TECHNICAL MEMORANDUM

160

Evaluation and development of the ECMWF humidity analysis

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1. INTRODUCTION

In recent years, as the data assimilation system has moved to higher resolution, the initial humidity field is becoming more important for Numerical Weather Prediction (NWP). Some effort is now needed to improve the quality of the present humidity analysis. Illari (1989) made a comprehensive assessment of the ECMWF humidity analysis system which was operational up to 1986. Since then there have been more developments and modifications in the operational analysis (see, for example, Kelly and Pailleux (1988) for developments related to the use of satellite data, and Lönnberg (1988) for the other optimum interpolation developments). It seems therefore necessary to reassess the performance of the humidity analysis in the context of the more recent system. Also, we will try to explore more fully the use of satellite moisture observations, such as Upper Tropospheric Humidity (UTH) retrieved from the Meteosat measurements (Schmetz and Turpeinen, 1988; and Turpeinen and Schmetz, 1989). It is also necessary to re-evaluate and further develop the present ECMWF humidity analysis system. There is some evidence that the present humidity analysis at ECMWF may not provide the best humidity initial field for the model, and the utilisation of available data (e.g satellite data) in some specific areas is still far from satisfactory. This will be shown later in this paper.

There are at least two factors which can influence the quality of a humidity analysis;

- The choice of the structure functions for the humidity variable in the OI scheme.
- The amount and the quality of humidity observation information used in the analysis system.

The purpose of this paper is to evaluate the present humidity analysis and to test some new developments, such as changing the vertical correlation between moisture variables. This might be useful to use new observational information in the system. Using the new scheme, we introduced the UTH data into the humidity analysis. In section 2, we will give a brief description of the ECMWF humidity analysis system. In section 3, the performance of the humidity analysis produced by the ECMWF data assimilation system is studied, and the current humidity analysis system is evaluated. Section 4 discusses the impact of Precipitable Water Content (PWC) available from the TOVS data on the assimilation and the forecast. Some problems in the use of PWC data are pointed out. The modifications for solving these problems have been implemented operationally in January 1989. In section 5, a new vertical correlation model, more appropriate for thick layers, is suggested. A short period assimilation test experiment has been run with this new vertical correlation model, which shows reasonable results. In section 6, UTH data are introduced into the current humidity analysis. Currently UTH data are received regularly from Meteosat, but they are not used in the operational system. Some comments on the use of UTH data are made in this section as well.

2. PRESENT HUMIDITY ANALYSIS SCHEME

The present humidity analysis is similar to the mass/wind analysis in that it is a 3-D Optimum Interpolation (OI) scheme. It is performed directly on the model levels and the T106 Gaussian grid. The analysis variable is relative humidity and it is analysed up to 250 hPa. In this section, we briefly describe the main points of the current humidity analysis scheme, which are related to the study of the present paper. For more detailed information, see Lorenc and Tibaldi(1979), Lönnberg and Shaw(1984) and Undén(1984).

2.1 Humidity data

There are at present four types of observations available for humidity analysis:

(i) TEMPs and TEMPSHIPs (radiosondes)
(ii) SYNOPs and SHIPs (surface obvervations)
(iii) SATEMs (orbiting satellite soundings)
(iv) SATOBs (geostationary satellite data)

All the humidity data listed above are used in the operational system except SATOBs. We now describe what is provided by each type of observation.

(i) Radiosondes provide temperature and dew-point at standard and significant levels. They are used to estimate the relative humidity at observation levels.

(ii) Surface observations provide temperature and dew-point, as well as cloud amounts and types, from which some humidity information can be inferred in the upper-air (only when the cloud cover is at least 7/8).

(iii) Satellite soundings provide PWC data between a reference level and other standard pressure levels. PWC data are converted to mean relative humidity (RH) between observation levels by using the temperature information from the first guess field. In the current operational system, these RH data are treated as spot values of relative humidity in the middle of the layers. Also, the 3 layers available in SATEM messages are split into 5 (all standard layers up to 300 hPa).

(iv) One geostationary satellite (Meteosat) provides operationally UTH data, which gives mean relative humidity for the layer between about 600 hPa and the tropopause. These data are not used in the present assimilation system.

2.2 The vertical correlation model

In the current analysis system the vertical forecast correlation model of relative humidity is very similar to the one used in the mass/wind analysis: a representation by a continuous function is used. The forecast errors are expressed as polynomials in ln(p) and a sixth degree polynomial is fitted to the forecast error at 15 standard pressure levels.

$$\sigma = \sum_{m=0}^{M} D_m [\ell np]^m \qquad M=6 \tag{1}$$

The forecast correlation model is

$$V_{i,j} = \frac{1}{e-1} \exp\left[\frac{a}{a+(X_i-X_j)^2}\right] - \frac{1}{e-1} \tag{2}$$

where $V_{i,j}$ is the correlation between levels i and j, a is a tuning constant and X_i,X_j are transformed vertical coordinates, see Undén (1984).

The values of X_i define the coordinate transformation from the pressure levels and can be found by setting j=i-1 in (2).

$$X_i=0$$

$$X_i - X_{i-1} = \sqrt{\frac{a}{\ell n\left(\frac{V_{i,i-1}+b}{b}\right)} - a} \qquad \text{where } b = \frac{1}{e-1} \tag{3}$$

The steps for constructing the continuous representation of forecast errors and correlations from a discrete covariance matrix, which is determined empirically, are as follows:

(i) Fit the humidity forecast errors at pressure levels to a sixth degree polynomial.

(ii) Take the calculated humidity error correlation ($V_{i,j}$) between adjacent pressure levels and compute the transformed vertical coordinates X_i's for all levels using (3) with a first guess value of parameter a. The X_i's are then fitted to a sixth order polynomial in ln(p) to give a continuous function representation.

$$X = \sum_{\rho=0}^{L} C_\rho [\ell np]^\ell \qquad L = 6 \tag{4}$$

(iii) With the correlation model (2) and the functional expression of X from (6), find a new value of the parameter a which fits the two off-diagonal correlations, i.e. $V_{i,i+1}$ and $V_{i,i+2}$, as well as $V_{i,i-1}$ and $V_{i,i-2}$ where applicable.

3. IMPACT OF SATEM DATA

In order to evaluate the impact of SATEM data on the present assimilation system, several experiments have been run, see Andersson et al. (1989):

- a control experiment for a 15½ day period from 30 January 00UTC to 14 February 12UTC in 1987;
- a No-SATEM experiment for the same period as the control one, in which all SATEM data, containing both thickness and PWC data, are removed;
- a No-PWC experiment for the short period from 30 January 00UTC to 31 January 12UTC in 1987, in which only thickness data are used;
- a No-thickness experiment for the same period as No-PWC. Only PWC data are used in this experiment.

All the experiments listed above are based on the assimilation libraries of July 1988 (see Andersson et al, 1989). A similar set of satellite experiments was run before at ECMWF, based on the July 87 version of the assimilation libraries, except that the impact of PWC data was not tested (Kelly and Pailleux, 1988). Experiments with the satellite retrieval scheme developed in Laboratoire de Meteorologie Dynamique, called 3I, are documented in Flobert et al. (1989).

3.1 Impact on the analysis

As expected, there is a large impact of the satellite data on the humidity analysis, affecting mainly data-sparse areas over the oceans. Normally, it is difficult to assess whether the impact improves the description of the analysis moisture field in the assimilation, because there is no 'real' moisture field to be compared with. But since Illari (1989) has concluded that satellite PWC data are of reasonable quality (compared to radiosondes), it became possible to evaluate the impact of SATEM data on the humidity analysis. Figs.1 to 4 show the increment maps at 850 hPa between the analysis and the first guess humidity fields of the No-SATEM and control experiments, in the Northern and Southern hemispheres. Fig.5 and Fig.6 show the humidity fields themselves in the Southern hemisphere, for the same date (31 January 1987, 00 UTC).

Several points can be noted:

- A majority of radiosondes have a drying effect on the analysis, shown in Fig. 1 and 3 by negative spots on the 850 hPa humidity increment map.

- PWC data dry almost all the oceanic areas. This is particularly clear in Fig. 4 where the Southern Hemisphere oceans are covered with negative increments. This will be explained later in this paper. This drying effect can be seen also from the mean difference humidity maps between No-SATEM and Control experiments as plotted in Fig. 7 for a model level in the lower troposphere. Similar maps plotted at other model levels in the middle of the troposphere (not shown) confirm this result. This is quite a different result compared with Illari (1989), where it is said that the PWC data at surface tend to moisten oceanic regions. The likely explanation is the change of humidity analysis scheme in September 86: from a 2D correction scheme to a 3D OI scheme. If we assume that the PWC data are correct, then the first guess of the humidity field provided by the present model is too wet.

- PWC data seem to smooth the first guess field. We can see from Figs. 5 and 6 that the humidity fields are smoother in the assimilation using PWC data, whereas the No-satem assimilation tends to preserve sharper gradients. This is true in both hemispheres, but more obvious in the Southern Hemisphere where PWC data are predominant.

Figs. 8 and 9 illustrate SATEM quality problems in some specific areas and in some particular situations. Fig.8 shows the difference map between Control and No-SATEM analyses of the 500 hPa relative humidity field for 30 January 1987, 00UTC. On top of the general drying effect over the oceans, there is a large systematic moistening effect in some dry continental areas. The largest difference (more than 30%) appears in the Sahara region. Fig. 9 shows the coverage of the SATEM data which contain PWC data only, without having temperatures (thicknesses). These data are doubtful in principle, as it is hard to imagine that a good TOVS humidity retrieval can be achieved when it is not possible to retrieve any temperature profile. Obviously these data are corresponding to the moistening effect over the Sahara, which was confirmed by a small analysis experiment in which all the PWC data over land were removed, as well as the PWC data coming from some SATEMs which do not contain any temperature data.

From various case studies focused on relative humidity maps in some specific areas, such as weather systems, fronts, desert areas, the following practical conclusions can be drawn:

- The SATEM data, containing PWC data only, without any corresponding temperatures (thicknesses), are doubtful. It seems to be inacceptable to retrieve PWC data without temperature (or thickness). Many of such data have been found to be of questionable quality over the Antarctic Ocean. These PWC data also seem to be responsible for the spurious features on the difference maps, such as the tendency of the Sahara to become too wet, or the noisy increments near the Antarctic coast.

- The quality of the PWC data over land seems to be low, compared with radiosonde data. Removing the PWC data over land appears to be beneficial for the assimilation, judging from the statistical plots.

- Both satellite and radiosonde data dry the first-guess field in the areas where humidity is close to saturation. The sharp frontal structures are destroyed.

3.2 Special remarks on the 3I experiment

In the assimilation experiments using the 3I scheme (Flobert et al., 1989), the humidity analysis scheme has been modified to some extent:

(i) The relative humidity is the interface between the satellite retrieval scheme and OI analysis (avoiding then the PWC interface);

(ii) The cloud information from the satellite has been used to create some humidity bogus data (equal to 100%), this is not possible in current operations, but will become possible operationally at ECMWF after the ad hoc files are transmitted from Washington;

(iii) The weight given in OI to the satellite humidity data has been reduced.

Although the impact of these modifications as such on the forecast has not been evaluated, the subjective evaluation of the 3I humidity analysis maps (compared to No-SATEM and Control) indicate a positive effect of these modifications. We note a reduction of the drying effect of satellite data, and also more realistic structures of the humidity fields, especially along the fronts and in the weather systems.

3.3 Impact on the forecast

The general impact of SATEM data on the forecast has been tested by running 10-day forecasts in 15 different cases from 31 January 1987, 12 UTC to 14 February 1987, 12 UTC, from both the Control and the No-SATEM assimilations. The results of this impact study are documented in Andersson et al. (1989). In this paragraph we concentrate on the results related to humidity.

For the No-PWC and No-thickness experiments, only one case has been run which is January 31, 12 UTC in 1987. Although this is not enough to draw any definite conclusions, it should give some indications about the separate contribution of PWC data and thickness (mean temperature) data to the quality of the forecast. Fig.10 shows the scores of a 10-day forecast related to No-PWC and No-thickness experiments for the Northern Hemisphere. Fig. 11 is the same but for the Southern hemisphere. Let us note the following points:

- In the Southern hemisphere, the degradation of the scores obtained by removing the thickness data is clearly more than the degradation obtained by removing the PWC data. This means that the contribution of the thickness data to the forecast quality is higher than the contribution of PWC data (as expected). The impact of PWC data on the Southern hemisphere forecast appears to be positive and significant for this case.

- No overall conclusion can be drawn from the Northern hemisphere scores. They indicate that the no-thickness forecast is slightly better than the operational one; and although the "no-PWC" forecast is losing at the 60% line, it looks better in the short-range. Studies of the forecast, area per area, seem to confirm that the short-range forecast is slightly degraded by the use of PWC. One likely explanation is that the overall weight given to PWC in the OI analysis is too large.

3.4 Set of operational modifications related to humidity analysis

Based on the previous studies, the following list of modifications related to humidity analysis have been tested and implemented operationally in January 1989 at ECMWF together with other modifications which are described by Andersson (1989).

a) Blacklist of the satellite PWC data over land.

b) Removal of the satellite PWC data when no thickness data are available in the same report.

c) An increase of the PWC observation error standard deviation from 10% to 15% in terms of relative humidity. The observation error standard deviation used in the OI equations is now 15% plus a contribution of the " rounding error " due to the SATEM code which contains PWC rounded in millimeters.

4. VERTICAL CORRELATION MODEL FOR USING PWC DATA IN OI SCHEME

In an OI analysis system an important factor for the quality of the analysis is the use of reasonable error statistics. It is also important to have an error statistics model which can make the system use more observational information. In this section, we will introduce a new vertical correlation model into the present OI scheme. The vertical correlation used by the current humidity analysis has been described in section 2. As the correlations between RH and mean RH have not been set up, in the current humidity analysis system, the PWC data have to be processed in the following steps before running the main analysis.

- split the thicker layers into thinner layers. For example, split the layer 1000/700 into two layers 1000/850 and 850/700, using the first-guess profile as a reference;

- convert the PWC data into mean relative humidity by using the temperature from the first guess field;

- treat this mean RH of the split layer as a normal relative humidity at the middle level.

It seems reasonable to use PWC data in observation layers without splitting the thick layers. So we are suggesting to set up a vertical correlation model, which can handle the mean relative humidity, i.e. treating not only the level/level correlations, but also the level/layer and layer/layer correlations.

By integrating (1), the mean error standard deviation for the layer (p_o/p_n) can be evaluated by,

$$\bar{\sigma}_{p_o}^{p_n} = \frac{1}{X(p_n) - X(p_o)} \int_{X(p_o)}^{X(p_n)} \sigma \, dx \tag{5}$$

Substituting (1) and (4) into (5), the mean σ becomes,

$$\bar{\sigma}_{p_o}^{p_n} = \frac{1}{X(p_n)-X(p_o)} \sum_{m=0}^{M} \sum_{\ell=0}^{L} \frac{D_m C_\ell}{m+\ell} \cdot \ell \, [(\ell n p_n)^{m+\ell} - (\ell n p_o)^{m+\ell}] \tag{6}$$

For setting up the covariance model, we should assume the mean RH for layer (p_o/p_n) can be expressed by,

$$\overline{RH}_{p_o}^{p_n} = \frac{1}{X(p_n)-X(p_o)} \int_{X(p_o)}^{X(p_n)} RH.dX \tag{7}$$

then the covariance between level RH and the mean layer RH becomes,

$$\langle RH_i, \overline{RH}_j{}_{p_o}^{p_n} \rangle = \frac{1}{X_j(p_n)-X_j(p_o)} \int_{X_j(p_o)}^{X_j(p_n)} \langle RH_i, RH_j \rangle \, \sigma(X_j) \, dX_j$$

$$= \frac{1}{X_j(p_n)-X_j(p_o)} \int_{X_j(p_o)}^{X_j(p_n)} V_{i,j} \, \sigma(X_j) \, dX_j \tag{8}$$

where i,j are the different horizontal points. To integrate (7) with respect to X_j, (7) is approximated by the sum over the ΔX for the layer.

The covariance between the mean RH of two different layers, i.e. $\langle \overline{RH}_i, \overline{RH}_j \rangle$, can be evaluated as a double integration, which are approximated by the sum over the X's for the two layers as well.

Let us note that the integration operator used in the vertical covariance model is not optimal, since it is the vertical average of relative humidity instead of Q/Q_s (specific humidity normalized by saturated specific humidity). Physically, it would be better to integrate Q and Q_S in the vertical because the profile of specific humidity decreases very quickly in the vertical. In fact, the operator of Q/Q_S is used to compute the first-guess value corresponding to the PWC and UTH observation. So, the suggested vertical covariance model is not fully consistent with the way we compute the departure "OBS-FG" in the humidity analysis. However, there is no simple way to take into account the large vertical variations of the water content in the covariance model, and the suggested covariance model is still better than the operational one which assumes that the integral is equal to the spot value in the middle of layer.

The suggested scheme has a potential application if the UTH data, which are received from Meteosat (mean relative humidity for the layer 600-300 hPa), are to be used in the humidity analysis, in the future, because the present code is not very suitable for using the humidity data integrated on a very thick layer.

In order to test the performance of the suggested scheme as well as its impact on the forecast, a short (from Jan. 30, 00UTC to Jan. 31, 12UTC, 1987) data assimilation experiment has been carried out followed by a 10-day forecast starting from Jan. 31 12UTC. The maps of the assimilation experiment (not shown) indicate there is no significant impact of the scheme on the humidity analysis at 850 hPa (as expected). Also we compare the correlation method after and before the changes of the vertical correlation: there is only a slight difference between these two matrices (table 1.). The comparison of forecast scores between the Control and the one including the suggested scheme is depicted in Fig.12. They are almost identical as expected, which means that the new vertical correlation scheme is reasonable and can be then used to evaluate the impact of UTH data.

5. USE OF METEOSAT UPPER TROPOSPHERIC HUMIDITY

The UTH data are a measure of the mean column humidity of the upper atmosphere between about 600 hPa and tropopause. The product is retrieved from the European Space Operations Centre (ESOC) twice each day, using images close to 0000 and 1200 UTC, and disseminated as SATOB code via the Global Telecommunication System (GTS). The data coverage is the METEOSAT processing area (Fig.13). It has not been used in the operational humidity analysis at ECMWF.

Obviously a global analysis of humidity fields is only possible with the horizontal coverage provided by satellite data. It is very important to make an effort to use satellite data in the humidity analysis system of the future. TOVS humidity data have been used in the ECMWF operational system since 1986. They have shown a beneficial impact on the humidity analysis and forecast of the ECMWF (Illari,1989). But there is still a lack of humidity information, especially in the tropical region, where there are few observations. It is hoped that this situation can be improved by introducing UTH data into the humidity analysis.

Recently Schmetz & Turpeinen (1988), Turpeinen & Schmetz (1989), and Van de Berg (pers. comm) have made a lot of efforts to validate the UTH. The results of comparisons between radiosondes and UTH data were presented in their studies. It is encouraging that their results showed a good quality of UTH data, compared with radiosondes (Fig.14). The overall feeling from their studies is that the UTH data are comparable with radiosondes and seem to be a bit wetter, which, as they pointed out, is consistent with the fact that radiosonde measurements also capture variability at smaller scales. According to their studies, the best agreement between the estimated and observed humidity is in the tropical region. The error statistics showed that the RMS-error of the UTH was less than 10%.

Before introducing UTH data into the operational analysis, there is a need to modify the present ECMWF analysis code, because it is difficult for the present code to deal with those humidity data which are integrated over a very thick layer. The modifications were discussed in the previous section of this paper. An assimilation experiment has been run during the period from 4 October 00 UTC to 7 October 12 UTC in 1988, in which UTH data were available twice each day (00 UTC,12 UTC). The UTH data were used in the humidity analysis of this experiment in the same way as SATEM moisture data are routinely used. It seems reasonable to assume that the observation error for UTH is 15% plus rounding error. Four cases of 10-day forecasts from 12 UTC of each day have been run.

Fig.15 is the first guess humidity field on 4 October 1988, 00 UTC. Both experiments, with UTH (AAT) and without UTH (AAE), are starting from the same first-guess. Fig.16 is the difference map between AAT and AAE for the UTH area which shows the impact of UTH data on the 500 hPa relative humidity analysis field. It is somewhat surprising that there is a large impact of UTH on the analysis but almost nome on the forecast scores (Fig.17). Negative difference values dominate over the whole UTH area. From Fig.15 and Fig.16 it seems likely that the large negative values appear, because the first-guess of the humidity field is clearly wetter than the UTH observation data. Again, it illustrates evidence that the humidity first-guess field provided by the ECMWF model (model cycle 31 is used in our cases) is wetter than the observations (see section 3.1 of this paper). Of cause, four cases is not enough to draw definite conclusions. Further studies about UTH data need to be done.

6. CONCLUDING REMARKS

In this report, we evaluate the present humidity analysis system at ECMWF concentrating on the use of satellite data, and introduce a new vertical correlation model which is suitable for the utilisation of UTH data in the present system. Based on the new correlation model, a 4½ day data assimilation followed by 10-day forecast from each 12 UTC have been carried out. The main points are:

- SATEM data have some impact on the present humidity analysis and forecast system. But some SATEM data, such as the data over desert areas and even over land, in general have doubtful quality. These data have been removed in the operational analysis from January 1989 onwards (as well as PWC data which are produced without any corresponding temperature);

- A new vertical correlation model has been developed and tested. The results show that the new version has at least the same quality as the old version;

- Based on the new correlation model, the UTH data modify the relative humidity analysis field, but there is no significant impact on the forecast;

- The first-guess humidity field provided by the ECMWF model (cycle 30) is wetter than the observations, such as PWC, UTH and radiosondes.

Acknowledgements

The authors are grateful to E.Andersson, J.F.Flobert and E.Klinker for interesting discussions on satellite data experimentation, as they were involved in different aspects of satellite data evaluation. The humidity aspects documented in the present paper have to be seen as part of a large project fully documented in Andersson et al. (1989), Kelly et al. (1989) and Flobert et al. (1989).

The study documented at the end of this paper was possible thanks to the Meteosat Exploitation group in Darmstadt (FRG) who provided the UTH data, and especially to J.Schmetz, L. van de Berg and M.Nuret who provided interesting comments and results on the UTH quality.

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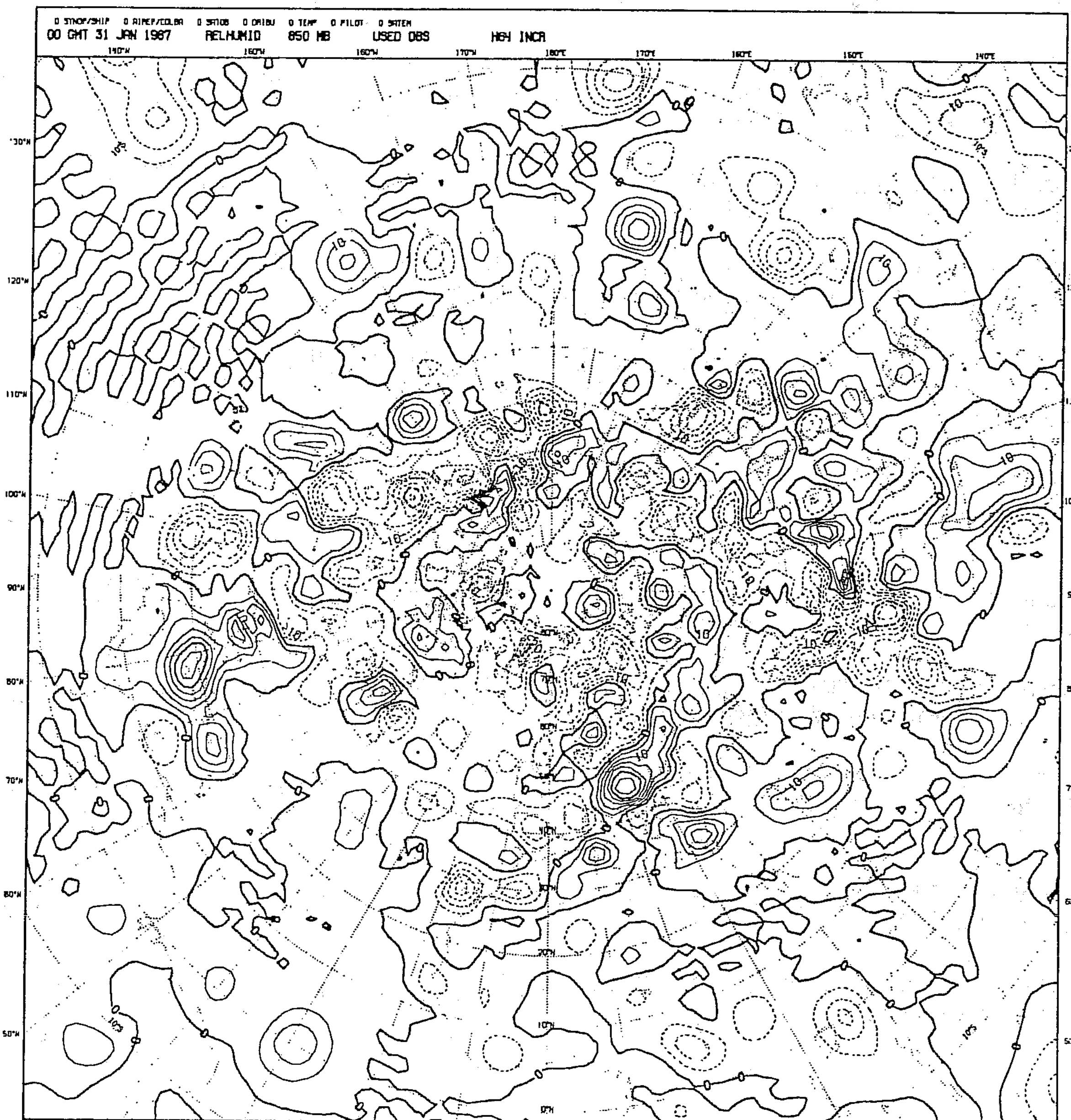


Fig. 1 Increment map between analysis and first guess humidity fields on 00 UTC 31 Jan. 1987, for 850 hPa and Northern Hemisphere, for No-satem experiment.

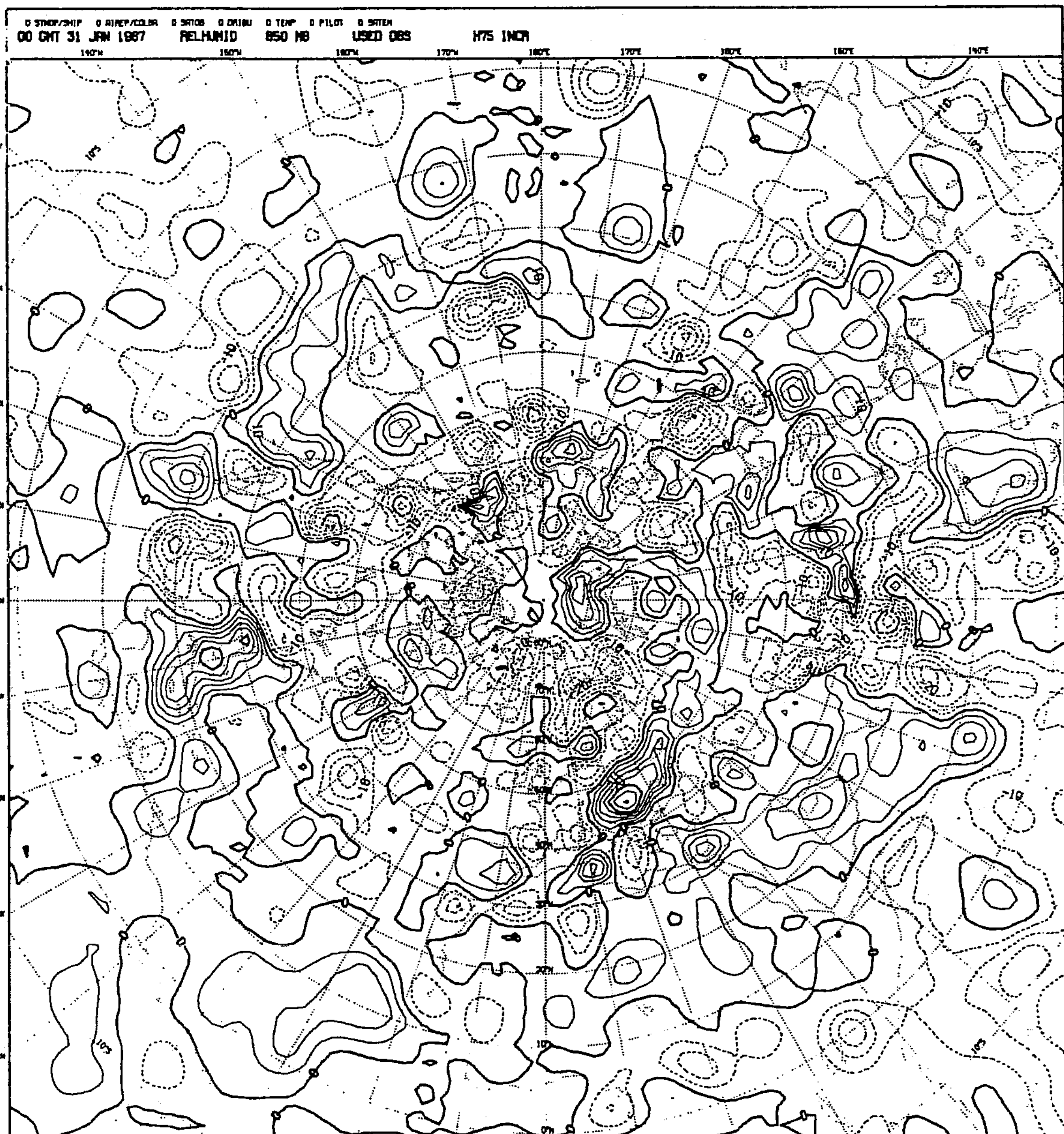


Fig. 2 As Fig. 1 , but for Control experiment (operational assimilation system, as it was in July 1988).

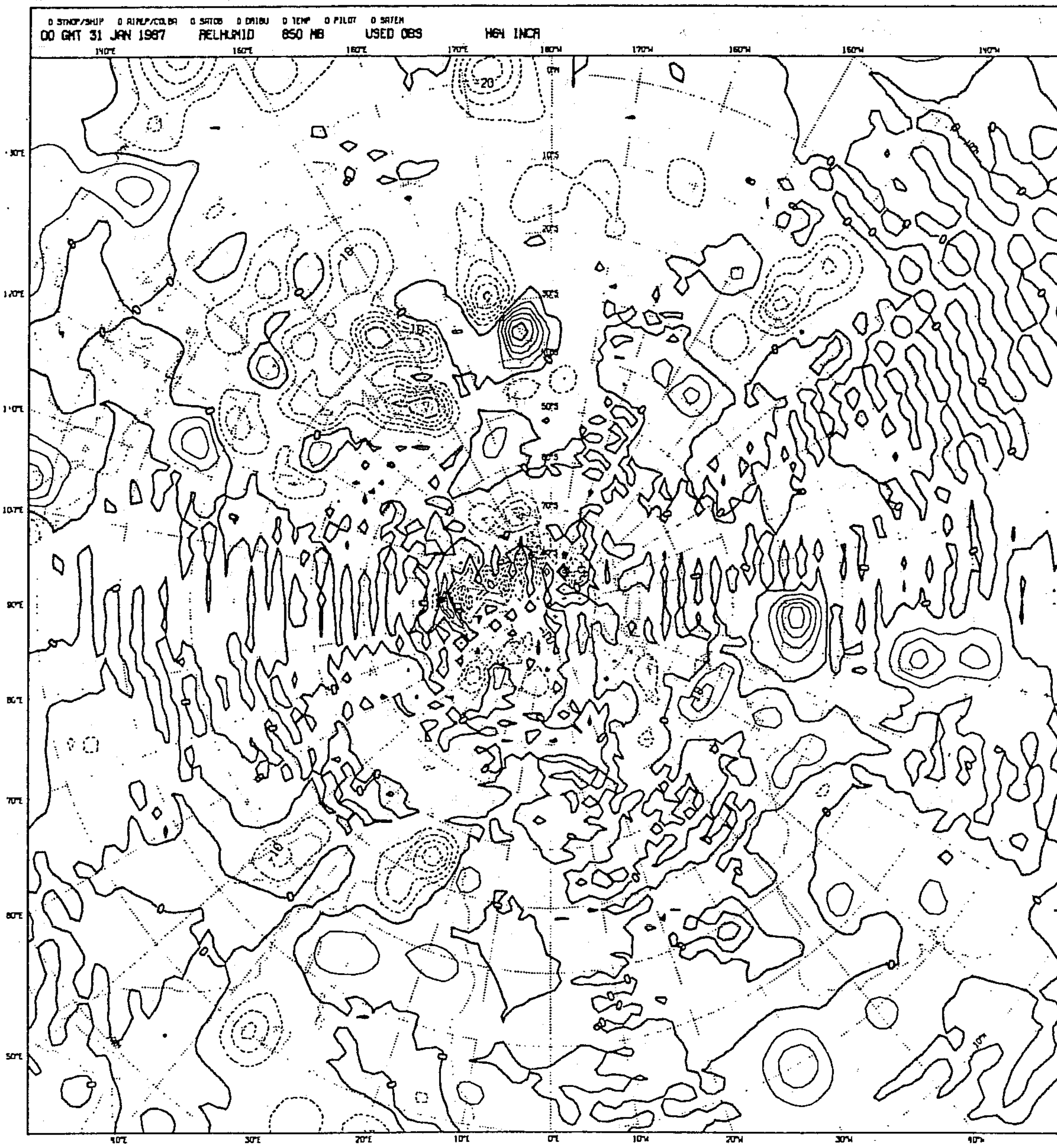


Fig. 3 As Fig. 1 but for Southern Hemisphere.

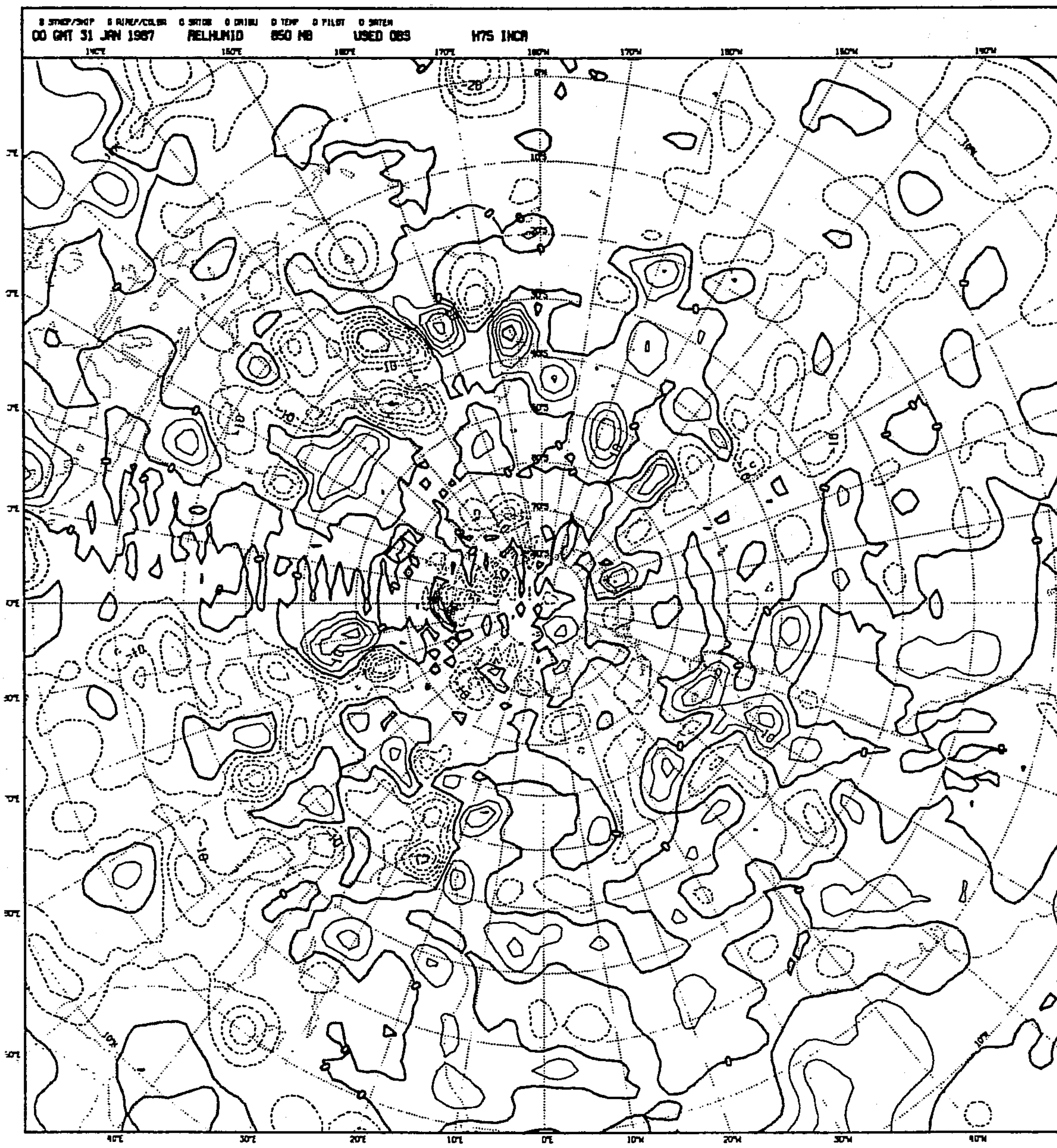


Fig. 4 As Fig. 2 but for Southern Hemisphere.

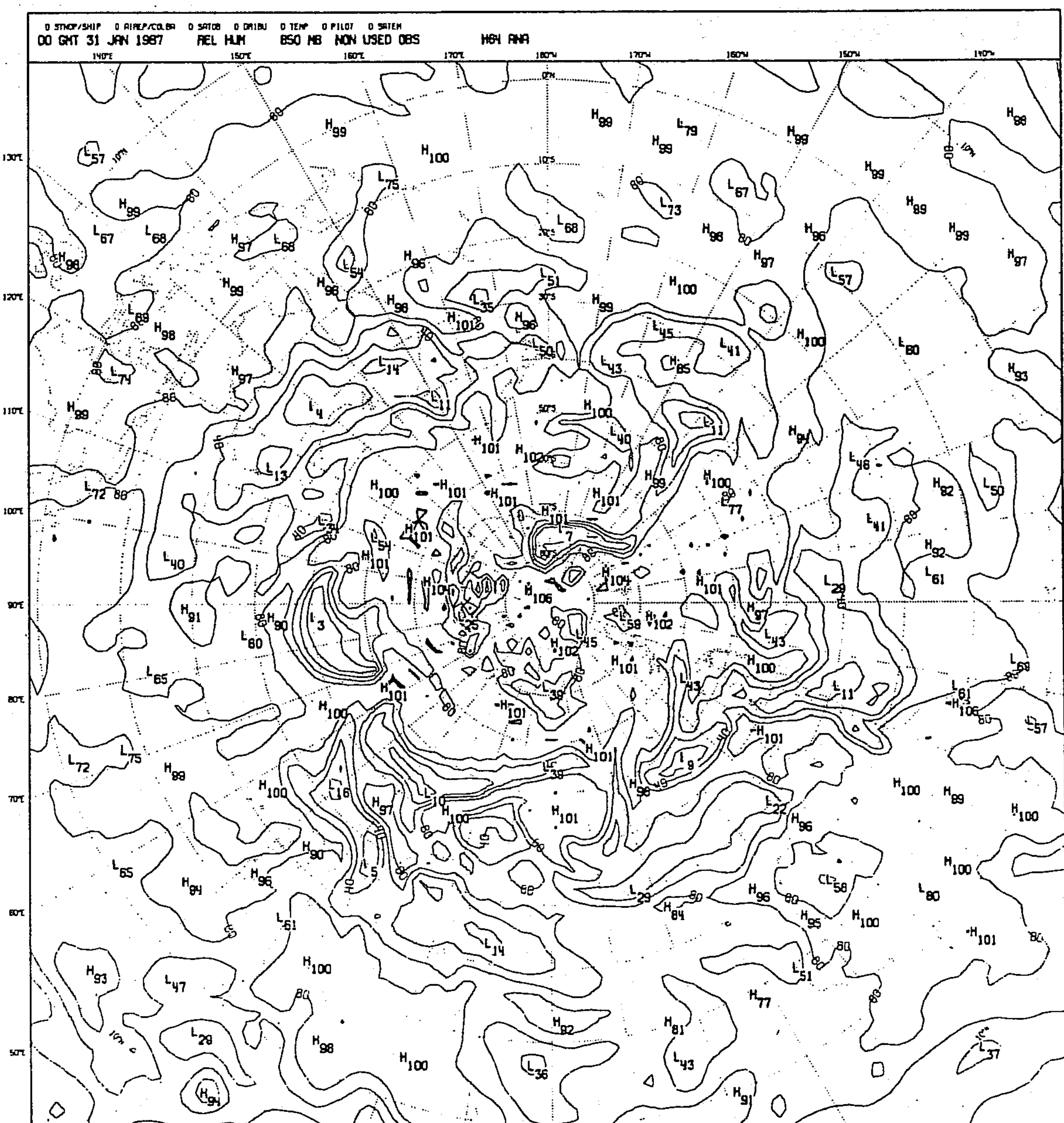


Fig. 5 850 hPa relative humidity analysis for 12 UTC 30 Jan. 1987, from No-Satem assimilation, for the Southern Hemisphere (where the SATEM PWC are the main source of data).

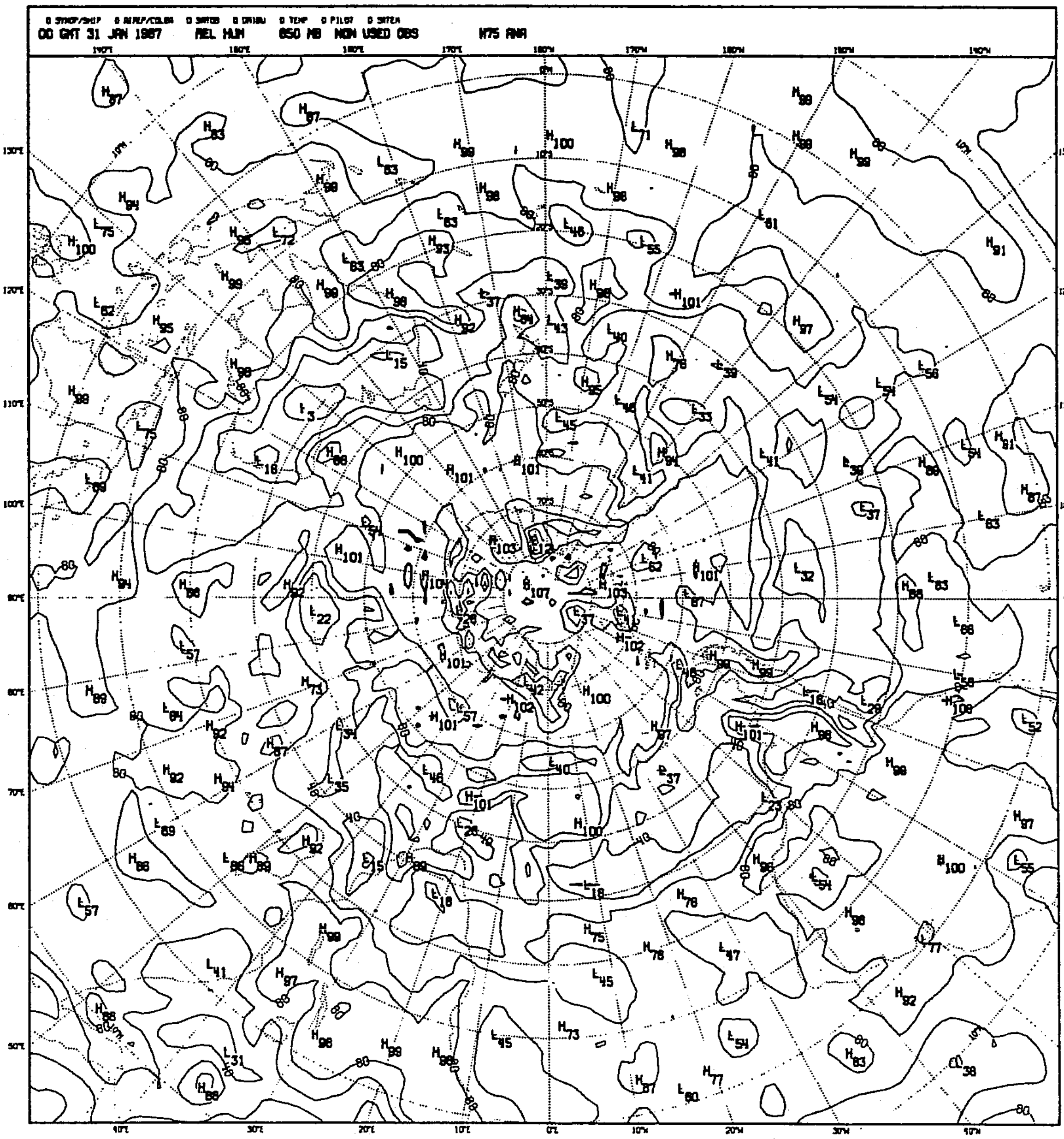


Fig. 6 As Fig. 3 , but for Control experiment.

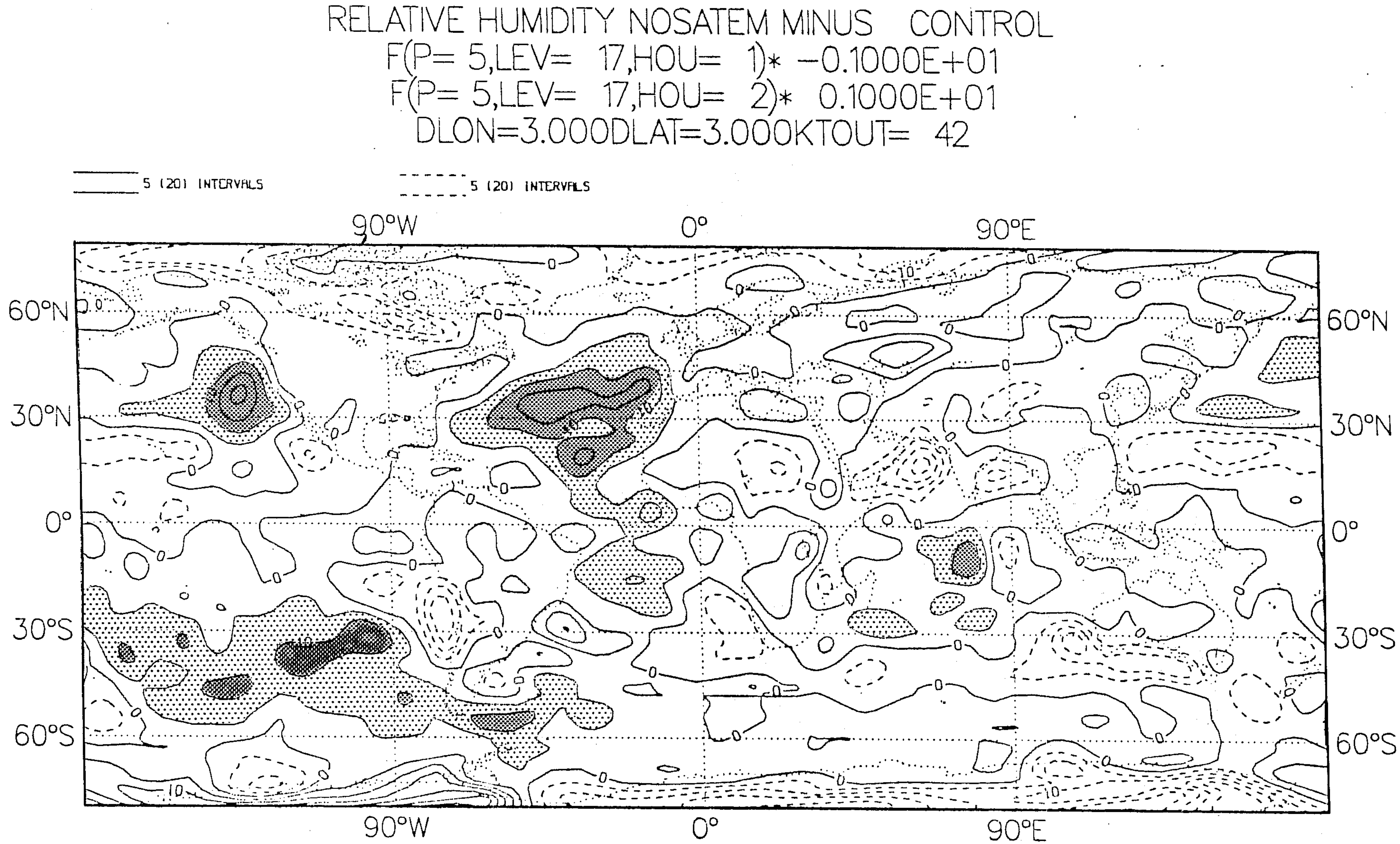


Fig. 7 10-day mean difference map between No-satem and Control experiment for humidity analysis field, for 967 hPa (model level 17). The period is beginning of February 1987. The oceanic areas where No-satem is significantly wetter than control are coloured in grey (light grey: more than 5%; dark grey: more than 10%).

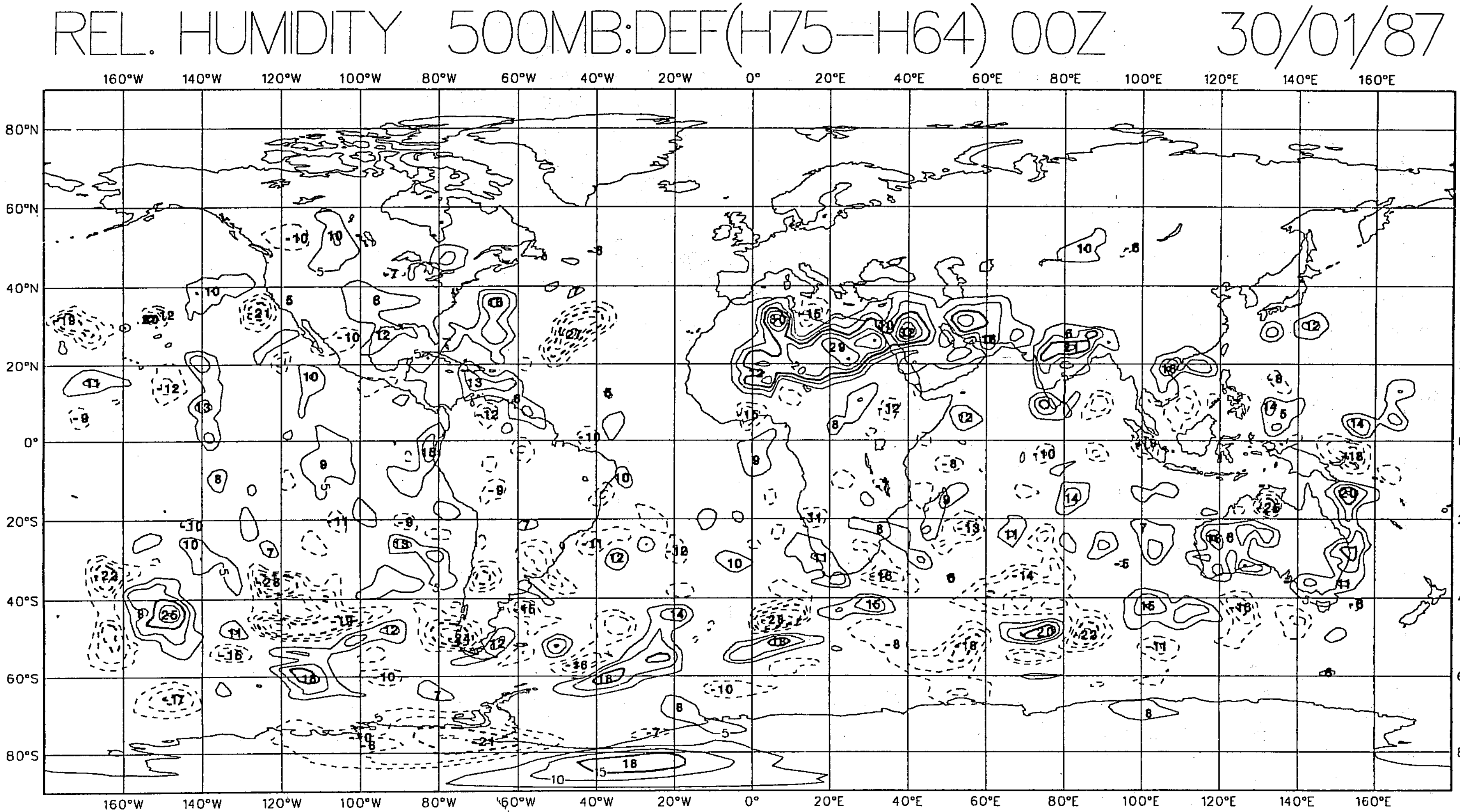


Fig. 8 Difference map between Control and No-satem analyses for humidity analysis field on 00 GMT 30 Jan. 1987, for 500 hPa. The interval of the contour is 5%.

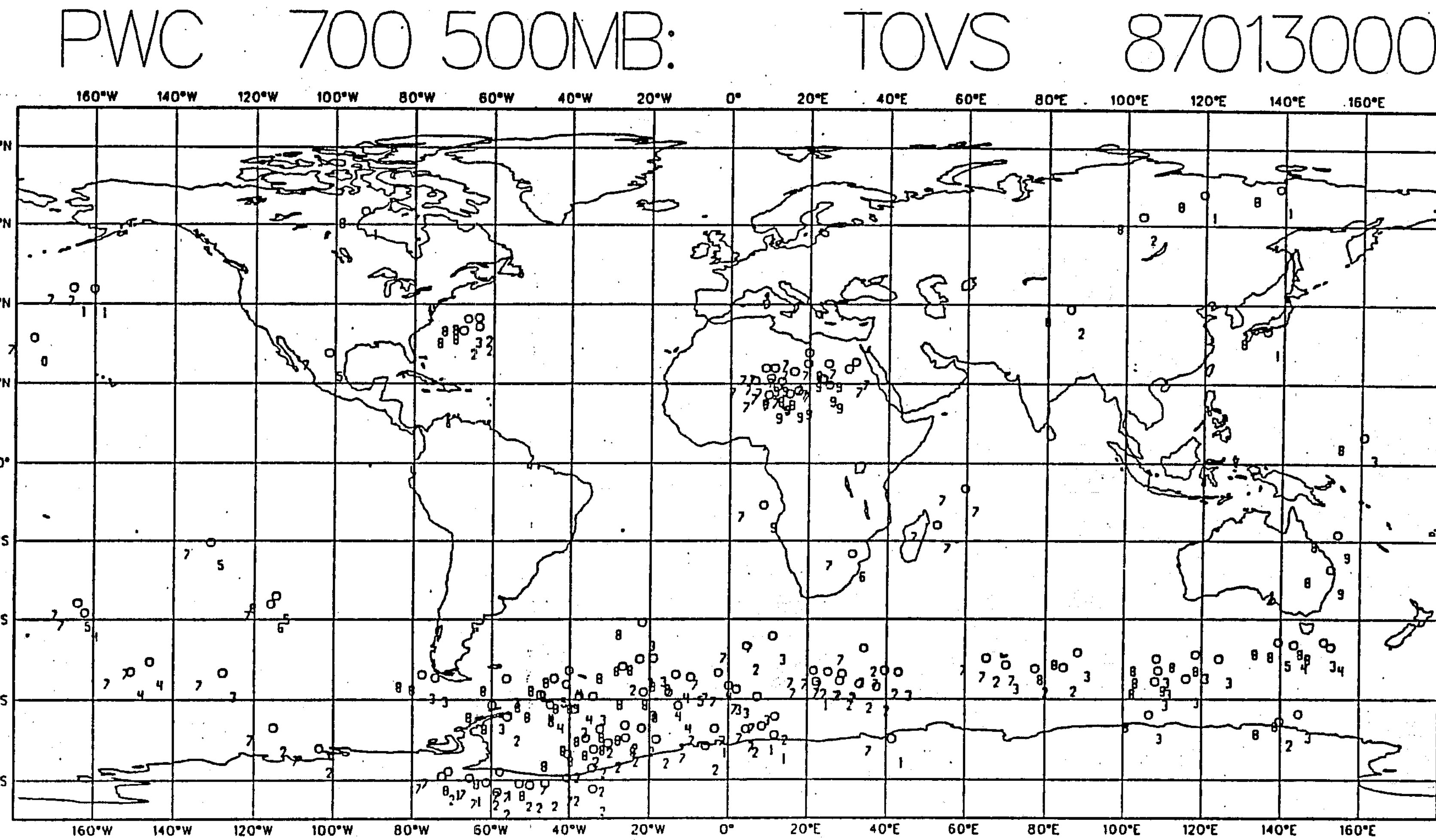
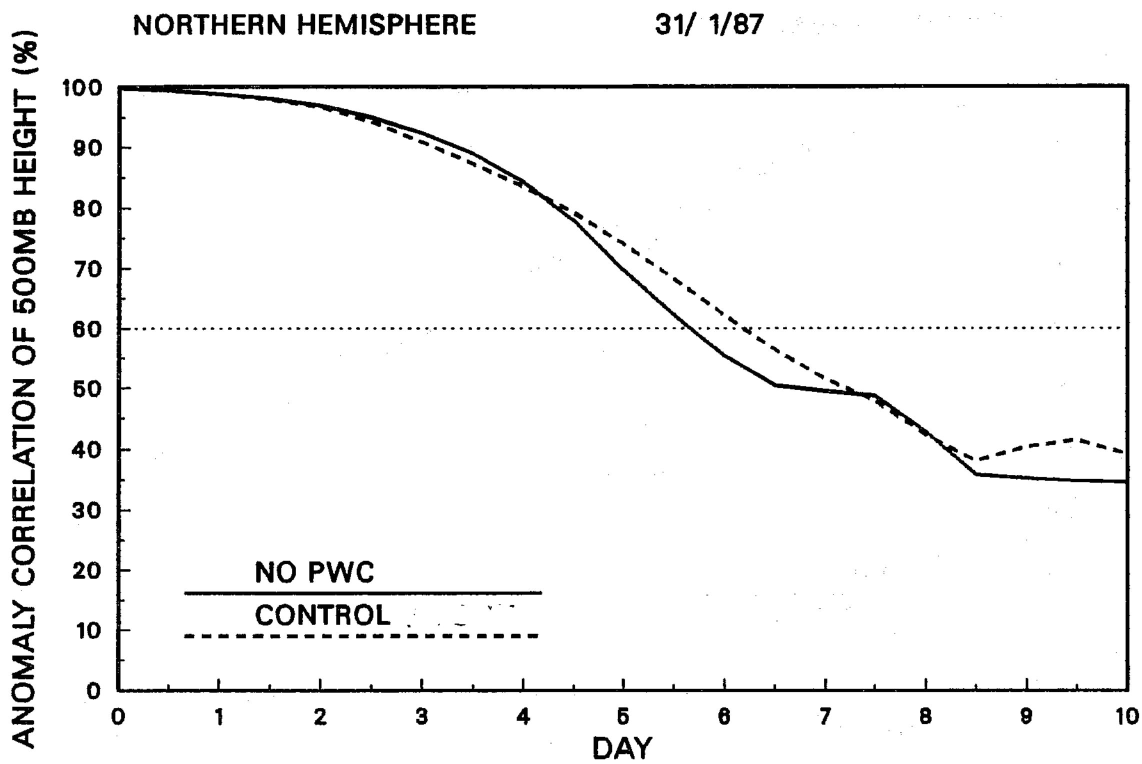


Fig. 9 Geographical distribution of the SATEM data which contain PWC report only without temperature (thickness). The circles indicate the position of the SATEM, the left number the satellite identification (7=NOAA9, 8=NOAA10), the right number is the PWC between 700 and 500 hPa in mm.



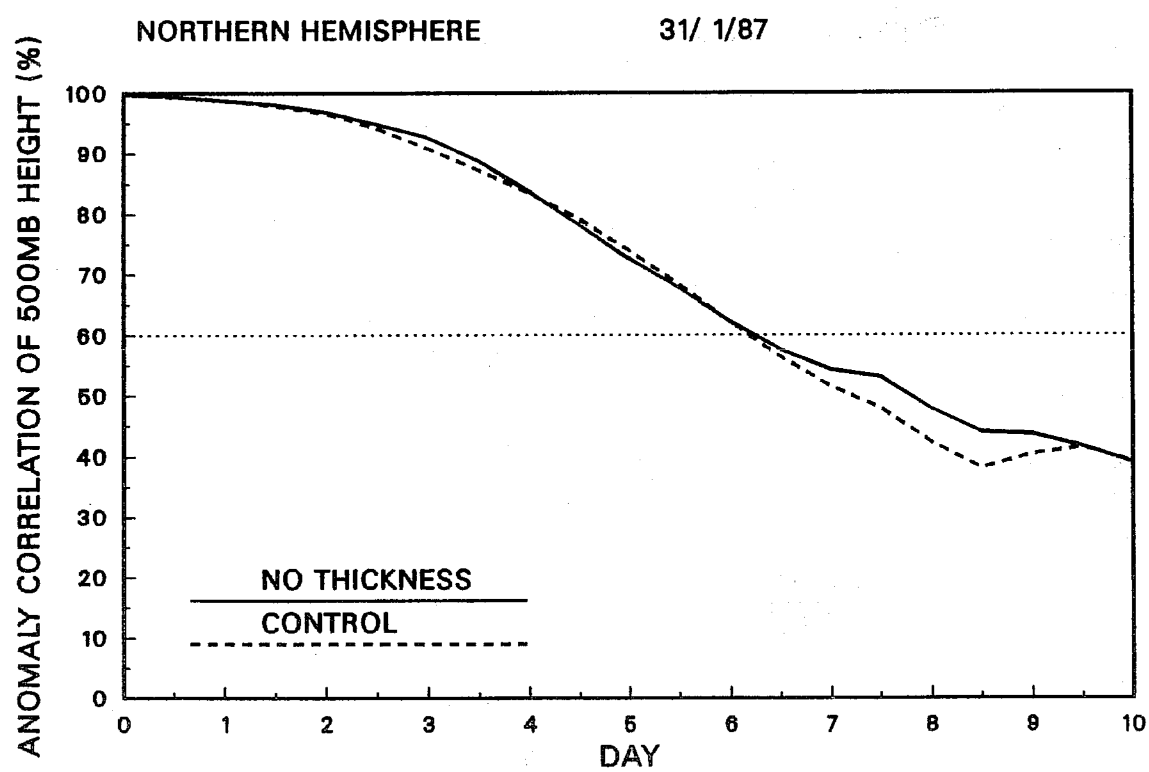


Fig. 10 Northern hemisphere forecast anomaly correlations showing the separate impact of thicknesses and PWC from TOVS, on 31 Jan. 1987, 12 UTC.
Top: no PWC compared to Control.
Bottom: no thickness compared to Control.

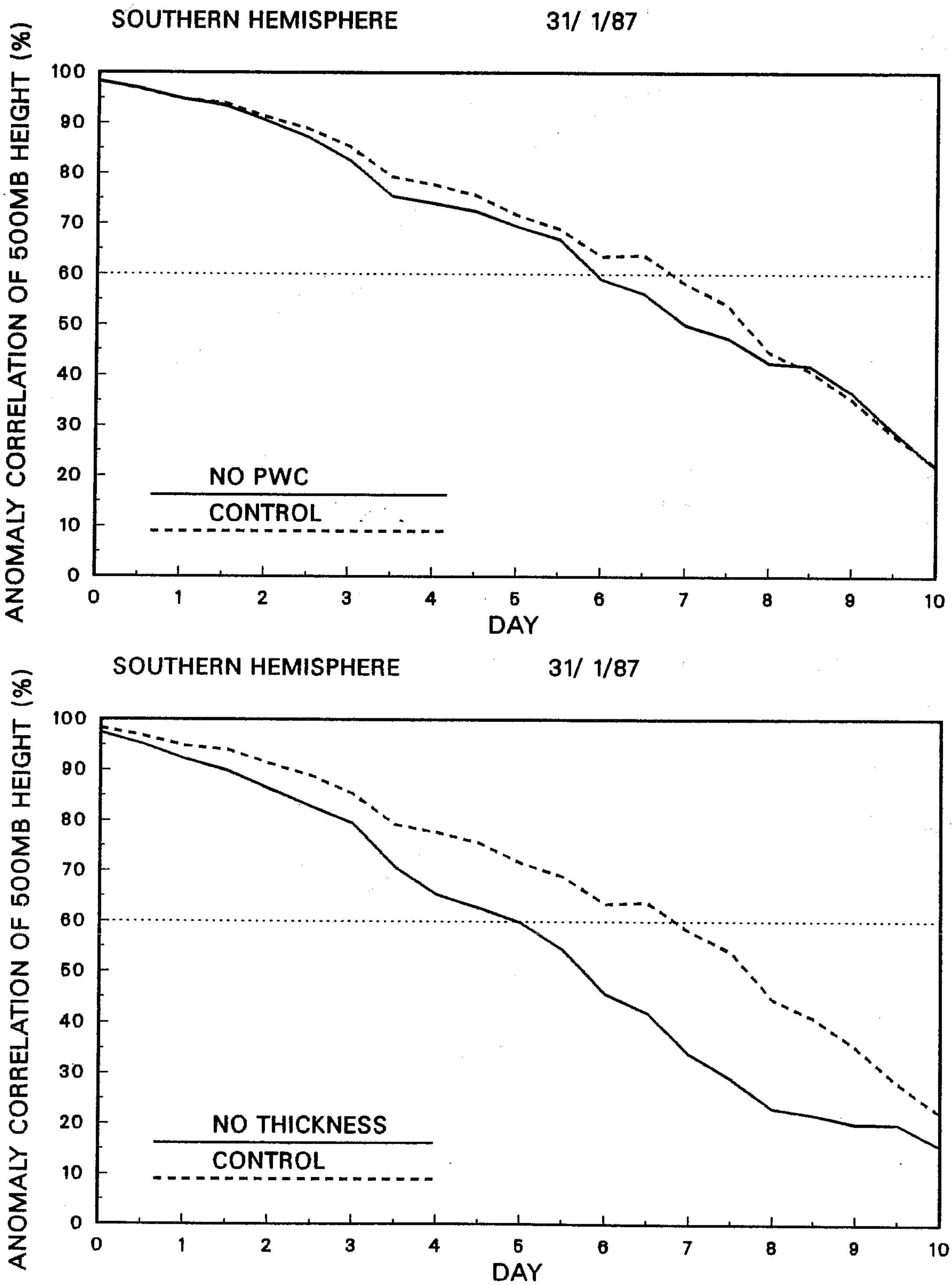


Fig. 11 Same as Fig. 10 for Southern hemisphere.

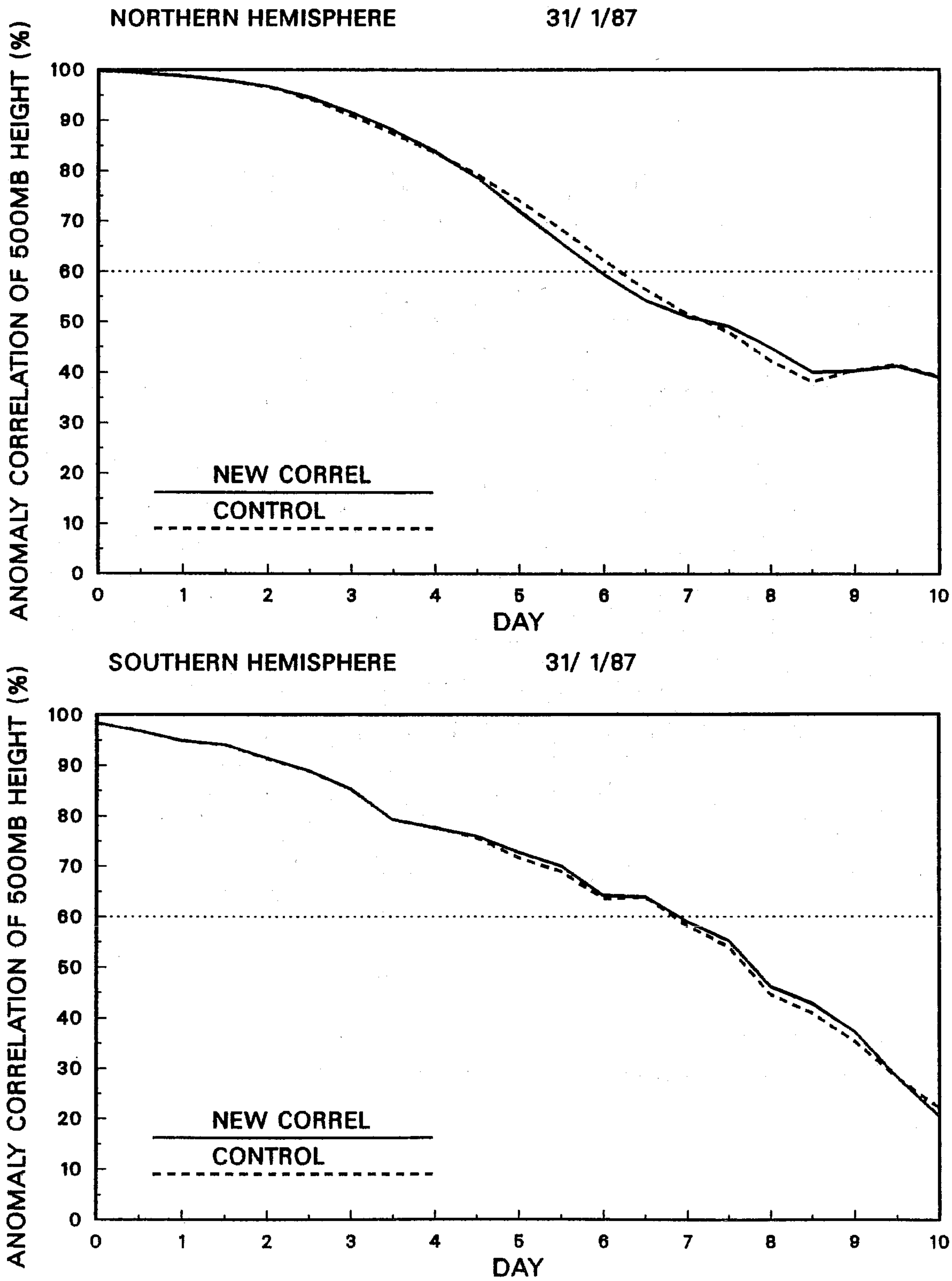


Fig. 12 The comparison between Control forecast and the one in which new vertical correlation model is used. HV7: Control, J9B: New version. Top: Northern Hemisphere; bottom: Southern Hemisphere.

METEOSAT UTH 600 – 300 HPA 00 UTC 881004

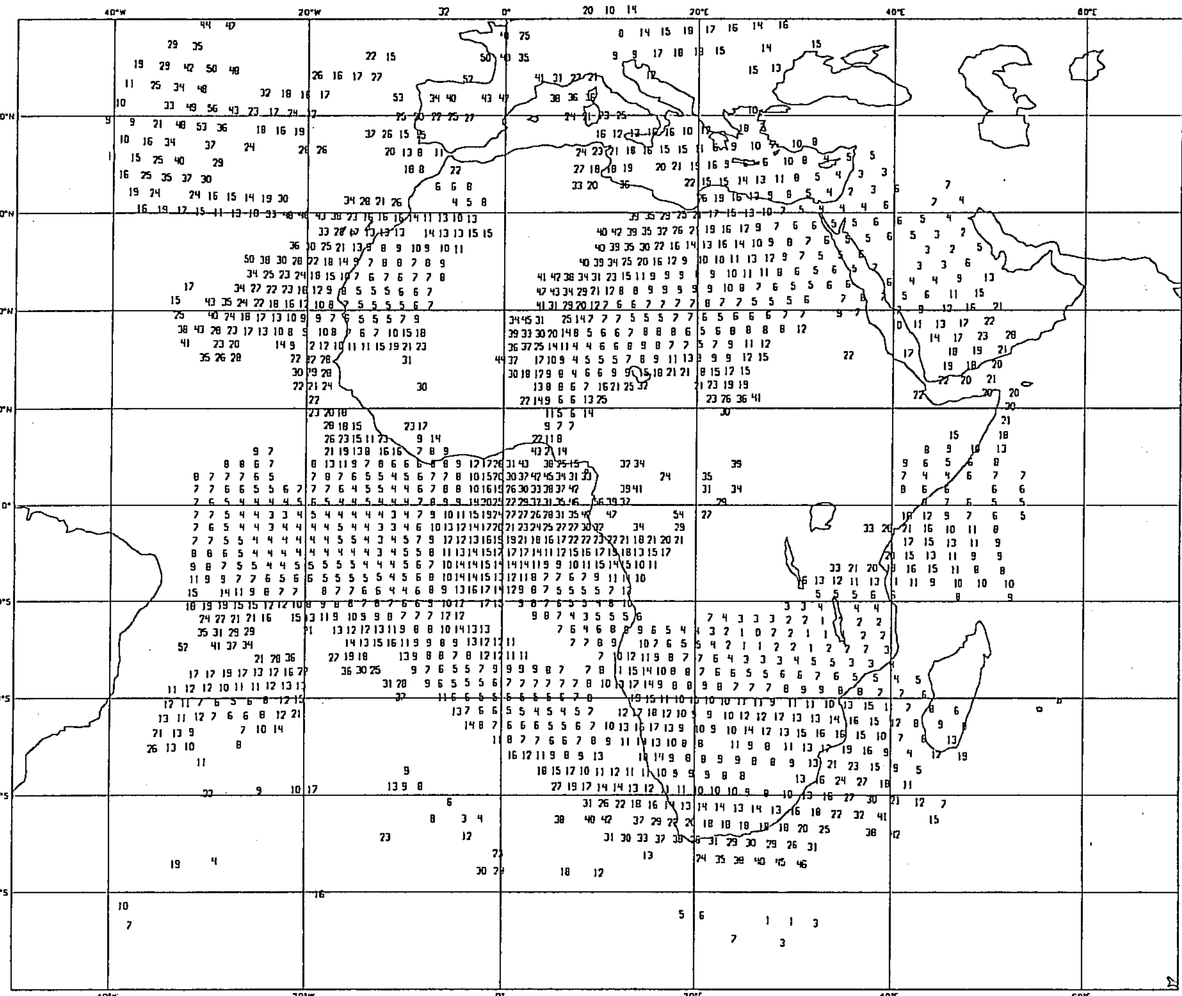


Fig. 13 The typical coverage of the UTH data, 04 October 1988,00 GMT.

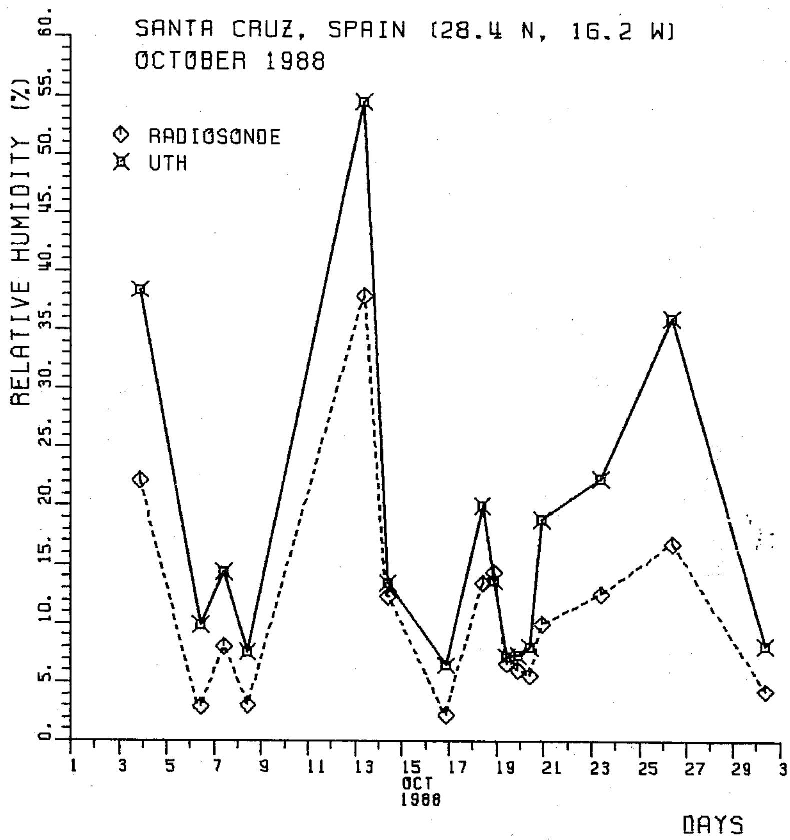


Fig. 14 Comparison between radiosonde humidity and UTH data at Santa Cruz, Spain (28.4 N, 16.2 W). (Picture provided by ESA/ESOC).

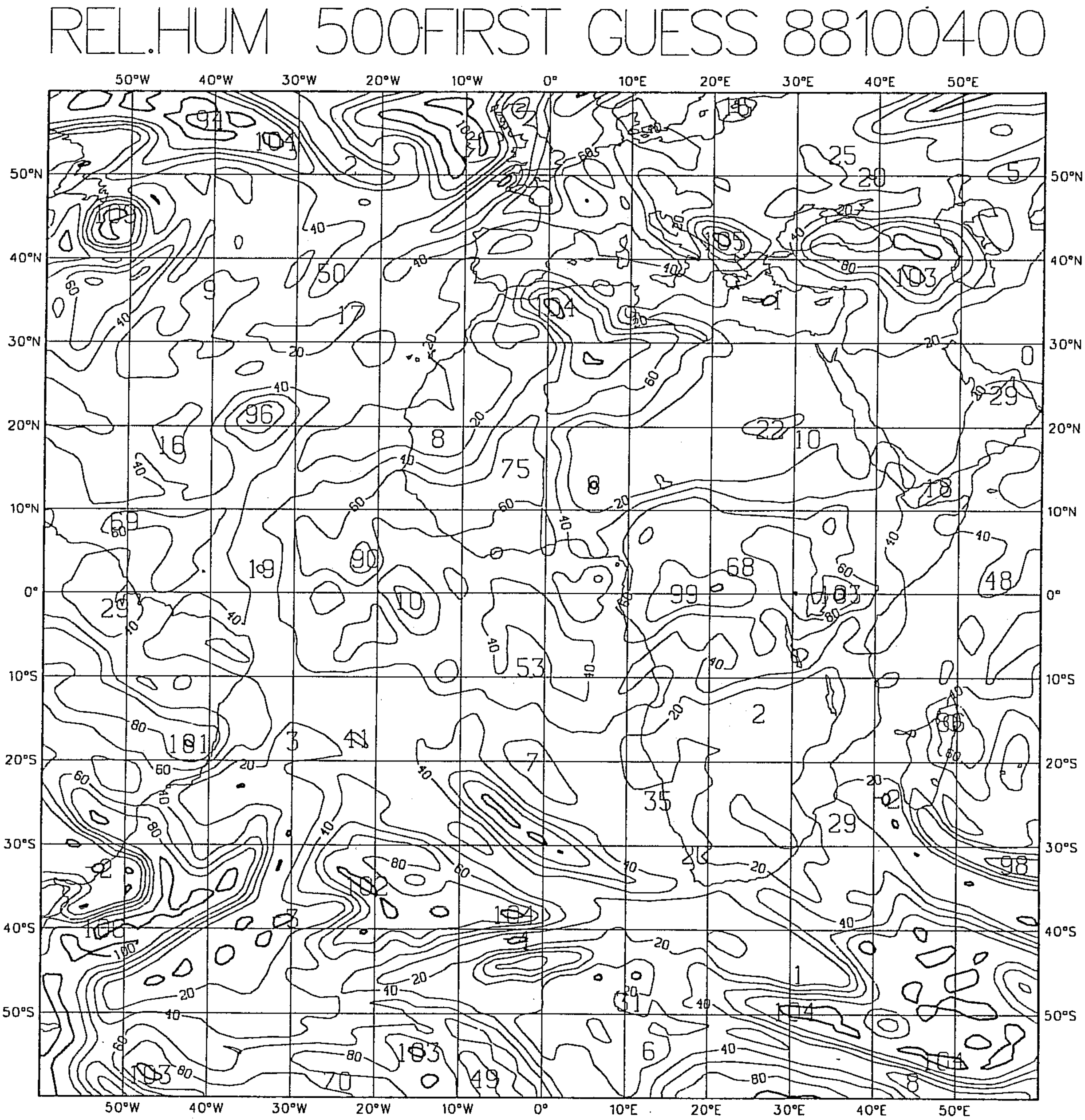


Fig. 15 The relative humidity first-guess field on 04 October 1988, 00z, from when both experiments with and without UTH start.

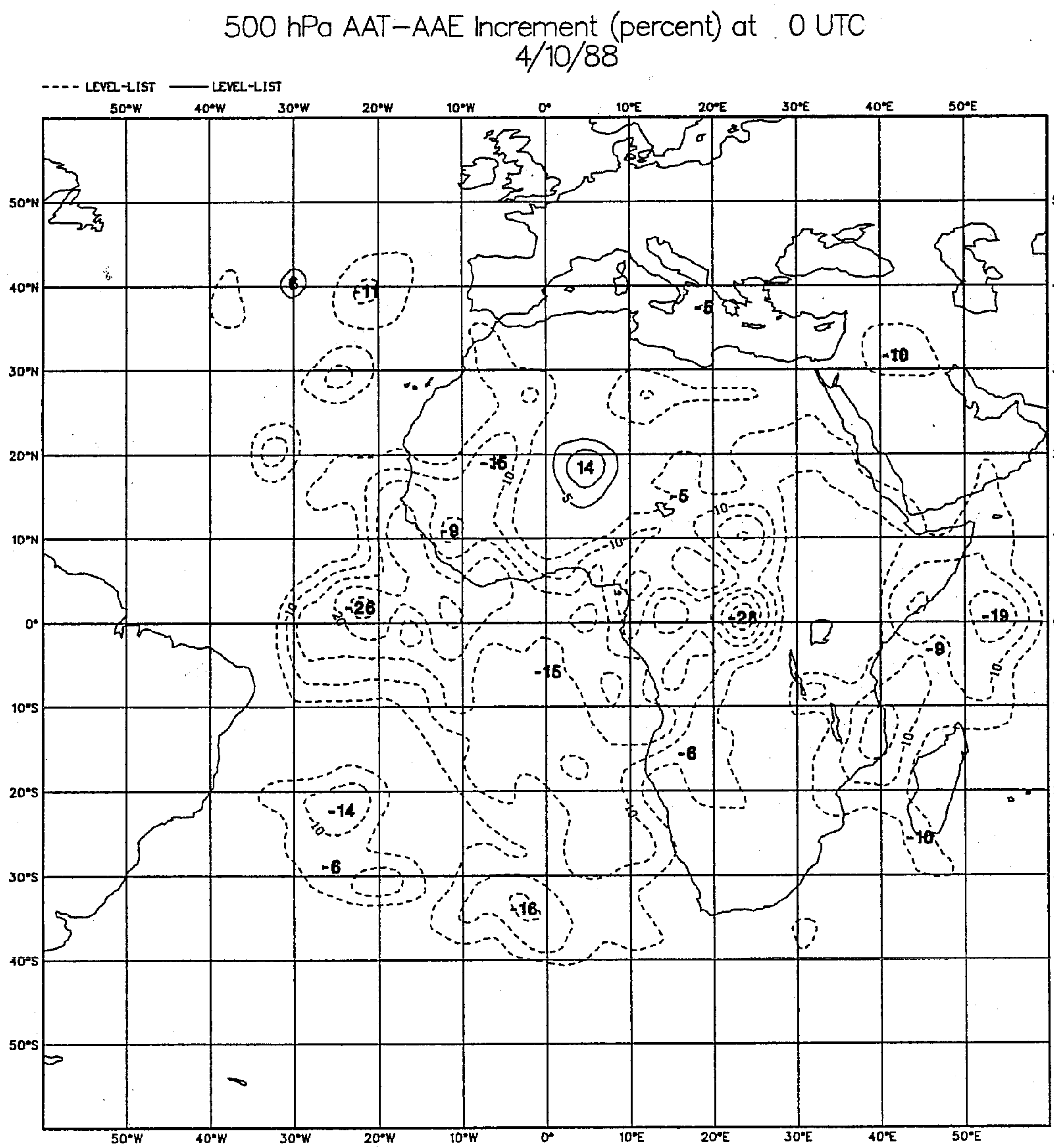


Fig. 16 The difference map between two experiments with and without UTH on 04 October 1988,00z. AAT: with UTH, AAE: without UTH.

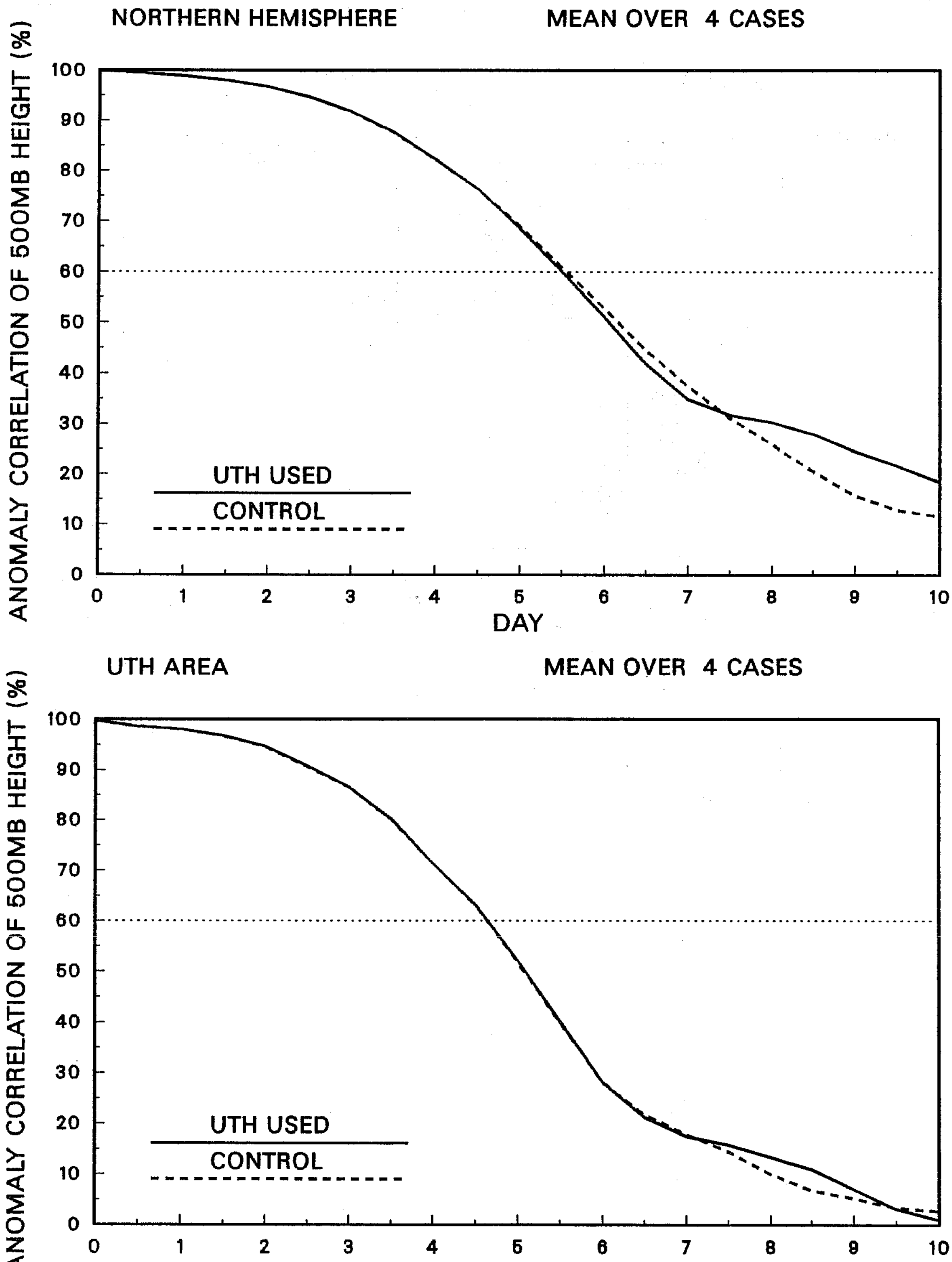


Fig. 17. The comparisons between the accumulated forecast scores for two data assimilation experiments with and without UTH (4 cases from 4 to 7 October 1988).
Top: Northern Hemisphere,
Bottom: UTH processing area (55 S-55 N, 55 W-55 E).

CORRELATION MATRIX OF NEW VERSION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.00																		
2	0.97	1.00																	
3	0.32	0.37	1.00																
4	0.12	0.14	0.42	1.00															
5	0.05	0.06	0.12	0.30	1.00														
6	0.04	0.04	0.07	0.14	0.56	1.00													
7	0.02	0.03	0.04	0.07	0.19	0.42	1.00												
8	1.00	0.97	0.32	0.12	0.05	0.04	0.02	1.00											
9	0.34	0.39	1.00	0.40	0.11	0.07	0.04	0.34	1.00										
10	0.02	0.02	0.02	0.01	0.00	0.00	0.00	0.02	0.02	1.00									
11	0.00	0.01	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.37	1.00								
12	0.00	0.00	0.01	0.02	0.02	0.01	0.00	0.00	0.01	0.12	0.33	1.00							
13	0.00	0.00	0.00	0.01	0.02	0.02	0.01	0.00	0.00	0.06	0.12	0.39	1.00						
14	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.00	0.00	0.04	0.07	0.16	0.47	1.00					
15	0.05	0.05	0.05	0.02	0.01	0.00	0.00	0.05	0.06	0.14	0.06	0.02	0.01	0.01	1.00				
16	0.02	0.02	0.06	0.06	0.01	0.01	0.00	0.02	0.06	0.05	0.14	0.05	0.02	0.01	0.37	1.00			
17	0.01	0.01	0.02	0.05	0.05	0.02	0.01	0.01	0.02	0.02	0.05	0.14	0.06	0.02	0.12	0.33	1.00		
18	0.00	0.00	0.01	0.02	0.06	0.06	0.02	0.00	0.01	0.01	0.02	0.05	0.14	0.07	0.06	0.12	0.39	1.00	
19	0.00	0.00	0.00	0.01	0.03	0.06	0.06	0.00	0.00	0.01	0.01	0.02	0.06	0.14	0.04	0.07	0.16	0.47	1.00

CORRELATION MATRIX OF CURRENT VERSION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.00																		
2	0.97	1.00																	
3	0.32	0.37	1.00																
4	0.12	0.14	0.42	1.00															
5	0.05	0.06	0.12	0.30	1.00														
6	0.04	0.04	0.07	0.14	0.56	1.00													
7	0.02	0.03	0.04	0.07	0.19	0.42	1.00												
8	1.00	0.97	0.32	0.12	0.05	0.04	0.02	1.00											
9	0.34	0.39	1.00	0.40	0.11	0.07	0.04	0.34	1.00										
10	0.01	0.02	0.02	0.01	0.00	0.00	0.00	0.01	0.02	1.00									
11	0.00	0.01	0.02	0.02	0.00	0.00	0.00	0.00	0.02	0.40	1.00								
12	0.00	0.00	0.01	0.02	0.02	0.01	0.00	0.00	0.00	0.13	0.36	1.00							
13	0.00	0.00	0.00	0.00	0.02	0.02	0.01	0.00	0.00	0.06	0.13	0.41	1.00						
14	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.00	0.00	0.04	0.07	0.17	0.50	1.00					
15	0.05	0.05	0.06	0.02	0.01	0.00	0.00	0.05	0.06	0.14	0.05	0.02	0.01	0.01	1.00				
16	0.01	0.02	0.06	0.06	0.01	0.01	0.00	0.01	0.05	0.05	0.14	0.05	0.02	0.01	0.40	1.00			
17	0.01	0.01	0.02	0.05	0.05	0.02	0.01	0.01	0.02	0.02	0.05	0.14	0.06	0.02	0.13	0.36	1.00		
18	0.00	0.00	0.01	0.02	0.07	0.06	0.02	0.00	0.01	0.01	0.02	0.06	0.14	0.07	0.06	0.13	0.41	1.00	
19	0.00	0.00	0.00	0.01	0.03	0.06	0.06	0.00	0.00	0.01	0.01	0.02	0.07	0.14	0.04	0.07	0.17	0.50	1.00

Table.1 The correlation matrix of new version (top) and current version (bottom) for humidity forecast error. The data from line 1 to line 7 is one radiosonde (TEMP) report, pressure levels: 1017.9, 1000, 850, 700, 500, 400, 300 hPa. The data from line 8 to 9 is one SYNOP report, pressure levels: 1017.9, 856.6 hPa. The SYNOP report is collocated with the radiosonde. Line 10 to 19 contain two SATEM reports (PWC) for 5 standard SATEM observation levels.