PHYSICAL BASIS FOR PREDICTION
OF
TROPICAL DROUGHTS

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Physical Basis for Prediction of Tropical Droughts

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1. Introduction

The day to day fluctuations of the atmospheric circulation are comprised of periodic components, viz., seasonal cycle and diurnal variation, and aperiodic components due to the instabilities of the flow and nonlnear interactions among different space and time scales of motion. It is instructive to consider a quasi-stationary component of the flow which is due to external forcing of meridional gradients of radiative heating, and asymmetries of orography and land-sea contrast at the lower boundary of the atmosphere. If such a flow is hydrodynamically unstable, and it is known that it is, atmospheric disturbances will form and amplify, the space scale and growth rate of the disturbances being dependent upon the structure of the prevailing basic flow, the acceleration due to gravity for the planet, the size of the planet, the rotation rate of the planet, and vertical stratification of the basic flow. The unstable disturbances will grow and modify the basic flow by nonlinear interactions as well as by modifying the diabatic heating fields. The problem of weather prediction is essentially an initial value problem and our ability to make a successful weather prediction depends primarily on the correctness of the observed initial conditions and our ability to predict the propagation and growth/decay of atmospheric disturbances caused by dynamical instabilities. The external forcing of radiation and the slowly varying boundary conditions of sea surface temperature (SST), soil moisture, snow and ice, etc., at the earth's surface are not considered to be too important for short range prediction.

On the other hand, the mechanism responsible for the interannual variability of monthly and seasonal means is much more complex. These mechanisms can be broadly divided into the following two categories:

a. Internal dynamics. Even in the absence of any fluctuations of external forcings, dynamical instabilities and nonlinear interactions among different space and time scales will produce low frequency components, and monthly means can also be different simply due to sampling of different 30 days. The combined effects of instabilities, wave-mean and wave-wave interactions, fluctuations of zonal wind and its interaction with orography, heat sources, and interactions among tropical large scale overturnings (Hadley and Walker cells) and extratropical circulations, etc. can be considered as the possible internal dynamical mechanisms responsible for producing interannual variability of monthly and seasonal means.

b. Boundary forcing. As shown schematically in Figure 1, SST, soil moisture, and snow and ice act as slowly varying boundary forcings at the earth's surface. The characteristic time of atmospheric fluctuations is smaller than that of such boundary forcing, and, therefore, they provide a possible mechanisms to procuce interannual variability of monthly and seasonal means. Due to slow time scale, they can be potential predictive tools to be used in conjunction with realistic dynamical models and statistical-dynamical techniques.

In this paper, we suggest that there is a physical basis to predict the monthly means, and possibly even the seasonal means, by using a realistic dynamical model and correct global boundary conditions of SST, soil moisture, sea ice, and snow.

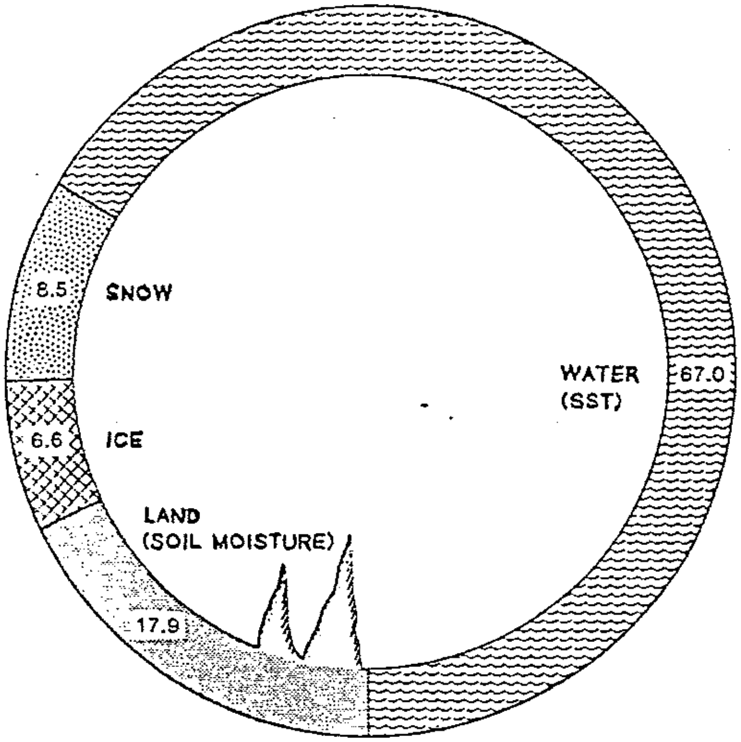

Figure 1. Schematic representation of the atmosphere's lower boundary. Numbers denote the percentage of earth surface area (January).

The tropical atmosphere is potentially more predictable because its planetary scale circulations are dominated by Hadley, Walker, and monsoon circulations which are intrinsically more stable than mid-latitude Rossby regime. Interaction of these large scale overturnings with tropical disturbances (easterly waves, depressions, cyclones, etc.) is not strong enough to make the former unpredictable due to unpredictability of the latter. Tropical disturbances are initiated by barotropic-baroclinic instabilities but their main energy source is latent heat of condensation. Although their growth rate is fast and they are deterministically less predictable, their amplitude equilibration is also quite rapid and they attain only moderate intensity. The intensity and geographical locations of Hadley and Walker cells is primarily determined by the boundary conditions and not by synoptic scale disturbances. It is reasonable to assume that frequency and tracks of depressions and easterly waves is primarily determined by the location and intensity of Hadley and Walker cells, and distribution of SST and soil moisture fields. It is highly unlikely that tropical disturbances will drastically alter the character of large scale tropical circulation. This is in marked contrast to the case of mid-latitudes where interaction between synoptic scale instabilities and planetary scale circulations is sufficiently strong so that baroclinically unstable disturbances can depredictabilize the large scales. Mid-latitude circulation consists of baroclinic waves, long waves, and planetary waves of different wave number and frequency, whereas tropical circulation has a clear scale separation, the large scale Hadley and Walker cells and synoptic scale disturbances. In other words, tropical spectra in space, as well as in time, is redder than the mid-latitudes spectra.

It is known that mid-latitude atmospheric anomalies show a rapid decay of autocorrelation function, whereas tropical atmospheric anomalies persist for several months. Since the atmospheric dynamics by itself is not known to have any mechanism for long term memory, persistence of tropical anomalies can change the location and intensity of Hadley and Walker cells, which can produce persistent anomalies of precipitation. Similarly, anomalies of soil moisture can be very important in determining the intensity of tropical stationary heat sources for which the maxima occur over the continents.

We have presented brief descriptions of the physical mechanism through which the boundary conditions affect the atmospheric circulation. We have also presented a few illustrative examples from GCM sensitivity studies. It should be recognized that the boundary conditions themselves are altered by the atmospheric fluctuations, but once they are generated, they tend to persist, and, therefore, for certain time scales, there is some potential for predictability due to boundary conditions.

2. Role of Slowly Changing Boundary Conditions

2.1 Sea surface temperature

The influence of sea surface temperature anomaly depends upon the space scale and magnitude of the anomaly as well as the geographical location of the anomaly. The dynamical response of the atmosphere depends upon the ability of the anomaly to produce a deep heat source, which is possible mainly by enhanced moisture convergence and deep moist convective activity. A warm anomaly in the areas of large scale convergence (ascending branches of Hadley and Walker cells) will be more effective than a comparable anomaly in the area of divergence. A warm anomaly in the tropics enhances the evaporation by a much larger amount than a similar anomaly in the middle and high latitudes (due to nonlinearity of Clausius-Clapeyron equation). The enhanced moisture flux convergence is the main contributor to the enhanced precipitation over warm SST anomalies. Increased evaporation lowers the lifting condensation level, increases the buoyancy of the moist air, and accelerates the deep convective activity. Due to the smallness of the coriolis parameter in the low latitudes, SST anomaly produces larger convergence compared to the middle and high latitudes. The structure of the prevailing zonal flow is of crucial importance in determining the propagation characteristics of the disturbances produced by the diabatic heat source associated with SST anomaly.

a. Effect of Arabian sea surface temperature anomaly on Indian monsoon rainfall. Figure 2(a) and (b) shows the model simulated rainfall over India (for areas A and B shown in Figure 2(c)) for a control run of the GLAS general circulation model with climatological boundary conditions of SST and another run in which Arabian Sea SST anomaly was warm but had a pattern similar to the one used by Shukla (1975) and Washington et al. (1977). It shows that warm SST anomaly over Arabian Sea enhances monsoon rainfall which is in agreement with the earlier results by Shukla (1975) using GFDL model and results of observational study by Shukla and Misra (1977). An apparent disagreement between the results of Washington et al. (1977) using the NCAR model and the results of Shukla using GFDL and GLAS models can be explained by examining the low level monsoon flow as simulated by the three models (Figure 2(d)). The low level monsoon flow simulation by GFDL and GLAS model (whose results of SST sensitivity are similar) is more realistic compared to the NCAR model.

This example illustrates the importance of realistic dynamical models to detect the effects of changes in the boundary conditions and their possible use for prediction of time averages.

b. Effect of tropical Atlantic SST anomaly on drought over northeast Brazil. Moura and Shukla (1981) have shown that simultaneous occurrence of a warm SST anomaly in north tropical Atlantic, and cold SST anomaly in south tropical Atlantic produces droughts over northeast Brazil. Presence of a warm SST anomaly at about 10-15°N makes the ITCZ persist rather than move to south, and thermally direct circulation with ascending branch over warm SST anomaly enhances rainfall over ocean and suppresses rainfall over northeast Brazil giving rise to severe droughts. The drought over northeast is not a regional phenomena but only a local manifestation of a large scale phenomena.

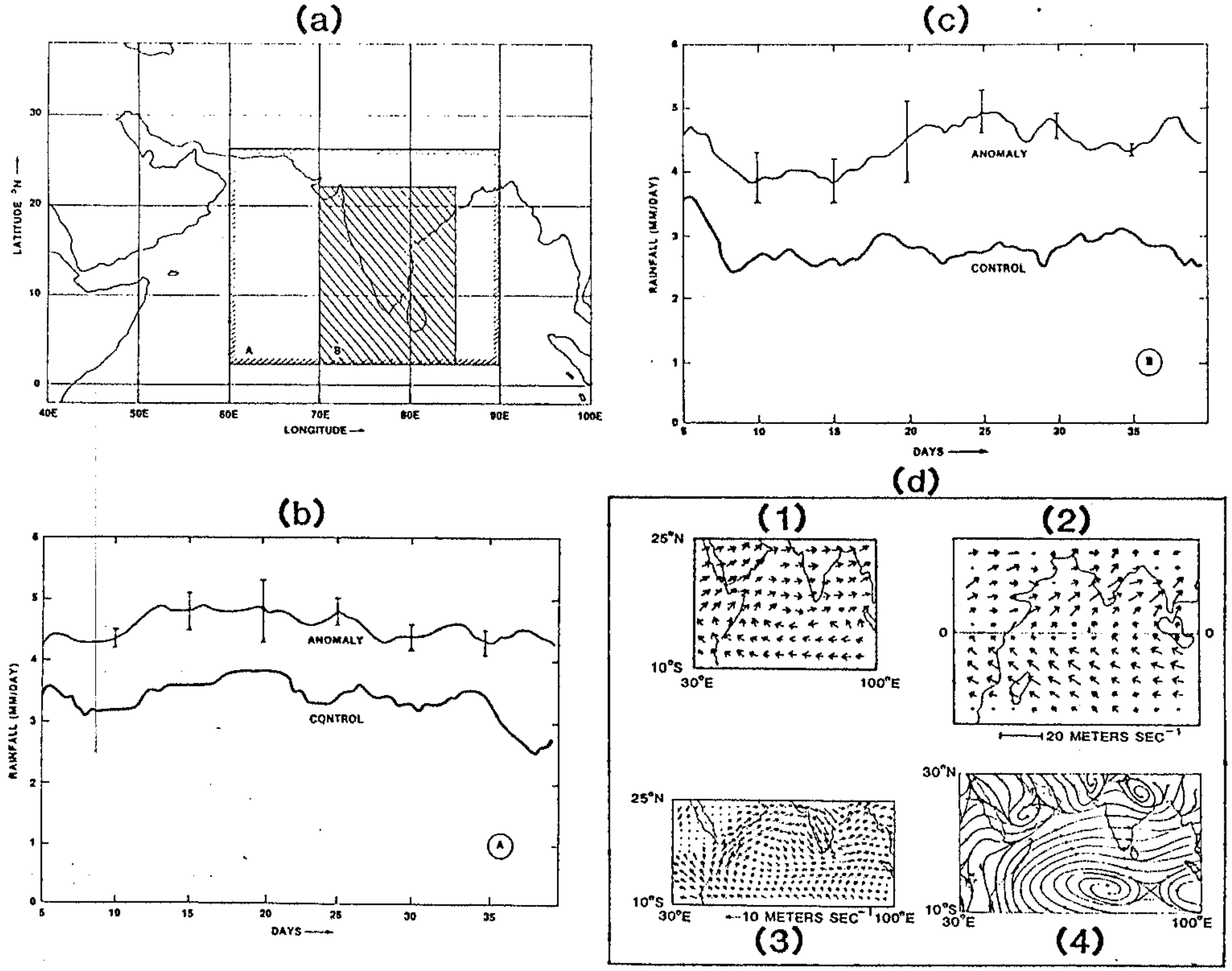

Figure 2. Panels (b) and (c) show the daily values of rainfall for control and anomaly runs averaged over areas A and B shown in panel (a). Length of the error bars represent standard deviation among three anomaly runs. Panel (d) shows the low level wind field for: (1) GLAS model, (2) GFDL model, (3) NCAR model, and (4) Observations.

Figure 3(a) from Moura and Shukla (1981) shows the monthly mean SST anomaly during March at 15°N, 45°W along absissa, and at 5°S, 25°W along ordinate and the numbers denote the average of rainfall departure (mm) for Fortaleza (4°S, 39°W) and Quixeramobin (5°S,.39°W), averaged for the months of March, April, and May. It is seen that during the 25 year period (1948-1972) examined in this study, the most severe droughts occurred when north tropical Atlantic had the warmest SST anomalies and south tropical Atlàntic had the coldest SST anomalies. Figure 3(b) shows the difference between two model generated meridional circulations for the Atlantic sector, one with the climatological SST and the other with the prescribed warm SST anomaly over north Atlantic and cold SST anomaly over south Atlantic. It is seen that the ascending branch of the anomalous Hadley circulation is over the warm SST anomaly and the descending branch is over the latitudes of northeast Brazil. There is also some evidence of teleconnections between tropical and extra-tropical circulations.

c. Effects of equatorial Pacific SST anomaly on atmospheric circulation. Horel and Wallace (1981) and Rasmusson and Carpenter (1981) have presented observational evidences of remarkable relationships between sea surface temperature anomalies in tropical Pacific and variety of atmospheric fluctuations including the southern oscillation and Northern Hemispheric mid-latitude circulations. Warm episodes of equatorial Pacific SST anomalies are associated with the negative phase of the southern oscillation, weakening of easterlies in equatorial central Pacific, enhanced precipitation at equatorial stations east of 160°E, intensified Hadley cell in the Pacific sector, and a deepending and southward displacement of the Aleutian low (Horel and Wallace, 1981).

We (M. Wallace and author) have conducted sensitivity experiments with the GLAS climate model to study the response of SST anomalies shown in Figure 4(a), which is a composite of observed SST anomalies for November, December, and January of 1957-58, 1965-66, 1969-70, and 1972-73 provided to us by Dr. Rasmusson. Figure 4(b) shows the 30 day mean differences between the Hadley cell for the anomaly run and the control run (anomaly-control). It is noticed that the zonally averaged Hadley cell intensifies due to warm SST anomalies over equatorial Pacific. The Hadley cell over the Pacific sector alone is intensified even more. Figure 4(c) shows the difference (anomaly-control) for the model simulated Walker circulations averaged between 6°N and 6°S. Anomalous ascending motion occurs between the longitude sector 170°E-150°W and descending motion between the longitudes 140°E-165°E. This is consistent with the observational evidence of enhanced precipitation east of 160°E being related to warm SST anomalies.

2.2 Soil moisture and albedo

Globally and annually averaged run-off (266 mm) from the continents is only about 35% of annual mean precipitation (764 mm) over the continents (Baumgartner and Reichel, 1975) and, therefore, annual evaporation from the global land surfaces is about 60-70% of the rainfall over the global land surfaces. For certain regions and seasons, the mean evaporation from the land is greater than precipitation because water stored in root zone is evaporated by solar energy. This would suggest that the evaporation from the land must be one of the important components of the global hydrological cycle. The amount of soil moisture influences the hydrological cycle and atmospheric circulation in two ways. Firstly, it influences the rate of evaporation and therefore determines the available moisture for convection and precipitation. Secondly, it determines the partition of incoming net radiative energy into sensible heat and latent heat components. If land surface is wet, most of the energy (net short wave and long wave radiation) is utilized for evaporating water, whereas if land surface is dry, most of the energy goes into sensible heating of the atmosphere. This, in turn, can produce low pressure areas and large scale convergence. The effects of persistent anomalies of soil moisture will therefore also depend upon the geographical location with respect to oceans, the prevailing motion field, and the nature of boundary layer and convection in the area.

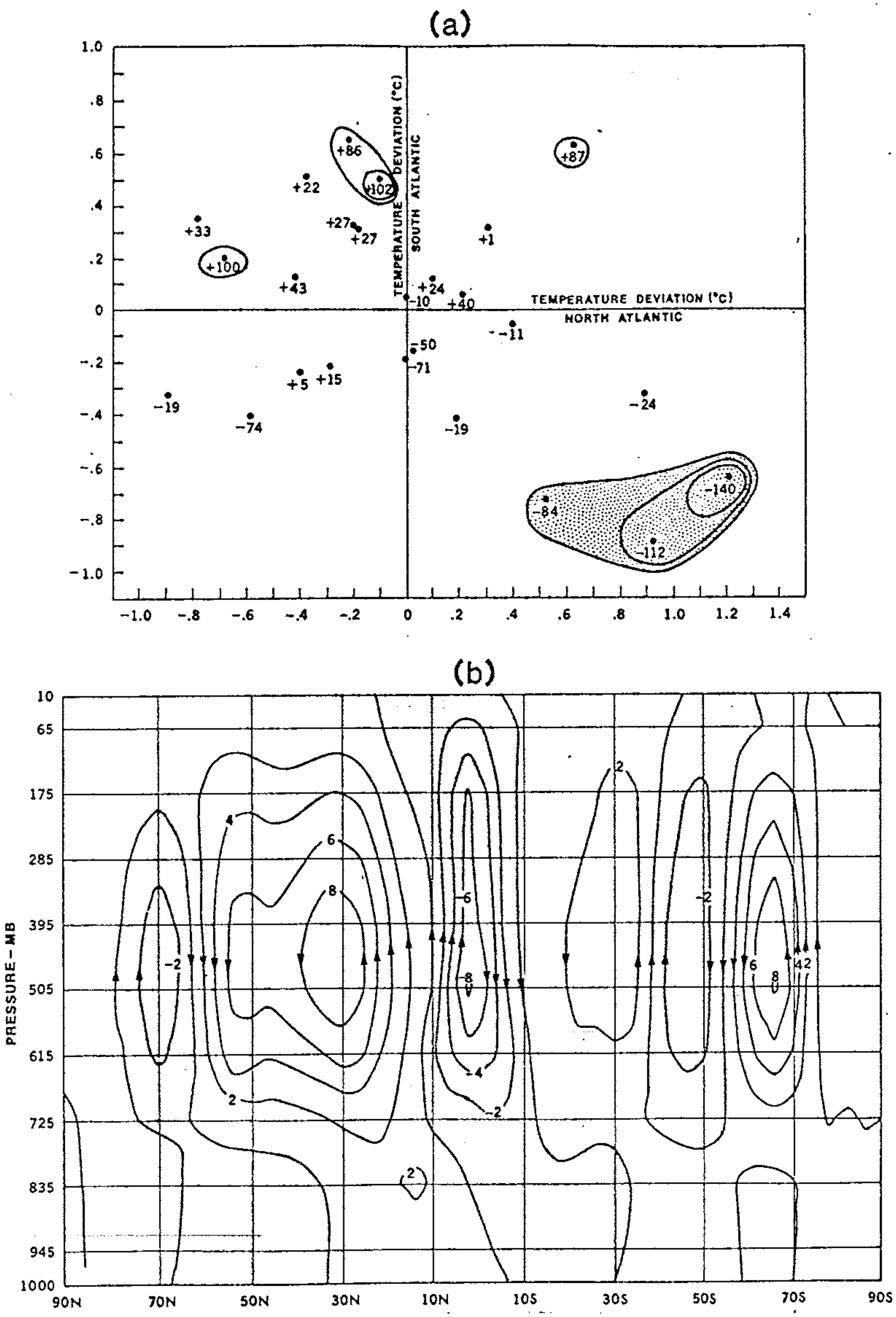

Figure 3. Panel (a): SST anomaly during March at 15°N, 45°W along absissa and at 5°S, 25°W alng ordinate. The numbers denote the rainfall departure (mm) for Fortaleza (4°S, 39°W) and Quixeramobin (5°S, 39°W) averaged for March, April, and May. Panel (b): difference (anomaly-control) beween the meridional circulations averaged for Atlantic sector.

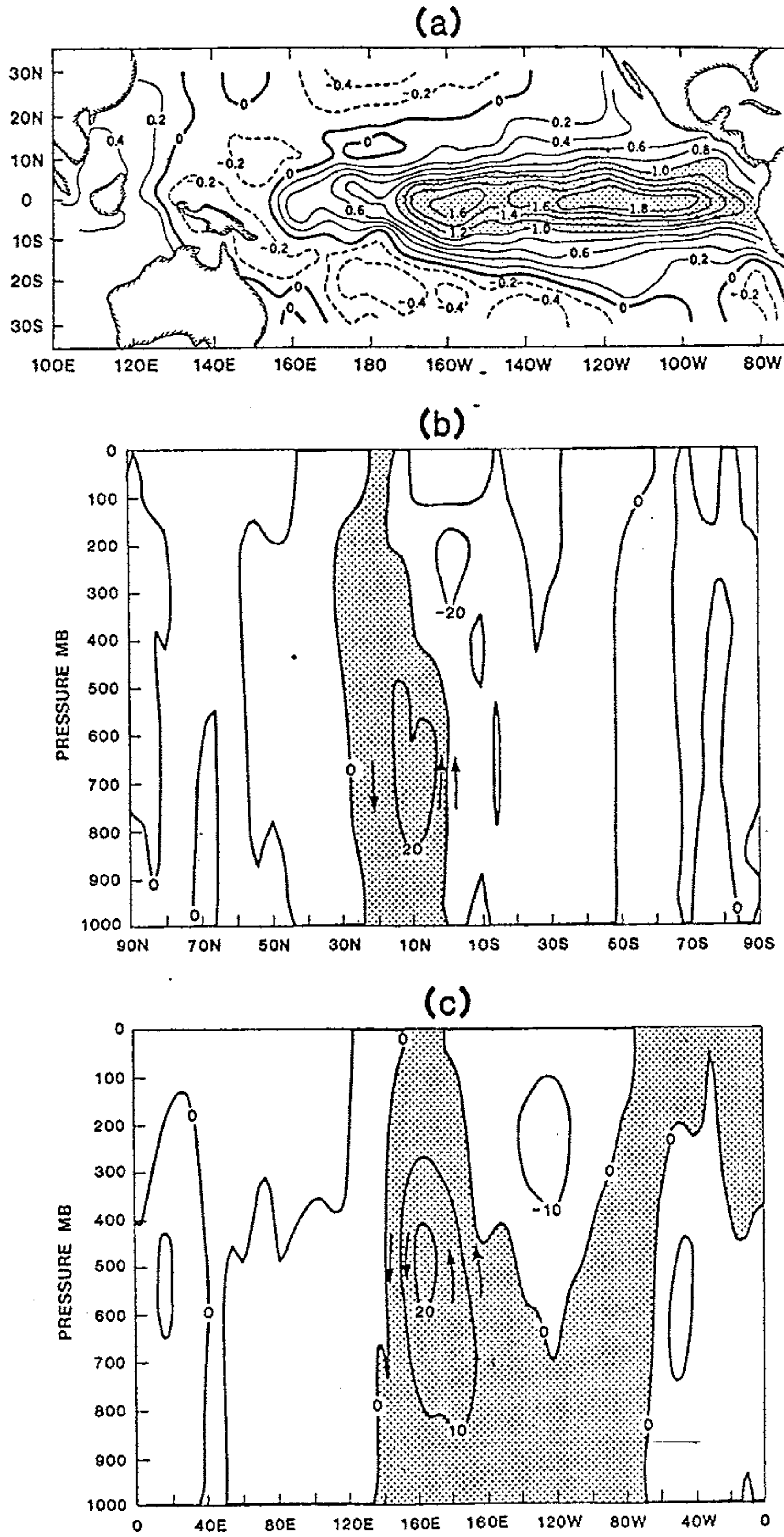

Figure 4. Panel (a) shows the SST anomaly used. Difference between anomaly and control runs for Hadley cell (Panel (b)) and Walker cell averaged between 6°N-6°S (Panel (c)), in units of 10^9 kg/sec.

Shukla and Mintz (1981) have conducted two numerical experiments with the GLAS climate model: A) no evaporation from the land surfaces, and, B) potential evapotranspiration from the land surfaces. Ocean SST is identical in both numerical experiments. Figure 5((a),(b), and (c)) shows the difference map (A-B) for ground temperature, sea level pressure, and rainfall, respectively. In the dry ground case, the land surface is hotter by 20-30°C, the sea level pressure over land is lower by 15-20 mb, and the oceanic high pressure centers are stronger. The resulting flow field is very different, and the rainfall over most of the land surfaces reduces by 40-50% with a remarkable exception of three monsoonal areas. For example, over the Indian monsoon region, the absence of evaporation from the land is more than compensated by the enhanced moisture flux convergence from the surrounding oceans, which is due to a more intense monsoon low over India. We are not aware of any observational evidence for such overcompensation, although the frequency of pre-monsoon thunderstorm activity is considered to be an indicator of monsoon rainfall.

This idealized experiment suggests that persistent anomalies of soil moisture can be one of the important determinants of monthly and seasonal atmospheric anomalies. More observational and numerical studies are needed to understand the role of these physical processes quantitatively. These results also suggest that the effects of large scale modifications of land surfaces (viz. deforestation, aforestation, large scale irrigation, etc.) strongly depend upon the geographical location of the area and the prevailing dynamical circulation of the atmosphere.

Schickendanz (1976) has studied the effects of large scale irrigation on the summer rainfall in the central United States. He found that the large scale irrigation increased the total summer rainfall by 19-35%.

Charney et al. (1977) have shown that changes in the albedo over the subtropical desert margin areas can produce significant reduction in rainfall. Since albedo can be changed by overgrazing or other agricultural practices, they proposed the hypothesis of a biogeophysical feedback leading to occurrence and maintenance of droughts. Increase in albedo reduces the incoming solar radiation, and therefore, reduces the evaporation, cloudiness, and rainfall. Increase in the incoming solar radiation due to reduced cloudiness is more than compensated by decrease in the long wave radiation coming at the surface from the cloud base. Thus the net radiative energy coming at the earth's surface is reduced due to increase in albedo. Due to decrease in the surface heating, evaporation, and moist convection, there is decrease in the convergence and ascending motion which causes decrease in precipitation. This feedback can perpetuate drought in desert margin regions if generation of moist static energy is not larger than its removal by advective processes. This effect is not very important over monsoon areas of large scale convergence and ascent because dynamical transports and convergence of moist static energy are more important than anomalies of surface fluxes. Results of Charney et al. (1977) have been recently confirmed by Sud and Fennessy (1981), using a more realistic treatment of ground hydrology in the GLAS climate model. It is further shown that increase in albedo also decreases rainfall over northeast Brazil.

2.3 Snow cover

Persistent anomaly of snow cover can affect the meridional temperature gradient (baroclinicity) and, therefore, vertical shear of the extra-tropical large scale flow. Changes in the sensible heat flux and radiative heating (due to increased albedo of snow) coupled with changes in the structure of the large scale flow can produce changes in the location, frequency, and amplitude of middle latitude disturbances. We do now know whether these changes are significantly different from the mid-latitude natural variability. The effects of snow cover on tropical and monsoon circulation are largely determined by planetary scale forcing of snow anomalies. For example, a large and deep snow cover over Eurasia during winter can keep the soil wet for longer time in spring and summer. This will delay and reduce the heating of the land masses (because

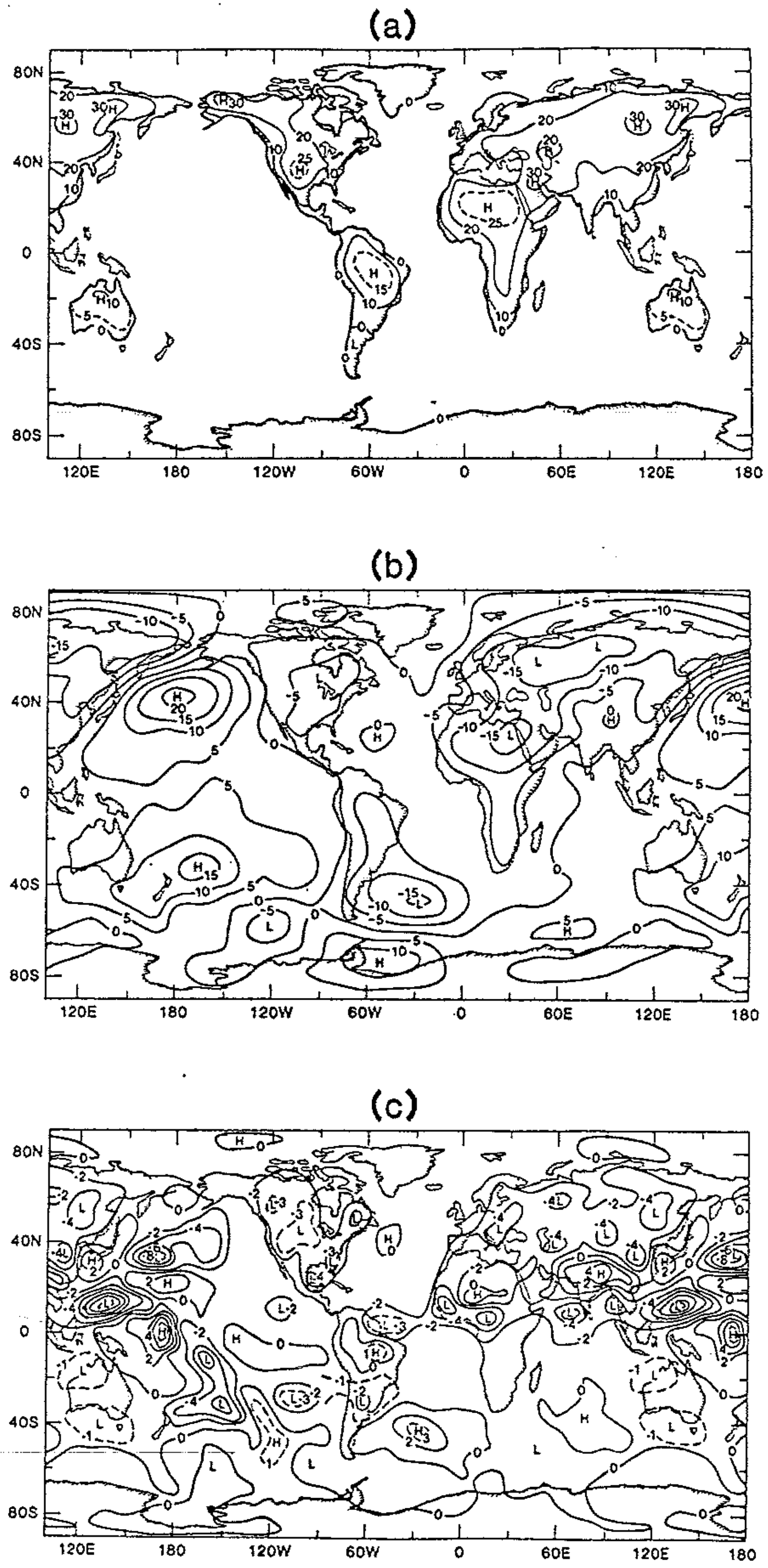

Figure 5. Difference (no evaporation-potential evaporation) between two model simulations for (a) ground temperature, (b) sea level pressure, and (c) rainfall.

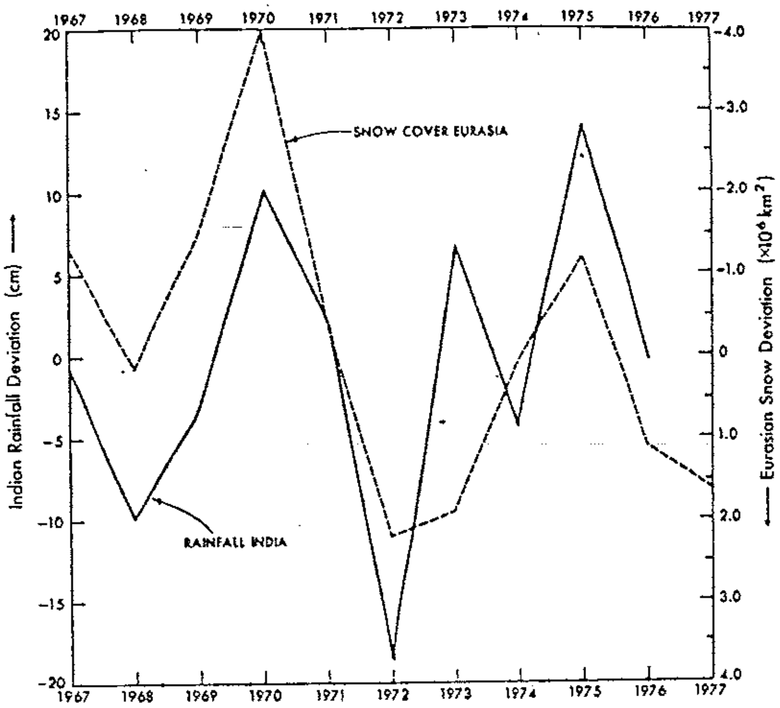

Figure 6. Time series of area weighted average of percentage departure from normal rainfall over Indian subdivisions (solid line) and winter snow cover departure over Eurasia south of 52°N snow cover (dashed line).

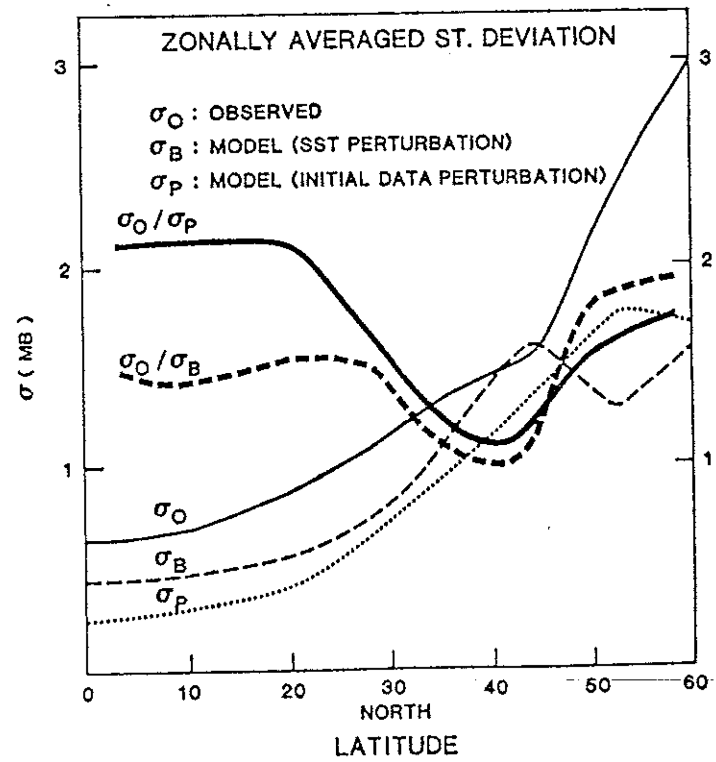

Figure 7. Zonally averaged standard deviation among monthly mean (July) sea level pressure (mb) for 10 years of observations (σ_O, thin solid line) four model runs with variable boundary conditions (σ_B, thin thin dashed line) and four model runs with identical boundary conditions (σ_p, thin dotted line). Thick solid line and thick dashed line show the ratio σ_O / σ_p and σ_O / σ_B respectively.

most of the radiative energy will be consumed for evaporation rather than sensible heating), which in turn can either delay the onset of the Asiatic monsoon or reduce its intensity. Following suggestions by Walker (1910), Hahn and Shukla (1976) found an apparent relationship between Eurasian snow cover and Indian monsoon rainfall, (Figure 6). Large and persistent winter snow cover anomalies over Eurasia can produce colder mid-latitude troposphere in the following spring, which can strengthen the upper level anticyclone and slow its northward movement over India, giving rise to delayed and weaker monsoon rainfall.

No systematic numerical experiments have yet been carried out with realistic global general circulation models to determine the sensitivity of snow cover; however, some studies by Yeh and et al. (1981) have suggested that snow anomalies may be one of the important determinants of interannual atmospheric variations over China.

3. Predictability of Monthly and Seasonal Means for Tropics

Charney and Shukla (1981) have suggested that since large scale monsoon circulation is stable with respect to dynamic instabilities, and since boundary conditions exert significant influence on the time averaged monsoon flow, monsoon circulation is potentially more predictable than the middle latitude circulation. This suggestion was made by examining the variability among the monthly mean (July) circulation of four model runs for which the boundary conditions were kept identical, but the initial conditions were randomly perturbed. It was found that although the observed and the model variabilities were comparable for middle and high latitudes, the variability among the four model runs for the monsoon region was far less than the observed interannual variability of the atmosphere. This led to the suggestion that part of the remaining variability could be due to the boundary conditions.

We have extended the work of Charney and Shukla (1981) and compared the model variability for climatological and observed SST anomalies. We have carried out 45 day integrations of the GLAS climate model for seven different initial and boundary conditions. In four of these integrations, climatological global SST was used. In the remaining three, the observed SST for 1973, 1974 and 1975 was used between 0-30°N. Figure 7 shows the plots of zonally averaged values of standard deviations σ_p, σ_B and σ_o, and ratios σ_o/σ_p and σ_o/σ_B as a function of latitude. σ_p is the model standard deviation among predictability integrations (climatological SST and random perturbation in initial conditions), σ_B is the model standard deviation for SST anomalies, and σ_o is the standard deviation for 10 years of observations. It is seen that, in agreement with the results of Charney and Shukla, the ratio σ_o/σ_p is more than two in the tropics and close to one in the middle latitudes. The new result of this study is that σ_B (variability due to changes in SST boundary conditions) lies nearly halfway between σ_o and σ_p. This suggests that nearly half of the remaining variability is accounted for by changes in sea surface temperature between 0-30°N. These conclusions are further supported by a more comprehensive study by Manabe and Hahn (1981). As discussed in the earlier sections, the anomalies of soil moisture, albedo and snow, etc. can, likewise, also contribute towards explaining the interannual variability of the tropical atmosphere.

It should also be recognized that tropical-extra-tropical interactions also contribute to tropical variability, and if mid-latitude circulation is unpredictable at longer time scales, its effects upon the tropical circulation will also be unpredictable.

4. Summary and Conclusions

We have examined the physical and dynamical mechanisms responsible for the interannual variability of the tropical circulation. It is suggested that a major component of the tropical interannual variability, as evidenced by anomalous rain and drought regimes, is forced by slowly varying boundary conditions of sea surface temperature, soil moisture and northern hemispheric snow cover.

Changes in the boundary conditions affect the intensity and location of large scale Hadley and Walker circulations in the low latitudes, and the amplitudes and phases of quasi-stationary waves in the middle latitudes, which in turn can change the frequency, intensity, and propagation properites of synoptic scale disturbances (storm tracks).

We present the results of observational and numerical studies carried out with a realistic global general circulation model of the atmosphere to determine the sensitivity of the tropical circulation to changes in the boundary conditions of sea surface temperature and soil moisture. We have also examined the relative contributions of the internal dynamics and external forcings towards predictability of tropical droughts and other anomalous circulations.

We have briefly reviewed the physical mechanisms through which boundary conditions can influence the initiation and maintenance of tropical droughts. The internal dynamical interactions between the synoptic scale tropical disturbances and the large scale Hadley and Walker circulations are found to be influenced by anomalies in the boundary conditions of sea surface temperature and soil moisture. Tropical disturbances themselves, being condensation driven instabilities, seem to be less predictable; however, potential for predictability of monthly and seasonal anomalies appears to be relatively high. Part of the tropical variability can be related to the interactions with the extratropical circulation regimes and they cannot be any more predictable than the extratropical circulations themselves. On the other hand, some tropical anomalies are found to affect the middle latitude circulation and therefore they can contribute to middle latitude predictability.

We have briefly summarized the results of specific studies on the dynamical aspects of droughts in northeast Brazil, fluctuations of the Asiatic monsoon, effects of equatorial Pacific SST anomalies, and influence of soil moisture on atmospheric circulation. Results of these studies, which are presented as a set of illustrations, support the hypothesis that boundary conditions play an important role in determining the tropical variability. Most of the tropical droughts are manifestations of either the weakening of the Hadley and Walker cells or their displacements from mean climatological position. Anomalies of SST, soil moisture, and snow can produce such displacements and changes in the intensity.

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