Chapter 2.4 The Global Distribution of Precipitation and Clouds

Submitted for review as a Chapter for the report: SCIENTIFIC ASSESSMENT OF THE EFFECTS OF AEROSOLS ON PRECIPITATION

(Prepared by the International Aerosol-Precipitation Science Assessment Group (IAPSAG)) for the World Meteorological Organization

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The water cycle is the key circuit moving water through the Earth's system. This large system, powered by energy from the sun, is a continuous exchange of moisture between the oceans, the atmosphere, and the land. Precipitation (including rain, snow, sleet, freezing rain, and hail), is the primary mechanism for transporting water from the atmosphere back to the Earth's surface and is the key physical process that links aspects of climate, weather, and the global water cycle. Global precipitation and associate cloud processes are critical for understanding the water cycle balance on a global scale and interactions with the Earth's climate system. However, unlike measurement of less dynamic and more homogenous meteorological fields such as pressure or even temperature, accurate assessment of global precipitation is particularly challenging due to its highly stochastic and rapidly changing nature. It is not uncommon to observe a broad spectrum of precipitation rates and distributions over very localized time scales. Furthermore, precipitating systems generally exhibit nonhomogeneous spatial distributions of rain rates over local to global domains.

Over the last century, numerous investigators have attempted to characterize the global distribution of precipitation. Bruckner, as early as 1905, published one of the first worldwide precipitation maps, and roughly 50 years later Moller published a set of seasonal precipitation maps for the globe (Rudolf and Rubel (2004). Jaeger (1976) provided the first numerical gridded precipitation values. Legates and Willmott (1990) compiled the first objectively analyzed global precipitation climatology based on over 25,000 bias-corrected rain gauges. The *Global Precipitation Climatology Project* (GPCP) was established by the *World Climate Research Program* (WCRP) in 1986 with the goal of providing monthly mean precipitation data on a 2.5 x 2.5 degree latitude-longitude grid. The GPCP version-2 precipitation climatology compiles 24 years (1979-2002) of global monthly data based on techniques that combine various satellite products and gauge data (Adler et al. 2003). Rudolf and Rubel (2004) provides the most complete reference of on historical and current efforts to represent globally distributed precipitation.

Global Distribution of Clouds

A discussion of the global distribution of clouds is relevant to any treatise on global precipitation distribution since the global-, synoptic-, and regional-scale processes are so interconnected. The International Satellite Cloud Climatology Project (ISCCP) was established in 1982 as part of the WCRP to collect weather satellite radiance measurements and to analyze them to infer the global distribution of clouds, their properties, and their diurnal, seasonal and interannual variations (Rossow and Schiffer, 1991). The resulting datasets and analysis products are being used to study the role of clouds in climate, both their effects on radiative energy exchanges and their role in the global water cycle. The ISCCP cloud datasets provide the first systematic global view of cloud behavior of the space and time scales of the weather yet covering a long enough time period to encompass several El Nino - La Nina cycles. Though numerous investigators have studied the global distribution of clouds (see Arking 1964; Chahine 1982; Hughes 1984; Mohkov and Schlesinger 1993; Rossow and Cairns 1995), the discussion herein is anchored by recent results from the ISCCP project (http://isccp.giss.nasa.gov).

Global and Seasonal Distribution of Cloud Amount

When the cloud variations on time scales less than a month (weather) are removed, the largest remaining variations of clouds occur from region-to-region and are constant in time. That is, once weather variability is removed the regional differences in average cloud properties are larger than the seasonal and slower climate variations. Figure 1 shows the time-averaged geographic pattern of cloud amount as the annual mean distribution averaged over the whole ISCCP dataset along with the average variation with latitude. Cloud amount is greater in the mid-latitude storm tracks and in the convective zone in the tropics. The "desert" zone exhibits much less cloud amount. The regional cloud amount variations at low latitudes are presence of the subtropical high-pressure systems. Subsiding air from high pressure suppresses uplift, which inhibits the formation of precipitation. Precipitation increases in the mid-latitudes where vastly contrasting air masses collide along synoptic frontal systems to cause precipitation. At the poles, precipitation decreases due to cold temperatures, polar subsidence, and associated low saturation points. The latent heating associated with precipitation, particularly in the tropics, is a primary atmospheric energy source that drives the Earth's weather and climate engine. For example, the annual global mean precipitation P is typically referenced as 1000 mm/yr or 2.74 mm//d (Jaeger 1976). This number corresponds to the energy flux of 78.5 W/m^2, which represents the global latent heat transfer from the atmosphere to the Earth's surface by the release of sensible energy from condensation in the clouds and consumption by evaporation of rain at the surface (Rudolf and Rubel 2004). Actual values of P vary from a minimum of 0 millimeters per day or to a maximum of 10 millimeters per day depending on location. The reasons for these patterns are related to variations in general circulation, synoptic, and mesoscale processes:

- The deserts in the subtropical regions occur due to a lack of mechanism for lifting air masses. In fact, these areas are dominated by subsiding air that results from global circulation patterns.
- Continental areas tend to be dry because of their distance from moisture sources.
- Polar areas are dry because cold air cannot hold as much moisture as warm air.
- Areas near the equator are characterized by high rainfall amounts because constant solar heating forces convection in the ITCZ and other circulation-generated convergence regions.
- Mid-latitudes weather systems are primarily governed by cyclonic activity and frontal lifting where polar and subtropical air masses meet at the polar front. Further, the air masses in this region generally propagate from west to east, causing levels of precipitation to decrease East of source regions.
- Mountain ranges near water sources can receive high rainfall amounts because of orographic uplift, if and only if the prevailing winds are in their favor. This can also result in a sharp reduction in rainfall in regions adjacent or on the leeward slopes of these areas. This phenomenon is commonly known as the rainshadow effect.

The aforementioned discussion is a gross representation of the true geographical distribution of precipitation. Orientation of winds, mountain systems, and air mass dominance play important roles in the pattern of precipitation. The temporal variation of precipitation over the earth is also important. The temporal variation is directly linked to the seasonal changes in the heating of the Earth and its affect on the movement of global pressure systems and air masses. Precipitation becomes more seasonal as one moves away from the Equator. This is primarily due to the shifting locations of global wind and pressure systems.

The Climatology of Global Precipitation

The GPCP Version-2 merged precipitation product (Adler et al. 2003) is now considered a standard for assessing the climatology and spatial structure of global precipitation. Figure 6 displays the 1979-2001 GPCP precipitation climatology map. The climatology shows the expected main features in the tropics and subtropics: (1) maxima in the ITCZ in the Atlantic, Pacific, and Indian Oceans; in the South Pacific convergence zone (SPCZ); and over tropical Africa, South America, and the Maritime Continent between the Pacific and Indian Oceans, (2) dry zones in the eastern parts of the subtropical oceans and the deserts over land, (3) a narrow Pacific ITCZ in the northern hemisphere with peaks in both the western and eastern parts of the ocean (values of 8.8 and 9.1 mm day^{-1}, respectively), (4) weaker Atlantic Ocean ITCZ, and (5) an Indian Ocean feature extending westward from Sumatra and narrowing along the equator. The climatology is equally successful in revealing many features of the mid-latitude: (1) distinct storm tracks in the Atlantic and Pacific Oceans with peak values larger than those in the Southern Hemisphere circumpolar storm track, (2) a secondary maximum along the northwest coast of North America, (3) a weak maxima southeast of Africa and South America, and (4) a poleward extension of the SPCZ in the South Pacific Ocean.

Adler et al. (2003) also present a zonal-averaged latitudinal profile of precipitation (figure 7a) for the GPCP, Jaeger (1976) and Legates and Willmott (1990) climatologies. Variations in the different profiles represent uncertainty in global precipitation estimation techniques and understanding. All three climatologies peak near in the 0-10° N latitudinal belt (roughly 6° N and 5.5 mm/day^{-1} for GPCP). A secondary peak or slope change near 5°S is a composite of various ocean and land features that do not connect over any large longitudinal range (Adler et al. 2003). Figure 7b shows the zonal profile for GPCP decomposed into ocean and land. It is evident that the land peak is closer the equator than the ocean peak. The relative maxima in the ranges of 30-60° N and 35-65° S represent the mid-latitude peaks associated with storm tracks and other mid-latitude precipitation processes. Figure 7b also indicates that the northern hemisphere has more rainfall in the subtropics due to more extensive land mass. Adler et al. (2003) theorize that the land extent likely draws the ITCZ into the northern hemisphere and helps produce the stronger Asian monsoon. Conversely, in the 25-65° S belts, the southern hemisphere has slightly greater precipitation although the northern hemisphere has a greater total in the belt, if only oceans are considered. This fact may indicate that wave processes produce larger precipitation amounts over the oceans, but drier landmasses in this latitude zone reduce amounts to below southern hemisphere values.

Seasonal Variations in Global Precipitation

Seasonal variations are also evident in the global precipitation record. In figure 8, zonally averaged seasonal precipitation maps of Adler et al. (2003) indicate that the major precipitation peaks in the tropical regions of the Indian and Pacific Oceans, South America, and Maritime Continent are south of the equator in January. At mid-latitudes the northern hemisphere ocean peaks are the strongest and are located further south in January. In the southern hemisphere storm track the precipitation maximum is weakest. Another interesting observation is that by July the tropical precipitation peaks have shifted northward as the sun ebbs higher. The northern hemisphere storm tracks are now weaker but the southern hemisphere circumpolar track is strongest. Figure 8 also indicates the strong influence of land. The latitudinal ranges covered by the precipitation maximum during the annual cycle are larger for land areas, which indicates the amplification of the annual cycle by land heating. Other interesting seasonal variations are evident in these and other climatologies.

Interannual Variations in Global Precipitation

The El-Nino-Southern Oscillation (ENSO) is a significant forcing function for the interannual variability in global and hemispheric precipitation distributions (Bjerknes 1969; Arkin 1982). According to New et al. (2001), ENSO explains about 38% of the interannual variance in globally averaged land precipitation and about 8% of the variability of global precipitation. Curtis and Adler (2000) revealed the GPCP precipitation anomalies associated with the 1997-1998 El Nino event (figure 9). Numerous investigators have described ENSO-related changes in global precipitation using ground-based and satellite-based techniques (Dai and Wigley 2000; Arkin et al. 1994; Ropelewski and Halpert 1996). Curtis and Adler (2000) created the ENSO precipitation index (ESPI). Curtis and Adler (2003) characterized the evolution of global precipitation during six El Nino events in the 23-year GPCP record. In the analysis, precipitation anomaly patterns were a function of state of evolution and intensity. They found the strongest precipitation anomalies near the equator, with increases in rainfall over much of the Pacific and decreases over the Maritime Continent, the Amazon, and Central Africa. Significant changes in mid- and high-latitude, seasonal precipitation were also observed. These are observations are consistent with other studies in the literature.

Global Climate Change and Trends in Global Precipitation

The TA Report of the International Panel on Climate Change (IPCC, 2001) suggests that increasing global surface temperatures are likely to lead to changes in precipitation, a more active hydrological cycle, and increased water holding capacity throughout the atmosphere. Yet, the calculation of changes in global precipitation is a challenge. Currently, there are no sufficiently long-term satellite-base records (thus no observations over oceans before 1979). The IPCC (2001) indicated that positive trends in precipitation were evident over North America and negative trends in other parts of the world. A time series of monthly, global anomalies from the 23-year mean value is shown in figure 10 (Adler et al. 2003). There is no noticeable positive trend over the observed period whereas climate model projections have suggested that such a trend should exist. As Adler et al. (2003) point out, the predicted increase is small and may not be detectable over a short period (e.g. 20 years). Long-term records now emerging from GPCP, the Tropical Rainfall Measuring Mission, and eventually the Global Precipitation Measurement (GPM) mission will provide the needed climate record to adequately address this issue.

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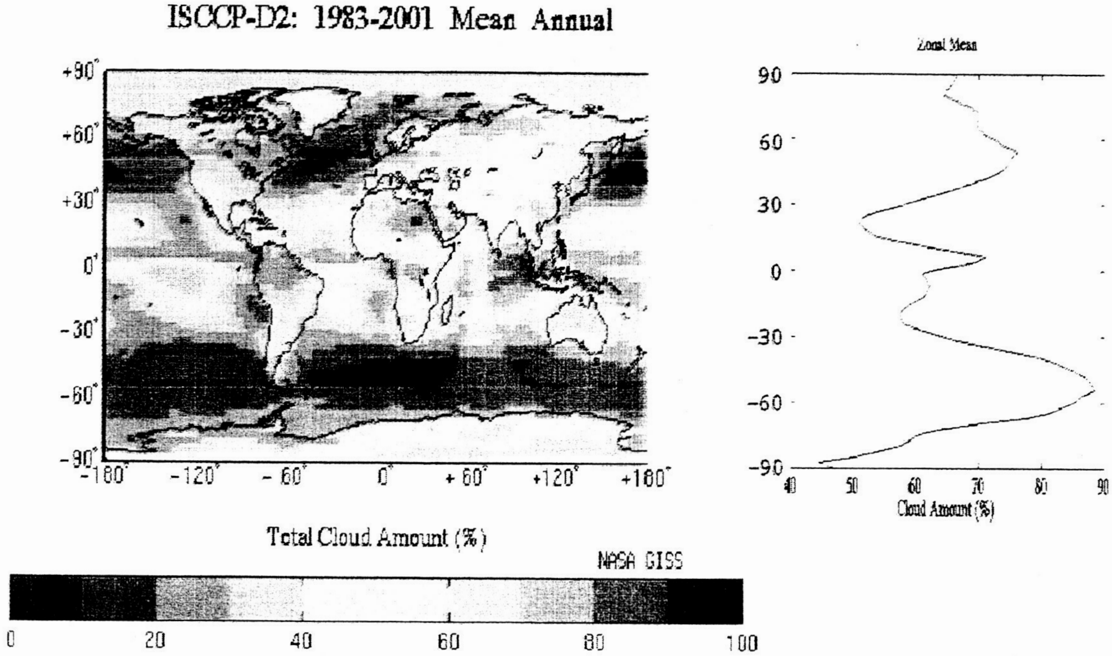


Fig. 1-Mean annual total cloud amount and zonal means from 1983-2001 (courtesy of W. Rossow/NASA GISS).

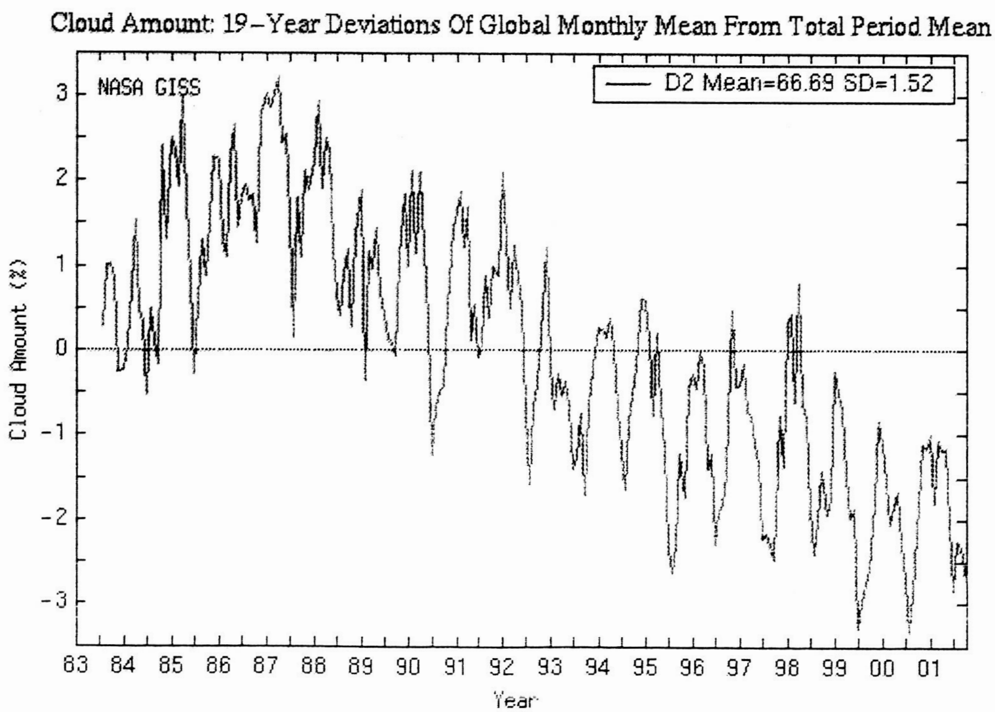


Fig. 2-19-year deviations of global monthly mean cloud amount from total period mean (courtesy of W. Rossow/NASA GISS)

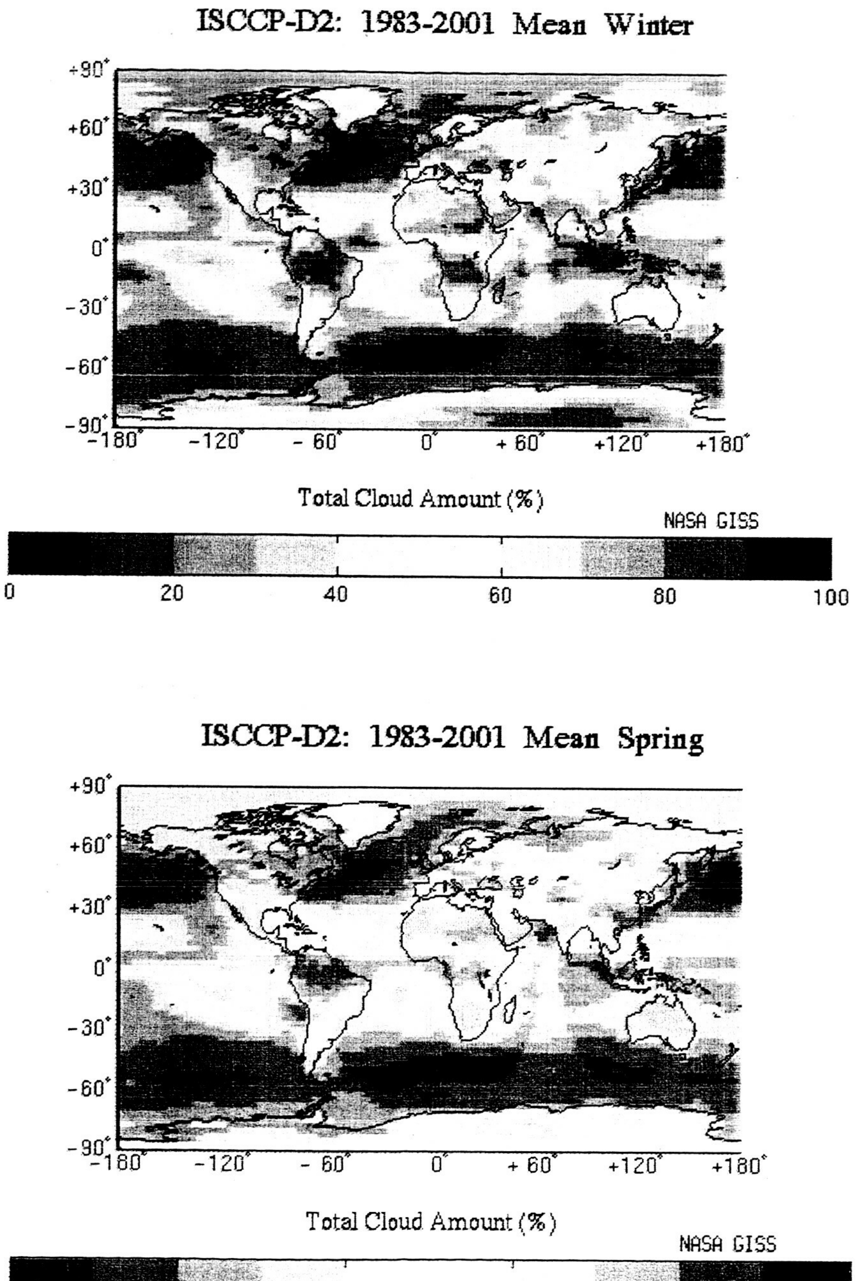
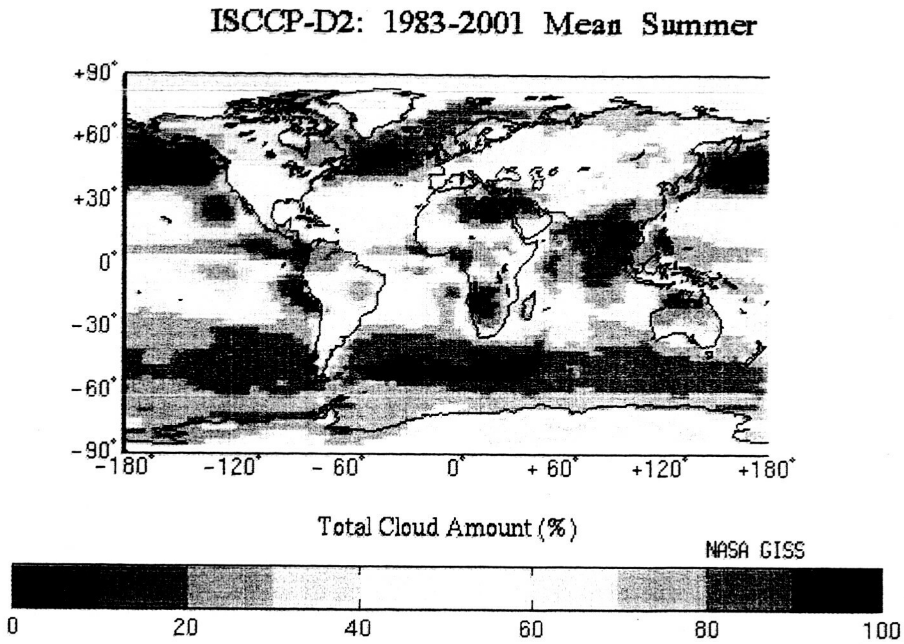


Fig. 3-Mean total cloud amount from 1983-2001 (winter and spring). Courtesy of W. Rossow (NASA/GISS)



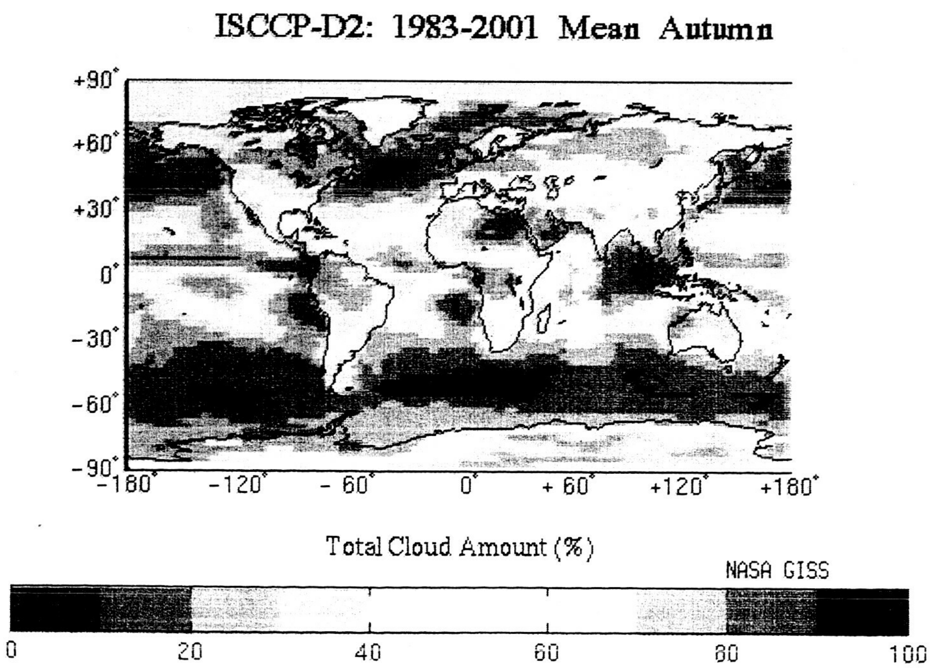


Fig. 3 cont.-Mean total cloud amount from 1983-2001 (summer and autumn). Courtesy of W. Rossow (NASA GISS)

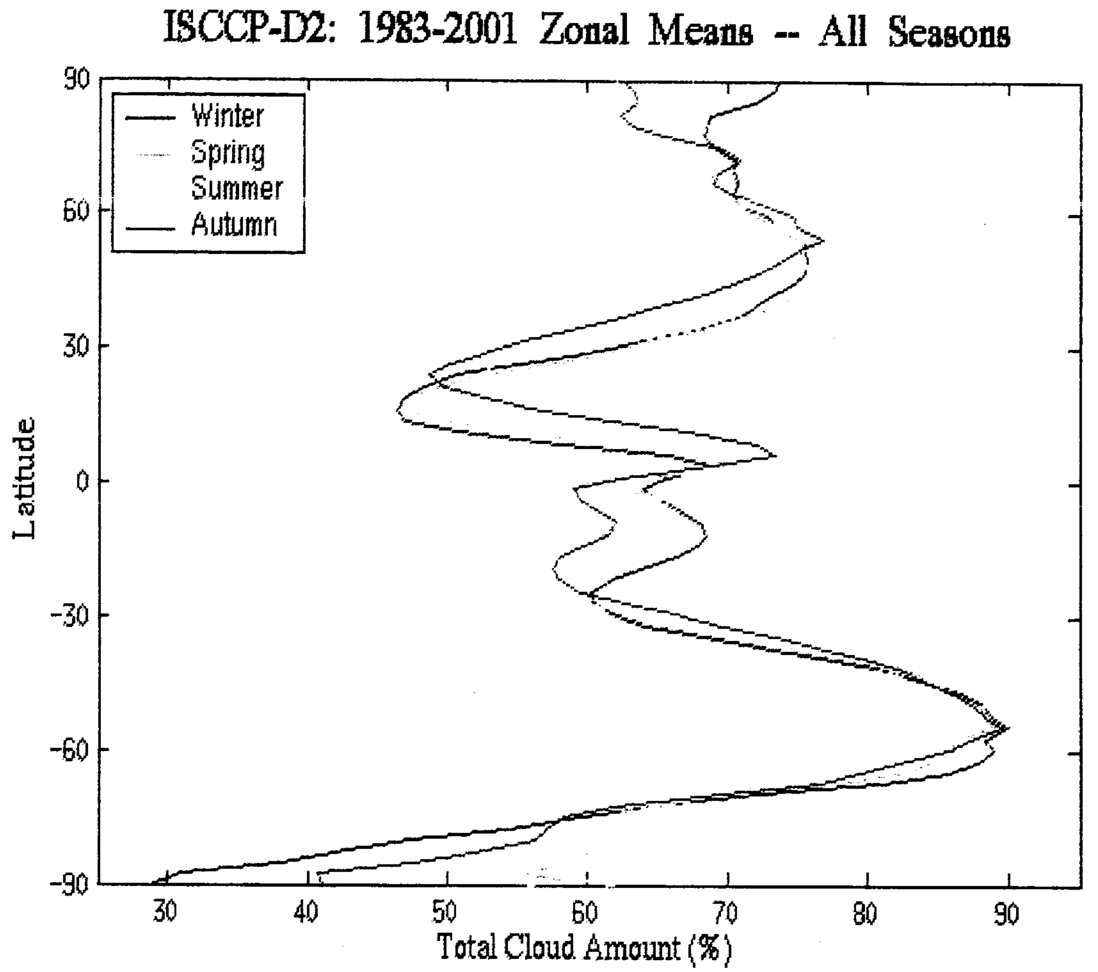


Fig. 4-Latitudinal variation in seasonal zonal mean total cloud amount (Courtesy of W. Rossow/NASA GISS)

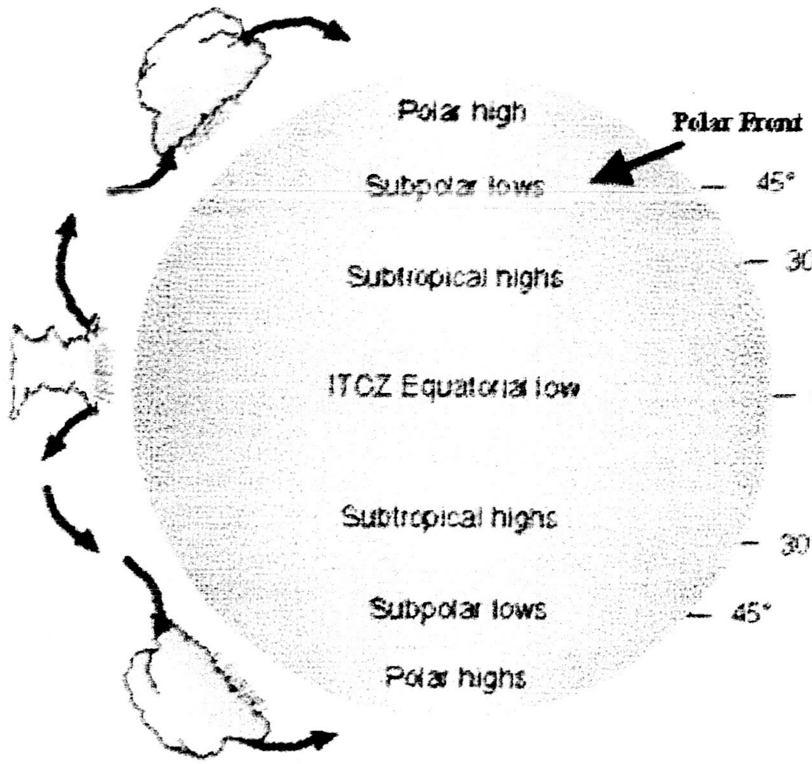


Fig. 5. Schematic of the Earth's general circulation pattern.

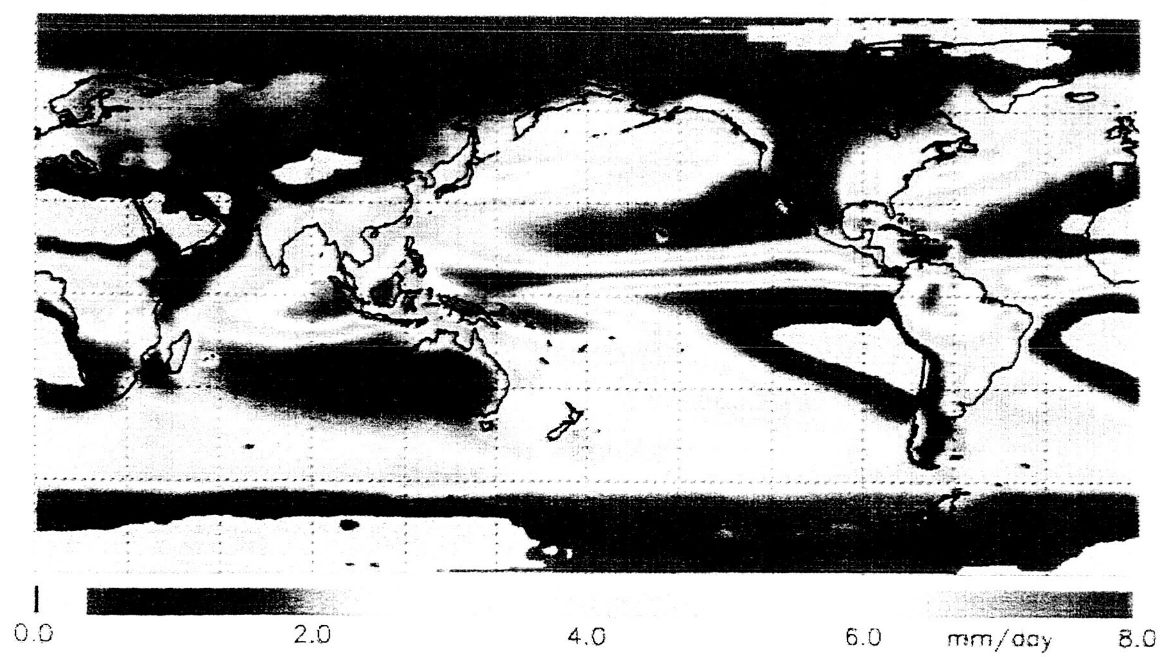
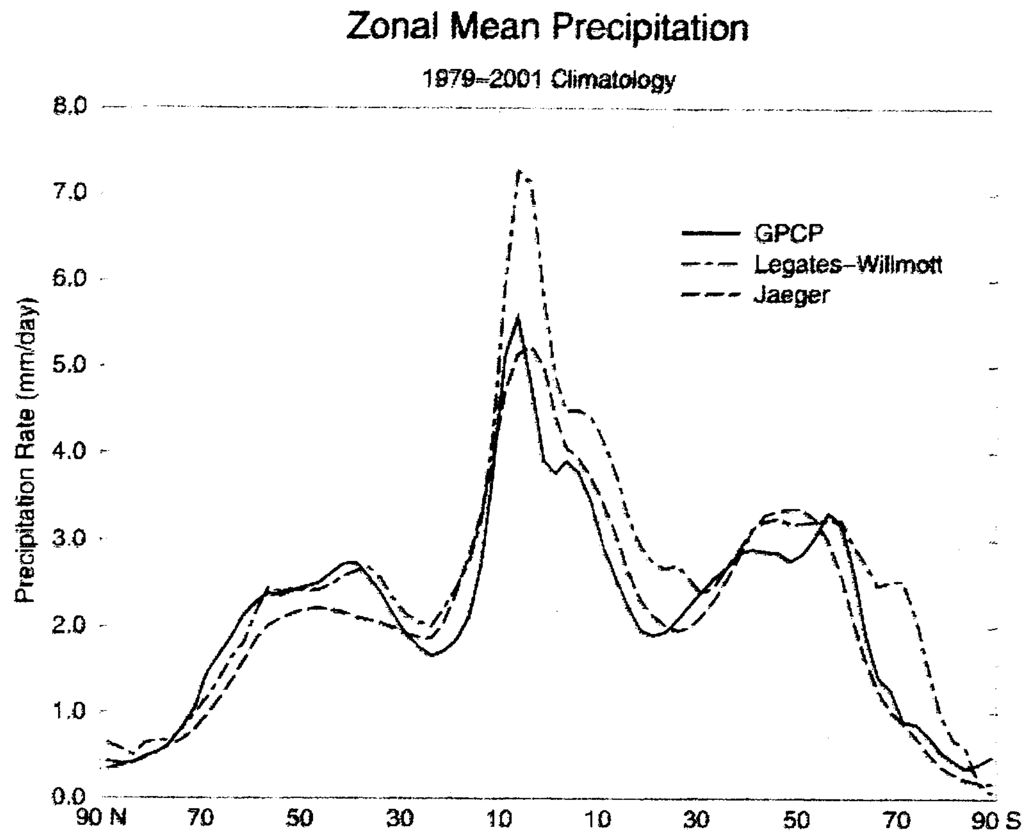


Fig. 6- The 1979-2001 GPCP precipitation (mm/day(climatology (following Adler et al. 2003).



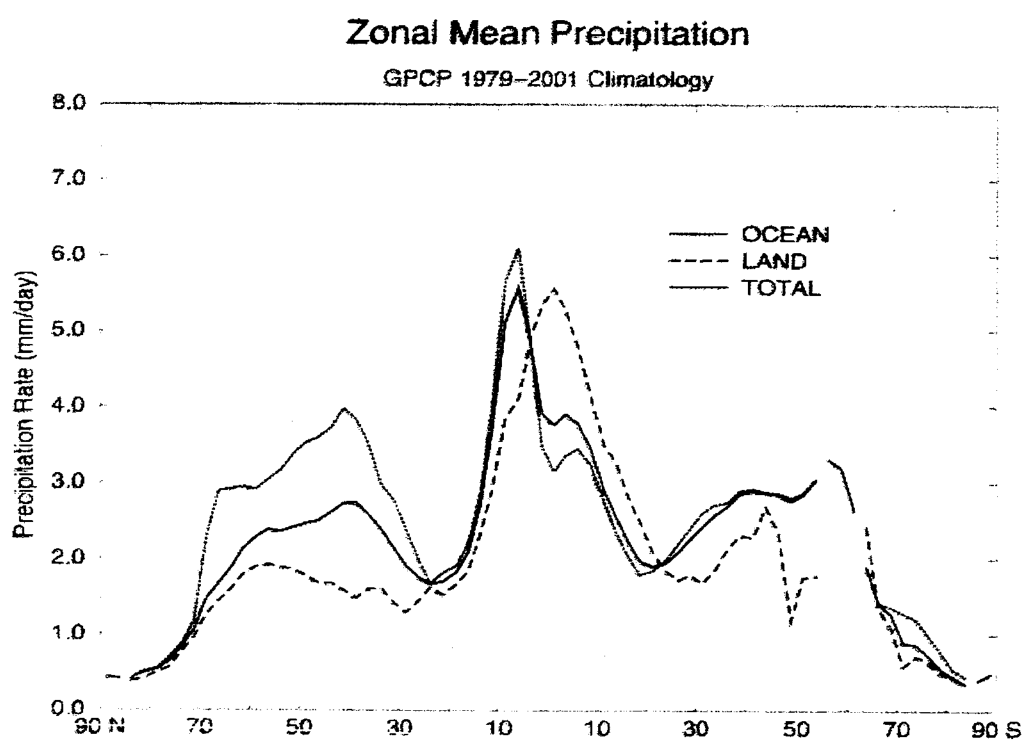


Fig. 7a- Zonal-averaged latitudinal profile of precipitation for GPCP (Adler et al. 2003), Legates and Wilmott (1990), and Jaeger (1976).

Fig. 7b-Zonal-averaged latitudinal profile of precipitation for GPCP for land, ocean, and total amount.

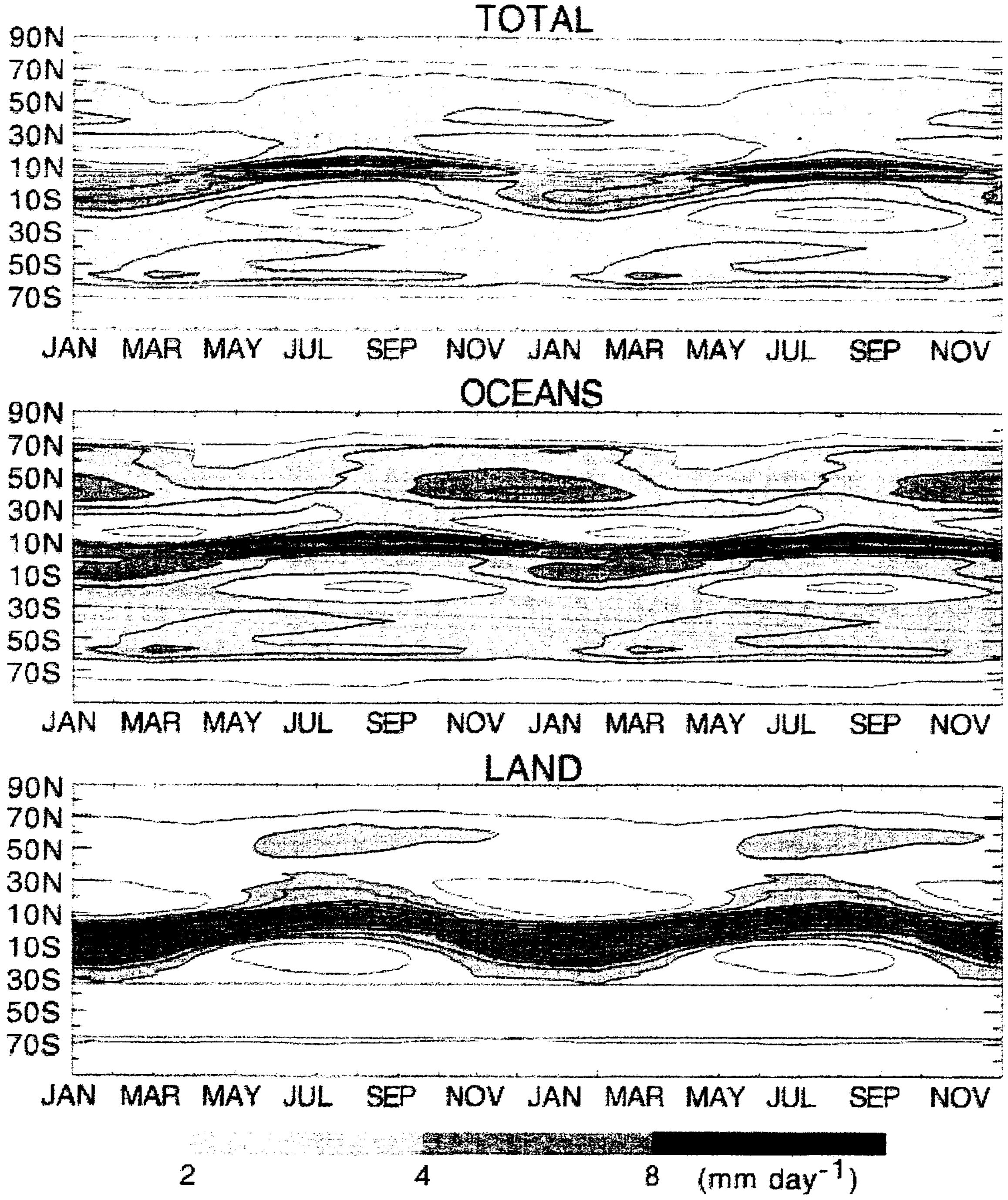


Fig. 8-Two annual cycles of zonally averaged precipitation (mm day-1) over the globe (90°N–90°S) for the (top) total field, (middle) ocean only, and (bottom) land only. Contours are every 1 mm day-1, beginning at 1 mm day-1. Darker shading indicates greater precipitation rates. There is no appreciable land around 50°S as indicated by the lack of data there in the bottom panel, (Courtesy of Adler et al. 2003).

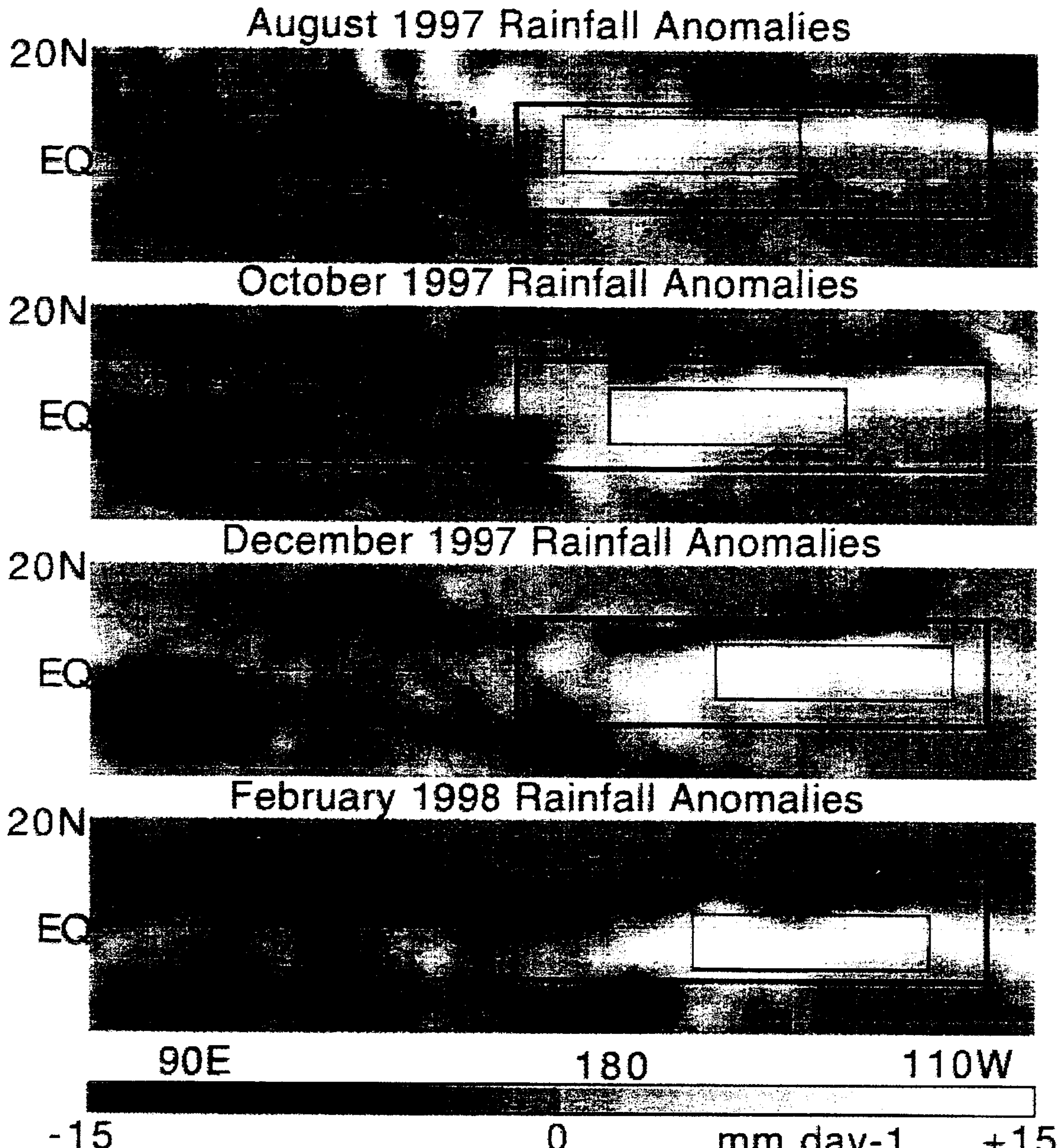


Fig. 9-GPCP-dervid rainfall anomalies (mm/day) associated with the 1997-1998 ENSO event (following Curtis and Adler 2000).

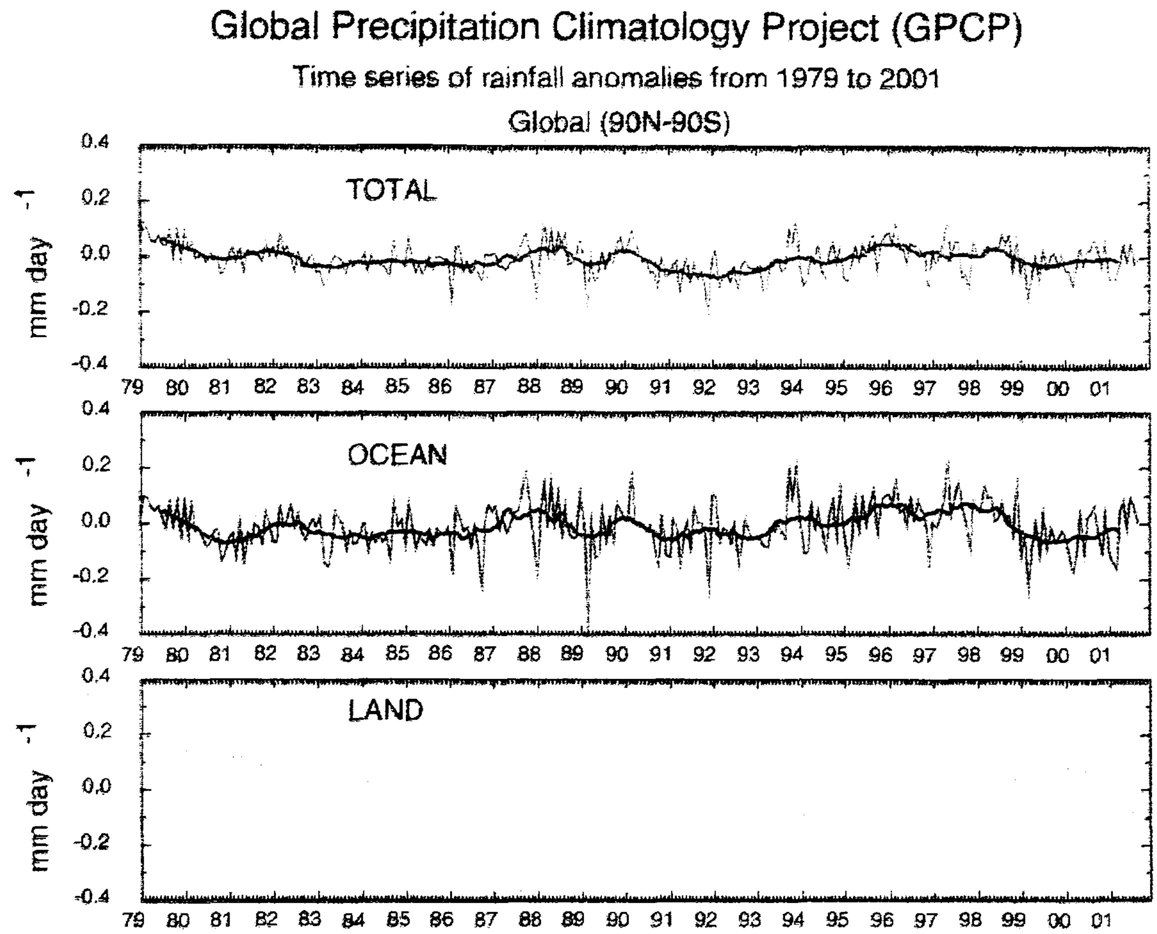


Fig. 10-Time series of rainfall anomalies from 1979-2001 (following Adler et al. 2003).

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Popular Summary:

The role of aerosols on the Earth's weather and climate is being detected in many areas. Aerosols are particles like dusts, sea salt, are particles emitted from automobile exhausts. The United Nation's (UN) World Meteorological Organization has created a special panel of experts to assess the role of human-generated and natural aerosols on precipitation and clouds. In preparing an assessment of how the Earth's precipitation patterns are changing, it is important to understand how the sun's energy, Earth rotation, and other factors combine to create the average cloud and precipitation distribution on the planet. Once this is known, it will be easier to for the UN committee to determine how the dust, soot, and other aerosols are impacting those basic precipitation climate patterns. This paper provides an overview of the most current understanding global distribution of precipitation and clouds using satellite and ground measurements.