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The quality of satellite precipitable water content data and their impact on analyzed moisture fields

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ABSTRACT

The quality of satellite Precipitable Water Content (PWC) moisture data is assessed by comparing them with radiosondes and the first-guess humidity field from the ECMWF operational model. Collocation studies show that PWC data from satellites are of comparable quality to radiosonde data and that the error in the inferred relative humidity varies from 15% in the Tropics to 35% in the extra-tropics, similar to the typical error levels of radiosonde humidity data. The model first-guess provides moisture information of comparable accuracy. Using a large sample of radiosonde and first-guess moisture information over North America, the typical forecast error correlation scale for the humidity analysis variable has been found to be 250 km at the surface rising to 300 km at upper levels. Finally, impact studies have shown that the inclusion of satellite PWC data in the ECMWF humidity analysis has a small but beneficial impact on the forecast, especially of the forecast rain in the Tropics.

1. Introduction

In recent years, there has been much emphasis placed on the representation of dynamical processes in the tropics in General Circulation Models (GCM), because of possible strong coupling between the tropics and middle latitudes. The humidity field is particularly important in the tropics, more so than in mid-latitudes, because geostrophic adjustment time scales are much longer in the tropics, where the internal Rossby radius of deformation increases as the equator is approached. As a result the relaxation time for vertical motion, and hence humidity and rainfall fields, is of order three days in the tropics as compared to 12 h in middle latitudes. Although it has been argued that it may not be necessary in the extra-tropics to specify the humidity field as an independent input to the model (Smagorinsky et al., 1970), detailed studies of selected cases (see for example Atkins, 1974) do show a positive forecast impact from humidity data, even in middle latitudes, particularly on rainfall amounts during the first few hours.

There is no doubt, however, that in the tropics it is important to ensure that humidity data are introduced with some care so that the analysis/initialization procedure does not interrupt the dynamical evolution of the tropical atmosphere. The humidity analysis is thus an important component in a numerical weather prediction system particularly if the goal is medium range weather forecasting in which the interaction between the tropics and middle latitudes is very important.

The quality of the humidity analysis depends critically on the quality of the moisture data. However, since moisture is a highly variable quantity both in space and in time, it is very difficult to devise an observing system to sample moisture. In addition to instrumental errors, moisture data suffers from large errors in representativeness. Certainly the instantaneous spot profiles obtained from radiosondes once or twice a day are not adequate. Additional proxy information for moisture is provided by surface observations of "actual weather" and "cloud cover", and by satellites using remote sensing techniques. Surface data are of variable quality, because of their subjective nature. Satellite data, on the other hand, because of their high temporal and spatial resolution, could provide a very valuable additional means of sampling moisture. Precipitable Water Content (PWC) data from TIROS-N were successfully used by Cadet (1983) in a study of the evolution of the humidity field over the Indian Ocean during the 1979 Summer Monsoon. Here a statistical evaluation of the quality of satellite PWC is presented. Our study exploits the approach outlined in Hollingsworth et al. (1986) in which a data assimilation system is used to monitor the relative quality of the various inputs of information. In particular, satellite data are compared to other data types, such as radiosondes, and to the model "first-guess", given by the 6-h forecast of the ECMWF spectral model. After a brief description of the humidity analysis scheme in Section 2 and the various sources of humidity data in Section 3, collocation studies are used to evaluate the relative quality of satellite PWC, Section 4, and the model first-guess, Section 5, as compared to radiosondes. Having deduced that satellite PWC is of comparable quality to both the first-guess and radiosondes, the impact of PWC data on the assimilation, Section 6, and forecast, Section 7, are evaluated. The study indicates that satellite derived PWC measurements have a beneficial impact on the forecast of rain and has led to the operational implementation of satellite derived PWC measurements in the ECMWF humidity analysis.

2. ECMWF humidity analysis scheme

Before describing the collocation technique and the collocation results, the humidity analysis used in the study is briefly described* (for more detailed information see Lorenc and Tibaldi (1979)).

The analysed humidity variable is the vertically integrated mixing ratio between successive analysis levels:

$$R_{12} = \int_{p_1}^{p_2} r\,\mathrm{d}p,$$

where r is the mixing ratio (g/kg) and p_1 and p_2 are standard pressure levels up to 300 mb and $p_1 < p_2$.

The quantity R_{12} is proportional to Precipitable Water Content, defined as:

$$\mathrm{PWC}_{12} = \frac{1}{g} \int_{p_1}^{p_2} r\,\mathrm{d}p$$

and so hereafter we refer to the analysis variable as PWC.

No humidity analysis is performed above 300 mb; instead R is extrapolated towards a climatological value.

The humidity analysis scheme used in the present study, is a single scan correction scheme as described, for example, in Cressman (1959), which blends together observations with the model first guess. The weights are statistically determined in a manner which is consistent with the estimated structure of the error covariances of the various fields; model and data. The humidity analysis is based on the assumption that the background field (or first-guess) provided by the model forecast is reasonably accurate. This assumption will be tested in Section 5.

The prediction error correlation is assumed to have a Gaussian structure with a horizontal correlation scale which varies from 250 km at the surface to 350 km at 300 mb, consistent with the correlation scales deduced in Section 4. The magnitude of the estimated prediction error and the estimated observational error ascribed to the various observation types are taken into account when determining the weight given to each observation. The quantity interpolated in the analysis is the deviation of the observation from the background field and so the background field is left unchanged if no datum disagrees with it.

Three types of observations are available for use in the humidity analysis:

(i) radiosondes (TEMPS);
(ii) surface observations (SYNOPS);
(iii) satellites (SATEMS).

They are now considered briefly in turn:

(i) Radiosondes provide temperature and dew point at standard and significant levels. They are used to estimate the mixing ratio at all levels and the integrated mixing ratio (the analysis variable) between standard pressure levels.

(ii) Surface observations provide temperature and dew point (at 2 m), as well as current weather, cloud amounts and types, from which

* The version of the humidity analysis scheme operational before September 1986 was used in this study. A description of the currently used scheme can be found in Lönnberg et al. (1986).

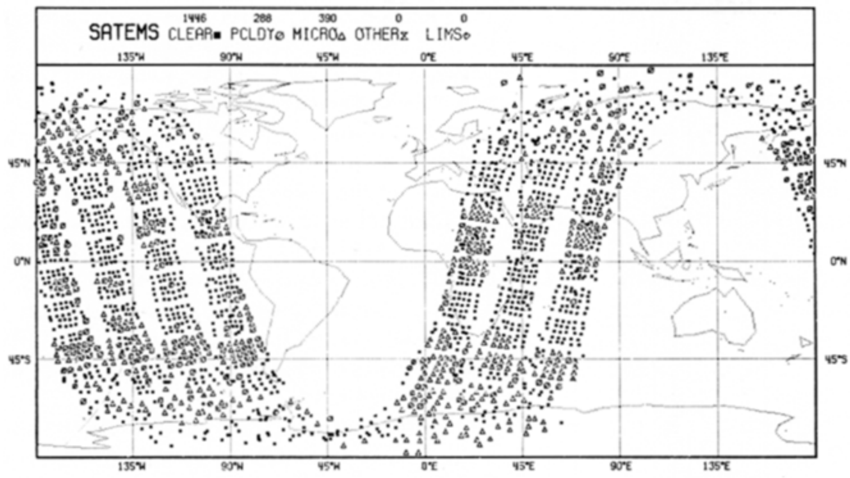

Fig. 1. The coverage of the TIROS-N satellite on 12 June 1979, 00 GMT (FGGE IIb data).

some humidity information can be inferred, following the algorithm developed by Chu and Parrish (1977).

(iii) Satellite soundings provide precipitable water content between a reference level and standard pressure levels.

3. Satellite precipitable water content data

Here we will consider the quality of TOVS (TIROS-Operational Vertical Sounder) moisture data, which are produced by NESDIS (National Environmental Satellite Data Information Service) using a statistical retrieval method. The method is based on the premise that the eigenvectors of the covariance matrices of radiances measured by satellite, along with those of collocated radiosonde moisture profiles, can provide the statistical relationship needed to retrieve the humidity data from other satellite radiances measurements. The collocations are averaged over one week and over fairly broad latitude bands (for a comprehensive review see Johnson, 1984).

Fig. 1 indicates the typical density of data coverage obtained from TIROS-N for a 6-h period during FGGE (12 June 00 GMT, 1979). It is clear that the satellite provides extensive spatial and temporal coverage. It should be remembered, however, that cloud contamination, even in partly cloudy conditions, can be very severe in the infra-red channels. The data are also deficient in resolving vertical structures. The principle by which moisture information is derived from satellite measured radiances is very similar to that used in temperature retrievals (see Hayden et al. (1981) and Smith and Woolf (1976)). The TOVS operational system uses the output of the temperature retrieval to establish the temperature of the water vapour in the atmospheric column. The same eigenvector regression technique is used to obtain the vertical profile of water vapour mixing ratio from the radiances measured by those channels which are particularly sensitive to water vapour. Fig. 2 shows the vertical resolutions of the four channels most sensitive to water vapour, of which only three, (10), (11), (12) are relevant to the atmosphere. As can be seen, the resolution is rather poor. The total precipitable water at levels higher than the pressure level at which each radiance measurement becomes sensitive to water vapour, is the natural product of the measuring technique. Therefore, satellite soundings provide an integrated measure of PWC between a reference level and pressure standard levels:

surface-700
700–500
500–300

Perhaps because of this poor vertical resolution, little effort has been put into an evaluation of satellite derived moisture data or their use in the analysis. One study, however, that of Gruber

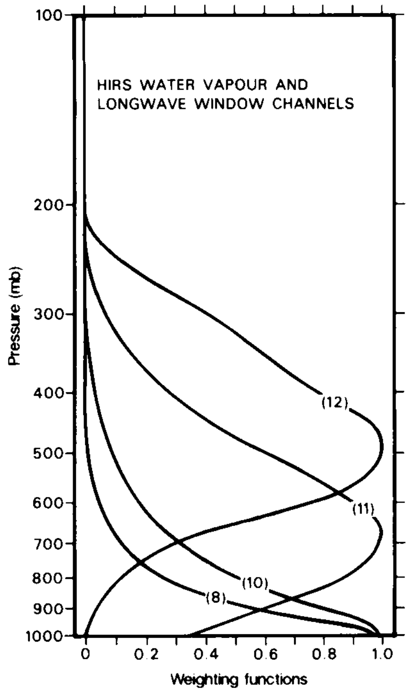

Fig. 2. TOVS normalized weighting functions for water vapour and long wave window channels, indicative of the sensitivity of each channel to water vapour as a function of pressure.

and Watkins (1981), evaluated TIROS-N atmospheric moisture profiles against radiosonde data. Their study was confined to the United States and to a limited period of few days. They concluded that although the satellite technique produces highly smoothed vertical profiles and that it fails in cloudy and partly cloud areas, nevertheless gives reasonable value of Precipitable Water Content in cloud free areas. In the next section a more comprehensive evaluation of the information contained in PWC measurements is presented.

4. Collocation of satellites with radiosondes

In this section, the quality of satellite PWC is assessed by means of global collocation studies based on large samples of data. Before describing the collocation technique it is important to remember that it is inherently difficult to devise a satisfactory method of verifying satellite data. Instantaneous spot profiles obtained on an irregular grid from radiosondes are not ideal for this purpose. Nevertheless, because radiosondes probably provide the most reliable moisture data, the radiosonde data was chosen as a reference with which to compare the TOVS PWC.

Since satellite derived PWC only gives an integrated measure to compare with radiosondes, the integrated values were interpolated to layers bounded by standard pressure levels using a numerical model first-guess. The first-guess is provided by the 6-h forecast of the T63 ECMWF spectral model, as described in Simmons and Jarraud (1984).

Our study is based on the "humidity statistics file", a database which is routinely produced at the end of each analysis cycle containing departures of the observed values from the first guess (FG), analysed (AN) and initialized (IN) fields: the departures of (OB-FG), (OB-AN), (OB-IN) are stored at each observation point for the analysis variable. This data base was extensively exploited in the study of Hollingsworth et al. (1986). Using the PWC departures, a statistical evaluation of the humidity data is performed by means of collocation studies.

The collocation procedure is the following: from an ensemble of humidity statistics files, the variance of the difference between the departures of each observation type from the first guess is evaluated. For example, collocating satellite data at position 1 with radiosonde data at position 2 gives:

$$\mathrm{Var}[(\mathrm{SAT}\text{-}\mathrm{FG}_1) - (\mathrm{RS}\text{-}\mathrm{FG}_2)] = E_{\mathrm{SAT}}^2 + E_{\mathrm{RS}}^2 + E_{\mathrm{FG}_1}^2 + E_{\mathrm{FG}_2}^2 - 2\,\mathrm{cov}(E_{\mathrm{FG}_1}, E_{\mathrm{FG}_2}) \quad (1)$$

where E_{SAT} is the standard deviation of the observational error in satellite measurements, E_{RS} is the standard deviation of the observational error in radiosonde measurements, and $E_{\mathrm{FG}_1} = E_{\mathrm{FG}_2} = E_{\mathrm{FG}}$ is the prediction error standard deviation, where it has been assumed that $\mathrm{cov}(E_{\mathrm{SAT}}, E_{\mathrm{RS}}) = 0$ (i.e., observational errors are not correlated).

In the limiting case where the collocation distance is small compared to the correlation scale for the prediction error, (1) can be approximated by

$$\mathrm{Var}[(\mathrm{SAT}\text{-}\mathrm{FG}_1) - (\mathrm{RS}\text{-}\mathrm{FG}_2)] \simeq E_{\mathrm{SAT}}^2 + E_{\mathrm{RS}}^2, \quad (2)$$

that is, the variance of the difference of the two departures is equal to the sum of the squares of the observational errors.

Thus to obtain meaningful results from the collocation studies, it is important to use a collocation window for moisture data which is small compared to the typical correlation scale for the forecast error.

To begin, therefore, we estimate the typical correlation scale for the forecast error of the humidity variable PWC. The data used are the difference between the observation and first-guess provided by the 6-h forecast of the ECMWF model, during October 1985. Only radiosonde data for 1200 GMT were chosen from those stations providing a minimum of 20 acceptable reports in the month considered. Attention is concentrated on the North American region between 30° N and 60° N, where the radiosonde coverage is of uniformly high quality. The mean difference between the station reports and the forecast is removed separately from each station.

Fig. 3 shows the correlation of forecast error as a function of station separation for the surface–850 mb layer and the 500–400 mb layer. The dots show the empirically determined average values for each 25 km interval, and the number of station pairs in that interval is plotted nearby. The continuous line represents the least square fitting curve derived using 6 terms in a Bessel function expansion for the spatial correlation of the PWC variable. For a more detailed discussion of the rationale behind fitting a Bessel function to the statistical structure function, see Hollingsworth and Lönnberg (1986) and Lönnberg and Hollingsworth (1986). It is clear from Fig. 3 that the correlation scale of forecast error of the PWC varies from about 250 km at the surface to 300 km at upper levels. These scales are consistent with earlier estimates from Van Maanen (1981), using European radiosondes and they are in accord with the assumptions made in the ECMWF humidity analysis scheme, as described in Section 2.

Based on these results a collocation window of 100 km has been chosen so that it is small compared to the typical humidity forecast error correlation scale (and so the assumption on which eq. (2) is based, is expected to hold) yet not so small so as to exclude too many observations. The

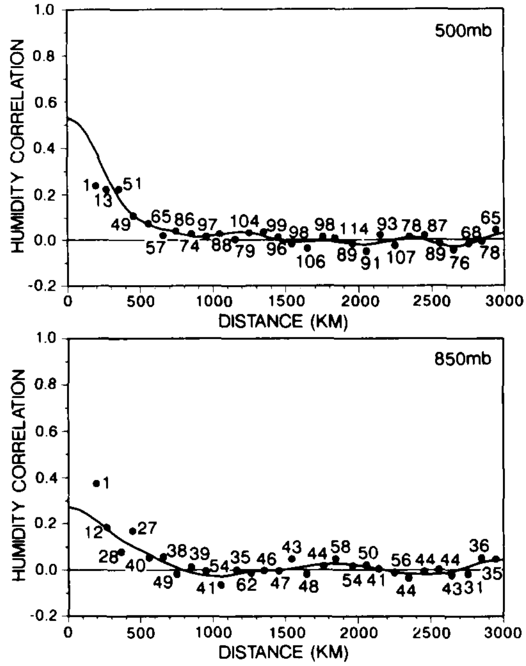

Fig. 3. The variation of the correlation of the forecast error in PWC as a function of station separation at (a) 500 mb and (b) 850 mb. The dots show the empirically determined average value for each 100 km interval, together with the number of station pairs in that interval.

time-window of the collocation is ± 3 h, a choice dictated by practical reasons due to the six-hourly sorting of the data by the assimilation suite.

The periods chosen for the collocation study were:

(a) December 1985 (a winter case);

(b) June 1979 (a summer case).

The results are presented for two different areas: the northern hemisphere (90° N–20° N) and the tropical belt (20° N–20° S).

Fig. 4 shows the collocation results during June 1979 over the northern hemisphere and the tropics for the PWC. The bias is generally small, but in the tropics it can be significant in the 700–500 mb layers, where the satellites show a tendency to overestimate the moisture. In the extratropics, instead, the satellite tends to underestimate the moisture at lower levels and overestimate it at upper levels. The variance of the differences closely follows the climatological variance, decreasing sharply with height. Since

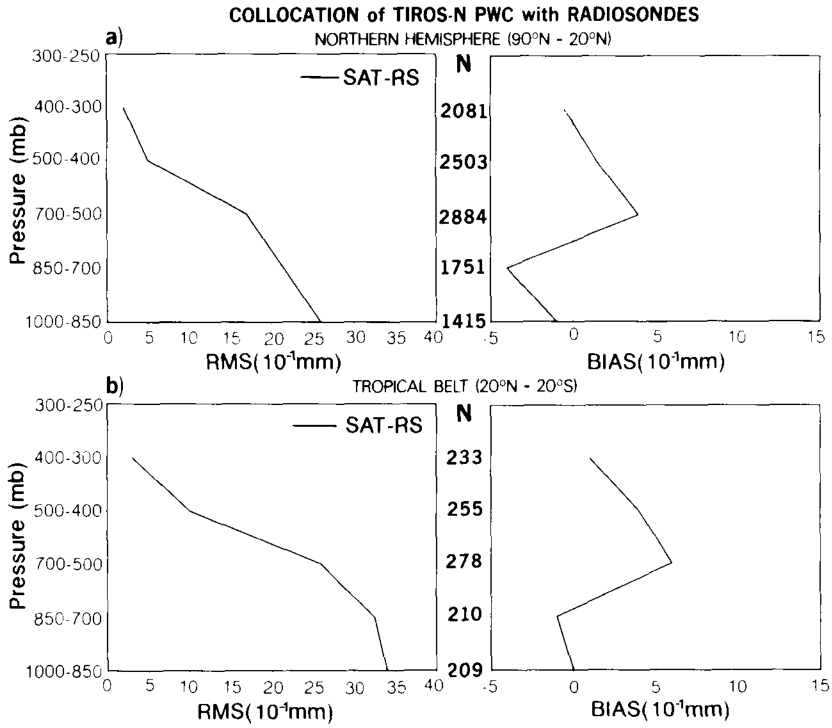

Fig. 4. Root mean square and bias statistics of the difference in PWC between satellite and radiosonde over: (a) Northern Hemisphere, (b) tropical belt. Data volumes are indicated by N at each level.

the obervational error ascribed to radiosondes is given in terms of relative humidity, the root mean square error (rmse) curves of Fig. 4 have been normalized so as to obtain the error in relative humidity. These are presented in Fig. 5, which gives the total error after normalization with the saturation mixing ratio evaluated at the mean temperature of the layer:

$$\mathrm{STD(REL.\,HU)} = \sqrt{E_{\mathrm{SAT}}^2 + E_{\mathrm{RS}}^2}.$$

According to the manufacturers (WMO Vol. 8—Guide to meteorological instruments and methods of observations), the expected accuracy for radiosonde humidity measurements (E_{RS}) is 10% for normal conditions and 20% for dry and very cold conditions.

From Fig. 5, it is clear that the satellite data are not grossly in error and are of comparable quality to the radiosonde. In the tropics the satellite error varies between 15% and 20% for both Summer and Winter cases. However in the Northern Hemisphere it varies from 15% in the lower troposphere to 35% in the upper troposphere, for the Summer case, while in the Winter case the satellite error in the upper troposphere can reach values of 50%. It should be remembered that these high values are mainly due to the difficulty of sampling moisture in very dry and cold conditions.

Generally, it can be concluded that the satellite data are of comparable quality to radiosonde data. The satellite is able to measure the total moisture in a layer without a large bias. It should be noted, however, that in abnormal situations the bias may be larger than found here, because the regression coefficients used are based on the statistics of the previous week and so do not contain local information (see Gruber and Watkins, 1981).

5. Quality of the first-guess

The GCM may be regarded as a measuring instrument providing estimates, or a first-guess, of the humidity field. It is natural, therefore, to

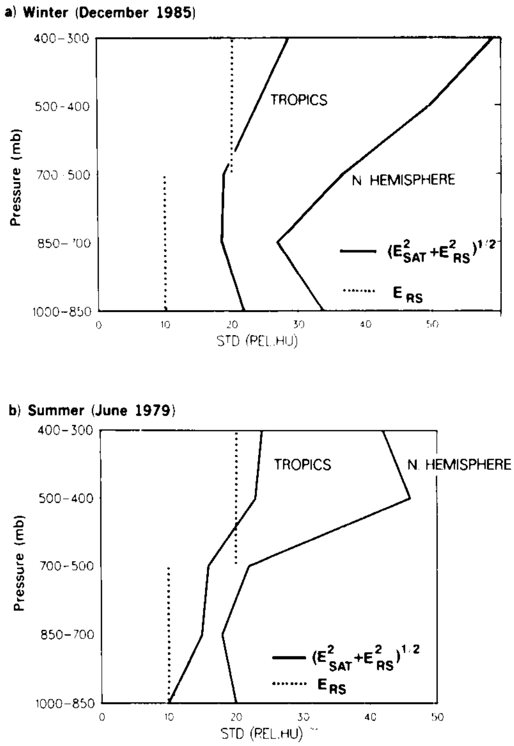

Fig. 5. Standard deviation of the difference between satellite and radiosonde measurements of relative humidity (continuous line). The error in the radiosonde estimated by the manufacture is also indicated (dotted line): (a) December 1985; (b) June 1979.

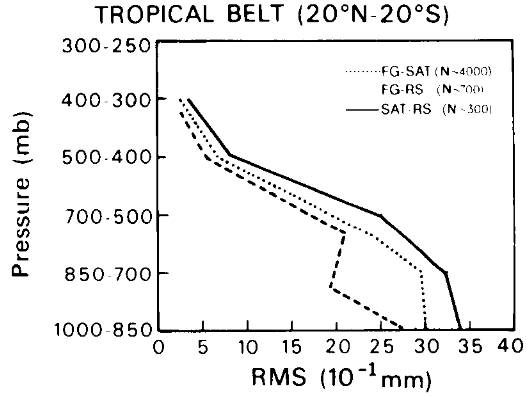

Fig. 6. Root mean square statistics for the difference in PWC between: (a) first-guess and satellite (dashed line), (b) first-guess and radiosonde (dotted line) and (c) satellite and radiosonde (continuous line).

enquire into the accuracy of the first guess. The first guess is provided by the 6-h forecast of the ECMWF T63 spectral model and it is compared to radiosondes and satellite data. Using the humidity statistics file for the summer period of June 1979, the variance of the difference of the observations from the first guess is calculated thus:

$$\text{Var(OB-FG)} = E_{\text{OB}}^2 + E_{\text{FG}}^2.$$

This states that the variance of the difference is equal to the sum of the squares of observational error (E_{OB}) and first guess error (E_{FG}), assuming that observational errors and first-guess errors are uncorrelated.

Fig. 6 shows the rmse of the difference in PWC over the tropics between (a) first guess and satellite, (b) first guess and radiosonde and for comparison (c) satellites and radiosondes. It is clear that the first guess and the data are of comparable accuracy. Furthermore, the rmse curves closely follow the climatological variance sharply decreasing with height. They rise to 70% of the climatological variance. This highlights the difficulty of measuring a field such as moisture which is highly variable both in space and time. However it is worth emphasizing that there appear to be only moderate differences between the quality of satellites, radiosondes and first-guess. This strongly suggests that useful information is contained in the satellite data and that this information could be profitably exploited in forming the humidity analysis.

6. Data assimilation experiments

Sensitivity studies have been performed to assess the quality of the humidity analysis and its sensitivity to the first guess field and to different observation types. The results of data assimilation experiments will be described which have been carried out to evaluate the impact of satellite PWC data on the quality of the analysis. Two experiments have been carried out each for a different season.

(a) *Winter case* (December 1985): 3 days of data assimilation from 12 GMT on 12 December 1985 to 12 GMT on 15 December 1985, using satellite data (SAT) and the control (NOSAT).

(b) *Summer case* (June 1979—FGGE): 3 days

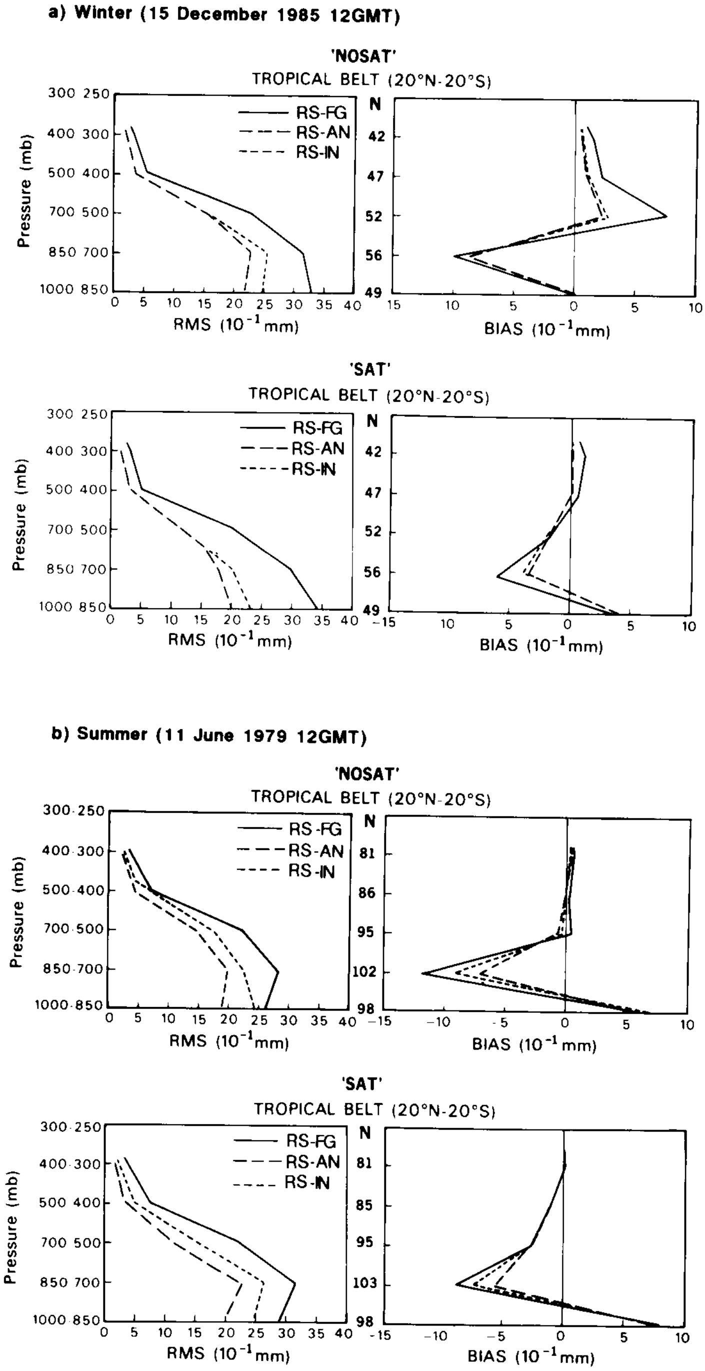

Fig. 7. Root mean square and bias statistics measuring the fit of the first-guess, analysis and initialized fields to radiosonde data over the Tropics (20° N; 20° S) for the NOSAT and SAT assimilations; (a) Winter case (December 1985), (b) Summer case (June 1979).

of data assimilation from 12 GMT on 8 June 1979 to 12 GMT on 11 June 1979, using satellite data (SAT) and the control (NOSAT).

Based on the statistical evaluation of satellite data described in Section 3, the observational error ascribed to satellite data has been chosen to be 20%, twice that of the radiosonde error (10%), while the prediction error is specified to be 10% in the extra-tropics and 15% in the tropics. Cloud observations from surface data have been used in order to make up for lack of moisture information in cloudy areas where satellite data cannot be used. The algorithm used to deduce moisture information from cloud data follows closely that outlined in Chu and Parrish (1979), with the important exception that cloud data are used only when cloud cover exceeds 7 octas (following the study of Pasch and Illari (1985), which has shown that cloud information tends to be unreliable especially when cloud cover is low).

Fig. 7 shows the rmse and bias of the first-guess, analysed and initialized fields of PWC with respect to radiosonde data over the tropical band (20°N–20°S) for the NOSAT and SAT analysis. The NOSAT first-guess and analysis both in the winter and summer case have a large bias especially in the 850–700 mb layer, where the NOSAT fields tend to be too wet. The use of satellite PWC data has reduced the bias of the first-guess and analysis with respect to the radiosonde data. In the winter assimilation (Fig. 7a) the bias has also been reduced in the 700/500 mb layer. Rms-errors have decreased mainly above 700 mb, implying a better fit of the first-guess and analysis fields to the radiosonde data there.

The satellite data have a moderate impact on the humidity analysis, particularly affecting data-sparse areas over the oceans for example. It is of course difficult to assess whether these changes improve the description of the moisture field in the assimilation. One way to assess the quality of the humidity analysis is to compare derived quantities which should be highly dependent on moisture. The most obvious choice is the 6-h forecast of precipitation. However, one can only draw tentative conclusions since the vertical motion fields clearly play the most decisive role in determining the rainfall pattern, rather than the relative humidity fields. However, it would be incorrect to view the humidity as a purely passive variable, since the evolving vertical motion field is itself the product of feedback from diabatic processes as well as the dynamics. These diabatic processes can be modified by changes to the humidity variable. Thus, we expect changes in the precipitation field to contain a signature reflecting the impact of changes in the humidity analysis.

Fig. 8 shows the 6-h precipitation from the experiment without satellites (NOSAT) and the experiment with satellite (SAT). These should be compared with Fig. 9, which shows a satellite derived index of convective activity for the same period, derived by Murakami (1983) from the infra-red sensor on the GMS satellite. Values of 4 or greater denote active convection and significant rainfall.

The difference between the rainfall from the NOSAT assimilation (Fig. 8a) and the SAT assimilation (Fig. 8b), although small, appears to be meaningful when compared to the observed convective activity (Fig. 9). By incorporating the satellite data, more realistic rainfall features are obtained in some areas; for example the rainfall over Thailand (15°N, 100°E) has been reduced in agreement with observations, as has the rainfall over Indonesia (5°N, 125°E); the rainfall centred at 10°N, 140°E, as well as the maxima at 5°S, 85°E have been intensified by incorporating satellite data, in agreement with the observed convective activity. Note moreover, that no satellite data is generated in cloudy areas, so the improvements arise from data in the clear and partly cloudy areas.

Although these changes are small, it can be concluded that the use of satellite data in the humidity analysis is beneficial and improves the prediction of rainfall.

7. Forecast experiments

The impact of changes in the moisture analysis, introduced by exploitation of satellite PWC data, has been assessed in several 10-days forecast experiments. The model used in the experiments is the ECMWF spectral model at the resolution of T63 or T106 (see Simmons and Jarraud (1983) for a detailed description of the adiabatic formulation of the model and Tiedtke

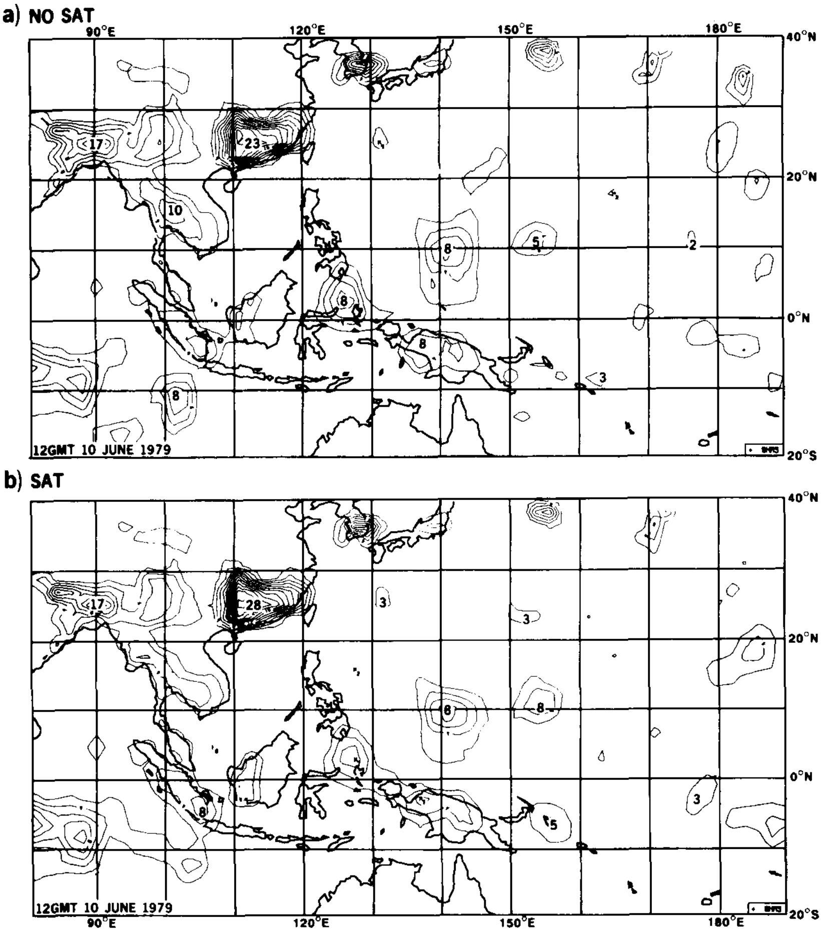

Fig. 8. Accumulated precipitation during the 6-h period ending 12 GMT, 10 June 1979 for: (a) NOSAT experiment and (b) SAT experiment. Contour interval 2 mm.

and Slingo (1985) for the description of the physical parameterization schemes used).

Two sets of 10-days forecasts will be discussed in this section: a *Winter case* from 12 GMT on 15 December 1985; a *Summer case* from 12 GMT on 11 June 1979, corresponding to the Monsoon onset during FGGE.

7.1. *Winter case*

Several T106 forecasts for December 1985 have been carried out to investigate the impact of humidity analysis changes on the quality of the forecasts. Here three 10-day forecasts for 15 December 1985 are described, each run from a different initial condition obtained after 3 days of assimilation with: (1) no humidity data which we call the NOHUM experiment; (2) no satellite data but only radiosondes and synops, the NOSAT experiment; (3) satellite data, radiosondes and synops, the SAT experiment.

The skill of the forecast is measured in terms of the objective score of the anomaly correlation in the height and temperature fields. Fig. 10 shows the temperature scores in the Northern Hemisphere for each forecast. It is clear that the SAT experiment gives the best forecast, while the NOHUM experiment is the least successful. On this particular occasion the inclusion of satellite data enhanced the predictability of the model. It is also clear that the positive impact derived from

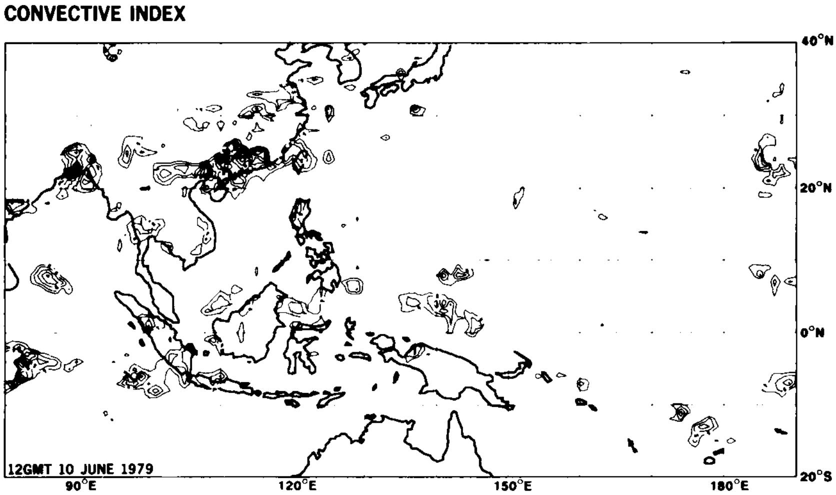

Fig. 9. The field of convective activity index for the 6-h period ending 12 GMT, 10 June 1979 derived by Murakami (1985). Only areas of vigorous convective activity (more than 4 units) are plotted.

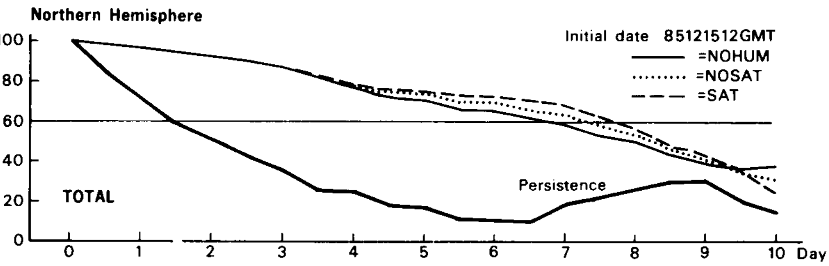

Fig. 10. Anomaly correlation of temperature forecasts for the experiments carried out on 12 GMT, 15 December 1985. Mean values are evaluated between 1000 mb and 200 mb over Northern Hemisphere.

the use of satellite data is of the same order of magnitude as that derived from more conventional data types, such as radiosondes and synops. The wave band decomposition of anomaly correlation indicates that the largest positive contribution is made by the medium-scale waves (4–9), baroclinic waves, although it is evident both at smaller and larger scales.

In interpreting these scores it is important to remember that, particularly in the extra-tropics, changes in the humidity analysis cannot be expected to directly affect fields such as geopotential and temperature. They can, however, affect the forecast of rain in the first few hours and thus, through latent heat release, influence to some extent the development of the weather systems and hence have an impact on scores for the geopotential and temperature fields. A more direct measure may be obtained, therefore, if we assess the impact of changes in the humidity analysis directly on the forecast of rain. The impact should be greater in the Tropics, where diabatic processes have a more direct influence on the pattern of vertical motion and therefore rain. In the Tropics, however, verification against observed rain is more difficult because of the lack of observations. The tropical forecast, therefore, will be assessed in the context of a case study of the June 1979 monsoon onset where the rainfall forecast can be verified against Monex data (Krishnamurti et al., 1980).

7.2. Summer case—June 1979 monsoon onset

We now describe results from two 10-day fore-

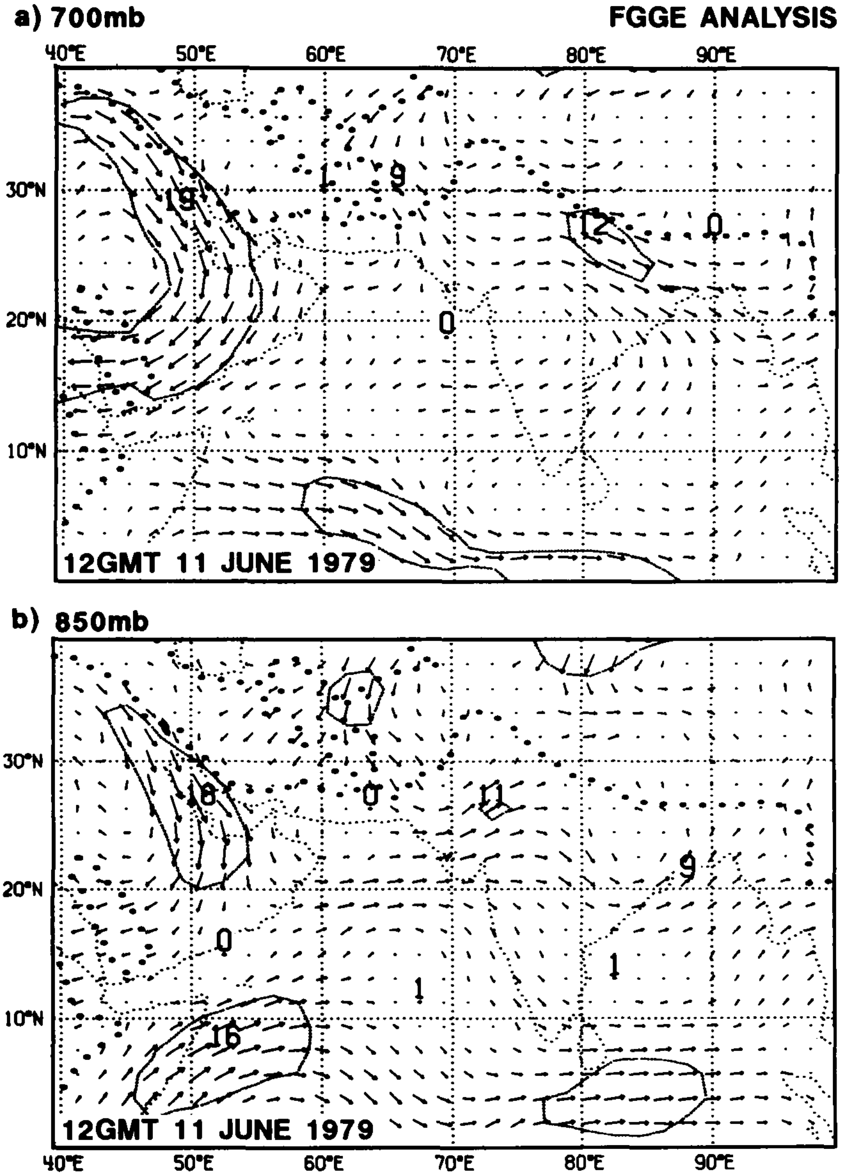

Fig. 11. FGGE analysis of the wind field for 12 GMT, 11 June 1979 at: (a) 700 mb and (b) 850 mb. The dotted line marks the main orographic features.

cast experiments for 11 June 1979, which provide further evidence of the benefits derived from the inclusion of satellite PWC in the humidity analysis.

A detailed study of the monsoon onset in June 1979 can be found in Pearce and Mohanti (1984), whilst the performance of the ECMWF model in representing the monsoon onset has been studied in Mohanti et al. (1984) and Datta et al. (1985). Here we discuss the impact of the humidity analysis, incorporating satellite data, on the forecast of the monsoon onset, paying particular attention to the rainfall forecast.

As described in Krishnamurti et al. (1980), the onset of the monsoon during June 1979 was late; a weak equatorial trough first appeared at the

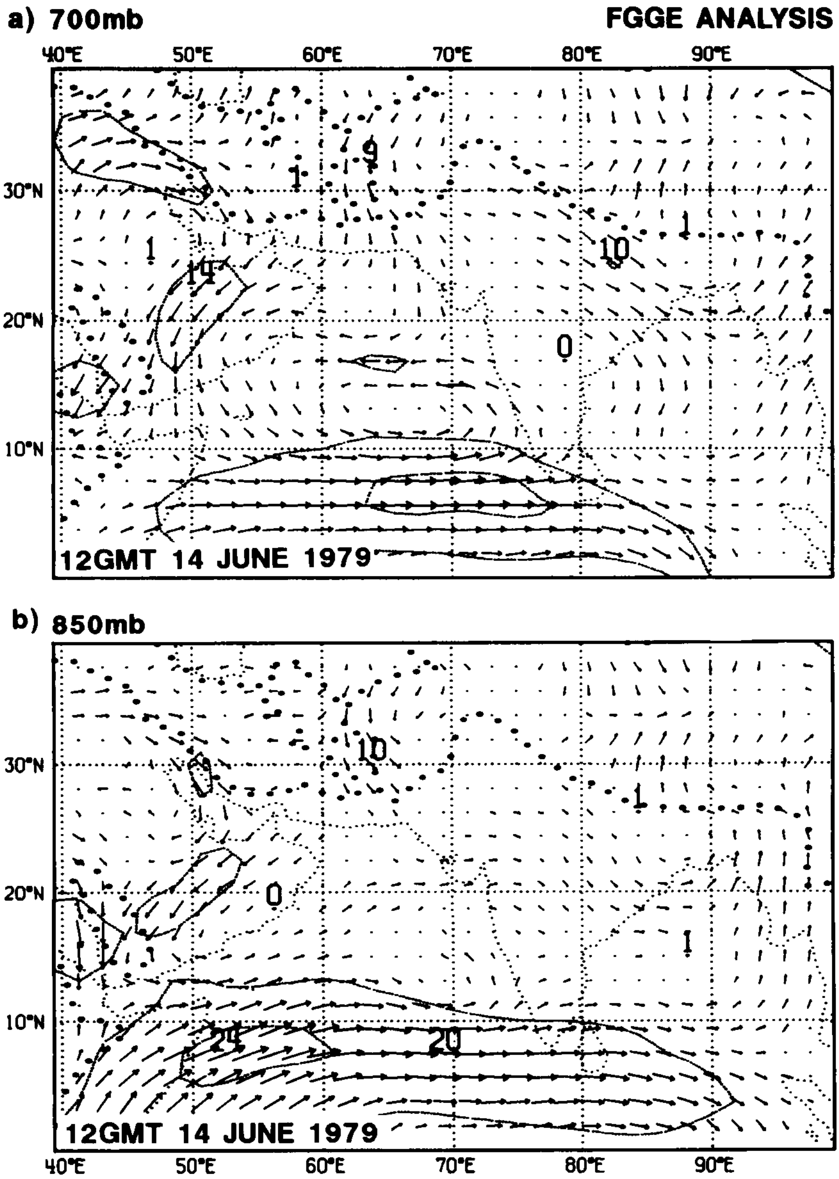

Fig. 12. As in Fig. 11 except for 12 GMT, 14 June 1979.

beginning of June 1979 at 700 mb. It steadily moved northward, bringing monsoon flow to the west coast of India. Fig. 11 shows the flow as given by the latest FGGE analysis (Uppala, 1986) for 12 GMT on 11 June at 850 mb and 700 mb respectively. At 850 mb (Fig. 11b) it is clear that the south westerly winds have intensified giving northward equatorial flow off the east African Coast (the Somali Jet), while at 700 mb, (see Fig. 11a) there is a broad band of east to north-east winds extending across the whole of the Tropical Indian Ocean into Africa as described in Datta et al., 1985. These features are typical of the monsoon onset.

As the monsoon flow intensifies, there is a strengthening of the equatorial westerlies. A well

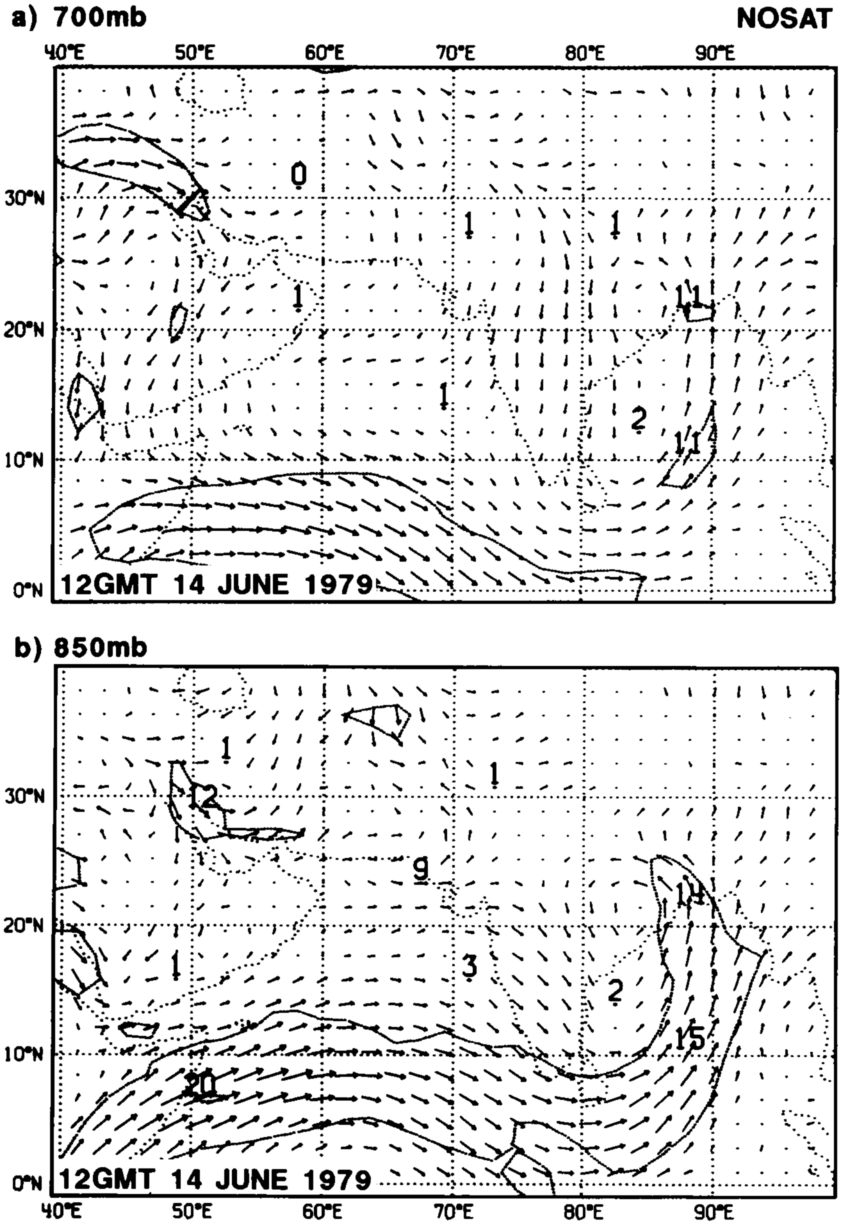

Fig. 13. The 72-h forecast of the wind field from 12 GMT, 11 June 1979 for the NOSAT experiment at: (a) 700 mb and (b) 850 mb.

marked circulation, centred on 70°E, 10°N, is formed on 14 June (Fig. 12) which develops into a tropical depression on 16 June.

To investigate the impact of the humidity analysis on the ability of the ECMWF model to forecast the monsoon onset, the analysed fields described above are compared with results from two different T63 forecast experiments, each starting from 11 June 1979, 12 GMT.

(a) The "NOSAT" experiment started from an initial state in which satellite PWC data are not used in the humidity analysis.

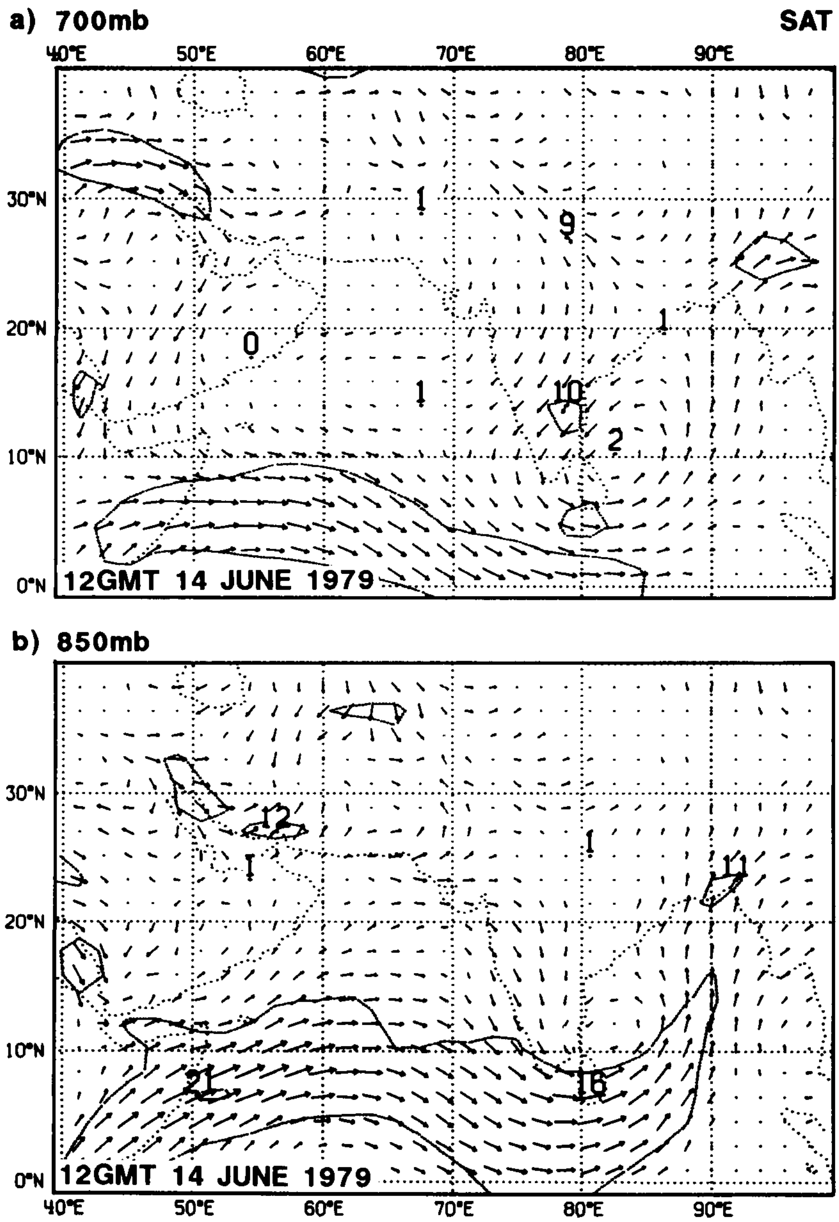

Fig. 14. As in Fig. 13 except for the SAT experiment.

(b) The "SAT" experiment, which used the same version of the model and physics as in the NOSAT experiment, but the forecast was made from an initial state (obtained after 4 days of assimilation) which made use of satellite PWC data in the humidity analysis.

The "NOSAT" experiment resulted in a good 24-h forecast, capturing the evolution of the low level Jet and of the strong westerlies over the Kerala Coast, but it failed to develop a satisfactory equatorial trough after 72 h. The 72-h NOSAT forecast is shown in Fig. 13 and should be compared with Fig. 12.

The inclusion of the satellite PWC data in the

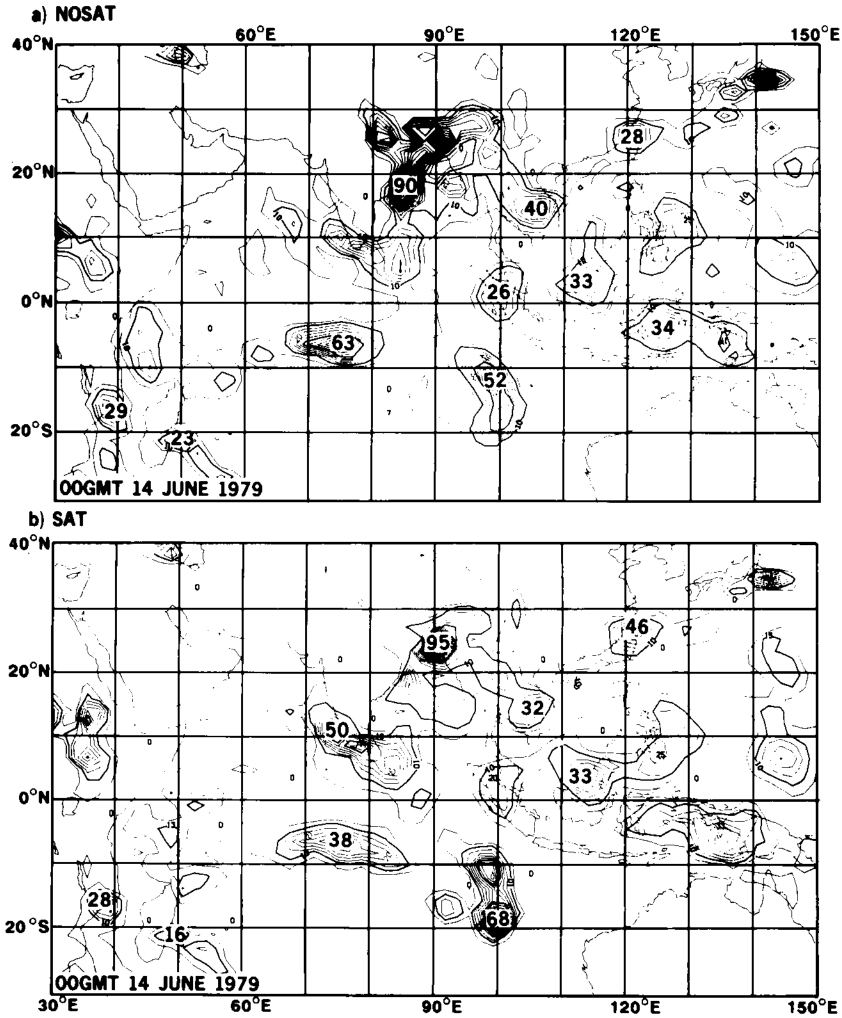

Fig. 15. The 24-h accumulated rainfall after $2\frac{1}{2}$ days during the forecast from 12 GMT, 11 June 1979 for the: (a) NOSAT experiment and (b) SAT experiment.

humidity analysis has a beneficial effect on the representation of the "onset" processes. The SAT experiment produces not only a good 24-h forecast with strong winds over the Kerala coast typical of the Monsoon onset, but also an improved 72-h forecast. It should be emphasized, however, that in the tropics, the skill of the forecast at day three is quite low. Fig. 14 shows the "SAT" 72-h forecast. At 850 mb (Fig. 14b), the wind speed has increased further to 15 m/s, with an enhanced circulation over the Bay of Bengal. At 700 mb (Fig. 14a), there are two circulations over the easterly jet, one over the Bay of Bengal and one over the Arabian Sea, more closely in agreement with the analysed flow (Fig. 12a), although the position of the circulation in the Arabian Sea is displaced slightly too far north.

From these results it is clear that the "SAT" analysis has a small but significant impact on the forecast of the monsoon onset. This is further evidenced in the forecast of rainfall. The Monex Rainfall Atlas (Fig. 16) is an indication of the

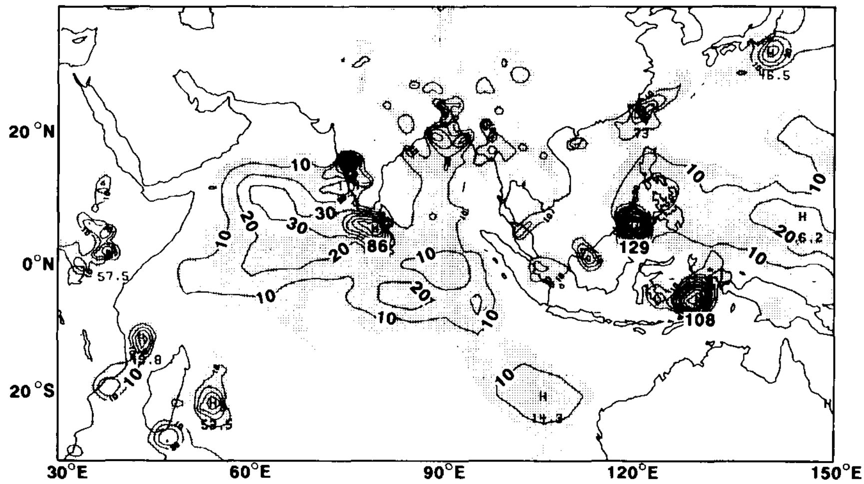

Fig. 16. The 24-h observed rainfall for 0 GMT, 14 June 1979 (Monex Atlas).

actual rainfall. Fig. 15 shows the rainfall after 72 h for the "NOSAT" and the "SAT" experiment respectively. The "NOSAT" experiment develops spurious heavy rain over Eastern India and the Bay of Bengal, whilst in the "SAT" experiment the rainfall is reduced in these locations. On the other hand, over western India the "SAT" experiment has more rain, following the intensification of the monsoon flow, apparently in closer agreement with the Monex data.

It may be concluded then that the forecast from the analysis produced after 3 days of assimilation with the "SAT" humidity analysis, markedly improves the representation of the monsoon onset and the forecast of rain.

8. Conclusions

This study has attempted to evaluate the quality of TIROS-N PWC moisture data, as provided by NESDIS by means of a statistical retrieval method. Collocation studies have shown that the PWC data from satellites are of comparable quality to radiosonde data and to the moisture field in the model first-guess. The collocation indicates that the error in relative humidity that can be ascribed to satellite PWC data varies from 15% in the Tropics rising to 35% in the extratropics. Satellite data can describe the total moisture in a column without a large bias. Only in abnormally dry situations, or at upper levels, where the PWC is low, is the bias unacceptably large.

A valuable by-product of this study has been an assessment of the quality of the humidity first-guess field. It has been found that the model first-guess provides moisture information of comparable accuracy to radiosonde and satellite data and suggests that the humidity analysis behaves satisfactorily, blending various sources of information together of comparable quality.

Using a large sample of radiosonde and first-guess moisture data over North America, the typical forecast error correlation scale for the humidity variable of PWC has been evaluated. It is found to be 250 km at the surface, rising to 300 km at upper levels. This is in agreement with a previous study by van Maanen (1976) and consistent with the assumptions made in the ECMWF analysis scheme concerning the scale of humidity structure functions.

The inclusion of satellite PWC data in the ECMWF humidity analysis scheme has proved to have a beneficial impact on the forecast, especially on the forecast of rain. A case study of the June 1979 monsoon onset has shown that the use of satellite moisture data in the analysis has a beneficial impact on the forecast of the monsoon.

To summarize, it can be concluded that the satellite derived moisture data have useful information which can be profitably exploited in performing the humidity analysis. Satellite derived humidity data are now used operationally in the ECMWF humidity analysis.

There are several improvements in the technique for retrieving PWC from satellite radiances that might further improve their quality. The TIROS-N PWC data examined in this study are produced by means of a statistical retrieval method, which tends to depict a rather smooth spatial and temporal structure of the moisture field. More sophisticated retrieval technique may be needed for moisture. Our study indicates that the model first-guess humidity field is of good quality, suggesting that a promising approach may be to use the first-guess directly in the moisture retrievals, the so called "physical" retrieval. The physical retrieval method may be able to provide more detailed information on the structure of the humidity field (e.g., sharper gradients) than the statistical retrievals; such physical retrieval methods are under investigation (Kelly, 1985).

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