Estimating Climatic-Scale Precipitation from Space: A Review*

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ABSTRACT

Measurement of climatic-scale precipitation (defined here as averages over areas of $>10^4$ km^2 and periods of five days or longer) is impractical for many areas of the earth without the use of space-based observations. We briefly discuss the history of satellite rainfall estimation schemes and their application to climate studies. Two approaches—direct and indirect—have dominated work until very recently, when attempts to use more integrated techniques began. Indirect schemes, primarily based on visible and infrared (IR) observations of the characteristics of clouds, have been used in the majority of such studies. Direct schemes, such as those that use microwave observations of raindrop-sized hydrometeors, have been limited by a relative lack of the required measurements. A large number of studies have used datasets not originally intended as precipitation estimates at all, such as the NOAA outgoing longwave radiation data, to produce estimates of very large scale rainfall. Current and prospective attempts to overcome some of the difficulties affecting climatic-scale precipitation estimation are described. The Global Precipitation Climatology Project will integrate data from surface observations, geostationary IR sensors, and polar-orbiting microwave and IR sensors to produce near-global analyses of monthly rainfall. The proposed Tropical Rainfall Measuring Mission will use a single satellite with an instrument package that will make visible, IR, and microwave radiometric observations. The package will also include a precipitation radar. We discuss certain other proposed satellite missions and international programs and their contributions to the production of climatic-scale precipitation estimates. Finally, we propose the development of a global rainfall analysis system.

1. Introduction

Observations from space play a critical role in the description of spatial and temporal variations in rainfall on climatic scales. This assertion is defendable only when the term "climatic" is appropriately defined; one can certainly determine time and space scales for which rain gage and/or radar observations are more than adequate.

The definition of a time and/or space scale appropriate to climate studies is not a trivial task; several concepts are involved. One is the characteristic time scale of the phenomena of interest, such as several years for the El Niño/Southern Oscillation (ENSO) phenomenon, 18 months for an ENSO warm episode (Rasmusson and Carpenter 1982), and 1–2 months for the Madden–Julian oscillations in tropical convection and circulation (e.g., Lau and Chan 1983a). Another is the time resolution required for the study of such phenomena—e.g., seasonal, monthly, and 5-day for the three examples above. A third is the temporal resolution of data required for the construction of datasets used in the study of such phenomena. That is, seasonal mean and anomalous circulation maps are required for the study of ENSO, but twice-daily analyses are generally used in the construction of such charts. Thus, for ENSO one might characterize the time scale as interannual, seasonal, or 12-hourly. A similar discussion can be given for spatial scales.

In many studies, climatic scale is used as roughly equivalent to large (spatial) or long (temporal) scale. In this paper, we will use the second of the possibilities discussed in the preceding paragraph, i.e., the resolution required for the study of climatic phenomena. We will define climatic scale as *area-averaged over regions of at least* 10^4 *km*^{2} (1° latitude/longitude) and *averaged or accumulated over time periods of down to 5 days.*

As an illustration of the significance of variations in tropical rainfall to the climate, consider the ENSO phenomenon. ENSO is characterized by large changes in tropical sea surface temperatures (SSTs) and associated changes in atmospheric circulation and precip-

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itation on time scales of several years (Rasmusson and Carpenter 1982). *Circulation and precipitation* changes in many parts of the globe remote from the tropical Pacific have been associated with ENSO warm episodes (Arkin 1982; Rasmusson and Carpenter 1983; Ropelewski and Halpert 1987), but the physical link between changes in the ocean–atmosphere interactions in the tropical Pacific and global climate anomalies is believed to be associated with the changes in the distribution and intensity of convection that are related to the changes in SST. Understanding the physics involved certainly requires observations of the climatic-scale rainfall over the tropical Pacific Ocean.

Two important considerations for the development of datasets of any type for the study of climate are consistency and continuity. Observations and analyses that are severely restricted in space or time—e.g., to just a few years or to a small part of the earth—are of little use in gaining a comprehensive description of climate variability. Even long duration datasets may be inadequate for such studies if inhomogeneities are introduced by changes in instrumentation and/or processing techniques. Variability due to such inhomogeneities can be extremely difficult to distinguish from any actual climate signal.

In this paper we will 1) discuss the history of attempts to estimate climatic-scale rainfall from satellite observations, 2) describe the current state-of-the-art, and 3) discuss some of the potentially fruitful avenues to be pursued in the near future. We will attempt neither to perform an exhaustive inventory of rainfall estimation techniques, nor to list every case where an implicit estimate of climatic-scale precipitation has been used in studies of ENSO or other significant climate fluctuations. We *will* present overviews of such techniques and applications, and illustrate them with a few examples.

2. Background

The potential for estimating rainfall has been evident from the very earliest days of orbiting satellite imagery. Radiances observed in many different spectral regions were found to offer physically plausible means of deriving rainfall rates, and such applications developed quickly. Martin and Scherer (1973) and Barrett and Martin (1981) both contain good summaries of the wide variety of precipitation estimation techniques developed up to then. However, until recently, few if any rainfall estimation schemes were actually applied in a manner that allowed the products to be used for climate studies of the sort discussed here. In this section we restrict our discussion to rainfall estimates derived from passive radiometric observations made from above the atmosphere, which can be divided into two classes—direct, or observations of precipitating particles, and indirect, or observations of anything else.

a. Indirect rainfall estimation

Indirect estimates of rainfall, based on observations of clouds in visible and thermal IR imagery, have been used extensively. All such estimates rely first on the fact that rainfall is nearly always associated with clouds of some type, and second on the observation that higher and/or thicker clouds appear to be associated with heavier or more frequent precipitation. An early attempt to use cloud brightness alone to estimate rainfall was made by Kilonsky and Ramage (1976), who used the frequency of highly reflective cloud (HRC) in visible polar-orbiter imagery as an index of monthly rainfall in the tropical Pacific. They defined HRC as subjectively determined assemblages of areas of bright cloudiness with a radius equal to or greater than 2° of latitude. Correlation of HRC with monthly rainfall observed at atoll stations in the tropical Pacific was 0.75. From this beginning, the HRC dataset has been extended to cover the global tropics between the latitudes of 25°N and 25°S for each month since the beginning of 1971. Garcia (1981, 1985) described the characteristics of the data and the processing involved, and made comparisons with other rainfall estimation schemes. Even though the HRC was originally developed as a quantitative estimate of monthly rainfall, its most common usage has been as an index of convective activity. This application has served to ameliorate its two most serious defects—the poor diurnal sampling and the subjectivity involved. Despite these problems, the HRC has played an important role in climate studies because of its availability for the 1972–73 ENSO episode, as well as the three following episodes, and because of its high spatial resolution (1° × 1°).

Estimates of outgoing longwave radiation (OLR) were first made in June 1974 from window channel measurements of the operational NOAA polar-orbiting satellites (Gruber and Winston 1978; Gruber and Krueger 1984). Because values of OLR in the tropics respond more strongly to variations in cloudiness than any other factor, it was soon recognized (e.g., Heddinghaus and Krueger 1981; Liebmann and Hartmann 1982) that OLR was a useful index of convective activity in those latitudes. In that role it was used as a qualitative estimate of precipitation in a great number of studies beginning in the early 1980s. For example, Lau and Chan (1983a, 1983b, 1985, 1986) used the OLR as an estimate of tropical convective activity, and implicitly as precipitation, and to explore the role of tropical convection in the ENSO phenomenon and in intraseasonal oscillations. Weickmann (1983) and Weickmann et al. (1985) used OLR as an index of tropical convective activity in descriptive studies of intraseasonal oscillations.

The first published use of OLR as a quantitative estimate of rainfall in the tropics was by Lau and Chan (1983a) in their investigation of short-term climatic variability and teleconnections in tropical convection and circulation. They used the number of days in a month with OLR < 240 W m^{-2} as a predictor of monthly rainfall and calibrated it against a microwave-based estimate. Arkin (1984) used the mean OLR as an estimate and calibrated it against rainfall observations at island stations in the central Pacific, using the same set of stations as Kilonsky and Ramage (1976) but with data through 1980. Later extensions of this work have shown that threshold-based estimates, as in Lau and Chan, are correlated with those from mean OLR at 0.96 or greater over India. In the last few years, Morrissey (1986), Motell and Weare (1987) and Yoo and Carton (1988) have clearly demonstrated that OLR can be used, albeit with rather large error bounds, as a quantitative estimate of precipitation in the tropics. While its sampling (twice each day) is superior to that of the HRC, it is still less than optimum. There have also been changes in both instruments and equator crossing times during the period of the dataset (Gruber and Krueger 1984). Nevertheless, OLR-based rainfall estimates over the tropical oceans have already been used in climate studies (Gill and Rasmusson 1983; Weare 1987).

A shortcoming of both the HRC and OLR as precipitation estimators is their poor sampling of the diurnal cycle. Studies by Arkin (1979) and Richards and Arkin (1981) pointed out a potential means for overcoming this deficiency; using data from the GARP Atlantic Tropical Experiment (GATE), they showed that estimates of rainfall could be made using a simple thresholding technique on IR data from geostationary satellites, so long as the spatial and temporal scales were appropriately chosen. Area-averaged estimates based on the fractional coverage by pixels with equivalent blackbody temperature < 235 K for regions of 1.5° and 2.5° on a side for time periods of several hours to one day were found to be correlated with radar-based estimates at more than 0.85 for each of the three phases of the experiment.

Data from which such estimates could be derived were obtained from the operational U.S. geostationary satellites beginning in December 1981. The estimates were labeled the GOES precipitation index (GPI) by Arkin and Meisner (1987) and used to describe the 3-year mean seasonal cycle in estimated rainfall over the Americas and the interannual variability associated with the 1982–83 ENSO episode and to make a comparison with area-averaged station observations. Meisner and Arkin (1987) presented a description of the diurnal cycle in cloudiness and estimated rainfall for the same 3 years in the same region. Turpeinen et al. (1987) incorporated measurements of upper tropospheric humidity in an extension of this technique to data from METEOSAT over several regions in Africa, while similar data from the Japanese geostationary meteorological satellite (GMS) were used in a qualitative manner for a variety of studies in the western Pacific and Indonesian regions (Murakami 1983, 1984; Maruyana et al. 1986; Nitta 1986, 1987; Nitta and Motoki 1987). Estimates identical to the GPI were derived from INSAT-1B beginning in June 1986 and were used in studies of Indian rainfall during 1986 (Arkin et al. 1989).

b. Direct rainfall estimation

Rainfall estimation techniques that are based on observations of the radiative effects of precipitation-sized hydrometeors are called direct (Arkin and Meisner 1987). These techniques must use observations of radiation at frequencies that are not affected by cloud droplets nor by the gaseous constituents of the atmosphere. Such observations can be made in the microwave region of the spectrum.

Passive microwave radiation to space is modulated by three processes: emission, absorption, and scattering (Chandrashekar 1960). These processes depend upon the properties of the earth's surface, atmospheric constituents and hydrometeors (water droplets and ice crystals). The microwave emission from the surface of the earth depends both on its physical temperature and emissivity. Over oceans, the emissivity is relatively constant at approximately 0.4 to 0.5, and varies only weakly with the surface wind speed (Hollinger 1971; Nordberg et al. 1971). The emissivity also has the property—near the frequency of the Nimbus-5 ESMR, for example—of varying inversely with the surface temperature (Wilheit et al. 1977). As a result, microwave emissions from the oceans can provide a relatively constant and predictable background signal (Spencer et al. 1983a). Over land, however, both temperature and emissivity are highly variable. With lower thermal inertia, the skin temperature of the land varies with solar insolation, both diurnally and in response to cloud forcing. Land temperature is also a function of the surface albedo, evaporation and evapotranspiration, altitude, wind speed, and many other factors. The land-surface emissivity is dependent on the thickness, type, and water content of the vegetation canopy (Kirdiashev et al. 1979; Jackson et al. 1982; Mo et al. 1982) and the moisture content and type of the soil. This makes the microwave background signal over land highly variable (Spencer et al. 1983b), making its use there more difficult.

Hydrometeors in the atmosphere interact with microwave radiation both through absorption and scattering. Scattering is the dominant physical process above 60 GHz, and absorption is dominant below the 22 GHz water-vapor absorption line, while between the two regions both are important (Wilheit 1986). The absorptivity of water droplets depends on the cube of their radius and is inversely proportional to the wavelength of the observation (Wilheit et al. 1977). It is necessary, in the absence of any direct information, to parameterize the drop-size distribution statistically; e.g., a Marshall–Palmer (1948) distribution. By making assumptions about the thermodynamic structure of the atmosphere, the rain rate can be retrieved. When an absorption technique is used for space-based remote sensing, the constant microwave background of the oceans is a distinct advantage. Over land, the variable background signal makes retrievals of rain rate based on absorption more difficult.

Wilheit et al. (1982) reported on a set of aircraft-borne microwave observations of Tropical Storm Cora. The results showed, for the first time, a strong inverse relationship between rainfall rate derived from 19 GHz observations and the microwave brightness temperatures at 92 and 183 GHz. Wilheit et al. demonstrated that only the presence of scattering by frozen hydrometeors over a 4-km thick layer could explain the observations. Their results suggested that higher-frequency observations might be useful in discriminating between liquid and frozen particles. Hakkarinen and Adler (1988) confirmed this with observations in a variety of situations over both land and water. Spencer et al. (1983b) also recorded the presence of very low brightness temperatures in SMMR 37 GHz observations over land. In all cases, the very low temperatures were observed to coincide with heavy convective rainfall and were attributed to the presence of a thick layer of precipitation-sized frozen hydrometeors. In many cases, particularly in convective clouds, thick layers of large ice particles are associated with heavy rainfall at the surface. While this association is sufficient to make the use of scattering-based rainfall estimation algorithms feasible, one must be careful not to assume that the intensity of such scattering is a uniformly good measure of rain rate. In this sense, scattering algorithms are less direct than those based on the relationship between liquid droplets and rain rate in the case of absorption (Wilheit 1986).

It should be noted that many effects come into play between the time that space-based microwave radiometers detect the presence of precipitation-sized water droplets and ice particles and the time when the same water falls as precipitation. For example, the particles can be suspended in the clouds due to updrafts and advected horizontally by the wind, and partial or complete evaporation of the falling droplets can occur. In addition, the observations only offer a snapshot of a process involving variability on many time scales.

Four satellite-borne passive microwave imaging instruments have been used extensively for the estimation of rainfall. These are the Electronically Scanning Microwave Radiometer (ESMR)-5, ESMR-6, the Scanning Multichannel Microwave Radiometer (SMMR), and the Special Sensor Microwave/Imager (SSM/I). These have flown, respectively, on the Nimbus-5 (launched in December 1972), the Nimbus-6 (launched in June 1976), the Seasat and Nimbus-7 (launched in October 1978), and the DMSP-5D spacecraft (launched in June 1987).

The ESMR carried on Nimbus-5 measured the radiation emitted by the earth and its atmosphere at the single frequency of 19.35 GHz, scanned in a cross-track mode, and had a footprint at nadir of about 25 km (Wilheit 1972). The ESMR on board Nimbus-6 also measured microwave radiation in a single frequency, but at 37 GHz. The ESMR data were shown to be capable of detecting the presence of rain and of estimating the rain rate (Wilheit et al. 1973; Allison et al. 1974). The Nimbus-5 ESMR rainfall estimates, based on plane-parallel theory, were compared to radar observations taken over the GATE ship array and were found to substantially underestimate the observed rain rates (Smith and Kidder 1978; Austin and Geotis 1978). They attributed this to the incomplete filling of the field-of-view footprint by the active rain cells and to enhanced scattering due to the presence of ice.

The SMMR experiment has taken a long-term set of measurements at 6.6, 10.7, 18, 21, and 37 GHz for both horizontal and vertical polarizations. Data taken by the highest-resolution channel (37 GHz) were compared with radar rain rates over the Gulf of Mexico by Spencer et al. (1983a), who found a correlation of 0.85. The study concluded that the primary modulator of the brightness temperatures was not the rain opacity or rate, but instead the degree of filling of the 37 GHz footprint by the showers. Spencer et al. (1983b) also considered SMMR observations at 37 GHz of heavy thunderstorms over land. They found that the measured brightness temperatures were significantly lower than those possible from rain alone. Further, in each case, the cold brightness temperatures coincided with heavy rainfall at the surface. A thick layer of large frozen hydrometeors, as was postulated by Wilheit et al. (1982) over Tropical Storm Cora, was advanced as the likely explanation. It is clear that 37 GHz SMMR observations have yielded unambiguous indications of the presence of heavy rain rates even over land.

With the launch of the SSM/I instrument, having a multichannel imaging capability at 19.35, 22.24, 37, and 85.5 GHz (with a nominal 15 km footprint), a more robust capability for rainfall estimation now exists. Early results from the SSM/I show strong scattering signals in the 85.5 GHz measurements in the presence of convection in the tropics (e.g., Typhoon Sperry and Typhoon Roy) and over the central United States (N. Grody 1988, personal communication) and even from less strong convection embedded in frontal bands over the southern United Kingdom (Barrett et al. 1988). For the case of Typhoon Roy, the observations not only clearly indicated the intense convective activity in the eye wall, but also resolved the lack of any precipitation at the center of the eye. Spencer et al. (1989) have suggested that a technique using polarization corrected 86 GHz brightness temperature could provide quantitative estimates of areally averaged rainfall for both land and ocean areas in the midlatitudes, as well as the tropics.

Prabhakara et al. (1983, 1986) used SMMR observations to infer the atmospheric liquid water content and rainfall over the oceans on a monthly time scale. Only the lower-frequency (6.6 and 10.7 GHz) data were used due to their relative insensitivity to atmospheric water vapor and ice particle content. In their approach, the 6.6 GHz measurements are used to correct the 10.7 GHz observations for the effect of variations in sea surface roughness caused by the effects of near-surface winds and rain. An empirical linear relationship between the seasonal precipitation and column liquid water content was developed and validated against island station measurements in the tropical and subtropical Pacific Ocean. Correlations of from 0.35 to 0.54 were obtained. The relatively low correlations between island station rainfall and SMMR observations are probably due, at least in part, to the incompatibility between continuous, point measurements (raingages) and intermittent, area-averaged observations (satellite). The SMMR-estimated fields seemed to accurately depict the spatial distribution of the rainfall, delineating the intertropical convergence zone (ITCZ) and the subtropical highs over the Pacific Ocean. The derived fields also described the interannual variability of the rainfall during the period 1979–83 and illustrated the pronounced anomalies present in the Pacific and Indian oceans during the ENSO event of 1982–83. In the eastern equatorial Pacific Ocean, positive rainfall anomalies of greater than 100 cm were observed, while the drought regions over Indonesia and the subtropics of both hemispheres were also clearly portrayed. Ardanuy et al. (1987) used water vapor fields derived by Prabhakara et al. (1986) over the oceans and low-resolution tropical flow fields to obtain the flux convergence of water vapor over the Pacific Ocean during 1980–83. Estimates of rainfall over the domain were correlated with island raingage measurements at 0.60 in many cases. The results were in general agreement with those of Prabhakara et al. (1986). They vividly demonstrate the utility of satellite-derived rainfall observations to describe the time-mean rainfall, as well as its annual and interannual variability on large scales.

3. Current activities

The preceding section contains an overview of recent satellite estimation techniques that have been applied to climate studies. Clearly it is feasible to estimate large-scale rainfall in many areas that are devoid of ground-based measurements. However, all of the schemes discussed to this point have significant impediments to their use in studies of the global climate system. These problems include, for the indirect schemes, incomplete spatial coverage and a relatively weak relationship between clouds and rainfall, and, for the direct schemes, poor resolution and infrequent sampling. Both types suffer from inadequate calibrations. In this section we will describe the Global Precipitation Climatology Project (GPCP), which is an attempt to solve some of these problems.

The GPCP can be characterized as an attempt to make the best possible use of currently available data and algorithms. A workshop organized by the World Climate Research Programme (WCRP) in 1985 (WCRP 1986) examined possible methods of obtaining near global precipitation analyses for various WCRP projects. It concluded that a combination of satellite-based estimation schemes, such as geostationary IR thresholding methods and polar-orbiting microwave estimates, together with surface observations, could yield the required analyses of monthly precipitation amounts over most of the earth. The GPCP comprises several principal centers (Fig. 1), each of which will initially use existing observations and techniques to produce rainfall estimates and/or analyses for the period 1986–95.

The Geostationary Satellite Precipitation Data Center (GSPDC), located at the NOAA Climate Analysis Center (CAC) in Washington, D.C., acquires histograms of IR data for 2.5° × 2.5° areas from 40°N–40°S for 5-day periods from each of the geostationary meteorological satellites. Eight observations are used each day to assure adequate diurnal sampling. The GSPDC develops and applies quality control algorithms and creates a merged set of histograms covering as much of the tropical belt as possible. A simple threshold-type estimation algorithm is applied to this dataset to derive rainfall estimates for each 2.5° region for each time period.

At the present time, the GSPDC is receiving data from all of the Geostationary Satellite Data Processing Centers (operated by the European Space Operations Centre for METEOSAT, Japan Meteorological Agency for GMS, and CAC for GOES), except that for INSAT. Histograms are available from METEOSAT, GMS, and one GOES beginning in January 1986 (only 15-day temporal resolution for GOES until July 1986), and from a second GOES beginning in July 1987. The four-satellite areal coverage is illustrated in Fig. 2; the algorithm used to derive rainfall here is the GPI used by Arkin and Meisner (1987).

These estimates have incomplete tropical convergence due to lack of INSAT data and periods with only a single GOES. A closely related estimate can be computed from OLR observations from NOAA polar-orbiting satellite data using histograms in which the flux value corresponding to the threshold used in the GPI (235 K) is a class boundary. Such histograms have been available since November 1987 and were used where geostationary data were unavailable to complete the global tropical coverage shown in Fig. 3. OLR histograms are available from both NOAA polar-orbiting satellites beginning in June 1988. Thus the GSPDC, compared to previously available rainfall estimates, greatly enhances coverage of the tropics and subtropics, with excellent diurnal sampling in regions covered by geostationary satellite data and adequate sampling elsewhere.

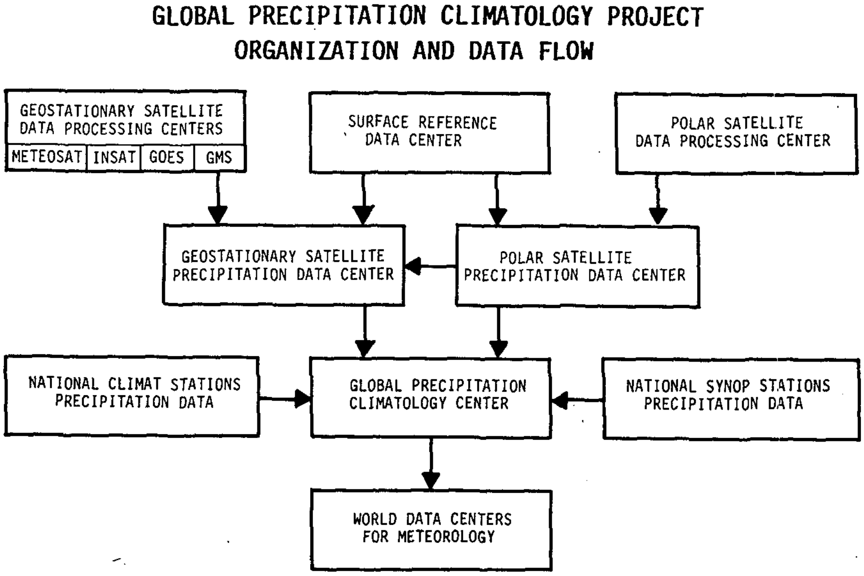

FIG. 1. Block diagram of the principal centers of the Global Precipitation Climatology Project and of the data flow through the project.

The Polar Satellite Precipitation Data Center (PSPDC), currently located at the Goddard Space Flight Center of NASA, uses radiometric observations from the SSM/I to derive estimates of rain rates over oceans. This is being done initially with an algorithm using only 19 GHz radiances for monthly time periods, and for 5° × 5° areas. Estimation over land areas using higher frequency data is being investigated. The Global Precipitation Climatology Center (GPCC) has been established by the Weather Service of the Federal Republic of Germany. It uses the estimates provided by both the GSPDC and the PSPDC, along with station observations derived from the Global Telecommunications System and other exchange methods, to produce global gridded analyses of monthly rainfall.

Both types of satellite estimates are subject to large uncertainties. The calibration of the IR-based algorithm relies on very limited measurements, while that of the microwave-based method is derived from a physical model with many approximations. It is extremely difficult to determine confidence bounds for such estimates. Independent measurements of area- and time-averaged rainfall in a variety of climatic regimes are needed. The Surface Reference Data Center (SRDC), to be operated by the National Climatic Data Center of NOAA, will use ground-based measurements of rainfall from meteorological radars and raingages to validate and calibrate the satellite estimates. It will also investigate the application of new technology to the problem of measuring rainfall at the surface.

4. The future

We have attempted to summarize and provide examples of the developments over the past 20 years in the field of climatic-scale precipitation estimation from passive satellite observations. A great many approaches have been tried, but they can be classified into two categories. The first, and that with the longer history, is termed indirect; it is based on the fact that clouds in general, and certain types of clouds in particular, are associated with rainfall, and therefore measurements of the clouds are of some use in specifying the amount of rainfall. In many applications, such proxy measurements have proven quite useful without the need to perform an explicit estimation of rainfall accumulations. The second approach, called direct, is based on observations of the effects of raindrop-sized hydrometeors on upwelling radiances in the microwave portion of the spectrum. Both physically and statistically based models of these effects have been used. Only very recently have attempts been made to combine these approaches in the estimation of climatic-scale rainfall.

A number of new satellite observing systems are planned for the next decade. These systems will offer important new sources of data that might be useful in the estimation of climatic-scale precipitation. They should provide a valuable supplement to the existing operational satellites. The upcoming series of NOAA polar orbiters will contain a new Advanced Microwave Sounding Unit (AMSU) which will, due to its greater number of channels and more complete spatial coverage, offer a significant potential for enhancement of the quality of rainfall estimates. The operational nature of AMSU will provide the temporal continuity needed for climate studies. The proposed NASA Earth Observing System (EOS) will include among its instruments a number of sensors with additional potential to improve climatic scale estimates of rainfall.

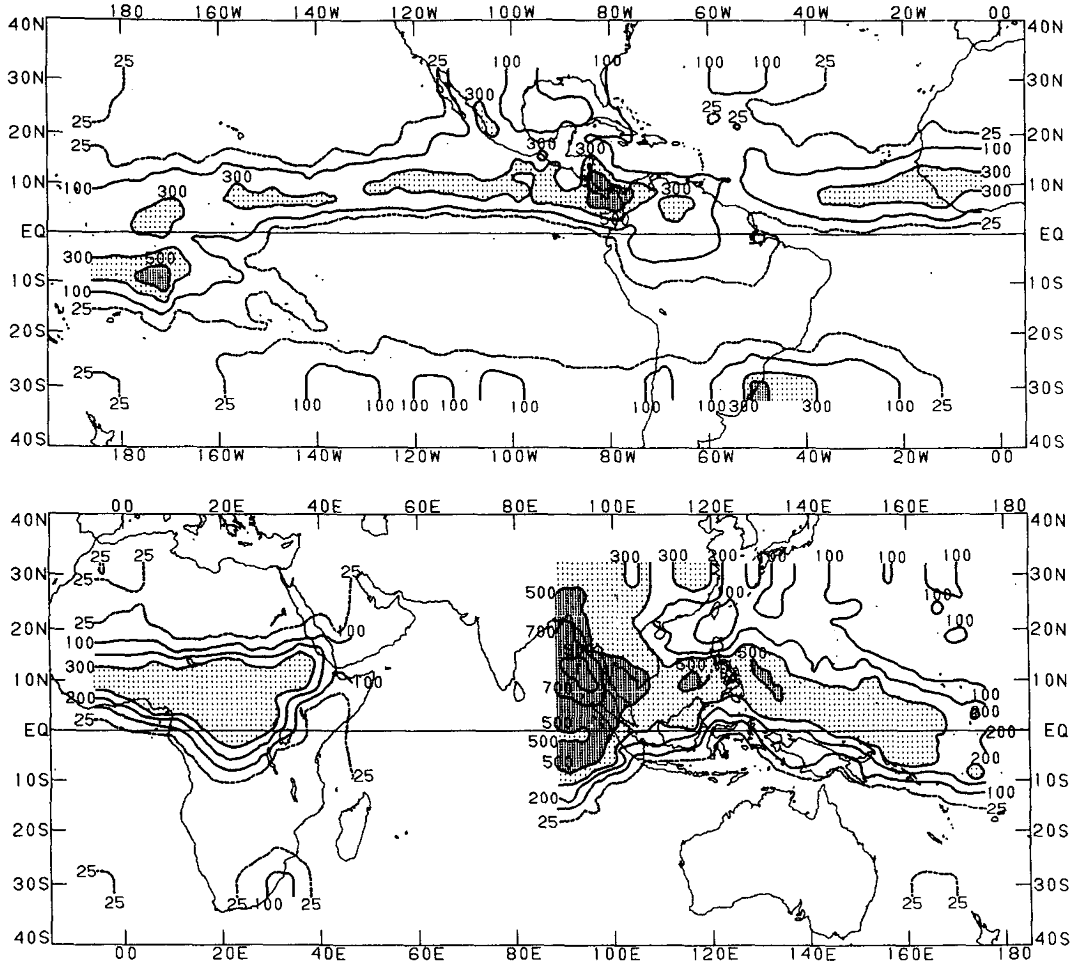

FIG. 2. Estimated rainfall (mm), on a 2.5° latitude by 2.5° longitude grid, for the period 30 July–28 August, 1987, derived by the GSPDC of the GPCP (see text) from geostationary satellite IR observations and a simple thresholding algorithm. Light/heavy stippling depicts areas with estimated rainfall totals greater than 300/500 mm.

NASA has proposed a Tropical Rainfall Measuring Mission (TRMM) (Simpson et al. 1988), which will measure monthly and seasonal rainfall over the global tropics and subtropics. TRMM will be a satellite with radiometers capable of high resolution visible, IR, and microwave measurements, and with a rain radar. It will fly in a low-altitude, low-inclination orbit to provide good resolution in the tropics and subtropics and will be non-sun-synchronous in order to provide good sampling of the diurnal cycle over monthly periods.

The importance of observations of the global hydrologic cycle to studies of the climate system has been emphasized recently. A Global Energy and Water Cycle Experiment (GEWEX) has been proposed by the WCRP (WCRP 1988) to better define the behavior of the global hydrologic cycle. The success of GEWEX will depend critically on the availability of accurate analyses of rainfall for the globe, and will require new types of observations and the development of new estimation techniques.

We believe, however, that the most critical advance required at this time is a method by which different types of observations can be integrated into an analyzed field of precipitation. A useful analogy to the problem of estimating climatic-scale precipitation might be drawn from the effort to obtain estimates of the large-scale tropospheric circulation for the specification of initial conditions for numerical weather prediction forecast models. That task involves the derivation of global fields of winds and temperatures from observations of widely varying characteristics and distribution. Historically, it began with simple interpolation of discrete rawinsonde observations and has evolved to a highly complex process in which satellite soundings and cloud motion vectors, rawinsondes, profilers, and aircraft observations are integrated with the use of a model first guess into a comprehensive depiction of the general circulation.

While the task of obtaining global analyses of large-scale rainfall differs in many ways, there are clearly

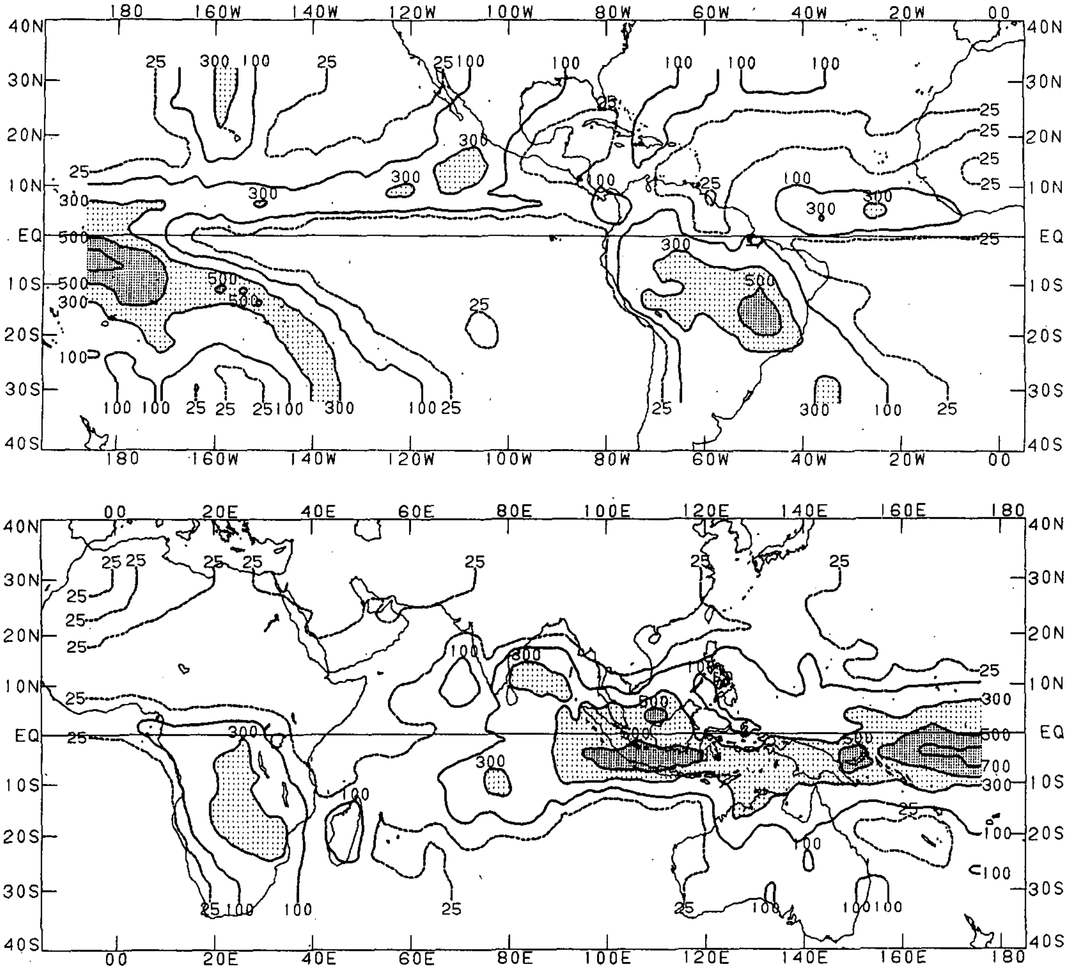

FIG. 3. As in Fig. 2, except for the period 2–31 December 1987. Areas of missing geostationary satellite data have been filled in using histograms of OLR from the operational NOAA polar-orbiting satellite.

lessons to be learned from numerical weather prediction experience. Perhaps the most important is that no single type of observation is likely to provide enough information to produce a complete and accurate analysis of global precipitation, any more than radiosondes alone can be relied upon to analyze the global circulation. We must search for means by which observations and estimates of rainfall, of widely differing characteristics, can be integrated into a global analysis. Such an approach would utilize rainfall estimates made from various instruments in differing ways, along with radar and station observations, with an initial guess possibly derived from a forecast model[1] to produce a global analysis of rainfall accumulations for some short time period. Successive analyses could then be accumulated to produce a climatic-scale analysis.

Such a scheme might be implemented at the present time; in fact, several groups are currently using similar approaches, but on spatially restricted areas. An example is provided in the recent work of Barrett (1988), in which visible, IR, and microwave satellite data are used together with conventional observations in an algorithm to estimate rainfall for large portions of Africa for periods of one month and longer. The Global Precipitation Climatology Center of the GPCP constitutes the first explicit attempt to develop and implement a complete global rainfall analysis. As the technology of measurements from space improves, and as our applications of that technology advance, it seems certain that our knowledge of the distribution of time-averaged global precipitation will benefit.

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[1] The use of a model forecast as a first guess would require a level of forecast skill that does not yet exist. In addition, the use of such forecasts in the analysis procedure leads to an evident difficulty in using the analyses to validate the predictions. This same conflict has already been faced by the operational Numerical Weather Prediction Centers in validation of circulation forecasts. They do, in fact, use their analyses as their principal verification tool.

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