The use of raw TOVS / ATOVS radiances in the ECMWF 4D-Var assimilation system

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Introduction

Radiance data from the NOAA polar orbiting satellites have been assimilated at ECMWF for a number of years and represent a major component of the global observing system. The analysis schemes used to assimilate the data have changed significantly in this time from the first 1D-Var in June 1992 (Eyre et al. 1993), to 3D-Var (Andersson et al. 1998) in January 1996 and most recently 4D-Var in November 1997 (Rabier et al. 1998). However, the basic form of the radiance data used in the analysis has remained unchanged from the original NESDIS pre-processed cloud-cleared (TOVS) radiance products. These data have undergone a number of significant pre-processing stages (at NESDIS) before they are distributed to NWP centres and it is known that some of these stages can introduce complicated random and systematic errors in the data that are not present in the original raw radiance observations. There are good historical reasons why the pre-processing is applied, related to the fact that the radiances were originally intended to be used in linear retrieval schemes. However, most of the pre-processing is not necessary to use the data in analysis schemes such as 3D or 4D-Var and, since it can introduce errors, it is in fact undesirable. Furthermore, when a new satellite is launched (e.g. the NOAA-15 spacecraft in April 1998 carrying the new ATOVS instruments), raw radiance data may be available for some considerable time (up to a year) before the pre-processed radiance products are distributed. This paper describes the recent modifications to the ECMWF assimilation scheme that allow the raw TOVS / ATOVS radiance observations to be used instead of the pre-processed data. The results of experiments carried out to test the meteorological impact of the change are also presented.

Technical changes to the analysis

A number of significant changes have been made to the analysis to allow the assimilation of raw radiance data. These are documented below.

Calibration

Calibration coefficients supplied by NESDIS (as part of the level-1b data) are applied to convert the raw radiometric counts to raw radiances (level-1c data). For TOVS data from the NOAA-14 satellite this operation is performed locally at ECMWF, but for ATOVS data from NOAA-15 the calibration is currently performed at the UK Met. Office.

Pre-screening

The raw radiances from the HIRS/MSU/SSU instruments (carried on NOAA-14) and the HIRS/AMSU-A/AMSU-B instruments (carried on NOAA-15) represent an enormous data volume. It is neither desirable nor possible to assimilate such a volume in the 4D-Var analysis so the data must be pre-screened. The pre-screening reduces the data volume by thinning the observation density (typically to a resolution of approximately 120Km). However, in the case of HIRS data the thinning also takes into account which observations are most likely to be used by the subsequent 4D-Var analysis. Using estimates of the surface skin temperature (SST) and total column water vapour (TCWV) (both provided by a shortrange forecast from the previous analysis) the pre-screening attempts to identify the HIRS observations that are heavily cloud contaminated. This is achieved by comparing the observed window channel (HIRS-8) with a value computed using a simplified (and thus extremely fast) radiative transfer model described by

$$\text{HIRS-8}^{*} = \text{SST} - c\ \text{TCWV}$$

where c is an empirically determined constant. In an area where cloud is detected the HIRS data are thinned much more (to a resolution of about 250Km) than in areas where no cloud is detected. The test is not applied too stringently (currently departures from the observed window channel up to 5K are still passed at the higher density) due to the inadequacies of the simplified model. A similar "targeted" thinning could be employed for the other instruments, but cases of e.g. precipitation in microwave data represent a much smaller data volume.

Observation operator for raw radiances

The raw data are not limb adjusted to nadir values or emissivity corrected, so the analysis observation operator must simulate first-guess radiances appropriate to the scan angle at which the observation was made. This requires the radiative transfer model (RTTOV) to compute off-nadir radiances, but also any angle dependence of the surface emissivity must be modelled explicitly. For the microwave instruments the surface emissivity model formulation described in Ulaby is used over sea (no angular variation over land is modelled) and for the infra-red instruments a parametric formulation of the Masuda emissivity model is used (again no angular variation over land is modelled).

Bias correction procedure

Systematic errors in the observed radiances and forward operator must be removed before the assimilation. These have been estimated in the usual way by comparing observed radiances with values computed from the first-guess (in the vicinity of radiosonde data where it is hoped the that first-guess is not significantly biased). The raw radiances have been found to have smaller and considerably more stable biases (particularly for data from the NOAA-15 instruments). These are readily corrected by fixed scan dependent bias correction combined with an air-mass dependent correction. However, a traditional concern of such an approach (i.e. diagnosing biases using the first-guess as a standard) is that the forecast model may itself have biases. In the troposphere the model is kept reasonably unbiased (in the vicinity of radiosonde data) by the assimilation radiosonde data, but in the stratosphere (above 10HPa) there are less radiosondes. It was found that uncorrected mean observed minus first-guess (obs-fg) departures for the high peaking (AMSU-A channels 12,13 and 14) were very similar to the mean radiosonde (obs-fg) departures. This suggested that a significant proportion of the systematic difference was due to a forecast model bias. Thus the decision was made to initially assimilate these channels with no bias correction (but use the full model diagnosed bias correction for all other lower-peaking channels channels). Under the influence of the uncorrected AMSU-A (12,13 and 14) the model stratosphere evolved to a mean state that was in better agreement with the radiosonde data. After two weeks of assimilation a small bias correction was applied to these channels to remove the residual systematic signal that could not be assimilated.

Channel Selection

Two different experimental raw radiance channel configurations were tested against a control that used pre-processed TOVS radiance data (actually the operational system of the time). The first experiment (subsequently called MW) used only a selection of microwave channels form the AMSU-A and MSU (note that at the time the AMSU-B data was experiencing interference problems that made the data unusable). The second configuration (subsequently called MW/IR) used the same microwave data , but also a selection of infra-red channels from the HIRS instrument. Details of the two configurations are listed below:

<u>Experiment MW</u>
NOAA-15 AMSU-A channels 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 over sea
NOAA-15 AMSU-A channels 7, 8, 9, 10, 11, 12, 13, 14 over land or sea ice
NOAA-14 MSU channels 2, 3, 4 over sea
NOAA-14 MSU channels 3, 4 over land or sea ice

<u>Experiment MW/IR (microwave channels used as above plus)</u>
NOAA-15 HIRS channels 1 to 15 over sea
NOAA-15 HIRS channels 1 to 3 over land or sea ice

Observation error specification
Observation errors for both experiments were set to the following values:

MSU channels 2 to 4 = 0.5K
AMSU-A channels 5 to 11 = 0.5K, channels 12 to 14 = 2.0K
HIRS channels 1 to 15 = 1.0K with channel 12 = 4.0K

Quality control and data screening within the analysis
The radiances are intended to make adjustments to the atmospheric temperature and humidity fields, but in some situations the observations may be strongly affected by other phenomena such as cloud, precipitation and the characteristics of the underlying surface (both its temperature and emissivity). It is important that these situations are screened out by the analysis and do not cause erroneous adjustments of the atmospheric temperature and humidity. A general approach has been adopted to this screening process that compares the observed radiance in the window channel on each sensor with the equivalent value computed (assuming clear sky) from the forecast background (note the full radiative transfer model is used at this stage rather than the approximate simplified version used in the pre-screening process). Large differences suggest the presence of either cloud of precipitation in the observation, or that the background estimate of the surface characteristics is poor (or any combination of these). The thresholds for each sensor were tuned empirically (using coincident satellite imagery) and represent a compromise between the need to safely reject contaminated data while maintaining an acceptable data density in the analysis. The values are as follows:

MSU channel 1 departure < 5K
AMSU-A channel 3 departure < 3K
HIRS channel 8 departure < 1K

If these thresholds are exceeded over sea all tropospheric channels are rejected leaving only the channels normally used over land and sea ice in the analysis. Note that the window channel check is not used to allow the use of tropospheric channels over land and sea ice as it is not reliable. Over land, gross problems in the surface specification could compensate and therefore mask cloud or precipitation contamination in the observations.

Two additional levels of quality control are applied independently from the window channel check. The first is a "gross" threshold on the observation departure from the model in each channel, causing rejection of only that channel if

$$(\text{obs-fg}) > 3.0 \times (\text{first-guess error}^2 + \text{observation error}^2)^{1/2}$$

Estimates of the first-guess error (expressed in radiance space) are generated from geographically varying estimates of temperature and humidity forecast error using the scheme described in (Andersson et al. 1999). The second level of quality control is the variational quality control scheme described in Andersson et al. 1999.

Analysis and forecast impact experiments

It is important to appreciate the two major differences between the experimental systems (MW and MW/IR) and the operational system (henceforth called OPS) against which they are compared. The OPS system assimilates pre-processed TOVS radiances (i.e. limb/emissivity adjusted HIRS/MSU/SSU data mapped to the HIRS field of view) from the NOAA-11 and NOAA-14 spacecraft. The experimental systems assimilate raw TOVS and ATOVS radiance data from the NOAA-14 and NOAA-15 spacecraft respectively. A cleaner comparison to test the raw radiance approach would have required pre-processed radiance data from NOAA-15 to be in the OPS assimilation, but this data had not been available from NESDIS (the raw data was available since August 1998). Alternatively, the experimental assimilations could have used raw TOVS radiances from NOAA-11 and NOAA-14 data, but as NOAA-11 was expected to become obsolete at the end of April 1999 it was not considered a worthwhile investment of effort to test a configuration with only a short anticipated lifetime (in fact the spacecraft failed at the end of February 1999). Thus when comparing the results presented here it must be understood that there will be differences due to the extra microwave information provided by AMSU on NOAA- 15 and differences resulting from the use of raw radiances (rather than pre-processed data) from the other sensors.

Analysis impact

The assimilation of raw radiances has resulted in some significant mean changes to the analysis. Figure 1 shows the zonal mean temperature analysis for OPS, and the difference OPS-MW. The largest changes are in the stratosphere and are due to the use of the AMSU-A radiances by the experimental assimilations. The AMSU-A instrument has six channels that peak above 100 hPa, the highest being sensitive to the atmospheric temperature around 2 hPa. This is a significant addition to the information previously provided by the uppermost channels of the HIRS and SSU instruments, and is timely with the recent extension of the ECMWF forecast model in to the stratosphere (the model top is now at 0.1hPa). Mean changes in the troposphere are generally small, but are significant over the polar areas where there have been changes to the radiance data usage (much more restrictive use of the raw radiances).

The mean temperature analysis from the experimental assimilation (MW/IR) that made additional use of raw HIRS data did not differ significantly from that of the microwave only system. To some extent this is a reflection that the HIRS data offers little extra information over the AMSU-A, but is also due to the very cautious use of the raw HIRS data. The thresholds described above that aim to identify and reject data in cloudy areas result in a rather limited usage of the HIRS tropospheric channels. However, it is believed that the extensive rejections do, to some extent, reflect the fact that in nature there are actually very few situations that are clear over the extent of a HIRS footprint. The limited use of tropospheric HIRS channels also goes some way to explain why only small systematic differences were found between the mean humidity analyses of MW and MW/IR. However, the most likely reason for this is that the humidity analysis in both experiments (and the control) is strongly controlled by the assimilation of SSM/I data.

A key quality indicator for any data assimilation system is the extent to which it draws to radiosonde and other conventional observations in the presence of (generally more numerous) satellite data. Experience has shown that the fit to conventional data (e.g. the root-mean-square temperature differences between the background/analysis and the radiosondes) are generally very stable quantities, but are often adversely affected when there are problems with the use of satellite data. An example of the fit of the experimental (again MW and MW/IR were found to be very similar and so only MW is shown) and OPS assimilations to radiosonde temperature data is shown in figure 2a. It can be seen that the raw radiance assimilation fits the tropical radiosonde data better than OPS at many levels but there is some degradation around 100 hPa and 20 hPa. There are improvements in the extra-tropical regions, but they are generally much smaller and are not shown here. Thus the radiosonde temperatures indicate a generally improved temperature analysis in the vicinity of the radiosonde data. It is also useful to examine wind statistics. These are sensitive to the correct specification of the horizontal gradient of temperature (particularly in the extra-tropics assuming a geostrophic balance) and thus represent a less local measure of the assimilation quality. Statistics for the southern hemisphere are shown in figure 2b and show a small, but consistent improvement in the wind fit of the raw radiance assimilation compared to that of OPS.

Forecast impact

It is always difficult to relate changes that have been made in the assimilation system to changes in the quality of forecasts. After a certain time (estimates vary between three and five days) it becomes impossible to trace forecast differences back to differences in the initial conditions (i.e. the analysis). Furthermore, before this so called non-linear stage of the forecast the choice of the truth against which we measure the quality of the forecast is significant. Usually the analysis is used, but if there are significant changes to the analysis (as there are for OPS and the raw radiance assimilations) it must be remembered that there are two possible versions of the truth. An obvious compromise is to verify the forecasts against radiosonde observations (which are not perfect but are the same for both experiments) and it is these results that are presented here. Figure 3 shows root-mean-square errors for the forecasts of 500 hPa height. It can be seen that the tropospheric impact of the MW raw radiances is generally neutral in the extra-tropical northern hemisphere (although clearly positive after day 6) and positive at all ranges in the southern hemisphere, note that the differences in spatial and temporal coverage of southern hemisphere radiosondes give different statistics at 00 UTC and 12 UTC. The forecasts from the MW/IR raw radiance assimilation showed a very slight improvement over the MW in the southern hemisphere, but also a slight degradation in regional scores over Europe (which actually made it worse than the OPS control). In the stratosphere a small improvement has been found with the temperature and wind forecasts using the raw radiances (most likely due to the use of AMSU-A).

Summary and future work

The ECMWF data assimilation has successfully been converted to use raw TOVS / ATOVS radiance data and has resulted in some useful improvements in the quality of analyses and forecasts. In the troposphere these are most likely due to the improved bias correction and quality control that are possible with the raw data. In the stratosphere the gain is almost certainly due to the extra information provided by the AMSU instrument. The system described here must be considered only a first step in the direction of raw radiance assimilation. Since 1992 we have gained a great deal of experience with the use of pre-processed NESDIS data and it will take some time before our understanding of the raw radiances reaches maturity. The next step will be to understand why the additional use of HIRS data does not give a consistent improvement over the microwave only system. The suggestion from the experiments so far is that the extra HIRS information does help in the southern hemisphere, but has not been screened sufficiently well to exclude cloud. This would certainly explain the degradation of European forecasts where data quality is of higher importance. We also need extend our use of the raw microwave data to the channels that are sensitive to the lower troposphere and surface. This is currently hindered by uncertainties in our knowledge of the physical characteristics of the surface and phenomena such as cloud and precipitation. Further in the future the challenge will be to extract valuable information on these processes and not regard them as contaminants to be removed. The development of the raw radiance assimilation system is timely for the next ECMWF re-analysis project ERA- 40. The use of raw radiance data will not be subject to the many changes that have occurred over the years in the NESDIS pre-processing and thus allow a greater degree of time consistency in the analyses.

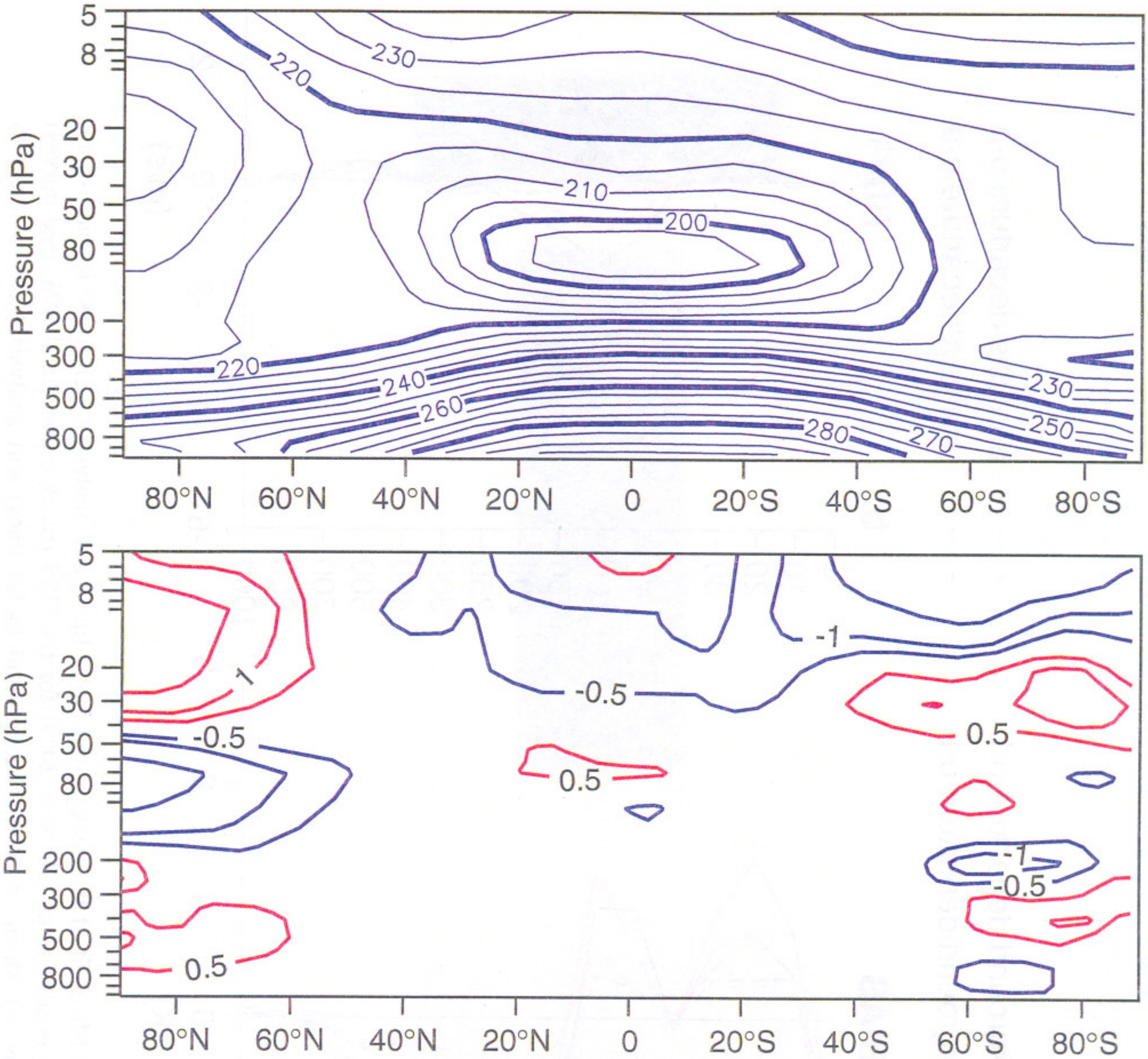

Figure 1: Zonally averaged monthly mean temperature analysis for the OPS assimilation in February 1999 (upper) and mean analysis differences (lower) defined as experiment MW minus control OPS. Units are degrees Kelvin.

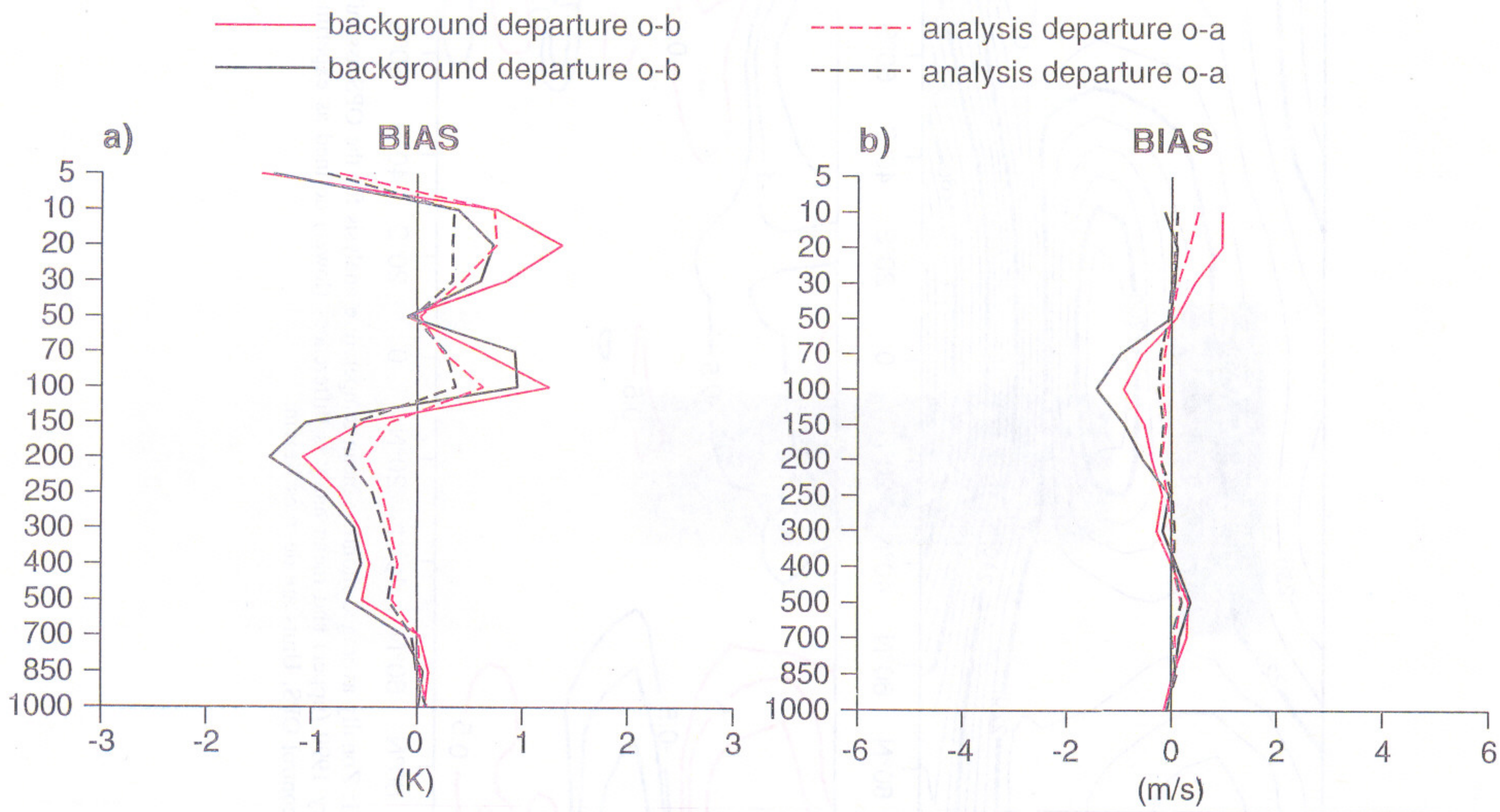

Figure 2: a) Mean fit of the background (solid lines) and analysis (dash lines) to radiosonde temperature observations (20°N to 20°S) for the OPS (black curves) and MW (red curves) assimilations. b) Mean fit of the background (solid lines) and analysis (dashed lines) to radiosonde observations of zonal wind (20°S to 90°S) for the OPS and MW assimilations.

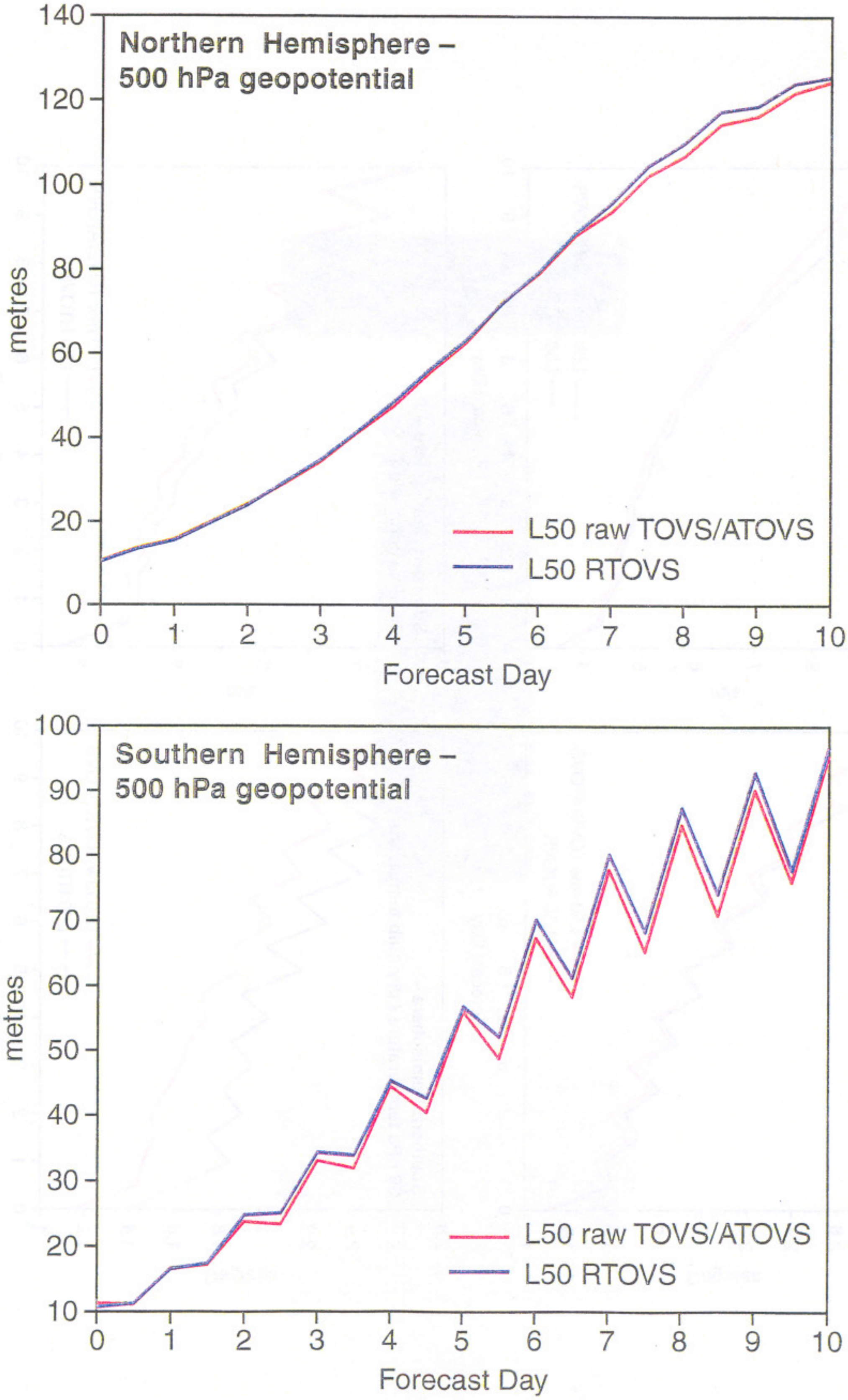

Figure 3: Root mean square forecast errors in the northern and southern extra-tropical regions for the OPS (blue curves) and MW (red curves) verified against radiosonde observations of 500 hPa geopotential. The sample consists of 127 cases.

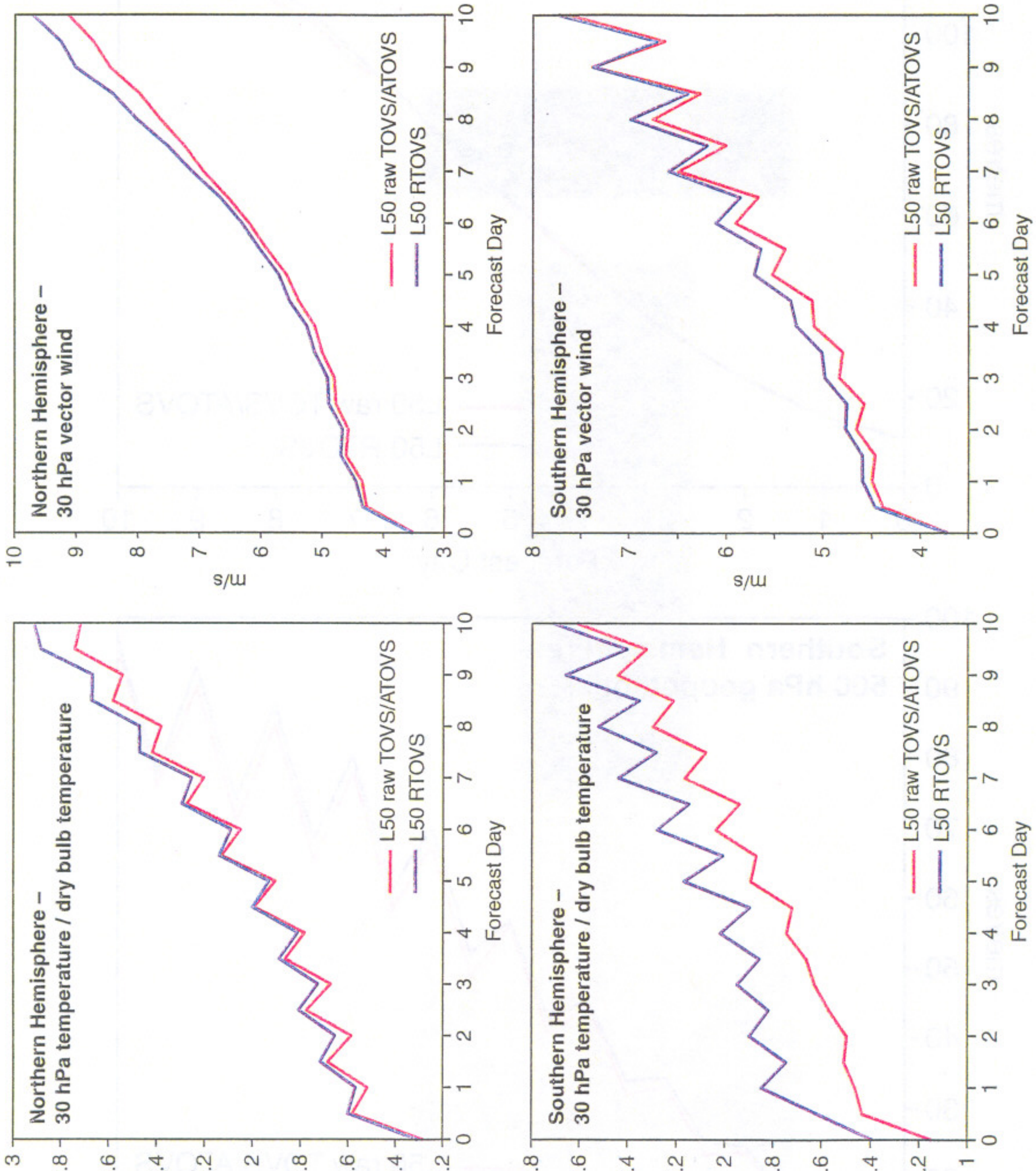

Figure 4: Root mean square forecast errors in the northern and southern extra-tropical regions for the OPS (blue curves) and MW (red curves) verified against radiosonde observations of 30 hPa temperature and vector wind.