CURRENT WORK AT ECMWF
ON THE USE OF SATELLITE DATA

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1. INTRODUCTION

This paper reviews work aimed at improving the use of satellite data in the ECMWF analysis system. The data discussed are vertical temperature/humidity soundings produced from the radiances of the polar orbiting satellites (SATEMs). The use of cloud motion winds from geostationary satellites (SATOBs) is not discussed, but it has been documented in Pailleux (1986b) and some recent analysis developments using SATOBs are described in this volume (Lönnberg, 1988).

The ECMWF analysis system is based on a 3 dimensional (3D) multivariate optimum interpolation (OI) scheme for mass/wind analysis, and on a 3D univariate OI scheme for relative humidity. All the general scientific aspects of this analysis scheme are documented in Lorenc (1981), with the more recent developments explained in Lönnberg et al. (1986) and in Lönnberg (1988). The aspects related to the interface between the OI analysis and the SATEMs and SATOBs are discussed in Pailleux (1986a) and Kelly and Pailleux (1988).

The present paper deals with the following aspects:

- An assessment of the impact of SATEMs on the quality of the ECMWF analysis and forecast (Section 2). It is a reassessment since this question was already addressed several years ago: see Uppala et al. (1984) and Pailleux (1986a).

- The description of latest developments in the operational ECMWF analysis (Section 3). These developments are related to SATEM vertical and horizontal resolution and quality control.

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- The description and initial results of satellite retrieval experiments (which begin with raw radiances) producing sets of experimental temperature and humidity soundings which are then passed to the ECMWF analysis (Section 4). Most of this work makes use of the retrieval scheme "3I" developed in the "Laboratoire de Météorologie Dynamique": see Chedin et al. (1985) and Chedin (1988) in this volume;

- The use of satellite data in a variational analysis which is a potential improvement for the 90's. It is addressed in the conclusion (Section 5) and also in Pailleux (1988), companion paper in this volume.

2. THE IMPACT OF SATEM DATA ON THE ECMWF ANALYSIS AND FORECAST

At ECMWF, an extensive set of Observing System Experiments (OSEs) were carried out in 1982/83 using data from the First GARP Global Experiment (FGGE). Two FGGE periods have been studied in detail: the first (OSE-I) in November 1979, the second (OSE-II) in February 1979. The impact of satellite data has been examined carefully during these two periods and is documented in Uppala et al. (1984).

In the Southern Hemisphere the impact of satellite sounding data is large and positive. However in the Northern Hemisphere there was positive impact in OSE-1, and a neutral impact during the OSE-2 period. These results demonstrate the importance of the meteorological situation. They also were obtained with an old version of the ECMWF assimilation system (beginning of 1983). More recent OSEs made on the November 1979 period with the ECMWF assimilation system of 1987 reconfirm the positive impact of SATEMs on the Northern Hemisphere in this period: see Kelly and Pailleux (1988).

A large ensemble of assimilation and forecast experiments has been run during the period 30 January to 14 February 1987. This period was chosen because of the meteorological situation and the availability of the two satellites, NOAA9 and NOAA10. In addition, complete sets of raw radiances, cloud-cleared radiances and soundings were obtained from NESDIS. Most of the satellite work described here relates to this period using these data sets. The operational retrieval scheme used at NESDIS at that time was a statistical inversion scheme (Reale et al., 1986). The inversion algorithm has since been changed to a physical method in September 1988 (Fleming et al. 1986).

An OSE was run during the February 1987 period, to test the impact of SATEMs and a comparison made between "NO SATEM" and the operational run. The results were similar to the FGGE OSE II with a large positive impact of SATEMs in the Southern Hemisphere, but no impact, on average, in the Northern Hemisphere. This is illustrated by the forecast anomaly correlation curves (averaged on 15 cases) and by the scatter diagrams shown in Figure 1. Figure 2 shows the impact of SATEMs on the stratospheric analysis of the Southern Hemisphere at the end of the period (14 February 1987, 12 Z). It was noted that after two weeks of assimilation without SATEMs, a spurious feature had developed over the 10 hPa geopotential height near Antarctica, which does not exist in the operational assimilation. This result confirms the inability of the ECMWF assimilation to cope for a long period with a total absence of data. As the SATEMs are almost the only data in the stratosphere in this region, they are very important to "drive" the ECMWF assimilation and prevent it from becoming noisy and unrealistic.

Another result from this OSE is the large regional dependency of the impact on the Northern Hemisphere. The anomaly correlation curves, Figure 1, have been computed for several regional areas. The neutral impact obtained is due to compensation. On one side of the hemisphere (North America, North Atlantic, Europe) there is a positive impact and on the other side (Siberia, North Pacific) the impact is negative. The regions where the negative impact occurs are affected by a very anomalous circulation in the stratosphere (strong vortex over Siberia) and by poor quality SATEMs in this region. The poor quality SATEMs are almost certainly related to the difficulty of performing the satellite retrieval in exceptional air-masses, and it is also obvious that in this experiment the ECMWF analysis quality control is not stringent enough and accepts bad SATEMs.

At this point, one can conclude that the analysis quality control algorithm is extremely important for using satellite data properly and assessing their impact. This is clear that in the case of 1 February 1987, 12 Z small negative impact of SATEMs in the Northern Hemisphere forecast was firstly obtained but by rerunning the same OSE with a more recent version of the assimilation libraries which includes a modified quality control check, the SATEM impact becomes positive.

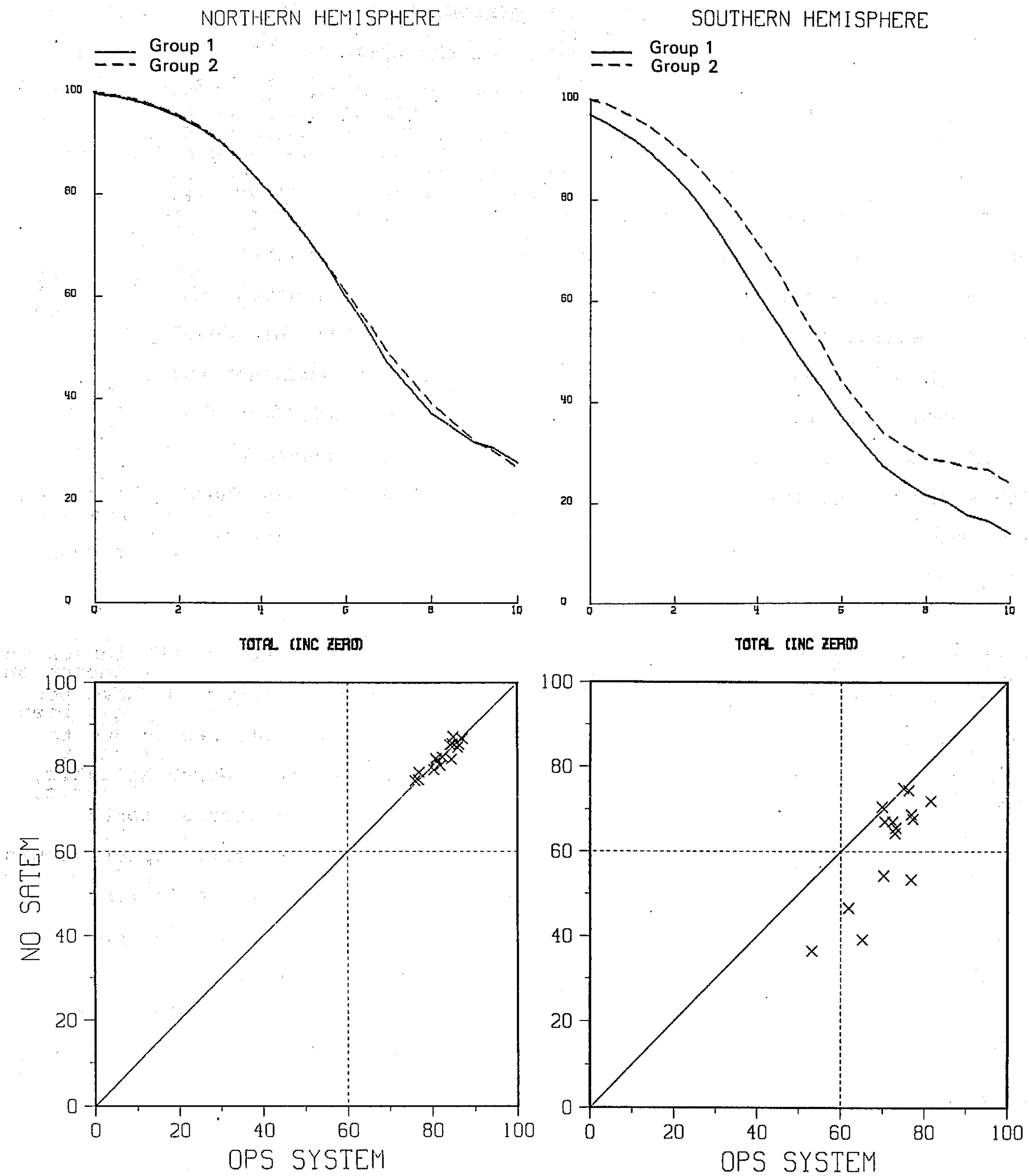


Fig. 1 Accumulated forecast scores on 15 cases comparing "NO SATEM" (full line) and "operational" (dashed line) assimilations (top). Scatter diagrams for NO SATEM versus operations at day 4 (bottom). Left: Northern Hemisphere. Right: Southern Hemisphere. The period is from 31 January to 14 February 1987.

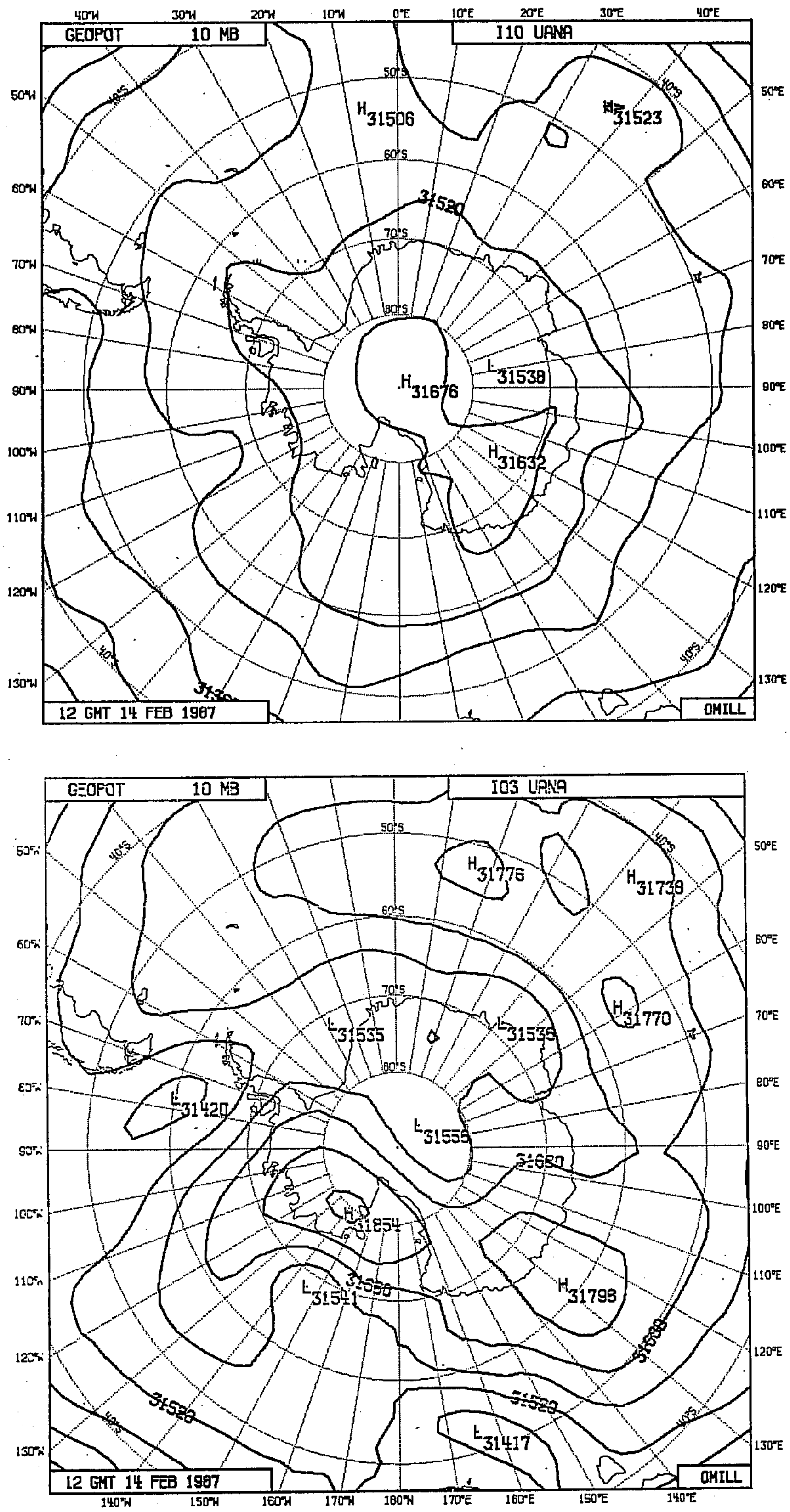


Fig. 2 10 hPa geopotential height analysis from operational assimilation (top) and NO SATEM assimilation (bottom) on 14 February 1987, 12Z.

The evaluation of SATEM impact is continuing and a new OSE is being run with the current operational version of the assimilation which contains all the OI modifications and tunings implemented in July 1988 and described in Lönnberg (1988). From the partial results currently available, it appears that the recent OI developments improve both assimilations. The improvement is greater in the "NO-SATEM" assimilation than in the operational one. In the Northern Hemisphere, the impact of SATEMs which was neutral on average with the assimilation version of February 1987 now becomes negative with the current operational version (July 1988). The purpose of the current evaluation is to try to understand the negative impact, and to understand why the recent OI developments are less beneficial in the normal operational context than in the "NO-SATEM" context. The first indications are that the ECMWF analysis still tries to use too many low quality SATEM data and does not reject enough (see Section 3). In addition, the recent analysis appears to be more sensitive to bad data than the previous one. The preliminary results in the Southern Hemisphere of the more recent OSE still show a large positive impact of SATEMs.

3. RECENT AND CURRENT DEVELOPMENTS RELATED TO SATELLITE DATA IN THE OPERATIONAL ANALYSIS

3.1 Vertical resolution in SATEMs

In the SATEM messages transmitted on the Global Telecommunication System (GTS), the thicknesses are available between all the standard pressure levels, between 1000 and 10 hPa. These 14 layers were used in the early versions of the ECMWF mass/wind analysis.

In November 1985 the SATEM resolution was reduced from 14 to 11 in the operational ECMWF analysis:

- layers 300/250 and 250/200 summed up in layer 300/200;
- layers 200/150 and 150/100 summed up in layer 200/100;
- layers 30/20 and 20/10 summed up in layer 30/10.

A small positive impact of this modification was found, pointing to the fact that 11 layers is more appropriate than 14 to represent the real information content of a SATEM profile.

Based on some general considerations about the information content of the TOVS channels, it was concluded that 11 pieces of information was still too many to

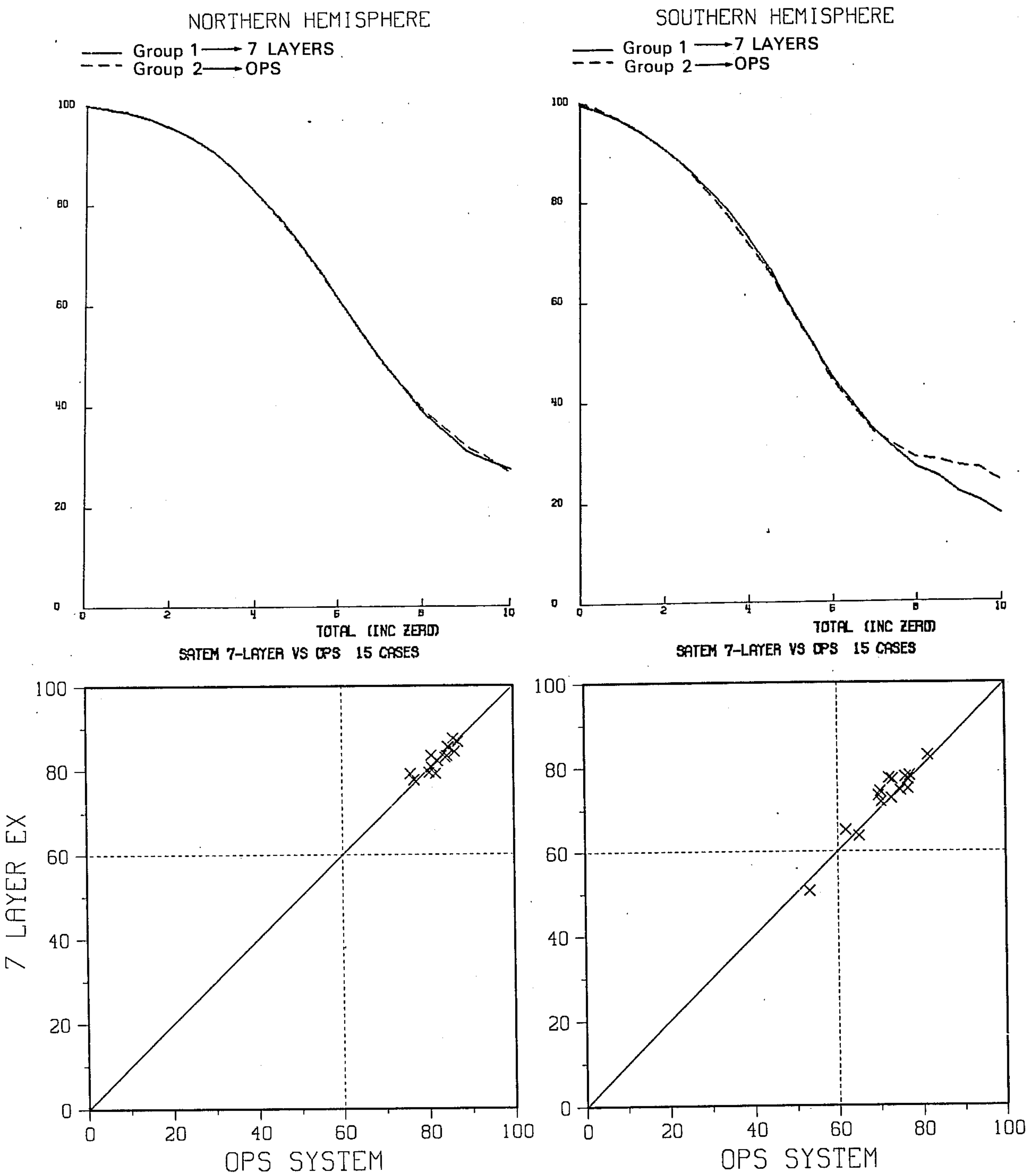


Fig. 3 Accumulated forecast scores on 15 cases comparing 7 layer (full line) and 11 layer (dashed line) curves (top).
Scatter diagrams for 7 layer versus 11 layer forecast at day 4 (bottom).
Left: Northern Hemisphere. Right: Southern Hemisphere.

represent the vertical resolution of a satellite temperature profile, and that a number between 5 and 8 would be more appropriate: see Kelly (1988) in this volume. After an attempt to use 6 layers in the vertical, it was decided to use 7 layers from the SATEM profiles:

- 4 tropospheric layers: 1000/700, 700/500, 500/300, and 300/100 hPa (used only over oceans);

- 3 stratospheric layers: 100/50, 50/30 and 30/10 hPa.

An assimilation experiment with 7 SATEM layers and several other retunings including the vertical covariance matrix for observation errors, has been run on the period 30 January - 14 February 1987. The analyses and forecasts have been compared to the corresponding control 11 layer run (operational at this time). The impact as shown in Figure 3 is small, but slightly positive on the Southern Hemisphere. A likely explanation is that the noise is reduced in the analysis by using 7 layers rather than 11. The "7 layer version" of the analysis was implemented operationally at ECMWF in July 1987.

The humidity data available from the SATEMs consist of Precipitable Water Content for three layers 1000/700, 700/500 and 500/300 hPa. They have been used operationally since March 1986 (Illari, 1988).

3.2 <u>Horizontal resolution in SATEMs</u>

The horizontal resolution of SATEMs transmitted on the GTS is not regular, but about 500 km on average. It is only a small subset of the TOVS information. Another data set containing the same soundings with a higher resolution (roughly 250 km) has also been available at ECMWF for several years. The 250 km SATEMs have been used operationally in the analysis since February 1985. Towards the end of 1988 a new TOVS data set should be made available by NESDIS to Europe, and will contain the soundings at roughly 80 km resolution (actually the resolution of 3x3 HIRS pixel boxes), as well as the corresponding cloud-cleared radiances.

Based on the previous experiments, it is not intended to use all the high resolution SATEMs without extra precautions. The clear radiances will be used to perform extra-quality control checks, perhaps through an air-mass classification based on a few microwave channels. Estimates of clear radiances will also be calculated from the 6 hour forecast and used for quality control. The general idea is to thin the 80 km data set to improve the general quality rather than simply increasing the volume of satellite information.

An experiment related to horizontal resolution is also run with the 3I scheme: the 3I scheme is used to produce some "SATEMs" at a resolution which is about 80 km; then a subset of 3I soundings is extracted through a random data selection which is set up in order to give a horizontal resolution equivalent to the operational one (250 km). Two assimilation experiments are then run on the same period:

- 3I high density, using all the soundings;
- 3I low density, using only the subset of 3I soundings.

The results currently available on these two experiments are inconclusive with respect to the impact of the data density mainly because the strongest signal obtained when comparing these two experiments is the one coming from using/not using some poor quality data. Again the main conclusion is the need to improve the quality control before evaluating the satellite data impact.

3.3 Quality control of satellite data

One clear message coming out from the satellite experiments described before is that the quality control is a key area for the success of using satellite information in the data assimilation. Improving quality control appears a necessary condition before more information can be extracted from the satellite observations to perform global analysis at higher resolution. This is illustrated by a quality control experiment run on 1 February 1987, 12 Z, when the SATEMs were affected by many quality problems (most likely related to the extreme weather situation in the Northern Hemisphere, Section 2). It has been noted that consistently wrong SATEMs have a tendency to support each other in the OI check. Then, following the series of experiments made with the February 87 version of the analysis, the OI check has been modified for SATEMs in such a way that when performing the tests for one particular SATEM profile, the other SATEMs are not used. The modified OI check leads to more SATEM data rejected on 1 February, especially over Siberia (the area affected by the strong vortex in the stratosphere), and the impact on the 10 day forecast is shown on Figure 4 (distance of the full line to the dashed line which is the anomaly correlation of a control). In this analysis the number of rejected SATEMs increased from 20 to 69 (still a very small number compared to the total number of SATEMs used globally: more than 4000). It is a striking result that such a small modification in the data rejection is enough to change significantly the anomaly correlation of the forecast on the Northern Hemisphere from day 2 onwards. This modified OI check has been used operationally since July 1988.

Another idea to improve the quality control consists in using "passive" satellite data. The active SATEM data which are currently used in the ECMWF operational analysis are from NOAA10 (used fully over the sea and only above 100 hPa over land). The NOAA10 data over land below 100 hPa and DMSP8 and 9 data are then passive. The first experiment already tried consisted of:

- applying the normal first-guess check to the passive data;
- use these passive data as independent source of information in the OI check.

These current experiments are temporarily suspended because of quality problems encountered with the DMSP data. Inconsistencies were found between different limb angles in one track and between the retrieved data when crossing the parallel 30°S or 60°S. Such a quality control technique could become operational in the ECMWF analysis as soon as the quality of DMSP retrievals improves.

Finally, following the investigation of several cases when the SATEM profiles were bad in the troposphere over the ice, SATEM data over ice will be considered as over land, and used only above 100 hPa. Also, for non-clear soundings, a more careful usage will be considered below 100 hPa, especially in the Northern Hemisphere.

3.4 Summary of the recent operational analysis developments related to use of SATEMs

- February 1985: 250 km rather than 500 km for the SATEM horizontal resolution.

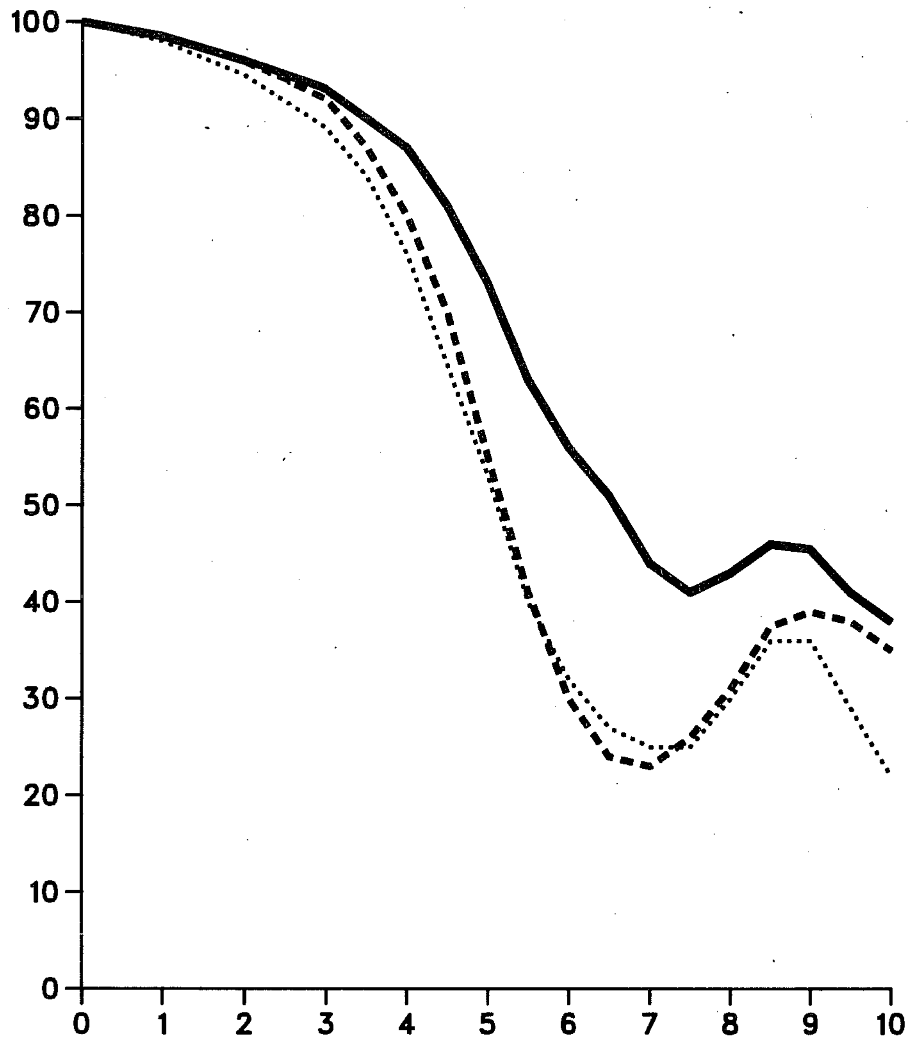


Fig. 4 Anomaly correlation curves of three forecasts from the analysis of 1 February 1987, 12 Z, for the Northern Hemisphere geopotential height in the troposphere:

a) ——— : full line: analysis using modified OI check for SATEMs

b) ---- : dashed line: control (same as a) without the modified OI check).

c) .... : dotted line: operations of February 1987 (same as b) but with an older version of the analysis).

- November 1985: 11 thickness layers in the vertical rather than 14 layers.

- February 1986: use of PWC from SATEMs.

- July 1987: 7 thickness layers in the vertical rather than 11 layers. Also several OI retunings.

- July 1988: modified OI check for SATEMs.

3.5 Potential improvements which could become operational in the next few months

- Tighter first-guess check, especially for lower layer (1000/700 hPa) and upper layer (30/10 hPa).

- Use SATEMs over ice as over land (above 100 hPa only).

- Use non-clear SATEMs over the ocean as over land in the Northern Hemisphere (above 100 hPa only).

- Revised the use of PWC and retune the statistics used in the 3D OI humidity analysis.

- Use DMSP data and/or NOAA SATEMs over land below 100 hPa, as an additional independent information in the OI check.

- Use of the 80 km sounding/clear radiance data set.

4. SATELLITE RETRIEVAL EXPERIMENTS AT ECMWF

4.1 Generalities

The projects described in Section 3 are the short-term developments in the ECMWF operational analysis. On the other hand the goal of the retrieval experiments is to define the longer term strategy for the use of satellite data in assimilation.

A physical retrieval experiment was made at ECMWF in 1985/86. (Pailleux et al. (1986)). It was based on a version of the International TOVS Processing

Package (Smith et al., 1983) and the ECMWF first-guess was used as initial guess for inverting the radiative transfer equation. Consequently the soundings produced were containing some information coming from the first-guess and the soundings produced were on average better than the operational SATEMs. However, they were producing inferior forecasts partly because the correlation "SATEM error - first guess error" was not taken into account in the OI analysis ("incest" problem). This preliminary experiment was made in a FGGE period, using the TOVS clear radiances available in the FGGE II-b data set.

4.2 Experimental assimilation suite using 3I

A software system has now been implemented to run full retrieval experiments from TOVS raw radiances, together with the ECMWF assimilation. The first retrieval assimilations used the 3I method based on the scheme developed in LMD and the scientific aspects of the 3I scheme are described in this volume, see Chedin (1988). This method allows for the possibility of using some information from the assimilation in the retrieval scheme.

- Use of surface information from the first-guess for guiding the search of the initial profile in TIGR data set;

- Use of the first-guess to perform radiance computations and allow improved quality control checks.

Although this use of first-guess is in principle "incestuous", the level of "incest" is extremely small compared to the experiment described in 4.1, and there is no need to include a correlation between the first-guess error and the SATEM error in the OI analysis.

The 3I retrieval scheme has been run on the February 1987 period using NOAA9 and NOAA10 raw radiances. Temperature and humidity profiles are produced on 3x3 HIRS pixel boxes (non overlapping boxes). The 3I relative humidities are entered directly in the OI equations, avoiding the PWC interface which creates problems in the operational analysis. For each analysis, 15000 to 20000 soundings are produced globally from the two satellites, which corresponds roughly to the "so-called" 80 km NESDIS resolution. In addition, a thinning is performed on this data set which produces a subset having the same horizontal resolution as the current NESDIS data set (roughly 250 km).

4.3 Some results on the 3I experimentation

Four parallel assimilation experiments are currently run on the February 1987 period, with 10 day forecast experiments run from every day, 12Z. Only preliminary results are available. Two of them are 3I experiments:

- 3I (HR): using all the 3I retrieval soundings (high density);

- 3I (LR): using only the subset of 3I soundings (low density);

The other two experiments are:

- OPS: using the NESDIS operational soundings (similar to the ECMWF operational suite);

- NO SATEM: not using any SATEMs.

All the experiments are run with the recent versions of the analysis and forecast model (versions of July 1988 which includes also the modified OI check and the revised structure functions documented by Lönnberg (1988) in this volume).

When fully evaluated, it is hoped that the intercomparisons of the four experiments can answer a series of different questions which are related to:

- The impact of SATEM data on the more recent version of the ECMWF analysis scheme;

- The comparison of two different retrieval schemes: 3I and the NESDIS scheme which was operational in February 1987 (3I(LR) vs OPS);

- The horizontal resolution in SATEMs in the 3I context (3I(HR) vs 3I(LR)).

Figure 5 shows the anomaly correlation of the four experiments averaged on the first four cases of the experimental periods, for Northern and Southern Hemispheres. In the Southern Hemisphere, the impact of satellite data is positive and large, no significant difference on the quality of the other experiments can be found. In the Northern Hemisphere, the only clear signal is a small negative impact of satellite data (which was not found with the previous version of the libraries - see Section 2). No clear signal can be found when comparing the three experiments using satellite data: OPS, 3I(HR) and 3I(LR). Looking at individual cases we find large variations of behaviour in the quality of the forecasts OPS, 3I(HR) and 3I(LR).

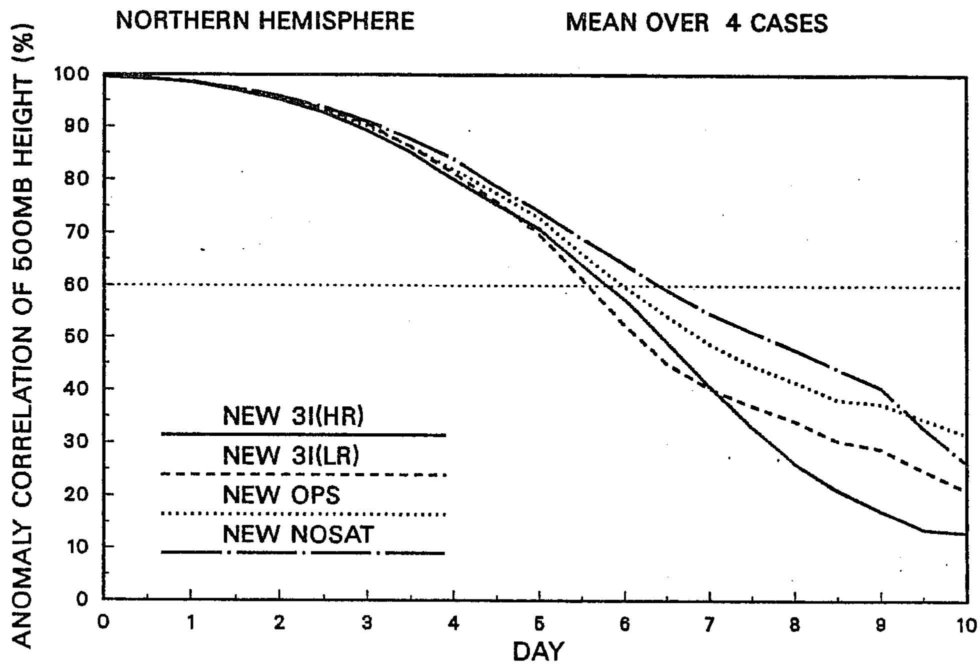
A preliminary synoptic evaluation of some cases has been made and the following conclusions can be drawn:

- Generally speaking, the ECMWF analysis still accepts too many satellite observations, many of them being poor or doubtful during the February 1987 period in the Northern Hemisphere. This is true for all the experiments (except NO SATEM of course) and in spite of recent quality control improvements made in the analysis (see Section 3).

- Some bad satellite data were also found over ice and at the edges of the satellite scan. The 3I experiments also showed some bad data related to rain contamination of the MSU 2.

- At the beginning of February 1987, the medium range forecast was very sensitive to the initial state in the Eastern Pacific. It is clear that in this situation, the satellite data have a tendency to smooth and/or destroy the synoptic structure of some weather systems in this region. This is true regardless of the retrieval technique, however the effect is greater in 3I (HR) because of the higher data.

- In certain cases, in particular regions, some poor retrieval soundings were produced by the 3I suite, whereas the portion of orbit was lacking in the NESDIS operational data. This adversely effected these 3I forecasts.



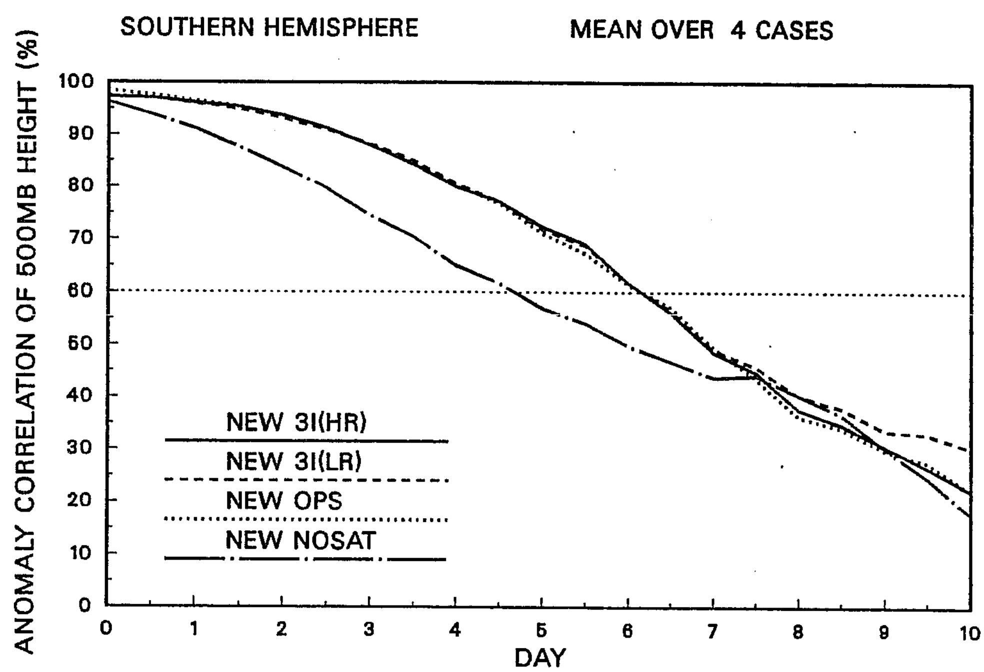


Fig. 5 Accumulated forecast scores on 4 cases from 31 January to 3 February. Four experiments are compared:

- 3I (HR): experiment using high density 3I soundings; (full line)
- 3I (LR): experiment using low density 3I soundings; (dashed line)
- OPS: experiment using NESDIS soundings like in operations; (dotted line)
- NOSAT: experiment without SATEMs (— . — .)

Top: Northern Hemisphere, Bottom: Southern Hemisphere

- Regardless of the quality of the forecast, the 3I retrieved temperatures appear to be more consistent and less noisy in the horizontal than the corresponding NESDIS soundings.

Some of these conclusions have been used also to plan short-term developments in the operational analysis (see 3.5). The quality problems have to be solved before an evaluation is made of retrieval schemes and the horizontal data density used in the assimilation.

5. CONCLUSIONS: TOWARDS A 3D/4D VARIATIONAL ASSIMILATION OF RADIANCES

Although some recent improvements have been made and implemented operationally on the quality control, further improvements are needed in order to be successful in using more information from satellites. This is true for all the work planned on satellite data: short, medium and long term.

The short-term work is concentrated on retuning the current operational analysis program with the main target being to use the information which will be available in the 80 km data set.

In the medium-term, the full experiments combining retrievals and assimilation, as run now with the 3I scheme, will hopefully help to decide whether or not it is an advantage for a global assimilation to incorporate also the satellite retrieval in operational mode.

In the longer term, the research in data assimilation is now "converging" towards using something which is as close as possible to the genuine observed quantity, rather than "interfaces". And SATEMs are actually a "sub-optimal" interface between the satellite retrieval scheme and the analysis scheme: this is the explanation why we felt a need for retuning this interface so often (going from 14 to 11, then to 7 layers), but a simple interface can never transmit the real information content as it is in the radiances. The integrated approach (using the radiances directly) is easier to achieve in the context of a variational analysis scheme than in the traditional OI analysis; it is discussed in the companion paper of this volume (Pailleux (1988)).

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