Circulation and Rainfall Climatology of a 10-Year (1979 - 1988) Integration With the Goddard Laboratory for Atmospheres General Circulation Model

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PREFACE

The 10-year simulation analyzed in this report was produced under Atmospheric Model Intercomparison Project (AMIP) by Dr. W. K.-M. Lau and his colleagues. The EOS-DIS funding by NASA Headquarters for studies of global hydrological process and climate enabled the participation of the primary author, JK, to carry out the analysis.
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I. Introduction

The Climate and Radiation Branch of Goddard Laboratory for Atmospheres (GLA) participated in the Atmospheric Model Intercomparison Project (AMIP) sponsored by the Department of Energy. Under this project, we produced a 10-year (1979 - 1988) integration with the GLA General Circulation Model (GCM). We present the first momentum fields (time mean averages) of major circulation variables and also hydrological variables including precipitation, evaporation, and soil moisture. A comparison of the model simulated radiative flux with those of the Earth Radiation Budget Experiment (ERBE) observation for the period 1985 to 1988 is also included.

The aim of this technical memorandum is to document the key features of the GCM simulations and to compare them whenever possible with the observed (or analyzed) atmosphere. Our goals are i) to produce a benchmark documentation of the GLA GCM for the AMIP intercomparison and future model improvements, ii) to examine systematic errors between the simulated and the observed circulation, precipitation, and hydrologic cycle, iii) to examine the interannual variability of the simulated atmosphere and compare it with observation, and iv) to examine the ability of the model to capture the major climate anomalies in response to an event such as El Niño.

II. Description of the AMIP Run

The current version of GLA GCM has evolved from the earlier 9-layer Goddard Laboratory for Atmospheric Sciences (GLAS) GCM (Kalnay et al., 1983). Although we have made several changes in the GCM, we continue to use the 4° latitude and 5° longitude resolution for climate studies. The fortuitous benefit of this is that the model improvements reflected in our results are not related to better horizontal resolution. Since it is difficult to describe the model in this memorandum, we give reference to the papers that discuss the various parameterizations in the model in Table 1. This version of the GLA GCM has 17 layers, together with a number of new physical parameterizations (see Table 1). The 10-year integration period is from January 1/00 UTC, 1979 to January 1/00 UTC, 1989.
<table>
<thead>
<tr>
<th>No.</th>
<th>ITEM</th>
<th>DESCRIPTION</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Horizontal Resolution</td>
<td>4° lat. x 5° long.</td>
<td>Kalnay et al., (1983)</td>
</tr>
<tr>
<td>3</td>
<td>Longwave Radiation</td>
<td>Modified HV Radiation Package</td>
<td>Harshvardhan et al., (1987)</td>
</tr>
<tr>
<td></td>
<td>absorption</td>
<td></td>
<td>Chou et al., (1983)</td>
</tr>
<tr>
<td></td>
<td>b) Ozone absorption</td>
<td>Modified Rodgers</td>
<td>Rodger (1968) and Rosenfield et al., (1987)</td>
</tr>
<tr>
<td>4</td>
<td>Shortwave Radiation</td>
<td>Slightly Modified HV Radiation Package</td>
<td>Harshvardhan et al., (1987)</td>
</tr>
<tr>
<td></td>
<td>a) Ozone absorption,</td>
<td>Slightly Modified Rodgers</td>
<td>Lacis and Hansen (1974)</td>
</tr>
<tr>
<td></td>
<td>Water-vapor absorption,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rayleigh Scattering</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scattering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Turbulence and PBL</td>
<td>Mellor-Yamada 2.5</td>
<td>Helfand and Labraga, (1988)</td>
</tr>
<tr>
<td>6</td>
<td>Biosphere</td>
<td>SiB (Simple Biosphere)</td>
<td>Sellers et al., (1986) and Sud et al., (1990)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Xue et al., (1991)</td>
</tr>
<tr>
<td>7</td>
<td>Non-Precipitating</td>
<td>Relative Humidity Dependent Fractional Clouds</td>
<td>Sud and Walker (1992)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Slingo (1987) adaptation</td>
</tr>
<tr>
<td>8</td>
<td>Cumulus Clouds</td>
<td>Detraining Anvils</td>
<td>Sud and Walker (1992)</td>
</tr>
<tr>
<td>10</td>
<td>Large-scale Precip.</td>
<td>Fractional Cover</td>
<td>Sud and Walker (1992)</td>
</tr>
<tr>
<td></td>
<td>Rain-evaporation</td>
<td>Cloud Fractions.</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ERBE data over Bare-land</td>
<td></td>
</tr>
<tr>
<td>15. General Modification</td>
<td>Several Improvements in the physics package</td>
<td>Sud and Walker (1992) (for a detailed discussion)</td>
<td></td>
</tr>
</tbody>
</table>

* Personal Communication

**HV = Harshvardhan**
III. List of Quantities

This section describes the analyzed quantities and units used. The first momentum fields in Section VI mainly follow those of Schubert et al. (1990) except for the following differences. The global maps for the 10-year averages primarily include the 850 and 200 mb fields. But the streamfunction field and its eddy part (deviation from the zonal mean) are shown only at the 200 mb level. The geopotential height and the vertical p-velocity fields are shown at the 500 mb level. The specific humidity fields are shown at the 850 mb level. The vertical cross sections are based on the zonal averages on the pressure levels 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, and 100 mb. The following table shows the fields whose seasonal and annual means have been plotted. The fields are shown in the sequence of the plots. Negative values are shaded for the fields marked with *.

### Seasonal and Annual Mean First Momentum Fields

#### Global Map

<table>
<thead>
<tr>
<th>Title</th>
<th>Field</th>
<th>Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>U850</td>
<td>850 mb zonal wind</td>
<td>3 m s⁻¹ *</td>
</tr>
<tr>
<td>U200</td>
<td>200 mb zonal wind</td>
<td>5 m s⁻¹ *</td>
</tr>
<tr>
<td>V850</td>
<td>850 mb meridional wind</td>
<td>2 m s⁻¹ *</td>
</tr>
<tr>
<td>V200</td>
<td>200 mb meridional wind</td>
<td>2 m s⁻¹ *</td>
</tr>
<tr>
<td>T850</td>
<td>850 mb temperature</td>
<td>5 °K</td>
</tr>
<tr>
<td>T200</td>
<td>200 mb temperature</td>
<td>2 °K</td>
</tr>
<tr>
<td>SLP</td>
<td>sea level pressure</td>
<td>4 mb</td>
</tr>
<tr>
<td>Z500</td>
<td>500 mb geopotential height</td>
<td>20 m</td>
</tr>
<tr>
<td>q850</td>
<td>850 mb specific humidity</td>
<td>1 g kg⁻¹</td>
</tr>
<tr>
<td>ω500</td>
<td>500 mb vertical p-velocity</td>
<td>3 × 10⁻² Pa s⁻¹ *</td>
</tr>
<tr>
<td>Full</td>
<td>200 mb streamfunction</td>
<td>10 × 10⁶ m² s⁻¹ *</td>
</tr>
<tr>
<td>EDDY</td>
<td>200 mb eddy streamfunction</td>
<td>5 × 10⁶ m² s⁻¹ *</td>
</tr>
<tr>
<td>χ850</td>
<td>850 mb velocity potential</td>
<td>1 × 10⁶ m² s⁻¹ *</td>
</tr>
<tr>
<td>χ200</td>
<td>200 mb velocity potential</td>
<td>1 × 10⁶ m² s⁻¹ *</td>
</tr>
</tbody>
</table>
Longitude-Height Cross Section

<table>
<thead>
<tr>
<th>Title</th>
<th>Field</th>
<th>Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>zonal wind</td>
<td>5 m s(^{-1})*</td>
</tr>
<tr>
<td>V</td>
<td>meridional wind</td>
<td>0.5 m s(^{-1})*</td>
</tr>
<tr>
<td>(\omega)</td>
<td>vertical p-velocity</td>
<td>0.5 (\times 10^{-2}) Pa s(^{-1})*</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>10 °K</td>
</tr>
<tr>
<td>q</td>
<td>specific humidity</td>
<td>1 g kg(^{-1})</td>
</tr>
</tbody>
</table>

Seasonal Cycle
The seasonal cycle of the following quantities is based on the 10-year monthly averages of zonal mean of each field.

<table>
<thead>
<tr>
<th>Title</th>
<th>Field</th>
<th>Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>U200</td>
<td>200 mb zonal wind</td>
<td>5 m s(^{-1})*</td>
</tr>
<tr>
<td>V200</td>
<td>200 mb meridional wind</td>
<td>3 m s(^{-1})*</td>
</tr>
<tr>
<td>T200</td>
<td>200 mb temperature</td>
<td>3 °K</td>
</tr>
<tr>
<td>U850</td>
<td>850 mb zonal wind</td>
<td>3 m s(^{-1})*</td>
</tr>
<tr>
<td>V850</td>
<td>850 mb meridional wind</td>
<td>2 m s(^{-1})*</td>
</tr>
<tr>
<td>T850</td>
<td>850 mb temperature</td>
<td>5 °K</td>
</tr>
<tr>
<td>Q850</td>
<td>950 mb specific humidity</td>
<td>1 g kg(^{-1})</td>
</tr>
<tr>
<td>(\omega)500</td>
<td>500 mb vertical p-velocity</td>
<td>2 (\times 10^{-2}) Pa s(^{-1})*</td>
</tr>
<tr>
<td>E-P</td>
<td>evaporation - precipitation</td>
<td>1 mm day(^{-1})</td>
</tr>
</tbody>
</table>

Zonal Mean Anomalies
The zonal averages of the monthly mean deviation from the seasonal cycle is shown from 1979 to 1988.

<table>
<thead>
<tr>
<th>Title</th>
<th>Field</th>
<th>Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>U200</td>
<td>200 mb zonal wind</td>
<td>2 m s(^{-1})*</td>
</tr>
<tr>
<td>V200</td>
<td>200 mb meridional wind</td>
<td>0.5 m s(^{-1})*</td>
</tr>
<tr>
<td>T200</td>
<td>200 mb temperature</td>
<td>0.5 °K*</td>
</tr>
<tr>
<td>T850</td>
<td>850 mb temperature</td>
<td>0.5 °K*</td>
</tr>
<tr>
<td>Q850</td>
<td>850 mb specific humidity</td>
<td>0.3 g kg(^{-1})*</td>
</tr>
<tr>
<td>(\omega)500</td>
<td>500 mb vertical p-velocity</td>
<td>1 (\times 10^{-2}) Pa s(^{-1})*</td>
</tr>
</tbody>
</table>
Hydrology

Precipitation

The model-simulated total precipitation $P$, as well as the observed precipitation, are shown for the seasonal and annual averages of 10 year mean fields. The observed precipitation is a combination of raingauge measurement over land and Microwave Sounding Unit (MSU) analysis over the ocean (Spencer, 1993). The precipitation anomalies for the simulated and the observed are shown as deviations from their seasonal cycles. The annual anomalies are yearly deviations from the 10-year mean fields. The time series of the zonal mean precipitation for the simulated and observation is shown for the total, anomaly with seasonal cycle (10-year climatology subtracted), and anomaly with seasonal cycle removed (10-year seasonal mean subtracted). These maps have contours with 1 mm day$^{-1}$ interval.

Evaporation

The 10-year mean seasonal and annual averages of simulated evaporation $E$ (and also monthly averages) are shown using 1 mm day$^{-1}$ contour interval. The seasonal and annual evaporation anomaly are shown with thick (thin) contours of interval 1 (0.5) mm day$^{-1}$. The time series of the zonal mean evaporation is shown for the total, as well as anomaly with seasonal cycle (contour interval 0.5 mm day$^{-1}$), and the anomaly without seasonal cycle (0.2 mm day$^{-1}$). The time series of the zonal mean $P-E$ (precipitation minus evaporation) is shown for the total, anomaly with seasonal cycle, and anomaly without seasonal cycle with contour intervals of 1 mm day$^{-1}$.

Soil Moisture

The 10-year mean seasonal and annual mean soil moisture at the SiB model layer-2 is shown with shading for regions having soil moisture fraction from 0.3 to 0.8. The seasonal and annual anomaly soil moisture are shown with contours at $\pm$ 0.05, 0.1, 0.2, and 0.3.
Time Series of P, E, and Soil Moisture in 12 SiB Vegetation Region

These are the averaged quantities over the area of 12 different Simple Biosphere (SiB) Model vegetation types (also called biomes). All curves with open circle or rectangle are from AMIP run, and the curves with closed circle are either from observation or from estimation. The upper two curves in the left panel are the soil moisture at the SiB layer 2 (root zone) with scale on the left ordinate (fraction from 0 to 0.75). The estimated soil moisture in closed circle is taken from the Liston et al. (1993a, b), where off-line SiB model is run, with the gridded raingauge precipitation produced by J. Schemm (personal communication), following Mintz and Walker (1993) procedure. The lower two curves in the left panel are the evapotranspiration with scale on the ordinate in the right panel from 0 to 10 mm day$^{-1}$. The curves in the right panel are the AMIP (open circle) and observed (closed circle) precipitation, and they follow the scale from 0 to 10 mm day$^{-1}$.

Monthly Mean Radiative Flux

The monthly mean net shortwave radiation into the earth-atmosphere system and outgoing longwave radiation (OLR) out of the atmosphere are plotted for the simulated radiative flux (AMIP, top panel), and for the ERBE observations (ERBE, middle panel). The simulated radiative flux minus observed/analyzed radiative flux (DIFF, bottom panel) are also shown. The contour interval for these fields is 20 W m$^{-2}$.

IV. Discussion

A. First Momentum Fields

a. Zonal Winds

The 850 mb zonal winds show a realistic meridional structure, i.e., easterlies in the tropics, westerlies in the midlatitudes, and easterlies again in the polar regions. The winds also show a decent annual cycle. For example, in the summer season, the easterlies change to westerlies over tropical Africa and India. As expected, they are stronger in the local winters and weaker in local summers. As compared to the
European Center for Medium Range Weather Forecast (ECMWF) analysis (hereafter analysis/observations), the simulated winds are much stronger. Particularly at the polar latitudes, the simulated winds become quite unrealistic and large, which suggests model deficiency. Also, wintertime north Atlantic storm track winds are stronger than the observed. At the 200 mb level, the zonal winds, although somewhat stronger than the observed, better agree with the analysis except for the polar regions. Some notable deficiencies are: the simulated easterlies in the tropics are not as widely spread as those in the observations; moreover, winds in the polar regions are too strong. These effects can also be identified in the seasonal and annual mean fields.

b. Meridional Winds

The 850 mb meridional winds have a reasonable distribution except for the excessive magnitudes in the polar regions. Over North America, the winds are equatorwards while over the north Pacific and Atlantic regions, they are polewards: this agrees well with observations. The wind magnitudes over South America, Northern and Southern Africa and Eurasia are large in the seasonal means but appear quite reasonable in the annual mean. The meridional winds at the 200 mb level are somewhat stronger than observed, but better agree with the analysis than they do at the 850 mb level except for the polar regions. Some notable deficiencies are in the European regions, Highland regions of India, and China while both polar regions have much stronger winds, which may well be related to inaccurate solutions of the primitive equations in the vicinity of orography.

c. Temperature

As compared to observation, the 850 mb temperature distribution seems much better than that of 200 mb level. In the latter case, particularly during winter and spring, the temperature gradients in the meridional direction are much stronger than observed, with the highest gradients in the polar regions. This is accompanied by excessive cooling in the entire troposphere, which is strong in the polar regions. The 200 mb temperature over the south (north) polar region is about 20 (10) K too
low, and this seems to be consistent throughout all the seasons, except that south polar regions at upper levels are warm enough to be close to the observed during summer and autumn. This is a model deficiency that needs to be addressed.

d. SLP and 500 mb Height

The SLP and the zonal departure of 500 mb height fields show some strong gradients in the poleward direction. They appear quite reasonable in the southern high latitude regions in both seasonal, as well as annual, variations, but the gradients are much too strong in the northern high latitudes. Often SLP gradients translate into the geopotential height gradients for which only the eddy part has been shown. Lower SLPs, simulated over the western Antarctic, produce convergence, as opposed to divergence, in the region leading to spurious precipitation. This weakness did not exist in the 9-layer model and needs further investigation.

e. Specific Humidity at 850 mb and 500 mb ω

The 850 mb specific humidities are well simulated. The model is somewhat drier in the tropics because the 850 mb level is above the cloud base level where sinking dries it. A new downdraft scheme (Sud and Walker, 1993) is implemented into the model, which is likely to improve this condition. The 500 mb ω (vertical p-velocity) fields appear to be quite reasonable. Strong values in the vicinity of orographic gradients are related to rising/sinking components of the strong motion fields. The large-scale vertical p-velocity structure appears quite reasonable as compared to ECMWF analysis. However, rising motion over the western and central tropical Pacific is up to four times stronger than the analysis.

f. Streamfunction at 200 mb

The 200 mb streamfunction depicts the rotational part of wind structure of the model. The simulated winds correspond well with the ECMWF analysis. Strong gradients over the south pole region point to the pole problems. The analyzed winds in the region have a smooth zonal pattern. The winds over the midlatitudes seem quite reasonable and agree well with the analysis, except that they are a bit too
strong, particularly in their seasonal depictions.

g. Velocity Potentials at 200 and 850 mb

The 200 and 850 mb velocity potentials depict the planetary scale divergent motion fields. The convergence towards the center of the maximum velocity potential and divergence away from the minimum value agree well with the ECMWF analysis. The velocity potential gradients at 850 mb are stronger than those in the ECMWF analysis, which is consistent with stronger simulated winds at the 850 mb level. Otherwise, the location of the centers of convergence and divergence appear reasonable.

h. Zonal Mean U, V, and ω

The zonal mean U-winds are somewhat weaker in the tropics. Although the variation of the annual cycle is well simulated (with the strongest winds in the summer), the middle tropospheric winds do not become easterly in the tropics. The subtropical jets seem to have reasonable strength: a closed (open) jet of annual mean strength of 25 (35) m s⁻¹ at the 200 mb level in the northern (southern) latitudes is quite reasonable as compared to ECMWF analysis. The V-wind simulation also appears quite reasonable; whereas, the vertical motion fields, ω's, are somewhat stronger. In the seasonal depictions, the intra-annual variation of these fields seems to be quite reasonable. The extreme vertical motion over Antarctica is again the manifestation of the orographic influence on the strong simulated wind. Another point to be noted is that in the midlatitude, the upward motion is not strong enough to be comparable to the observation.

i. Zonal Mean Temperature and Humidity

The temperature fields show upper level cooling everywhere and some significant cooling at the high latitudes. This problem has already been pointed out earlier. In fact, the problem of cooling at the poles has been plaguing the GLA GCM for quite some time, and it has still to be solved. The humidity fields cannot be compared because the analyses are model dependant; therefore, we reckon that
they cannot be verified and are shown here for completeness.

j. Zonal Mean Annual Cycle for U, V, and T at 200 and 850 mb

The seasonal cycle of U and V at 200 mb level agrees well with the observations. The T-field shows closed highs at 30° N – 60° N latitudes. This is not seen in the ECMWF analysis. Since it is the middle of summer for the northern latitudes, we believe that such a depiction is not unreasonable. At the 850 mb level, we get stronger winds and stronger wind gradients. This is reflected in the seasonal structure of U-winds; for example, the strong subtropical westerlies from May to October are not seen in the observation. The pole problems reflect severely in the V-wind errors at high latitudes. The annual cycle of wind structure simulated by the model is much stronger than that in the ECMWF analysis. However, the improvement in the analysis in the later years (1984 - 1987) helps to close the large gap between our simulations and the analysis.

k. Annual Cycle for Zonal-Mean Humidity-850 mb, ω-500 mb, and E–P

The simulated humidities appear reasonable. In this case, too, the recent improvement in the ECMWF analysis brings the analyzed fields closer to our simulations. This suggests that the discrepancies between the simulated and analyzed fields are not entirely caused by simulation errors. The large-scale seasonal variation of the vertical winds at 500 mb is quite reasonable, even if the strong upward motion from May to October is not seen in the observation. The 500 mb vertical winds and moisture divergence correspond well to each other. Rising motion is consistent with increased precipitation.

l. Fluctuations in U, V, T-200 mb and T-850 mb, Q-850 mb and ω-500 mb

At high latitudes, 200 mb winds have higher magnitude and lower frequencies, as compared to the tropics. The period appears to be about 90 days at mid-high latitudes, with only an annual fluctuation. Correspondingly, T-200 mb has much stronger fluctuations, as compared to T-850 mb. As expected, the strongest fluctuations occur in the polar regions. The humidities over the southern polar caps
are naturally quite low, while over the southern oceans, they are quite uniform; therefore, the fluctuations appear over the northern high latitude regions only. In the tropics, low (high) humidities can be seen in 1987 (1988).

B. Hydrology

a. Total Precipitation Climatology

The seasonal vis-a-vis observed precipitation climatologies show that the model does a good job of simulating the rainfall patterns. The fields are much more realistic over the oceans, as compared to land; however, the simulation is poor, particularly in the vicinity of orography. High rainfall over Colombia in South America is spurious; the Indian monsoon is also somewhat displaced because of sharp Himalayan orography; the precipitation over the South Pole, which the 9-layer model did not have, has appeared as a result of strong convergence and is a source of some concern. It is related to the polar problems where extremely strong vertical winds dominate over Antarctica. In the observations, some mismatch between the land and ocean rainfall is the result of blending satellite inferred rainfall over the oceans with raingauge observations. The differences show that the model-simulated precipitation are systematically less, as compared to satellite data in the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) regions, whereas, they are better correlated with observations over land. Systematic errors over the Sahara region may be related to 4% – 8% lower albedo of deserts, as compared to ERBE products. Model tends to rain more over coastal North America but less over coastal West Africa. High simulated rainfall over the tropics in Columbia seems to be a problem. The monthly precipitation climatology in the next four figures can be compared with the observations given in the following figures. Problems with precipitation structure over Amazonia, monsoonal northern India, North America, and Africa can be noted. Strong precipitation from May through December over Greenland deserves attention.

b. Simulated and Observed Precipitation Anomalies

The seasonal and annual rainfall anomalies show that the model has some
large systematic errors, but it capture salient features of Sahelian droughts for 1982 and 1983; influence of El Niño sea surface temperature (SST) anomaly on the tropical Pacific for 1983 and its reversal in 1984, which is accompanied by increased rainfall over western tropical Africa; the reduced (increased) rainfall over the tropical Pacific, in 1985 (1986) is also well captured. By 1987 another El Niño began to affect tropical Pacific and the model simulates it reasonably. It is associated with droughts over India and North Africa and Amazonia, and the model captures it. However, the skill in the midlatitudes is not good enough, as can be inferred from the simulated and the observed fields. We believe that this is related to the unrealistically strong winds, which affect the orientation of stationary waves in the midlatitudes. As we have seen before, the zonal winds in the 850 mb are comparable to the observed values, while the vertical winds are weaker than the observation. We assume that this is related to insufficient baroclinic activity in the storm track. The coarse resolution of our model could also yield weaker-than-observed transient activity over storm track region. In turn, the midlatitude baroclinic system itself might not be efficient enough to create sufficient meridional and vertical energy transfer, and the unrealistically strong upper layer winds could be a part of this deficient dynamic system.

Some large-scale features of the rainfall anomaly are well captured by the simulation. By 1988 the warm El Niño SST event was replaced by the cold La Niña event. The rainfall over the tropical Pacific was reduced significantly. There were also changes in India, Indonesia, Tropical North Africa and North and South America.

c. Zonal-Mean Simulated Vis-a-Vis Observed Precipitation

The zonal mean precipitation shows north-south excursions in association with the change of solar declination. The tropical rainfall appears a little too strong; whereas, high latitude rainfall is weak; see, for example, the rainfall in the region of roaring 40° S - 60° S. The zonal mean rainfall anomaly with seasonal cycle has a stronger structure in the model, as compared to observation. The observed precipitation anomaly has strong interannual variability between 30° N to 60° N,
but it is not apparent in the model. In the tropics, however, the simulated seasonal cycle is stronger than the observed for the entire period. The reduced rainfall in 1987 is not picked up by the model, even though the resemblance of patterns or lack of it in the zonal mean precipitation may be fortutious. The rainfall anomaly patterns in the Southern Hemisphere do not convey much, except for some correlation at a few places. The patterns with 10-year monthly mean subtracted do not show much resemblance with observations, but in 1983 and 1986 the northward propagation of the negative anomalies in the tropics shows some correspondence to the observation.

d. Surface Evaporation Climatology

The simulated seasonal vis-a-vis observed seasonal and annual evaporation climatologies that are consistent with the precipitation fields are included for completeness. There are no observations or analysis of observations for this field. A correspondence between evaporation and SST anomalies can be expected over the oceanic regions. This is evident for the tropical Pacific El Niño/La Niña years: 1982/1983 and 1987/1988. The zonal mean evaporation shows a stronger seasonal signal at higher latitudes when we examine the patterns after subtracting the 10-year mean, which is to be expected. The summer and winter patterns in the Northern Hemisphere show how an evaporation anomaly seasaw pattern develops between mid and high latitudes. In the annual cycle, higher (lower) evaporation in winter over the oceans (land) in midlatitudes and higher (lower) evaporation over land (ocean) occurs in summer in the high latitudes. The pattern results from land ocean distribution in the northern latitudes.

e. Annual Cycle for Zonal-Mean P–E

The patterns appear quite reasonable. The net drying can only occur over the oceans, because precipitation has to exceed evaporation over land to compensate for the runoff. The plots are included for completeness, because currently there is no data to compare. We hope future observations/analysis of observations can help us verify these.
f. Soil-Moisture Fraction

The simulated soil-moisture fractions climatology produced by the model for the root zone region appears to be reasonable. Although deserts are dry and precipitating regions are moist, there are some differences between the estimated and model simulated soil moistures. Some of these differences, such as the soil-moisture patterns over northern India, Amazonia, tropical Africa, and north Africa, can be related to the simulated rainfall deficiencies. The model produces soil moistures with an assumption that all snow melt gets into the soil, which produces the discrepancy over Greenland, but that is really inconsequential. In the evolving soil-moisture anomaly, one notices drying and moistening in response to initial adjustment that lasts up to 2-years. After a couple of years, the soil-moisture adjustment is reduced to simple interannual variability, as well as response to prescribed boundary forcings. The 10-year cycle for soil moisture and evaporation with the raingauge rainfall verification for different SiB biome regions shows the biospheric component of the model's performance. The soil moisture over the tropical forest is always below the estimated value and shows stronger seasonal variation. Also, there is some persistent decrease of the soil moisture over the years in the biome type-4 region (needleleaf evergreen trees). Other differences can be found in biome type-5 (needleleaf deciduous trees), biome type-6 (Savannah), and biome type-8 and 9 (broadleaf deciduous shrubs).

g. Radiation

The monthly mean net shortwave radiation entering the earth-atmosphere system (incoming solar radiation minus reflected solar radiation by the surface and atmosphere), as well as monthly mean OLR averaged from 1985 to 1988, is compared with the data generated by ERBE observation. The ERBE data is read from the CD-ROM made by NASA Climate Data System Staff (Olsen and Warnock, 1992). In general, the net shortwave radiation shows good agreement with ERBE data. There are, however, some systematic errors over oceans off the coast of Chile in South America, the west coast of the United States, and the west coast of Southern Africa. These areas are believed to have low level stratus clouds, which are
not well simulated by the model. These clouds reflect a significant amount of the solar radiation. We also notice that the magnitude of errors becomes larger in the Summer Hemisphere when the incoming solar radiation is stronger. The maximum error in these areas does reach up to 100 W m$^{-2}$. Errors can also be noted over the high orographic regions, especially Himalayas. There are significant errors near the snow boundary regions over Antarctica and the North Pole. OLR simulated by the model is also in good agreement with the ERBE data, except over a few regions such as Indonesia and Himalaya. Over the Sahara region, the simulated OLR is less than that of the ERBE data. These differences are being analyzed to help us improve our cloud and land-surface albedo parameterizations.
V. References


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VI. THE FIRST MOMENTUM FIELDS

A. SEASONAL AVERAGES
Zonal Wind (m/s)
10 Year Mean (1979–88)
Winter (DJF)
Meridional Wind (m/s)
10 Year Mean (1979–88)
Winter (DJF)
Temperature (K)
10 Year Mean (1979–88)
Winter (DJF)
SLP-1000 (mb) and 500 mb eddy Z (m)
10 Year Mean (1979–88)
Winter (DJF)
850 mb q (g/kg) and 500 mb W (Pa/s)
10 Year Mean (1979-88)
Winter (DJF)
200 mb Stream Function (10E6 m**2/s)
10 Year Mean (1979–88)
Winter (DJF)
Velocity Potential (10E6 m**2/s)
10 Year Mean (1979-88)
Winter (DJF)
Zonal Wind (m/s)
10 Year Mean (1979–88)
Spring (MAM)
Meridional Wind (m/s)
10 Year Mean (1979–88)
Spring (MAM)
Temperature (K)
10 Year Mean (1979-88)
Spring (MAM)
850 mb q (g/kg) and 500 mb W (Pa/s)
10 Year Mean (1979-88)
Spring (MAM)
200 mb Stream Function (10E6 m**2/s)
10 Year Mean (1979–88)
Spring (MAM)
Velocity Potential ($10^6 \text{ m}^2/\text{s}$)

10 Year Mean (1979–88)

Spring (MAM)
Spring (MAM)
10 Year Mean (1979–88)
U (m/s), V (m/s), W (Pa/s)
Spring (MAM)
10 Year Mean (1979-88)
T (K), q (g/kg)
Zonal Wind (m/s)
10 Year Mean (1979-88)
Summer (JJA)
Temperature (K)
10 Year Mean (1979-88)
Summer (JJA)
SLP-1000 (mb) and 500 mb eddy Z (m)
10 Year Mean (1979-88)
Summer (JJA)
850 mb $q$ (g/kg) and 500 mb $W$ (Pa/s)
10 Year Mean (1979-88)
Summer (JJA)
200 mb Stream Function (10E6 m**2/s)
10 Year Mean (1979–88)
Summer (JJA)
Velocity Potential (10E6 m**2/s)
10 Year Mean (1979-88)
Summer (JJA)
Summer (JJA)
10 Year Mean (1979–88)
T (K), q (g/kg)
Zonal Wind (m/s)
10 Year Mean (1979–88)
Autumn (SON)
Meridional Wind (m/s)
10 Year Mean (1979-88)
Autumn (SON)
Temperature (K)
10 Year Mean (1979–88)
Autumn (SON)
SLP-1000 (mb) and 500 mb eddy Z (m)
10 Year Mean (1979-88)
Autumn (SON)
850 mb $q$ (g/kg) and 500 mb $W$ (Pa/s)
10 Year Mean (1979–88)
Autumn (SON)
200 mb Stream Function (10E6 m**2/s)
10 Year Mean (1979-88)
Autumn (SON)
Velocity Potential ($10E6 \text{ m}^2/\text{s}$)
10 Year Mean (1979–88)
Autumn (SON)
Autumn (SON)
10 Year Mean (1979-88)
U (m/s), V (m/s), W (Pa/s)
B. ANNUAL AVERAGES
Zonal Wind (m/s)
10 Year Mean (1979–88)
Annual

PRECEDING PAGE BLANK NOT FILMED
Meridional Wind (m/s)
10 Year Mean (1979–88)
Annual
SLP–1000 (mb) and 500 mb eddy Z (m)
10 Year Mean (1979–88)
Annual
850 mb $q \text{ (g/kg)}$ and 500 mb $W \text{ (Pa/s)}$

10 Year Mean (1979–88)

Annual
200 mb Stream Function (10E6 m**2/s)
10 Year Mean (1979–88)
Annual
Velocity Potential (10E6 m**2/s)
10 Year Mean (1979–88)
Annual
Annual
10 Year Mean (1979-88)
T (K), q (g/kg)

T

q

90N 60N 30N EQ 30S 60S 90S

90N 60N 30N EQ 30S 60S 90S

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C. SEASONAL CYCLE
Seasonal Cycle
10 Year Mean (1979-88)
Seasonal Cycle
10 Year Mean (1979-88)
D. ZONAL MEAN ANOMALIES
Anomaly Zonal Mean Wind (m/sec)
seasonal cycle removed
Anomaly Zonal Mean $T$ (deg K)
Anomaly Zonal Mean Q (g/kg) and W (Pa/s)
seasonal cycle removed
VII. HYDROLOGY

A. PRECIPITATION
A set of simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are 2, 4, 8, 12, and 16 (1, 3, 6, 10, and 14) mm/day. Bar on the right shows range of the shaded regions. Area weighted global mean values are DJF: 2.89, MAM: 3.03, JJA: 3.45, SON: 2.94, and ALL: 3.08, respectively. Tropics are relatively well simulated. Orographically induced precipitation shows deficiencies. Excessive rainfall appears over Antarctica.
A set of observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Raingauge data over land and MSU analysis over ocean (Spencer, 1993) are merged together. Thick (thin) contours are 2, 4, 8, 12, and 16 (1, 3, 6, 10, and 14) mm/day. Bar on the right shows range of the shaded regions. Area weighted global mean values are DJF: 3.13, MAM: 3.12, JJA: 3.60, SON: 3.20, and ALL: 3.26, respectively.
Simulated minus observed differences for precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±4, 8, and 12… (2, 6, and 10…) mm/day. The differences are not necessarily caused by the simulation errors because of the well known biases in the analyzed precipitation.
Precipitation AMIP–MSU (mm/day)
10 Year Mean (1979–88)

CONTOURS +/- 4 8 12 (thick), 2 6 10 14 (thin)
Total Precipitation (mm/day)
10 Year Mean (1979-88)

CONTOURS 2 4 8 12 24 (thick), 1 3 6 10 18 (thinner)
Observed Precipitation (mm/day)
10 Year Mean (1979-88)

Contours: 2 4 8 12 24 (thick), 1 3 6 10 18 (thin)
Observed Precipitation (mm/day)
10 Year Mean (1979–88)

CONTOURS 2 4 8 12 24 (thick), 1 3 6 10 18 (thin)
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 1 (1979)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 2 (1980)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded

[Map showing precipitation anomalies for different seasons with contour lines and shaded areas to indicate deficits.]
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 3 (1981)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however, the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 5 (1983)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 6 (1984)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are $\pm 2, 4, 8,$ and $12 (1, 3, 6,$ and $10) \text{ mm/day}$. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 8 (1986)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Anomaly Precipitation (mm/day)
Simulation Year 9 (1987)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Anomaly Precipitation (mm/day)  
Simulation Year 10 (1988)  
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded

Deviations from the seasonal and annual averages (10 year means) for the simulated precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are \( \pm 2, 4, 8, \) and 12 \( (1, 3, 6, \) and 10) mm/day. Seasonal anomalies over tropical Pacific are relatively well simulated especially during El Niño/La Niña periods. For example, MAM and SON/1982 versus 1983 and JJA 1987 versus 1988; however the anomalies for DJF 1982 versus 1983 are weaker than the observed (see next set of figures).
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)

Year 1 (1979)

Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 2 (1980)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)

Year 3 (1981)

Contours labeled -12 -6 -4 -2 2 4 8 12, deficit shaded
Deviation from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 4 (1982)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 5 (1983)
Contours labeled -12 -6 -4 -2 2 4 8 12, deficit shaded
Observed Anomaly Rainfall (mm/day)
Year 6 (1984)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded

Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 6 (1984)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviation from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (±1, ±3, ±6, and ±10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 7 (1985)
Contour labeled -12 -8 -4 -2 2 4 8 12, deficit shaded

JJA

SON

ALL
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 8 (1986)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded

JJA

SON

ALL
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are $\pm 2$, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around $130^\circ$W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 9 (1987)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded
Deviations from the seasonal and annual averages (10 year means) for the observed precipitation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±2, 4, 8, and 12 (1, 3, 6, and 10) mm/day. Maximum positive anomaly in DJF and MAM, 1983 over tropical Pacific around 130°W is followed by maximum negative anomaly in DJF and MAM, 1984 over central tropical Pacific as part of the El Niño episode.
Observed Anomaly Rainfall (mm/day)
Year 10 (1988)
Contours labeled -12 -8 -4 -2 2 4 8 12, deficit shaded.
Zonal Mean Precipitation (mm/day)
10 year annual mean subtracted
B. EVAPORATION
A set of simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Contour interval is 1 mm/day. Bar on the right shows range of the shaded regions. Area weighted global mean values are DJF: 2.77, MAM: 2.84, JJA: 3.11, SON: 2.79, and ALL: 2.88, respectively.
Evaporation (mm/day)
10 Year Mean (1979-88)
shaded 1 2 3 4 6, contour interval 1

JAN

FEB

MAR
Evaporation (mm/day)
10 Year Mean (1979-88)

shaded 1 2 3 4 6, contour interval 1

OCT

NOV

DEC

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Anomaly Evaporation (mm/day)
Simulation Year 1 (1979)

Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 1 (1979)
Contour interval 0.5 with negative values shaded
Anomaly Evaporation (mm/day)
Simulation Year 2 (1980)
Contour interval 0.5 with negative values shaded

Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 2 (1980)
Contour interval 0.5 with negative values shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 3 (1981)
Contour interval 0.5 with negative values shaded
Anomaly Evaporation (mm/day)
Simulation Year 4 (1982)
Contour interval 0.5 with negative values shaded

Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 4 (1982)
Contour interval 0.5 with negative values shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are \( \pm 1, 2 \) (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 5 (1983)
Contour interval 0.5 with negative values shaded.
Anomaly Evaporation (mm/day)
Simulation Year 6 (1984)
Contour interval 0.5 with negative values shaded

Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 6 (1984)
Contour interval 0.5 with negative values shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 8 (1986)
Contour interval 0.5 with negative values shaded
Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ±1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Anomaly Evaporation (mm/day)
Simulation Year 9 (1987)
Contour interval 0.5 with negative values shaded

60N
30N
EQ
30S
60S

JJA

60N
30N
EQ
30S
60S

SON

60N
30N
EQ
30S
60S

ALL

60N
30N
EQ
30S
60S

0 60E 120E 180 120W 60W 0
Deviations from the seasonal and annual averages (10 year means) for the simulated evaporation fields. Panel labels show seasonal means: December, January, February (DJF), March, April, May (MAM), June, July, August (JJA), September, October, November (SON), and annual mean (ALL). Thick (thin) contours are ± 1, 2 (0.5, 1.5, and 2.5) mm/day. El Niño response can be seen in JJA/1987 versus 1988 and MAM/1984 versus 1985 over most of the Pacific Ocean.
Zonal Mean Evaporation (mm/day)

10 year annual mean subtracted
Zonal Mean Evaporation (mm/day)

10 year monthly mean subtracted
C. TIME SERIES P-E
Zonal Mean P-E (mm/day)
10 year monthly mean subtracted
D. SOIL MOISTURE
Soil Wetness in Layer 2
10 Year Mean (1979–88)
Soil Wetness in Layer 2
10 Year Mean (1979-88)
Estimated Soil Wetness L2
10 Year Mean (1979-88)
Anomaly Soil Moisture Simulation Year 1 (1979)

Contours -0.3 -0.2 -0.1 -0.05 0.05 0.1 0.2 0.3 deficit dashed

[World map showing soil moisture anomalies for DJF and MAM seasons]
Anomaly Soil Moisture
Simulation Year 2 (1980)

Contours: -0.3, -0.2, -0.1, -0.05, 0.05, 0.1, 0.2, 0.3 deficit dashed
Anomaly Soil Moisture
Simulation Year 4 (1982)
Contours -.3 -.2 -.1 -.05 .05 .1 .2 .3 deficit dashed
Anomaly Soil Moisture Simulation Year 5 (1983)

Contour -0.3 -0.2 -0.1 -0.05 0.05 0.1 0.2 0.3 deficit dashed
Anomaly Soil Moisture
Simulation Year 7 (1985)
Contours -.3 -.2 -.1 -.05 .05 .1 .2 .3 deficit dashed
Anomaly Soil Moisture
Simulation Year 8 (1986)
Contours -0.3 -0.2 -0.1 -0.05 0.05 0.1 0.2 0.3 deficit dashed
Anomaly Soil Moisture
Simulation Year 8 (1986)
Contours -3 -2 -1 -0.05 0.05 0.1 0.2 0.3 deficit dashed
Anomaly Soil Moisture
Simulation Year 9 (1987)
Contour -0.3 -0.2 -0.1 -0.05 0.05 0.1 0.2 0.3 deficit dashed
Anomaly Soil Moisture
Simulation Year 10 (1988)
Contours: -.3 -.2 -.1 -.05 .05 .1 .2 .3 deficit dashed
Anomaly Soil Moisture
Simulation Year 10 (1988)

Contour: -.3 -.2 -.1 -.05 .05 .1 .2 .3 deficit dashed

JJA

SON

ALL
E. TIME SERIES P, E, SOIL MOISTURE
VIII. RADIATION

A. NET SHORTWAVE RADIATION
NETSWTOA/JAN(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 60 160 260 360, contour interval 20
NETSWTOA/JUN(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 60 160 260 360, contour interval 20

AMIP

ERBE

DIFF

216
NETSWTOA/JUL (85-88) (W/m**2)
4 Year Mean (1985-88)
shaded 60 160 260 360, contour interval 20
NETSWTOA/AUG(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 60 160 260 360, contour interval 20
NETSWTOA/SEP(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 60 160 260 360, contour interval 20

60N
50N
EQ
30S
60S

0 60E 120E 180 120W 60W 0
NETSWTOA/OCT (85-88) (W/m**2)
4 Year Mean (1985-88)

shaded 60 160 260 360, contour interval 20
NETSWTOA/DEC(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 60 160 260 360, contour interval 20
B. OLR
OLR/JAN(85–88) (W/m²²)
4 Year Mean (1985–88)
shaded 140 180 220 260, contour interval 20
OLR/FEB (85–88) (W/m²)
4 Year Mean (1985–88)
shaded 140 180 220 260, contour interval 20

AMIP

ERBE

DIFF

226
OLR/MAR (85–88) (W/m²²)
4 Year Mean (1985–88)
shaded 140 180 220 260, contour interval 20
OLR/MAY(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 140 180 220 260, contour interval 20
OLR/JUN(85-88) (W/m**2)
4 Year Mean (1985-88)

Shaded 140 180 220 260, contour interval 20
OLR/SEP(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 140 180 220 260, contour interval 20
OLR/NOV (85–88) (W/m²²)  
4 Year Mean (1985–88) 
shaded 140 180 220 260, contour interval 20
OLR/DEC(85–88) (W/m**2)
4 Year Mean (1985–88)
shaded 140 180 220 260, contour interval 20
Circulation and Rainfall Climatology of a 10-Year (1979-1988) Integration With the Goddard Laboratory for Atmospheres General Circulation Model

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A 10-year (1979-1988) integration of Goddard Laboratory for Atmospheres (GLA) general circulation model (GCM) under Atmospheric Model Intercomparison Project (AMIP) is analyzed and compared with observation. We present the first momentum fields of circulation variables and also hydrological variables including precipitation, evaporation, and soil moisture. Our goals are i) to produce a benchmark documentation of the GLA GCM for future model improvements, ii) to examine systematic errors between the simulated and the observed circulation, precipitation, and hydrologic cycle, iii) to examine the interannual variability of the simulated atmosphere and compare it with observation, and iv) to examine the ability of the model to capture the major climate anomalies in response to events such as El Niño and La Niña. The 10-year mean seasonal and annual simulated circulation is quite reasonable compared to the analyzed circulation, except the polar regions and area of high orography. Precipitation over tropics are quite well simulated, and the signal of El Niño/La Niña episodes can be easily identified. The time series of evaporation and soil moisture in the 12 biomes of the biosphere also show reasonable patterns compared to the estimated evaporation and soil moisture.

Simulated/Observed Climate; Atmospheric Circulation; Global Hydrologic Cycle; Seasonal and Annual Mean Field