PRELIMINARY RESULTS FROM USING NON-LINEAR OPTIMAL ESTIMATION RETRIEVALS IN THE CANADIAN REGIONAL ANALYSIS SYSTEM

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1. INTRODUCTION

We have carried out non-linear optimal estimation retrievals for several TOVS passes over eastern North America and the western Atlantic following the approach developed by Eyre (1987). The background field was a six-hour forecast produced by the Canadian hemispheric spectral model. Regional analyses on a 100 km grid were performed using the TOVS retrievals only. The TOVS-only analysis increments (i.e. analysis minus trial field differences) were compared to analysis increments based on conventional data. Although the TOVS-only analyses did not account for the error characteristics particular to the retrievals, they did provide an indication of the changes the retrievals could make to the trial field. In this paper we present some results from the comparisons, which were intended to provide a preliminary assessment of the performance of the retrieval scheme.

2. RETRIEVAL SCHEME

Although the retrieval scheme we used generally follows the approach proposed by Eyre (1987), there are some differences in the profile vector, the measurement vector, and the calculation of the Jacobian.

The profile vector contains the temperature and water vapour profiles, the cloud top pressure, cloud amount, and the (surface skin temperature minus surface air temperature) difference. Relative humidity is used as the water vapour variable. The temperature and relative humidity profiles are represented by a linear combination of first-order B-splines (chapeau functions) with the knots at the pressure levels used by the analysis scheme.

The measurement vector contains brightness temperatures for HIRS channels 1-8 and 10-15 in addition to MSU channels 1-4. Over water, an external estimate of the sea surface temperature as well as near-surface air temperature and relative humidity estimates retrieved from GOES images by a cloud classification scheme (Garand et al. 1989) could be added to the measurement vector.

The calculation of the Jacobian is based on the approximation scheme used by Eyre (1987). Extra terms resulting from the choice of moisture variable appear in the derivatives of the brightness temperatures with respect to the atmospheric temperature profile. These terms describe the effect of the change in transmittance which results from the change in mixing ratio when the temperature is changed holding relative humidity constant. An extra factor (the derivative of mixing ratio with respect to relative humidity) also appears in the "moisture profile" rows of the Jacobian.

The Jacobian calculation code was tested by comparing it with the "brute force" approach used in previous work (Steenbergen et al. 1988). Test retrievals for the May-June 1984 data set used in that work were done using the same constraints (a constant first guess and climatological covariance matrix derived from radiosondes), and changing only the method of calculating the Jacobian. Results from the new Jacobian calculation code were essentially the same as results using the "brute force" method.

The TOVS retrievals were carried out every third HIRS spot using single-pixel HIRS data from three NOAA-9 passes on 6 March 1986.

3. RETRIEVAL CONSTRAINTS AND ANCILLARY MEASUREMENTS

The background error covariance matrix for temperature and relative humidity was estimated from collocated radiosonde and six-hour model forecasts collected between 15 January and 15 March 1986 (during the GALE/CASP experiment). The cloud top pressure, cloud amount, and microwave emissivity background values and covariances were as in Eyre (1987). The background value of the surface skin temperature - surface air temperature difference was set to zero and the standard deviation of this quantity was set to 2 K. However, over water where both a sea-surface temperature estimate and a near-surface air temperature retrieval (from cloud classification) were available, the constraint on the air-sea temperature difference was relaxed by setting its standard deviation to 10 K.

The brightness temperature error covariance matrix was estimated using collocated radiosondes and satellite observations obtained during clear conditions. The collocations were obtained over central and eastern North America between 10 February and 4 March 1986. The same data were used for estimating the empirical forward model corrections which were applied. The (observed minus calculated) brightness temperature variances were multiplied by 50% to try to account for collocation errors and sonde errors.[1] The off-diagonal elements of the measurement error covariance matrix were set to zero.

Sea-surface temperature estimates obtained from the NESDIS Monthly Oceanographic Summary were used over the region from the coast of North America east to approximately 55W. The Summary contains monthly mean SST values at a resolution of 1 degree latitude by 1 degree longitude. To obtain an estimate of the error variance of the SST estimates, we used a chart of the standard deviation of the difference between the daily SST and the monthly mean from Van Loon (1984). Only two charts were available (for January and June) so we used the January one. The standard deviation values were manually digitized from the chart on a 1 degree latitude by 1 degree longitude grid and the values were rounded up to the nearest half degree.

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[1]The variances for HIRS channels 7, 8, 10, 12, and 13 were multiplied by smaller factors (35%, 20%, 30%, 20%, and 35% respectively) on the assumption that collocation errors and skin temperature effects would have a larger influence on these channels.

The SST estimates and their variances were then interpolated to the TOVS sounding locations using a Cressman analysis.

The near-surface air temperature and dewpoint depression retrievals were obtained from Dr. Louis Garand, who retrieved them using the technique described in Garand et al. (1989). The retrievals are based on a cloud classification technique using GOES data. Each retrieval is accompanied by an estimate of its error variance which varies according to the cloud class. The retrievals and their error variances, which were available at roughly 150 km intervals, were also interpolated to the sounding locations using a Cressman analysis. The retrievals covered roughly the same area as the SST data.

Comparisons of retrievals over water with and without the additional constraints (from the SST, and near-surface air temperature and dewpoint depression retrievals) were only partly completed. The results will be presented in a future paper.

4. THE REGIONAL ANALYSIS SCHEME

The regional analysis scheme used in this study is currently under development at the Canadian Meteorological Centre (CMC), where it will be used to provide analyses for the regional model. The regional analysis code allows the horizontal and vertical resolution of the analysis to be easily changed. The regional analysis is based on updating a six-hour forecast by either the hemispheric spectral or the regional finite-element model. For this study, we used 11 levels in the vertical (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, and 50 mb) and a horizontal resolution of 100 km. The trial fields for this study came from the hemispheric spectral model (running at T89 resolution) which was initialized from archived CMC analyses.

The regional analysis is a dimensionally split scheme in which the vertical analysis step is done first at each observation site followed by a set of horizontal analyses (one per variable (u,v,z,T, and $T-T_d$) for each pressure level). Each of the vertical and horizontal steps is multi-variate. Eyre (1987) proposed that a one-dimensional non-linear optimal estimation TOVS retrieval could be considered as the vertical analysis step in such a split scheme. The horizontal analysis would take into account the vertical analysis error produced by each retrieval. In this preliminary investigation, we did not use this information in the horizontal analysis. The retrieved temperature and moisture profiles were treated as if they were radiosondes and given the same observational errors. This simplistic treatment would not be suitable if the TOVS data were being combined with other data in the analysis. However, when the TOVS data are used alone, it is sufficient to indicate the direction and strength of the signal in the differences between the TOVS retrievals and the trial field.

5. QUALITY CONTROL

The TOVS retrievals were subjected to two levels of quality control. Before being passed to the analysis, retrievals which had failed to converge (i.e. those in which any element of the profile vector was still changing by more than 10% of its background standard deviation after 11 iterations) were removed. Brightness temperatures were also calculated from the retrieved profiles and compared to the observed values. Retrievals for which two or more observed brightness temperatures differed from the calculated values by more than twice their a priori standard deviations were also removed. These two filtering steps removed about 7% of the retrievals.

The retrievals were also subjected to the operational quality control routines which form part of the regional analysis package. The same rejection criteria which are used for radiosondes were applied, resulting in rejection of about 2% of the retrievals. The main cause of rejection appeared to be unreasonably cold temperatures in the lowest levels associated with low-level cloud.

6. TEMPERATURE ANALYSIS COMPARISONS

A regional analysis for 1200Z 6 March 1986 was carried out using all available conventional data. The locations of radiosonde observations used in the analysis are shown in figure 1. The rectangle in the figure shows the coverage of the TOVS data from NOAA-9 orbit 6333. The time of the TOVS observations was about 0945Z. NLOE TOVS retrievals using a four-hour forecast valid at 1000Z were performed and an analysis using TOVS data only was done using the 1000Z trial field. Figure 2 shows a cross-section of the 1200Z temperature analysis increments along the line A-B-C-D-E in figure 1. Figure 3 shows a cross-section of the temperature analysis increments along the same line for the TOVS-only analysis.

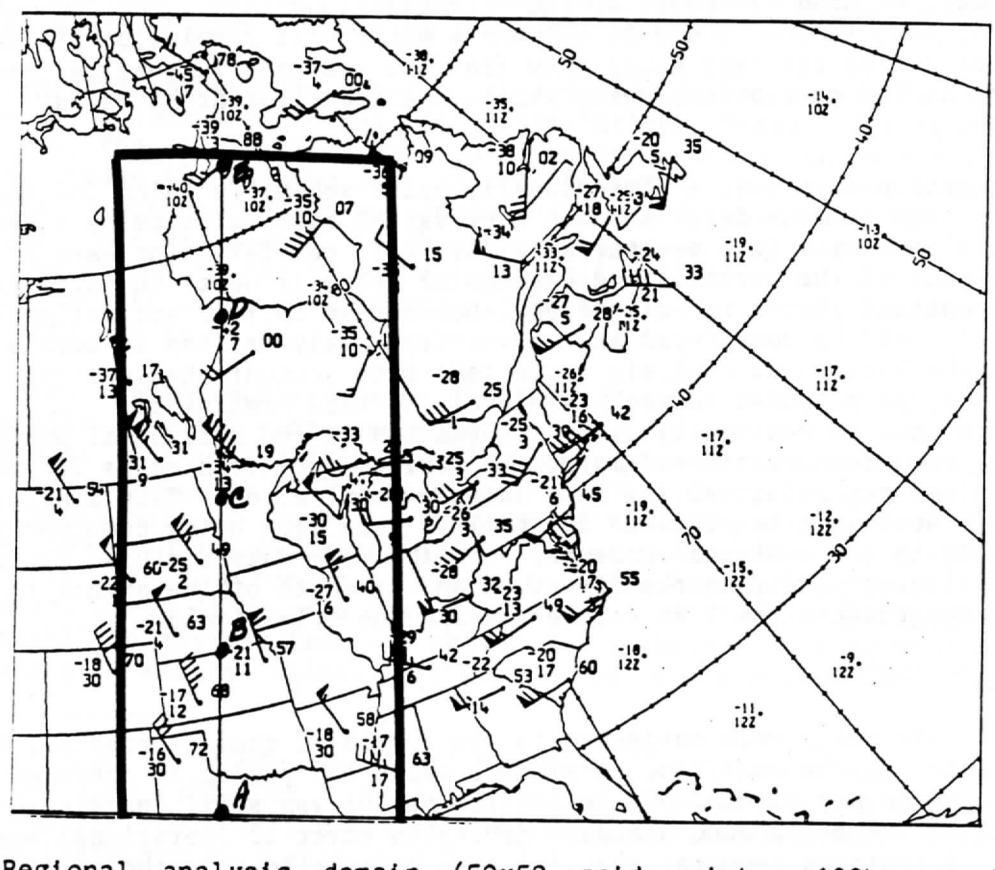

Fig. 1 Regional analysis domain (50x50 grid points, 100km resolution) and plotted data in standard format for 1200 Z 6 March 1986. Line segment ABCDE indicates the baseline of the cross-sections in Fig. 2 and Fig. 3. The rectangle indicates the TOVS data coverage of orbit 6333.

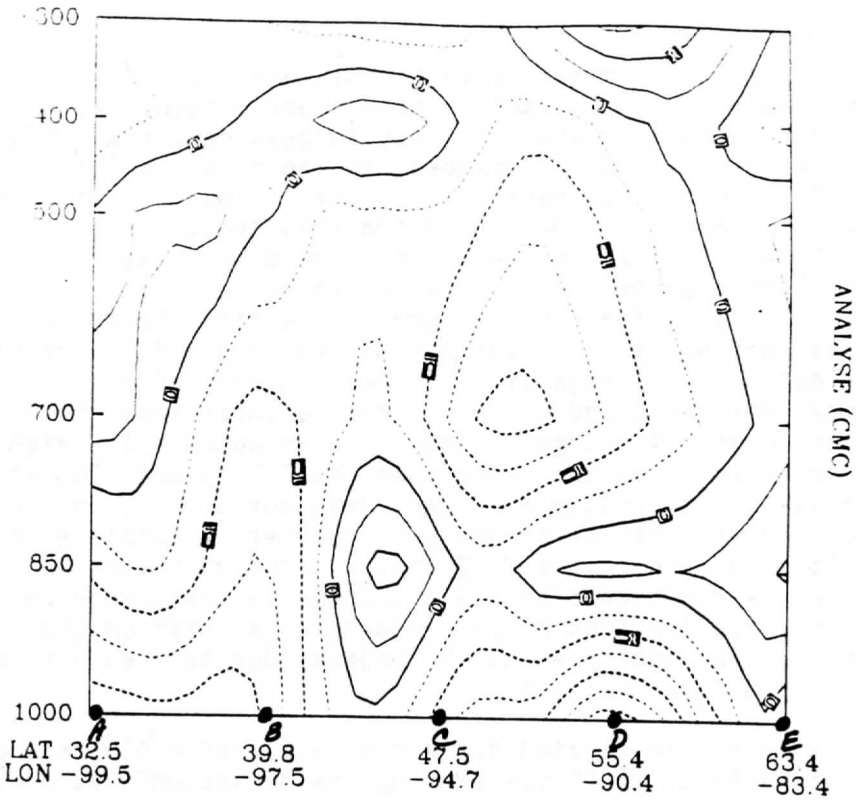

Fig. 2 Cross-section of the temperature analysis increments between 1000 and 300 mb using conventional data only. Baseline indicated in Fig. 1.

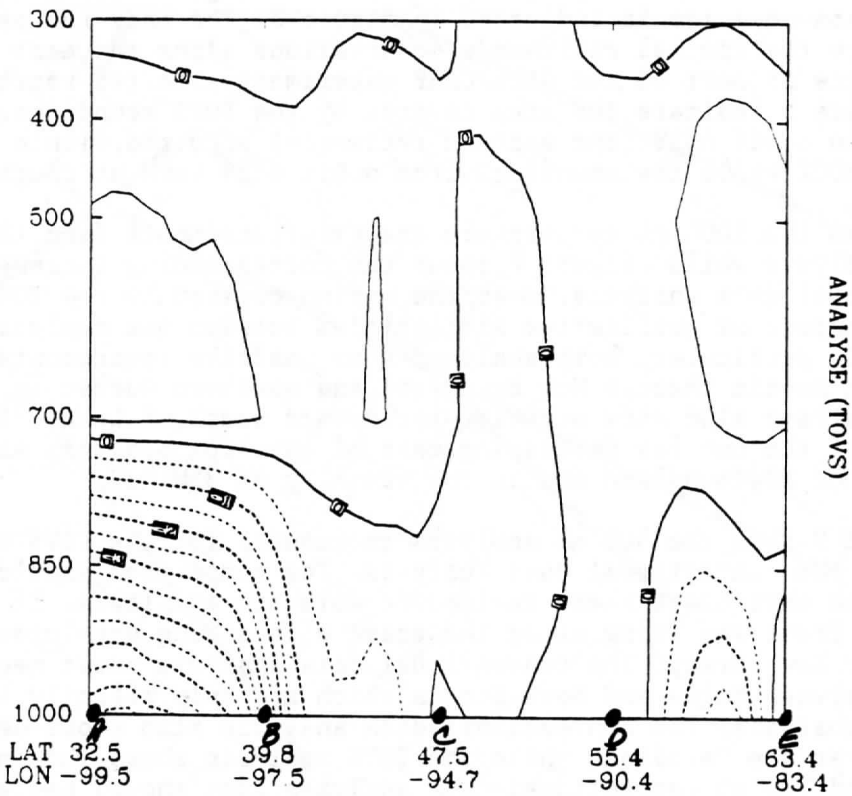

Fig. 3 Same as Fig. 2 but using TOVS data only.

Not surprisingly, the analysis increments obtained from the radiosonde data show much more amplitude and structure than those obtained from the TOVS. The TOVS analysis increments are generally largest near the surface. The negative increments (cooling with respect to the trial field) below 700 mb between A and B in both cross-sections are associated with high terrain; the very large increments at 1000 mb in the TOVS section are probably an artifact resulting from different extrapolation procedures. The AVHRR imagery and surface reports show that skies were clear and strong nocturnal cooling was occurring at the southern end of the cross-section. Both TOVS and radiosondes show positive increments between 500 and 700 mb near A but the TOVS does not show the negative increments above 400 mb indicated by the radiosondes. Between B and C the radiosonde increments show complex vertical structure with 4 changes of sign in the column. The sign of the TOVS increments agrees with the radiosondes at 300 mb and 1000 mb but the structure between is vertically averaged. Just north of C, on the other hand, the radiosondes indicate a much deeper layer of negative increments. This feature is also seen in the TOVS analysis but with much less intensity. At D the radiosonde analysis increments again show several changes of sign. This location corresponds to a calibration gap in the TOVS data. At E the warming indicated by the radiosondes between 850 and 400 mb is also seen in the TOVS analysis.

TOVS retrievals were also carried out for NOAA-9 orbits 6338 and 6339. A 6-hour forecast valid at 1800Z was used as the background field for both orbits. An analysis was done using only the TOVS data from the two passes together and the 1800Z forecast as the trial field. An 1800Z analysis was also done using all available conventional data. The surface data coverage used in the conventional analysis is indicated in figure 4, and the radiosonde data coverage is indicated in figure 5. The only radiosonde data available were the special radiosonde observations along the east coast which were made as part of the GALE/CASP experiment. The two rectangular boxes in figure 5 indicate the area covered by the TOVS soundings. The soundings from orbit 6338 (the eastern rectangle) occurred within a few minutes of 1800Z while the soundings from orbit 6339 were at roughly 1930Z.

Figure 6 shows the 1000 mb temperature analysis increments from the TOVS-only analysis while figure 7 shows the corresponding increments from the conventional data analysis. Over the region covered by the TOVS data, there are a number of qualitative similarities between the analysis increments. In particular, both analyses show positive ioncrements from south of Nova Scotia through New Brunswick and southern Quebec to James Bay. Both analyses also show negative increments south of Lake Erie, which is upstream of the new low developing east of the Appalachians; as well as to the south of Newfoundland and in the vicinity of 35N 63W.

Figures 8 and 9 show the 500 mb analysis increments for the TOVS-only analysis and the conventional data analysis. The comparison should be limited to the east coast where radiosonde data are available. It should be noted that a front was lying along the coast with strong development ocurring over New Jersey. The conventional data analysis shows negative increments between Maine and Nova Scotia which are only slightly indicated on the TOVS analysis. The conventional data analysis also shows negative increments over the Carolinas while the TOVS analysis shows the opposite. The 850 mb and 700 mb conventional data analyses (not shown) had positive increments over this region which were reflected in the TOVS analysis.

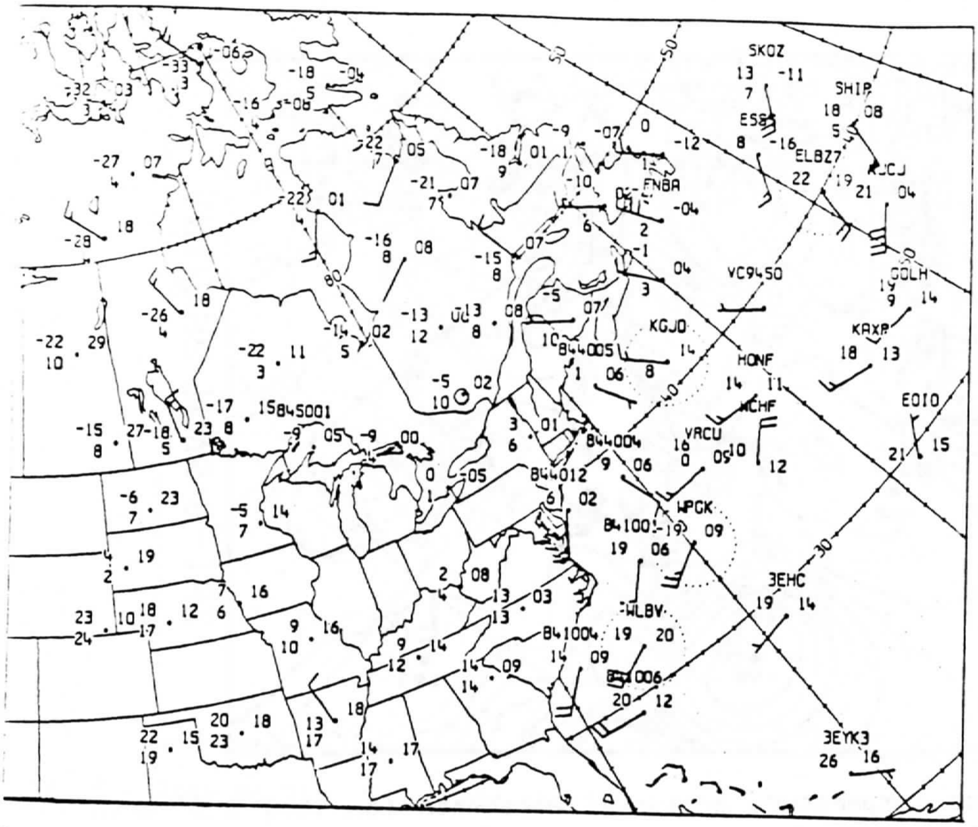

Fig. 4 Plotted surface data for the 1800 Z 6 March 1986 case.

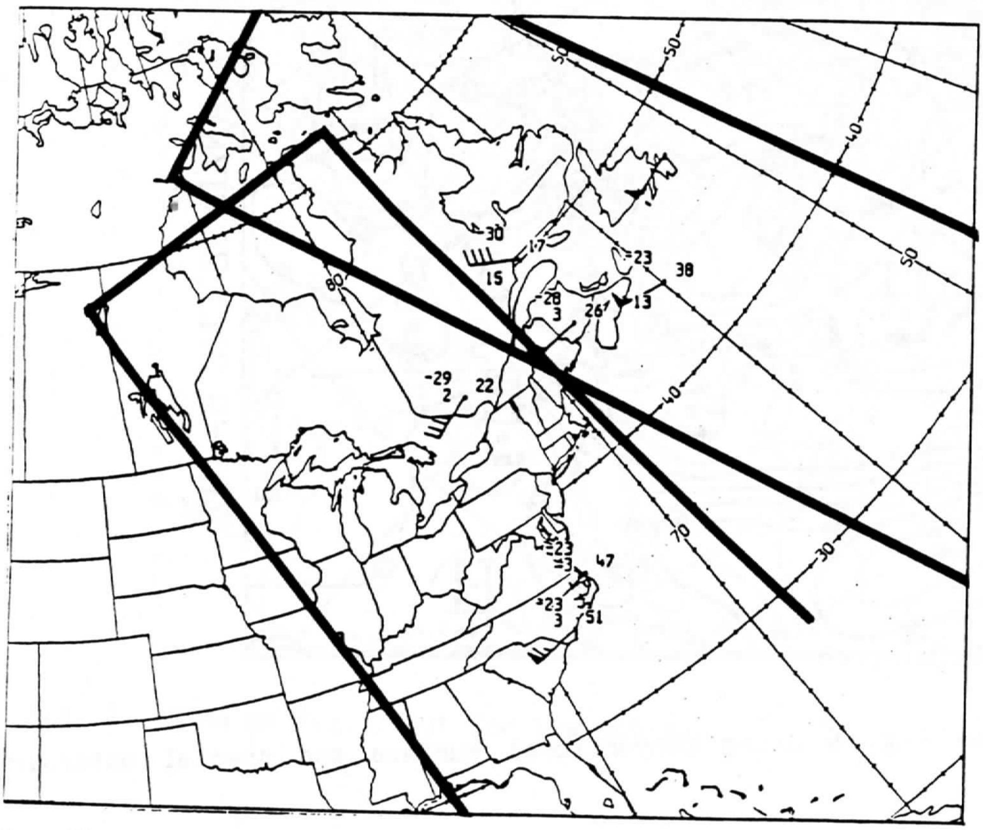

Fig. 5 Plotted special CASP radiosonde data for 1800 Z 6 March 1986. The two rectangles indicate the TOVS data coverage of orbits 6338 and 6339.

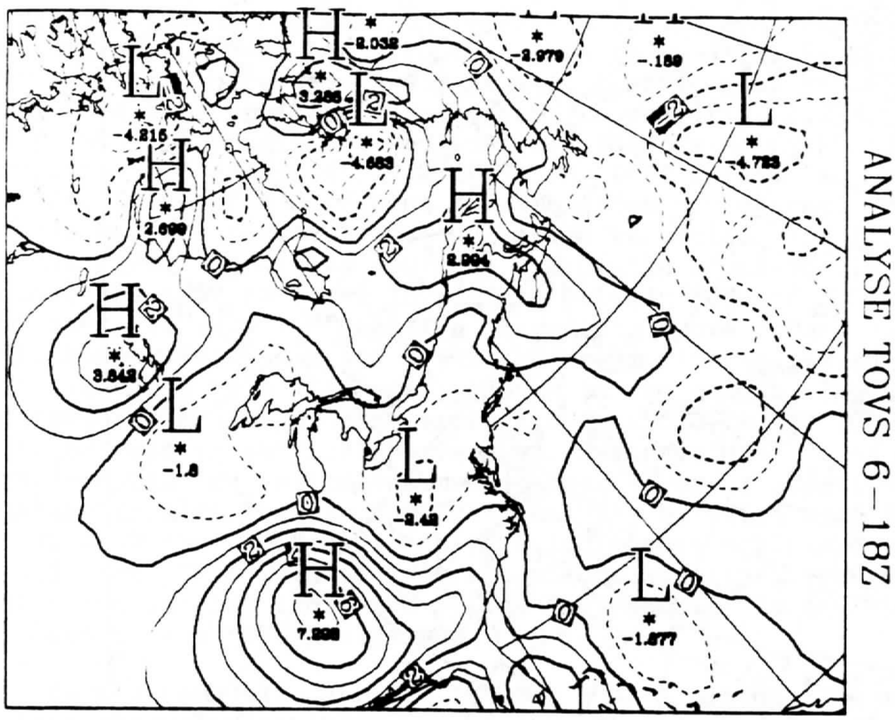

Fig. 6 1000 mb temperature analysis increments for 1800 Z 6 March 1986 using TOVS data only.

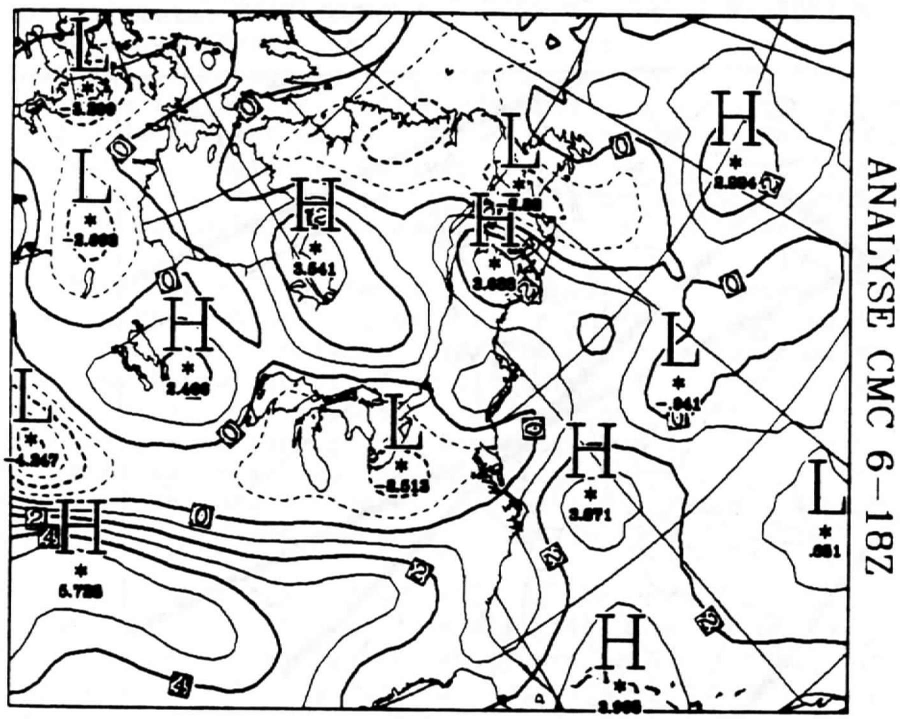

Fig. 7 Same as Fig. 6 using conventional surface and special upperair data only.

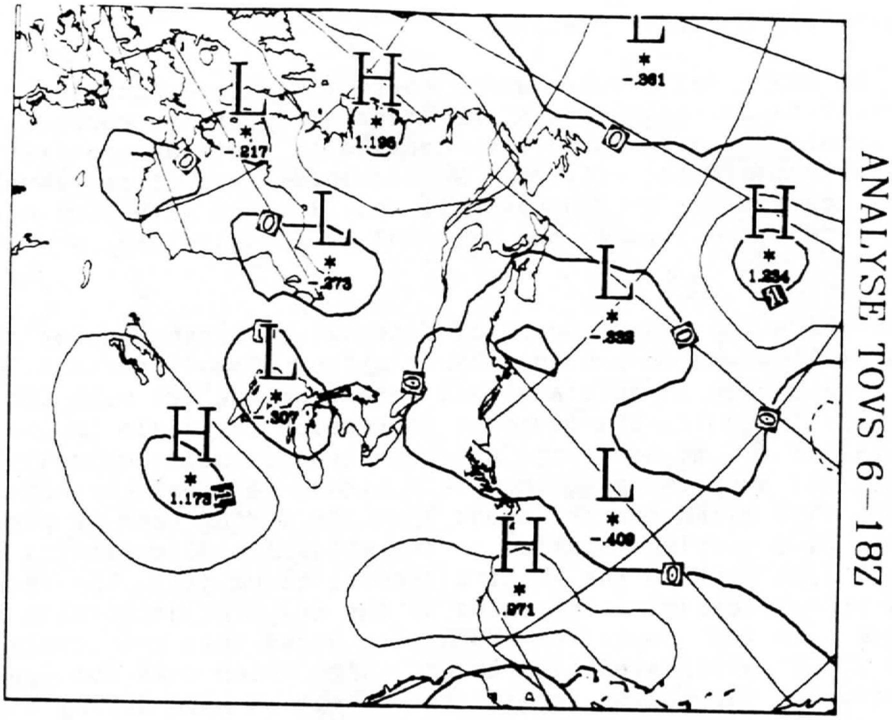

Fig. 8 Same as Fig. 6 but for the 500 mb.

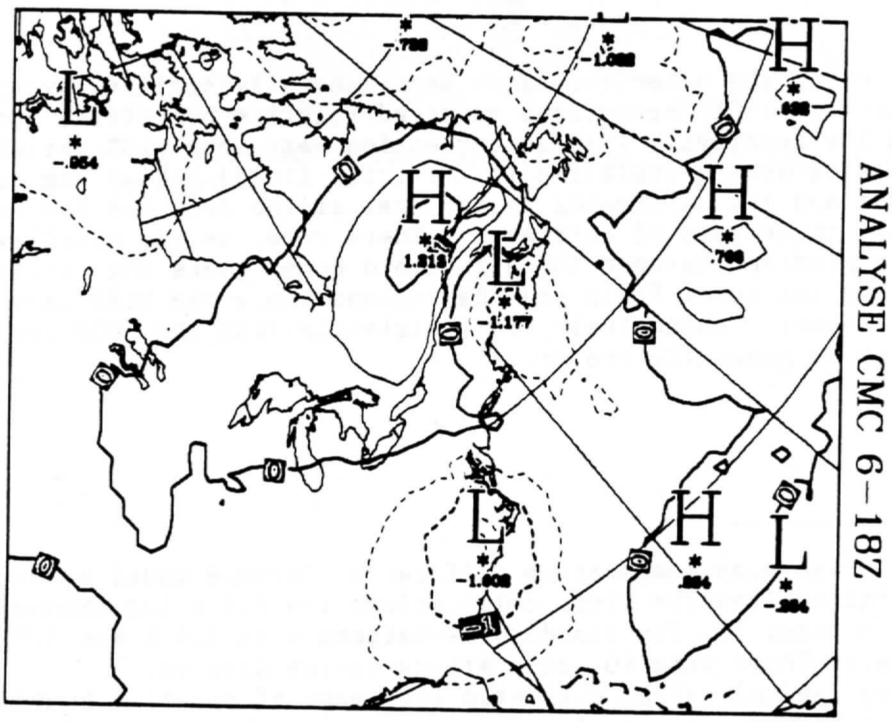

Fig. 9 Same as Fig. 7 but for the 500 mb.

7. RESULTS FROM HUMIDITY ANALYSIS

Because the empirical forward model corrections for channels 11 and 12 were particularly large, and because the uncertainty of the corrections for those channels was also large[2], we decided to test the sensitivity of the retrievals to those corrections. We did three sets of retrievals with different corrections for channels 11 and 12 - one with 100% of the values obtained from collocations, one with 50% of those values, and one with no correction.

Figure 10 shows the 500 mb dewpoint depression increments for the TOVS-only analysis at 1800Z March 6 using the data from NOAA-9 orbits 6338 and 6339. The retrievals used in this analysis were from the set with 50% corrections in channels 11 and 12. The dewpoint depression residuals in the TOVS analysis above 700 mb are large and show considerable horizontal structure. They also, not surprisingly, show very strong vertical correlation. Comparison with AVHRR imagery shows that the strong band of positive increments (i.e. drying relative to the trial field) extending from 33N 55W to 40N 47W lies just to the NW of a frontal cloud band. The result in the analysis is considerable tightening of the dewpoint depression gradient associated with the front. The AVHRR also shows that the moistening region near 43N 50W is associated with an occlusion which does not appear strongly in the dewpoint depression trial field. There is also drying indicated behind the cold front associated with the developing system on the east coast although there is a region of drying to the southwest of the frontal band (in its less active region) as well.

The patterns in the other two cases were generally similar, except that the retrievals with 100% corrections produced relative humidities about 10-15% drier and the retrievals with no correction were about 10% wetter.[3] The regions of drying (relative to the trial field) behind the frontal cloud bands and the moistening in the area of the occluded low could be seen in all three sets of retrievals. There were, as one would expect, changes in gradient between the high-cloud areas where the retrievals were dominated by the trial field and the regions where the HIRS data had a strong influence. Subjectively, the retrievals from the 100% correction set appeared to be generally too dry.

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[2] The mean brightness temperature difference (forward model minus observed value) obtained from the clear collocations was 2.4 K for channel 11 and 4.5 K for channel 12. The standard deviations were 2.4 K and 3.8 K respectively. There were 90 collocations in the data set.

[3] These were typical values estimated from maps of relative humidity differences between the retrieval sets. Areas with high cloud where the retrievals were dominated by the background field, and areas where either 0 or 100% relative humidity values were retrieved were excluded. The differences between the retrievals were largest at 300 mb and almost disappeared below 700 mb. As one would expect, the differences were also larger in the north than in the south (by about 5% in relative humidity).

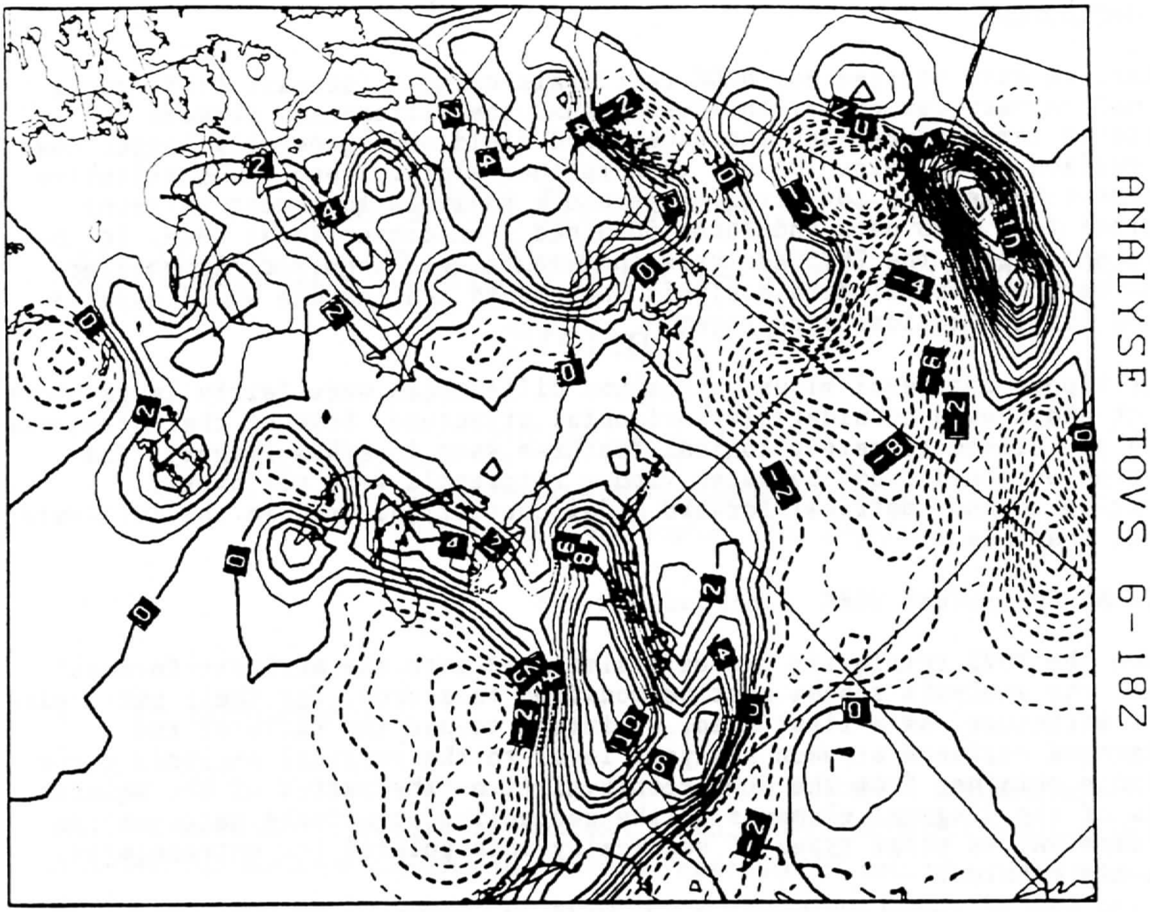

Fig. 10 500 mb dewpoint depression analysis increments for 1800 Z 6 March 1986 using TOVS data only.

8. CONCLUSIONS

So far, we have carried out NLOE retrievals using a forecast first guess for only a very few cases. In those cases, the differences between retrieved temperatures and the background field were generally larger near the surface (i.e. below 700 mb) than further aloft. There was qualitative agreement beween the low-level temperature analysis increment patterns obtained from TOVS data and those obtained from conventional data. In the mid-troposphere, the TOVS analysis increments were considerably smaller than the conventional data analysis increments and (as one would expect) showed little vertical structure.

Water vapour retrieval minus background differences were fairly large above 700 mb and showed considerable horizontal structure. Some of that structure could be related to meteorological features seen in AVHRR imagery. The patterns obtained from the water vapour retrievals were not overly sensitive to the empirical forward model corrections used in the TOVS water vapour channels.

9. PLANS FOR FUTURE WORK

Before the TOVS retrievals can be assimilated into the analysis/forecast cycle, the analysis scheme must be modified to account for their particular error structure. As a first step, we intend to use the ratio of the background variance at each analysis level to the vertical analysis error variance obtained from the NLOE retrieval (i.e. the ratios of the square roots of the diagonal elements of the respective covariance matrices) in the same way as other types of vertically interpolated (or extrapolated) data are treated.

We expect that the largest impact of TOVS data in the Canadian forecast system would come from data over the eastern Pacific. We intend to carry out a several-week test using TOVS data over that region from either January/February 1987 or February 1989.

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