AIR-SEA-LAND INTERACTIONS: GLOBAL AND REGIONAL HABITABILITY

J. SHUKLA

Center for Ocean-Land-Atmosphere Interactions, Department of Meteorology, University of Maryland, College Park, MD 20742, U.S.A.

Abstract. We first suggest that the air-sea interactions and the air-land interactions are the most important mechanisms for the *changes* in the atmosphere-ocean-biosphere system at the time-scales of 10^{-1} 10^{2} years. Due to very wide range of space and time-scales at which these interactions operate, and because of their nonlinearities, considerable interannual fluctuations can be produced even without any external (or anthropogenic) forcing. We present some examples of the observed changes in the atmosphere, ocean and land surface properties and describe the abilities and limitations of our current models to simulate these changes.

We propose a method for calculating the 'natural variability' of the atmosphere-ocean-biosphere system and suggest possible techniques for detecting the changes caused by external anthropogenic factors. It is obvious that we are going to be limited in our ability to detect the changes due to external or anthropogenic factors unless we clearly understand the structure and the magnitude of the natural variability of the atmosphere-ocean-biosphere system.

We further suggest that much before we are faced with the problems of global habitability, there will be severe problems of regional habitability. This occurs either due to regional nature of the forcing functions or amplified regional response of a global forcing function.

1. Introduction

The basic driving force for the atmospheric and oceanic motions is the uneven solar heating of the Earth-atmosphere system due to spherical geometry of the Earth's surface and the revolution of the Earth around the Sun. The actual rates of heating or cooling vary with height, depth, latitude, longitude and time and day of the year. The magnitudes of heating are also determined by the chemical composition and three-dimensional distribution of gases and fluids in the Earth-atmosphere system. Asymmetries in heating produce horizontal and vertical gradients of temperature and pressure. The magnitudes of these gradients are also determined by the acceleration due to gravity and Earth's rotation rate. The heating at the Earth's surface and cooling aloft produces vertical overturnings of mass, momentum and water vapor.

The heating of the warmer equatorial regions and the cooling of the colder polar regions generates the kinetic energy for the motion of air parcels in the atmosphere and fluid parcels in the ocean. The land and ocean distribution on the Earth's surface provides additional forcing functions for the atmospheric and oceanic motions, in part due to longitudinal asymmetry in heating due to different thermal properties of land and ocean, and in part due to mechanical effects of the presence of mountain barriers. The radiation energy falling over the oceans and the land surfaces evaporates the water which later condenses and releases latent heat of condensation in the atmosphere which provides a very important energy source for the atmospheric motions.

The three-dimensional structure of the latent heat source is determined by the

Origins of Life **15** (1985) 353-363. 0046-5763/85.15.

motion field itself, producing one of the most complex non-linearities of the atmospheric dynamics. The mean circulation produced by the above described latitudinally and longitudinally varying forcing functions can be considered, hypothetically, as the seasonal mean climate of the Earth-atmosphere system. This seasonal mean climate, however, is characterized by horizontal and vertical gradients of wind, temperature and moisture, which are favorable for the growth of thermodynamical and hydrodynamical instabilities. The day-to-day weather fluctuations are the manifestations of the growth, decay and propagation of such unstable disturbances which can derive their energy from the mean circulation and thereby change the mean circulation itself. The observed quasi-equilibrium mean circulation, to be referred to as the mean climate, is produced by interactions among the stationary and quasi-stationary forcing functions, and transient disturbances.

Since the changes in the weather occur due to instabilities of the atmospheric state, and since the atmospheric dynamics are intrinsically nonlinear, the atmospheric behavior becomes aperiodic and, therefore, at long ranges, unpredictable. This inherent aperiodicity of the weather at all time-scales also produces aperiodicity of monthly, seasonal and annual averages. Therefore, even if there were no changes in the external forcings, it is reasonable to expect that seasonal and annual averages would be different from one year to another. The solar energy input for a given season remains nearly the same from one year to the other, although there may be small changes due to interannual variability of seasonal mean cloudiness. The land-ocean configuration and the height of the mountains remains constant, although there may be large changes in the circulation because the wind impinging on the mountains may be quite different. Nonlinear interactions among the internal dynamical processes themselves can also produce interannual variability. Another plausible reason for the interannual variability of seasonal mean climate appears to be the interannual variability of seasonal mean sea surface temperature (SST), soil moisture, sea ice and snow, etc. Traditionally, the former is referred to as the internal variability or the 'natural' variability and the latter as the variability due to external forcing, or, boundary forced variability.

An attempt to understand the basic physical mechanisms that 'maintain' the observed mean climate of the ocean-atmosphere-land system has been one of the important goals of the geophysical fluid dynamicists during the past century (Lorenz, 1967). In the present article we shall only concentrate on the mechanisms for '*changes*' in the ocean-atmosphere-land system at monthly, seasonal, annual and decadal time-scales. It should be noted that although Sun is the only major 'external' forcing for the ocean-atmosphere-land system, for changes at monthly, seasonal and annual time-scales, forcing functions at the Earth's surface (viz. slowly changing anomalies of sea surface temperatures, soil moisture, vegetation, albedo, sea ice, snow cover, etc.) can be considered external to the atmosphere.

This distinction looses its meaning when we consider variability at annual and decadal time scales because then the variability due to interactions among the different components (i.e. ocean, atmosphere and land) should be considered as the natural variability of the coupled system. An understanding of the natural variability of the coupled atmosphere-ocean-land system is one of the most important aspects of global and regional habitability.

Based on large number of observational and numerical studies of climate system carried out during the past 50 years, it is reasonable to present the following summary:

(a) The most significant fluctuations in the atmosphere-ocean-land system, as observed during the past 50–100 years, are due to interactions among these three components and there is no reason to assume that they are not due to the natural variability of the coupled system. Possible changes due to external factors (viz solar activity, volcanism, anthropogenic causes, etc.) are much smaller than the natural variability of the coupled system at annual and decadal time scales.

(b) The time-scales of biogeochemical cycles are much larger than the time-scales of interactions between the physical processes at atmosphere-ocean-land interfaces, and therefore, the latter can be studied without a deterministic evolution of the former.

(c) Unless we have a better understanding of the magnitude and structure of the natural variability of the coupled atmosphere-ocean-land system, we can neither detect nor understand the changes due to external or anthropogenic factors, unless, of course, they are comparable to or larger than the natural variability.

(d) Global observations for 10–20 year period are needed to define the structure and space-time variability of the atmosphere-ocean-land system. There is also need for improved coupled models of the whole system so that controlled numerical experiments can be carried out to understand the relative significance of different components of the system.

2. An Example of Observed Variability

Figure 1 shows a time series of monthly mean sea level pressure at Darwin for 80 year period (Shukla and Paolino, 1983). The time series has been smoothed by making a 12 month running mean. The departure of observed monthly mean from the climatological monthly mean has been divided by the standard deviation of the monthly mean to normalize the series. Therefore the annual cycle, which is the most dominant variability of the atmosphere, has been removed from the data, and it shows only the interannual variability of monthly mean sea level pressure. It should be noted that Darwin pressure is taken as a measure of the intensity of a planetary scale nonseasonal fluctuation known as the Southern Oscillation shown in Figure 2. It can be seen that the intervals between the successive major maxima and minima range between 5–10 years. This planetary scale pressure fluctuation is known to be due to complex interactions between the atmospheric and oceanic processes. This figure also shows (vertical bars) normalized summer monsoon rainfall over India. For the monsoon seasons followed by decreasing and increasing sea level pressure from winter

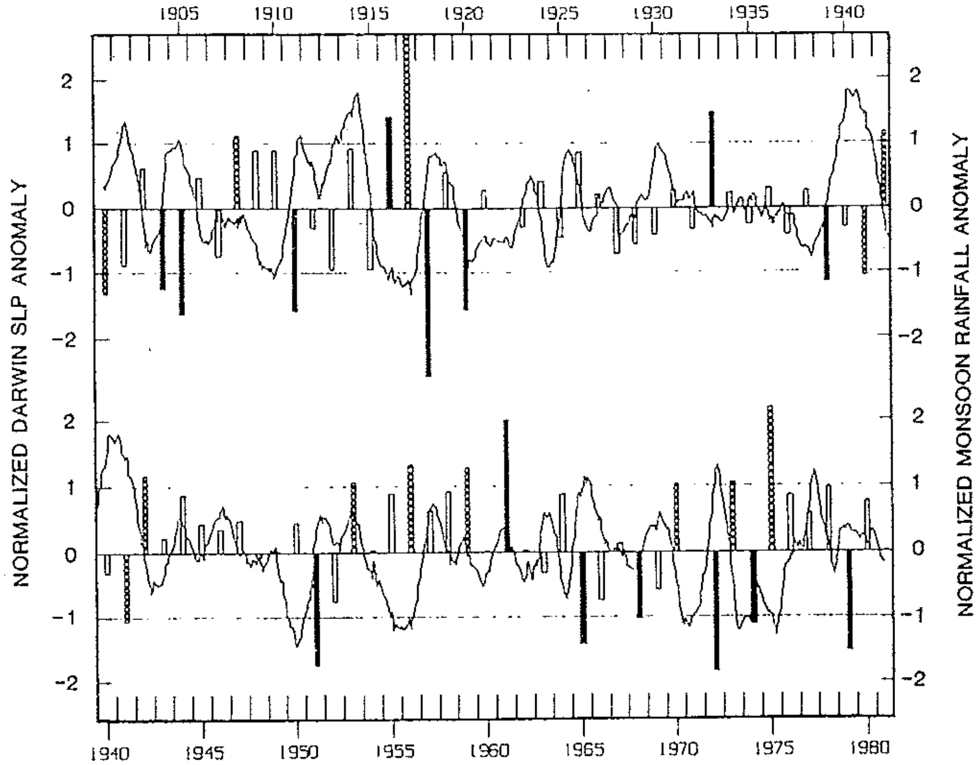


Fig. 1. Twelve month running mean of normalized Darwin pressure anomaly (thin line) and normalized Indian monsoon rainfall anomaly (bars).

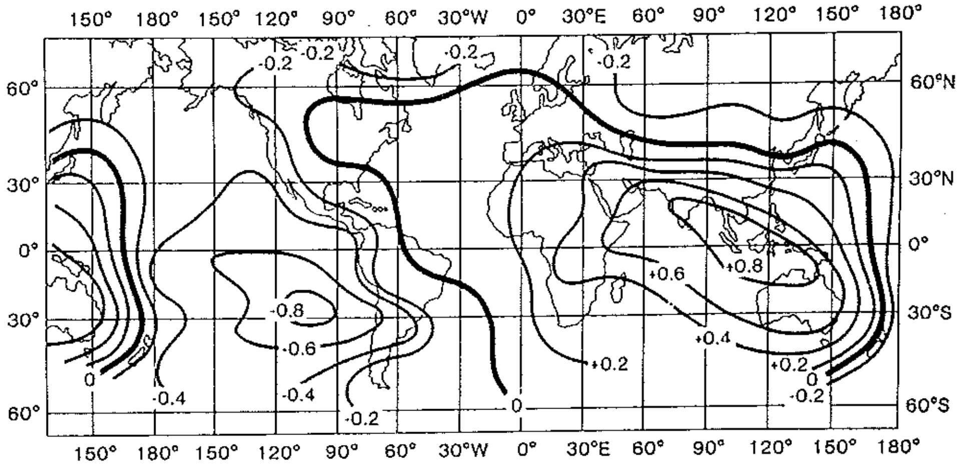


Fig. 2. Correlation of worldwide annual averaged atmospheric pressure anomalies with pressure anomalies at Djakarta, Indonesia (from Berlage, 1957).

to spring, vertical bars are hatched and soild black respectively. This has been done only for those years for which normalized monsoon rainfall anomaly is more than plus one or less than minus one standard deviation. It is rather remarkable that for the years when winter to spring pressure is decreasing, there is very little chance for the Indian monsoon to have a severe drought, and conversely, if pressure is increasing from winter to spring, it is less likely to have heavy monsoon rainfall over India.

This example illustrates that planetary scale fluctuations not only have a long period (i.e. longer compared to the annual cycle) but also have strong interrelationships among different components. For example, it is well established by now that warmer ocean temperatures over the equatorial Pacific (known as El Niño) give rise to severe droughts over Indonesia and heavy rains over central Pacific. There is also considerable influence of these ocean temperature anomalies on mid-latitude atmospheric circulation. It is also known that warm ocean temperatures in north equatorial Atlantic and cold ocean temperatures in south equatorial Atlantic produce severe droughts over Brazil; heavy snow cover over Eurasia in preceding winter and El Niño ocean anomalies are followed by severe droughts over India. These observational and numerical results collectively suggest that interactions among the atmosphere-ocean-land processes can and do produce large fluctuations which have time-scales of months to years. We need better data sets (global coverage for 10-20 years) and better models to determine the nature of this variability.

3. Natural Variability of the Atmosphere-Ocean-Land System

In the preceding discussion we pointed out that on annual and decadal time scales the atmosphere, ocean, and biosphere act as an integrated system and in order to understand the relative roles of natural causes and human activities responsible for the observed changes, interactions among hydrologic, oceanic, and atmospheric processes must be realistically modelled. It is reasonable to hypothesize that even if the planet Earth were not inhabited by humans, and therefore, there were no human interventions, there could be considerable interannual variability of rainfall (droughts and floods) and circulation. We cannot understand the impacts of human intervention unless we understand the complex interactions between physical-chemical-biological processes. If we can simulate the observed variability by a mathematical model of the coupled system, we can then use that model to calculate the possible influences of human interventions.

Unfortunately, no such model of the coupled air-sea-land system exists as yet which can simulate even the observed variability during the past 50 years. There has been considerable success in simulating some of the components of the system by 'prescribing' the other. For example, atmospheric circulation is reasonably simulated by prescribing (from observations) the state of the ocean and land surfaces. Similarly ocean circulation has been simulated by prescribing the atmospheric state over the ocean. These developments give us hope for further development of realistic coupled models.

4. Atmosphere-Ocean-Land Model

During the last 30 years, meteorology has advanced to an extent that we can write the equations for rate of change of wind, pressure, temperature and moisture, and parameterize heating and cooling due to radiation and convection, and dissipation due to friction, and integrate the resulting equations with use of high speed computers. Such models are commonly referred to as "General Circulation Models (GCM)". The Earth's surface (and distribution of land, mountains, deserts, forests, oceans, lakes, etc.) is represented by a grid of 3000 to 20 000 points and the vertical structure of the atmosphere at each grid point is described by 10–50 layers. A model with 30 000 (3000 × 10) grid points is considered a coarse resolution model, and a model with 1 000 000 (20 000 × 50) grid points is considered a high resolution model. Since we have to solve about 10 equations at each grid point, a high resolution model requires solution of about 10 million equations at each time step and integration is performed in time steps of 5–30 minutes, which implies that a 24 hour forecast from a given initial condition requires about 100–200 steps of integration in which 10 million equations are solved at each step. We are now continuing such integrations for a whole season (90 days) or even a whole year. As the time length of integrations increase, we must parameterize correctly even those slow physical processes which are normally ignored for prediction of weather for a few days.

Important physical processes take place in the atmosphere, ocean, land, and at their interfaces, and separate detailed models are needed to study those processes. However, one integrated model of the whole system is also needed so that high resolution global data from atmosphere, ocean, and land can be assimilated together to define the complete system. A good dynamical model is an essential and integrated part of any observing system. Existing observing systems can not provide global information simultaneously and therefore a good model is needed to fill up the gaps in space and time coverage of the observed data, and moreover, realistic models can derive even those parameters which can not be observed with present technology.

5. Simulation of Atmospheric Change by a Global General Circulation Model

We present here two examples of numerical experiments in which in global general circulation model of the atmosphere (with prescribed boundary conditions of ocean temperature, snow, sea ice and soil moisture, etc. at the Earth surface) was used to simulate the possible effects of changes in the boundary conditions at the Earth's surface. In these experiments the procedure consists of first integrating the model with mean climatological boundary conditions, and this is referred to as the 'control' integration; the model is then again integrated with a modification of the boundary condition and this is referred to as the 'anomaly' integration. The modification usually consists of adding or subtracting a small value of the boundary condition, for example, if the mean ocean temperature in equatorial Pacific is about 28 °C in control integration, in order to assess the influence of warmer ocean temperature (viz one

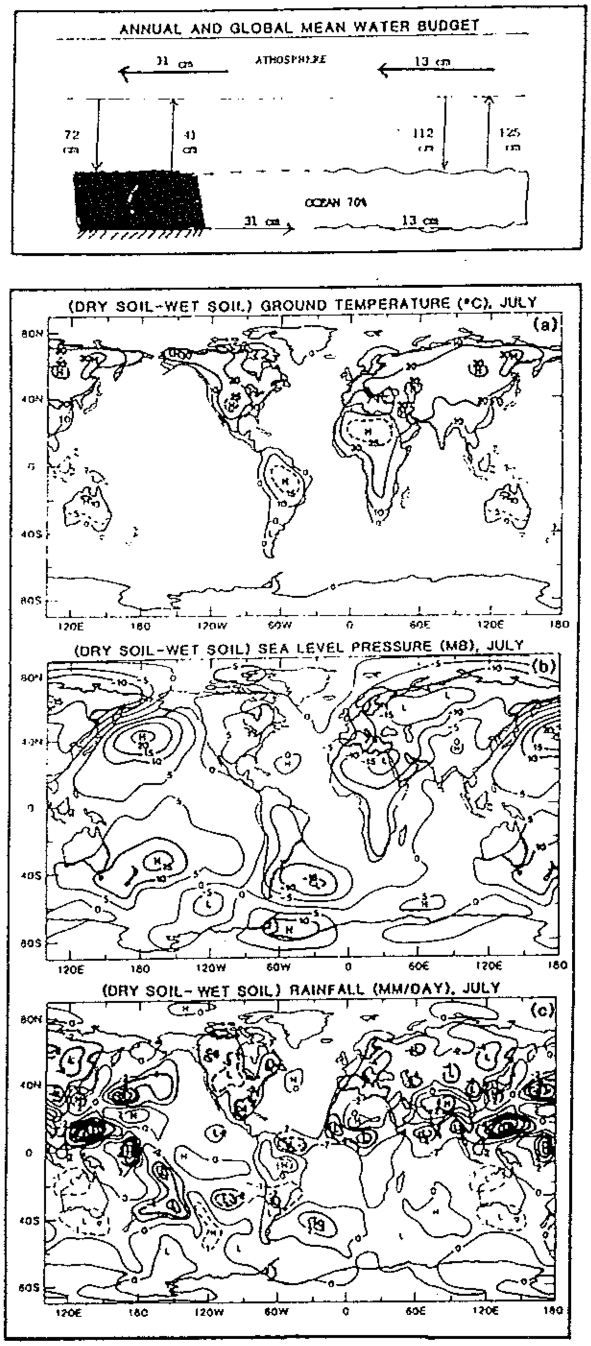


Fig. 3. Top Panel: Hydrological cycle of the earth. Bottom Panel: Differences between two model simulations (dry soilwet soil) for the month of July for (a) ground temperature (°C), (b) sea level pressure (mb), and (c) rainfall (mm/day).

degree warm anomaly), ocean temperature will be changed to 29 °C and the model will be integrated again. The length of integration is determined by the nature of problem and computing resources. Since these models are complex and cover global domain, it takes about 10–100 hours of CPU time on a modern supercomputer for each study involving several integrations.

5.1. INFLUENCE OF SOIL MOISTURE ON CLIMATE

Goddard Laboratory for Atmospheric Sciences (GLAS) climate model has been used to conduct a numerical experiment to determine the influence of soil moisture on climate (Shukla and Mintz, 1982). The model was run for 60 days with two assumed extreme global conditions of soil moisture, dry and saturated: for dry soil evaporation from the land surfaces is zero, and for saturated (wet) soil the evaporation equals the potential evapotranspiration. The differences in the simulated atmospheric circulations were enormous. For example, over most of North America and Europe the simulated rainfall for dry soil was about 40 percent less compared to the wet soil. The study showed that evaporation from land is an important factor in determining the rainfall over land.

The top panel in Figure 3 shows the observed annual and global mean water budget. The annual mean evaporation over land (41 cm) is about 60% of the annual mean precipitation over land (72 cm). The runoff from land to ocean is 31 cm. The lower three panels show the results of numerical experiment.

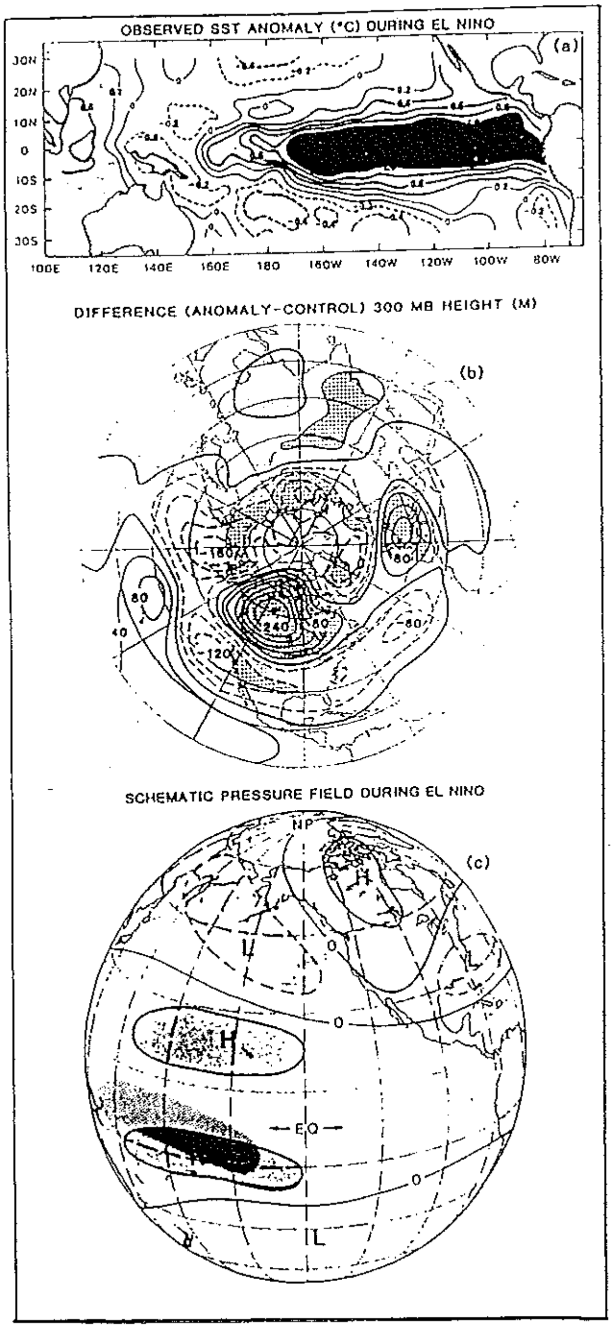
(a) *Ground temperature:* Difference [dry soil (no evaporation) – saturated soil (maximum evaporation)] for July in (°C). Positive values mean a warmer ground temperature. When land is dry, all of the solar radiation goes to heat the ground (and none to evaporate the water) and ground temperatures are very high.

(b) *Sea level pressure:* Difference [dry soil (no evaporation) – saturated soil (maximum evaporation)] for July in (mb). Maximum reductions of pressure occur over land for the dry soil case in the Northern Hemisphere. A compensating increase in pressure occurs over oceans.

(c) *Precipitation:* Difference [dry soil (no evaporation) - saturated soil maximum evaporation)] for July in mm/day. In the case of dry soil, there is a significant decrease of precipitation over land over most of the globe except for the monsoon regions. Over the Indian monsoon region, large surface heating creates very large flux convergence (moisture comes from the adjoining ocean) and leads to larger precipitation. Globally averaged precipitation (over land and ocean) in the dry soil case is reduced by about 18% of the saturated soil case. Globally averaged precipitation over land only is reduced by about 54% of the saturated soil case.

5.2 INFLUENCE OF EQUATORIAL PACIFIC OCEAN TEMPERATURE ANOMALIES

A number of recent observational and theoretical studies indicate that the equatorial Pacific SST anomalies, also referred to as El Niño events, can produce significant climate anomalies over the tropics as well as over North America. This phenomenon is illustrated schematically in the bottom panel of Figure 4 where the shaded area



OBSERVED SST ANOMALY (°C) DURING EL NINO

DIFFERENCE (ANOMALY-CONTROL) 300 MB HEIGHT (M)

SCHEMATIC PRESSURE FIELD DURING EL NINO

Fig. 4. (a) observed ocean temperature (El Niño) anomalies, (b) Difference (anomaly-control) between two model simulations for 300 mb height (meters), (c) Schematic representation of waves from tropics affecting North America.

represents a zone of enhanced precipitation associated with warm SST anomalies which force a wave pattern along a great circle path.

A numerical experiment was concluded (Shukla and Wallace, 1983) with the GLAS climate model to test the validity of above hypothesis with January initial condition based on observed data and an equatorial Pacific SST anomaly based on the recent analysis of Rasmusson and Carpenter (1982) shown in the top panel of Figure 4. The middle panel shows the difference between the anomaly and control integrations averaged for days 11–30 for geopotential height at 300 mb. The thick solid contour denotes the zero value. Positive and negative values of height differences indicate areas of warmer and colder air temperatures respectively. These are manifestations of a forced Rossby wave propagating from the region of forcing due to latent heating. It is seen that the maximum changes occur over North America. These results further confirm the earlier suggestions based on observational and simple model studies, and highlight the importance of equatorial Pacific SST anomalies in variability and predictability of monthly and seasonal mean atmospheric circulation over the tropics as well as over North America.

6. Global Data for 10–20 Years

For study of global and regional habitability, a detailed and consistent four-dimensional description of the atmosphere, ocean and land surface is required. This can be accomplished by combining all the available information from conventional and satellite sources and merge them with the help of a dynamical model which can fill the spatial data gaps by interpolation and temporal data gaps by prediction from a given state. Success of this procedure for the Global Weather Experiment carried out in 1979 has encouraged us to consider the possibility of carrying out such a data assimilation-prediction experiment for 10–20 year period. Now it will be necessary to assimilate the information from land and ocean surfaces and changing chemical composition of the atmosphere also. For example, earlier assimilation procedures did not use the observed values of ocean temperature, snow cover, sea ice, soil moisture, albedo and vegetation etc., however, for the 10–20 year assimilation it will be necessary to include the observed changing values of these boundary conditions. Same will be true of the chemical constituents like ozone, aerosols and other gases. Such a data set will help determine the nature of observed variability of the coupled system as well as provide a verification set for testing the models and hypotheses about possible causes of change.

The computing and scientific resources required to undertake such a project are, of course, enormously high, but it is feasible, and it has potential to give insight into the mechanisms which determine the habitability of the planet Earth for the present civilization. The habitability of the planet Earth (HOPE) needs to be studied from variety of standpoints, but none appears to be more promising as well as challenging than to understand and simulate the natural variability of the complex interacting habitat. High resolution models (a few hundred kilometers in horizontal, a few kilometers in vertical, daily or weekly in time) and actual observations are needed to determine the habitability of different regions of the Earth, because it is inevitable that regional effects of any natural or external perturbation are much larger than the global effects. HOPE depends upon some delicate balances between compensating forcing functions and even a small perturbation (smaller compared to any of the components) can upset the balance and bring the system to the verge of inhabitability. This again will be more true of the regional effects.

References

Berlage, H. P.: 1957, *Kon. Ned. Meteor. Inst.*, Mededeel en Verhandelingen, V. 69.
Lorenz, E. N.: 1967, The Nature and Theory of The General Circulation of The Atmosphere. *World Meteorological Organization*, p. 161.
Rasmusson, E., and T. Carpenter: 1982, *Mon. Wea. Rev.* **110**, 354–384.
Shukla, J., and Y. Mintz: 1982, *Science* **215**, 1498–1501.
Shukla, J., and D. A. Paolino: 1983, *Mon. Wea. Rev.* **111**, 1830–1837.
Shukla, J., and J. M. Wallace: 1983, *J. Atmos. Sci.* **40**, 1613–1630.

INDEX OF SUBJECTS