e., topography again does not appear to have much effect. The correlations of L with H and E in these cases indicate that the continents force the atmosphere primarily by heating it relative to the ocean. This heating forces rising motion which then causes moisture convergence and condensation. The condensation heating then reinforces the vertical motion. The associated precipitation is a source of moisture for the land, so that the land becomes a secondary source of moisture for the atmosphere through evaporation. This in turn enhances the condensation, precipitation and vertical motions. In these experiments, linear regressions showed that the zonal precipitation anomalies were, on average, 50% greater than the zonal anomalies in moisture convergence, and zonal anomalies in the net surface heating of 25 W m^{-2} led to zonal anomalies in the vertical motion of 1.1 mm s^{-1} on the average.

The correlations of T_s with H and E for Case NCAG indicate that zonal forcing by OST gradients alone, like continentality, works primarily through heating the atmosphere. The resulting rising motions again produce moisture convergence and condensation which reinforces the rising motion. In this case, however, there is very little secondary reinforcement by the zonal variations in evaporation. This is indicated by the very small correlation between E and T_s and by the fact that in this experiment the zonal precipitation anomalies were on average only 20% greater than the zonal moisture convergence anomalies. However, the zonal heating anomalies associated with the OST gradients were much more efficient in producing vertical motions—in Case NCAG, zonal anomalies of 25 W m^{-2} were associated, on the average with zonal anomalies of 2.1 mm s^{-1} in the vertical motion. The corresponding anomalies in ocean surface temperature averaged 3°C.

The greater efficiency of the OST gradient forcing in producing vertical motions is probably due to the different distribution of the two forcing mechanisms. The forcing by OST gradients is dominated by a single feature, the warm temperatures in the western Pacific, and this is reflected in the dominance of the strong rising motion in this region in the vertical velocity pattern (See Fig. 3). However, the continental forcing is associated with three sources: South America, Africa and the Indonesian "continent." These sources are not equally spaced; therefore, one can expect a considerable amount of destructive interference between their individual effects.

We see that the correlations in the control are much more like those when the forcing is by continents than those when the forcing is by OST gradients. In particular, the variations in heating of the atmosphere by the underlying surface are highly correlated with L, but not with T_s. This supports our conclusion that continentality is the major forcing mechanism for the model's global Walker circulation. The precipitation and vertical motions seem to be associated primarily with moisture convergence forced by land–ocean heating contrasts rather than by OST gradients. The high correlation between the vertical motions and ocean surface temperatures in the control, which mimics the real world, appears to be a coincidence.

Also we note that the correlation between the vertical motions and the surface heating in the control is lower than in all the experiments. This indicates that the ocean–continent contrasts and the OST gradients do not reinforce each other. This lack of reinforcement is particularly noticeable in the rising branches of motion over Africa and the west Pacific (see Fig. 3). In the control, zonal heating anomalies of 25 W m^{-2} were associated on the average with zonal vertical motion anomalies of only 1.0 mm s^{-1}. This relatively low efficiency of the zonal heating anomalies is another indication that continentality rather than OST gradients is the dominant factor in producing the global Walker circulation.

Because of the dominance of continentality, the manner in which OST gradients force the atmosphere in Case NCAG may be misleading, i.e., the presence of continentality may alter considerably how the atmosphere and the Walker circulation respond to OST gradients. To investigate this possibility we calculated the difference fields between the control and case ACNG. These difference fields describe the effect of adding the observed OST gradients in the presence of the observed continents and topography. We then repeated our correlation calculations for these difference fields, and include the results in Table 3.

One notable difference between these results and the results for Case NCAG is the substantial decrease in the correlation between T_s and the surface heating. Apparently, the degree to which local changes in surface heating are determined by local changes in ocean surface temperature is modified by the presence of the continents. The variance in T_s can account for 53% of the variance in surface heating in Case NCAG, but only 15% of the variance in the surface heating changes between the control and Case ACNG. The remaining part of the variances must be attributed to nonlocal changes in T_s. Another dramatic effect of the continents is the reversal of the sign of the correlation between H and S associated with the ocean temperature anomalies in Case NCAG and in the control minus Case ACNG.

The way that the dynamical response is modified by the presence of the continents is shown particularly

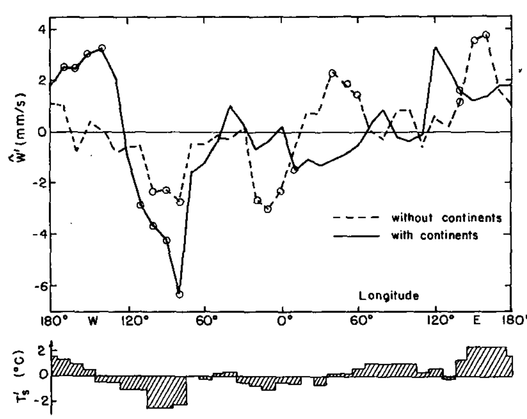

FIG. 5. Bottom: Observed OST (with zonal mean subtracted) for 16°S–8°N. Top: Mean vertical velocity perturbations for 16°S–8°N produced by adding the observed OSTs first to the model without continents (dashed line, Case NCAG with zonal mean removed) and then to the model with continents (solid line, control minus Case ACNG with zonal mean removed). The circles indicate perturbations that exceeded three σ_c.

clearly in Fig. 5. Here we have plotted the mean vertically averaged vertical velocity in the latitude band 16°S–8°N in Case NCAG, with the zonal mean removed (dashed line). This velocity perturbation represents the impact of adding the observed OST gradients to a world with no zonally asymmetric forcing. We have also plotted the difference between the mean vertical velocities in the control and Case ACNG, with the zonal mean difference removed (solid line). This velocity perturbation represents the impact of adding the observed OST gradients to a world with the observed distribution of continents and topography. The two velocity distributions are quite different and the correlation between the two is only 0.48. The difference between the two in the Pacific from 180 to 70°W is particularly noteworthy; the impact of the OST gradients is greatly enhanced by the continentality.

5. Extratropical response

As in Part I, the most straightforward way to evaluate the model's extratropical response to the prescribed changes is by means of the zonal-mean mass streamfunction. This streamfunction and its changes are shown in Figs. 6 and 7. In Case ACNG, the major difference is a narrowing of the Northern Hemisphere Hadley cell. In contrast, the response in Case FCNG is very small, i.e., removing the mountains compensated to a considerable extent for removing the OST gradients.

The most dramatic changes in the streamfunction

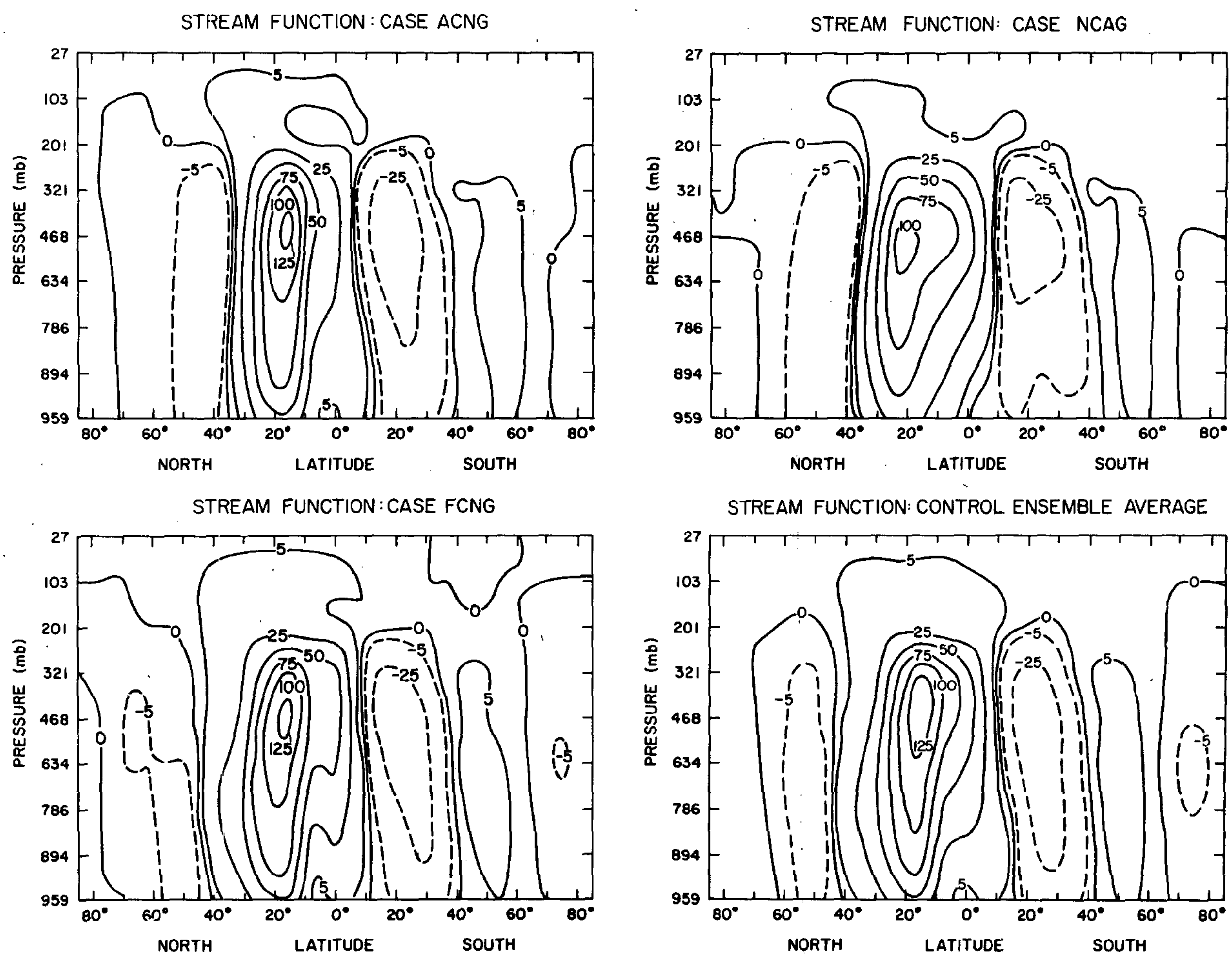

FIG. 6. Zonal-mean mass streamfunctions averaged for January: upper left, case with all continents included but with no OST gradients (Case ACNG); lower left, case with flat continents and no OST gradients (Case FCNG); upper right, case with continents replaced by oceans with zonal average values of OST but with all other OST gradients retained (Case NCAG); lower right, control ensemble average as estimated from five independent simulated Januaries. Units are 10^9 kg s^{-1}. Positive values correspond to counterclockwise circulation and negative values to clockwise circulation in this meridional plane.

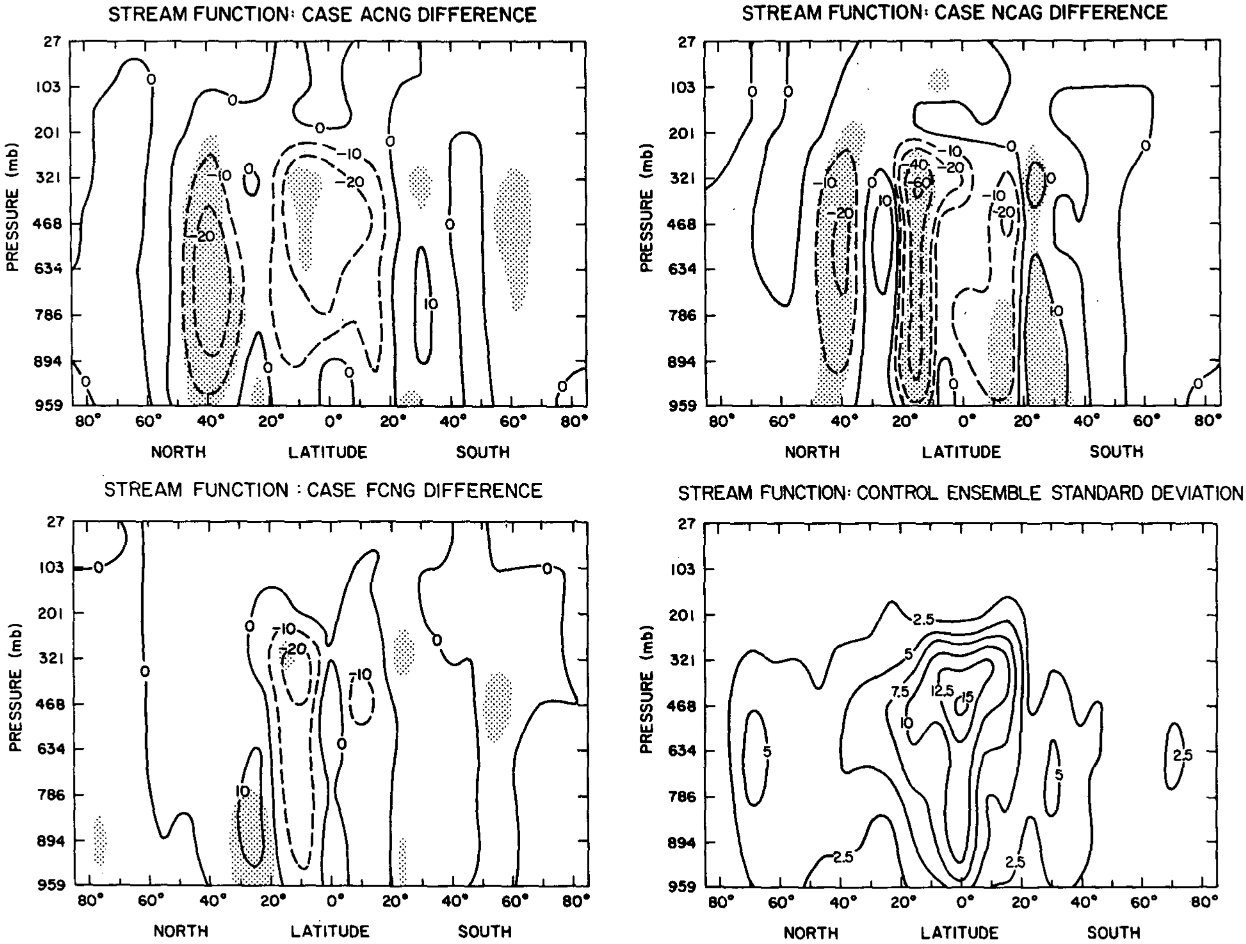

FIG. 7. As in Fig. 6 except for prescribed change responses (i.e., the control ensemble average as estimated from five simulated Januaries is subtracted from the January mean for each experiment) and control ensemble standard deviation. Stippled areas correspond to normalized response $r \geq 3$ and indicate statistically significant differences at the 5% significance level.

were found in Case NCAG. Here the Northern Hemisphere Hadley cell weakens by 27%, and the center of the cell shifts slightly northward. Thus, the ocean–continent contrasts again appear to be the most important element of the asymmetric forcing.

6. Summary and concluding remarks

In this paper we have described experiments with the GISS Model II featuring massive changes in the prescribed boundary conditions. These experiments were designed for studying the forcing mechanisms for the global Walker circulation, i.e., the zonal and vertical circulations in the latitude band 8°N–16°S. In particular, they were designed to determine the relative importance of continentality, topography and OST gradients in driving the circulation.

The changes in the circulation patterns found in the experiments showed that continentality and OST gradients were the major factors in the asymmetric forcing, with the former appearing to be dominant. This result was anticipated by Ramage (1968) and Webster (1972). The result was verified by calculating correlations, showing that the atmospheric forcing correlates with the continentality rather than the OST gradients. A similar result was found for the forcing of the zonal mean Hadley cell, i.e., continentality was the most important asymmetric forcing affecting the Hadley cell. However, the OST gradients do appear to play a relatively more important role in forcing the asymmetric circulation in the south tropical Pacific.

The experiments also showed that both continentality and OST gradients force the model atmosphere by modifying the surface heat balance. Where the atmosphere is heated, rising motions are generated. This causes convergence of moisture and condensation, and the resulting heating of the atmosphere reinforces the rising motion. The efficiency with which the surface heating generates vertical motions appears to depend on the zonal distribution of the forcing. The resulting vertical motions are highly correlated with the precipitation and the surface heating, and the precipitation is correlated more with moisture convergence than with evaporation. The close relationships found between the vertical motion, precipitation and the moisture convergence agree with earlier studies by Webster (1972) and by Cornejo-Garrido and Stone (1977). The correlation between the vertical motions and precipitation is so high that it suggests that one could easily monitor vertical motions in the tropics by monitoring the precipitation.

The results also revealed some interesting features about the forcing by OST gradients. The model's atmospheric response to this forcing is strongly dependent on the continentality. Using models which do not include continentality to study air–sea interactions in the tropics is therefore highly suspect. In addition, the forcing contains a large nonlocal component, i.e., the changes in the local heat balance and forcing of the atmosphere can, to a large extent, depend on nonlocal changes in ocean surface temperatures. Thus, limited area models are likely to be inadequate for studying air–sea interactions in the tropics. Also, the changes in evaporation do not significantly enhance the condensation and forcing of the vertical motions resulting from OST gradients. This last feature contrasts with the forcing by continentality, where the changes in evaporation do enhance the atmospheric forcing.

We caution however that the manner in which OST anomalies force the atmosphere can be model-dependent. All of our experiments were also carried out using the GISS Model I. (See Hansen *et al.*, 1983, for a complete description of the difference between the two models.) The results using the two models were quite similar, except that in Model I, in the case with asymmetric forcing by OST gradients alone (Case NCAG), the zonal evaporation anomalies *were* highly correlated with the zonal OST and surface heating anomalies. The difference was traced to the different methods used for calculating surface winds. These winds directly affect the evaporation because it is calculated with a drag law in both models. In Model I the surface wind was calculated by linearly extrapolating the wind in the two lowest layers to the ground. In Model II the surface wind was calculated by a more sophisticated extrapolation which used boundary layer theory to allow for the unresolved boundary layer structure and its latitudinal variations. We believe the latter parameterization is the better one (see Hansen *et al.*, 1983), but it may not be the best parameterization.

Acknowledgments. We thank Jim Hansen and his colleagues at GISS for their help and cooperation in carrying out the experiments and for making available results from the GISS model. We also thank Mrs. L.-C. Tsang of Sigma Data Service Corp. for processing some of the results, and the NCAR Graphics Group for drafting most of the figures. The work reported here was supported in part by Grant NSG 5113 from the National Aeronautics and Space Administration to the Department of Meteorology and Physical Oceanography at M.I.T.

REFERENCES

Chervin, R. M., and S. H. Schneider, 1976: On determining the statistical significance of climate experiments with general circulation models. *J. Atmos. Sci.*, **33**, 405–412.

——, and L. M. Druyan, 1984: The influence of ocean surface temperature gradient and continentality on the Walker circulation. Part I: Prescribed tropical changes. *Mon. Wea. Rev.*, **112**, 1510–1523.

Cornejo-Garrido, A. G., and P. H. Stone, 1977: On the heat balance of the Walker circulation. *J. Atmos. Sci.*, **34**, 1155–1162.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy and L. Travis, 1983: Efficient three-dimensional global models for climate studies: Models I and II. *Mon. Wea. Rev.*, **111**, 609–662.

Ramage, C. S., 1968: Role of a tropical maritime continent in the atmospheric circulation. *Mon. Wea. Rev.*, **96**, 365–370.

Webster, P. J., 1972: Response of the tropical atmosphere to local, steady forcing. *Mon. Wea. Rev.*, **100**, 518–541.