TECHNICAL MEMORANDUM

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Research and operational developments related to the use of satellite data in the ECMWF assimilations system

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September 1989

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Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

E.C.M.W.F.
SCIENTIFIC ADVISORY COMMITTEE
17th SESSION

ECMWF/SAC(89)7
SHINFIELD
10 August 1989

Subject: Research and operational developments related to the use of satellite data in the ECMWF assimilation system

1. INTRODUCTION

Over the last ten years satellite temperature and humidity soundings (SATEMS), produced from the "TIROS Operational Vertical Sounder" (TOVS), have been in general used in global operational forecasting systems. Several attempts have been made to evaluate their impact on the quality of the analyses and of the forecasts: see for example Halem et al (1982) and Gilchrist (1982). The standard technique to evaluate their impact is to perform an Observing System Experiment (OSE): two data assimilations are run in parallel, one including and the other excluding the observing system under investigation. The parallel sets of analyses and forecasts from them are then compared.

At ECMWF, OSEs were carried out in 1982/83 using data from the First GARP Global Experiment (FGGE). Two FGGE periods were studied in detail: the first (OSE-1) in November 1979 and the second (OSE-2) in February 1979 the results of these experiments were reported in Uppala et al (1984). In the Southern Hemisphere the impact of satellite sounding data was found to be large and positive, however, in the Northern Hemisphere there was a positive impact during OSE-1 and a neutral impact during OSE-2.

The results were in accord with those obtained by other groups with different assimilation systems and the following common conclusions have emerged:

(a) There is a clear beneficial impact of SATEM data on the analysis and the forecast in the Southern Hemisphere.

(b) In the Northern Hemisphere it is very difficult to demonstrate any impact; it varies greatly according to the meteorological situation (e.g. positive impact during OSE-1, neutral impact during OSE-2). This is true also for the use of satellite data in high resolution limited area models, see Durand (1985) for example who reports on experience with the French PERIDOT system.

Three cases from the OSE-1 period (November 1979) have been rerun with and without SATEM data with the 1987 version of the ECMWF assimilation system of 1987. The results from this rerun reconfirm the positive impact of SATEMs in the Northern Hemisphere forecasts in this particular period, see Kelly and Pailleux (1988).

A more recent SATEM impact study, carried out at ECMWF, has been run on a 15½ day period from 30 January 1987, 00 UTC to 14 February 1987, 12 UTC. It used the ECMWF assimilation system which became operational at the end of July 1987 (referred to as "OPS JUL87" from here on), (Kelly and Pailleux (1988)). In general the results are similar to those from the FGGE OSE-2 experiment i.e. a neutral impact. In addition, a regional investigation of the analyses and the forecasts in the Northern Hemisphere showed that the overall neutral impact in the Northern Hemisphere results from a compensation between a positive impact on one side of the hemisphere (North America - Atlantic - Europe) and a negative impact on the other side (East Asia and Pacific). There is evidence that in some areas the SATEM quality is very poor, (the performance of the retrieval scheme being critically dependent on the air mass), and that the rejection tests in the analysis scheme are not stringent enough to reject all the bad SATEM data.

The February 1987 OSE has been repeated with a more recent version of the ECMWF assimilation system which was operational at the end of July 1988 (referred to as "OPS JUL88" from here on, Lönnberg (1989)). After a brief summary of the development of the ECMWF data assimilation system made between July 87 and July 88 (section 2), an important part of this paper (section 3) documents the SATEM OSE performed at ECMWF using OPS JUL88, on the February 87 period. Prompted by the results from this SATEM OSE further evaluation of the quality control applied to satellite data was carried out using winter 88-89 cases, and revised quality control were developed and were implemented operationally in January 1989. These aspects are described in section 4. Section 5 summarizes the results of experiments carried out with the 3I retrieval scheme, developed in Laboratoire de Météorologie Dynamique (LMD). The 3I experiments have been run on the same 15½ day period of February 1987. They are fully documented in Flobert et al (1989). In section 6, the preliminary studies aimed at a direct use of TOVS clear radiances in a variational analysis are described. Section 7 is devoted to reports on other satellite data studies performed at ECMWF involving Meteosat humidity data and satellite winds. Section 8 concludes the ensemble of the satellite work. The satellite studies related to the analysis of humidity are only briefly described in this paper and are more fully documented in Zhang et al (1989).

2. RECENT DEVELOPMENTS IN THE ECMWF ASSIMILATION SYSTEM

The most important changes made to the forecast model between July 88 and July 87 was a reduction in the vertical diffusion. This revision affected high frequency structures and smoothed fields less. The major change to the analysis system was the implementation of revised Optimum Interpolation (OI) statistics. A detailed description of this change and of its evaluation is given in Lönnberg (1988). The main elements of the analysis change are:

- A reduction of the horizontal scale of the forecast error correlation function which is now represented by a combination of 8 Bessel functions (instead of 5 originally);
- A widening of the forecast error vertical correlation over the Pacific Ocean;
- A retuning of the observation error standard deviations and of the rejection thresholds for all the observation types. The rejection criteria become more severe for certain observations types; especially for cloud track winds (SATOBs) and for SATEMs, partly because of the revised first-guess check and partly because of modifications in the OI check.

The main consequence of the forecast error horizontal correlation modifications is to produce a higher horizontal resolution in the analysis. The analysis scheme uses more of the observed structure, and the assimilation is then more sensitive to the observations. This sensitivity was confirmed in experiments see Lönnberg, 1988. The overall assessment was that the OPS JUL88 system performed somewhat better than the OPS JUL87 system.

3. QUALITY AND IMPACT OF SATEM DATA IN THE FEBRUARY 87 PERIOD

3.1 Monitoring the SATEM data - their impact on the analysis

The standard tools to evaluate the impact of SATEM data on the analysis are maps of differences between the operational analysis and the "NO-SATEM" analysis, and statistics of these differences. Comparisons between OPS JUL88 and NO-SATEM show that these differences are large on the Southern hemisphere and over the oceanic areas in the Northern hemisphere. They affect all horizontal scales and all levels in the vertical. It is however, not obvious that the current use of satellite data is always beneficial for the operational analyses.

In order to asses the quality of SATEM data, the following stability index (S) has been used:

$$S = T_V\,(1000/700) - T_V\,(500/300)$$

where $T_V(1000/700)$ and $T_V(500/300)$ are the layer mean virtual temperatures between 1000 hPa and 700 hPa, and 500 hPa and 300 hPa respectively. Values of this index have been used to carry out a systematic comparison of SATEM temperatures with first guess (6 hr forecast) temperatures. The choice of the two layers provides a measure of overall tropospheric static stability. SATEMs often have large errors near the surface which are compensated at upper levels, leading to unrealistic profiles.

The deviations between first guess and SATEM values of S provide a powerful tool for the quality control of SATEM data. Although there is generally a good agreement between the SATEM data and the first guess, there are some areas where the SATEM values for S are very inaccurate or biased. Scatter plots of stability were computed in these areas, for forecast/radiosondes and forecast/SATEMs, in order to compare the performance of SATEMs with radiosondes. Fig. 1 shows the scatter plots for a North Atlantic area and for a Pacific area to the South-East of Japan. In the Atlantic the scatter of the SATEM stability is much larger than for the radiosondes (of the order of five degrees). Near Japan, there is a large positive bias (all satellite soundings too unstable). Other investigations showed that the satellite lower layer is much too warm, and this bias is almost always observed in the cold westerly flow off the Asian continent, which occurs frequently throughout Wintertime.

It should be noted that the analysis quality control, as it operated in OPS JUL88, was not stringent enough to reject these SATEM data. In these particular areas, a large number of biased or inaccurate SATEMs (according to the stability criteria) were still accepted by the analysis system.

3.2 Impact of SATEM data on the forecast

The two experiments reported in Kelly and Pailleux (1988) (OPS JUL87 and NO SATEM JUL87) were repeated with the OPS JUL88 system described in section 2. The forecast scores are summarised in Fig. 2. In the Northern Hemisphere there were improvements in both experiments using the latest assimilation system. However, the NO-SATEM JUL88 improved more than the OPS JUL88 and now there is an overall negative impact of SATEM data.

The new assimilation has more scatter in daily forecast scores. Fig. 3 shows the increase in scatter of the anomaly correlation at day 5 in the OPS versus NO-SATEM comparison between July 87 and July 88. It is clear that a large sample is required to determine unambiguously forecast impact.

The results for the Southern Hemisphere, Fig. 2, shows an overall improvement of the OPS JUL88 which is consistent with the results of Lönnberg (1988), although the NO-SATEM JUL88 was slightly worse. This implies that with OPS JUL88 it is now more important to have a good data coverage, otherwise the forecast skill will be degraded.

In order to explore further the impact of SATEM data in the Northern Hemisphere in the July 88 system a series of 15 regional scores were computed; these are displayed in Fig. 4. It is clear that the SATEMs have a negative impact after day three in North Pacific and North America. The regional scores for the North Atlantic and Europe show a small positive impact of SATEM data after day three. It appears that the source of the poor forecasts from SATEM data may be due to the anomalous circulation over Europe and Asia which has been described previously by Kelly and Pailleux (1988).

The fundamental problem with SATEMs is the lack of vertical resolution in the satellite radiance measurements and this is more true of cloudy regions and in particular, in mid-latitude fronts. In cloudy regions the microwave channels of the MSU instrument contain the only information pertaining to the troposphere and this is not enough to resolve fine vertical temperature structures. In contrast the first guess and the analysis can often represent these frontal structures. The satellite data are often warmer on the cold side of the front and colder on the warm side. The use of SATEMs in these regions both weakens the horizontal temperature gradient and reduces the strength of the polar front jet in that region. This has also been reported in Gallimore and Johnson (1986).

3.3 Forecast case studies

There was particular interest in studying further the cases which showed a negative impact of satellite data. By tracing forecast errors back in time it was found that the problems often originated from the eastern part of the North Pacific, a large area with few conventional observations. A-priori one would assume that the satellite information would be most valuable in this region. The polar front was active in this area with waves developing over the ocean and moving towards North America.

The NO-SATEM and the OPS JUL88 analysis differ in the east Pacific, mainly in the lower troposphere. The general impression is that the NO-SATEM atmosphere is "livelier" in many respects. At 500 hPa, the waves in the temperature field appear to be of larger amplitude and there is stronger warm and cold air advection. At 850 hPa, the waves are more developed in the NO-SATEM assimilation. The fronts are often sharper in the active regions and there is an accompanying difference in the surface pressure fields. Fig. 5 shows the analyses of 1 February 1987, 12 UTC, Fig. 6 the 48-hour forecasts and in Fig. 7 is the verifying operational analysis of 3 February 1987, 12 UTC. The strong development in the NO-SATEM forecast started near (170W, 38N) in the analysis and the 48-hour forecast verifies well, although the centre is too deep. The OPS JUL88 forecast intensified too late and maintained a spurious double structure in the 48 hour forecast.

Though the NO-SATEM forecasts do not verify better than OPS JUL88 in the North Pacific in the short range, the NO-SATEM forecasts are superior after day 3. A likely explanation is that 'air-mass biases' and under-estimated tropospheric static stability in the baroclinic zones degrade the large scale features of the SATEM analyses, thus affecting the skill in the medium range forecasts.

4. RECENT QUALITY STUDIES AND QUALITY CONTROL DEVELOPMENTS.

In February 87, the operational SATEMs were produced by NESDIS using a statistical scheme. This was replaced in September 1988 by a physical retrieval scheme.

The new NESDIS retrieval scheme (Fleming et al, 1986) is based on a search through a library of atmospheric profiles and radiances. The library entry closest to the observed radiances is chosen as the initial profile for an iterative inversion of the radiances to temperatures, using the radiative transfer equation, linearized around the initial guess. Cloud clearing is carried out as before in a preceding step.

4.1 Errors in SATEMs produced with the physical retrieval scheme

The operational SATEMs received in November and December 1988 have been evaluated in order to determine if the error structure of the SATEMs changed with the new retrieval scheme. Comparisons were made against the guess and radiosondes.

A global radiosonde collocation study showed that the bias, SD (Standard Deviation) and RMS (Root Mean Square error) with respect to radiosonde values were very similar to the old retrieval scheme. On the global scale there were very small biases, generally below 0.5 K, the SD and RMS were around 2K in the mid troposphere and 3.5K near the surface. However by separating the data into air-mass classes it was found that large positive biases existed in the lowest layers in the Tropics and Subtropics, and negative biases in polar air-masses. These biases were often compensated aloft by biases in the upper troposphere of the opposite sign.

The bias of the satellite data relative to the first guess (OBS-FG) also shows a strong regional dependence, particularly in the lowest layer. The 1000/850 hPa bias has characteristic maxima in the Subtropical highs. It is positive and largest for the cloudy soundings, exceeding 4.0 degrees in the South Indian ocean. Only a small part of this bias comes from the first guess which is known to be almost unbiased in the Subtropics.

There are generally very large and coherent errors in the cloudy areas of the mid-latitudes. The organisation of these errors relative to the synoptic pattern of the increments made to the first guess to produce the analysis is striking. Fig. 8 shows an example of the SATEMs in the North Atlantic area, on 1 February 1989, 12 UTC. In the cold air, to the East of Newfoundland, and also between Greenland and Canada, the 1000/700 hPa SATEM layer is too warm by 4 to 6 degrees; this particular feature has been found to be correlated highly with cold air over a warmer ocean (Tsurface - T2m≥0). Note also in figure 8 the tendency to have a compensation in the upper troposphere (500/300 hPa). In the warm sector of the weather system (50N, 40W) we find opposite errors : -3 to -6 degrees in the lower layer.

The same pattern of SATEM observation errors can be seen on any daily chart in the winter 88/89. Where radiosondes are available they confirm the accuracy of the first guess. The major problems are along the Northern hemisphere storm tracks, especially with the cloudy (MSU) soundings. The bias patterns for NOAA10 and NOAA11 are almost identical.

4.2 Quality control developments

By considering the results of forecast experiments and the synoptic studies described in the previous sections two important problems have emerged with the SATEMs. These are 'air-mass biases' and errors in static stability in the mid-latitude baroclinic zones. These shortcomings of the data have a strong effect on the analysed fields. In the ECMWF analysis system observations and the first-guess are assumed to be unbiased and analysis cannot correct spatially coherent biases in the observations, hence a cluster of biased data will be drawn for. Erroneous vertical structure in the observations are also drawn for because the current tuning of the OI scheme does very little vertical smoothing of the SATEMs apart from combining them into seven thick layer mean temperatures (four below 100 hPa and three between 100 and 10 hPa).

The vertical correlation between the layers is currently prescribed by one correlation matrix which does not allow for regional or air mass variations. In cases when the SATEM errors compensate over larger depths the data can deteriorate the analysis. The little random noise that still exists after the screening by the OPS JUL88 data checking procedure appears to be relatively harmless. The analysis scheme is to a large extent able to filter out the adverse effect of these SATEMs given a sufficiently dense and uniform distribution of data.

The detrimental biases can either be reduced with empirical corrections, through filtering in the vertical or through data rejection. Correction of biased satellite data is made difficult because tuning by NESDIS is carried out continually. Filtering in the vertical might, through the strongly non-linear properties of the radiative transfer equation, result in a profile which no longer satisfies the observed radiances and may produce a filtered profile which is incorrect. The practical solution appears to be to develop tailored quality control procedures. The OPS JUL88 quality control has been enhanced with extensions to the first-guess check.

Between July 87 and July 88, the SATEM quality control was improved mainly by a modification of the OI check : when checking a particular SATEM, the other SATEMs in the vicinity (which are likely to support the one being checked) are not used as soon as two other different observations at least are available. However, it is still obvious that in OPS JUL88, the quality control is not stringent enough to cope with the problems mentioned above. Two further quality control developments were made and implemented operationally on 31 Jan '89.

a) Tighter first guess check

The OPS-JUL87 FG-check seems to be sufficient for the middle layers but very few rejections are obtained in the lowest layer and in the top two stratospheric layers. This is due to the higher FG error variance for those layers. In terms of standard deviation of 'normalized departure' ((OBS-fg)/SD of FG) we have implemented a reduction from 3.0 at all levels to 1.2, 2.1, 2.75, 2.75, 2.6, 2.3, listed from 1000/700 to 30/10 hPa. In absolute terms, this approximately corresponds to a rejection limit of 4 degrees for the 1000/700 hPa layer mean temperature in the eastern part of the North Pacific.

b) Stability check

A further possibility to identify incorrect data is to compare observed and first guess stabilities. Large errors in the lowest layer tend to be compensated aloft by errors of opposite sign. The satellite estimates of stability differ from the first guess mainly because of their limited vertical resolution in overcast situations. From comparisons with ocean stations and weather ships (Fig. 1.) it is clear that the most noisy tropospheric SATEM stability is the difference of temperature between the two layers 1000/700 hPa and 500/300. SATEMs have almost no skill in measuring this stability. Based on these scatter diagrams we chose a rejection limit in absolute terms of 4.5 degrees for the experiments (later tightened to 3.5 degrees for operational use).

These changes to the FG-check lead to a large increase in the number of rejections. Over the period 30 January 1987, 00 UTC to 2 February 1987, 12 UTC the increase compared to OPS JUL88 was from 85 to 240 on average per data assimilation cycle.

4.3 Impact of the quality control developments

In addition to a short experiment made on the February 87 period, a parallel data assimilation with improved quality control was run for several days on a period preceding the operational implementation of these quality control procedures (end of January 1989). This period was affected by particularly large air-mass dependent biases in the North Pacific. Fig. 9 shows the impact of the improvement of the quality control in the Pacific on 25 January 1989, 12 UTC, for the two layers used in the stability test : 1000/700 and 500/300 hPa. As expected the virtual temperature differences are large, exceeding 3° in some frontal structures.

In this particular period, there were unusually poor forecast scores and the forecast errors appeared to be unrelated to the use of satellite data. However the evaluation of the operational scores at day 1 on a long period of time (by comparison to the NMC scores) seems to confirm a small improvement due to the quality control modifications introduced end of January 1989 (Fig. 10). In Fig. 10 the first vertical line corresponds to the date of an important change at NMC (end of November 1988), whereas the second vertical line corresponds to the ECMWF change of January 1989. The two SD curves look closer during the period December/January 89.

5. EXPERIMENTATION WITH THE 3I RETRIEVAL SCHEME

This section summarizes the satellite work carried out in cooperation with LMD (France), a full documentation is given in Flobert et al (1989). The 3I method (Improved Initialization Inversion) which has been developed at LMD is described in Chedin et al (1985) and Chedin and Scott (1985). In the past, 3I retrievals have been produced for numerous limited areas throughout the globe, but not as input to a global assimilation system.

In order to perform the global 3I processing, it was first necessary to modify the preprocessing programs provided by the University of Wisconsin in order to input up to eight global TOVS orbits in any 6 hour period. Use was also made of the first guess to compute the radiances through the 3R (Reconnaissance Rapide de Radiances) fast forward model, in order to perform quality control of the raw MSU radiances prior to mapping. 3I allows for the use of some extra parameters such as surface temperature and pressure to help guide the initial profile search in the library called TIGR: the 6h forecast parameters were used for this purpose through an appropriate interface between the ECMWF assimilation and the 3I suite. The humidity aspects were also revised in this interface, see Zhang et al. (1989).

The global "3I suite" was then been tested on the February 1987 period. From the NOAA9 and NOAA10 raw radiances provided by NESDIS, the 3I scheme (cloud clearing and inversion algorithm) has been run experimentally to produce global data sets of retrieved soundings. More than 40,000 soundings on average have been produced for each 6 hour period from 30 January 00 UTC to 14 February 12 UTC in 1987. The quality of these soundings has been examined and compared with the quality of the operational NESDIS soundings. Around 15,000 3I soundings were used in the main data assimilation and forecast experiments. In a shorter experiment small samples of 5,000 to 6,000 3I soundings were used. The NO-SATEM and OPS JUL88 runs have been used for comparison. The results of this comparison can be summarized in the following way:

a) The data quality problems of the 3I soundings are very similar to the problems of the statistically derived NESDIS soundings. The problems with the retrieval algorithms are related mainly to specific air-masses or specific weather systems.

b) However, the quality of the 3I soundings is on the average slightly better than the quality of the NESDIS soundings. In particular 3I is consistently better in the lowest layer (1000/850 hPa) and the soundings exhibit very little random noise. As an example, in several areas of North Atlantic and North Pacific bad vertical gradients were clearly identified in both NESDIS and 3I soundings, but to a larger extent in NESDIS. Fig. 11 illustrates the better quality of 3I in the North Atlantic regarding the stability index S (compare also Fig. 11 with Fig. 1).

c) 3I has problems in areas with rain-contamination and 'jumps' in the MSU brightness temperatures.

d) The impact of the 3I soundings on the analysis is large as measured by differences between OPS and NO-SATEM analyses. This is the case at all levels and for all variables, including humidity. In terms of calculated radiances, however, the differences between the 3I analysis and the operational analysis are small except in areas with contaminated or otherwise corrupt radiances. This suggests that the observed radiances are well assimilated in spite of the artificial temperature retrieval interface between the primitive radiances and the analysis. Large local temperature differences between the analyses are often artifacts, probably introduced by the choice of initial profile for the retrieval.

e) When using the 3I soundings at the same resolution as the NESDIS soundings in the analysis (5,000 to 6,000 soundings per analysis), the forecasts from the 3I analyses are on average comparable with those made from NESDIS analyses. This comparison has been made on four cases only: 31 January to 3 February 1987. The main 3I assimilation experiment has been run using three times more soundings (more than

15,000 soundings per analysis). Then the 3I forecasts have been found on average to be worse than the operational forecasts. It should be noted that these experiments were run with an analysis system where the quality control was not severe enough and where most of the poor quality soundings were actually accepted by the analysis, leading on average to a negative impact of SATEM data on the forecast scores (see section 3). It is likely that the data volume is the critical problem in the main 3I experiment. The OI data selection is not able to cope properly with the large number of SATEMs produced from 3I, especially when the SATEM quality control is too loose.

The global weight given to SATEMs is then probably too high compared for example to the global weight given to about 600 radiosondes. This is the likely explanation of some bad forecast scores of the 3I experiment, which on average has a lightly worse anomaly correlation than OPS JUL88, in spite of better soundings.

An illustration of the differences between NESDIS and 3I soundings is given in Fig. 12. Points to be noted are the different data densities; the 3I map (bottom) has more than 15,000 soundings per analysis, note also the large differences between 3I and NESDIS in several areas of the North Pacific. By comparing the analysis maps (850 hPa temperature and MSL pressure) on the same date (4 February 1987, 12Z), fig. 13, problems very similar to those shown on fig. 5 can be seen. Note especially the small system near (40N-140W) which is strong in the No SATEM analysis and smoothed out in the 3I analysis.

6. USE OF CLEAR RADIANCES IN VARIATIONAL ANALYSIS

The problems that OI has with a large body of satellite data and quality control indicates the need to define a more optimum interface between the TOVS information and the assimilation. The fact that the improvement of the 3I soundings (compared to those produced by NESDIS) was not reflected in the forecast scores might seem surprising and somewhat discouraging after a superficial analysis. However, it probably indicates that there is scope for improvement in the way the TOVS data are utilized by the analysis scheme. In the 3I data assimilation the operational observation error statistics were used with, for example, no regional variations. Clearly this could be improved by taking into consideration their dependence on the retrieval scheme and the region or air-mass.

For the near future (within the context of the present OI scheme) progress in the use of TOVS data can be expected from the development of a more integrated system where the retrieval and the analysis schemes are at least made consistent regarding quality control and data selection.

For the longer term, a promising approach for a better use of satellite data is a variational approach. The theory and the organisation of a variational analysis are fully documented in Talagrand (1988), Courtier and Talagrand (1988), and Pailleux (1988). Variational methods provides a mathematical framework for the direct assimilation of all types of data in both 4 and 3 dimensions. Any observation for which a "post processed" value can be obtained from a model can be used in a variational analysis. The approach involves minimizing a "cost function" which is a "distance" between this post processed value and the observations (a model trajectory in the 4 dimensional context). Any datum d can be used provided it can be related to the model variables X by a post-processing operator H which is mathematically well defined, accurate enough and "differentiable". The operator H does not need to be linear. The gradient computations used to find the minimum can be handled by using the notion of adjoint operators.

Cloud-cleared radiances can be used in a variational analysis through an operator H which includes a radiative transfer model. Cloudy or raw radiances are more difficult to use because the clouds are not well described by model variables, particularly at the scale of the pixel of the current satellite instruments. However, a scheme combining the cloud-clearing and the TOVS inversion in a single variational approach has been developed by Eyre (1989).

At ECMWF, a new system is being developed to provide the framework needed to perform 3D and 4D variational assimilation experiments. To date only simple variational analysis experiments have been performed to assimilate directly simulated clear radiances. These experiments used the "ITPP" code for the direct radiative transfer operator, and its adjoint developed in the French Weather Service for the gradient computations, see Moll et al (1988). We envisage that the three dimensional variational approach will lead to much better use of the radiance data, as it provides a rational method to exploit the accuracy of the first guess and the true information content of the radiance data.

7. EVALUATION AND USE OF OTHER SATELLITE DATA SETS

In collaboration with external satellite groups, the evaluation of various "new" or "experimental" data sets has been carried out at ECMWF using the operational assimilation system. In this section we describe the evaluation of two such data sets. The first data set is the Upper Tropospheric Humidity (UTH) retrieved from Meteosat instruments. The second data set consists of cloud winds and water vapour winds produced by Wisconsin University from the VAS instrument on the GOES satellite.

7.1 Use of Meteosat Upper Tropospheric Humidity

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

Clearly satellites should have a major role in providing global data for humidity analyses and it is very important to make an effort to use satellite data in any future humidity analysis system. 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 observation stations. 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 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 that UTH data is of good quality compared with radiosondes. The overall feeling from their studies is that the UTH data are comparable with radiosondes and appear to be sampling a wetter atmosphere. They point out that this 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 develop the present ECMWF analysis code, because it is difficult for the present code to deal with such humidity data which pertain to a very thick layer. An assimilation experiment has been run during the period from 04 October 00 UTC to 07 October 12 UTC in 1988, in which UTH data are available twice each day (00 UTC, 12 UTC). The UTH data were used in the humidity analysis in the same way as SATEM moisture data are routinely used. It seems to be reasonable to assume that the observation error for UTH is 15% plus rounding error. Four cases of 10-day forecasts experiments from 12 UTC of each day have been run.

Fig. 14 is the difference map between the experiment and control for the UTH area which shows the impact of UTH data on the 500 hPa relative humidity analysis field. Negative difference values dominate over the whole UTH area. It is somewhat surprising that there is a large impact of UTH on the analysis but almost nothing on the forecast scores (Fig.1.5) It seems likely that the large negative values appear, because the first-guess of humidity field is clearly wetter than the UTH observation data. This negative difference is partly due to the fact that UTH is produced in clear areas and partly because the ECMWF model in too wet in the upper troposphere.

7.2 Evaluation of operational and experimental satellite winds.

For a period in February 1989 several geostationary satellite wind data sets have been collected at ECMWF in addition to that obtained operationally:

- Experimental cloud motion winds based on a new scheme developed by ESOC (Darmstadt);

- Cloud motion winds and water vapour winds derived from the VAS instrument on the GOES satellite by the University of Wisconsin.

In addition to the evaluation of these data sets by comparison against the first guess, or by including the data in the analysis, a short satellite wind OSE was run for the period 6 February, OOUTC to 9 February, 12UTC 1989. Fig. 16 shows the average impact of the operational cloud winds in this particular period, over an area covered by the Japanese satellite. Note that the differences "operations" - "No Satob" often exceed 5 m/s. In general, the results confirm very well a previous cloud wind OSE, see Kallberg et al (1982). The cloud motion winds are obviously beneficial for the analysis and the short-range forecasts within the tropics. In mid-latitudes and especially in the Northern hemisphere, the clear underestimation of the wind speed in the jet stream makes the use of cloud winds difficult. Demonstrating any impact on the forecast is also difficult.

Fig. 17 is a summary of the quality of the satellite wind data sets which have been examined. The scatter diagrams compare the satellite wind speed with the corresponding first-guess wind speed, they show also what are the rejections of the analysis quality control. It should be noted (left column), that although all the operational satellites are affected by the same weakness (some winds clearly underestimated at high speed), the Meteosat winds are slightly better than the Himawari winds. For the experimental winds produced by Wisconsin (right column in Fig. 17), both the scatter and the bias are considerably reduced compared to the operational winds.

8. SUMMARY OF RECENT WORK ON SATELLITE DATA

In this paper we have reported a variety of work on the use of satellite data in the ECMWF assimilation system.

a) NESDIS SATEMs Impact Study

The observing system experiment reported in section 3 evaluated the impact of the operational 250 km statistical SATEM retrievals produced by NESDIS from TOVS data during the period Jan30-Feb 14 1987. The parallel assimilations were performed with the

July 88 ECMWF operational assimilation system. We found the following results from the impact study:

a) Positive and large impact in the Southern Hemisphere;

b) Slight negative impact in the Northern Hemisphere, with large variations from case to case.

The earlier OSE performed by Kelly and Pailleux (1988) on the same period but using the July 1987 assimilation system found a neutral impact in the Northern Hemisphere. The model and analysis developments implemented between July 87 and July 88 led to forecast improvements whether or not SATEM data were used. Improvements were larger in the NO-SATEM context. Consequently the neutral impact of SATEM data with the 1987 system became a negative impact with the 1988 system.

Detailed synoptic and statistical study of the analyses show that the SATEM data usually have larger errors than the first-guess, even over the mid-oceans of the northern hemisphere. The SATEM data also have considerable biases which are air-mass dependent, and so have strong regional variations. The typical synoptic manifestations of air-mass dependent biases in the SATEM data include the weakening of frontal structures, and the associated jet streams and baroclinic zones. We have seen several examples where the forecast (and presumably therefore the analysis) of weather systems have been adversely affected by the use of SATEM data which should have been rejected, particulary in the baroclinic zones. Similar effects have been reported by Gallimore and Johnson (1986) in an impact study with the GLA system using 1979 SATEM data.

The scatter of the forecast scores comparing OPS and NOSATEM is much bigger in the JUL88 context than in the JUL87 context, which confirms that the analysis/forecast system has become more sensitive to the data, and to errors in the data. The results indicate the need to improve the quality control of SATEMs.

Rodgers (1976) defined the information content of an observing system as the logarithm of the ratio of volumes of the uncertainty ellipses before and after the measurement. The volume of the uncertainty ellipse is proportional to the determinant of the corresponding error covariance matrix. Suppose the error covariance of the first-guess is Ep, that the error covariance of the measurements is Eo, and that the two are combined in an optimal way, so that the posterior error covariance Ea is given by

$$Ea^{-1} = Ep^{-1} + Eo^{-1}.$$

Then the information content of the data is proportional to

$$\ln [\det(Ep)/\det(Ea)]$$

If Eo becomes substantially larger than Ep, i.e. if the observations become substantially less accurate than the first- guess, then their information content decreases to zero, although it remains positive.

However, the argument that data always have positive information content, however noisy they may be, ignores an important feature of the estimation problem in meteorology. The penalty for believing an erroneous observation in a meteorological context can be very heavy, because of the unstable nature of the atmosphere. If one is dealing with data which is noisier than the first guess, then one needs very effective quality control procedures which will prevent one accepting observations which are too far from the first guess, even if their error is nevertheless within the range of expected error for the observing system.

b) Quality Control of SATEM Data

As a preliminary to the quality control work we demonstrated that the SATEMs produced by the physical retrievals (introduced by NESDIS in September 1988) have just as serious errors and biases as the statistical retrievals. These errors in the SATEMs have an adverse effect on analysis and forecast quality.

Work on improved quality control of SATEM data is reported in section 4. We explored two approaches to quality controlling the SATEM data in the Northern hemisphere, where the problems are most serious. In our first experiments we retained only the best (clear) SATEM retrievals in the northern hemisphere and tropical troposphere, and excluded all SATEM data over ice. Although we only made limited tests of this approach, we found the paradoxical result that to retain only the best of the SATEM data, without any further changes in quality control, gave worse forecast scores in both hemispheres than using either all of the SATEM data or none of it. The reasons for this result need further investigation.

Our second approach was to develop a revised set of quality control tests for all SATEM data. These tests tightened existing tests against the first guess, and introduced a new test on a stability index related to the gross tropospheric static stability. SATEMs which depart too far from the first-guess in this index are discarded. A good understanding of the SATEM data errors and of the forecast guess errors, together with detailed synoptic studies, are important in quality controlling the data.

Following the introduction of the analysis changes on 31 January 1989, up to 30% of the SATEMs in the Northern Hemisphere are rejected, and there is now a much closer fit of SATEMs to the first guess. The vertical stability check is mostly responsible for the rejections. Routine monitoring against radiosondes has confirmed that the rejected SATEMs have large errors.

Further work is under way to improve the stability check by introducing a geographical dependence of the threshold and by using estimates of both observation and forecast errors. Other changes under investigation include the use of SATEMs over ice and land, and the use of DMSP soundings to quality control SATEMs.

c) Work With The 3I System

The SATEM OSE reported above is part of a larger set of satellite experiments which have been performed at ECMWF on the period 30 January to 14 February 1987. This period was initially chosen because of the meteorological situation and the availability of two satellites, NOAA-9 and NOAA-10. In addition, complete sets of raw radiances, cloud-cleared radiances and TOVS soundings were kindly provided by NESDIS. In section 5 we described the work by Flobert et al. (1989) on observing system experiments in which the 3-I retrieval system (Chedin et al 1986) is used to generate the retrievals during this period.

These experiments showed that the 3-I system has some problems in common with the NESDIS system, but that it does appear to offer some advantages, once short-comings identified in the tests (e.g in-effective rain-detection) have been remedied. Work on these problems is nearly complete at LMD.

As a result of the recent workshop on satellite data it was decided that further extensive experimentation with 3-I should await the results of a detailed evaluation and inter-comparison of the performance of the cloud-clearing algorithms of the NESDIS, GLA and LMD systems. This intercomparison will be done under the auspices of the International TOVS working group, with results expected in mid 1990.

d) Use of Clear Radiances in Variational Analysis

The results shown to date illustrate a number of serious short- comings in current methods of retrieving geophysical information from remotely sensed data. As a reasonable minimum requirement the observational data should have an RMS error comparable with the error of the first-guess. In many cases the SATEM data is considerably less accurate than the first guess.

he present results suggest that it is essential to exploit the accuracy of the first-guess in the retrieval procedure. The most rational way in which to do this is through a variational analysis of the radiance data. In this approach a forward calculation of the radiance is compared with the available measurements. Where the two differ, the corrections to the control variable are calculated using the adjoint of the radiative transfer equation. Any indeterminacy in the calculation is resolved by taking the values from the first-guess and the other observations in the area. Work on developing such a system is underway.

Such a variational procedure could start from the raw radiances or from the cloud-cleared radiances. We believe that it is better initially to work from the cloud-cleared radiances. This requires a good cloud-clearing algorithm. The planned intercomparison of the cloud-clearing algorithms will be of considerable value to our work.

e) The Need for Improved Observing Technology

A fundamental problem with SATEMs is the lack of vertical resolution in the satellite radiance measurements and this is more true of cloudy regions and in particular, in mid-latitude fronts. The microwave channels of the MSU instrument contain the only information in the troposphere and this is not enough to resolve fine vertical temperature structures in these active areas.

The AMSU instrument will probably have similar vertical resolution to the current TOVS instrument in clear conditions. Although the worst results were found for the cloudy retrievals, there are problems also with the clear retrievals. Given the long lead-time for the development of new instruments it is not too soon to press for improvements in instrumental technology.

f) Evaluation of Improved Satellite Products

We concluded the present report with descriptions of two short studies of the possibilities of improved products from current satellite technologies - improved winds from the geostationary satellites, and upper tropospheric humidity. These studies were done in collaboration with interested satellite data producers, and illustrate how both sides can profit from an active dialogue.

The wind study resulted from the repeated reports from ECMWF on the poor quality of current cloud-track winds near jets. Preliminary results from the current study are quite encouraging.

The evaluation of the UTH data from the water vapour channel showed some biases which may be partly due to the model and partly due to the retrieval algorithm. Further work is justified.

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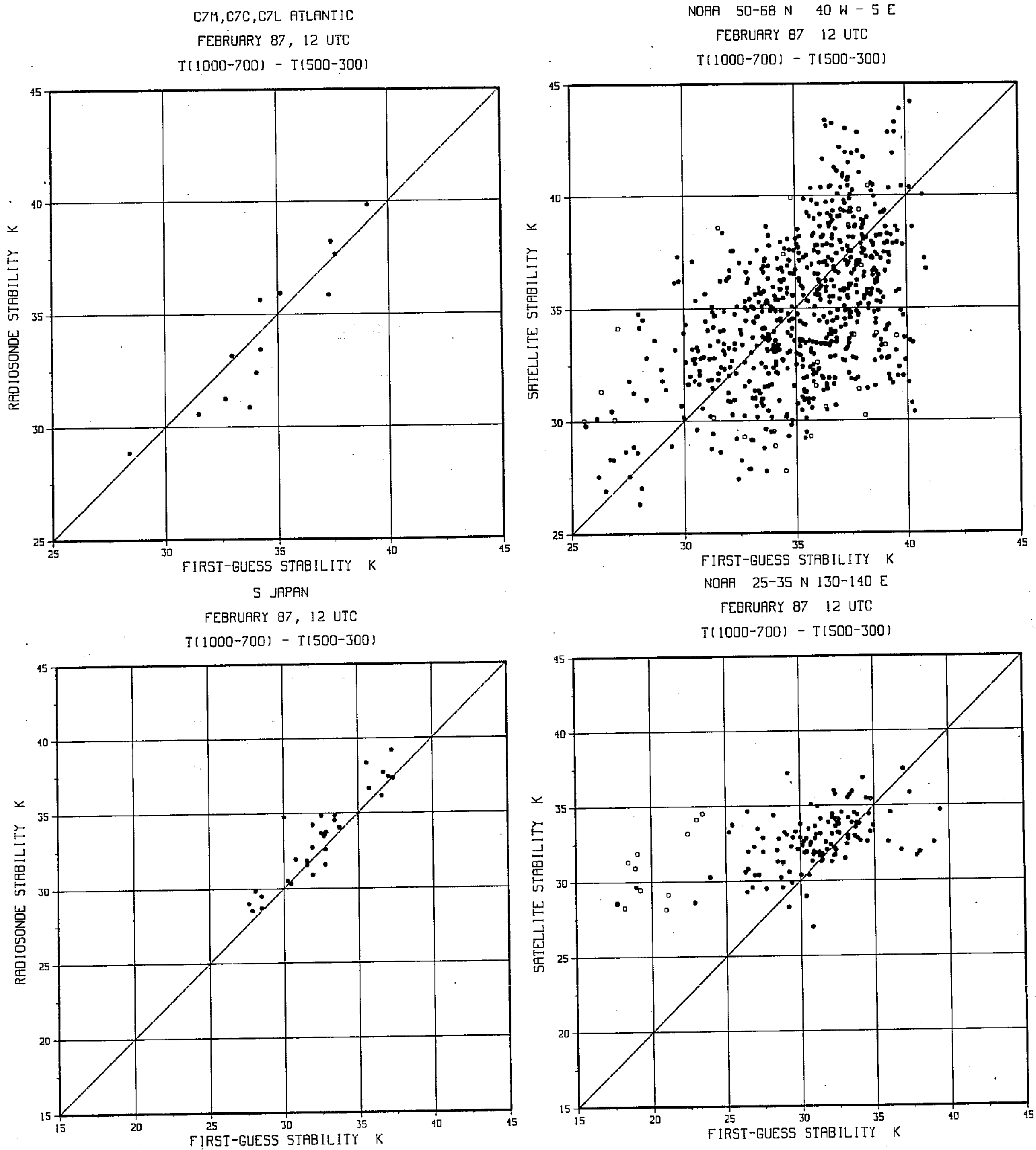


Fig. 1 Scatter diagrams comparing the stability index $S = T_V(1000/700) - T_V(500/300)$ of the first guess (horizontal axis) with either radiosondes or TOVS retrieved soundings (vertical axis), for a two-week period in February 1987.

The top panels are for a North Atlantic area, the bottom panels for a Pacific area to the South East of Japan. Left panels are for radiosondes (three weather ships for the Atlantic area); right panels are for TOVS.

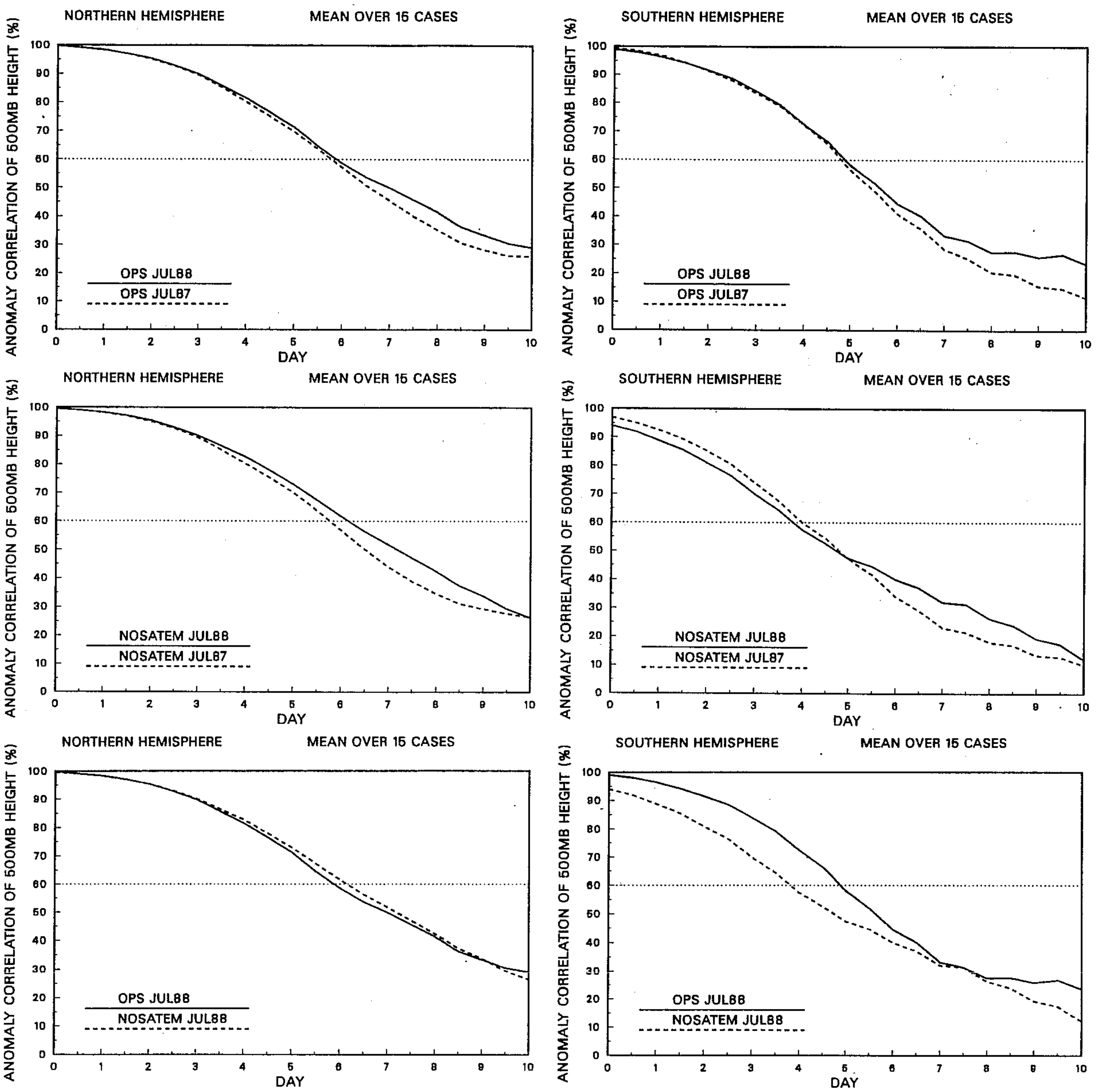
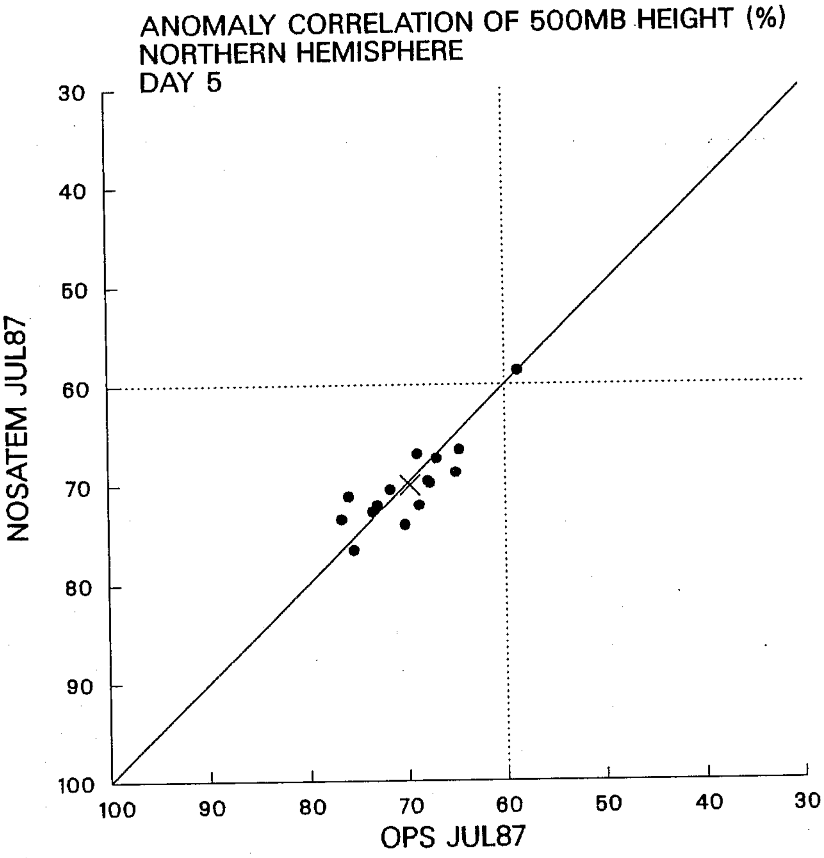


Fig. 2 Anomaly correlation forecast scores accumulated for 15 cases in February 1987, comparing performance of the operational (OPS) and "NO-SATEM" forecasts, with the ECMWF system of July 87 and July 88.

Top: OPS JUL88 VS OPS JUL87 (measures the improvement of the forecast due to the developments between July 1987 and July 1988).

Middle: NO-SATEM Jul88 VS NO-SATEM JUL87 (same as before in the absence of SATEM data).

Bottom: OPS JUL88 VS NO-SATEM JUL88 (impact of SATEM data). Leftmost panels - Northern hemisphere, rightmost panels - Southern hemisphere.



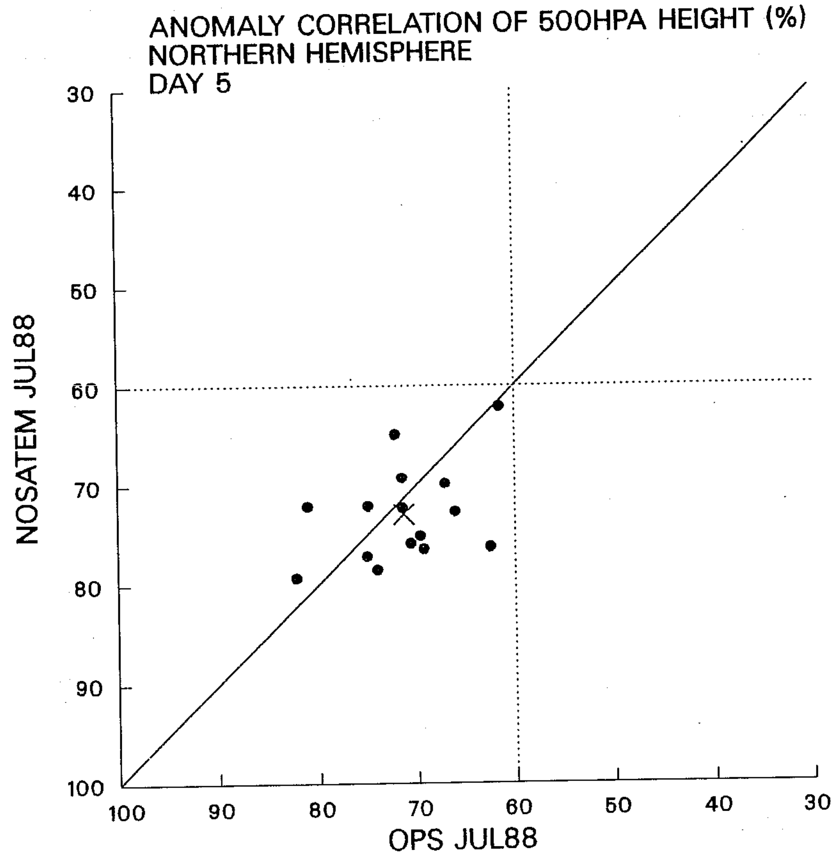


Fig. 3 Scatter diagrams comparing the anomaly correlation of operational forecasts (horizontal axis) and "NO-SATEM" forecasts (vertical axis), for 15 cases in February 1987. Top: with the assimilation version of July 87. Bottom : with the version of July 88 (note the much higher dispersion).

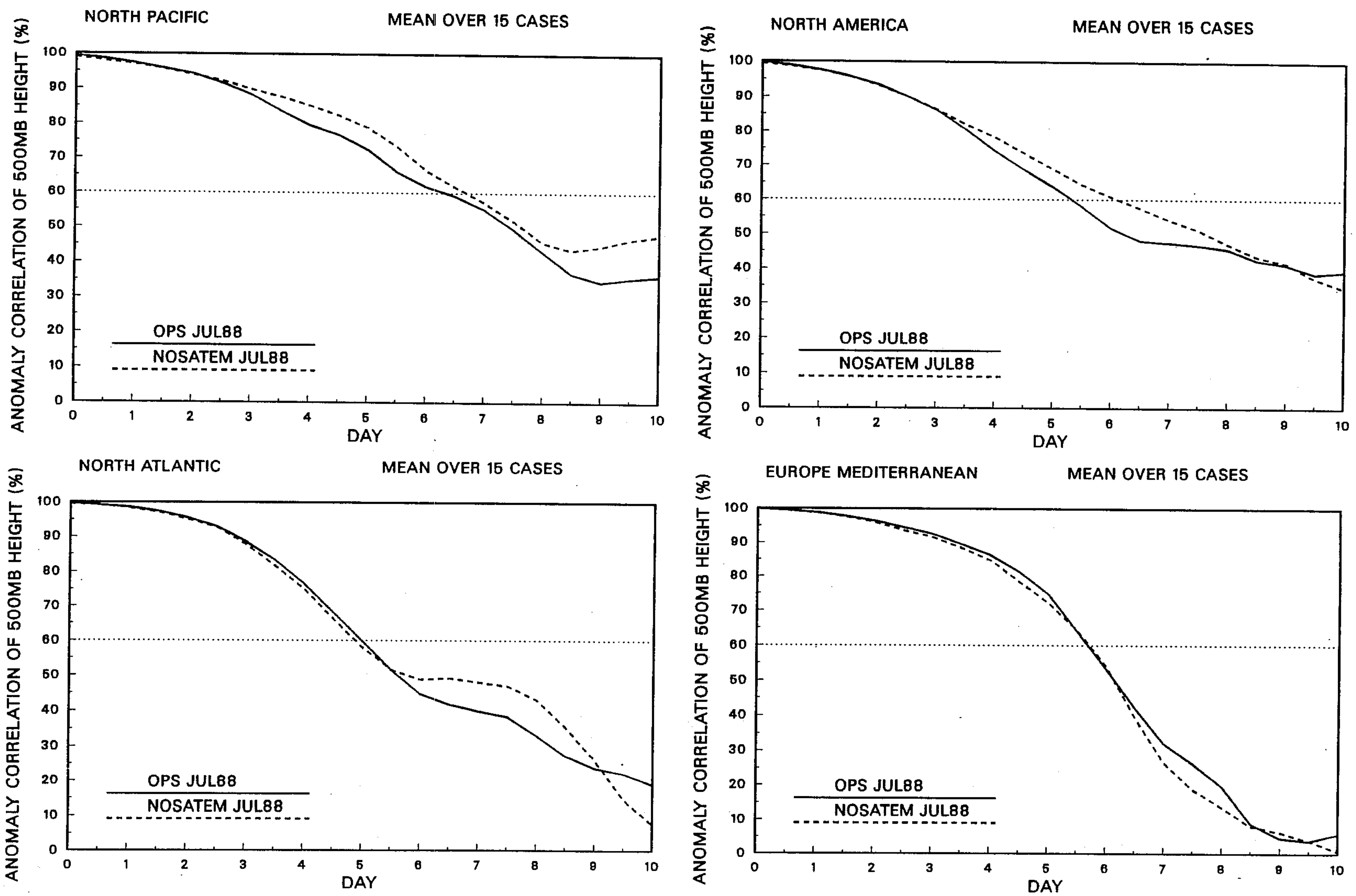
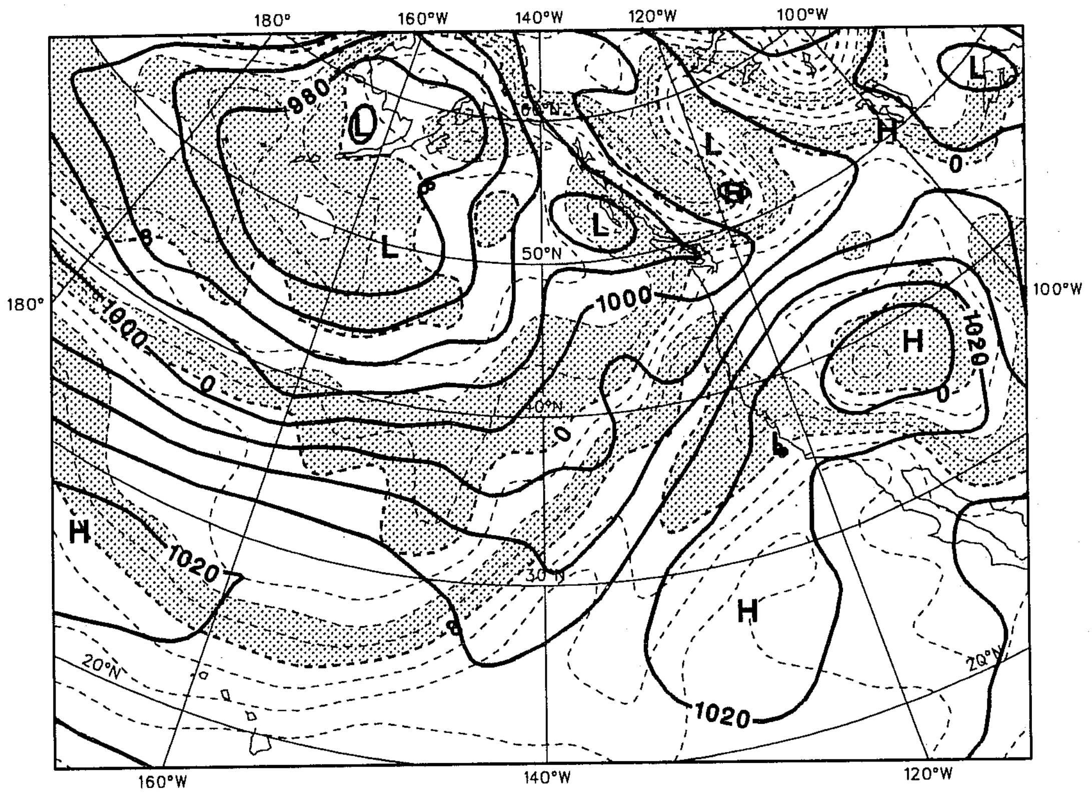


Fig. 4 Anomaly correlation forecast scores accumulated for 15 cases in February 1987, comparing operational and "NO-SATEM" assimilations (July 1988 versions) for four different areas of the Northern hemisphere : North Pacific, North America, North Atlantic and Europe/Mediterranean.


Pmsl and 850hPa temperature OPS JUL88
Analysis Date: 87020112

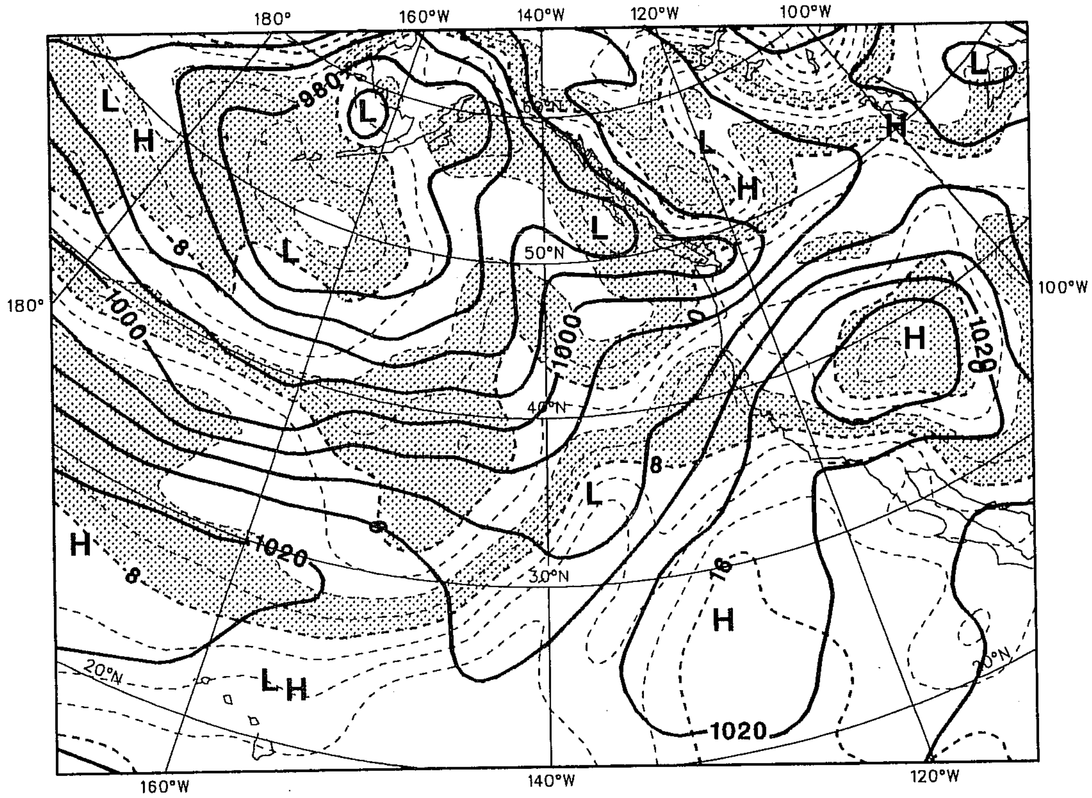
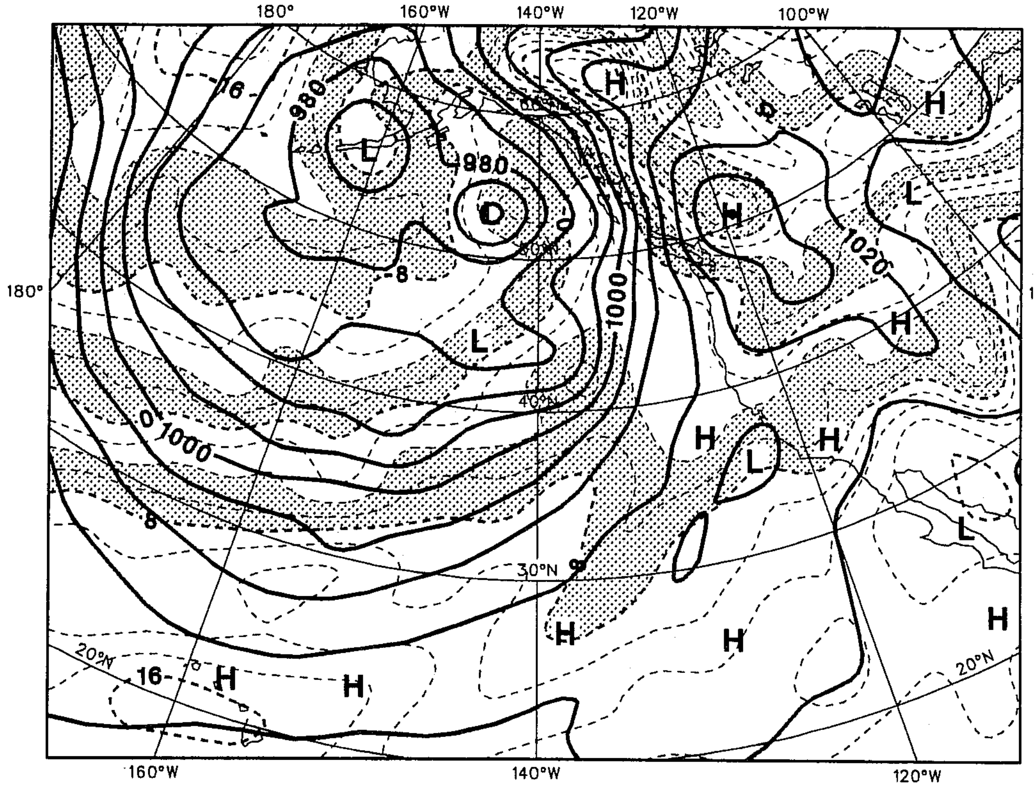

Pmsl and 850hPa temperature NoSATEM JUL88
Analysis Date: 87020112

Fig. 5 MSL pressure and 850 hPa temperature analyses for 1 February 1987, 12 UTC. Top : OPS JUL88; Bottom : NO-SATEM JUL88.

Pmsl and 850hPa temperature OPS JUL88
Verifying date: 87020312 Range: 48h



Pmsl and 850hPa temperature NoSATEM JUL88
Verifying date: 87020312 Range: 48h

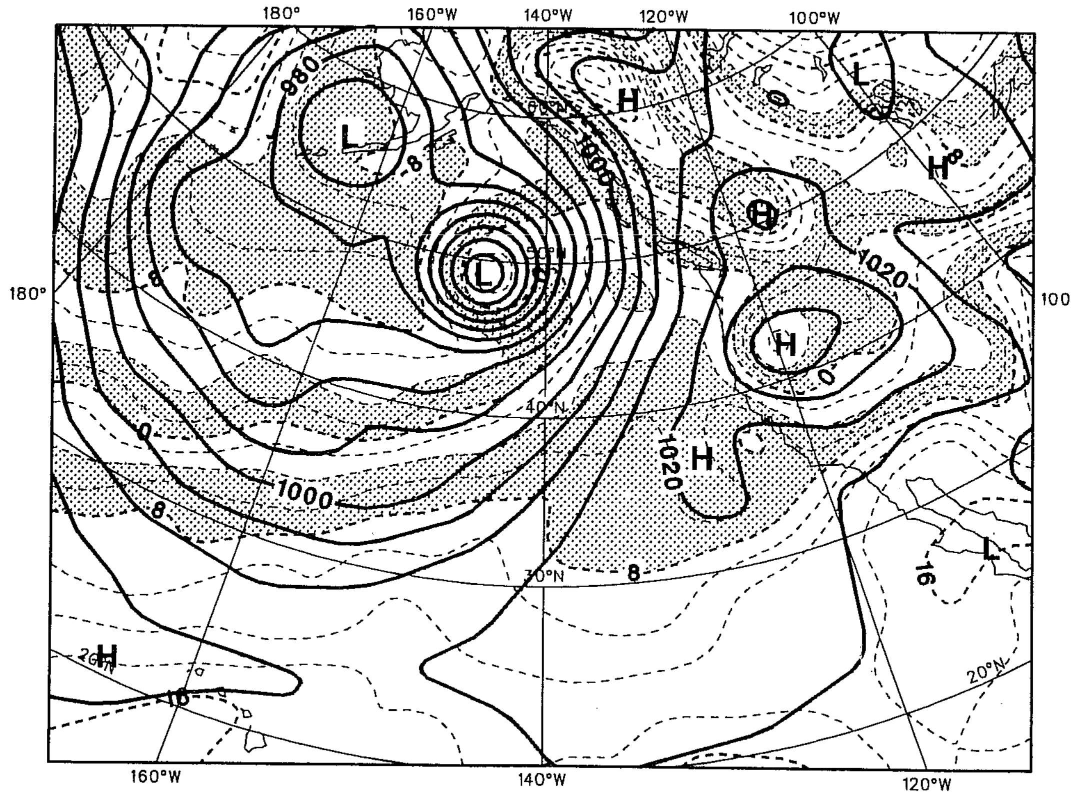


Fig. 6 As fig. 6, but for 48h forecasts from 1 February 1987, 12 UTC, verifying on 3 February 1987.

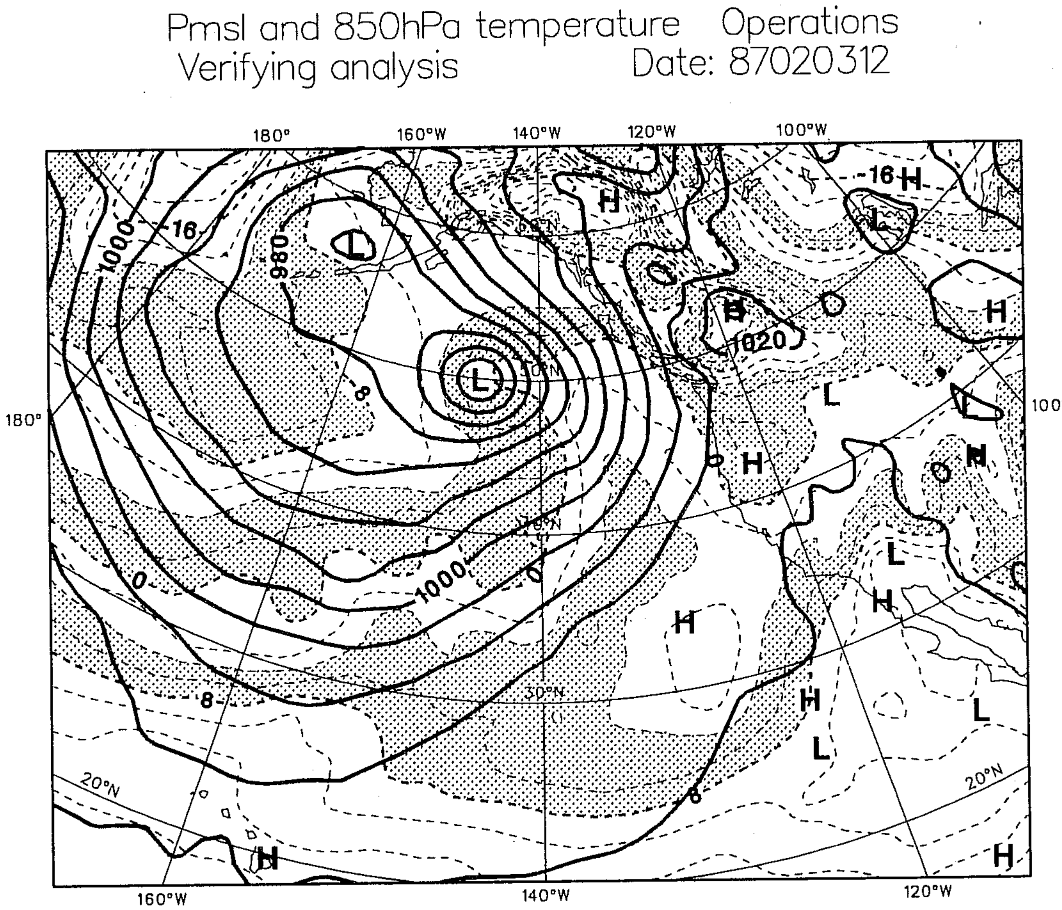
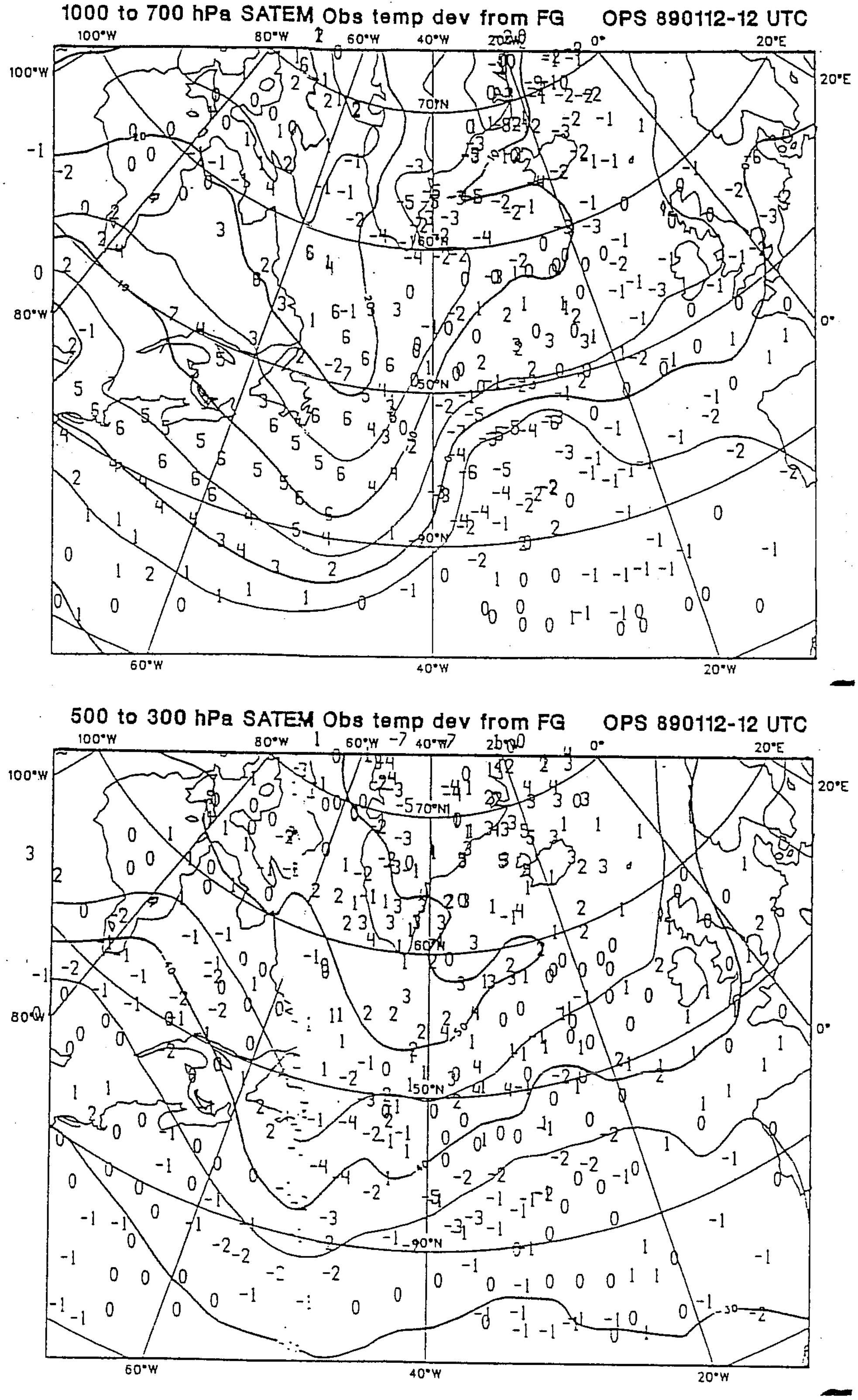


Fig. 7 Verifying analysis (OPS JUL88) for 3 February 1987, 12 UTC (verifying the forecasts of fig. 6).

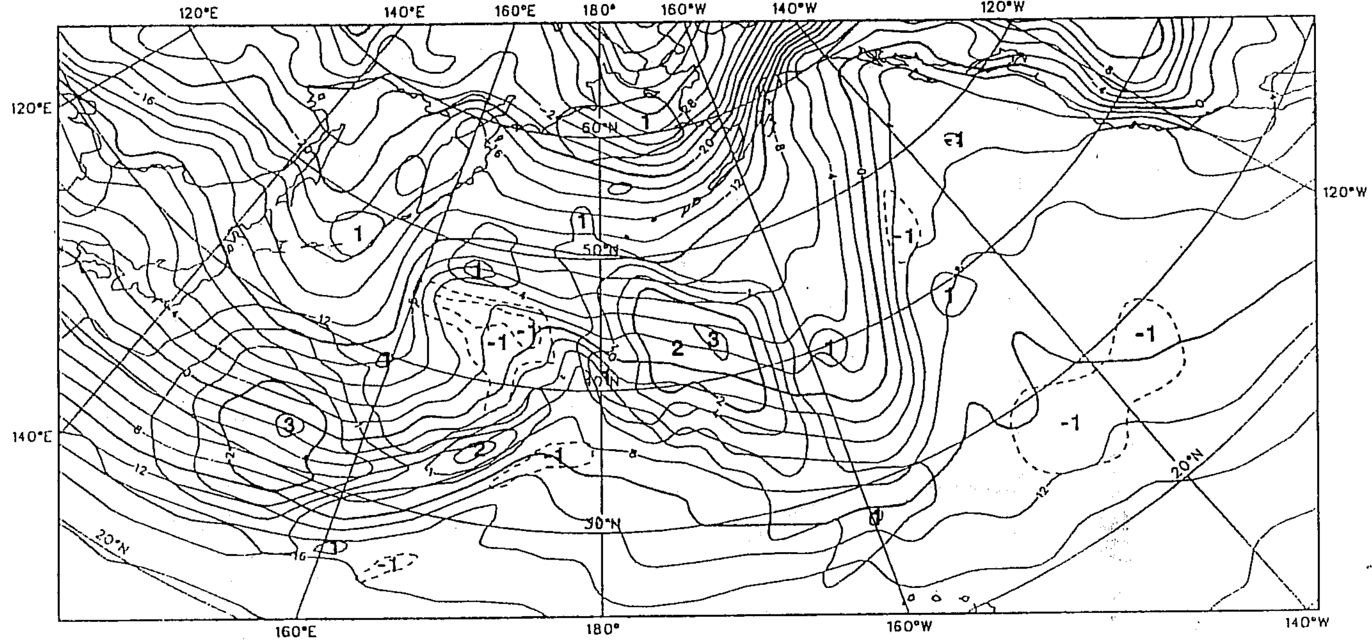


1000 to 700 hPa SATEM Obs temp dev from FG OPS 890112-12 UTC

500 to 300 hPa SATEM Obs temp dev from FG OPS 890112-12 UTC

Fig. 8 SATEM mean virtual temperature deviations from the first-guess, in degrees, for the North Atlantic, on 1 February 1989, 12 UTC. The first-guess is contoured with an interval of 5 degrees. Top panel - 1000/700hPa layer, bottom panel - 500/300hPa layer.

1000 to 700 hPa AN Layer mean temperature OPS − I78 890125−12Z



500 to 300 hPa AN Layer mean temperature OPS − I78 890125−12Z

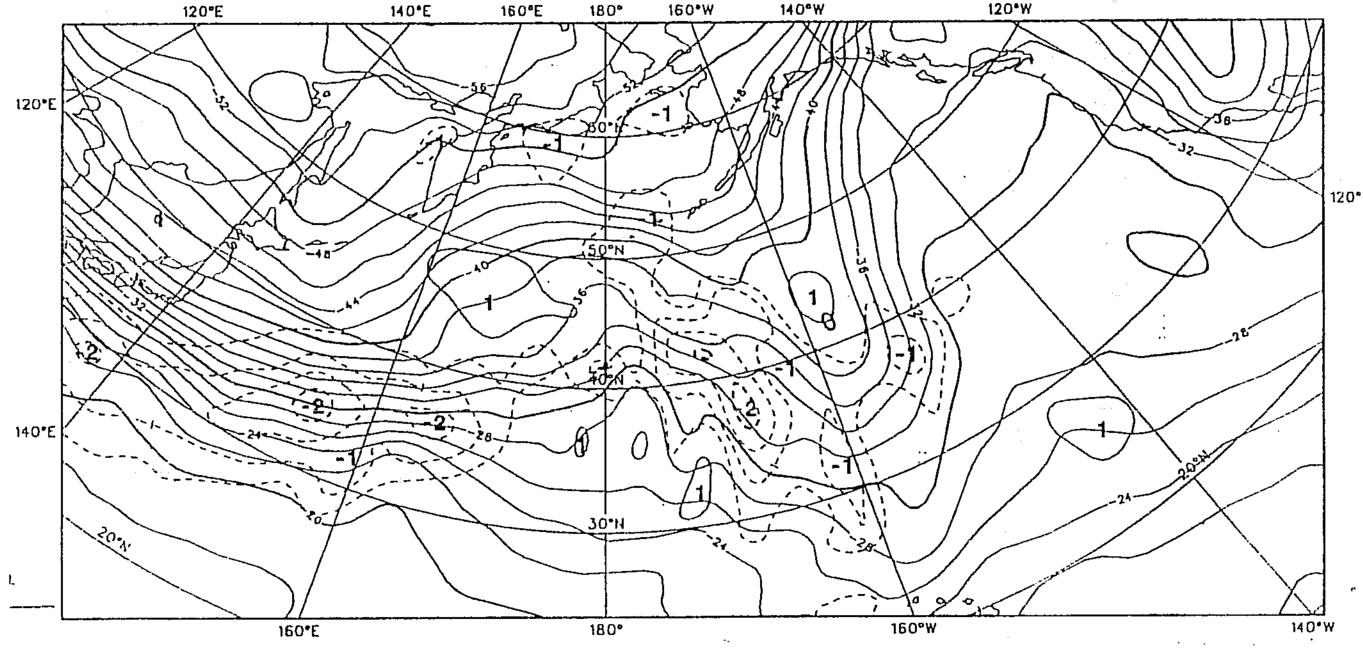


Fig. 9 Mean virtual temperature difference (in degrees) between two analyses with different quality control on SATEMs : OPS JUL88 minus OPS FEB89, the latter with the more stringent quality control. Contour interval: 0.5 degree.
Area and date: North Pacific on 25 January 1989, 12UTC. Also contoured is OPS JUL analysis (contour interval : 2 degrees). Top panel - 1000/700 hPa layer, bottom panel - 500/300 hPa layer.

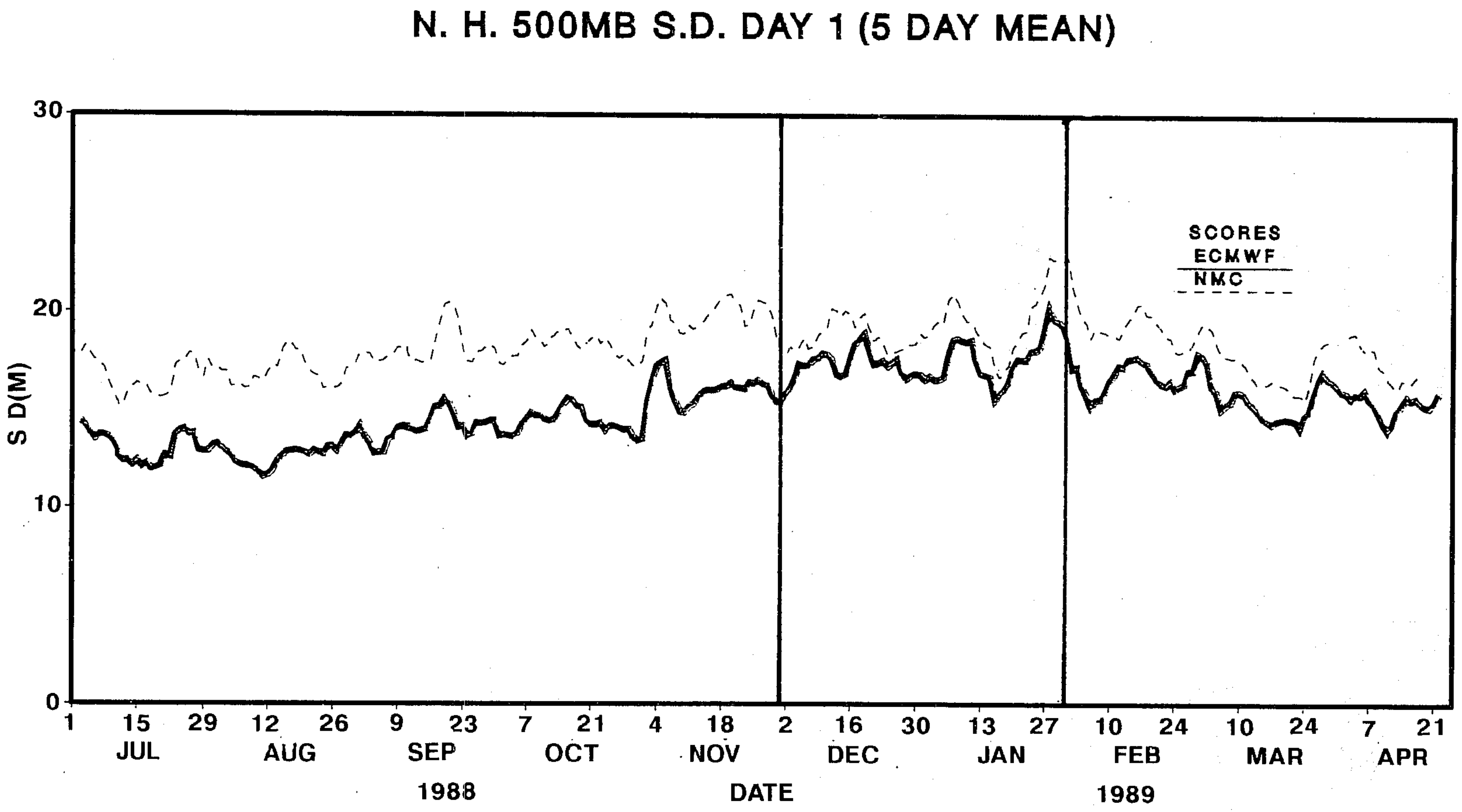


Fig. 10 24h forecast error standard deviations for the ECMWF (full line) and NMC (dashed line) operational systems for a 10-month period from 1 July 1988 to 1 May 1989. Each point of the curves is a 5-day running mean. The variable considered is the 500 hPa geopotential height for the Northern hemisphere (in metres). The two vertical lines correspond to the dates of operational changes : end of November 88 (NMC assimilation changes); end of January 89 (ECMWF changes, mainly changes to SATEM quality control).

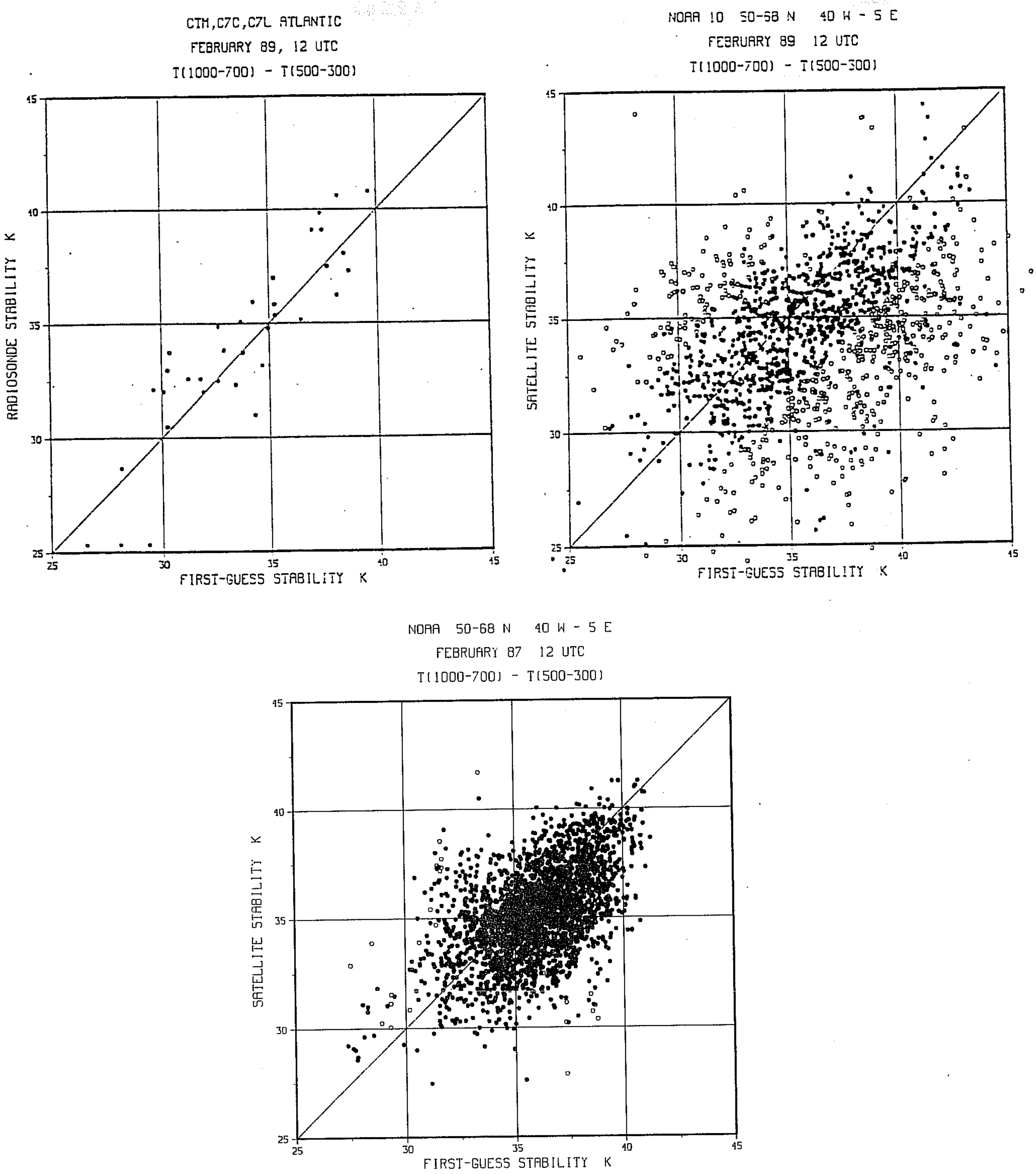
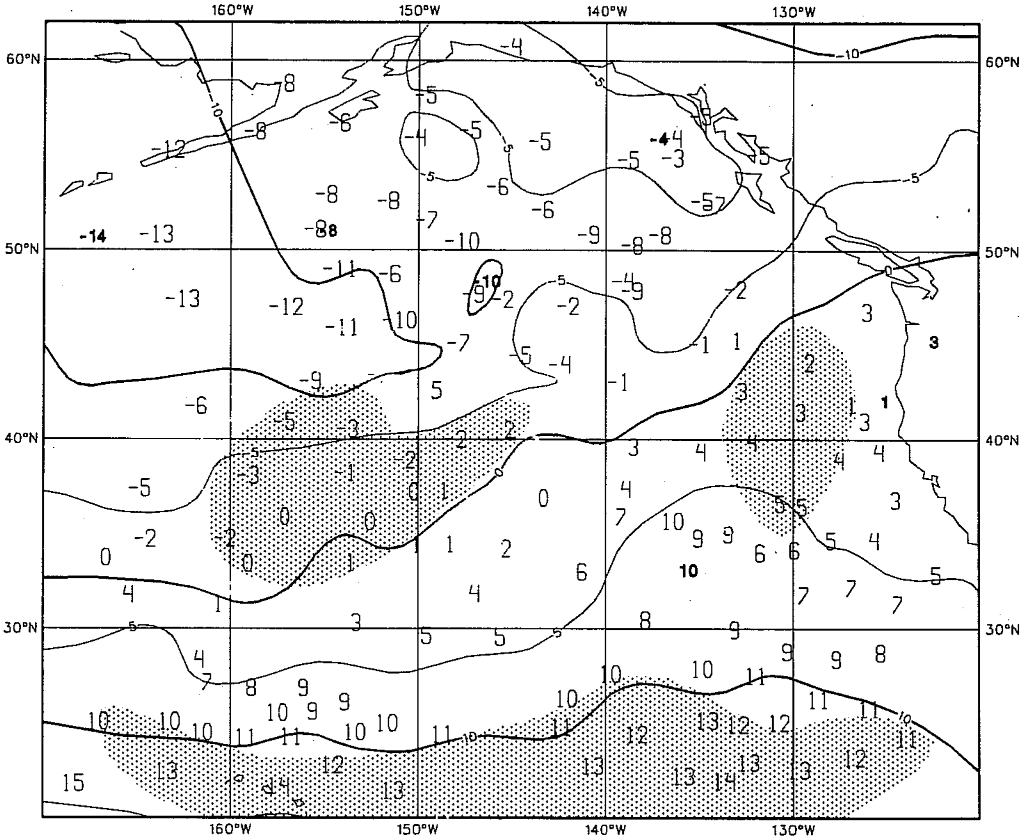


Fig. 11 Stability index scatter diagrams similar to fig. 1. Top left panel is for radiosondes in February 1989 over North Atlantic (three weather ships); top right panel is for NOAA-10 operational TOVS over North Atlantic in February 1989; bottom panel is for 3I soundings over the same area, but in February 1987. Open circles correspond to TOVS data rejected by the analysis.

1000 to 700 hPa TOVS Temp retrieved by NESDIS J75 870204–12 UTC



1000 to 700 hPa TOVS Temp retrieved by 3I HR J32 870204–12 UTC

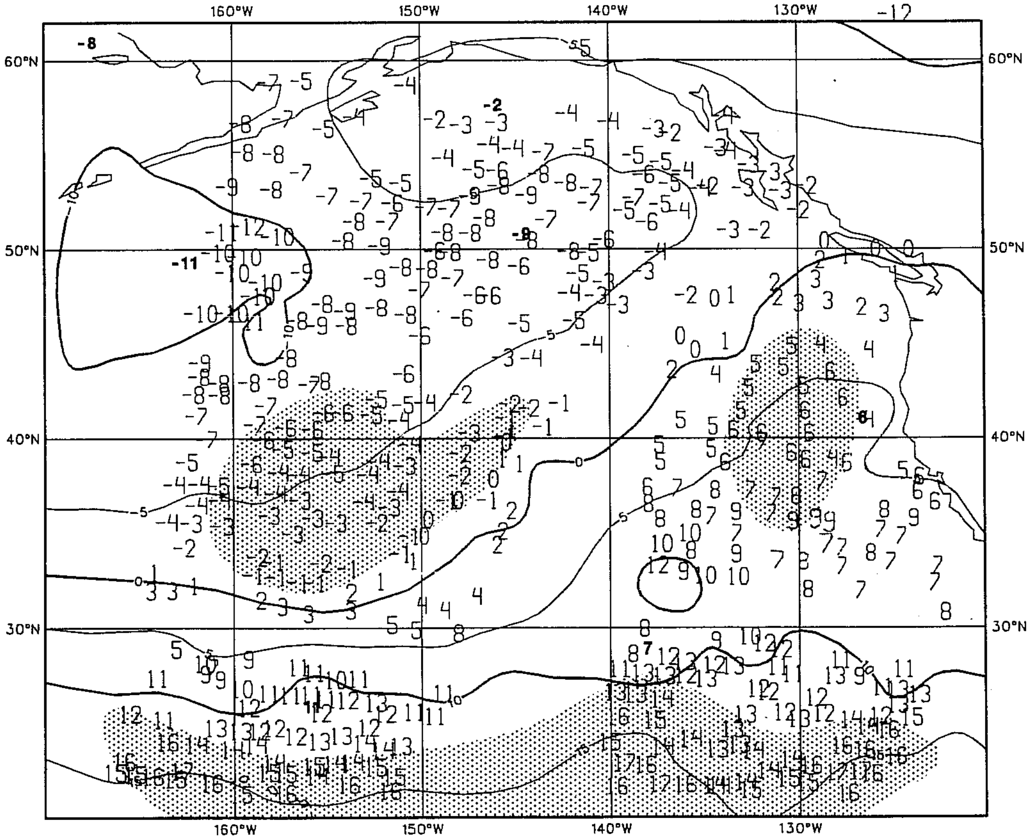
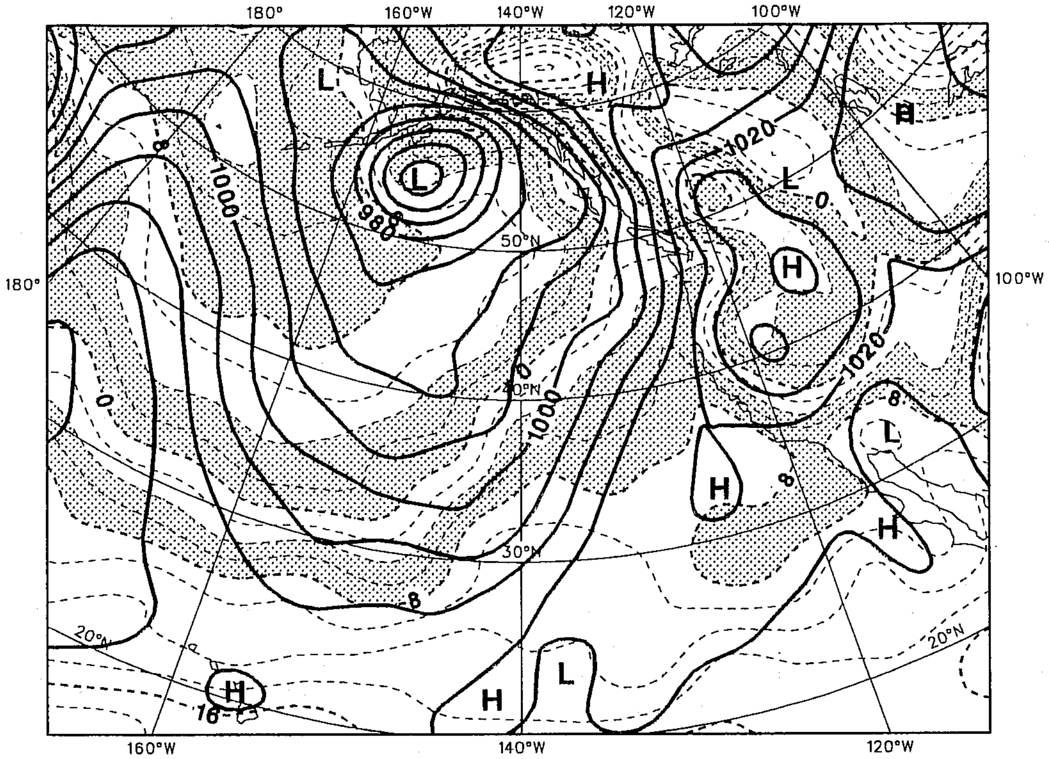
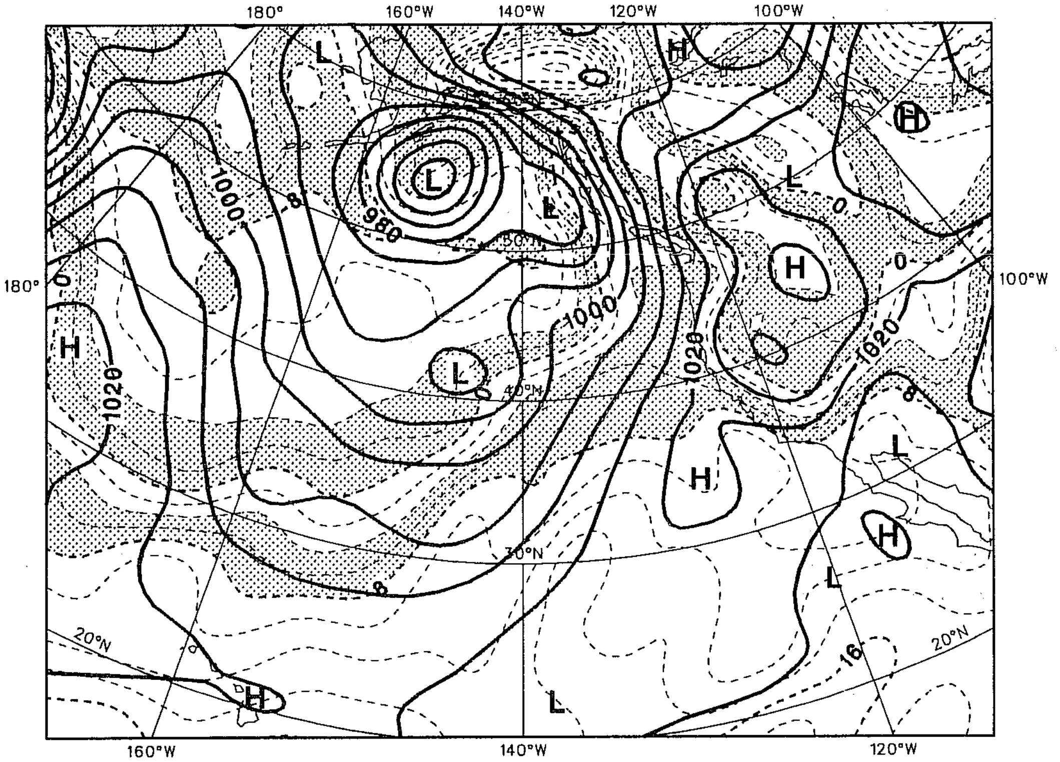


Fig. 12 1000/700 hPa mean virtual temperature retrieved by the NESDIS operational scheme (top) and the 3I scheme (bottom) on 4 February 1987, 12 UTC. The contouring is produced by a simple Cressman analysis.



Pmsl and 850hPa temperature 3I HR exp IBA
Analysis Date: 87020412



Pmsl and 850hPa temperature NoSATEM
Analysis Date: 87020412

Fig. 13 MSL pressure and 850 hPa temperature analysis for 4 February 1987, 12 UTC. Top : 3I assimilation; bottom : No-Satem assimilation.

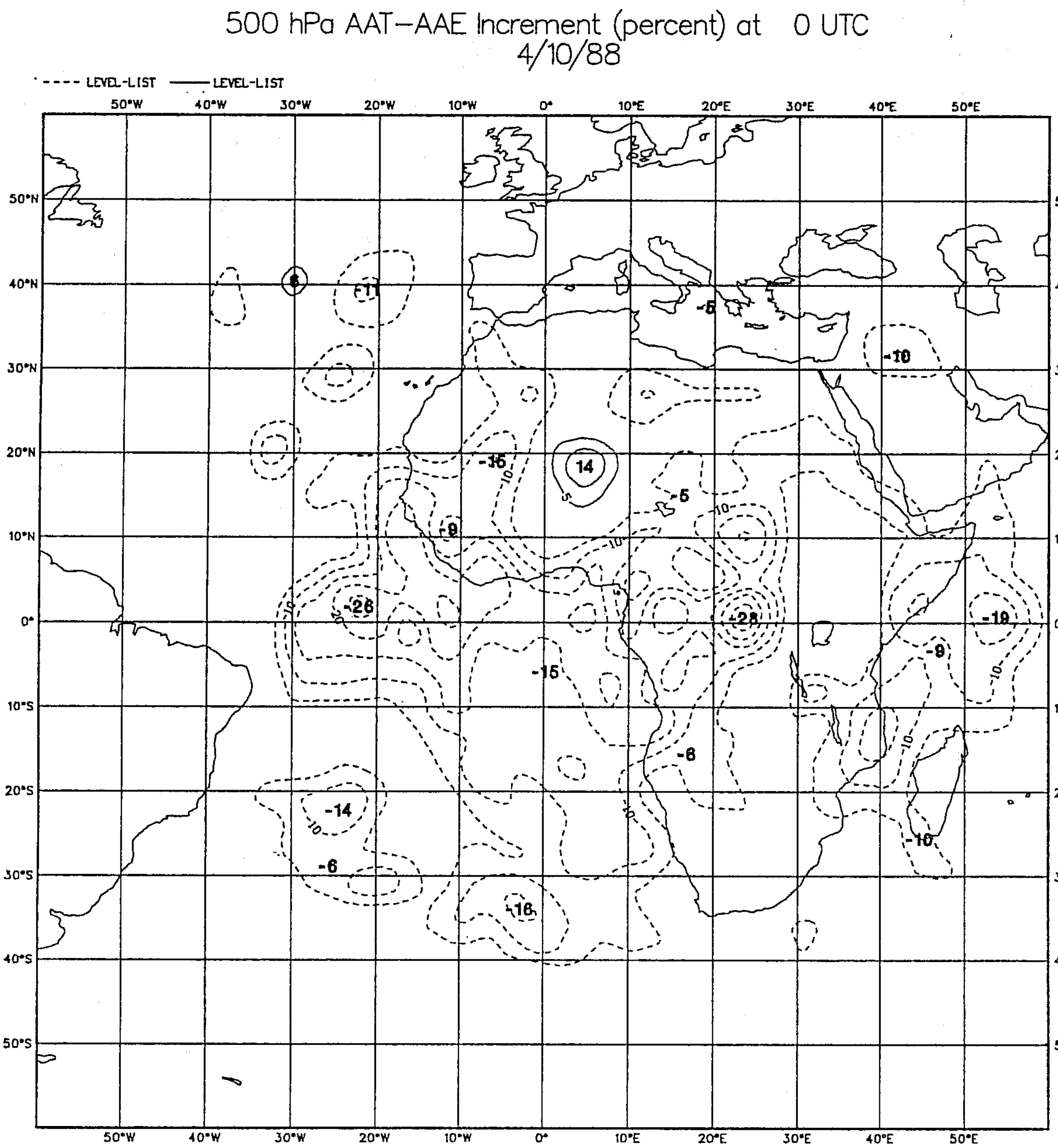


Fig. 14 500 hPa relative humidity analysis difference map for 4 October 1988, 00 UTC, between an assimilation using the Meteosat UTH data, and a control assimilation (without UTH data).

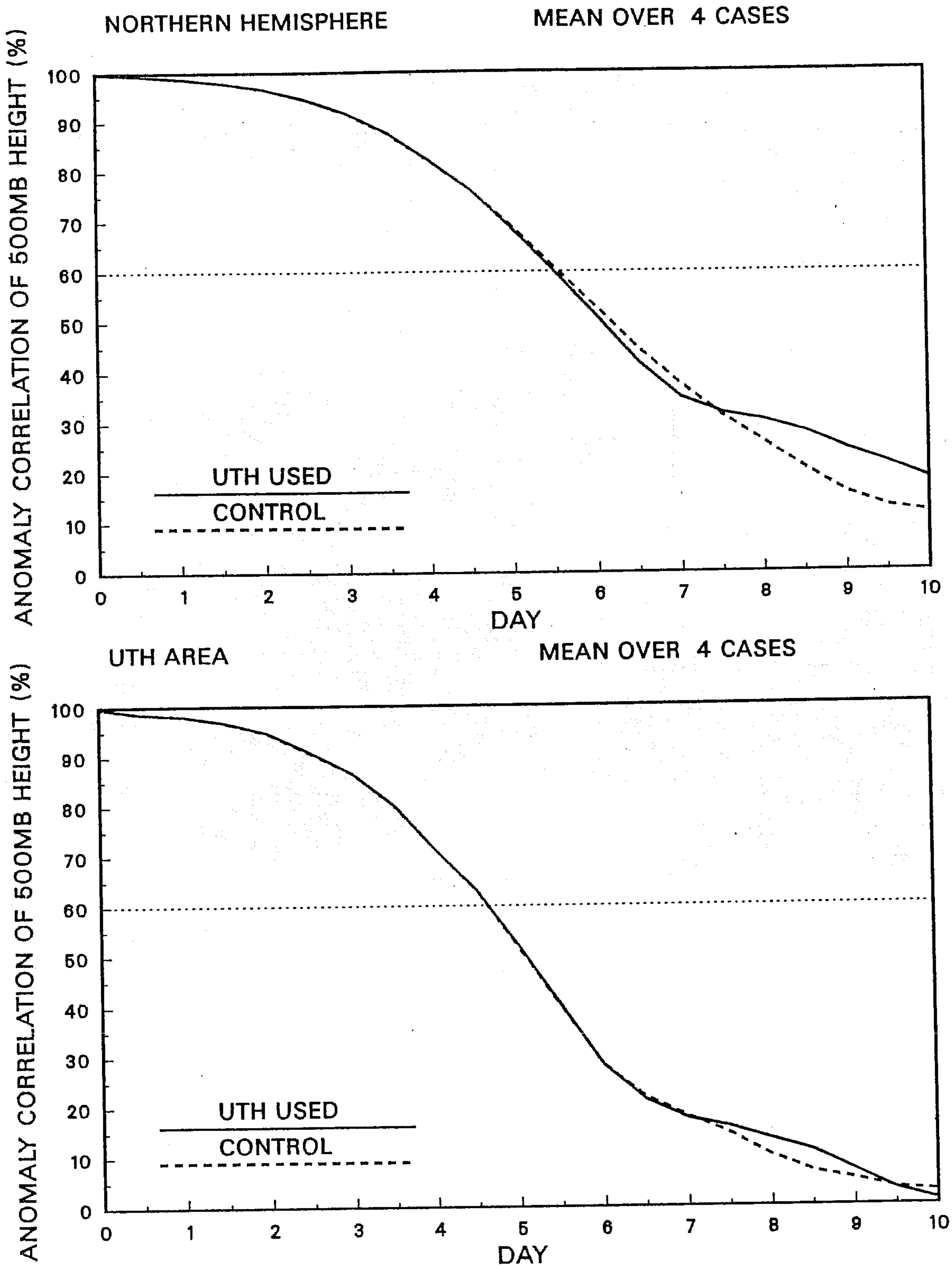


Fig. 15 Anomaly correlation forecast scores accumulated for 4 cases from October 1988, comparing assimilations with and without UTH data. Top: Northern hemisphere; bottom: "UTH area" (55N-55S; 55W-55E).

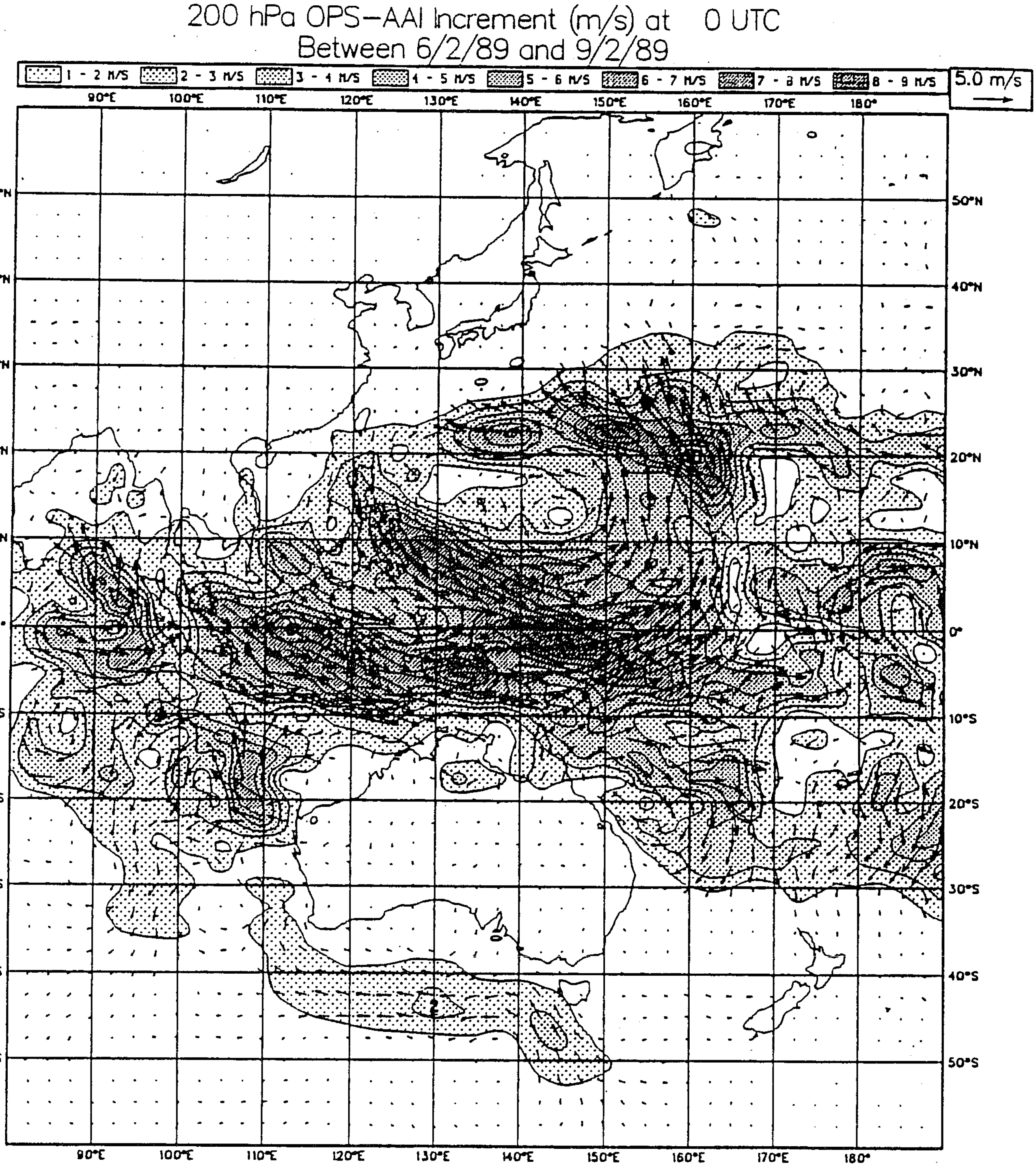


Fig. 16 200 hPa wind analysis difference maps for 6 February 1989, OOUTC, between the operational assimilation run without any cloud wind.

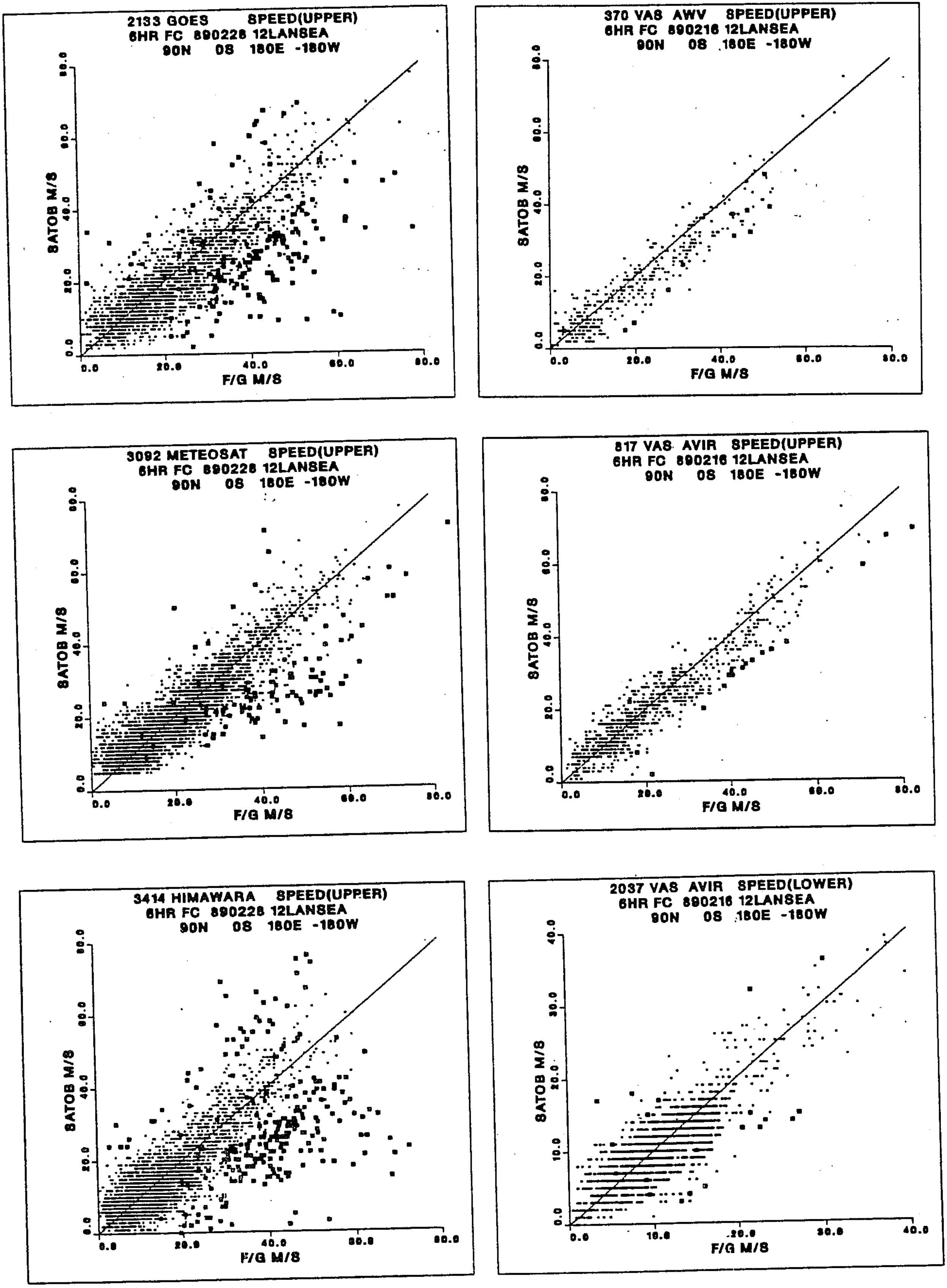


Fig. 17 Scatter diagrams comparing the firstguess wind speed (horizontal axis) with cloud wind speeds (vertical axis). Leftmost panels - operational cloud winds (GOES, Meteosat, Himawari); rightmost panels - experimental cloud winds produced by the Wisconsin University (Water vapour); Infra-red upper levels, infra-red lower levels). Dark squares correspond to the cloud winds rejected by the analyses. The period is February 1989.