THE USE OF ATOVS DATA IN THE CMC 3D VARIATIONAL ANALYSIS SYSTEM: ESTIMATION AND IMPORTANCE OF OBSERVATION ERRORS

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ABSTRACT

In June 1997, the CMC implemented its first global 3D-var analysis system for the preparation of daily 10 day forecasts. In the autumn of the same year, this incremental 3D-var was introduced for the preparation of the 35-km regional model analyses, later upgraded to a resolution of 24-km a year later. Both the global and regional systems produce increments on a 16 pressure level grid with the top level at 10 hPa. In their first implementation, because geopotential is used as mass variable and not temperature, it was decided to retain SATEM thickness as the main source of satellite data for the analysis. However, preliminary tests to replace SATEM retrievals with RTOVS/ATOVS radiances are very promising and the use of the former is about to cease.

Consistent with the variational approach where data is ingested by the system in its native or raw form, a complete monitoring system has been built to learn about the radiance data and most importantly to characterize its errors prior to assimilation tests. One of the most negative sources of error for any data type is a bias and this system's primary task is to monitor the bias as a function of time over large oceanic and continental areas. Once the monitoring is completed and the data are considered free of systematic errors, they are ready for assimilation. The data are then tested in pre-implementation suites and again monitored from within the analysis system so that final adjustments can be made to the specified error characteristics.

Results from data assimilation experiments and 10-day forecasts are presented. These show that significant progress can be achieved using RTOVS/ATOVS radiance data rather than SATEM retrievals, and that radiance data monitoring and quality control are key components of the analysis system.

1. INTRODUCTION

The SATEM data that is currently used in both the regional and global 3D-var operational analysis systems at the Canadian Meteorological Centre (Gauthier *et al.*, 1998) are thickness retrievals produced by NESDIS and readily available on the GTS. The direct assimilation of radiance data can improve the analysis as preliminary experiments using NOAA-11 and NOAA14 radiances have shown (Chouinard and Hallé, 1999), much like other centers have shown (Derber and Wu, 1998; Anderson *et al.*, 1998).

In this study, the steps needed to use the ATOVS data from NOAA-15 are described. This study differs from our most recent in that the radiative transfer model (RTM) used (RTTOV version 5), as well as a new global environmental multiscale (GEM) NWP forecast model described in Côté *et al.*, 1998.

Despite significant improvements in the radiative transfer modeling (Saunders and Matricardi 1997), there still remain very large biases in some channels. This cannot be attributed to data pre-processing since the ATOVS is distributed with minimum pre-processing. These biases in some channels are as large as the random errors and it is crucial to remove them prior to the assimilation step in order to achieve positive results. We will describe how a monitoring system has been integrated into the 3D-var system to estimate and effectively remove the biases. This system works in the following way. Biases are first estimated from one-month ensemble mean of the innovations in each channel. Because it is assumed that the error comes from the radiance data only and not the NWP model providing the first guess used to prepare the innovations, the radiance data are corrected prior to the assimilation step. Moreover, the corrected innovations provide a basis from which first estimate of random or observation errors are calculated.

2. THE 3D VARIATIONAL ANALYSIS

As proposed by Parrish and Derber. (1992) and Courtier et al. (1994), and without any loss of generality, the 3D-var formulation of this study is based on the incremental approach. For the incremental approach, the functional that is minimized is expressed as,

$$J(\Delta\tilde{X}) = (\Delta\tilde{X})^T B^{-1}(\Delta\tilde{X}) + (H'(\Delta\tilde{X}) - R')^T O^{-1}(H'(\Delta\tilde{X}) - R') \quad (1)$$

where $R' = R - H(X_b)$ are the observed innovations, and $\Delta\tilde{X}$ are the analysis increments. The innovations R' are computed in observation space using the full resolution background state X_b, whereas the analysis increments $\Delta\tilde{X}$ are calculated at lower resolution. In this study, the trial fields are used at the full resolution

(0.9-degree grid) of the GEM model and the analysis increments $\Delta\tilde{X}$ are calculated at the lower T108 spectral resolution. It remains a spectral analysis system even though the driving model is a global grid point model. This formulation is general enough to allow the use of higher vertical resolution trial fields to calculate the observed innovations. This was not exploited in this version. The CMC 3D-var remains a 16 pressure level system even though the GEM model is on 28 levels. For more details on the system the reader is referred to the papers by Gauthier *et al.* 1999 and Côté *et al.*, 1998.

3. PREPARATION AND MONITORING OF THE ATOVS and RTOVS DATA

The radiance data used in this study are of two types: the so-called revised TOVS (RTOVS) from NOAA-14 and the advanced TOVS (ATOVS) from NOAA-15. RTOVS data are radiances which have undergone some adjustments (Paris, 1997), including a statistically based limb adjustment. These data are also cloud-classified as clear or cloudy. The ATOVS data are cloud-classified but not limb adjusted. Finally, NOAA-15 has 15 thermal microwave channels whereas NOAA-14 has only 4.

The quantities that are monitored are the mean and square of the innovations i.e. the difference between simulated and observed radiances. The simulated radiance is calculated using RTTOV given a 6-hour forecast model state. The mean or bias of the innovations in each channel is monitored so as to ensure that, over large ensembles (space and time), it is very small, ideally zero. The square of the innovations is also used in the variational analysis and, in the monitoring system, it is used mainly to provide a-priori estimates of the random component of the radiance or observation errors. In Fig. 1, the daily variation of global mean bias for a subset of AMSU-A is illustrated with the blue curve. For these channels, the biases are large and can vary from -1 to -2 even though the standard deviations (dotted lines in Fig. 1) are relatively small.

All data used for monitoring and assimilation are quality controlled before use. A first series of checks involve validating the radiance data and its accompanying information, e.g. finding coding errors in the scan position, scan angle, cloud classification, inconsistency between the scan position and scan angle, radiance data out of physical range, etc. A second series of tests, which use the innovations, consist in detecting cloud classification errors, which show up as large cold biases in the HIRS channels 8 and 12 (used for cirrus cloud detection). A rogue check is finally performed to eliminate any residual larger than 4 standard deviations from an a-priori estimate. The complete list of checks follows;

1) invalid satellite data processing technique,
2) invalid land/sea qualifier,
3) invalid terrain type,
4) invalid field of view number,
5) satellite zenith angle out of range,
6) inconsistent field of view and sat. zenith angle,
7) inconsistent land/sea qualifier and model mask,
8) inconsistent terrain type and model ice,
9) uncorrected radiance,
10) rejected by RTTOV5,
11) radiance gross check failure,
12) channel 8 cloud detection test failure (-4/-8/-15 K),
13) channel 12 cirrus cloud detection test failure (<20K),
14) radiance residual rogue check failure (4 std).

3.1 The Bias correction procedure

The large innovation biases, as revealed in the monitoring (Fig. 1), require correction prior to assimilation. A bias correction system, consisting of a set of equations (one per channel j), is used to correct both the scan bias and the air-mass bias in the radiance residual. The correction can be expressed as follows:

$$\langle \delta T_j \rangle = \sum_{i=1}^{n} a_{i,j} P_i + b_j \tag{1}$$

where $\langle \delta T_j \rangle$ are the ensemble mean corrections, n is the number of predictors (8 for RTOVS and 11 for ATOVS). The predictors used are a subset of radiance observations and two positional parameters p, p^2, where p is the scan position number (-28,-27,...,0,...,27,28). The coefficients $a_{i,j}$ and b_j are obtained by regression. In order to ensure that only the biases due to the RTM are removed by the scheme, only the innovations δT over ocean and in proximity to radiosondes are used. The predictors for RTOVS and ATOVS are listed in Table 1.

RTOVS	ATOVS
MSU 2, 3, 4 SSU 1, 2, 3 p, p^2	AMSU-A 6, 7, 8, 9, 10, 11, 12, 13, 14 p, p^2

Table 1. Predictors used to correct the RTOVS and ATOVS radiance.

As indicated in Fig. 1 (the red curve), the bias-correction procedure does well in removing most of the bias. Time-series for the month of June 1999 show how the global bias is removed for the subset of AMSU-A channels presented. For most of these channels, the global bias is larger than one standard deviation; this underlines the importance of removing the bias if any success is to be obtained in assimilating radiance data.

3.2 Monitoring within the 3D-var

Following quality control and bias correction, an "effective" radiance observation error is determined in our system. From the total noise of the system, it is assumed that the noise is partitioned between instrument, RTM, and 6-h background error. The instrument and RTM error are combined and assumed to represent the effective a-priori observation error. That is, (2/3 for RTOVS and 1/2 for ATOVS) of the total variance measured is used as the observation error. The radiance data is then assimilated in the 3D-var. During an assimilation cycle, the innovations are kept on file. At this step, the innovations are in fact the radiance residuals normalized by the a-priori observation error. It is thus possible to verify that ensemble means of the normalized innovations (global 6-h time window) as measured within the 3D-var are truly zero. We can also verify that the normalized mean square error corresponds to the prescribed value, i.e. 1/(2/3)=1.5 for RTOVS and 1/(1/2)=2.0 for ATOVS. Fig.2a illustrates these quantities for a subset of HIRS NOAA-15 channels. It can be seen the normalized biases are close to zero and that the normalized mean square errors are close to the expected value of 1.5 for the first analysis of the cycle, i.e. June 12, 12UTC. However, the mean square errors quickly drop to a lower value, often near 1.0, in this first assimilation test of radiance data into the analysis. Observation errors were thus revised and subsequent monitoring, shown in Fig. 2b, indicate that the normalized mean square errors remained relatively constant near 1.5 during the whole cycle.

Finally, in order to estimate the reduction of variance from the analysis step, the normalized mean square errors are monitored in each of the channels at the end of the minimization step. These are the solution to the analysis problem and thus the normalized analysis increments. When compared to the same quantity at the beginning of the minimization i.e. the innovations, they provide a direct measure of variance reduction and indirectly a measure of the effective weight the data has received. As indicated in Fig. 2c, it is evident that the weight given to the higher peaking ATOVS channels is about 1/2 (lower three plates of Fig. 2c) as specified from a-priori statistics of background and observation errors, but less in the lower peaking channels (upper three plates of Fig. 2c). The HIRS channels (not shown) do not exhibit such a reduction of variance in some channels, it appears that it is more difficult to arrive at appropriate a-priori error estimates for these channels. This is possibly due to cloud contamination and is presently under investigation.

4. RESULTS FROM ASSIMILATION CYCLES

The 3D-var using TOVS data was tested during a 33-day period in June and July 1999 and compared to a control run using SATEM data. Both systems used all other conventional observations as well. Every 36h, 10-day forecasts were prepared from both the TOVS and SATEM runs. In Fig. 3, the 6-h, 2-day and 10-day verification statistics against radiosondes are presented. Over North America (Fig. 3a), errors for TOVS forecasts are significantly smaller in the troposphere from day 2 to day 10 even if the 6-h statistics are not much different. In the Southern Hemisphere (Fig. 3b), large improvements are seen at 6h as well as from day 2 to day 10 in the troposphere. However, errors in the TOVS system above 50 hPa are larger. This problem is related to the top boundary condition of the model and is still under investigation.

5. CONCLUSIONS

A quality control, bias correction and monitoring system has been developed for ATOVS and RTOVS radiance observations to allow their assimilation into a 3D-var analysis system. Further monitoring built within the 3D-var provides a mechanism by which we can validate both the bias correction scheme and the specification of effective observation errors. The effective weight of the data is monitored to improve a-priori estimates of background and observation error statistics.

The assimilation tests show overall improvement in the troposphere with some degradation in the stratosphere, possibly caused by the extrapolation scheme necessary to extend the atmosphere above the NWP model top, i.e. 10 hpa. This problem is compounded by the fact that the current operational global model has a large positive temperature bias at the top level particularly in the tropical band. It appears that the only solution to this problem will be to raise the model top level from the current 10 hPa to the same as the RTM i.e. 0.1 hPa.

6. REFERENCES

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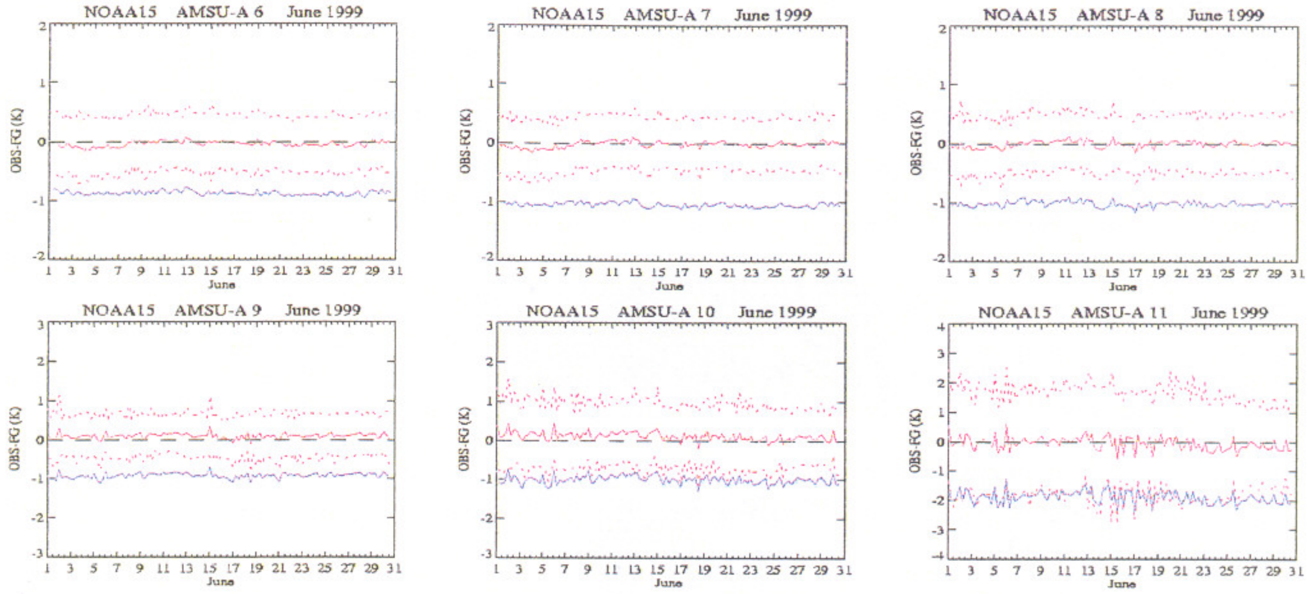


Fig. 1. Time series of residual global biases, uncorrected (solid blue) and corrected (solid red), for NOAA-15 AMSU-A channels 6 to 11 for the month of June 1999. The dashed red lines represent plus and minus one standard deviation from the corrected bias. Units are in degrees Kelvin.

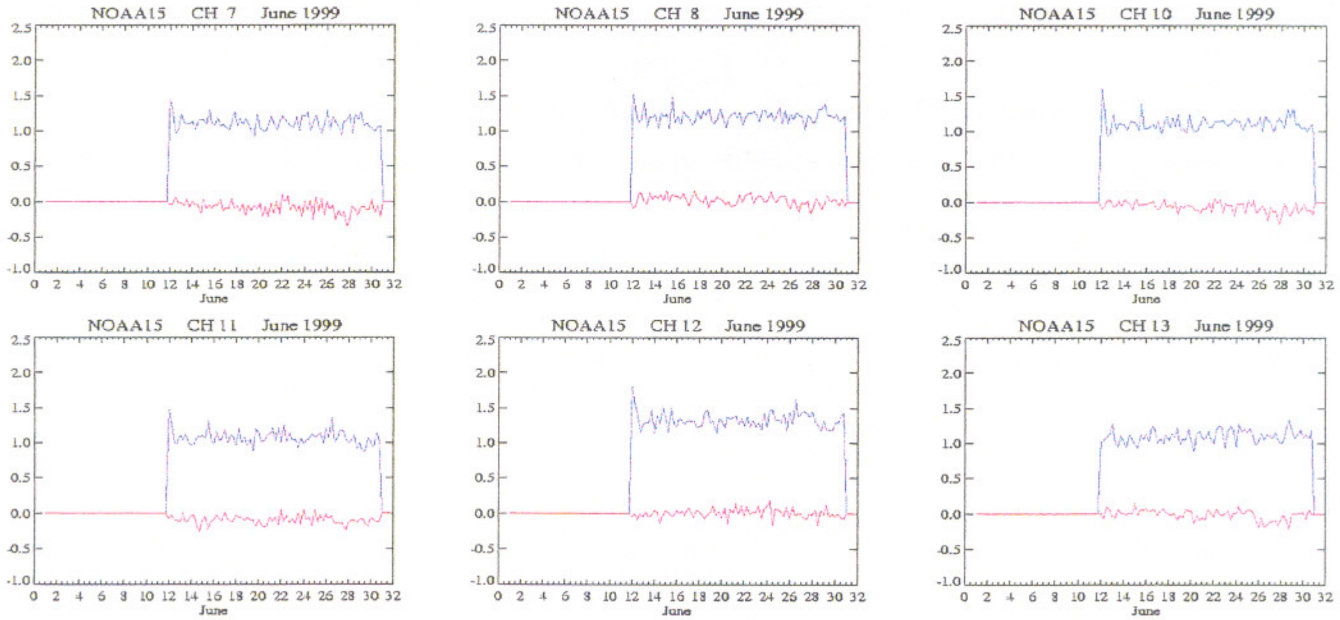


Fig. 2a. Normalized biases (red) and mean square errors (blue) for 12-30 June 1999 for HIRS channels 7 to 13 of NOAA-15, resulting from the first a-priori estimates of observational errors.

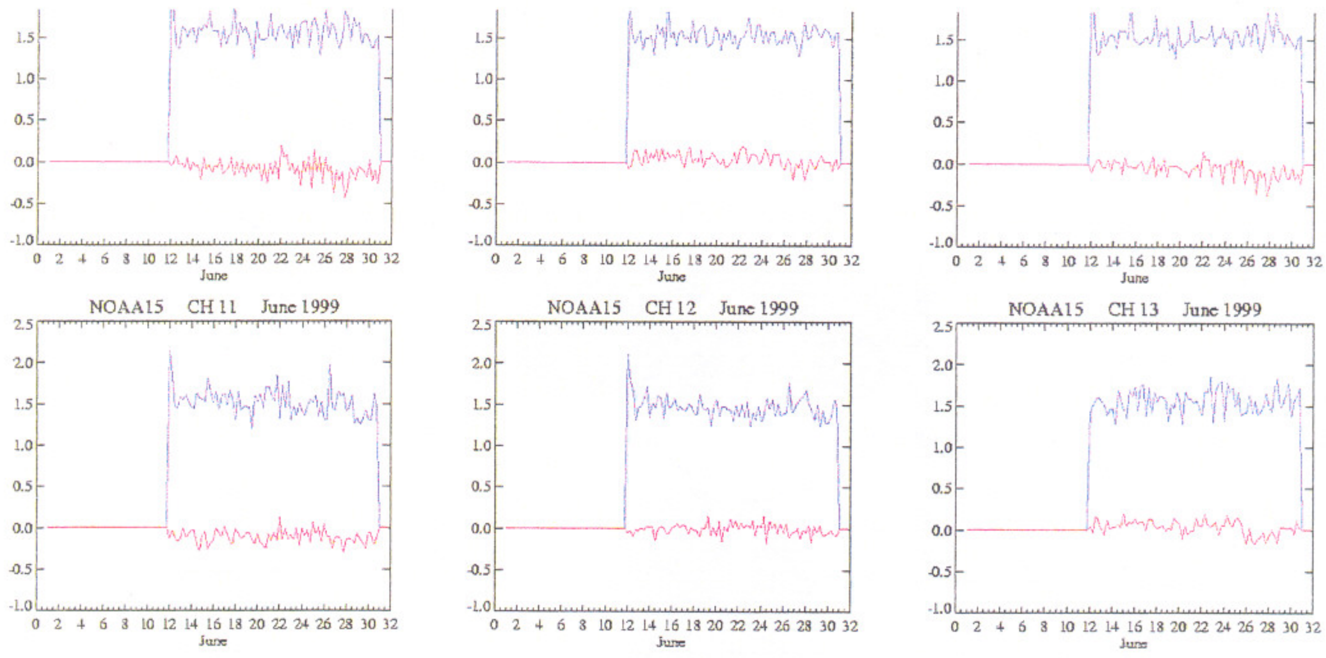


Fig. 2b. Same as Fig. 2a but with observational errors adjusted following the 3D-var monitoring.

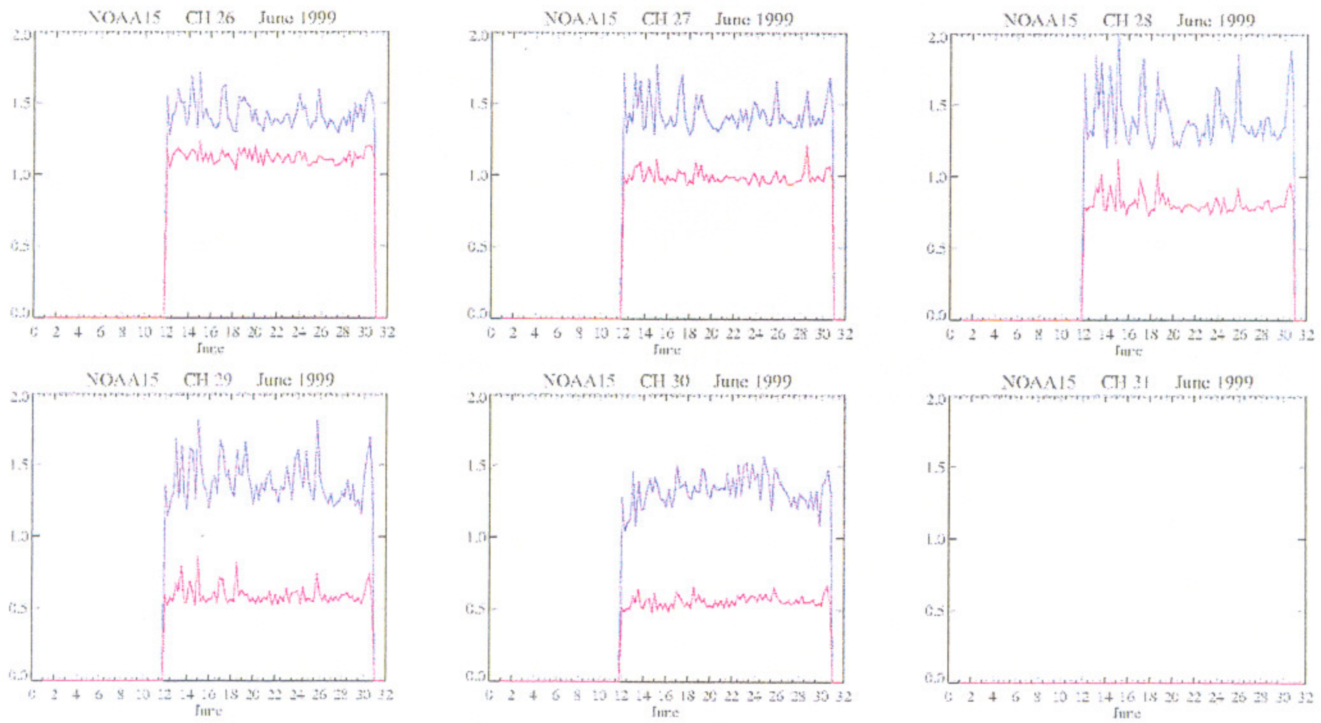


Fig. 2c. Reduction in variance from the analysis step for AMSU-A channels 6-11during the 12-30 June 1999 period.

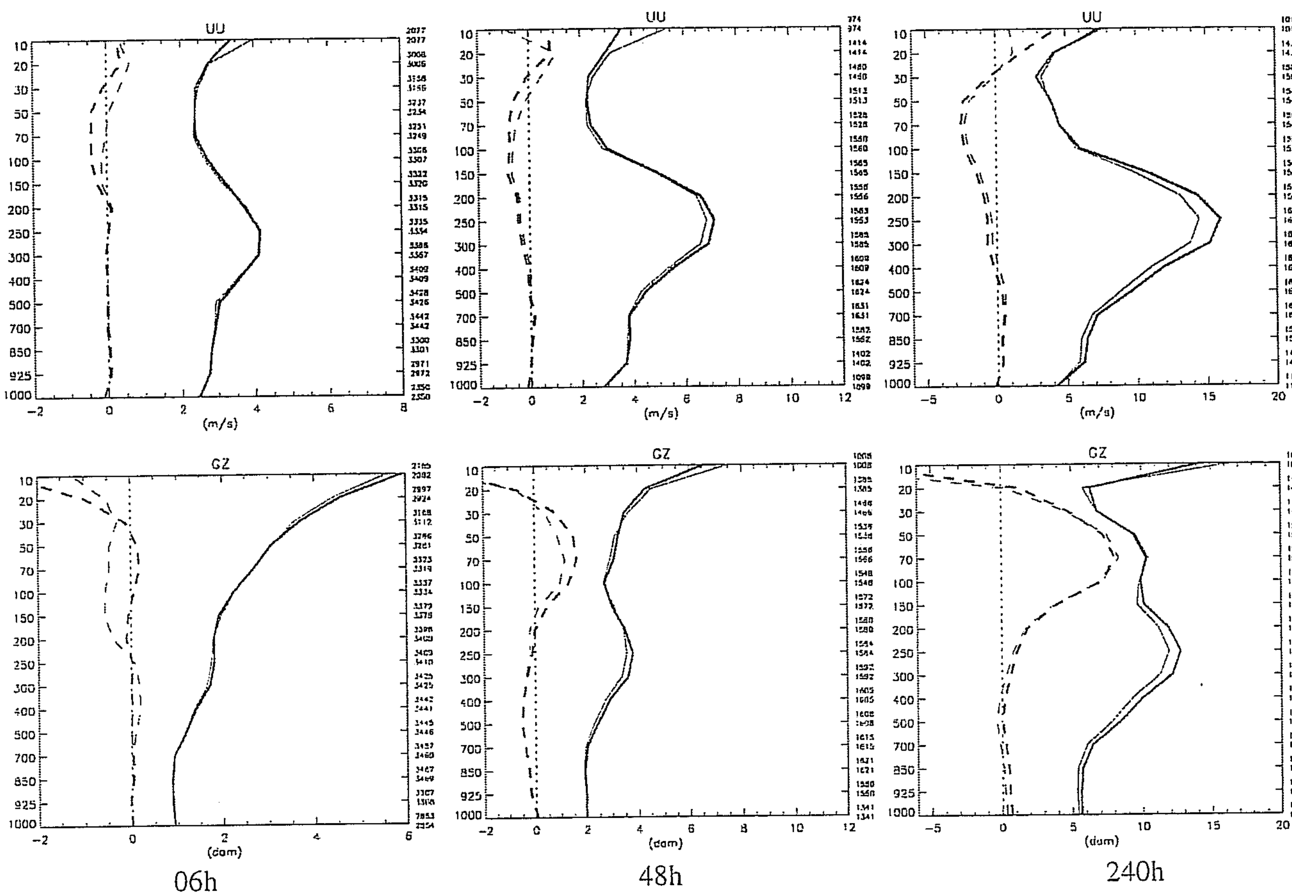
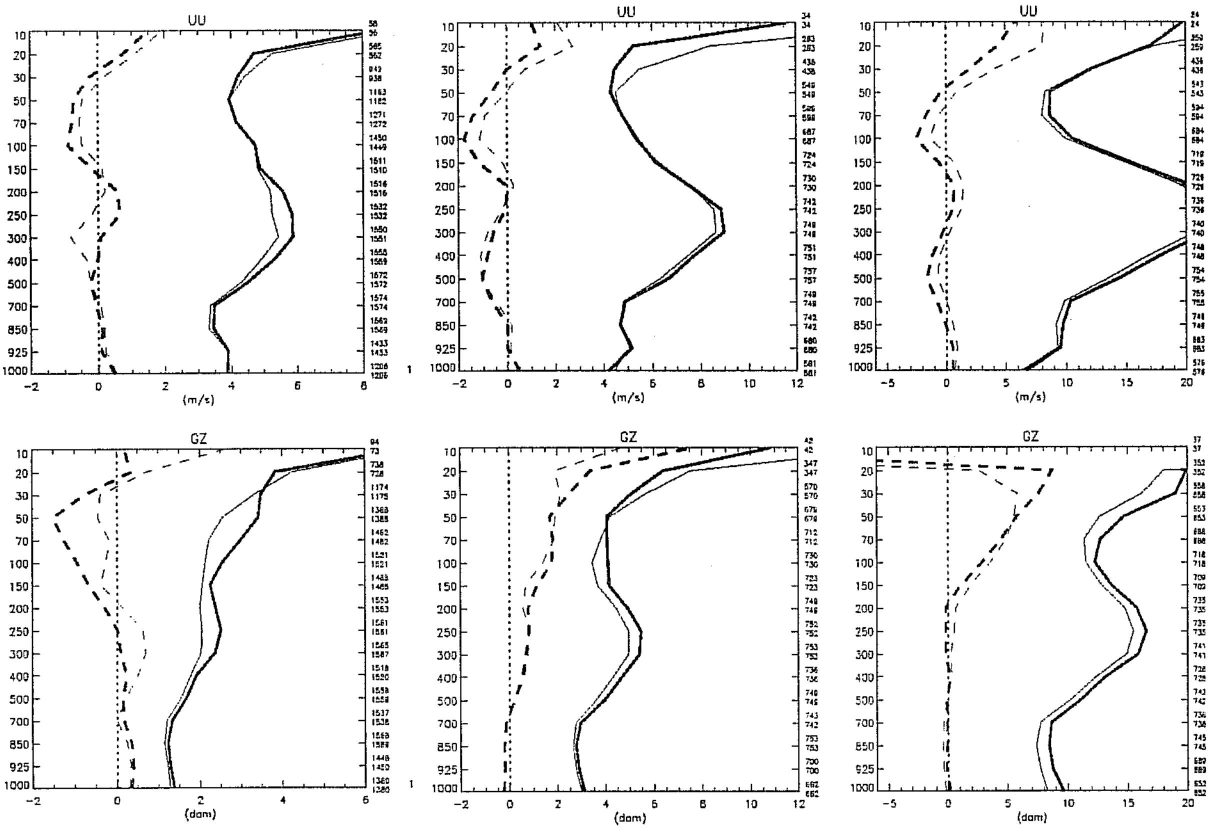


Fig. 3a. Evaluation of 18 forecasts against radiosondes (total number indicated on the right column of each panel) for North America at 6h (left), 48h (middle) and 240h (right). Winds are in the top row and geopotential in the bottom row. Thin lines represent TOVS, thick lines SATEM, solid lines root mean square error and dashed lines mean error or bias. Units are m/s amd dam.



06h 48h 240h

Fig. 3b. Same as Fig. 3a but for the SH.