VARIABILITY OF THE TROPICAL CIRCULATION

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Abstract

The interannual variability of the seasonal mean tropical circulation and rainfall can be described, to a large extent, as changes in the location and intensity of the thermally driven Hadley and Walker circulations. Although the physical mechanisms responsible for the locations and intensities of the climatological mean rainfall maxima (representing the ascending branches of Hadley and Walker cells) are not well understood, there is a large body of observational and model experimental evidence which suggests that the interannual fluctuations of these thermally driven circulations are closely related to changes in boundary conditions (viz. sea surface temperature and soil moisture) at the earth's surface. We review several examples of correlations based on observations and controlled numerical sensitivity experiments with global general circulation models (GCM) that support the hypothesis that changes in the lower boundary conditions are one of the most significant factors responsible for the interannual variability of the tropical atmosphere. We further show that a significant fraction of the local interannual variability over different parts of the tropics is in fact a regional manifestation of the planetary scale El Niño-Southern Oscillation-Monsoon phenomena which is considered to be due to interactions among the atmosphere, the oceans and the land processes. Some of the largest anomalies in circulation and rainfall, comprising a major portion of the interannual variability, are strongly phase-locked with the seasonal cycle, and, the major tropical droughts and floods are either due to modulation of the annual cycle or shifts in the locations, or timing of maximum amplitude.

It is conjectured that the tropical variability related to the slowly changing boundary conditions, and the associated low frequency planetary

scale circulations, is potentially predictable at a range beyond the limits of deterministic predictability. This also provides a potential for extended range prediction in the extra-tropics due to the possible influence of tropical forcing on the extra-tropical circulation.

1. INTRODUCTION

The mechanisms responsible for the interannual variability of the monthly and seasonal mean atmospheric circulation can be understood, conceptually, as arising from internal dynamical processes and the influence of slowly varying boundary conditions at the earth's surface (Shukla, 1981a). Figure 1 gives a schematic description of the conceptual framework adopted to aid in understanding the mechanisms of interannual variability. Our main emphasis will be on the influence of the boundary conditions. A large number of observational and modeling studies have shown significant associations between the atmospheric circulation and boundary conditions, i.e., sea surface temperature (SST), soil moisture, snow cover and sea ice. Anomalies of SST and soil mositure are particularly important for the tropical variability. It has also been found empiricially that large persistent snow cover anomalies over Eurasia are correlated with fluctuations of monsoon rainfall over India. The actual physical processes through which anomalies in surface boundary conditions influence the atmospheric circulation are different for different boundary conditions. In general, however, changes in the boundary conditions produce local changes in heating, evaporation and moisture convergence, which in turn produce larger and deeper heat sources. The size, shape and location of the anomaly, together with the structure of the large scale flow, primarily determine whether a local heat source (boundary layer heating) can be transformed into a larger and deeper heat source, and whether such local effects can propagate away from the source and produce remote effects.

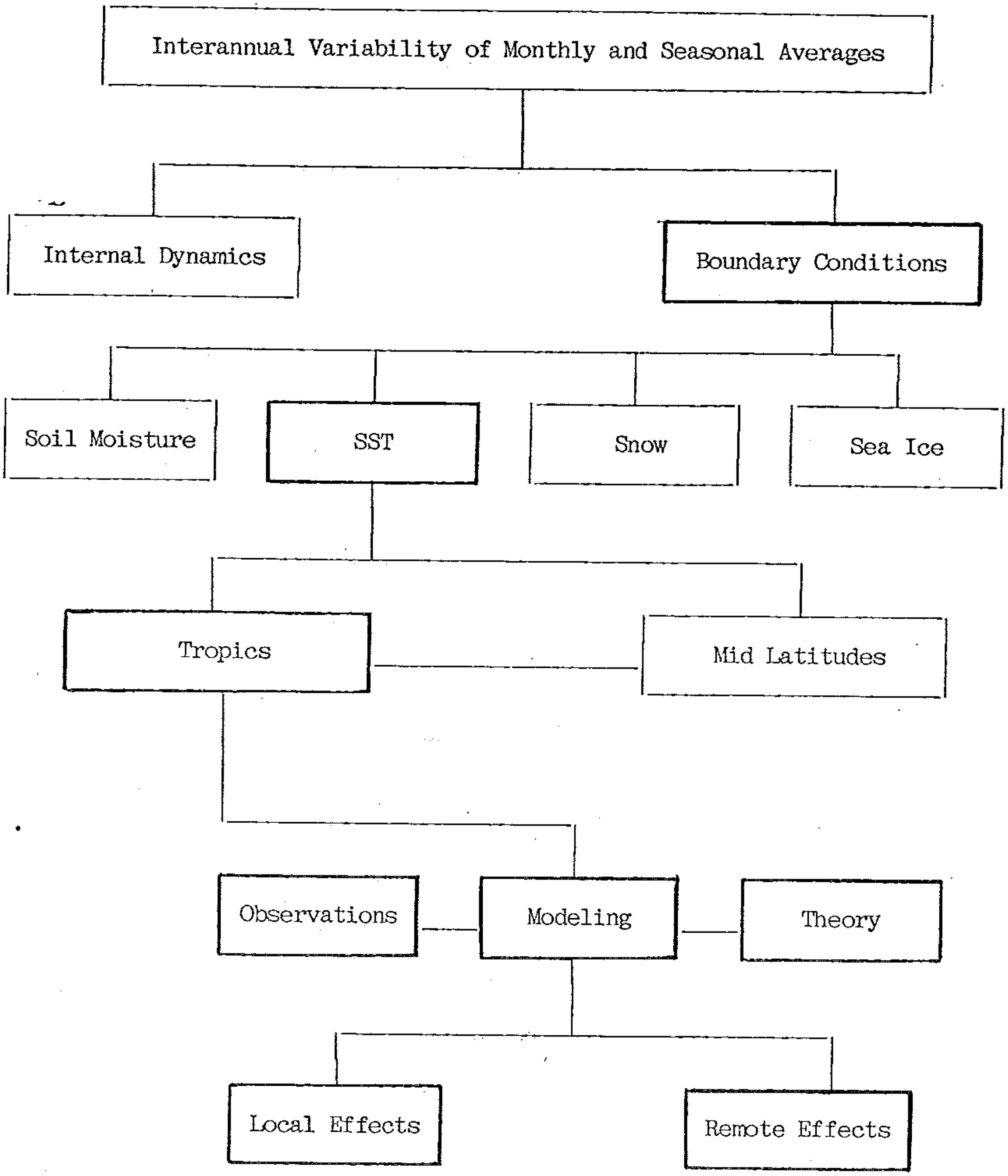

Figure 1: Schematic representation of mechanisms for interannual variability of monthly and seasonal averages. Heavy lines denote the scope of TOGA.

It has been hypothesized that internal dynamical processes are dominant in the extra-tropics while in the tropics the boundary conditions are the dominant influence (Shukla, 1981b, 1982). The planetary scale tropical circulations consist, in large part, of Hadley, Walker and monsoon overturnings associated with large scale heat sources over the equatorial land massess of Africa and South America, and over the maritime continent of Indonesia, the eastern Indian Ocean and the western Pacific. We will refer to this heat source over the eastern Indian Ocean as the monsoon heat source. The heat sources have a well defined north-south seasonal migration; following the sun over the land and overlying the warm sea surface temperature over the eastern Indian Ocean and western Pacific.

The interannual variability of the location and intensity of the monsoon heat source is related to SST changes in the tropical Pacific. SST anomalies, especially over warm waters, produce shifts in areas of moisture convergence and latent heat of condensation, thus changing the location and intensity of ascending branches of Hadley and Walker cells. Similarly, it also seems likely, though not well established, that changes in the land-surface properties (viz., soil moisture) associated with changes in evapotranspiration and convergence of water vapor, also change the location and intensity of the African and South American heat sources. Of the three heat sources described above, the annual cycle and the interannual variability of the monsoon heat source has been studied in greatest detail, both observationally and through the use of numerical models of the atmosphere.

We shall confine our discussion to the role of tropical SST anomalies in the interannual variability of the atmosphere, particularly the fluctuations of the monsoon heat source. The results of a numerical experiment to examine the sensitivity of the atmospheric circulation and rainfall to the SST anomalies observed during winter of 1982-83 are reviewed in section 2. In section 3, we show that a significant fraction of the local anomalies over the tropics can be related to the planetary scale El Nino-Southern Oscillation-Monsoon phenomena. The basic premises of TOGA and the potential for extended range prediction using realistic models of the coupled atmosphere-ocean-land system are reviewed in section 4.

2. INFLUENCE OF TROPICAL PACIFIC SST ANOMALIES ON ATMOSPHERIC CIRCULATION

Numerous observational and modeling studies suggest that tropical SST anomalies in the equatorial Pacific strongly influence atmospheric circulation and rainfall. Using the seasonal mean data during the period 1951-78, Horel and Wallace (1981) showed that correlation coefficients between an SST anomaly index over equatorial Pacific and rainfall over Tarawa, Canton, Christmas and Fanning Islands were 0.78, 0.82, 0.64 and 0.79 respectively. Correlation coefficients between an index of tropical sea level pressure (Tahiti minus Darwin), and 200 mb geopotential height anomaly over selected tropical stations was found to be -0.83 and 0.80 respectively. Considering the large intrinsic variability of the atmosphere, these correlations are quite high indeed. Rasmusson and Carpenter (1983) have shown that the area averaged summer monsoon rainfall over India was below the median value in 21 out of 25 El-Nino events. Shukla and Paolino (1983) have shown that for 12 out of 14 cases of deficient rainfall over India, the Darwin pressure anomaly was increasing, while for 9 out of 12 cases of excess rainfall over India, the anomaly was decreasing from the northern spring to summer seasons.

In a numerical experiment with the GLAS climate model, Shukla and Wallace (1983), using the El-Nino composite SST anomalies, showed that the model correctly simulated the eastward displacement of the climatological rainfall maximum over Indonesia, giving rise to a dipole pattern of simulated rainfall anomaly. The signature of the Southern Oscillation (lower pressure over the eastern Pacific and higher pressure over the Indian Ocean) was also correctly simulated, as was the low level wind flow. A general warming of the tropical atmosphere, as observed during the El-Nino events was also produced. There was also a recognizable signature of the so called PNA pattern.

There is considerable agreement between these model results and those of Blackmon et al. (1983) who used a NCAR spectral model to study the sensitivity of equatorial Pacific SST anomalies. At the 16th Liege Colloquium on Hydrodynamics, the following groups examined the sensitivty of different models to the 1982-83 El-Nino SST anomalies.

1. M. Blackmon: National Center for Atmospheric Research
2. G. Boer: Canadian Climate Center
3. V. Cubash: European Center
4. S. Esbensen: Oregon State University
5. M. Fennessy, L. Marx, J. Shukla: University of Maryland
6. A. Oort, N. C. Lau: Geophysical Fluid Dynamics Laboratory
7. T. N. Palmer, D. Mansfield: British Meteorological Office
8. R. Sadourny, R. Michand: Laboratories de Meteorologie Dynamique
9. M. Suarez: Goddard Laboratory for Atmospheres

All the model simulations showed an eastward shift of the rainfall maximum as was inferred from the observed outgoing long wave radiation data. The location and intensity of the simulated rainfall anomaly was different for different models, presumably due to different parameterizations of boundary layer and moist convection. The details of the simulated midlatitude response, which depends on the location and intensity of the anomalous heat source as well as the structure of the large-scale flow, were also different for different models. As an illustration we have summarized below the results of Fennessy et al. (1985).

The GLAS Climate Model (Shukla et al., 1981c) was integrated for 75 days starting from the observed initial conditions of 16 December 1982 and the climatological annually varying SST over the globe. This 'control' run integration was repeated using the observed SST anomalies over the tropical Pacific Ocean. Figure 2a shows the observed SST anomaly field during January 1983. These anomalies were added to the climatological SST values shown in Figure 2b, giving rise to the SST pattern shown in Figure 2c. The integration using this SST field will be referred to as the 'anomaly' run. Figure 3 shows the 11-60 day precipitation difference (anomaly run minus control run) averaged for simulations with three different initial conditions, and Figure 4 shows the observed outgoing longwave radiation anomaly for December, January and February 1983 converted to the units of rainfall anomaly using an empirical relation developed by Arkin (1983). The simulated rainfall anomaly patterns are rather remarkable. The enhanced precipitation observed over the equatorial region along 140°W, and reduced precipitation over Indonesia and northern Australia is correctly simulated by the model. The magnitude, location and spatial structure of the model-simulated rainfall anomaly over the Pacific resembles the "observations" quite well. The enhanced rainfall over the northern Amazon and reduced rainfall over the southern Amazon is also simulated reasonably well. The simulated low level wind field and sea level pressure (not shown) were in good agreement with the observations. The simulated large scale circulation anomalies over the Northern Hemisphere mid-latitudes did not show good agreement with the observations. The question of extra-tropical influences from tropical SST anomalies requires further investigation.

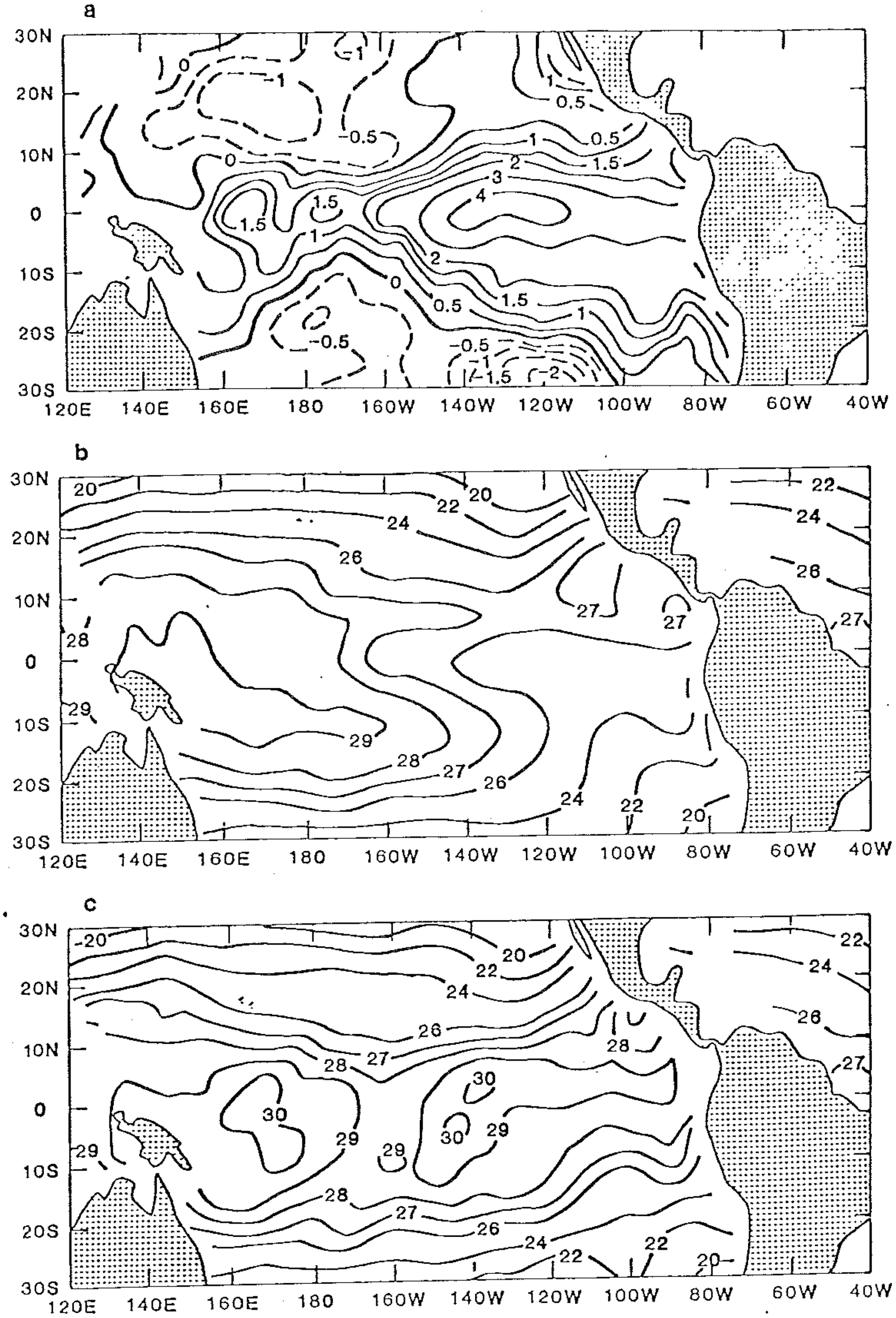

Figure 2: January 1983 sea surface temperature fields. a) SST anomaly, b) climatological SST for control simulation and c) observed SST for anomaly simulation. (SST obtained from Dr. R. Reynolds, Climate Analysis Center) Units are °C. Dashed contours are negative.

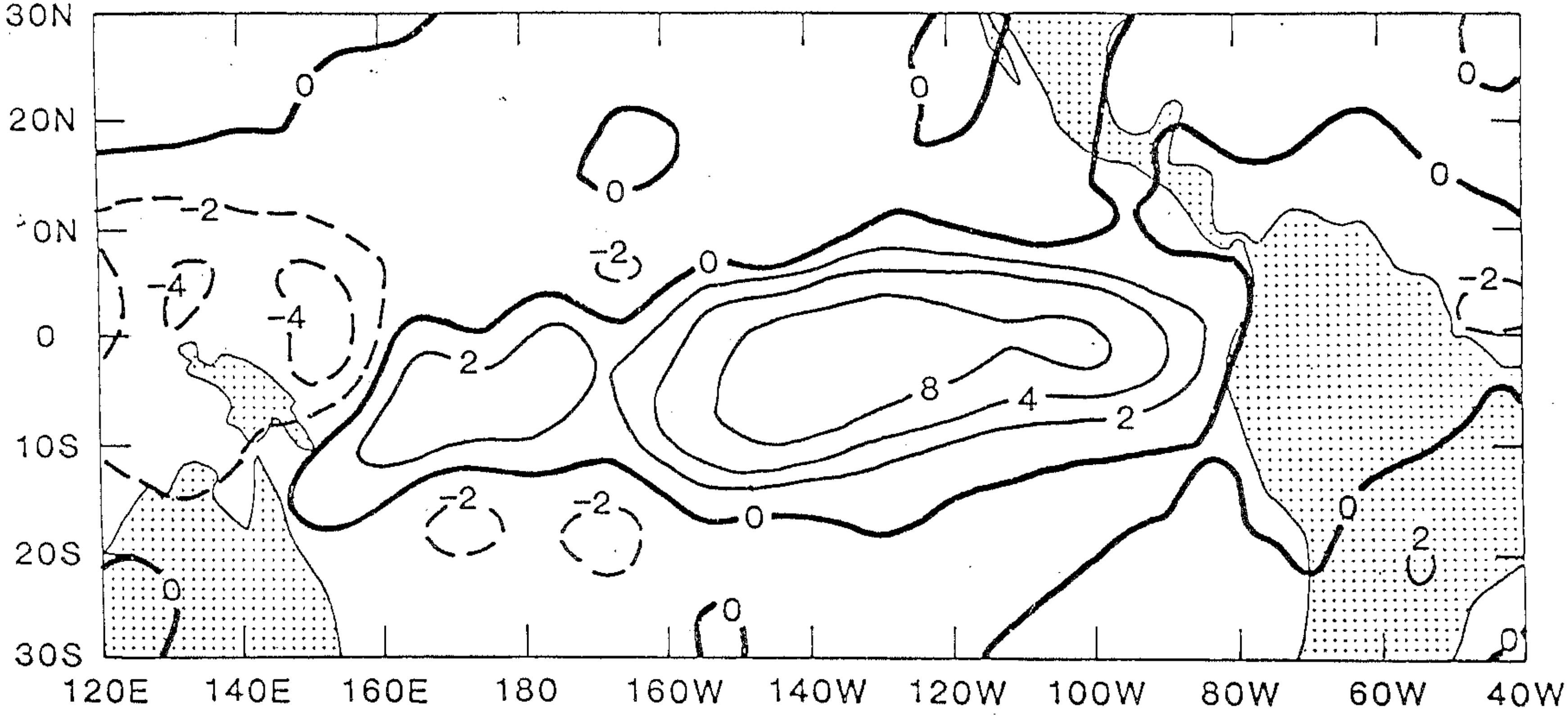

Figure 3: Model simulated precipitation difference (anomaly-control) averaged for days 11-60 for three different simulations.

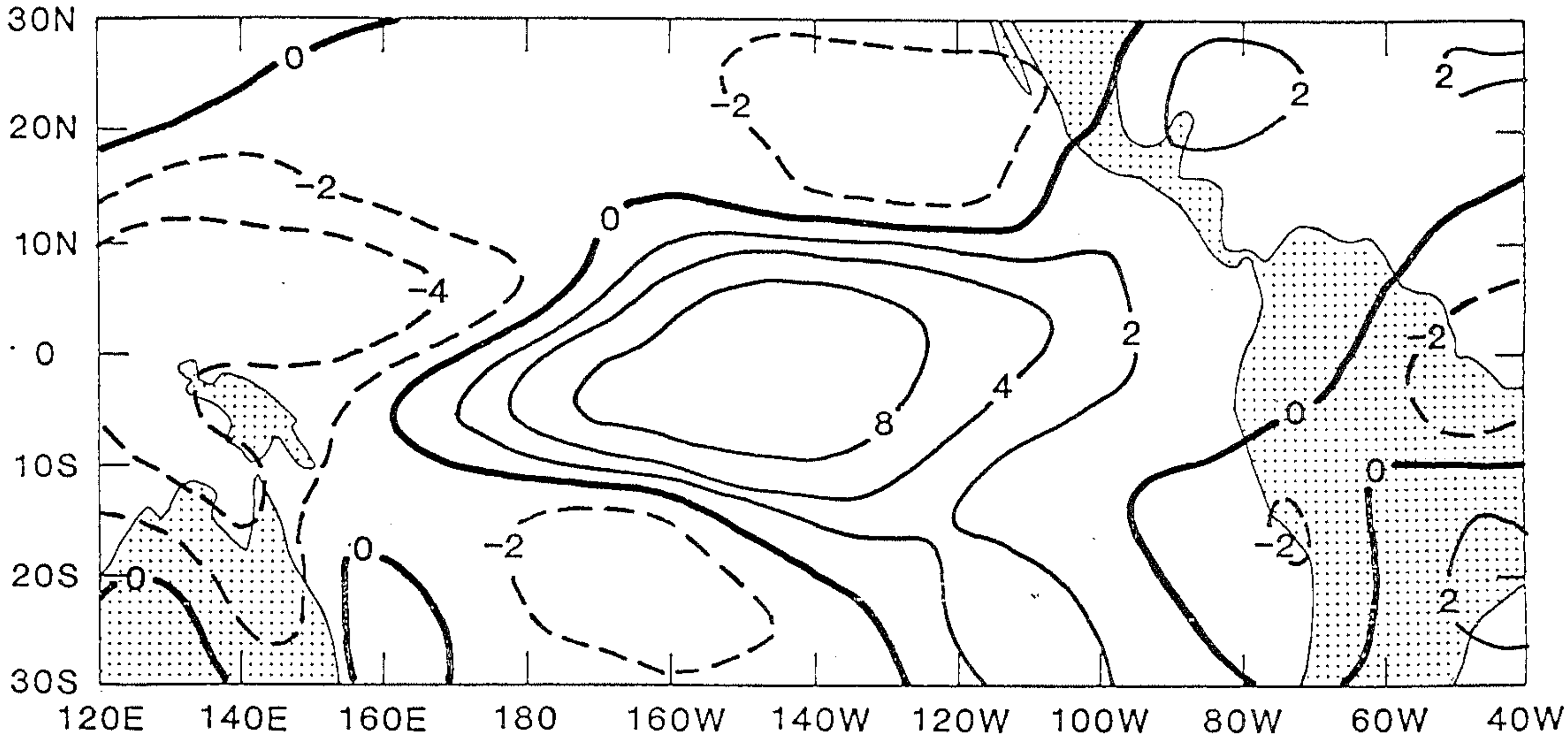

Figure 4: 'Observed' precipitation anomaly for December, January, February 1983 inferred from the observed outgoing long wave radiation anomaly.

3. GLOBAL MANIFESTATIONS OF EL-NIÑO/SOUTHERN OSCILLATION-MONSOON

A significant fraction of the local interannual variability over different parts of the tropics is in fact a regional manifestation of the planetary scale El Niño/Southern Oscillation (ENSO)-Monsoon phenomena. The typical pattern of global anomalies associated with ENSO episodes is shown schematically in Figure 5. All such episodes evolve in a broadly similar manner over a period of 18-24 months (Rasmusson, 1985). The anomalies are strongly phase-locked with the annual cycle; thus the local anomaly appears at a particular time of the year. Examples of ENSO anomaly patterns at three widely separated locations are shown in Figure 6. In these particular regions there is a tendency for below normal rainfall during the rainy season. However, different patterns could also be cited e.g. drought during the relatively dry winter season in southern Indonesia, and heavy rainfall during the rainy season in northwest Peru.

The pattern of tropical rainfall anomalies associated with ENSO episodes can be described largely in terms of large-scale shifts in the major rainfall regimes of the tropics. These in turn can be associated with modulations and/or phase shifts of the annual cycle.

4. PROSPECTS FOR EXTENDED RANGE PREDICTABILITY OF COUPLED TROPICAL OCEAN-GLOBAL ATMOSPHERE (TOGA) SYSTEM

The basic premises that have lead to the launching of the TOGA program can be stated as follows:

a) Tropical SST anomalies influence the atmospheric circulation significantly and deterministically.

b) These influences can be calculated with realistic atmospheric GCMs if the SST anomalies can be specified.

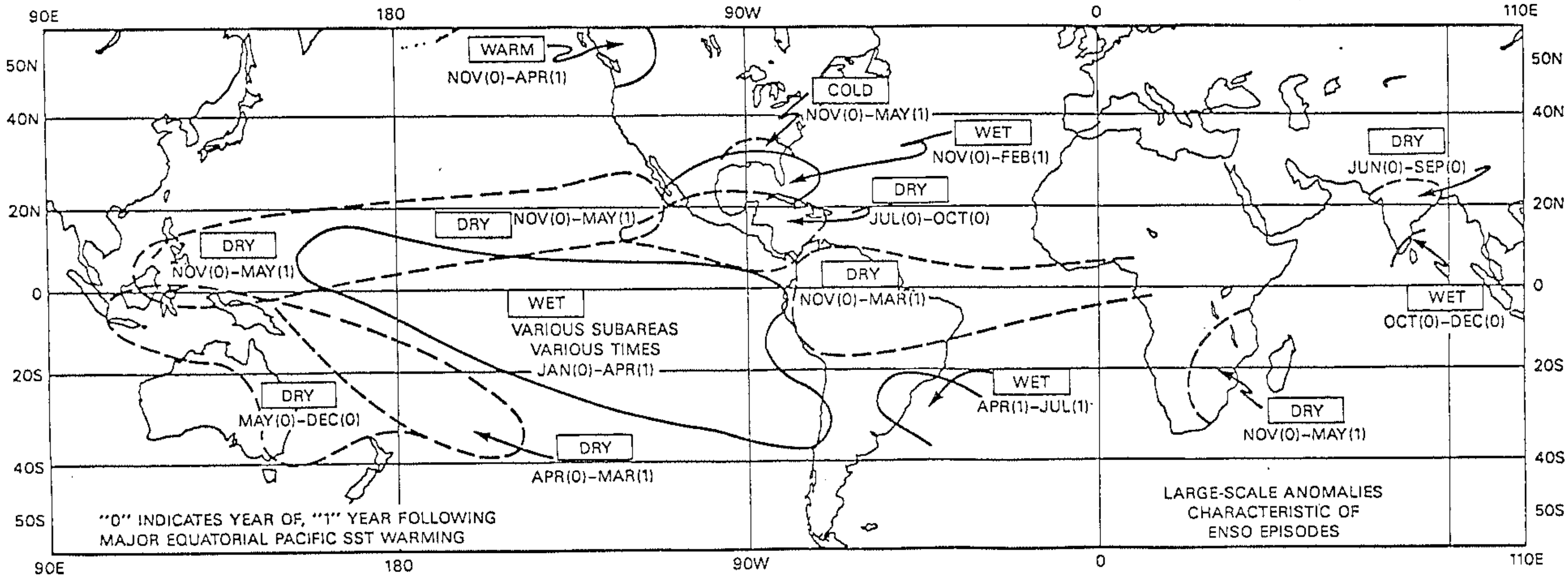

Figure 5: Typical anomaly pattern during an El Nino/Southern Oscillation (ENSO) episode. (0) indicates the year of the major warming along the Ecuador-Peru Coast; (1) indicates the following year.

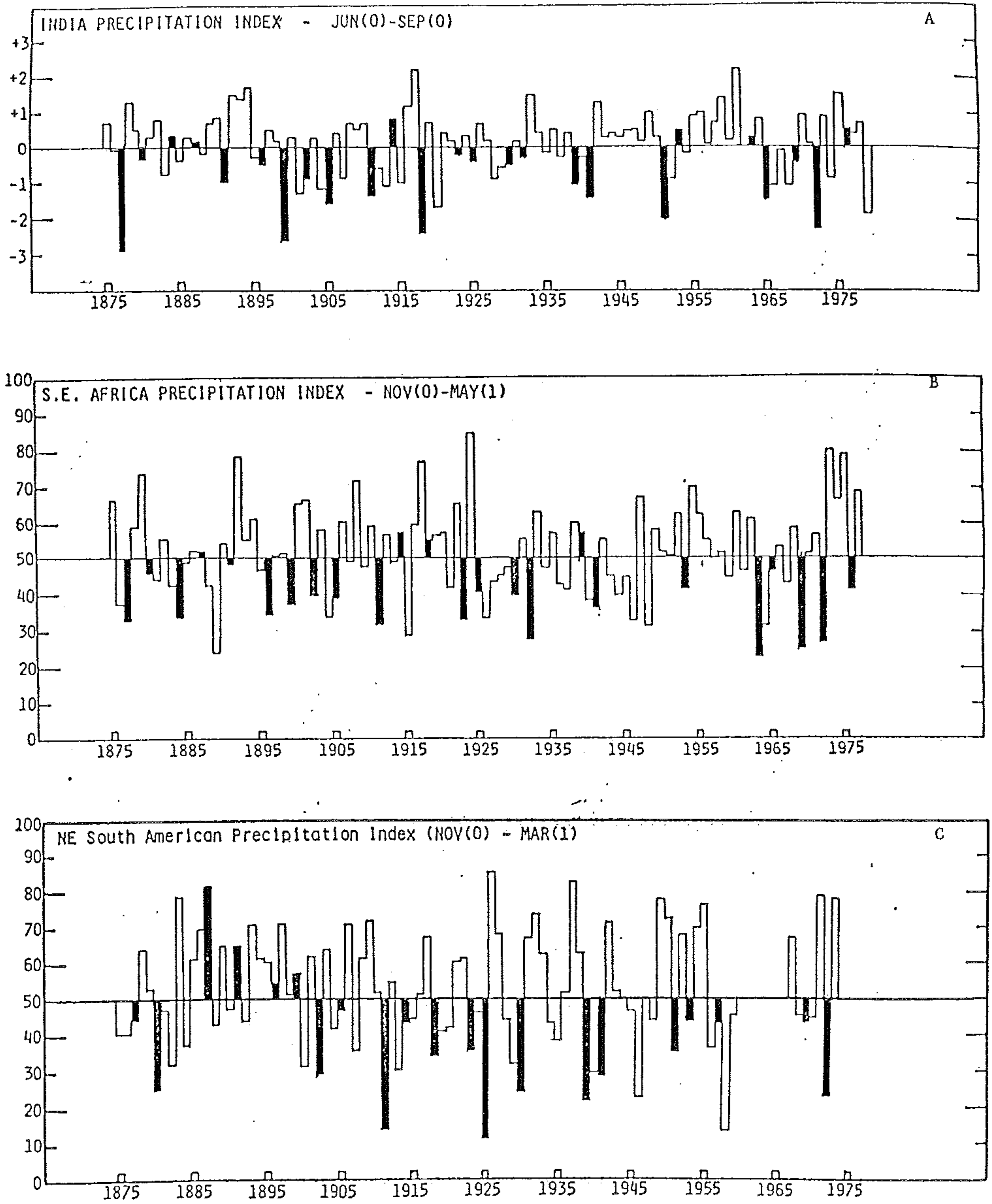

Figure 6: Regional ENSO rainfall anomalies for specified times of the ENSO episode.

A. India (weighted average of 31 subdivisions).
B. S.E. Africa (average of 18 stations).
C. N.E. South America (3 stations from Suriname and Guayana).

c) Tropical ocean SST anomalies are largely determined by surface wind-stress and heat flux.

d) SST anomalies can be calculated with a realistic tropical ocean GCM if the surface wind-stress and heat flux can be specified.

e) Predictability of the coupled tropical ocean-global atmosphere system may be greater than that of the atmosphere alone, since the anomalous tropical wind field is largely determined by the anomalous heating field which in turn is determined by the SST anomalies.

If these premises are true, there is reason to be optimistic about the extended range predictability of the coupled ocean-atmosphere system using realistic dynamical models. However, the premises themselves are based on our interpretation of a large number of observational and modeling studies. Thus we must be cognizant of the quality and interpretation of the results and continue to examine the validity of these premises.

One of the most important issues concerning the predictability of the tropical atmosphere is the validity of the hypothesis, according to which: unlike the mid-latitudes, the synoptic scale instabilities in the tropics are weak and do not interact strongly with, and therefore do not influence significantly, the planetary scale circulations in the tropics (Charney and Shukla; 1977, 1981). The large scale heat sources influence the planetary scale Hadley, Walker and monsoon circulations, and location, frequency and intensity of synoptic scale disturbances is determined by the structure of the planetary scale flow. The obvious key question is, what determines the variability of the large scale heat sources? Observational and modeling studies (Moura and Shukla, 1981; Horel and Wallace, 1981) have shown that tropical SST anomalies strongly influence the location and intensity of the large scale heat sources.

There are several related questions which need to be examined and understood. For example, it is important to know whether the transformation of a surface boundary forcing into a deep heat source is accomplished mainly by the boundary layer processes or by the dynamics of the transient disturbances. Similarly, what is the relative importance of wind-stress induced dynamics and surface heat fluxes in generating SST anomalies in ocean GCMs.

Implicit in the optimistic scenario for the success of TOGA is the assumption that the integration of numerical models of the coupled ocean-atmosphere system will not be severely degraded by the instabilities of the coupled system. If the coupled system (as modeled) is intrinsically unstable, the range of useful predictability will depend on the relative strengths of the deterministic components arising from boundary forcings and uncertainties due to the instability of the coupled system. A systematic study of the predictability of the coupled system using realistic models should clarify this issue during the next several years. What is already known, and reasonably established, is that SST anomalies, once formed, usually persist for a few months. Therefore even if the coupled system were highly unpredictable, the enhanced predictability of the atmosphere due to SST anomalies can be realised to some extent either by assuming persistence of the SST anomaly, or by making making empirical predictions of the SST anomaly.

Finally it should be recognized that TOGA does not address all the aspects of the predictability of the atmosphere, but only those components which are influenced by the tropical oceans. It is now well established that land surface processes also play important role in the variability of the model simulated atmosphere. Therefore a more comprehensive attack on the problem of prediction requires that land surface processes also be considered.

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