USE OF SATELLITE SOUNDINGS IN GLOBAL MODELLING

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1. INTRODUCTION

During the seventies Meteorological Satellites began to provide the NWP community with vertical temperature and humidity profiles. In 1979 the 'TIROS Operational Vertical Sounder' (TOVS) onboard the NOAA series of polar satellites became available. The greatest impact of satellite data has been demonstrated in the Southern Hemisphere (Kelly et al., 1978; Bengtsson, 1985; and Kashiwagi, 1987). In the Northern Hemisphere the forecast impact is less evident and dependent on both the accuracy of the data assimilation system and the synoptic situation. With early versions of the ECMWF system the impact was generally neutral or positive (Kelly and Pailleux, 1988) and as improvements were added to both the analysis and the forecast model the impact on some occasions became slightly negative (Andersson et al., 1989). Strong quality control is now applied to the TOVS data before they enter the analysis to overcome this problem (Kelly et al., 1989). It is now important that the interface between the satellite radiances and the data assimilation be examined to extract the true information content. It is also clear that more accurate satellite instruments will be required if improvements are to be found in NWP.

2. SATELLITE TEMPERATURE AND HUMIDITY SOUNDINGS

2.1 Instruments

Infrared instruments have evolved from the medium spectral and low spatial resolution interferometer and grating spectrometer flown on the Nimbus-3 satellite in 1969 to the high spatial and low spectral resolution filter radiometers currently flying on the operational polar orbiting (NOAA) and geostationary (GOES) satellites. The microwave radiometers utilized have been of the conventional Dicke design. The evolution of the infrared sounding instruments has been driven by the need for high spatial resolution to probe the clear air interstices of the earth's broken cloud cover. Microwave soundings, which penetrate clouds, were initially much larger and heavier and consumed more power than infrared radiometers when compared with infrared sounders on a per channel per unit field-of-view basis. Advances in microwave radiometer technology have permitted the number of spectral channels to be increased, the field-of-view reduced, and the signal-to-noise ratio (SNR) to be improved without a corresponding increase in the weight, volume, and power requirements.

The current satellite sounding capability is represented by the 27 spectral channel system of infrared and microwave instruments called the TIROS Operational Vertical Sounder

(TOVS) flying aboard NOAA polar orbiting satellites, the seven channel Special Sensor Microwave Temperature (SSM/T) sounder aboard the U.S. Air Force's polar orbiting Defense Meteorological Satellite (DMSP), and the 12 spectral channel infrared VISSR Atmospheric Sounder (VAS) aboard the U.S. Geostationary Operational Environment Satellite (GOES). These three currently operational sounding systems are quite different in their capabilities. The polar orbiting NOAA/TOVS (Fig. 1(a)) has higher spatial resolution than its SSM/T counterpart aboard the DMSP Fig. 1(b) (22-km in the IR and 110-km in the MW versus 175-km in the MW for SSM/T). The temporal resolution is limited to 12 hours by the polar orbit of each satellite (higher temporal coverage is achieved by assimilating data from the combination of satellites). On the other hand, the VAS possesses a very high spatial (8-km) and temporal (typically one hour) resolution, but its data are geographically limited to that portion of the earth's area (typically 20% of the earth's area) in view of the GOES. The vertical resolution of each system is also different as shown by the temperature profile weighting functions (discussed in the next section) for each spectral channel (Fig. 2).

2.2 Radiance processing

The first problem is to remove the effect of cloud on the satellite measurements, principally on the infrared channels. However, liquid water and rain affect certain microwave channels. The current NESDIS operational method produces so-called "clear" and "cloud-cleared" radiances (McMillin and Dean, 1982), however, cloud detection and cloud-clearing processes still are a major source of error. Some retrieval methods limit themselves to the detection of cloud and only use cloud-free channels (Smith et al., 1985; Chedin, 1988; McMillin, 1989). Other methods attempt to retrieve temperature and humidity profiles simultaneously (e.g. Susskind et al., 1984; Smith et al., 1987; Eyre, 1989).

2.3 Radiative transfer equation

The physical principal governing the temperature profile measurements is the same for all of these sensors. The temperature structure of the atmosphere is inferred from measurements of the earth's radiance in an absorption band due to gaseous constituents whose concentration is uniform. (The 4.3 µm CO_2, 15 µm CO_2, and 5 mm O_2 bands are used for the temperature profile sensing. Fig. 2 shows the TOVS sounding channels characteristics). The instruments are designed to measure the radiance of different frequencies or wavelengths within one or more of these bands. By varying the frequency, one varies the level of the atmosphere from which the measured radiation originates. For example, absorption is most intense at the centre of the band; consequently, this radiation emanates from only the very top of the atmosphere because of the strong attenuation at lower levels. On the other hand, radiation arising from the lowest regions of the

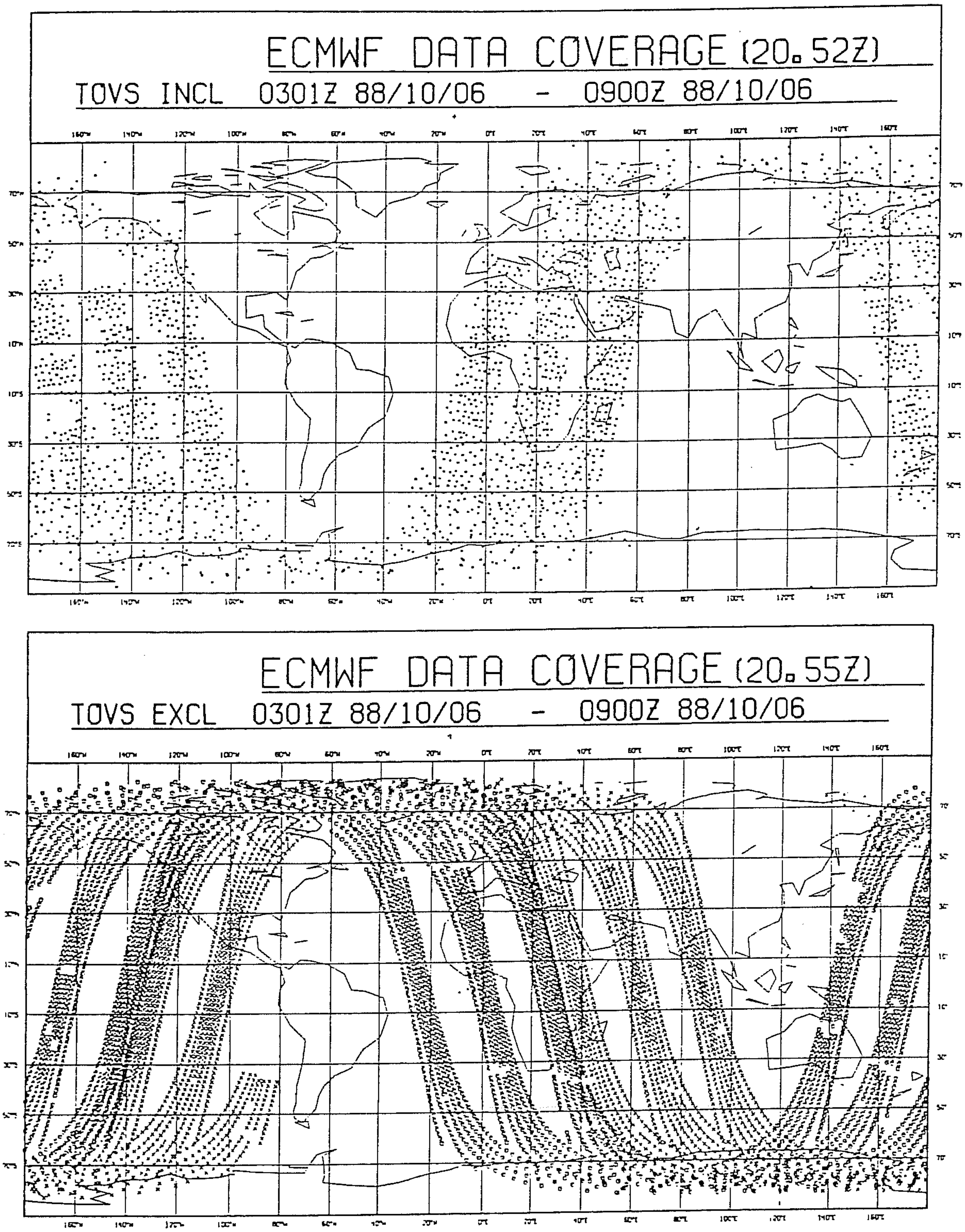

Fig. 1 Data coverage received at ECMWF for a typical six hour period.

(a) NOAA-10 data used in an active mode in the ECMWF assimilation.

(b) DMSP-8 and 9 data used in a passive mode in the ECMWF assimilation.

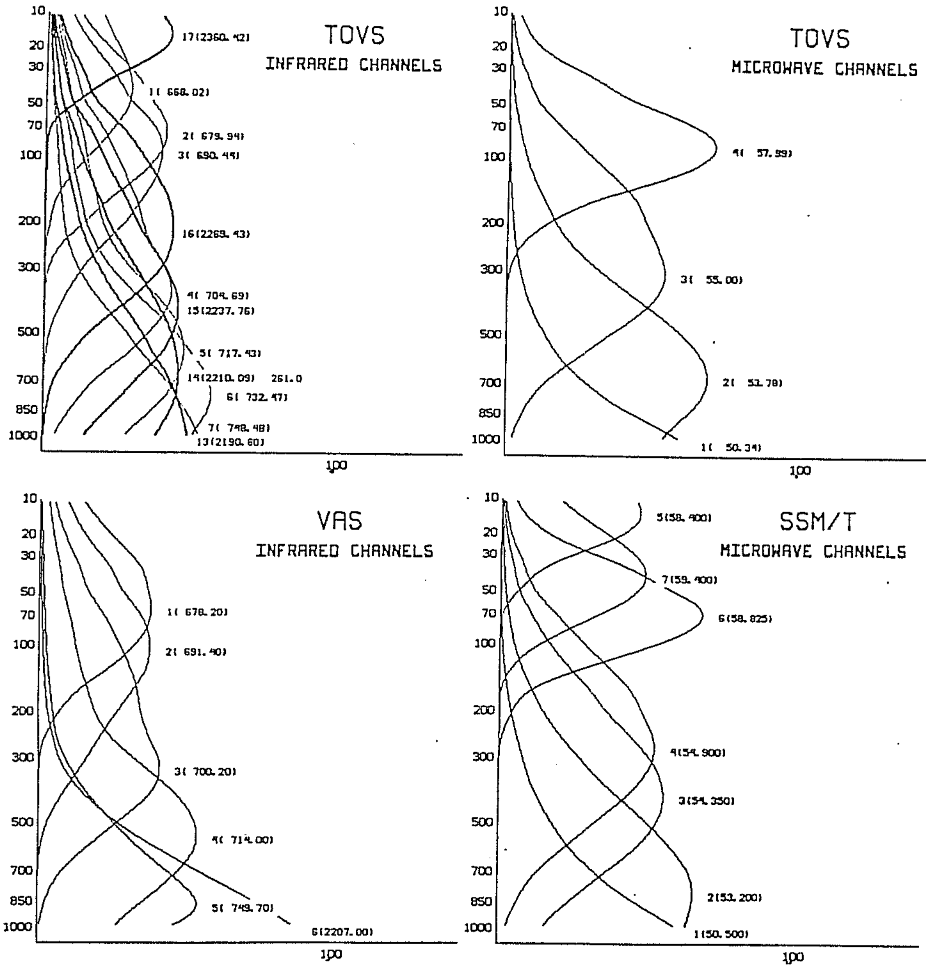

Fig. 2 Standard atmosphere dry component Planck radiance weighting functions (dτ/dlnp) for infrared and microwave channels of TOVS, VAS and the SSM/T. The channel central frequencies (cm^{-1}) for infrared and GHz for microwave) are given in parentheses.

atmosphere can be measured at those frequencies far from the band centre which are characterized by little absorption. Radiation received from intermediate levels is measured at frequencies associated with moderate absorption.

The outgoing radiance from the earth measured by any channel of TOVS is related to the atmosphere's temperature and absorbing gas structure by the radiative transfer equation.

$$R(\nu) = B_\nu[T(p_o)]\,\tau_\nu(p_o) - \int_o^{p_o} B_\nu[T(p)]\,\frac{d\tau_\nu(p)}{dx(p)}\,dx(p), \qquad (1)$$

where $R(\nu)$ is the outgoing spectral radiance within a spectral channel centred at frequency ν, B_ν the Planck radiance for temperature $T(p)$ at pressure p, $\tau_\nu(p)$ the transmittance of the atmosphere above pressure p, and $x(p)$ is an arbitrary function of pressure.

In particular, the radiation received at frequency ν is the sum of all the radiance contributions from the earth's surface and from all individual levels in the atmosphere.

$$R(\nu_j) = \sum_{i=1}^{N} B[\nu_j, T(p_i)]\,w(\nu_j, p_i) \qquad (2)$$

with

$$w(\nu_j, p_i) = \varepsilon(\nu_j, p_i)\,\tau(\nu_j, \sigma_{P_i})$$

In (2) $B[\nu_j, T(p_i)]$ is the Planck radiance source for the i^{th} pressure level (p_i), having a temperature T, $\varepsilon(\nu_j, p_i)$ is the emissivity of the emitting medium at the pressure p_j for the radiation of frequency ν_j, $\tau(\sigma_{P_i})$ is the transmissivity of the atmosphere above the i^{th} level.

B(ν,T) is explicitly

$$B(\nu, T) = C_1\nu^3/[\exp(C_2\nu/T)-1] \qquad (3)$$

where C_1 and C_2 are the constants of the Planck function.

The term on the right of (2) is the sum of the component of radiance arising from the surface and all the radiation components originating in the atmosphere itself. These radiance contributions are weighted by the function $w(v_j, P_i)$, see Fig. 2.

The problem is to determine the temperature of the N levels from radiance observations at say M discrete frequencies. However, because of the vertical width of the weighting functions, there is no unique solution; that is, many different temperature profiles will give rise to the same radiance measurements. Furthermore, the temperature profile solution tends to be unstable in the sense that small radiance measurement errors tend to produce disproportionately large errors of temperature.

Various retrieval methods have been used and a comprehensive review is given by Rodgers (1976). In the past NESDIS used a real time regression method as described by Smith (1976) and (1979). Currently, NESDIS have changed to a library search method to obtain the background profile and follow this with a minimum variance solution (Golberg et al., 1986, 1988; Fleming et al., 1988).

3. OBSERVATION SYSTEM EXPERIMENTS WITH TOVS

At ECMWF, observation system experiments 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:

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

(ii) 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, for example, Durand (1985) 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. The results from this rerun reconfirm the positive impact of SATEMs in the Northern Hemisphere forecasts in this particular period (Kelly and Pailleux, 1988).

3.1 July 87 TOVS OSE

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.

3.2 Developments in the ECMWF assimilation system, July 88

The most important changes made to the forecast model between July 87 and July 88 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 observation 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 (Lönnberg, 1988). The overall assessment was that the OPS JUL88 system performed somewhat better than the OPS JUL87 system.

3.3 Impact of SATEM using July 88 changes

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 3.1. The forecast scores are summarized in Fig. 3. 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. 4 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. 3, show 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. 5. It is clear that the SATEMs have a negative impact after day three in the North Pacific and in 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).

4. QUALITY OF OPERATIONAL SATEMS (1987)

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

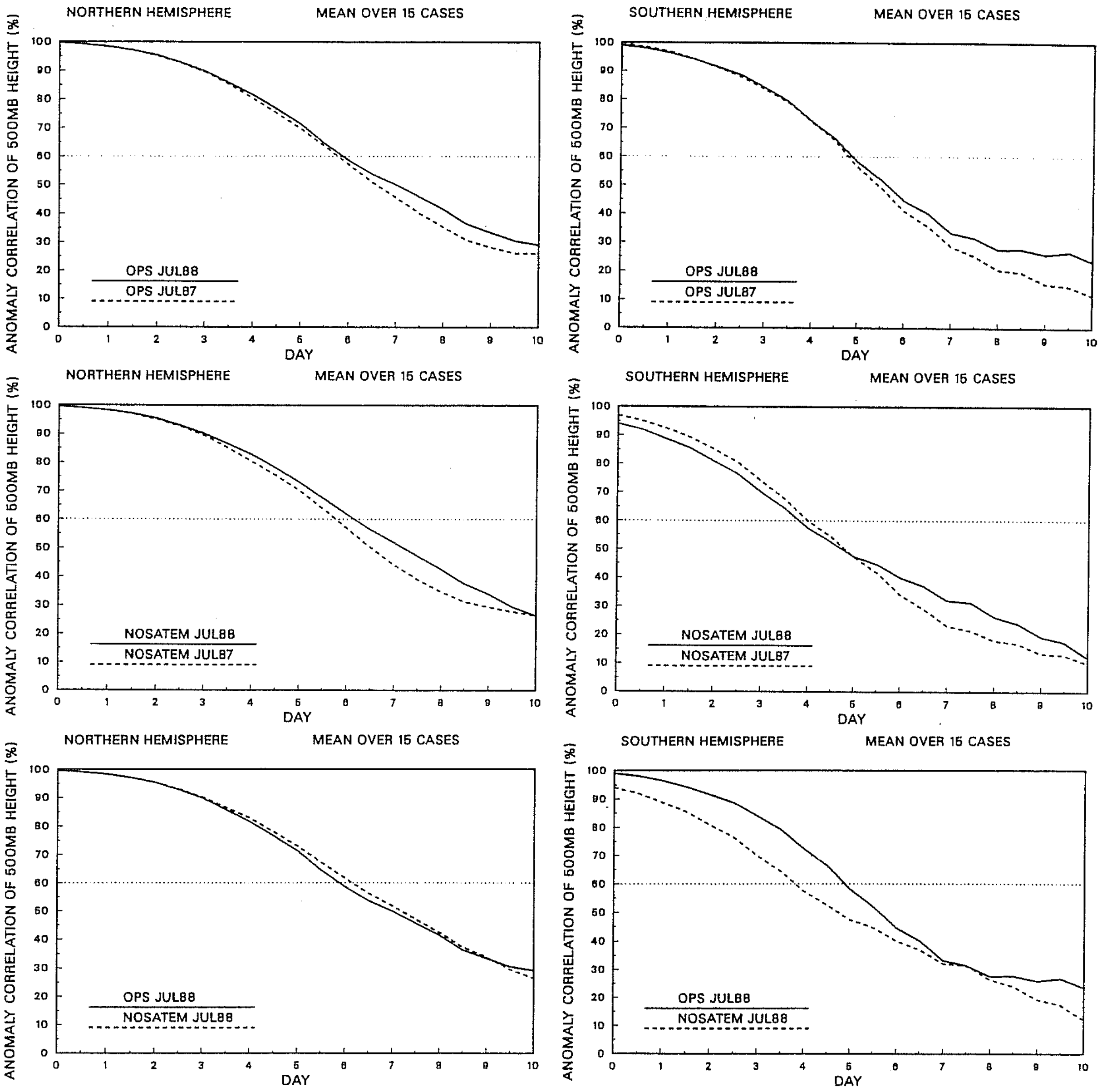

Fig. 3 Anomaly correlation forecast scores accumulated for 15 cases in February 1987, comparing performance of the operational (OPS) and "NO-SATEM" forecasts, with the ECMWF system of July 87 and July 88.

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 JUL 88 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.

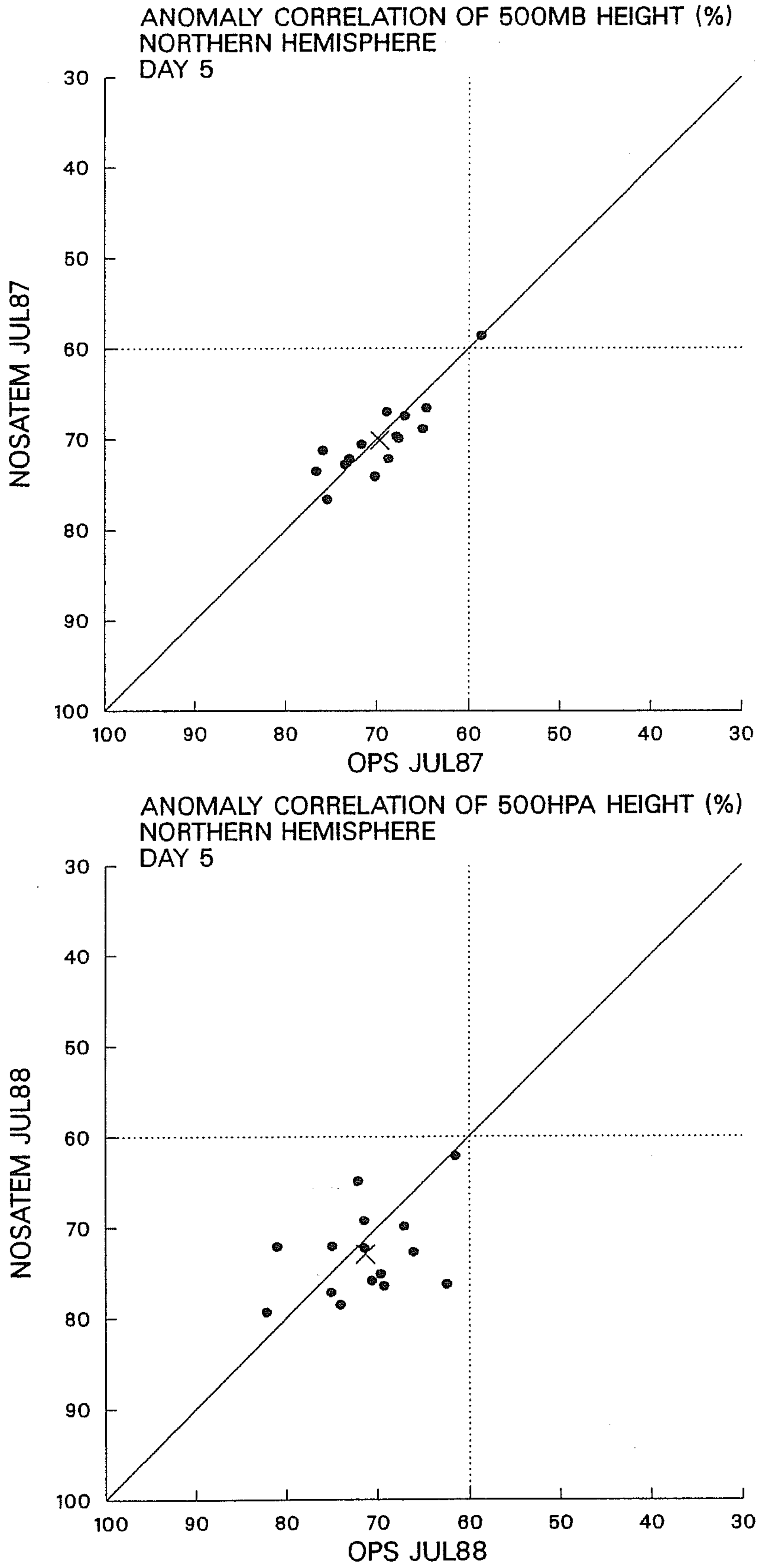

Fig. 4 Scatter diagrams comparing the anomaly correlation of operational forecasts (horizontal axis) and "NO-SATEM" forecasts (vertical axis), for 15 cases in February 1987. Top: with the assimilation version of July 87. Bottom: with the version of July 88 (note the much higher dispersion).

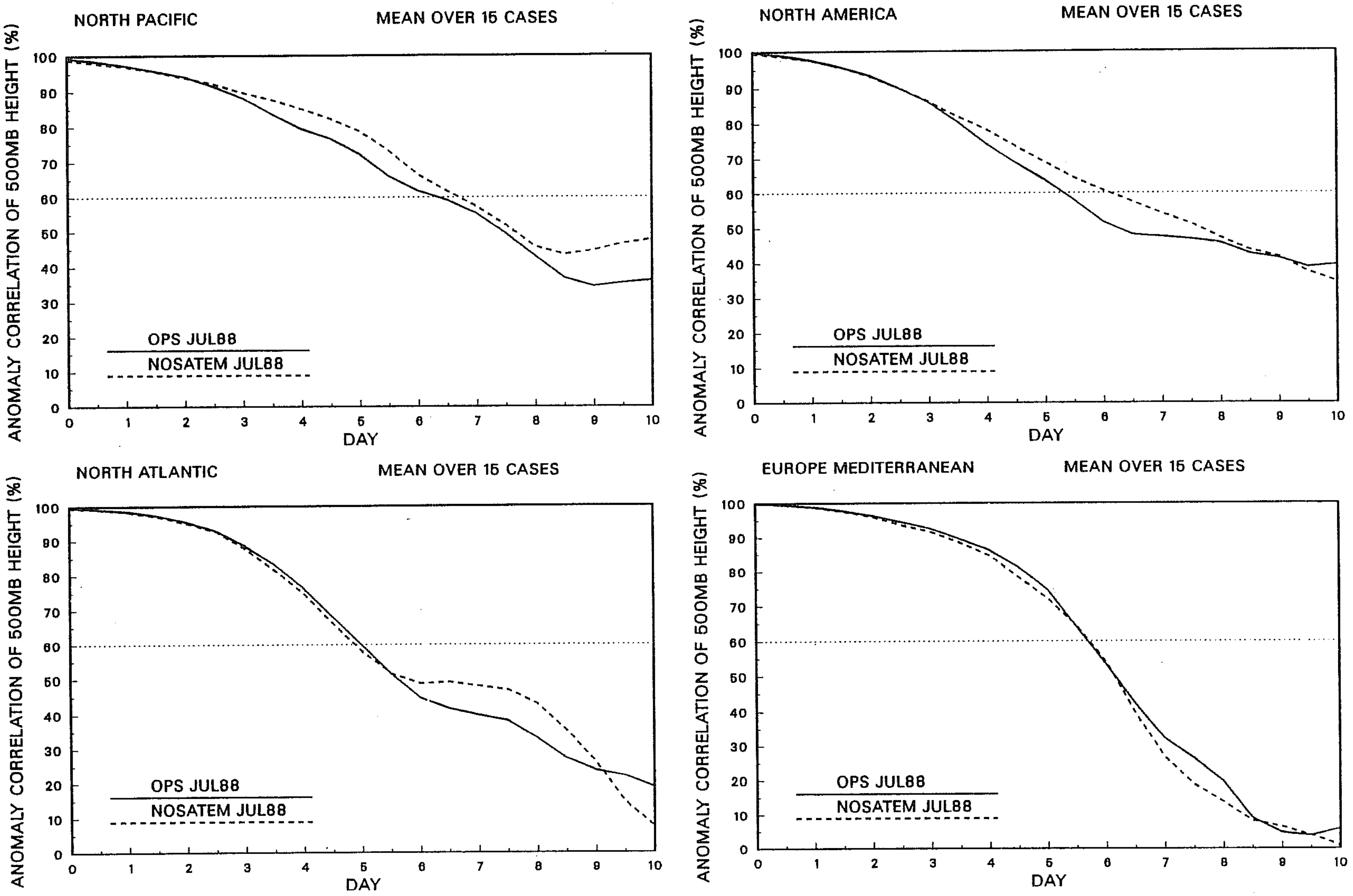

Fig. 5 Anomaly correlation forecast scores accumulated for 15 cases in February 1987, comparing operational and "NO-SATEM" assimilations (July 1988 versions) for four different areas of the Northern Hemisphere: North Pacific, North America, North Atlantic and Europe/Mediterranean.

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. 6 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.

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).

5. 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.

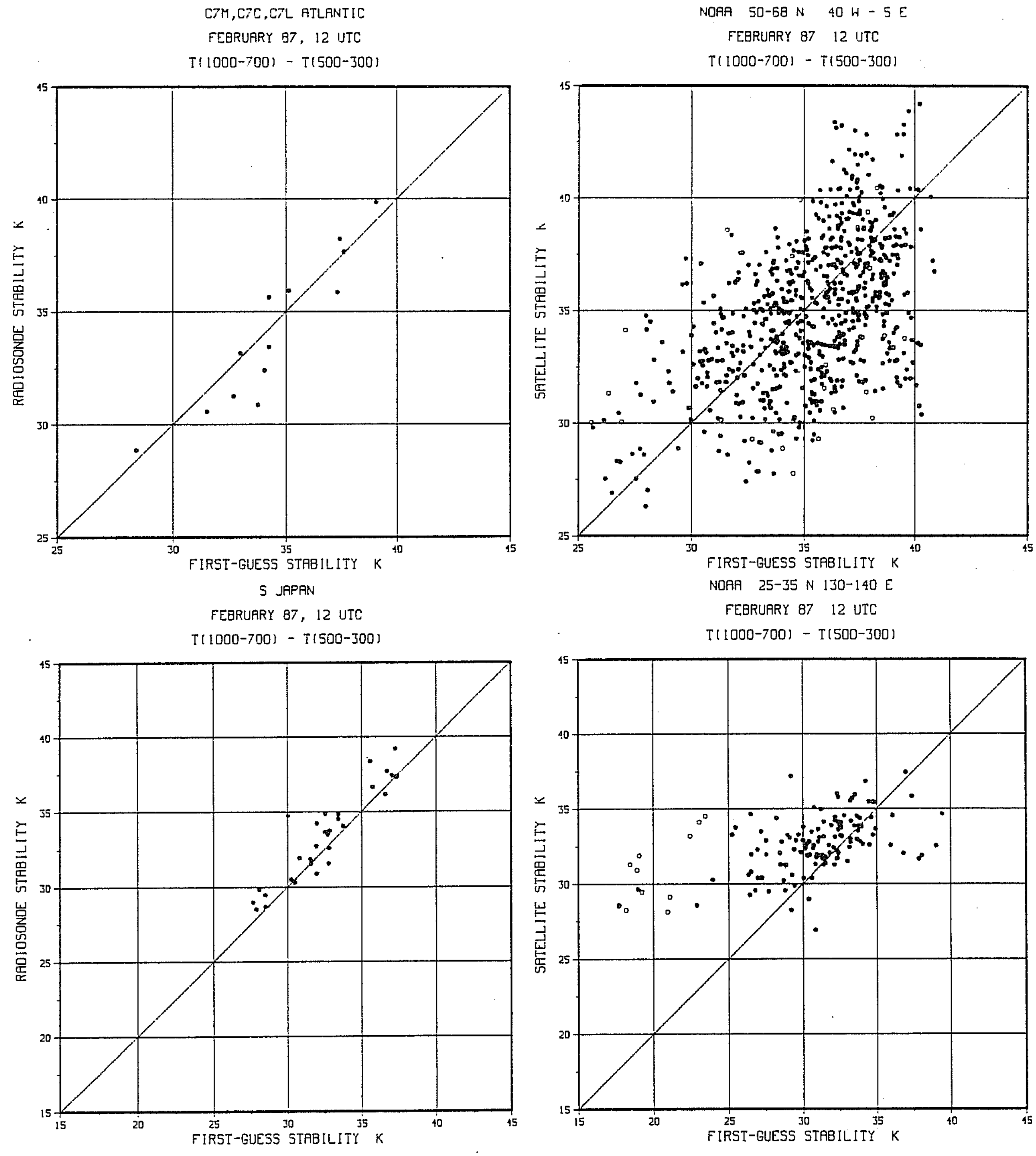

Fig. 6 Scatter diagrams comparing the stability index S = $T_V(1000/700)$ - $T_V(500/300)$ of the first guess (horizontal axis) with either radiosondes or TOVS retrieved soundings (vertical axis), for a two-week period in February 1987.

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.

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. 7 shows the analyses of 1 February 1987, 12 UTC, Fig. 8 the 48-hour forecasts and in Fig. 9 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.

6. 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.

6.1 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

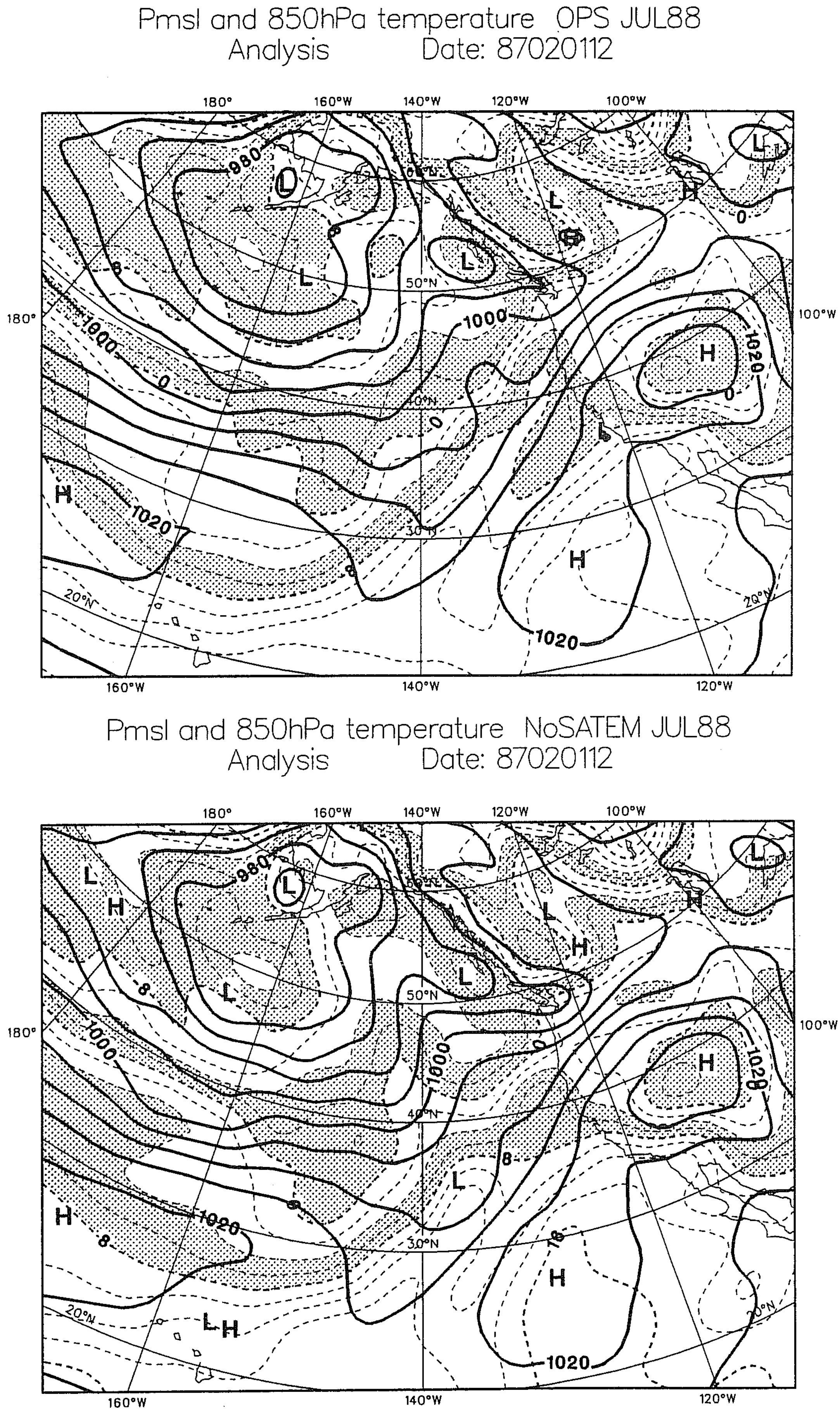

Fig. 7 MSL pressure and 850 hPa temperature analyses for 1 February 1987, 12 UTC. Top: OPS JUL88; Bottom: NO-SATEM JUL88.

Pmsl and 850hPa temperature OPS JUL88
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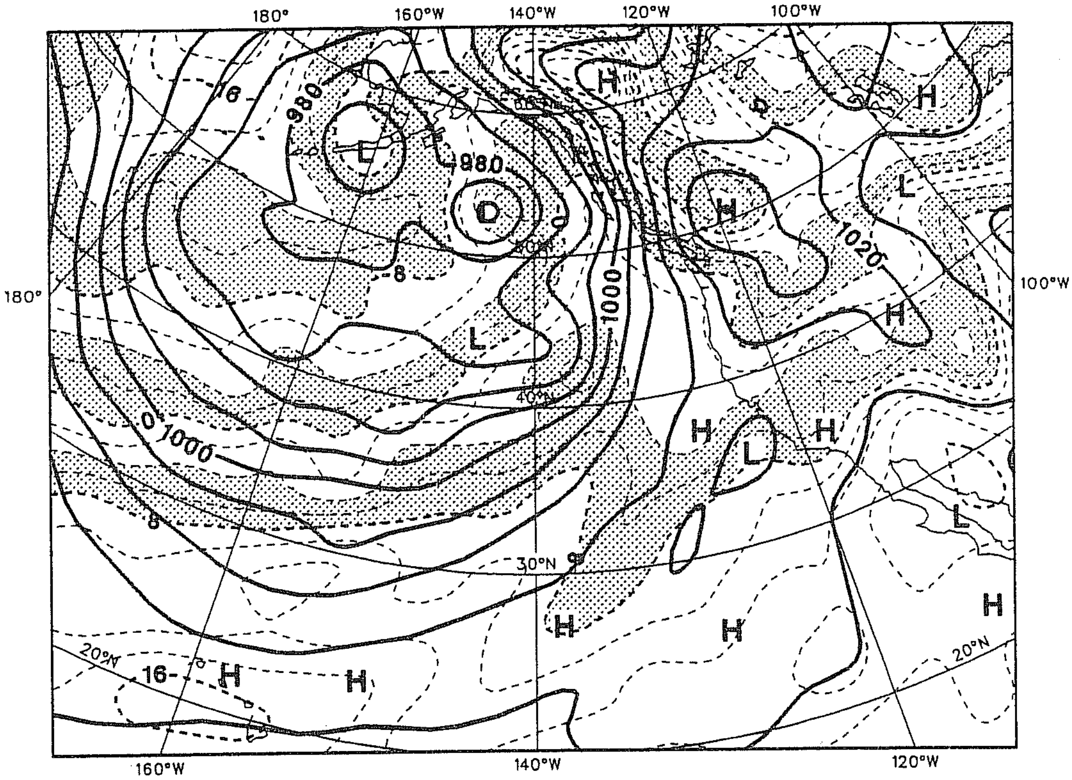

Pmsl and 850hPa temperature NoSATEM JUL88
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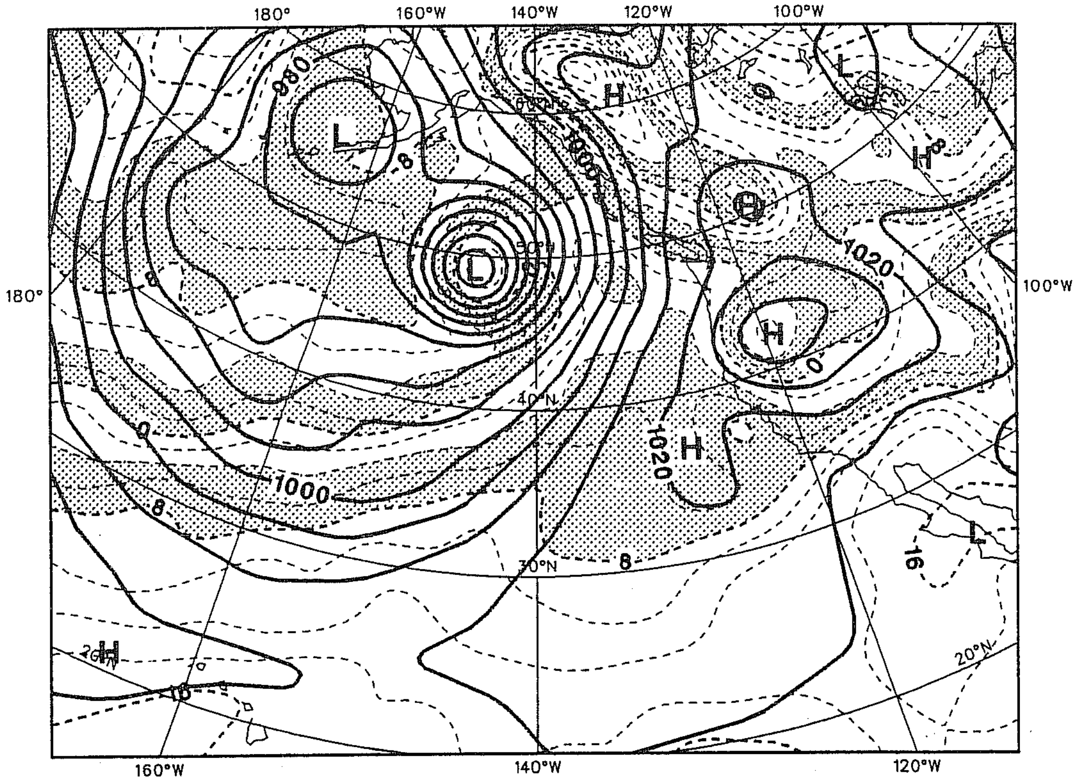


Fig. 8 As Fig. 6, but for 48 h forecasts from 1 February 1987, 12 UTC, verifying on 3 February 1987.

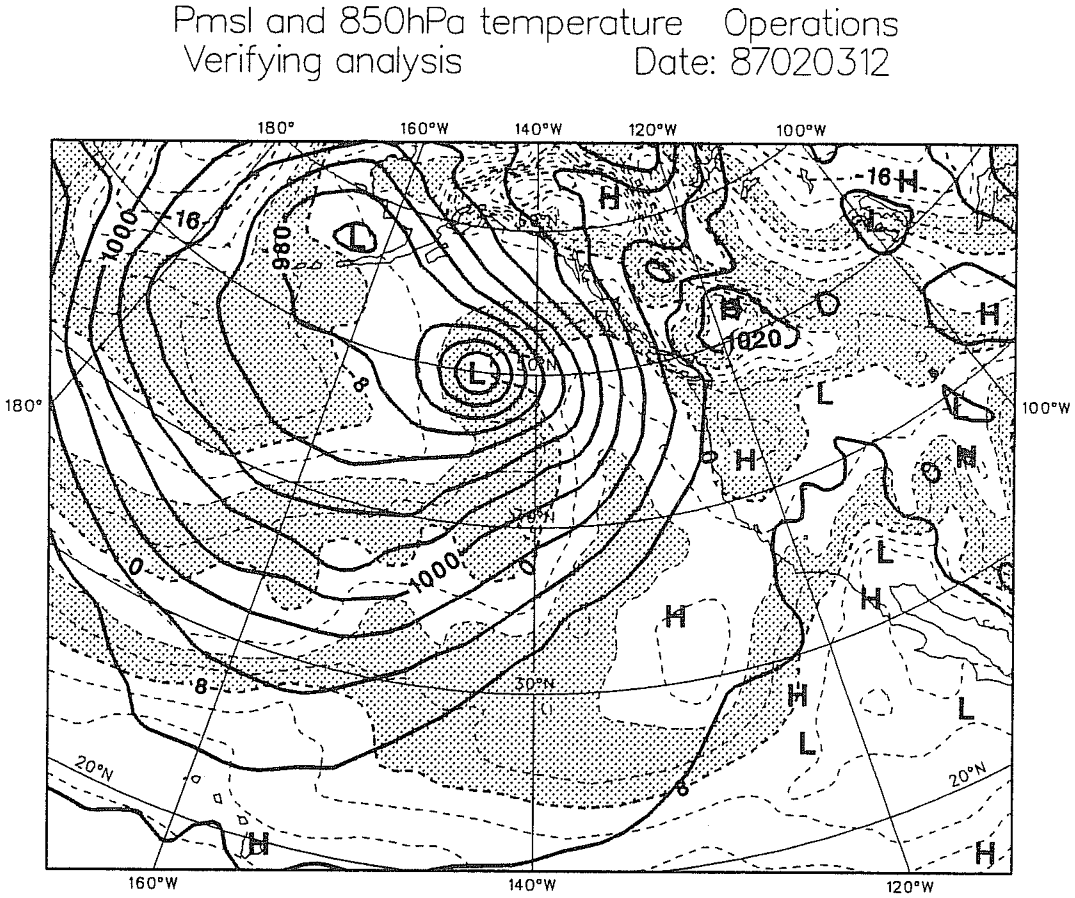


Fig. 9 Verifying analysis (OPS JUL88) for 3 February 1987, 12 UTC (verifying the forecasts of Fig. 6).

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.

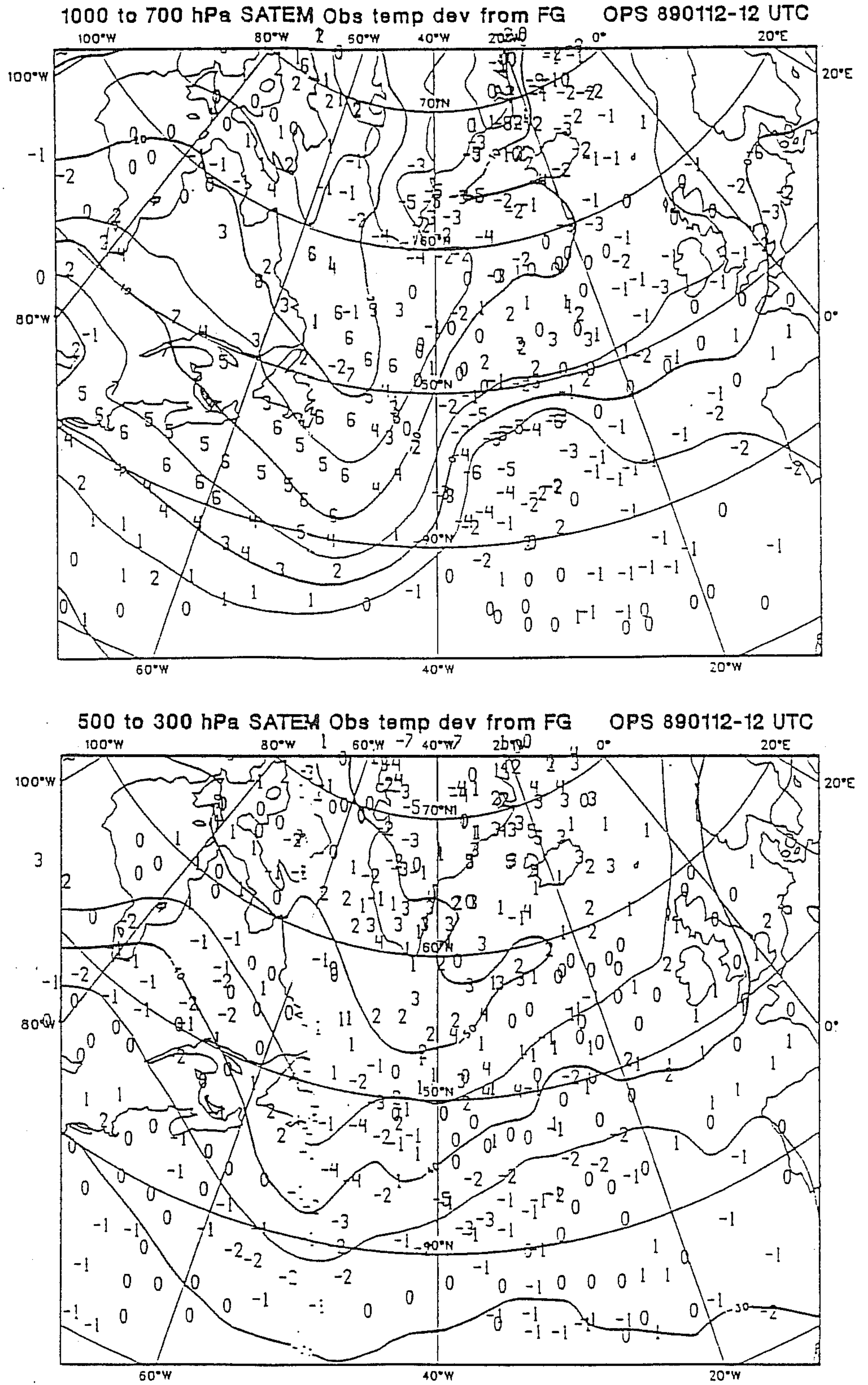
The bias of the satellite data relative to the first guess (OBS-FG) also shows a strong regional dependence, particularly in the lowest layer. The 1000/850 hPa bias has characteristic maxima in the Subtropical highs. It is positive and largest for the cloudy soundings, exceeding 4.0 degrees in the South 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 ($T_{surface} - T_{2m} \geq 0$). Note also in Fig. 10 the tendency to have a compensation in the upper troposphere (500/300 hPa). In the warm sector of the weather system (50°N, 40°W) 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.

6.2 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).



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. 10 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 - 1000/700 hPa layer, bottom panel - 500/300 hPa layer.

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. 6) 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.

6.3 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. 11 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.

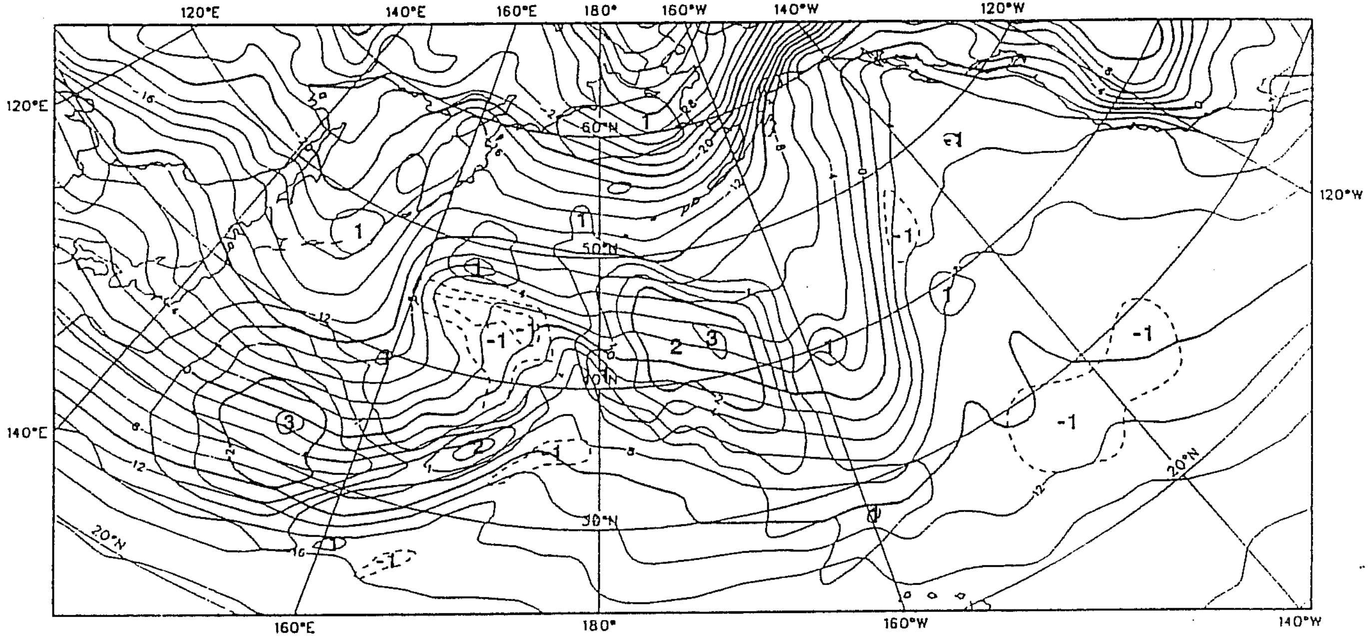
In this particular period, there were unusually poor forecast scores and the forecast errors appeared to be unrelated to the use of satellite data. However the evaluation of the operational scores at day 1 on a long period of time (by comparison to the NMC scores) seems to confirm a small improvement due to the quality control modifications introduced end of January 1989 (Fig. 12). In Fig. 12 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.

7. FUTURE PROSPECTS

7.1 Instruments

In the near term, satellite sounding capabilities will be enhanced through the addition of more microwave channels on the NOAA and DMSP satellite systems. The NOAA satellite will possess an Advanced Microwave Sounding Unit (AMSU) which possesses much higher spatial resolution (15-50 km) and many more spectral channels than the current MSU (twenty channels for the AMSU rather than four channels for the MSU). The DMSP will add an SSM/T2 package which, like the AMSU, will add a water vapour profiling capability in the microwave region. Figure 14 shows the profile weighting functions for the AMSU; the combined SSM/T and SSM/T2 weighting functions (not shown) are similar.

1000 to 700 hPa AN Layer mean temperature OPS – 178 890125–12Z



500 to 300 hPa AN Layer mean temperature OPS – 178 890125–12Z

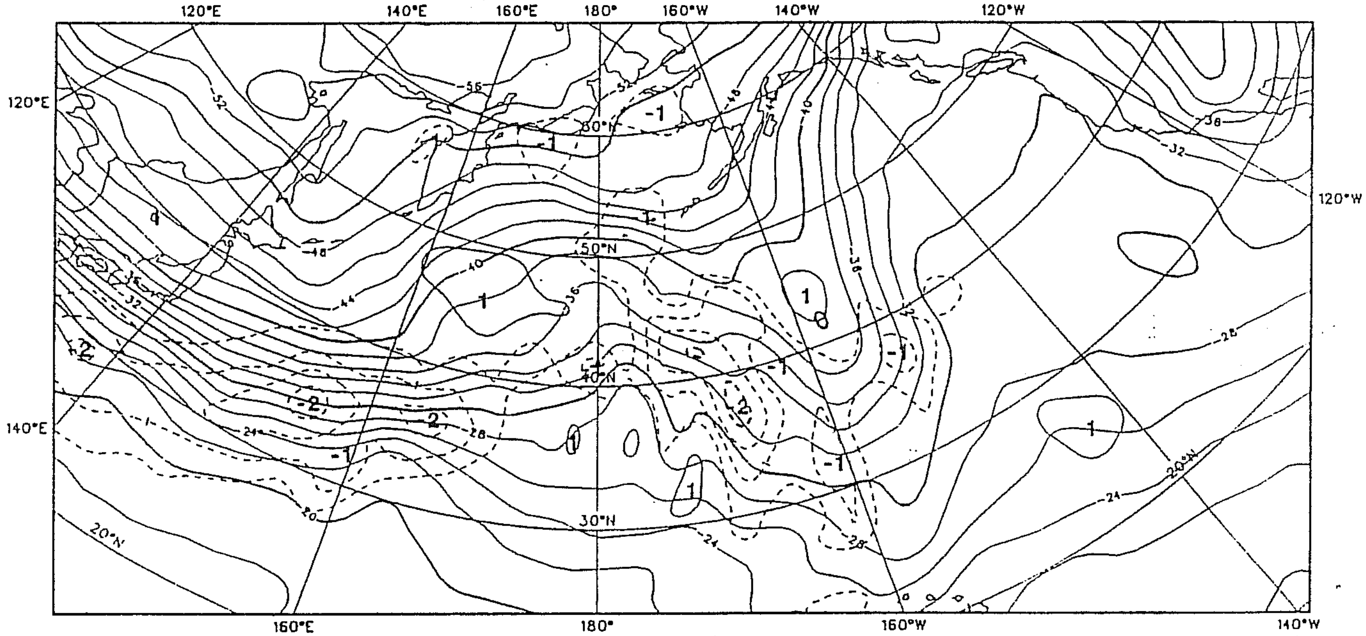


Fig. 11 Mean virtual temperature difference (in degrees) between two analyses with different quality control on SATEMs: OPS JUL 88 minus OPS FEB 89, the latter with the more stringent quality control. Contour interval_ 0.5 degree.
Area and date: North Pacific on 25 January 1989, 12 UTC. Also contoured is OPS JUL analysis (contour interval: 2 degrees). Top panel - 1000/700 hPa layer, bottom panel - 500/300 hPa layer.

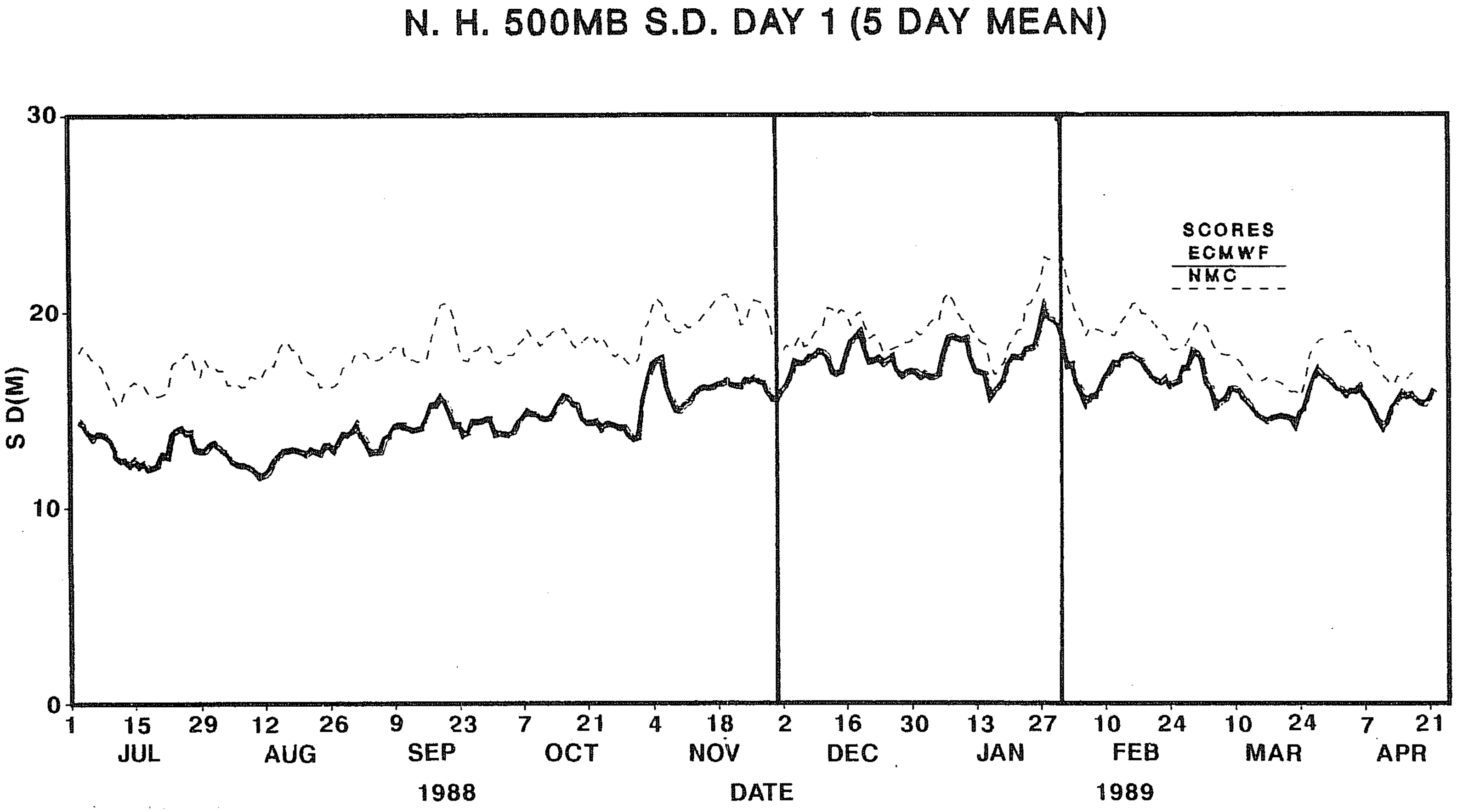


Fig. 12 24 h forecast error standard deviations for the ECMWF (full line) and NMC (dashed line) operational systems for a 10-month period from 1 July 1988 to 1 May 1989. Each point of the curves is a 5-day running mean. The variable considered is the 500 hPa geopotential height for the Northern Hemisphere (in metres). The two vertical lines correspond to the dates of operational changes: end of November 88 (NMV assimilation changes); end of January 89 (ECMWF changes, mainly changes to SATEM quality control).

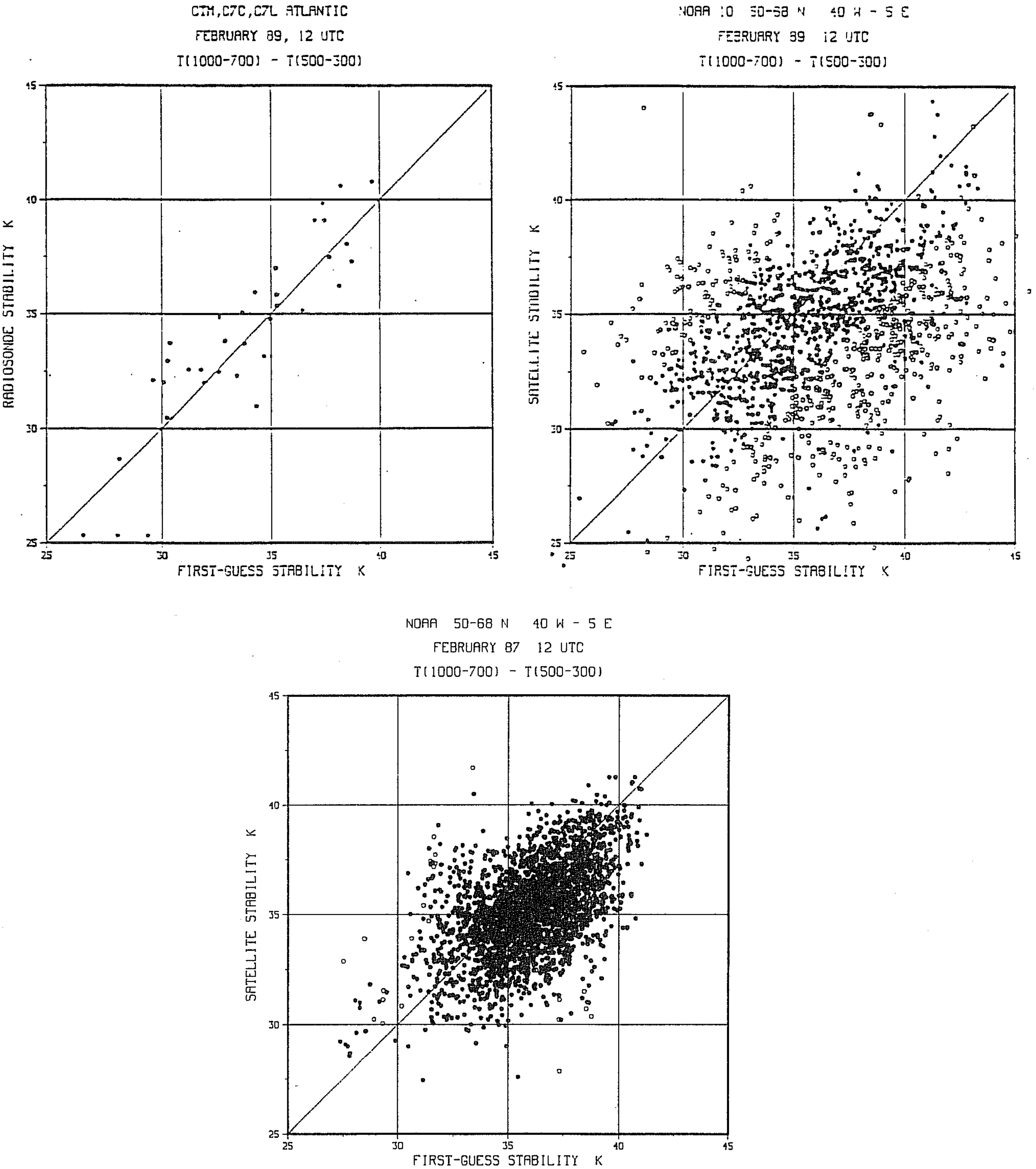


Fig. 13 Stability index scatter diagrams similar to Fig. 1. Top left panel is for radiosondes in February 1989 over North Atlantic (three weather ships); top right panel is for NOAA-10 operational TOVS over North Atlantic in February 1989; circles correspond to TGOVS data rejected by the analysis.

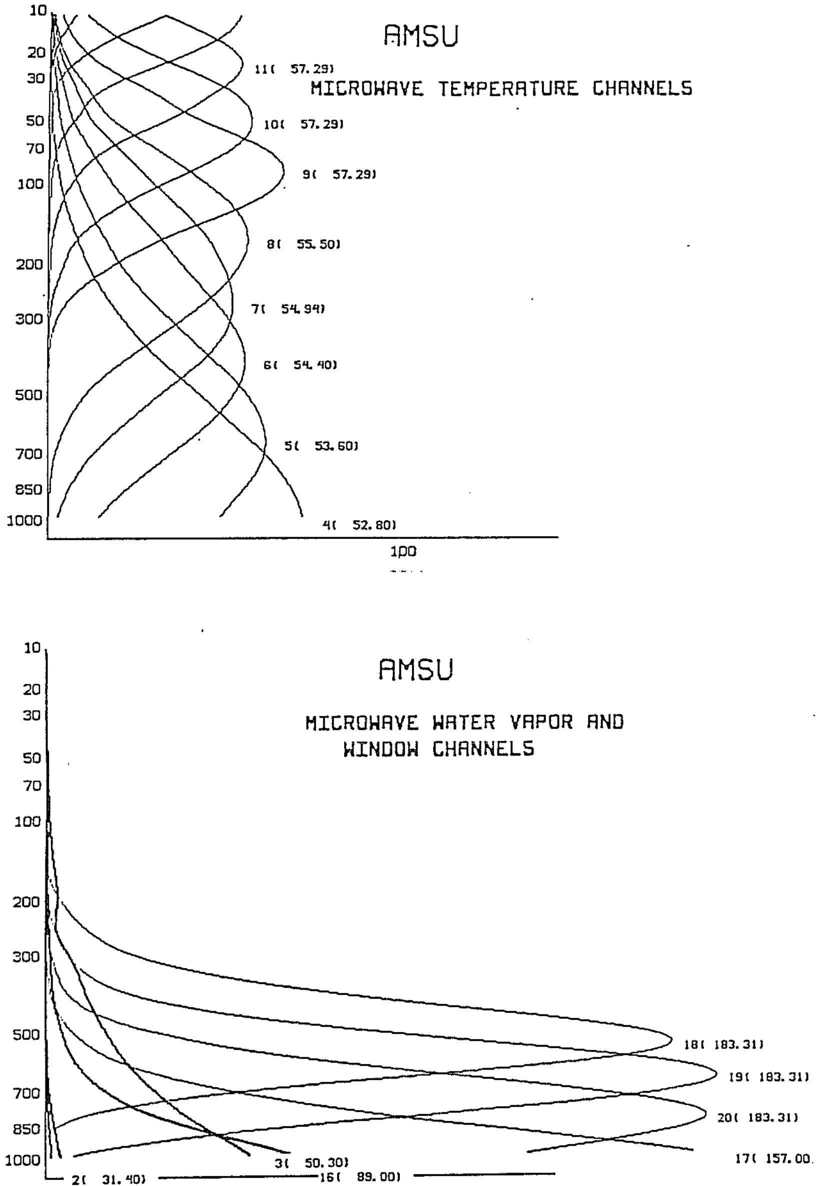


Fig. 14 Standard atmosphere radiance weighting functions for AMSU (a) temperature, and (b) sounding channels.

7.2 Data assimilation

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 provide 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.

The greatest advance in satellite sounding capability will take place in the mid to late 1990's when high spectral resolution, broad spectral coverage interferometers (and/or grading spectrometers) are implemented on geostationary and polar orbiting satellites.

This advance results in much higher vertical sounding resolution which is achieved by having a spectral resolution high enough to avoid smearing the upper atmosphere contributions from absorption line centres with lower atmospheric contributions from in between the absorption lines. In addition, broad spectral coverage enables more independent information to be achieved because of the spectrally varying: (1) absorption by various absorbing constituents, (2) line strength dependence upon temperature, and (3) Planck function temperature dependence. Also, redundant information gathered from sampling the quasi-complete spectrum helps to improve the signal-to-noise ratio of the sounding system. The systems proposed possess as many as 4000 spectral channels at 0.5 to 1.0 cm^{-1} resolution as opposed to the 10 to 20 channel instruments with 20 cm^{-1} resolution. This two order of magnitude increase in spectral data density and spectral resolution enables a factor of two to three improvement in vertical sounding resolution (Smith et al., 1988). This vertical resolution improvement is crucial for improving both short range and extended range numerical weather forecasts.

Fig. 15 shows temperature and water vapour profile weighting functions for a selection of channels from an Advanced Interferometer Radiometer Sounder (AIRS) proposed for the Polar Platform and a next generation GOES (Smith et al., 1987). Note that the ordinate and abscissa for the water vapour functions is different from that for the temperature functions. (The water vapour component weighting functions are two to three times sharper than the dry component). Each individual weighting function is at least 50% sharper than its low resolution counterpart (see Fig. 2). This weighting function resolution coupled with the quasi-complete spectral coverage provides higher sounding performance. To quantify this improvement, Fig. 16 shows the RMS errors of atmospheric temperature and water vapour expected for the AIRS with full spectral coverage (3.14-18 μm) versus an "optimal" selection of 115 spectral channels (MIN), both compared to the current HIRS infrared component of TOVS. (These error estimates were obtained from retrievals from radiances simulated from a global sample of 1200 radiosonde observations). As may be seen, the combination of high spectral resolution and quasi-complete spectral coverage enables 1°C temperature and a 10-20% tropospheric precipitable water vapour profile accuracy to be achieved.

8. CONCLUSIONS

Satellite temperature soundings derived from current instruments increase the accuracy of forecasts in the Southern Hemisphere. However, in the Northern Hemisphere more advanced instruments may be required to make substantial improvements to Numerical Forecasts. Improved retrieval methods and the use of Variational Analysis methods should lead to some improvements using the current operational instruments, however the new satellite instrument programs must be strongly supported by the NWP centres.

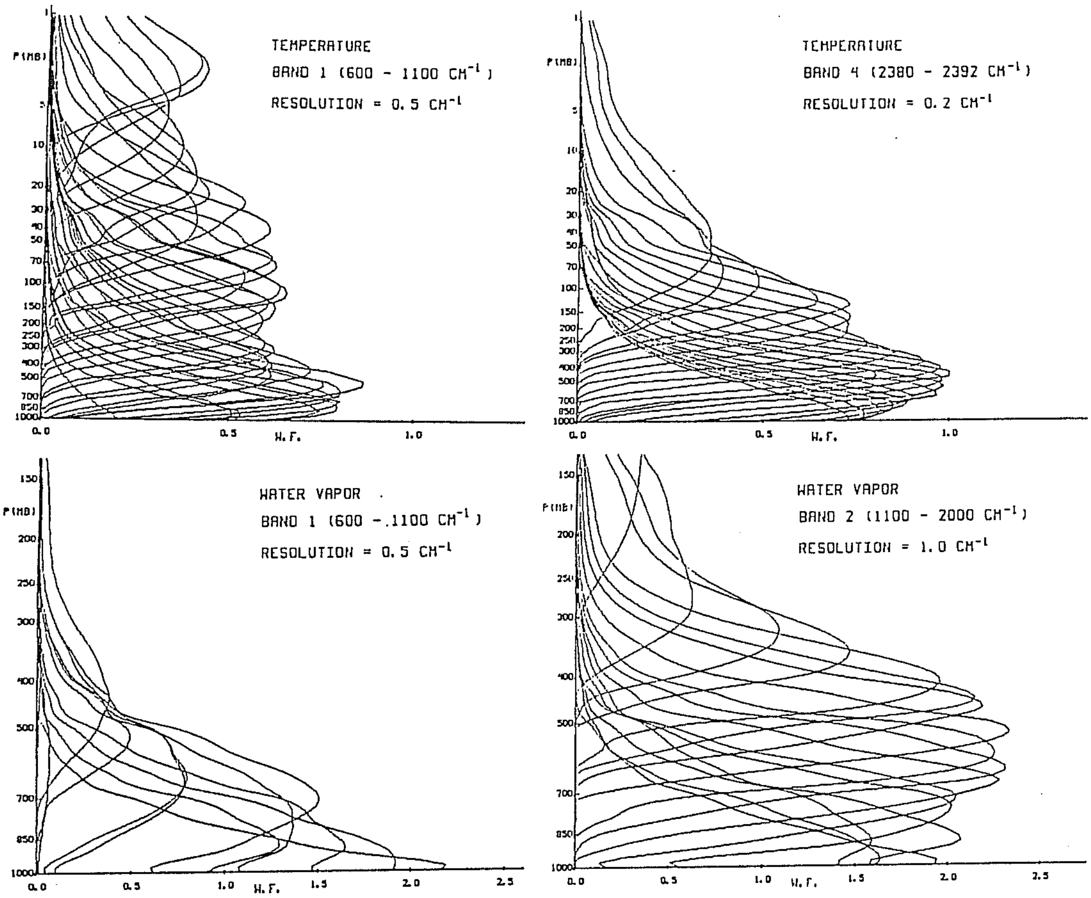


Fig. 15 A selection of temperature (dry) and water vapor (wet) components of the Planck radiance weighting functions ($\tau_{H2O}.d\tau_{dry}$/dlnp, and $\tau_{dry}.d\tau_{H2O}$/dlnp, respectively) for several spectral bands of the AIRS interferometer. Note the scale differences for the temperature (dry) and water vapor (wet) components.

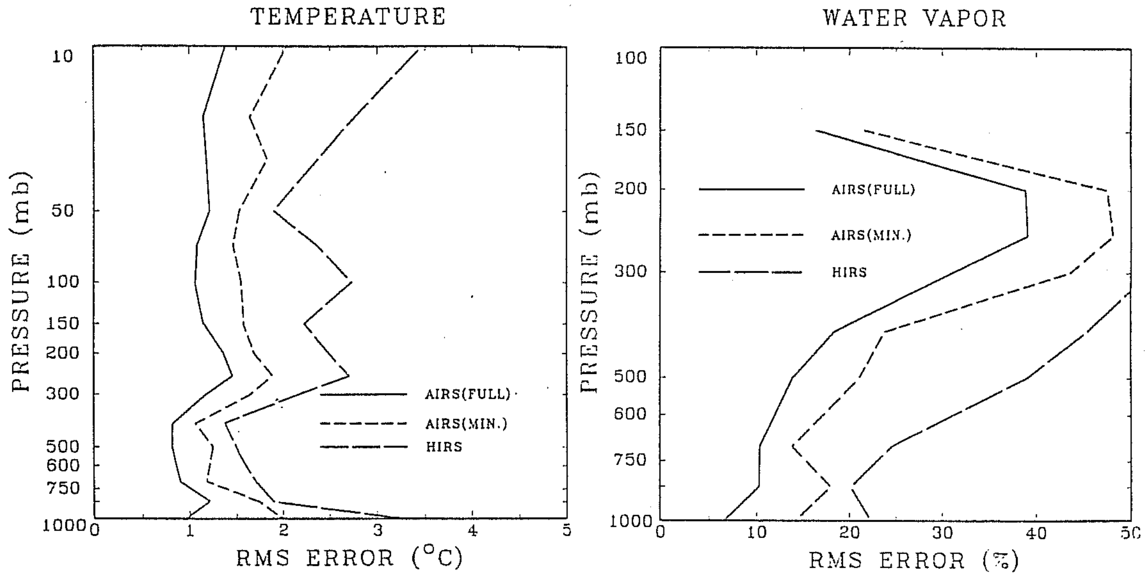


Fig. 16 Profile retrieval errors expected for the AIRS interferometer assuming a brightness temperature noise level of 0.25°C. AIRS (full) denotes all spectral channels used, AIRS (MIN) denotes 115 carefully selected spectral channels used, and HIRS denotes the 19 infrared spectral channels of the TOVS used.

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