STATE-OF-THE-ART IN PRECIPITATION ESTIMATES FROM SATELLITES

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Summary: In this paper, we discribe the present state-of-the-art in the estimation of precipitation from satellite observations, concentrating on the use of infrared data in tropical regions. Such methods, as well as those making use of visible observations, rely primarily on the detection of precipitating clouds. Some also make inferences regarding the intensity of precipitation from the texture, temperature or growth rate of the cloud. The Global Precipitation Climatology Project of the World Climate Research Programme is engaged in an effort to use various forms of satellite and in-situ measurements to produce monthly analyses of global precipitation. NOAA is also developing analysis procedures which will yield precipitation analyses on smaller space and shorter time scales.

1. INTRODUCTION

The estimation of precipitation from satellite observations has been attempted many times in many ways over the past 25 years. Applications ranging from flash flood prediction to forcing of climate models have been attempted, often with some success. At the present, climate research and extended range forecasting efforts have clearly identified requirements for time series of analyzed fields of precipitation. In this paper, we will describe the current capabilities in retrieving estimates of precipitation from satellite observations and discuss current and prospective efforts to use such observations in global analyses of precipitation for a variety of applications.

It is clear that analyses of time- and area-averaged precipitation <u>can</u> be constructed from point measurements provided by rain gages, provided enough gages are available. However, there are large areas of the earth where there are not and very probably will never be enough gages to permit this. Most obvious among these areas are the oceans, particularly the tropical oceans, where a great deal of rain falls and where the spatial and temporal variability are large. Even over land areas, there are regions where the number of gages is insufficient to adequately sample rainfall. Complete analyses of rainfall over the globe require some form of satellite-derived precipitation estimates in such regions.

Until the advent of meteorological satellite observations, rainfall in regions of inadequate information was analyzed primarily through the interpolation of scattered island stations (Jaeger, 1976), from values inferred from ship observations of current weather (Dorman and Bourke, 1979, 1981) and as a residual of the fresh water budget of the ocean (Bryan and Oort, 1984). Imagery and digital data from satellites offered another means to improve the analyses in such regions, and they began to be so used more than 20 years ago. A review of methods of estimating climatic-scale precipitation from satellite observations is given by Arkin and Ardanuy (1989).

2. THE USE OF SATELLITE ESTIMATES

Analyses of global precipitation can have many applications, some of which impose particular constraints on the analytical techniques. In climate observation and research, two of the most common requirements entail the validation of model simulations of long term climate or climatic events, and skill in the detection of climate change and variability. Such applications make three characteristics essential:

1. the analyses must be internally consistent, so that variations in precipitation can be distinguished from changes in the observation or analysis techniques;
2. the analyses must be spatially complete over substantial regions of the globe, so that important phenomena are observed in their entirety; and
3. the analyses must be temporally continuous over long periods of time (certainly at least years), so that significant phenomena are observed over their entire life history and in multiple incarnations, if possible.

Each of these characteristics has a further implication for the sorts of satellite rainfall estimation techniques which might therefore be useful. Consistency requires objectivity; estimates based on subjective judgements will necessarily change when the individuals involved change. Spatial completeness and temporal continuity jointly imply that any method to be used must be relatively simple (compared to the complexity which might be practical over more restricted domains). Furthermore, the difficulty in retrospective processing of large volumes of satellite data adds the practical requirement that the method must be routinely applied.

Another potential application for precipitation analyses is in the initialization and validation of numerical weather prediction (NWP) model forecasts. Here too, satellite-derived estimates are essential, both for ocean regions and for land areas poorly sampled by rain gages. While not all of the contraints described in the preceding paragraph for climate applications apply here, they are replaced by other considerations. The resolution requirements, both in time and space, are more exacting in NWP applications than in climate. In addition, particularly for use in the initialization process, estimates must be available in nearly real time.

3. SATELLITE PRECIPITATION ESTIMATION ALGORITHMS

Historically, two sorts of satellite observations have been used to estimate precipitation. They are:

1. observations of the tops (and to some extent the thickness) of clouds, generally inferred from infrared (IR) temperature and/or visible brightness; and
2. observations of liquid and solid hydrometeors, inferred from their effects on microwave radiation relative to that emitted by the surface of the land or ocean.

These techniques have been labeled indirect and direct, respectively, by Arkin and Meisner (1987), and those thought most relevant to the generation of rainfall estimates suitable for climate studies have been discussed there as well as in Arkin and Ardanuy (1989). Other useful references include Barrett and Martin (1981), Griffith et al. (1979), and Simpson et al. (1988).

The vis/IR techniques have by far the longer history, up to 25 years in some cases. A great deal of data, from experimental and operational polar orbiting and geostationary satellites, has been available, and an enormous number of approaches have been attempted. The most commonly used single parameter appears to be "cloud" area, which actually means in general the area encompassed by certain temperature or brightness thresholds. It is easy to conclude that many of these techniques are quite successful in a qualitative sense, and some have been shown to have useful quantitative skill in some regions, given appropriate calibrations. The other most commonly used parameters are the change in area of a precipitating system (growing systems are thought to precipitate more heavily), the temperature or brightness of the system (deeper, hence colder, and thicker, hence brighter systems are presumed to precipitate more), and the texture of the top of the system (more intense systems are thought to be characterized by such features as overshooting tops). While algorithms which utilize observations of these features have sometimes been shown superior to the simpler techniques, it has not been shown in general that their enhanced performance is cost effective. One of the simplest algorithms, called the GOES Precipitation Index (GPI - Arkin and Meisner, 1987) is used in the Global Precipitation Climatology Project (GPCP) and will be discussed in the next section. An example of an objective algorithm which is somewhat more sophisticated is the Convective-Stratiform Technique (CST - Adler and Negri, 1988). The CST uses local variations in brightness temperature to locate intense convective cores and to remove non-precipitating cirrus, and partitions estimated rainfall into convective and stratiform components. The objective character of the CST makes it a plausible candidate for both climate and NWP applications, and its performance on selected cases has been superior to simpler techniques. However, it has only recently begun to be tested in a variety of locations and its suitability for use in the production of global estimates is as yet uncertain.

The microwave techniques have only been possible since the mid-1970's, since no instruments producing such observations were flown sooner, and only since 1987 has an operational microwave instrument, the SSM/I, been available. Two types of algorithms have been used with such observations, one based on the emission of radiation at frequencies below about 20 GHz by raindrops, and the other based on the scattering of radiation at frequencies above about 60 GHz by large ice particles. The former, against the cold background of the low emissivity ocean surface, permits a nearly direct estimate of rainrate, while the latter allows an inference of rain rate in situations where the rain is well correlated with the density of ice particles, such as in convective storms. The low sampling rate of existing microwave radiometers make these techniques unsuitable for estimates over large areas on short time scales, although they have been used to produce near global monthly analyses. Spencer (this volume) describes these techniques in more detail.

4. THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT

The Global Precipitation Climatology Project (GPCP - see Arkin and Ardanuy, 1989) is an element of the World Climate Research Programme. The GPCP has as its goal the production of a 10-year set of monthly analyses of area-averaged precipitation on a 2.5° grid. It uses satellite estimates based on IR and microwave data, together with station observations. The primary data sources for the satellite estimates are the GOES (U. S.), GMS (Japan), and METEOSAT (European community) geostationary satellites and the operational NOAA polar orbiting satellites, together with the SSM/I data from the U. S. DMSP satellite.

The IR estimates for the GPCP are derived using the GPI, which is one of the simplest, and therefore most easily applied, of the indirect techniques. It is based on a comparison of rainfall analyses derived from radar and rain gage observations and geostationary satellite IR observations made during the GARP Atlantic Tropical Experiment (GATE) by Arkin (1979) and Richards and Arkin (1981). They found that the coverage of large areas (1.5° latitude x 1.5° longitude and larger) by clouds with equivalent black body temperature of 235K was highly correlated with accumulated rainfall at all time scales from hourly to daily. Rainfall estimates made from just the fractional coverage of cold cloud over large areas appeared to be as accurate as those derived from more sophisticated algorithms (Richards and Arkin, 1981). The GPI was applied to observations from the operational U. S. geostationary satellites beginning in December 1981. Analyses of the annual and diurnal cycles in estimated rainfall and their interannual variability were presented by Arkin and Meisner (1987) and Meisner and Arkin (1987). Analyses for the global tropics which exhibited the large interannual changes in rainfall associated with the warm and cold extremes of the Southern Oscillation observed in 1987 and 1988 were shown by Janowiak and Arkin (1990). Rainfall estimated from this technique for the month of August 1987 (fig. 1) shows the features expected of tropical rainfall, with maxima over southeast Asia, Africa north of the equator, Central America, and associated with the Intertropical Convergence Zone, and minima over the subtropics. The accuracy of the amounts is difficult to assess, but they are reasonably consistent with climatological analyses (see, for example, Jaeger, 1976).

The microwave estimates used in the GPCP to this point are based on the work of Wilheit and Chang (1990). They have developed an algorithm which estimates rain rates over the non-ice-covered oceans from the histogram of 19 GHz brightness temperatures in $5^{o}x5^{o}$ areas over a month. They compare the observed histogram with that calculated from a radiative transfer model, and modify the model calculation until agreement is reached. At convergence, the parameters of the model are used to derive the rain rate. An example of their product for August 1987 (fig. 2) shows that the features are generally in agreement with those seen in the IR estimate (fig. 1). Two interesting differences worth noting are the smoother features in the IR, despite the lower spatial resolution of the microwave product, and the larger amounts in the higher latitudes of the Southern Hemisphere in the IR. We believe that the first difference reflects the tendency of clouds to be of greater expanse than the associated precipitation, while the second probably indicates a bias in the IR estimate associated with surface temperature. The microwave-based analysis is more convincing in oceanic extratropical regions (see, for example, the area of the South Pacific Convergence Zone in the central South Pacific Ocean), but has evident errors in the vicinty of land.

One of the principal difficulties in the development and improvement of rainfall estimation algorithms is the lack of suitable calibration and validation data sets. The GPCP has begun a series of Algorithm Intercomparison Projects (AIPs), the purpose of which is to provide to researchers data sets that will allow the testing of existing techniques and the development of new ones. The first AIP, using satellite and

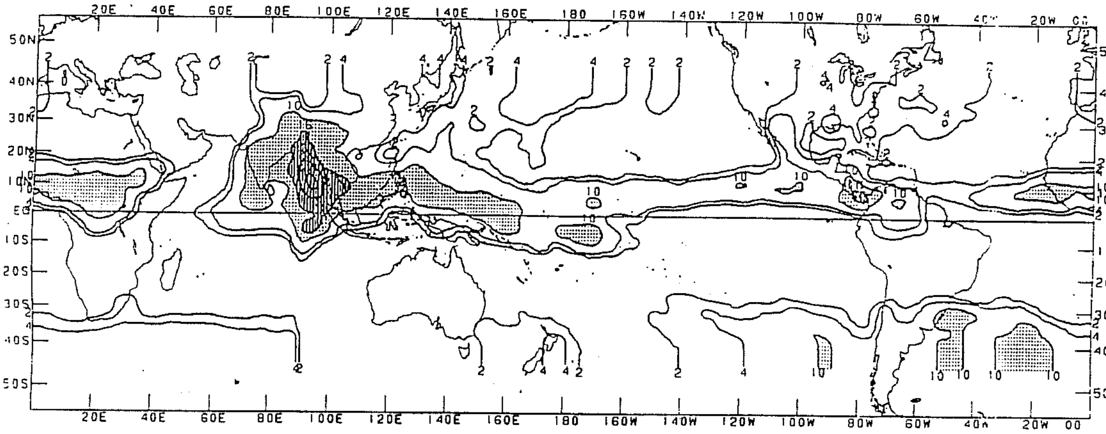

Fig. 1 Estimated precipitation (mm/day) derived from histograms of IR imagery from geostationary and polar orbiting satellites. Contours begin at 2 mm/day and are at intervals of 4 mm/day. Areas greater than 10 mm/day are stippled; areas greater than 14 mm/day are hatched.

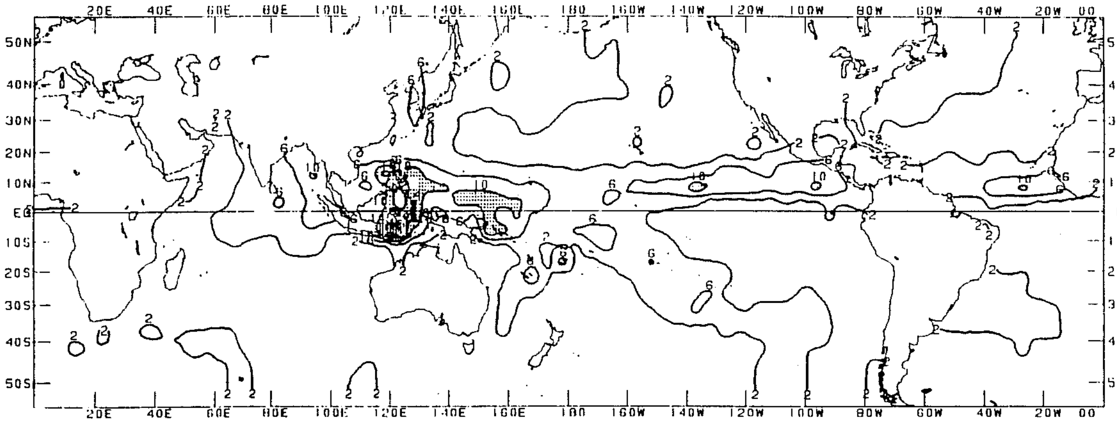

Fig. 2 Estimated precipitation (mm/day) derived from histograms of SSM/I observations from DMSP by Wilheit and Chang (1990). Contours begin at 2 mm/day and are at intervals of 4 mm/day. Areas greater than 10 mm/day are stippled; areas greater than 14 mm/day are hatched.

rainfall data from the area of Japan during June-August 1989, is currently in progress, while a second, for the area including and surrounding the British Isles during February-March 1991, is being planned. Data from the first AIP have been sent to 21 research groups in 7 countries, and results have been received from 9 with at least 4 more expected (see Table 1). IR estimates will be compared over the entire region on both short time scales and for the two months of the AIP, while SSM/I-based estimates will be compared for 10 selected swaths. Examples of the GPCP estimates and the validating data for one of these swaths are shown in fig. 3.

Table 1. Participants in the 1st AIP.

Data Sent		Products Received	Expected
Adler	NASA	IR,SSM/I	
Alishouse	NOAA		1 Nov.
Barrett	U. Bristol - UK		1 Nov.
Chang	NASA	SSM/I	
Cuddapah	NASA	SSM/I	
Desbois	LMD - France		
Ferriday	U. Colorado	SSM/I	
Gautier	UCSB		
Janowiak	NOAA	IR	
King	AES - Canada	IR	
Lynch	Curtin U. Tech. - Australia		1 Nov.
Manton	BMRC - Australia		
Milford	U. Reading - UK		
Morrissey	U. Hawaii		
Nicholson	FSU		
North-Wilheit	Texas A&M		
Ohno	JMA - Japan	IR	
Petty-Katsaros	U. Washington	SSM/I	
Robertson	NASA		
Wash	Naval PG School		1 Nov.
Wu	PRC	IR	

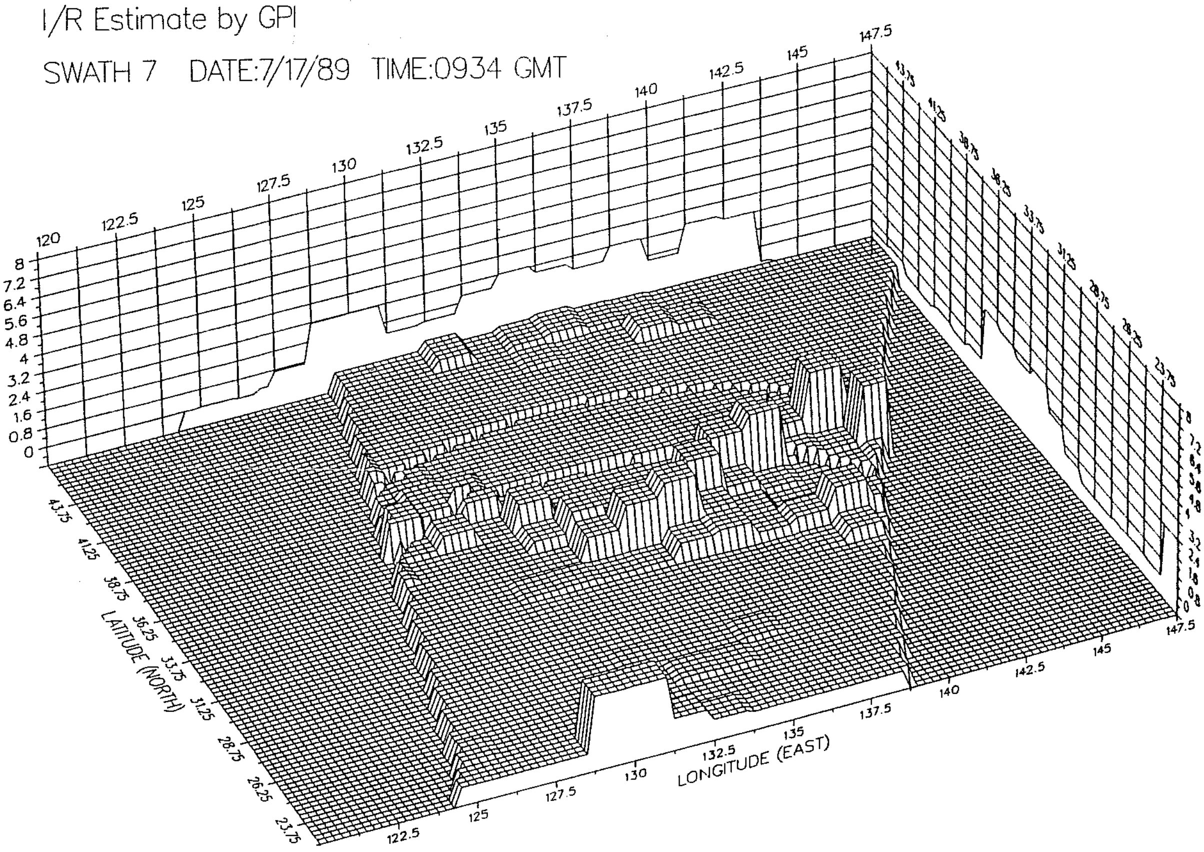

Fig. 3a Rainfall estimated using the GOES Precipitation Index for the time of a specified SSM/I swath. Values are mm/hr, where values of less than zero indicate that no estimate was made.

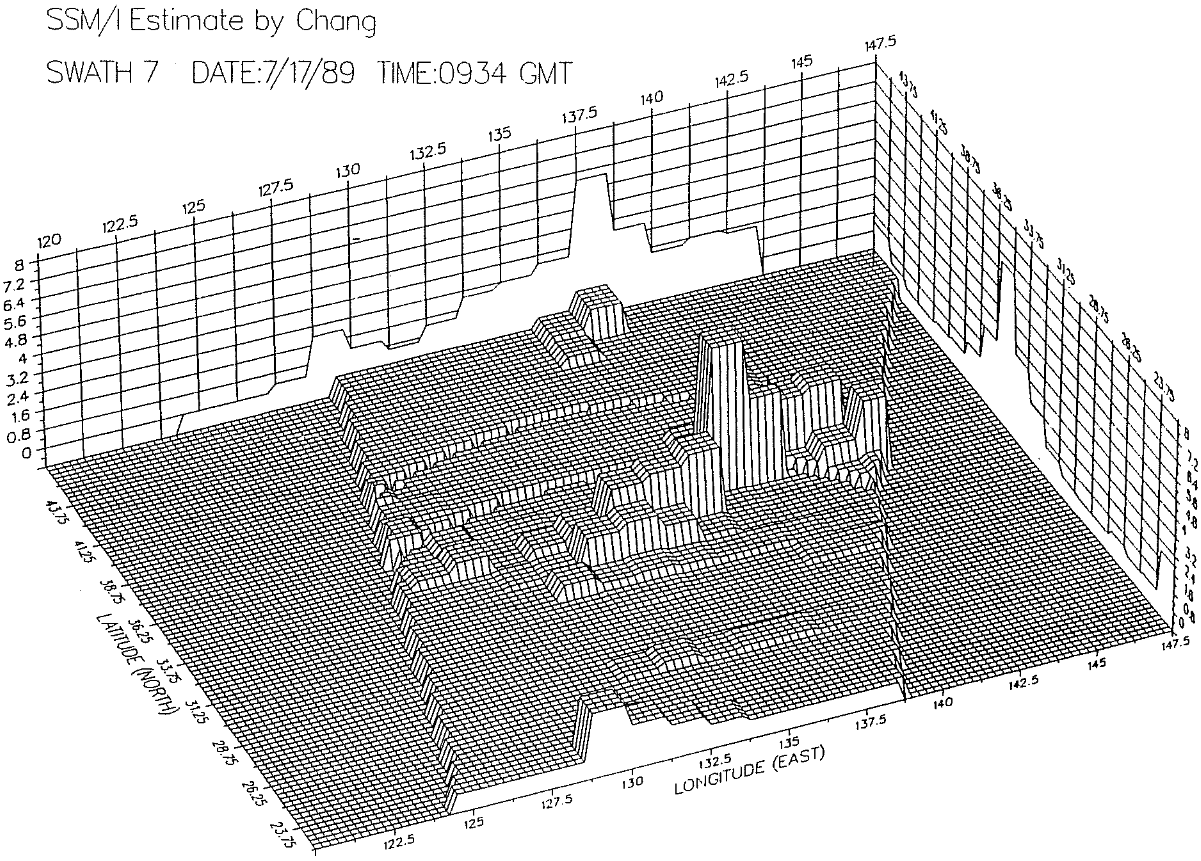

Fig. 3b As in fig. 3a except estimate made from SSM/I data by Chang.

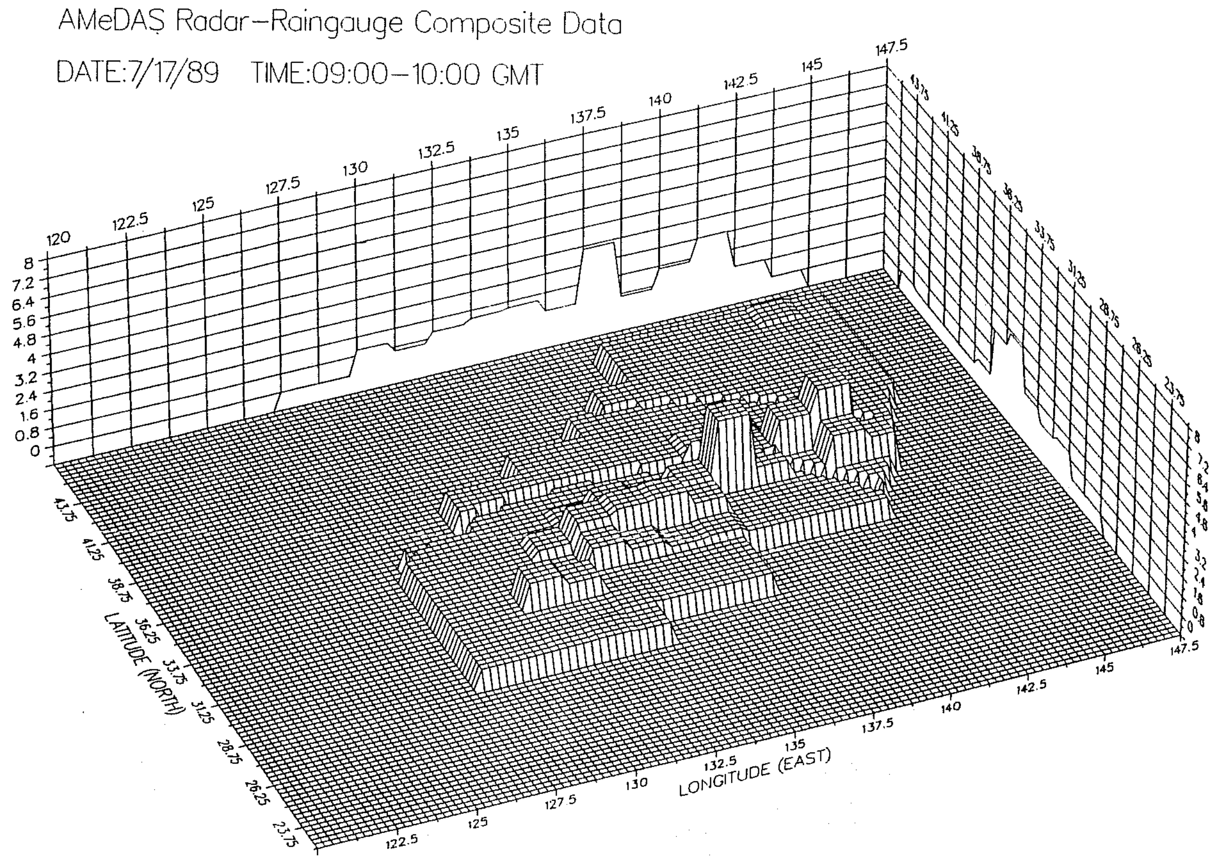

Fig. 3c As in fig. 3a except for composite rain gage-radar rainfall analysis.

5. PRECIPITATION ANALYSIS

In this section we will describe the current plan for research directed at the improvement of the GPI and the development of methods of analyzing precipitation over large areas using many sources of information. Our objective in this work is to develop and implement, as a part of the GPCP, an objective analysis which will use all available observations to produce the best possible field of rainfall for the globe for use in climate and NWP applications. This will involve several activities, including:

a) calibration and validation of and improvements to the GPI, including testing the use of different thresholds and/or coefficients, based upon comparisons with various "ground-truth" data sets;
b) development and implementation of an analysis which blends two types of rainfall observations;
c) evaluation of the relative merits of using model forecasts or simulations of rainfall in an analysis compared with the use of climatology or persistence; and
d) the development and implementation of an optimum interpolation (OI) analysis which effectively uses the information from all available in-situ and satellite observations.

5.1 GPI Calibration/Validation and Improvements

As described above, the GPI was developed from a comparison between IR satellite observations and a radar/rain gage rainfall analysis for GATE. The liklihood that the constant derived for this limited space and time domain is optimal for use in other areas is uncertain, and at the very least needs to be investigated. Furthermore, the temperature threshold used in GATE to distinguish between raining and non-raining clouds might not be appropriate in other regions. We will continue and expand the calibration and validation of the GPI. We will also investigate both improvements in the GPI, through the use of different coefficients and/or thresholds, and the establishment of error bounds on the GPI estimates.

Arkin and Meisner (1987) compared the GPI for the period 1982-84 over the western hemisphere with both climatological and observed rainfall, and found that the relationship between cold cloud and rainfall in the tropics and subtropics was similar to that observed in the GATE area. Arkin (1988) compared the GPI and rainfall from station observations over the U.S. during 1982-86, and found that good linear correlations existed over level terrain, better during the warm season, but that large biases, increasing with distance from the coast, were found in the interior. Arkin et al. (1989) found that the GPI over India during the 1986 summer monsoon was well correlated with observed rainfall in most areas, but that much lower correlations were found near the Western Ghats. However, high correlations were found in those areas when warmer temperature thresholds, 270 or 265k, were used to distinguish raining from non-raining cloud.

We intend to take advantage of several data sets to validate the GPI algorithm and to improve the coefficient and threshold used for the GPI in regions where correlations can be improved. Several regions where detailed rainfall analyses derived from radars combined with gages are available will be examined to determine the variations of the cold cloud/rainfall relationship in those areas. These include Japan, where data from the first Algorithm Intercomparison Project of the GPCP will be used, Darwin Australia, where the TRMM/TOGA radar has collected a data set for several rainy seasons since 1987-88, the western Pacific, where TOGA/COARE is expected to produce an oceanic rainfall data set unequalled since GATE, and Niamey Niger, where a French project which will produce a detailed radar/gage analysis for several rainy seasons is planned. In each of these areas, we intend to replicate the statistical studies of Arkin (1979) and Richards and Arkin (1981), by comparing the fractional coverage of cloud colder than thresholds ranging from near freezing to about 200K over a range of areas. An intercomparison of the results of these studies should enable us to understand better the stability of the coefficient relating cold cloud and rainfall in various areas as well as the variation in temperature threshold for which the highest correlations are found. We will also repeat the GATE studies but using an ensemble of spatial areas in different parts of the GATE domain, again in order to determine the uncertainty in the coefficient used in the operational GPI. These data sets will also afford us the opportunity to examine the skill of alternative simple estimation techniques, particularly those in which the cloud top temperature, as well as the extent, play some role.

Two methods which will allow a broader view of the accuracy of the GPI coefficient, but with less precision, will be attempted as well. In the first, a dense set of rain gage observations for the U.S. (the Climate Division data used by Arkin and Meisner, 1987 and Arkin, 1988) will be compared with GPI estimates for months from December 1981 through the present. The effect on the correlations of changes in threshold will be investigated, in particular to determine whether there is any benefit to be gained over mountainous terrain from the use of warmer thresholds as observed in India. The spatial variation of the bias between the GPI and rainfall will be used if possible to devise a spatially dependent correction. A similar investigation using less dense but more broadly distributed gage observations from other parts of the world will be attempted as well, although the comparison between estimates for areas of $2.5^{\circ}x2.5^{\circ}$ and the average of a few gages is much less likely to yield useful results.

The second method will involved the intercomparison of monthly oceanic GPI estimates for the period 1986-present over the tropical and subtropical Pacific Ocean with observations of sea surface salinity for that period (see the discussion of the salinity observations in Delcroix and Henin, 1989). While this comparison is certainly unlikely to yield a direct quantitative measure of the error of the GPI estimates, we hope that this approach will enable us to assess the error to within a factor of two. Over oceanic regions, where rainfall observations for large areas are simply not available, such an assessment is of some value. We will then compare the rainfall estimates with the fresh water flux required to balance the salinity budget in the operation ocean model run at the Climate Analysis Center (Leetma, personal communication). These comparisons should provide us with an independent check on the accuracy of the GPI estimates over oceanic regions.

5.2 Blended Analysis

From its beginning, the GPCP has relied upon the availability of two satellite precipitation estimates: the GPI and an estimate based on microwave observations from the SSM/I on the operational Defense Meteorological Satellite Program satellites. It also relies on the use of rain gage observations where they are available. It seems clear that the information from these various sources is not entirely redundant (see, e.g., figs. 1 and 2), and that some sort of combination of the observations could yield a better final product. This will of course be even more true when data from TRMM (Simpson et al., 1988) become available. We expect to begin the development and implementation of a relatively simple, and therefore easily understood and applied, method of combining two types of data where one provides more information on the gradients of a field and the other provides more accurate values at individual points.

Such an analysis technique, referred to as a "blend" of the two fields, was developed by Reynolds (1988) and used to generate an analyzed field of sea surface temperature (SST). In his case, the blend was of satellite and in-situ observations, and was desirable because the satellite data have far superior spatial coverage but are subject to various biases which make them in general less accurate than most in-situ observations. In brief, the technique requires that the blended field satisfy Poisson's equation (see Oort and Rasmusson, 1971) on a sphere, where points with sufficient in-situ observations serve as internal "anchor points" and the Laplacian of the satellite observations in areas where sufficient satellite data are available serves as the forcing term in the Poisson equation. A specified external boundary is also required for solution.

The extension of this procedure to precipitation is computationally straightfoward: one simply allows two types of rainfall observations/estimates to take on the roles of the two SST observation types, and defines an external boundary for the region of interest. Since there are many more than two types of precipitation estimates and observations available to us, we propose to engage in some experimentation to determine the best method of combining them. For example, we expect that microwave-based estimates from SSM/I data will prove to be more accurate than the GPI. However, their limited spatial and temporal sampling makes it difficult to derive even a monthly analyzed field from SSM/I alone. A blend of an SSM/I-based estimate and the GPI would quite probably be better than either alone. We will experiment with the development of blended analyses which use GPI with SSM/I, surface measurements with GPI, and surface measurements with the satellite blend.

5.3 Model-generated Precipitation Comparisons

No blended analysis of rainfall estimates or observations is likely to provide a spatially complete field for the time and space resolutions we desire for all times. Some of the grid points for which we desire values will inevitably end up to be too far removed from all the available observations. This problem is faced in any analysis procedure, most of which require that some spatially complete field be available as a "first guess". Commonly used procedures for generating first guesses include the use of a climatological field, the field from the previous analysis (persistence), and the forecast field from a numerical model of the processes which generate the field. This last is typically used in operational numerical weather prediction, while the other two have both been used in the analysis of sea surface temperatures (Reynolds and Leetma, 1990). We are investigating the information content of precipitation fields generated by two types of numerical models of the atmosphere: the operational model used for forecasting at the National Meteorological Center, and the atmospheric component of the experimental coupled ocean/atmosphere model being developed by the Climate Analysis Center.

Unfortunately, direct observations of precipitation are inadequate in many parts of the world, particularly over the tropical oceans, to assess the accuracy of numerical model forecasts or simulations of precipitation. While we will use station observations to the extent possible, the principal methods of evaluation will have to be comparison with the various satellite estimates and blended analyses available. In the beginning of this work, we will compare several different forecast/simulated precipitation fields to the GPI estimates for 5-day periods over the tropics. Intuitively, one might expect the shortest range forecasts to be the most accurate, since they are closest, in time, to the initial conditions. However, the MRF model is known to under-forecast precipitation during the first 12 to 18 hours (M. Kanamitsu, personal communication), by about 20% compared to when the model has stabilized. Therefore, we intend to compare the GPI estimated rainfall in the tropics to pentad accumulated rainfall from both the Global Data Assimilation System (GDAS), which are 6-h forecasts from the Medium-Range Forecast Model (MRF) that are used as a first guess for each data assimilation cycle, and to the 12-36 h rainfall forecasts from the MRF. The period of comparison will be July, 1989 through June, 1990. In addition, there is some indication (A. Leetma, personal communication) that the surface heat fluxes generated by a coupled model simulation are superior to the same quantities forecast by the GDAS. While it seems unlikely that this would be true for rainfall as well, it seems sensible to add the simulated rainfall for the period available to the intercomparison. At the present, about 3 months of coupled model simulation (July-September 1990) are available.

We will intercompare the model forecast and simulated rainfall over the tropics and subtropics with 5-day GPI over the study period. We will be particularly interested in the magnitude and character of the error associated with the model spin-up, and in spatial and seasonal differences in the relationship. After preparation of the GPI estimates and model forecasts and simulations, we will calculate the spatial and temporal correlations among the various data sets, for land and ocean separately, for each season (excluding locations where both the GPI estimate and model forecasts are zero). We will also compare and analyze zonal mean rainfall, separately by season, from the GPI and the model forecasts and simulations. Since our eventual goal is to determine which, if any, of the model products will make the greatest contribution to the analysis of precipitation fields as a whole, we must be careful not to confuse disagreement between the estimates and the model products with model errors (or for that matter with estimation error). To this end we will also compare both types of fields with the various climatological fields that are available and with other information which might help to clarify the situation. For example, the CAC ocean model includes fields of near-surface salinity which depend strongly on the fresh water flux and therefore in most of the ocean on precipitation. The use of precipitation from different sources as forcing will result in different surface salinity fields that can be compared to observations, presumably yielding some information as to which precipitation fields are more accurate in different locations.

5.4 Optimum Interpolation Analysis

While methods of statistically blending two or more types of observations may produce more accurate fields of precipitation than the use of any by themselves, an optimum interpolation (OI - Gandin, 1965; Lorenc, 1981) might be expected to be needed to do the best job. Comparisons of analyses of fields of rainfall from scattered station observations using various techniques have shown that the OI performs best (Creutin and Obled, 1982; Tabios III and Salas, 1985). An OI-based analysis is currently used to derive initial conditions for all operational meteorological forecast models, and an experimental OI analysis of sea surface temperature has been shown (Reynolds and Leetma, 1990) to be able to produce better spatial and temporal resolution than other techniques. We are beginning the development of an OI analysis of rainfall that will use observations and estimates of rainfall from any source, making optimal use of their information content.

The application of OI analysis is quite well understood, and we do not expect its formal application to precipitation to pose any significant problem. However, the formal application of OI is a long way from its successful application. Several significant practical difficulties must be overcome beforea successful analysis is feasible. We propose to use the OI method described by Lorenc (1981). In his approach, observations are subject to quality control procedures and a first guess field is obtained. The OI technique determines least square weights which are multiplied by the difference between the data and the first guess values. These weights are "optimized" by choice of data and guess error variances and covariances. The OI method assumes that the data are not biased.

We face three principal problems in this attempt. Firstly, a first guess field must be obtained. The work described in section 5.3 will be critical here. The obvious available choices for the guess field include climatology, which assumes that the anomaly in the analysis is zero, persistence, which assumes that the change from the previous analysis is zero, and numerical model products, which assumes that the models are skillful enough to simulate or forecast rainfall so that the information content is better than either of the other assumptions. While other choices can be imagined, e.g. a blended analysis could be used, most OI applications use one of these three. In the case of rainfall, both climatology and persistence have significant defects: the former in cases where a significant long-time scale climatic event is in progress and the latter when the time scale of variations in precipitation is short compared to the period of analysis. Since both of these situations can be expected to occur with some frequency, the use of a model-based guess is desirable if feasible. Until we succeed in establishing that some such product is usable, we propose to experiment with the use of climatology and persistence, and to compare them with the use of a blended analysis as first guess.

Secondly, error variances and covariances must be obtained for both the guess field and the various data sources. Experience with the SST OI (R. Reynolds, personal communication) has shown that the analysis can be quite sensitive to the error values used, and that experimentation is required to establish usable ranges. The analysis tends to give greater weight to the observations (and the guess) that have smaller errors. We propose to begin with conservative assumptions and to experiment to determine a workable combination of observation and guess error statistics. Since all these statistics are quite poorly known at the present, we expect that considerable trial and error will be required.

The third difficulty involves the requirement that data be unbiased. It is quite likely that all the observations which will be used in this process, at least until TRMM data are available, will be biased to some significant degree. Certainly the GPI has been found to be biased in some regions (Arkin and Meisner, 1987; Arkin, 1988), and the various SSM/I-derived estimates are likely to contain biases related to inadequate temporal sampling and inhomogeneities in the field of view. Even rain gage observations are likely to contain some bias, particularly when combined into "super-observations" representing large areas (as is done with both the satellite and in-situ SST observations by Reynolds and Leetma, 1990). One possible solution to this problem is to use the various blended analyses (section 5.2) to develop bias corrections for the different data types. This approach has been used in the SST OI with some success, and we will try to extend its use to all our input data types here.

6. CONCLUSIONS

Global analyses of both the long-term mean and the time sequence of global precipitation are of great import in a variety of scientific and practical applications. In many parts of the world, conventional data from which to make these analyses are scarce, leading to the need for the use of various sorts of satellite data. A Global Precipitation Climatology Project has been begun to utilize a variety of observations to derive a climatology of monthly analyses of precipitation for the globe. At NOAA, the development of improved methods of precipitation estimation and analysis techniques has begun with the support of the Climate and Global Change Program.

The role of satellite estimates in the analysis of global precipitation is already significant, and should be expected to increase as technology and analysis techniques improve. There will never be adequate surface-based observations to permit the complete global analyses that will be required for climate research and extended-range prediction activities, and only the enhanced use of satellite information will allow us to succeed.

7. References

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