TECHNICAL MEMORANDUM

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FGGE moisture analysis and assimilation in the ECMWF system

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1. THE NATURE OF THE PROBLEM

It has become apparent that the treatment of the moisture variable in the ECMWF data assimilation system is deficient in the following respects:

- the first-guess fields of humidity are largely unaltered by the analysis/initialization procedure.

- the analyzed fields of humidity do not always agree with TEMP (radiosonde) observations - even when those observations appear to be accurate and representative of the synoptic or larger-scale feature.

- the moisture analysis fails to utilize all available sources of data, in particular from the polar-orbiting satellites.

These deficiencies are the result of shortcomings in a number of aspects of the system, the most important of which are:

- the analysis procedure

- the use, misuse and disuse of available observations

- the prediction model

We have focussed most of our efforts on the first two aspects, although the third aspect is of at least equal importance. Moreover, we have concentrated our attention on the tropics, where the proper description of the humidity variable is crucial for numerical weather prediction. Here we discuss assimilation experiments made with the Final and Main II-b data sets using the ECMWF 19-level T63 spectral model, with physical parameterizations which were in operational use in the spring of 1985 (see Tiedtke and Slingo, 1985).

Figs. 1a and 1b are skew T-log p diagrams for the radiosonde ascent from Johnston Island (16°N, 169°W) on 30 December, 1978, 12 GMT, together with the first guess and the initialised values from a final FGGE II-b data assimilation run. Since the initialisation procedure has negligible impact on the humidity analyses we consider the initialised fields to be nearly equivalent to the analyzed ones. From the dewpoint curves in Fig. 1, it is clear that the first-guess and initialised profiles are nearly identical and that neither of them conforms to the observed sounding. In particular, the initialised profile fails to describe the observed drying above the trade-wind PBL and is too moist at nearly all levels above 850mb. Similar results have been found when comparisons are made for other TEMP observations in the trade-wind belt. Although these are fairly isolated observations, they do imply a general problem in the assimilation.

Figs. 2a and 2b are maps of the 700mb mixing ratio (g kg^{-1}) for the first-guess and initialisation, respectively, over the tropical Atlantic region on 31 December 1978, 12 GMT for the same assimilation. The values with adjacent dots denote TEMP observations of mixing ratio. Over the entire domain, one can see that the first guess forecast is essentially unchanged after the analysis/initialisation procedure. Moreover, after examining a number of cases over the tropical belt, and comparing first-guess and initialised fields of mixing ratio with observations near this level, we conclude that the initialised fields are generally too moist. This is a defect in the first-guess fields which the current analysis is unable to correct by making use of the available TEMP data.

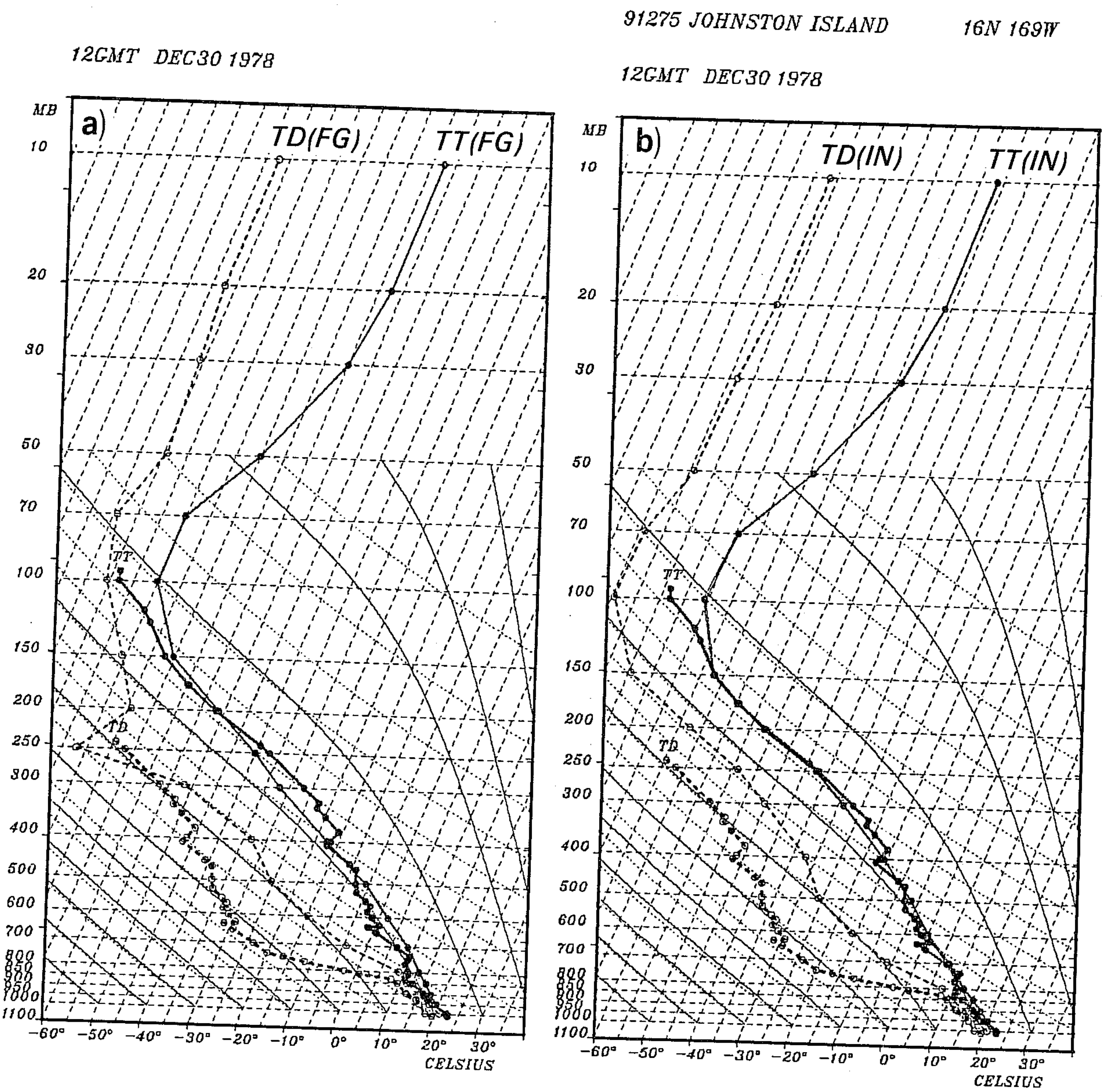

Fig. 1: Skew T-log p diagram for station 91275. Heavier curves, observed soundings, thinner curves, in (a): first-guess; in (b): initialised.

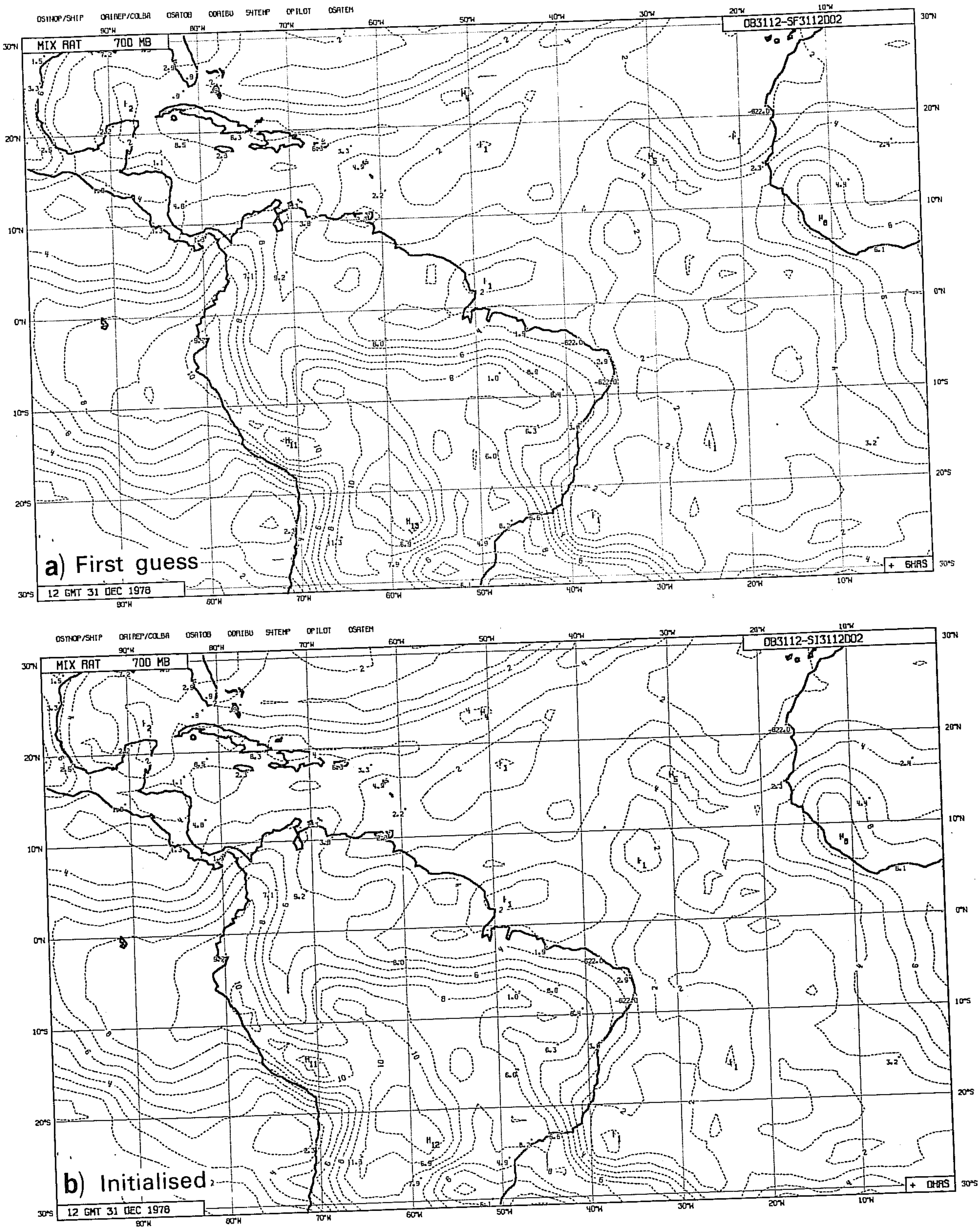

Fig. 2: Fields of 700mb mixing ratio from (a) first guess and (b) initialisation for 31 Dec., 1978, 1200 GMT. Contour interval $1 g kg^{-1}$.

2. THE HUMIDITY ASSIMILATION SCHEME AND ITS SHORTCOMINGS

2.1 Analysis/interpolation procedure

The humidity variable is not analysed with the multivariate optimal interpolation scheme as are the mass and wind data. It is analysed separately via a two-dimensional one-pass correction scheme where the prediction error correlation is assumed to have a Gaussian structure. The actual analysis variable is the precipitable water of atmospheric layers separated by the standard pressure surfaces of 1000, 850, 700, 500, 400 and 300 mb. Further details are given in Lönnberg and Shaw (1983), Lorenc and Tibaldi (1979).

It is considered a drawback that the analysis for humidity is not part of the multivariate scheme. A further major deficiency is the fact that the current version of the humidity analysis scheme presumes a very high degree of confidence in the first-guess fields. In the case of mass and wind fields this presumption is warranted because the quality of the 6-hour forecasts of the geopotential and motion fields has been well documented. However, we have no such statistics on the quality of the corresponding humidity forecasts, particularly in the tropics. In fact, the first-guess fields of moisture over the tropics are highly sensitive to the physical parameterizations of the model which have been undergoing changes (and are still being studied) in an effort to improve them. In view of this, and also from the results shown in Figs. 1 and 2, it would appear that the currently assigned prediction error is too low and/or the currently assigned observation error for TEMP data is too high. Moreover, in the Gaussian structure function for the humidity prediction error correlations, the horizontal length scale (i.e. distance at which the error correlation drops to $e^{-\frac{1}{2}}$) is currently set to a value of roughly 300km for the low to mid-tropospheric layers. This may be too large to resolve the sharp horizontal gradients in the humidity fields which the radiosondes are defining (e.g. note the observations over Florida and the Northwest Caribbean Sea in Fig. 2b, which imply sharp gradients).

2.2 On the use of humidity observations

There are basically three types of data which can be used in the humidity analysis; these are TEMP, SYNOP and SATEM data. The current method of utilisation of the first two types of data is discussed in Lönnberg and Shaw (1983). Additionally we have the option of including SATEM data in the FGGE assimilations. These are retrievals of precipitable water content for the layers 300-500 mb, 500-700 mb and 700-1000 mb from the TIROS-N infra-red sensor (Johnson, 1984). Before discussing the potential use of the SATEM humidity data, we must comment on the current technique for using the SYNOP data.

Surface-based observations of temperature, dewpoint, low, and middle and high cloud amount as well as current weather type from land and ship stations constitute the SYNOP data base. In the current procedure these data are used to infer the mean relative humidity for 4 layers from the surface to 300mb, separated (roughly) by the 950, 700 and 500 mb levels (depending on model surface pressure). For the humidity analysis, the most important observation from the SYNOP data is the surface dewpoint. This is used to infer the humidity in the 50mb thick surface layer (constant relative humidity for this layer is assumed). However, the cloud and weather reports are also incorporated to provide a final humidity estimate for this layer as well as for the upper layers (using empirical relationships derived by Chu and Parish, 1977). This use of cloud, and particularly, weather information from the SYNOP data is highly empirical and is a weakness of the humidity assimilation. One should, however, also recognise the need to incorporate some form of moisture information over those regions which are void of conventional data.

The SATEM humidity data should provide useful information for the Final FGGE assimilations.

We have two alternative sets of TIROS-N moisture data currently available for the SOP-II assimilations; these are the NESS and the GLA data sets. Both provide essentially the same kind of information, i.e. precipitable water for the layers mentioned above. However, the methods used for deriving these data are different. NESS used the statistical approach (Smith and Woolf, 1976). It is based on the premise that the eigenvectors of covariance matrices of cloud free radiances measured by the satellite, along with those of collocated radiosonde moisture profiles, will provide the statistical relationship needed to retrieve the humidity data from other cloud free satellite radiance measurements. The collocations are averaged over one week periods and over fairly broad latitude bands. Hence the NESS retrievals tend to depict a rather smooth spatial and temporal structure of the moisture fields. Cadet (1983) has successfully made use of these data over the Indian Ocean. However, he found it necessary to provide bogus "soundings" of humidity over the convectively active regions because the NESS data are mainly restricted to the clear or partly cloudy areas.

On the other hand, the GLA data have been produced via the so-called "physical" retrieval technique. The retrieved moisture (and temperature) profiles are derived from the iterative solution of the (linearised) radiative transfer equation. These retrieved profiles are consistent with the radiance of a first-guess field which have been corrected so as to minimise their departures from the actual satellite measurements (Kelly, 1985).

By virtue of the physical retrieval method, it is possible that the GLA data may be able to provide more detailed information on the humidity structure (e.g. sharper gradients, drier mid-tropospheric values, etc.) than the NESS statistical retrievals.

3. EXPERIMENTS ON THE HUMIDITY ASSIMILATION

We have made preleminary tests on the impact of the SATEM humidity data on the assimilation. These assimilation experiments are for June 1979 using the Main II-b data sets. So far we have utilised only the NESS retrievals, as the GLA data have only recently been made available to us. Assimilations have also been carried out to see the impact of handling the SYNOP data in a more discriminating way. We shall discuss briefly the results of three short (3-day) assimilation runs which all use the same version of the T63 model:

(i) A control assimilation (CONTR), using TEMP and SYNOP data only, which analyses these data in the manner described in Sect. 2.

(ii) An assimilation which is identical to (i), but includes the NESS precipitable water retrievals in the data base (as described by Illari, 1985); this is referred to as experiment SAT.

(iii) Same as (ii), but with an additional modification (described below) to the SYNOP data before their utilisation; this is referred to as experiment SYN.

In (iii) we modify the way in which we use the SYNOPS. It has been found (Illari, 1985) that the current treatment of these data produces estimates of layer mean relative humidity which are too moist in the 700-850mb and 850-1000mb layers. These biases result from the use of cloud and current weather observations from the surface reports to provide estimates of the lower tropospheric moisture profiles. In short, we feel it is impossible to use the current weather reports to provide any reliable estimate of the moisture and that, for less than 50% coverage of any layer by clouds, it is also impossible to reliably deduce humidity. The surface measurements of temperature, pressure and dewpoint (although sometimes having gross errors which are easily screened at the pre-analysis stage) are clearly the most useful information provided by the SYNOPS, hence we retain these data. Additionally, observations of broken to overcast lower, middle or upper level clouds should also be considered useful.

Hence, in (iii) we delete the humidity estimates from current weather as well as those from reported cloud amounts (in any layer) of less than 5 oktas. Moreover we have changed another aspect of the humidity interpolation (Lönnberg and Shaw, 1983) which had adjusted any estimates from SYNOP data so as to conform very closely with the first guess. We no longer adjust those SYNOP data (albeit we now exclude a greater number of them entirely). These three assimilations were run from 8 June 1979, 00 GMT.

Figs. 3, 4 and 5 are maps of the analysed fields of precipitable water at 11 June, 1979, 00 GMT (i.e. after several days of assimilation) in the 1000-700 mb layer for CONT, SAT and SYN experiments respectively, and Figs. 6, 7 and 8 are the corresponding maps for the 700-500 mb layer. Only TEMPS (indicated by their station identifier) and SATEM (indicated by dots) observations of precipitable water are plotted (however the SATEMS were not used in CONTR). Comparing the fields for both layers from CONTR with those from SAT, we can see the impact of the SATEM moisture data on the analysis/ assimilation. Although we ascribe a slightly larger observational error to the SATEMS, the analysis tends to fit them because of the large number of such data (for this case we have roughly four times as many SATEMS as TEMPS). The largest impact is evident over the oceanic regions. For example a pronounced minima in the 1000-700 mb precipitable water field which was evident near 25°N, 132°W (Fig. 3) has been largely wiped out by the satellite-derived analysis (Fig. 4). Also, in the 700-500 mb layer, a moisture maxima near 8°N, 108°W has been more clearly defined by the SATEMS (Fig. 6 vs. Fig. 7).

To get some idea of the impact of modifying the use of SYNOPS we can compare the result from experiment SYN (Figs. 5 and 8) with those from SAT (Figs. 4 and 7). The differences are rather small for both layers but a few interesting changes can be noted. For example a 1000-700 mb moisture maximum has become better defined near 20°N, 140°W after the modification to the SYNOPS (Fig. 5 vs. Fig. 4) in an area devoid of TEMPS or SATEMS. Moreover, in the 700-500 mb layer a moisture maximum near Puerto Rico, in better agreement with the nearby TEMP (78526, San Juan) observation, is now evident after the modification (Fig. 8 vs. Fig. 7).

It is difficult to assess whether these data changes improve the description of the moisture fields in the assimilations. One way, however, to assess the quality of the three humidity assimilations is to compare derived quantities which should be highly dependent on moisture; the most obvious choice is the 6-hour forecast precipitation. We must recognise that the vertical motion fields play a most decisive role in determining the rainfall patterns which are being studied here. However, one should not view the humidity as a purely passive variable in this case, since the evolving vertical motion fields are the result of feedbacks from diabatic processes in the model as well as the dynamics. These diabatic processes can be modified solely by changes to the humidity variable.

Figs. 9, 10 and 11 depict the accumulated precipitation fields for a 24-hour period ending on 11 June, 1979, 00 GMT (obtained by summing over four 6-hour

CONTR

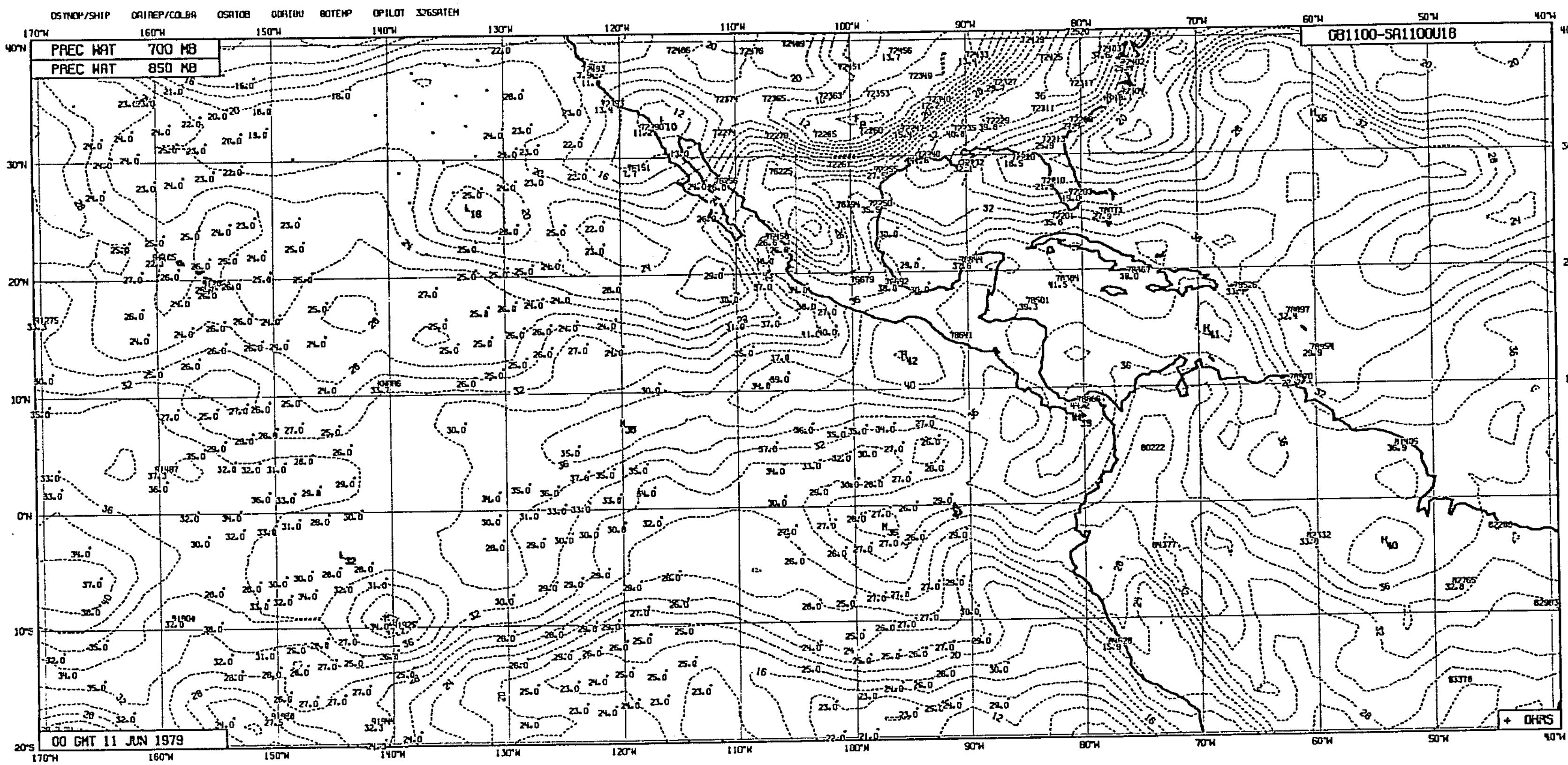

Fig. 3: Field of 1000-700mb precipitable water for the CONTR assimilation. Contour interval is 2mm.

SAT

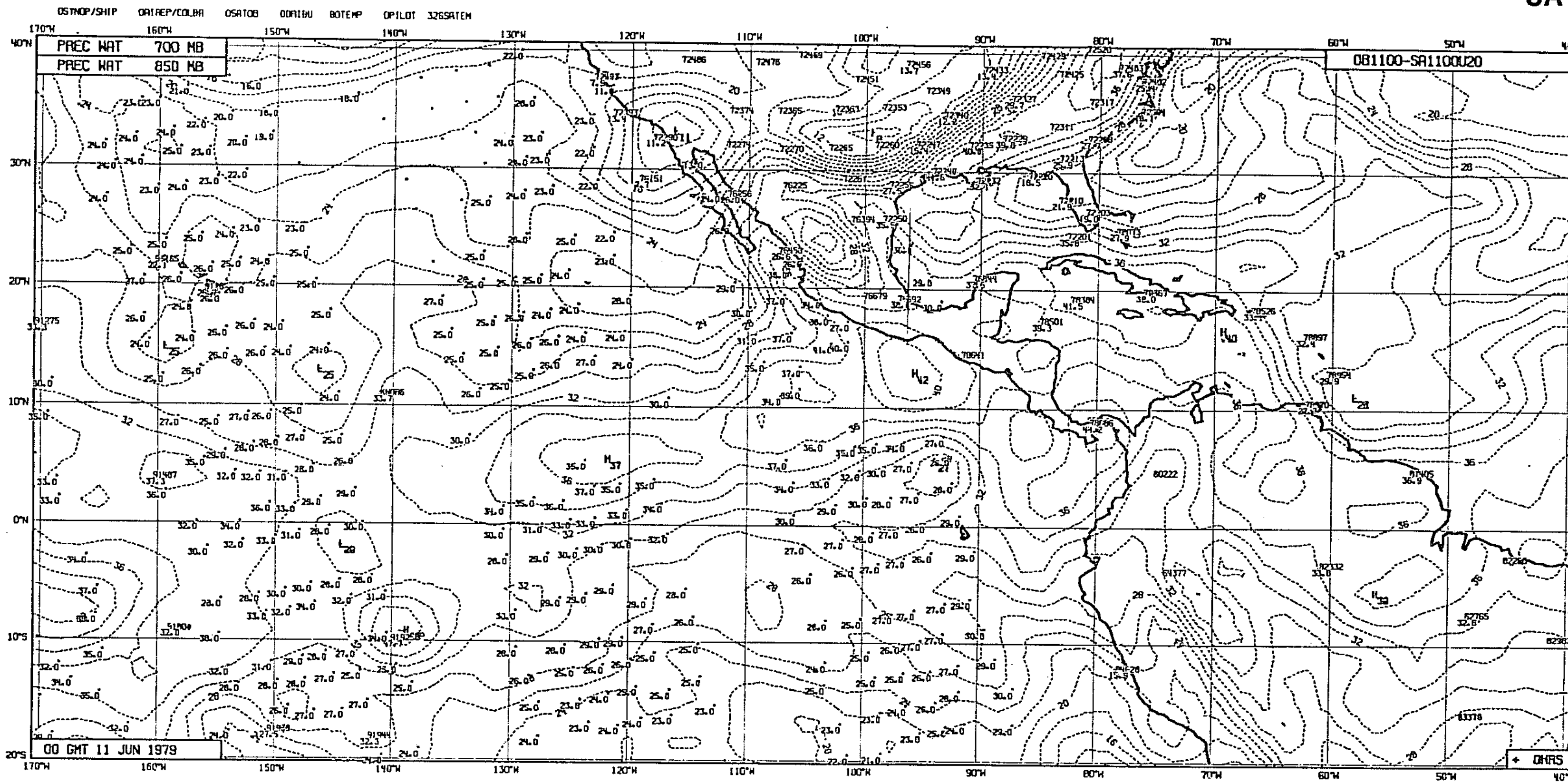

Fig. 4: As in Fig. 3 but for SAT.

SYN

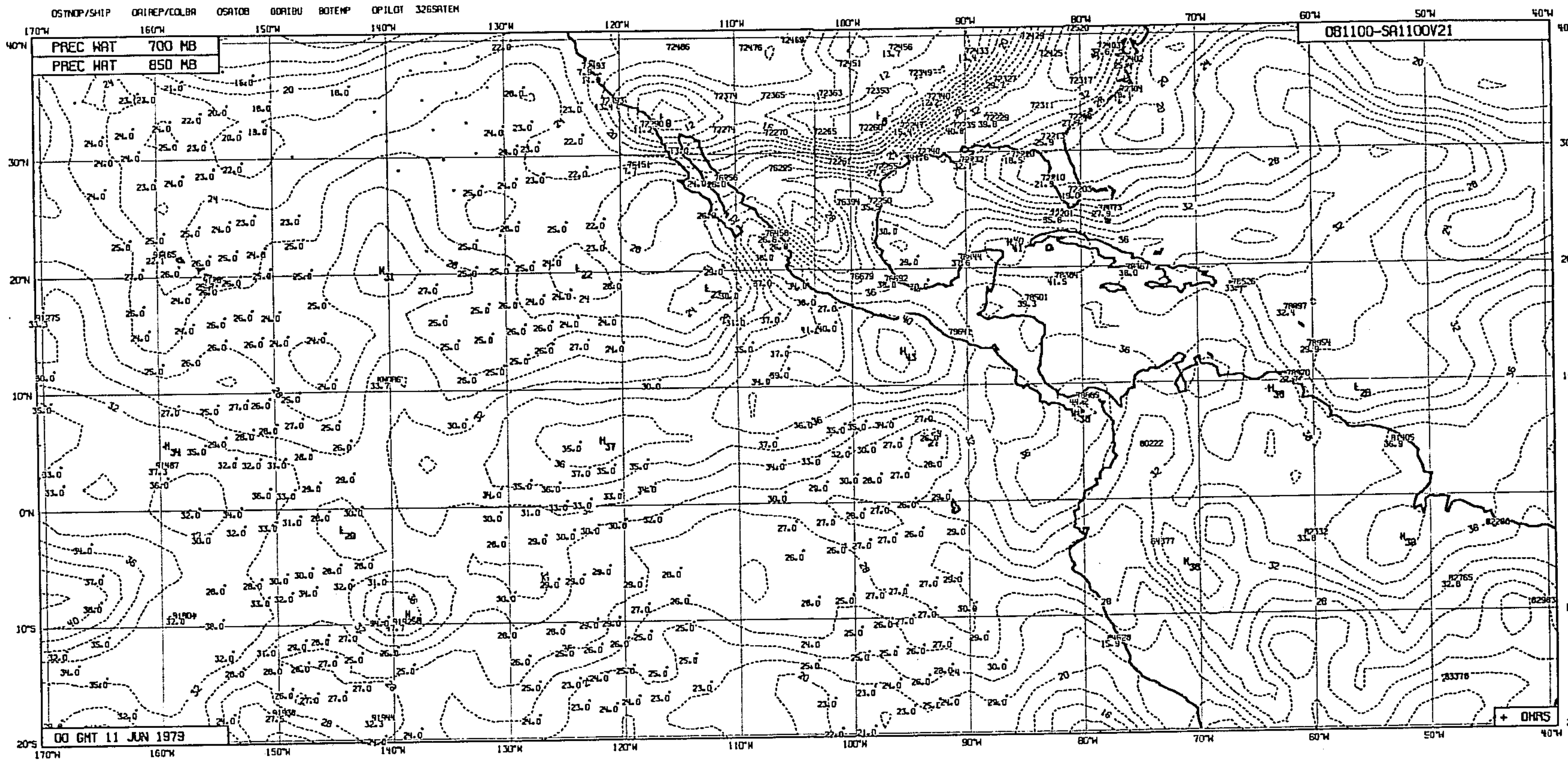

Fig. 5: As in Fig. 3 but for SYN.

CONTR

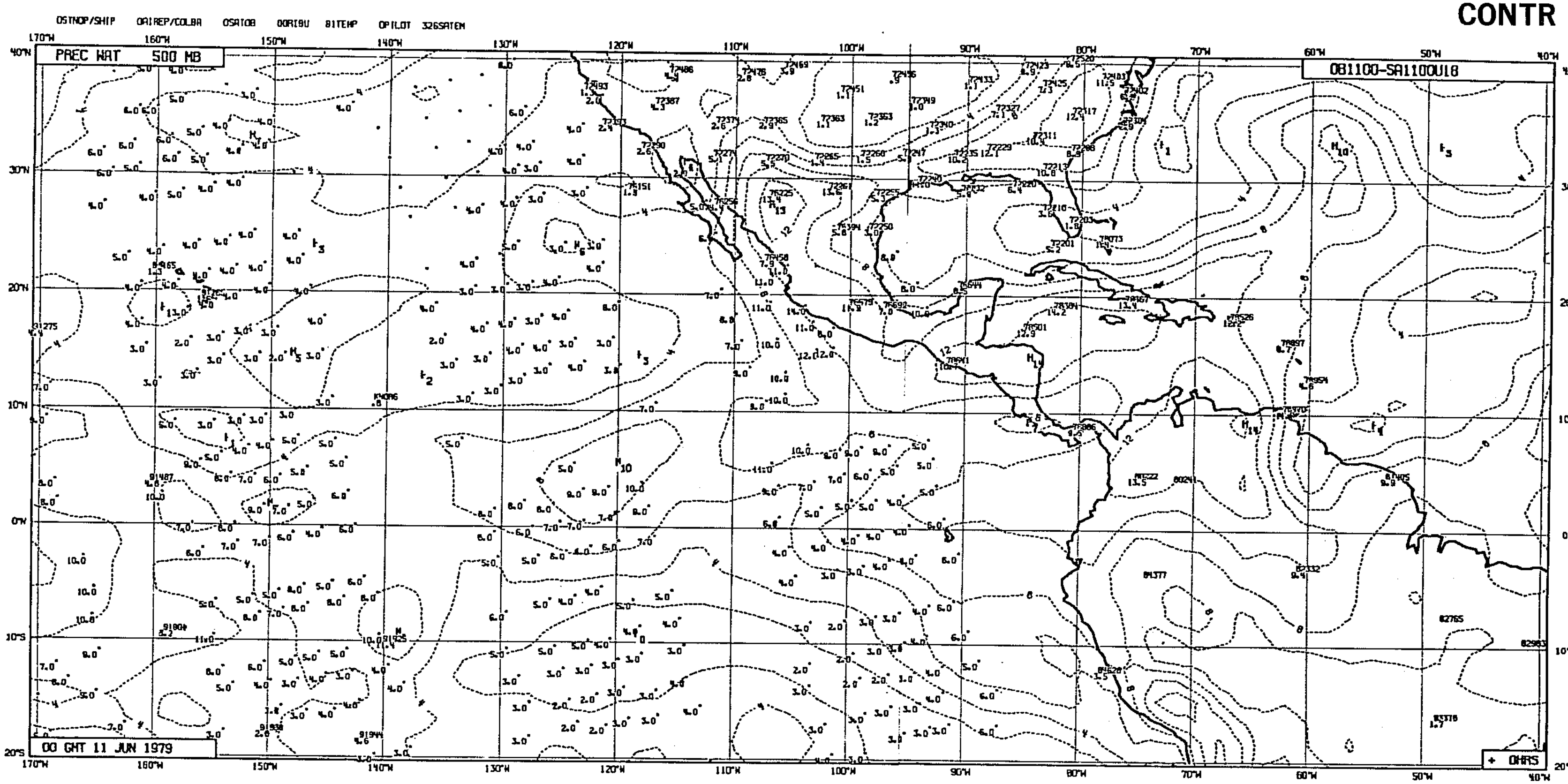

Fig. 6: Field of 700-500mb precipitable water for the CONTR assimilation. Contour interval is 2mm.

SAT

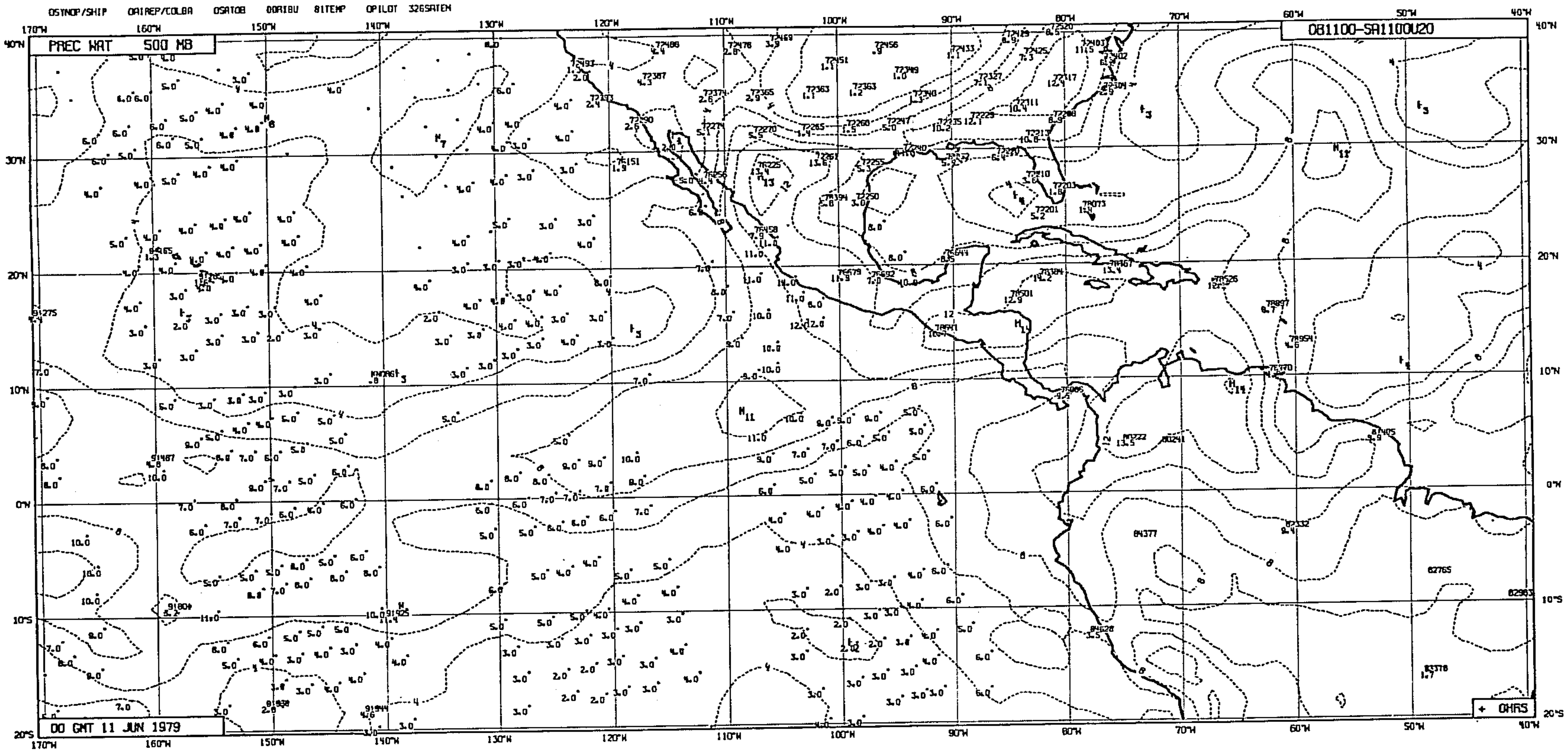

Fig. 7: As in Fig. 6 but for SAT.

SYN

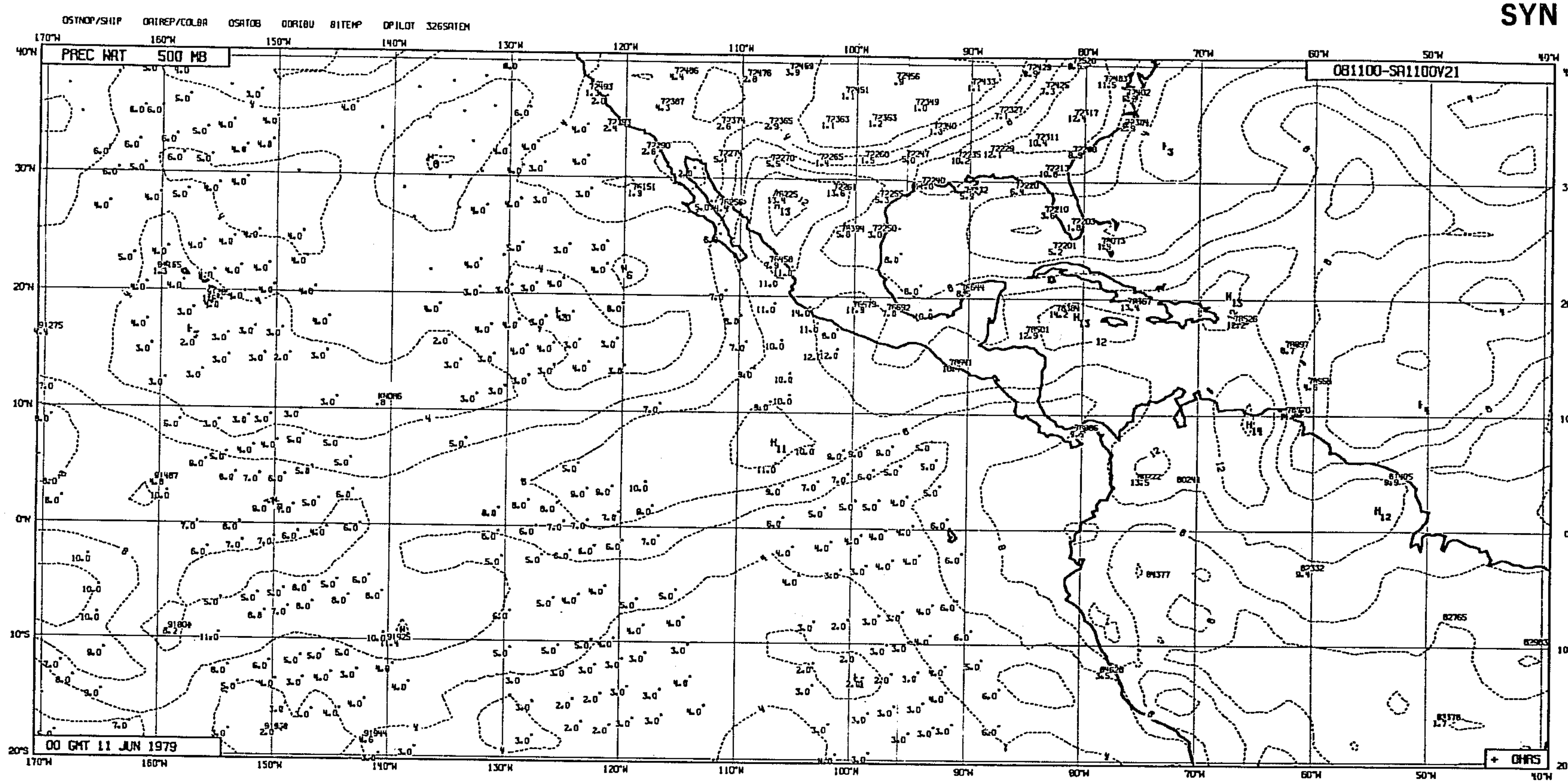

Fig. 8: As in Fig. 6 but for SYN.

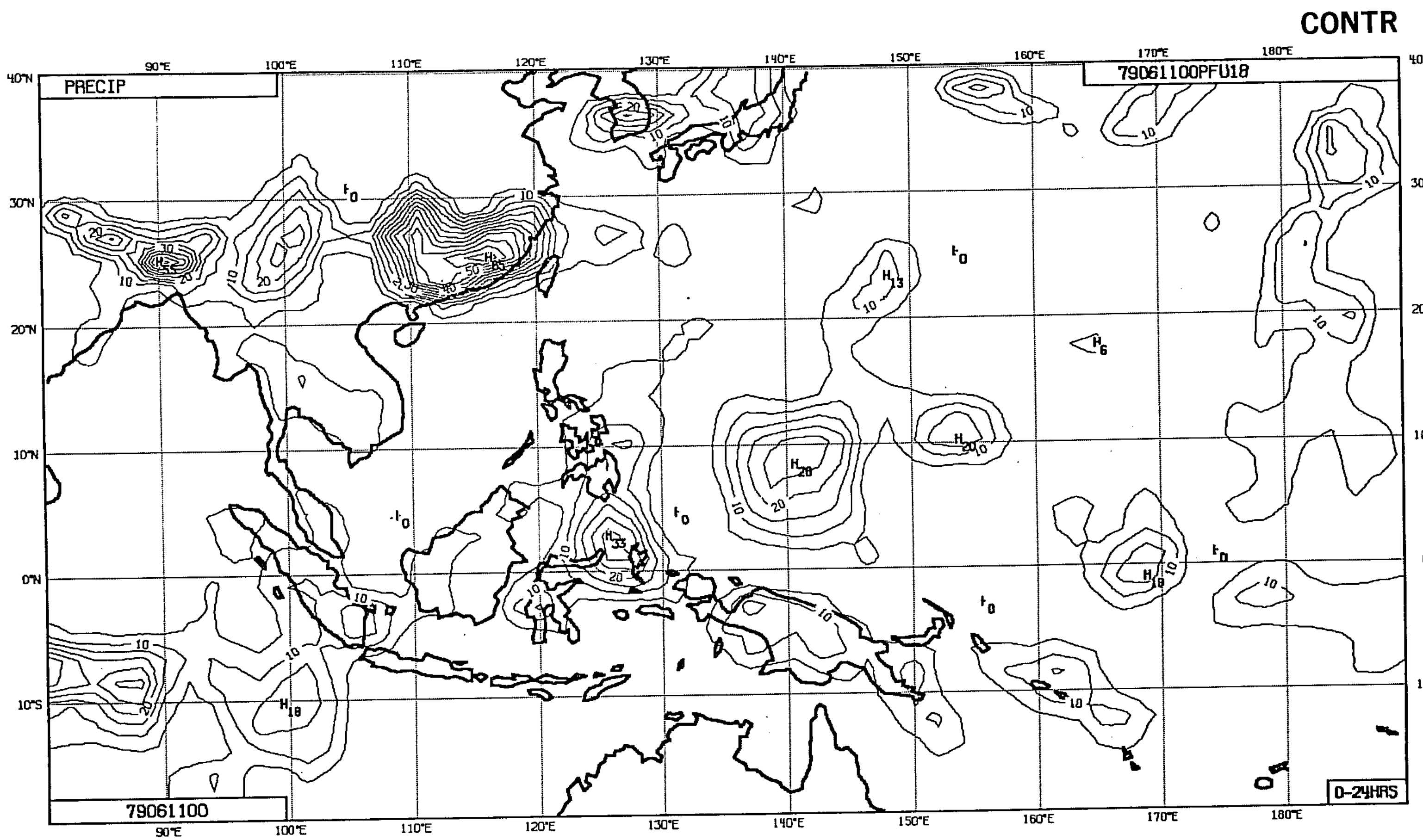

Fig. 9: Accumulated precipitation for the 24-hr period ending 00 GMT, 11 June 1979 from the CONTR assimilation. Contour interval is 5mm.

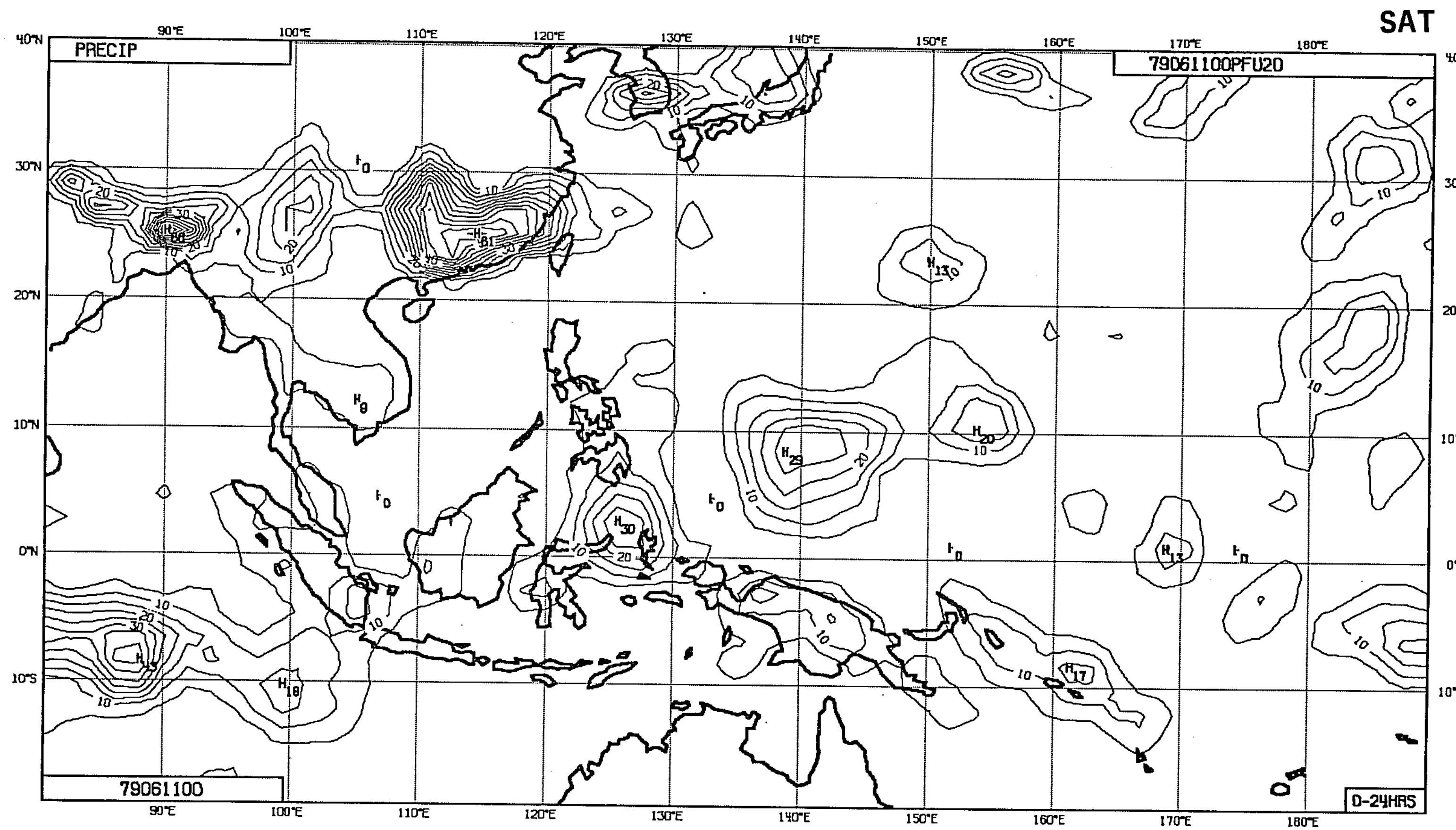

Fig. 10: As in Fig. 9 but for SAT.

SYN

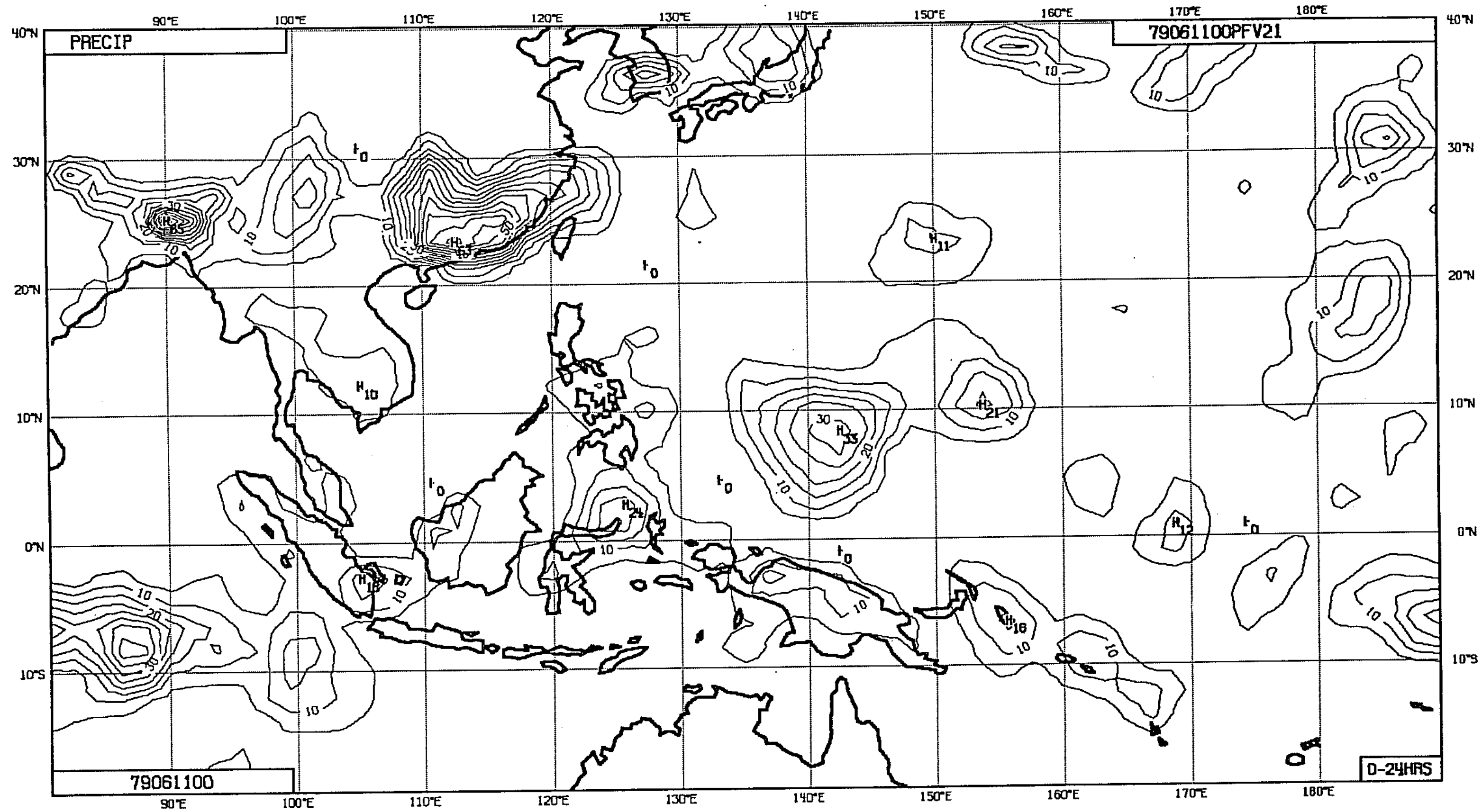

Fig. 11: As in Fig. 9 but for SYN.

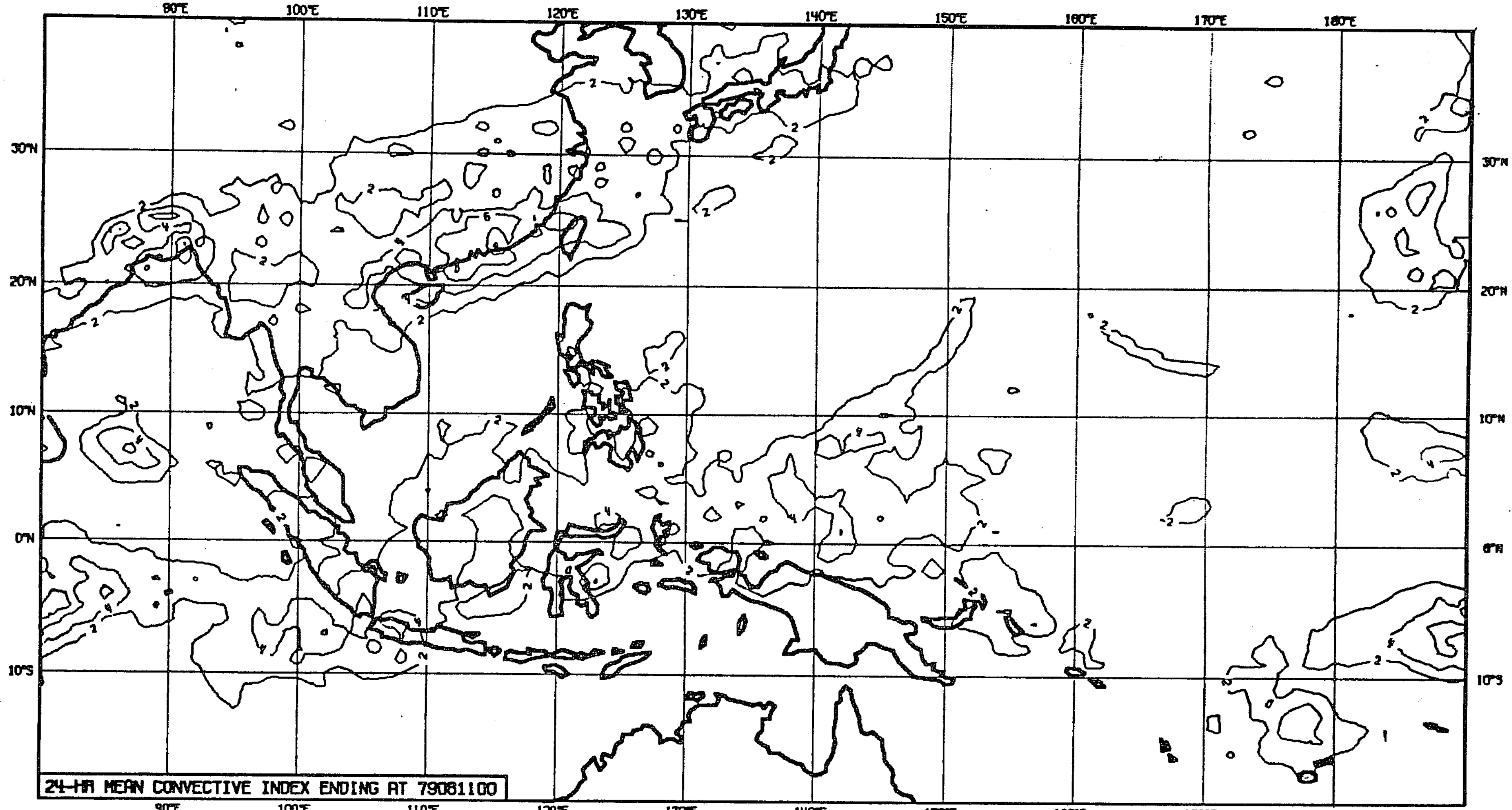

Fig. 12: Field of mean convective activity index for the 24-hr period ending 00 GMT, 11 June 1979 derived by Murakami (1983). Contour interval is 2 units; first contour has a value of 2.

cycles) for the CONTR, SAT and SYN assimilations respectively. Fig. 12 is the time-averaged satellite-derived index of convective activity, for the same period, derived by Murakami (1983). These are from the infra-red sensor on the GMS satellite and images have been processed every 3 hours. For this 1-day mean, values of 4 or greater denote very active convection and significant rainfall.

The differences between the rainfall accumulations "diagnosed" by the three assimilations (Figs. 9, 10 and 11), although small, appear meaningful when compared to the observed convective activity (Fig. 12). By incorporating the satellite data we can get more realistic rainfall features in some areas, e.g. the rainfall centre near 7°S, 170°W (comparing Fig. 10 with Fig. 9), where the convection was observed to be quite intense (Fig. 12).

The modification to the SYNOP data has also slightly improved the rainfall features. The rainfall centre near 9°S, 162°E in SAT (Fig. 10) has been shifted towards the northwest in SYN (Fig. 11) near Bougainville Island, which is an improvement. Also the intense rainfall centre near the south-east China coast has been shifted slightly to the south west in the SYN run and is now more in agreement with the observed convective maximum in Fig. 12.

We conclude that the use of these satellite data is beneficial and that the modification to the SYNOP data is also of some value. Each of these changes has made slight improvements to the rainfall patterns diagnosed from the humidity assimilations.

4. RECOMMENDATIONS FOR THE HUMIDITY ASSIMILATION

Based on the results presented thus far, we can make the following recommendations for the Final FGGE assimilations:

- The first-guess forecast error for humidity should be increased, probably from its current value of 15% to 20%.

- We must make use of satellite moisture data (either the statistical or the physical retrievals).

- Further tests, i.e. data assimilation experiments, will be needed to determine which of the two kinds of satellite moisture retrievals will be most beneficial to the humidity analysis. It is likely that there is probably some moist bias in the NESS retrievals for the 700-500 mb layer. Preliminary tests on the GLA data suggests no such moist bias, and that the GLA retrievals describe a more detailed structure. Collocation with radiosondes has shown that the NESS and GLA retrievals are of similar quality. An additional set of physical retrievals is being produced by G. Kelly at ECMWF and these look quite realistic. We do have the additional option of using those retrievals (in principle, for the entire FGGE) but, again, some testing via assimilation experiments would be required to determine if they are superior to both NESS and GLA. They are, in fact, currently being tested in some Final FGGE assimilations. This provides a viable third option on the SATEM data choice.

- Modify the use the SYNOPS to derive moisture data reported in SYN but with one exception: do not use the reported cloud information for less than 7 oktas cloud coverage in any layer. This assumes that the SYNOPS do not introduce biases which could result from the partly cloudy to broken sky estimates of moisture. We feel that the cloud information is useful for the almost or completely overcast situations, since these are precisely the cases which the TIROS-N infra-red sensor is incapable of providing humidity data.

Finally, although the testing of satellite data should continue, particularly if we are to provide reliable moisture fields for SOP1, we think that the use of NESS retrievals together with the modification in the use of SYNOPS described above, should prove to be a viable system for use in SOP2.

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