RESEARCH AND DEVELOPMENT ON TOVS RETRIEVALS IN THE U.K.

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1. INTRODUCTION

This paper describes research and development on TOVS retrievals at two centres in the UK: the Meteorological Office headquarters at Bracknell, and the new Robert Hooke Institute for Co-operative Atmospheric Research at Oxford. The Satellite Meteorology branch at Bracknell is responsible for running the operational system for real-time processing of TOVS data from the local reception area, for monitoring the performance of the system and for implementing improvements to it. Also at Bracknell, groups concerned with the development of the numerical forecasting system are engaged in work to assess and improve the use of TOVS retrievals in the current numerical forecast models and to develop techniques for improved assimilation of satellite sounding data in the future. Satellite meteorology research at Oxford involves the new Meteorological Office Unit and the Department of Atmospheric Physics of Oxford University, working closely together within a co-operative institute. One of the major activities of the joint group is the development of improved retrievals schemes for TOVS data. This work is being conducted in close collaboration with the groups at Bracknell, with the aim of providing improved retrieval schemes for operational implementation within the Meteorological Office.

At the time of the First International TOVS Study Conference (TOVS-I), the Meteorological Office was implementing a scheme to acquire and process real-time TOVS data for use in operational weather forecasting (Eyre, 1984b). The processing scheme is known as "LASS" (the local area sounding system). This paper outlines progress on this project since TOVS-I and discusses the lines of research and development currently being pursued or planned.
The TOVS case study of 7 June 1984, for which data were distributed to TOVS Conference participants in preparation for the Second International TOVS Study Conference, has been processed. The results obtained with the present operational retrieval scheme have been sent to the Australian Bureau of Meteorology for analysis. Some additional results are presented in section 4.

2. PROGRESS ON THE LOCAL-AREA SOUNGING SYSTEM (LASS) SINCE THE FIRST INTERNATIONAL TOVS STUDY CONFERENCE

2.1 Operational aspects

Following the delivery of the hardware for the HERMES (High-resolution Evaluation of Radiances from Meteorological Satellites) system in March 1983, the TOVS Export Package obtained from the NOAA/NESDIS Development Laboratory (Madison) was modified to run on the particular hardware configuration of the HERMES system. The TOVS data are received at Lasham in Hampshire and transmitted to Bracknell over telephone lines. Real-time processing was first achieved in August 1983 and was routine by September 1983. Following a period of product validation, the soundings were supplied to the Central Forecasting Office (CFO) at Bracknell from November 1983. The data were initially supplied as charts of 1000-500 mb thicknesses along with thermal winds derived from the local gradient of the thickness field. By January 1984 the software had been developed to handle NOAA-8 data in addition to that from NOAA-7, and the system was capable of processing data from the two satellites simultaneously.

Throughout 1984 the groups within the Meteorological Office concerned with the development of the operational numerical forecasting system conducted a number of experiments to investigate the impact of such large amounts of satellite sounding data on the numerical forecasts. Following evaluation of the results of these experiments, it was decided to include the LASS temperature data in the analyses of the "coarse-mesh" model (a global model with a horizontal resolution of 150 km) from 12 September 1984, with the data averaged to a horizontal resolution of 240 km. The data were only included in the 00Z and 12Z "update" global analyses (run over 11 hours after the analysis time and designed mainly to give a good starting field for the next assimilation) and the 6Z and 18Z intermediate global analyses. From mid-November 1984 the Meteorological Office began running a separate 3-hour assimilation cycle.
specifically for the limited area "fine-mesh" model (of resolution 75 km), and the LASS data were included in these analyses at a resolution of 240 km. The data were included in all the assimilations except those from which the 36-hour forecasts were run. It was felt necessary to exclude the data from the main analyses prior to the forecasts until the impact of the data on the quality of the forecasts had been fully evaluated.

2.2 Retrieval scheme improvements

In most respects the retrieval scheme is unchanged from the version of the TOVS Export Package obtained from the NOAA/NESDIS Development Laboratory in 1980 (see Eyre, 1984b). However, minor improvements have been made since TOVS-I to overcome some of the problems identified during the development and early operational stages.

Some spurious thermal troughs were discovered over high terrain such as the Scandinavian massif, particularly in winter when the surface is very cold. These were caused by an error in the method used to compute thicknesses from the retrieved temperature profile (provided by the statistical regression inversion and extending down to 1000 mb) in high terrain areas where the surface pressure is much less than 1000 mb. A thickness correction scheme, which accounts approximately for the effects of an elevated surface on the retrieval, has been introduced (Eyre, 1984a). No retrieval products are generated in areas of very high terrain (where the mean surface elevation of a 1 deg-latitude x 1 deg-longitude box exceeds 1000 m).

Following concern that retrievals towards the edges of the TOVS scan contained biases with respect to the scan centre, an assessment was made of the mean MSU brightness temperatures at each scan position, averaged over many local area passes. Analysis of the results is complicated by the fact that the left side of the scan is always further south than the right side. For local area data, this introduces a "climatological" component into the variation of mean brightness temperature with scan angle. A scheme has been devised for removing this component to leave the "residual scan-dependent correction". Results from a preliminary assessment of these corrections is given in table 1. The data used in this analysis are MSU brightness temperatures corrected to nadir and corrected for antenna gain pattern and surface emissivity effects by the standard Export Package routines. They have also had applied the asymmetry correction calculated at Madison (values also given in
table 1), but they have not been mapped to HIRS sounding locations. The values obtained for the residual scan-dependent corrections are reasonably symmetric, indicating that they are probably compensating for biases in the mean nadir corrections rather than for an instrumental anomaly.

2.3 Validation activities and results

Since the start of routine production of LASS soundings there has been considerable effort devoted to validation of the derived profiles. This has mainly been through the generation of statistics from a database of collocations of LASS soundings and radiosonde ascents from weather ships or land stations. Temperature, thickness and dew point biases and standard deviation (SD) statistics are produced each day for all collocations within the LASS area and monthly mean figures are also derived. Table 2 gives an example of the routine statistics produced on HERMES and shows the December 1984 bias and SD statistics for the temperatures, thicknesses and dew points for all standard levels up to 100 mb (the thickness figures being for layers from 1000 mb up to the level specified).

These monthly mean figures illustrate many of the known problems of the LASS soundings and, in particular, highlight the errors noted around the tropopause and at low levels. At these two levels the SDs for the temperatures are larger than at other levels and the biases give an indication of some of the problems that have been encountered in using the soundings. At the level of the tropopause, examination of individual collocations has indicated that the LASS soundings are unable to resolve fully the sharpness of the tropopause. Close to the ground the negative bias is thought to be due largely to the inability of the scheme always to detect cloud and provide correctly cloud-cleared radiances.

Subjective assessments of charts of the LASS 1000-500 mb thicknesses by the Central Forecast Office has highlighted a number of additional problems. In particular the forecasters suggested that the soundings at the edges of the swaths exhibit larger differences from radiosondes than those at the centre of the swath and that the differences are related to the synoptic pattern. The "residual scan-dependent corrections" described above have recently been introduced to remove some of the anomalies at the edges. However, further work has recently begun on examining the problems at the edges of the swaths and the
relationship to the synoptic type. This is mainly based on comparing the analysed LASS soundings with the routine numerical analyses interpolated to the time of the satellite overpass, and first results from these comparisons have confirmed many of the subjective views of the forecasters. Work is now in progress on explaining the differences observed and examining possible ways of correcting these errors.

3. CURRENT DEVELOPMENTS AND FUTURE PLANS

3.1 Locally generated regression coefficients

The LASS operational retrieval scheme currently performs a multiple linear regression inversion to obtain temperature and humidity profiles from cloud-cleared brightness temperatures using the operational regression coefficients generated weekly by NESDIS. While this approach maintains a large degree of compatibility between LASS retrievals and SATEMs, it has been thought for some time that improvements should be possible using coefficients which are:

- tuned to the area of local data reception, and

- generated by regression of a well-screened and climatologically balanced set of radiosonde profiles on the corresponding brightness temperatures calculated theoretically using a radiative transfer model.

An appropriate set of 9600 radiosonde profiles has been constructed (Pescod and Eyre, 1983) from which corresponding T0VS brightness temperatures can be calculated using a radiative transfer model (Eyre, 1984c). A scheme has been developed to generate regression coefficients from these (Watts, 1984b). The scheme will be implemented as soon as possible. In trial comparisons, the new coefficients have shown modest improvements over the NESDIS coefficients. Moreover they provide a basis for more sophisticated uses of climatological information (see section 3.4).

3.2 Improved cloud-clearing scheme

A new cloud-clearing scheme with the following characteristics is under development:
it produces radiances fields in all channels which are more horizontally consistent than in the current operational scheme, and

- it assesses the estimated errors at each stage in the cloud-clearing process.

The principles behind the scheme are described by Eyre (1983). Briefly, it utilises the expected smoothness of the cloud-free radiances fields to provide a priori estimates of the clear radiances at each HIRS spot using estimates from adjacent spots.

If \( x_{n,m} \) is the cloud-cleared brightness temperature estimate at HIRS spot, (line \( n \), column \( m \)), with estimated error \( \sigma_{n,m} \), then we can improve the estimate by combining it with information from a previously processed spot, \( (\hat{x}_{n,m-1}, \hat{\sigma}_{n,m-1}) \) using a sequential estimator of the form:

\[
\sigma_{n,m}^{-2} = \left( \frac{1}{\sigma_{n,m}^2} + \frac{1}{\sigma_{n,m-1}^2 + \delta} \right)^{-1},
\]

\[
\hat{x}_{n,m} = \sigma_{n,m} \left( \frac{x_{n,m}}{\sigma_{n,m}^2} + \frac{\hat{x}_{n,m-1}}{\sigma_{n,m-1}^2 + \delta} \right),
\]

where \( \hat{x}_{n,m} \) and \( \sigma_{n,m} \) are the new estimate and its error, and \( \delta \) is a term to take account of the expected spatial variation of \( x \).

In practice the scheme is applied in 2 dimensions as illustrated in figure 1, and by running "forward" and "backward" filters information is "advected" uniformly from all directions. To date, the scheme has been developed for application to each channel in turn, but it could be extended to estimate all channels together.

The input data to the scheme can in principle be any independent estimates of the cloud-free radiances at each spot (together with an estimate of its error) derived by the best available method. At present we are using an extension of the current operational scheme; a HIRS cloud-free brightness temperature estimate is obtained from one of the following sources:

- The measured, pre-processed brightness temperature judged to be cloud-free through a comparison of measured MSU channel 2 with its value predicted from a linear combination of HIRS channels.

- An estimate obtained using the N\* technique on adjacent
spots (Smith, 1968) with MSU channel 2 effectively acting as the "cloud-free" channel. Only colder adjacent spots are utilised to avoid overuse of the data.

- An estimate obtained from a regression on MSU data. It has been found necessary to identify and correct for the local bias between the measured HIRS cloud-free brightness temperature and the corresponding values predicted from MSU data. The local bias field is estimated in a similar manner to the cloud-free brightness temperature field itself.

The scheme has not yet undergone a thorough validation, but a preliminary example of its results is given in section 4.

3.3 Investigation of retrievals using a forecast first guess

Some consideration has been given to the idea of assimilating cloud-cleared brightness temperatures into the numerical forecast models, thus avoiding the need for an explicit "inversion". This may be the optimal approach in the longer term. However, it is planned to investigate a scheme which, whilst it does perform an explicit inversion, uses forecast information and is almost equivalent mathematically to direct assimilation of radiance data.

The proposed inversion takes the optimal linear form set out by several authors (e.g. Rodgers, 1976):

\[ \hat{x} = x_0 + (K.C)^T(K.C.K^T + E)^{-1} \cdot (y_m - y_c(x_0)) \]

where \( \hat{x} \) is the retrieved profile vector (containing the humidity profile and surface radiative temperature, in addition to the temperature profile),

\( x_0 \) is a first guess profile obtained from a forecast model,

\( C \) is the forecast error covariance (i.e. the covariance matrix of the expected error in \( x_0 \)),

\( y_m \) is the measured, pre-processed, cloud-cleared brightness temperature vector,

\( E \) is the brightness temperature error covariance matrix,

\( y_c(x_0) \) is the brightness temperature vector calculated from the first guess profile using a radiative transfer model,

and \( K \) is a matrix containing the derivatives of \( y \) with respect to \( x \) (ideally evaluated at \( x = x_0 \)).
\( y_c(x_o) \) will be calculated in real time from the first guess profile \( x_o \) using a modified form of the radiative transfer model TOVSRAD (Eyre, 1984c). This model will also be used off-line to compute the derivative matrices \( K \), since it is anticipated that a small number of constraint matrices, \( D = (K.C)^T(K.C.K^T + E)^{-1} \), will be adequate, and that a more precise specification of \( K \) is not justified given the uncertainties in \( C \) and \( E \).

At the time of the forecast model assimilation it is possible to make an improvement to the retrieval, because we now have available an analysis \( \hat{x} \) which should be more accurate than the forecast \( x \). If we had possessed this at the time of the retrieval, it would have taken the form:

\[
\hat{x}' = x_o' + (K.C)^T(K.C.K^T + E)^{-1}(y_m - y_c(x_o')) . \tag{3.4}
\]

Using the linear approximation:

\[
y_c(x_o) - y_c(x_o') = K(x_o - x_o') , \tag{3.5}
\]

and subtracting 3.3 from 3.4, we obtain the improved retrieval:

\[
\hat{x}' = \hat{x} + I(K.C)^T(K.C.K^T + E)^{-1}.K - I . (x_o - x_o') , \tag{3.6}
\]

where \( I \) is an identity matrix.

Again it is anticipated that \( I(K.C)^T(K.C.K^T + E)^{-1}.K - I \) will be sufficiently stable to be pre-computed allowing a simple correction to \( \hat{x} \).

In most areas, where the forecast is quite accurate, this approach is expected to give considerable improvement over the current operational method, which produces the largest retrieval errors in regions where the atmosphere is far from the climatological mean (which acts as the implicit "first guess"). Potential problems are expected with the new approach in areas where the forecast is seriously in error. However it may be possible using the radiances to identify such occasions, on which it may be better to use a "climatological" first guess and constraint (see section 3.4).
3.4 Investigation of stratified statistics

It has been demonstrated that retrievals which make use of a first guess and statistical constraint drawn from climatology can be improved by "stratifying" the statistical data base according to air mass type or profile shape, and then using the radiances with a discriminant function to select the most appropriate sub-set (Uddstrom and Wark, 1984).

Research is underway to explore this approach using either the "typical shape function" approach proposed by Uddstrom and Wark, or a simpler stratification as suggested by Kelly et al. (1976). Given that an appropriate stratification is possible, the method could be applied either as a simple extension to the scheme described in section 3.1 or as an adjunct to the method outlined in section 3.3. If the measured radiances and those calculated from a forecast first guess have a high probability of belonging to the same sub-set, we have confirmed that the forecast is an appropriate first guess for the retrieval. Other probability conditions correspond to different situations which it would be useful to identify, including:

- the measured radiances have a low probability of belonging to any sub-set and so are probably in error, or

- the measured and forecast radiances have a high probability of belonging to different sub-sets, indicating perhaps that the forecast is seriously in error (in which case the mean and covariance of the sub-set corresponding to the measurements may be a better first guess and constraint for the inversion).

3.5 Investigation of use of AVHRR data with TOVS data

The usefulness of AVHRR data to improve HIRS cloud-clearing and as a diagnostic tool for testing TOVS-only cloud-clearing schemes is being explored (Lloyd et al., 1985).

3.6 Improved humidity retrieval

The present operational scheme retrieves humidity profiles through multiple linear regression of cloud-cleared HIRS brightness temperatures on water vapour mixing ratio profiles. A fundamental deficiency of this scheme lies in its attempt to represent a non-linear inversion problem by a
linear regression relation. An alternative approach proposed by Rosenkranz et al (1982) casts the humidity profile inversion in a linear form by attempting to retrieve the temperature profile at levels of constant water vapour over-burden. This approach has been applied to synthetic TOVS data (Watts, 1984a). The results show significant improvements over the current method in the mid-troposphere, particularly when the variance of the statistical data base is large, but no improvement close to the surface.

4. RESULTS OF CASE STUDY: 7 JUNE 1984

TOVS data for the NOAA-8 pass over the USA at 1350Z on 7 June 1984 have been processed by 3 methods. The pre-processing was the same in each case, using standard Export Package routines; HIRS calibrated brightness temperatures were converted to nadir and window channels corrected for water vapour, and MSU channels were corrected for off-nadir, surface emissivity and antenna gain pattern effects and then mapped to HIRS sounding locations. Three different methods have been applied to the cloud-clearing and inversion stages of the retrieval, and then common routines have been used to derive thicknesses, thermal winds, etc, from the retrieved temperature and humidity profiles. For each method the retrieved values of the 1000-500 mb thickness are presented for illustration.

The first method, illustrated in figure 2, is the standard operational method currently used at the Meteorological Office (Eyre, 1984b). The statistical inversion has used NESDIS regression coefficients for the appropriate week.

The second method, illustrated in figure 3, is the same as the first, except that the regression coefficients have been generated from a set of "historical" radiosondes and corresponding, theoretically calculated radiances for June for the European / N Atlantic area (see section 3.1). The coefficients are required both in the inversion and in the prediction of MSU channel 2 from HIRS brightness temperatures, which plays a vital role in the cloud-clearing. The application of the method to this particular case study is not entirely satisfactory for two reasons. Firstly, the regression coefficient data base was not designed to be used over continental USA and the Caribbean. Secondly, it is necessary in a physical-statistical method such as this to apply corrections for the biases between measured and
theoretically computed brightness temperatures, and these have not been thoroughly evaluated for NOAA-8. For these reasons the results may not merit too close a scrutiny and have not been analysed in detail. Nevertheless, they appear to be generally satisfactory. In particular, more retrievals have been obtained than with the first method (497 compared with 329), the increase coming mainly from a much greater number of N* retrievals. We have not made a detailed comparison of the retrieval types (clear, N* or MSU-only) with the corresponding AVHRR image in this case. However, in other cases for which such a comparison has been made, it has been found that the detection of low cloud is significantly better than with the NESDIS regression coefficients.

Figure 4 shows the results with the new cloud-clearing scheme outlined in section 3.2, also using the regression coefficients derived from the data base described in section 3.1. Validation of the new scheme is not yet complete, and so the results presented here are for illustration of the technique only. Qualitatively the results have the expected characteristics. The retrievals yield a denser and more continuous field, since a retrieval is attempted at each HIRS spot except over very high terrain. (To make the plotted fields legible, not all retrievals are shown in figure 4). Also the local noise in the retrievals is much lower than with the other two methods, in line with the objective of obtaining brightness temperature fields which are more horizontally consistent.

REFERENCES


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calculating synthetic HIRS-2 and MSU equivalent black body temperatures. Internal report, Met.0.19 Branch Memorandum 75.

Kelly G A, Powers P E, Gauntlett F J (1976): Temperature and water vapour retrievals from the NOAA 4 satellite in the Southern Hemisphere. Proc Symp on meteorological observations from space -- their contribution to FGGE; 8-10 June 1976; Philadelphia; pp 77-84.


Watts P D, 1984a: Statistical retrieval of humidity profiles from TOVS data. Internal report, Met.0.19 Branch Memorandum 74.

### TABLE 1

**MSU "asymmetry corrections" for NOAA-7 (in K)**
(as provided by CIMSS, Madison)

<table>
<thead>
<tr>
<th>MSU scan position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<td>channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MSU-2</td>
<td>1.36</td>
<td>0.90</td>
<td>0.57</td>
<td>0.29</td>
<td>0.11</td>
<td>0.00</td>
<td>0.08</td>
<td>0.21</td>
<td>0.42</td>
<td>0.73</td>
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<tr>
<td>MSU-3</td>
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<td>0.17</td>
<td>0.07</td>
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<td>0.11</td>
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<tr>
<td>MSU-4</td>
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<td>0.11</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.04</td>
<td>0.05</td>
<td>0.13</td>
<td>0.17</td>
<td>0.15</td>
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</table>

**MSU "residual scan-dependent corrections" for NOAA-7 (in K)**
(correction = mean value in spot n - mean value in spot 6, and is to be applied by subtracting it from the existing corrections given above)

<table>
<thead>
<tr>
<th>MSU scan position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>0.08</td>
<td>0.22</td>
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<td></td>
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<tr>
<td>MSU-4</td>
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<td>0.10</td>
<td>0.01</td>
<td>0.00</td>
<td>0.03</td>
<td>0.09</td>
<td>0.24</td>
<td>0.40</td>
<td>0.58</td>
</tr>
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### TABLE 2

**December 1984 collocation statistics.**
(Differences between retrievals and collocated radiosondes)

<table>
<thead>
<tr>
<th>Pressure (mb)</th>
<th>Thickness (dam)</th>
<th>Temperature (K)</th>
<th>Dew Point (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias</td>
<td>SD</td>
<td>Bias</td>
</tr>
<tr>
<td>100</td>
<td>-0.41</td>
<td>5.02</td>
<td>-0.41</td>
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<tr>
<td>150</td>
<td>0.44</td>
<td>4.24</td>
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<tr>
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<tr>
<td>300</td>
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<td>4.07</td>
<td>0.53</td>
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<tr>
<td>400</td>
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<td>3.61</td>
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</tr>
<tr>
<td>500</td>
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<td>3.08</td>
<td>-0.29</td>
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<tr>
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<td>2.12</td>
<td>-0.39</td>
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<tr>
<td>850</td>
<td>-0.59</td>
<td>1.31</td>
<td>-0.27</td>
</tr>
<tr>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-2.06</td>
</tr>
</tbody>
</table>

70
Figure 1: Illustrating a two-dimensional sequential estimation scheme for improving the cloud-cleared brightness temperature field.

\[ x_{n,m} \] is the original estimate and \( \hat{x}_{n,m} \) the new estimate at spot \((n,m)\).

\[ \rightarrow \text{"forward filter" and } \rightarrow \text{"backward filter"} \] indicate the flow of information for improving the estimate at spot \((n,m)\).
Figure 2

1000-500 mb thickness values from NOAA-8 TOVS data at 1350Z on 7 June, 1984. Operational retrieval scheme (using NESDIS regression coefficients).
Figure 3

1000-500 mb thickness values from NOAA-8 TOVS data at 1350Z on 7 June, 1984. Retrieval scheme as for figure 2, except using locally generated regression coefficients.
Figure 4

1000-500 mb thickness values from NOAA-8 TOVS data at 1350Z on 7 June, 1984. New cloud-clearing scheme and locally generated regression coefficients.
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