RECENT DEVELOPMENTS AT ECMWF IN THE ASSIMILATION OF TOVS RADIANCES

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1. BACKGROUND

Measurements from the TIROS Operational Vertical Sounder (TOVS) have been used at the European Centre for Medium-Range Weather Forecasts (ECMWF) to improve the forecast model's description of the initial state of the atmosphere (analysis) for many years. Initially the TOVS data were used in the form of temperature retrievals with a horizontal spacing of 500km (SATEM) but now only pre-processed radiances from the NESDIS RTOVS system (Paris, 1997) are actively assimilated although the retrievals are still monitored. The paper by Saunders et. al. (1997) at the ITSC-IX meeting gives more details of the history of the use of TOVS data at ECMWF up to 1996. This paper describes the current configuration of TOVS radiance assimilation at ECMWF, documents the changes to the use of TOVS data since the last meeting (i.e. from February 1997 to January 1999) and serves as a background for some of the other papers from ECMWF in this proceedings. It is planned that the use of the TOVS and newly available Advanced TOVS (ATOVS) data at ECMWF will radically change in the next few months and the details of this new phase of exploitation of the (A)TOVS data at ECMWF are described in the companion papers by McNally (1999) and Andersson (1999) in this proceedings.

2. CURRENT STATUS

2.1 Model and analysis configuration

The latest version of the ECMWF global atmospheric forecast model planned for operational implementation in March 1999 has 50 levels from the surface to 0.1hPa in eta (i.e. hybrid sigma-pressure co-ordinates) and a spectral resolution of T319 which resolves half wavelengths to about 62 km. The 10 day forecast is produced from the 12Z analysis each day but there are updated analyses computed once very 6 hours which allows a 6 hour forecast to be always used as the first guess for the next analysis. The analyses are obtained from a 4 dimensional variational data assimilation system, 4DVar, described by Rabier et. al. (1999) and Andersson (1999) in this proceedings. 4DVar attempts to derive an optimal balance between observations and the model background (governed by atmospheric dynamics and physical parameterisations) by finding a model solution which is as close as possible,

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in a least square sense, to the background and the observations available over a 6 hour time period. It is being used at ECMWF in its incremental formulation which comprises running a high-resolution (T319) model with the full physical parameterisation package to compare the atmospheric state with the observations and a low resolution model (T63) with simplified physics to minimise the cost function. A '2-update' configuration is used in the minimisation: 50 iterations are performed with minimal physics and, after updating the trajectory at high resolution, 20 iterations are performed with more sophisticated linear physics. A variational quality control (Andersson and Järvinen, 1999) is applied to all observations including TOVS radiances after the first 40 iterations of the minimisation (i.e. towards the end of the first update).

The primary observations assimilated in 4DVar are, surface reports (synops, ships and buoys), radiosonde/pilot winds, radiosonde temperature and humidity profiles, aircraft reports, geostationary satellite atmospheric motion winds, scatterometer sea surface winds, SSM/I total column water vapour and TOVS radiances. The data cut-off time is typically 7 hours after the nominal analysis time. In addition TOVS and ATOVS 1C radiances, METEOSAT-5/7 water vapour radiances and SSM/I wind speed and cloud liquid water path are all passed through the analysis passively to provide monitoring statistics.

2.2 Use of TOVS

An overview of where and how TOVS data are being used at ECMWF is given in the panels of Figure 1 and Table 1 lists the observation errors assigned to the different TOVS channels for each surface type. All the RTOVS radiances (120km sampling) are used in the initial screening with a 1DVar retrieval (Eyre et. al. 1993 and for the latest description see Saunders et. al. 1997) and then subsequently sampled to 250km for assimilation in 4DVar according to the 1DVar error flags, proximity to centre of scan and several other criteria. The 1DVar checks only reject typically 8% of the data compared to the reduction by a factor of 4 in the thinning. The majority of the 1DVar failures are due to the 'window channel' cloud test where HIRS channel 8 is used to check for residual cloud contamination of the clear radiances. Assimilation of the full 120km dataset is not implemented because of the current low resolution (T63) of the 4DVar analysis and the assumption of zero horizontal error correlation for the radiances. In addition to providing quality control flags the 1DVar retrieval also provides the first guess skin temperature for 4DVar and for the 31 level version of the model the temperature profile above 10hPa. The use of all the TOVS channels in 1/4DVar is listed in Table 1. When clear most of the channels are used over the sea but only a subset of channels which do not have large sensitivity to the

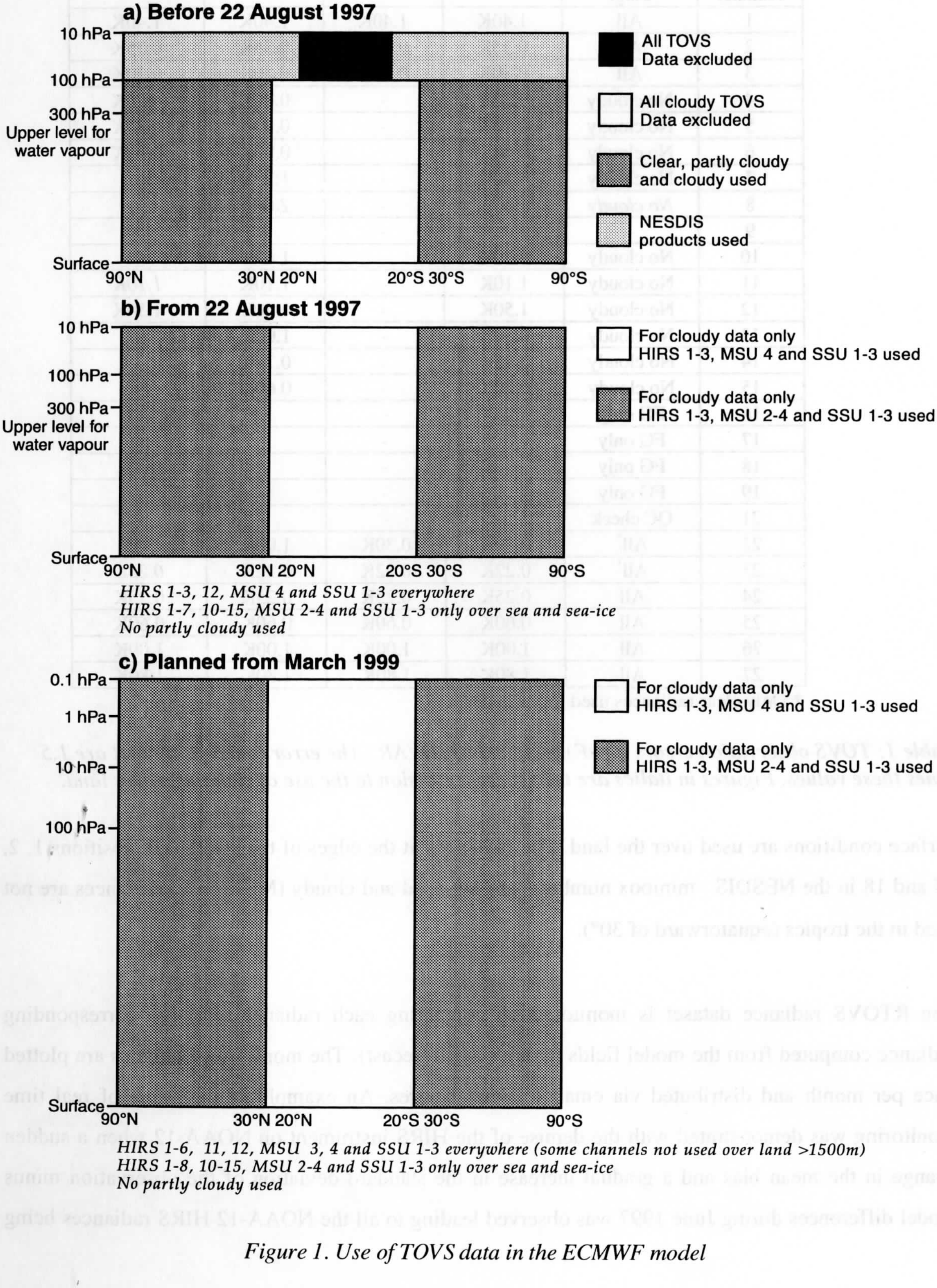

Figure 1. Use of TOVS data in the ECMWF model

Channel Number	4DVAR usage	Clear	Cloudy	Sea-ice	Land
1	All	1.40K	1.40K	1.40K	1.40K
2	All	0.35K	0.35K	0.35K	0.35K
3	All	0.30K	0.30K	0.30K	0.30K
4	No cloudy	0.20K	-	0.20K	*0.20K*
5	No cloudy	0.30K	-	0.30K	*0.30K*
6	No cloudy	0.40K	-	0.80K	*0.80K*
7	No cloudy	0.60K	-	1.20K	-
8	*No cloudy*	*1.00K*	-	*2.00K*	-
9			-	-	-
10	No cloudy	0.80K	-	1.60K	-
11	No cloudy	1.10K	-	1.10K	*1.10K*
12	No cloudy	1.50K	-	1.50K	1.50K
13	No cloudy	0.50K	-	1.00K	-
14	No cloudy	0.35K	-	0.70K	-
15	No cloudy	0.30K	-	0.60K	-
16	FG only	-	-		-
17	FG only	-	-	-	-
18	FG only	-	-	-	-
19	FG only	-	-	-	-
21	QC check	-	-	-	-
22	All*	0.30K	0.30K	1.00K	-
23	All*	0.22K	0.22K	0.22K	*0.22K*
24	All	0.25K	0.25K	0.25K	0.25K
25	All	0.60K	0.60K	0.60K	0.60K
26	All	1.00K	1.00K	1.00K	1.00K
27	All	1.80K	1.80K	1.80K	1.80K

* Only clear radiances used for latitudes < 30°

Table 1: TOVS observation errors (O+F) assigned in 1DVAR. The errors used in 4DVAR are 1.5 times these values. Figures in italics are the recent extension to the use of radiances over land.

surface conditions are used over the land. The radiances at the edges of the swath (i.e. positions 1, 2, 17 and 18 in the NESDIS minibox numbers) are not used and cloudy (MSU only) radiances are not used in the tropics (equatorward of 30°).

The RTOVS radiance dataset is monitored by comparing each radiance with the corresponding radiance computed from the model fields (from a 6 hr forecast). The monitoring statistics are plotted once per month and distributed via email to other centres. An example of the value of real time monitoring was demonstrated with the demise of the HIRS instrument on NOAA-12 when a sudden change in the mean bias and a gradual increase in the standard deviation of the observation minus model differences during June 1997 was observed leading to all the NOAA-12 HIRS radiances being blacklisted. The NOAA-12 MSU radiances remained stable and continued to be used until the replacement of the NOAA-12 RTOVS data with NOAA-11 data in September 1997.

3. RECENT DEVELOPMENTS TO USE OF TOVS RADIANCES

The significant changes to the use of TOVS radiances at ECMWF from Jan 1997 to March 1999 are now described in chronological order.

3.1 Revised radiance tuning method

To assimilate observations in a variational assimilation scheme it is necessary to make the assumption that they are unbiased globally with respect to the model equivalents. In practice, due to errors in the radiative transfer model, instrument calibration or data preprocessing, biases in the radiance observations or the first guess values can exist and have to be removed before assimilation. Two components of the radiance bias have been identified, a scan dependent bias and an airmass dependent bias where airmass refers to the mean atmospheric and surface state.

The scan dependent bias was removed by making a global mean computation of the bias as a function of scan angle from nadir and then subtracting the global mean correction from the instantaneous values. More recently it has been shown that the scan dependent bias is strongly latitude dependent and so a revision to the original scheme was to apply scan bias corrections only determined from the same latitude band (Harris and Kelly, 1999).

For the airmass related biases a method based on using the MSU radiances was developed (Eyre, 1992) and has been used successfully at many centres including ECMWF. However the method relies on the MSU channels 2, 3 and 4 radiance data being available and uncontaminated. Problems experienced with using MSU-2 radiances over sea-ice and land, particularly when the surface emissivity correction is not applied as is the case for the RTOVS product have led to the use of MSU data being abandoned for the bias correction. Another motivation to remove the reliance on MSU is the plan to use the 1C TOVS, ATOVS and METEOSAT radiances on their original fields of view which do not have collocated MSU data.

The solution was to use the model first guess fields themselves to provide predictors for the radiance tuning (Harris and Kelly, 1999). Two mean layer thicknesses (1000-300hPa, 200-50hPa), total column water vapour and surface skin temperature were found to be correlated to the radiance biases. An additional two mean layer thicknesses have been introduced in the stratosphere when the top of the model was raised to 0.1hPa as described in sec. 3.4. As with the original scheme only the radiance biases in the vicinity of reliable radiosonde stations are used to compute the airmass correction coefficients to ensure that the model does not adjust to the 'biased' radiances. This can be more of a problem in the upper stratosphere where only radiance observations, are present and so more reliance has to be placed on them being unbiased.

This revised TOVS radiance tuning was implemented in ECMWF operations on 27 August 1997. The radiance biases after tuning were reduced in many channels with the new scheme when averaged over a two week period. The impact on the forecast performance was also positive (Harris and Kelly, 1999). The radiance tuning coefficients are updated approximately monthly using the past 2-4 weeks of mean radiance observations minus first guess values. The scheme has also been successfully applied to METEOSAT and (A)TOVS 1C radiances.

At the same time the use of the TOVS data in 3DVar was modified so that the radiances replaced the NESDIS retrieved thicknesses everywhere above 100hPa and the 1DVar retrievals poleward of 70 °N resulting in a simpler radiance-only system as shown in the middle panel of Figure 1. This allowed SSU radiances to directly influence the analysis rather than through a 1DVar retrieval. In addition HIRS-12 radiances were used over land.

3.2 Change from TOVS to RTOVS radiances

During 1997 NESDIS began providing the new Revised TOVS (RTOVS) cloud cleared radiances, initially, in experimental mode, to replace the TOVS 120km product used operationally. The details of the RTOVS system are described by Paris (1997). The two major differences in terms of radiances was the removal of the water vapour absorption correction for HIRS channel 8 and the removal of the surface emissivity correction for the MSU channels. ECMWF monitored the RTOVS radiances for several months before their release operationally on the GTS. The radiance biases were similar for both systems although the scan dependent biases were observed to have a smoother dependence on scan angle with the RTOVS data.

The 1DVar and 3DVar observation operator was modified to include HIRS-8 radiances and the microwave surface emissivity for the MSU channels was changed from 1.0 to 0.6 over sea and 0.9 over land. In addition HIRS channel 8 replaced HIRS channel 10 for the window channel cloud check defined as only accepting observations when the HIRS-8 brightness temperature (Ob) is within the limits: $-4K < Ob-Fg < 10K$ over sea but applying tighter limits over land north of 20N. MSU channel 1 was also used as a quality check for MSU channel 2 using the criterion: if $|Ob-Fg| > 20K$ then reset the channel usage and inflate the observation errors to those used over land (see Table 1). An assimilation experiment was run comparing the impact of the TOVS system with the RTOVS system and the analysis and forecast impacts were neutral. The switch to RTOVS radiances in ECMWF operations was made on 3 December 1997, a few days after the implementation of 4DVar. Although HIRS-8 and MSU-1 radiances were then used for quality control of the radiance vector in 1DVar neither were assimilated in 4DVar at this time.

3.3 Extend use of TOVS radiances over land

Until recently most operational NWP centres have not used the TOVS radiances over land, with the exception of the stratospheric sounding channels, as the data void areas have only been over the oceans and sea-ice. However with the gradual reduction in the radiosonde network in some areas the need to assimilate satellite data over land has become more pressing in order to mitigate this loss of valuable upper air in-situ data. Recent experiments at ECMWF have demonstrated that medium range (3-7 days) forecasts can be improved over Europe and N. Hemisphere if more of the HIRS channels are used over land as shown in Figure 2. In addition to the stratospheric channels those HIRS channels with only a small sensitivity to the surface were assimilated but with an inflated observation error to reflect the uncertainties in the radiance simulation over land as defined in Table 1. HIRS-8 radiances were also added to the 4DVar assimilation over cloudfree ocean at this time as they can provide information on the tropical boundary layer humidity. The results suggest there are real benefits to extend the assimilation of TOVS radiances as far as possible over land to improve N. Hemisphere forecasts. Over the S. Hemisphere the improvements are smaller but the increased use of radiance data over the Antarctic landmass and the surrounding sea-ice will potentially contribute to improved analyses and forecasts. The analyses are only significantly modified over Russia (cooled by up to 1.5K at 500hPa) and over Antarctica where the larger background error can result in temperature differences of up to 2K at 500hPa. The mean fit to the few radiosondes available was improved over Russia when the additional radiances were used.

Further experiments to use more of the TOVS channels which sense more of the surface were unsuccessful due to the first guess surface properties not being close enough to the "truth" as seen by the TOVS window channel radiances. It was observed that the difference between the model first guess skin temperature and the 1DVar retrieved surface skin temperature around local noon can be greater than 10K. When the model has a better representation of the surface types, skin temperature and emissivity it may become possible to use more channels over land. The additional use of TOVS radiances over land became operational on 29 June 1998.

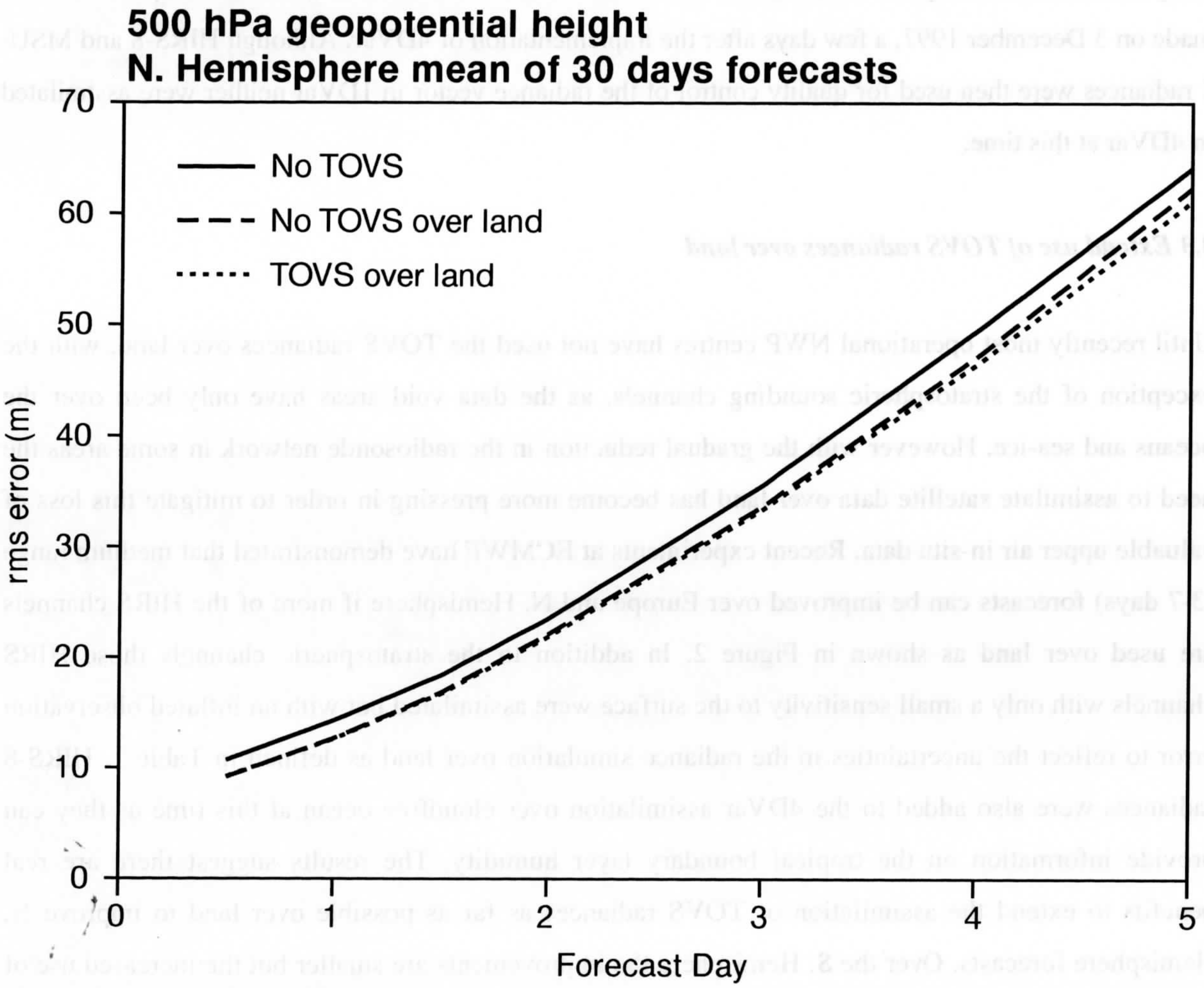

Figure 2. N. Hemisphere 500hPa geopotential height forecast errors for different usage of TOVS data in 4DVar.

3.4 Revision to fast radiative transfer model and extension of model stratosphere

To prepare for the assimilation of ATOVS radiances and to improve the existing TOVS fast radiative transfer (RT) model, RTTOV-3, an upgrade to the RT model referred hereafter as RTTOV-5 was made. The details are described in Saunders et. al. (1999). In summary the main changes are, generalisation of the code to allow simulation of any satellite radiances (currently ATOVS and METEOSAT), addition of water vapour above 300hPa, an ozone profile and individual channel surface emissivities to the state vector, improved transmittance predictors for the water vapour channels and profile validity flag returned. The optimisation of the code was improved for vector machines which resulted in a similar CPU time expended despite the profile vector increasing in length by a factor of 2. Finally a fast microwave ocean surface emissivity model (English and Hewison. 1998) was included as an option to allow surface emissivities for microwave channels to be computed from the sea surface temperature and surface wind speed. The line-by-line models used as the basis for the RTTOV-5 model

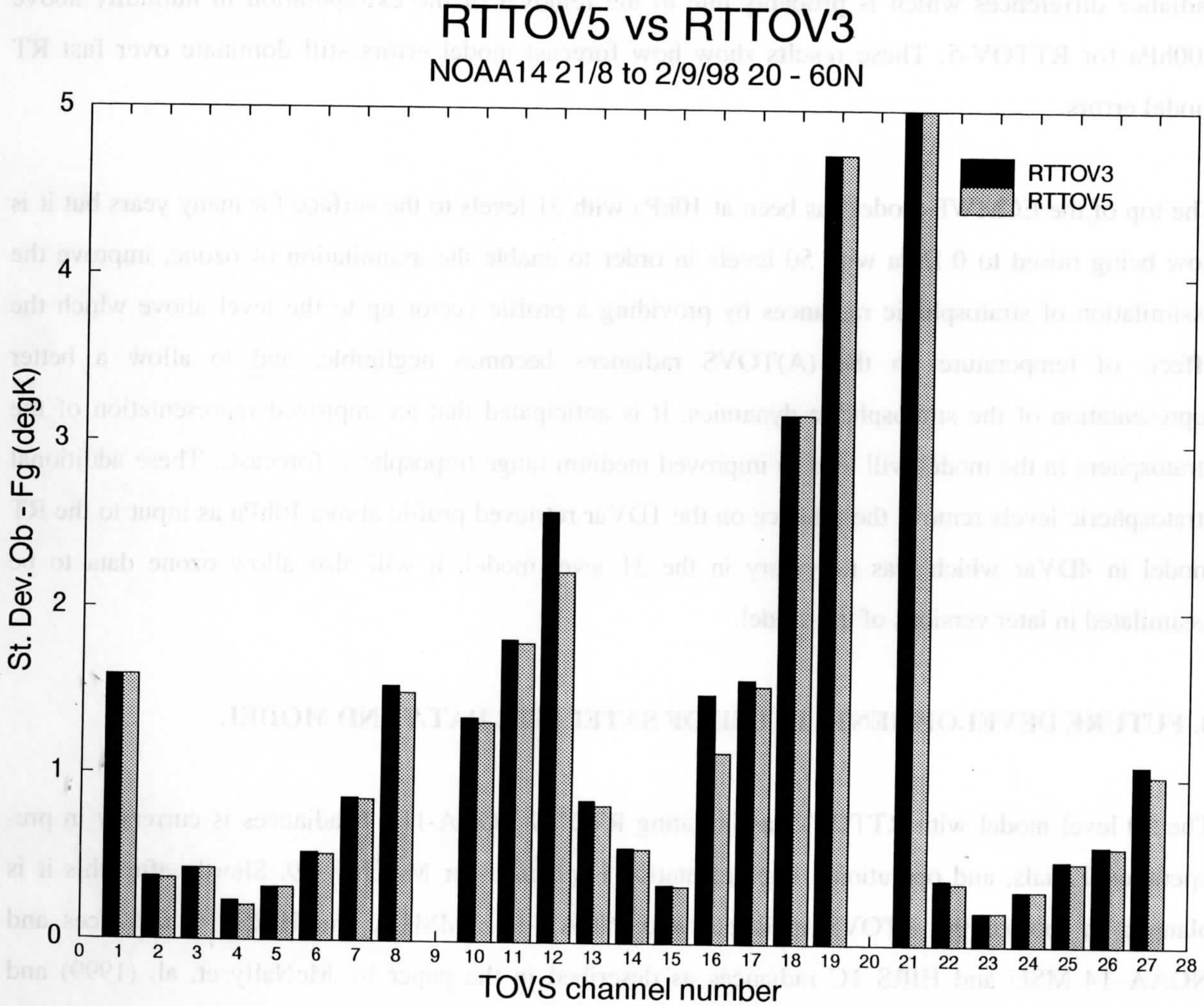

Figure 3. Standard deviation of observed minus first guess brightness temperatures for NOAA-14 TOVS channels for 13 days averaged over the latitude band 20-60°N.

was GENLN2 (Edwards, 1992) for the infrared channels and MPM89 (Liebe, 1989) with the 1992 update for oxygen absorption for the microwave channels. A set of 43 diverse profiles selected from the TIGR-2 set for temperature and water vapour and 34 for ozone were used as the dependent set to compute the transmittance pedictors for all channels. The inclusion of ozone in the profile vector allows accurate simulations of HIRS channel 9 to be made for the first time. Several validations of RTTOV-5 radiances have been made (Saunders et. al. 1999) against an independent set of line-by-line model radiances for HIRS and comparing the measured radiances with the first guess radiances from the ECMWF model over a 2 week period for the latter. The results are summarised in Figure 3 which show the standard deviations of the differences between the measured radiances with the model guess for RTTOV-3 and RTTOV-5. Only HIRS channel 12 has a significant reduction in the radiance differences which is probably due to the removal of the extrapolation in humidity above 300hPa for RTTOV-5. These results show how forecast model errors still dominate over fast RT model errors.

The top of the ECMWF model has been at 10hPa with 31 levels to the surface for many years but it is now being raised to 0.1hPa with 50 levels in order to enable the assimilation of ozone, improve the assimilation of stratospheric radiances by providing a profile vector up to the level above which the effects of temperature on the (A)TOVS radiances becomes negligible, and to allow a better representation of the stratospheric dynamics. It is anticipated that an improved representation of the stratosphere in the model will lead to improved medium range tropospheric forecasts. These additional stratospheric levels remove the reliance on the 1DVar retrieved profile above 10hPa as input to the RT model in 4DVar which was necessary in the 31 level model. It will also allow ozone data to be assimilated in later versions of the model.

4. FUTURE DEVELOPMENTS IN USE OF SATELLITE DATA AND MODEL

The 50 level model with RTTOV-5 assimilating RTOVS NOAA-11/14 radiances is currently in pre-operational trials, and operational implementation is planned for March 1999. Shortly after this it is planned to replace the RTOVS radiances with NOAA-15 AMSU-A and HIRS 1C radiances and NOAA–14 MSU and HIRS 1C radiances as described in the paper by McNally et. al. (1999) and McNally (1999) in this proceedings. Initially only the HIRS plus AMSU-A sounding channels will be used but later it is hoped to add AMSU-B radiances and some of the AMSU-A window channels. It is also planned to use HIRS channel 9 to influence the ozone fields once ozone is available in the 4DVar control variable.

With 4DVar use can be made of more frequent radiance measurements as is available from the geostationary satellites. Initial experimentation has begun with the METEOSAT water vapour channel radiances available hourly from METEOSAT-5 and 7 as described by Munro et. al. (1999) in this proceedings. It is hoped similar datasets will become available from the other geostationary satellites to give global coverage. Ozone observations from HIRS-9 radiances and SBUV/GOME profiles will be assimilated in the new model to provide a realistic representation of stratospheric ozone concentration in the model. This in turn should benefit the assimilation of the other HIRS longwave channel radiances as some of them are sensitive to ozone.

During 1999 the ECMWF model will have a further 10 levels added to improve the representation of the boundary layer. The 4DVar configuration is also planned to be upgraded so that the resolution of the minimisation in the inner loops is at least doubled to TL127. This should allow more of the ATOVS radiances to be used (i.e. less thinning) but the issue of horizontal correlation of the observation and forward model error covariances will need to be considered more carefully. The 6 hour window over which 4DVar is cycled will also be extended probably to 12 hours initially. Finally the representation of the model background error covariances for humidity are planned to be improved which should help the assimilation of the water vapour sensitive channels.

5. ACKNOWLEDGEMENTS

These developments could not have been possible without the continuous provision of (A)TOVS data on the GTS by NESDIS. The support of the data assimilation section at ECMWF is also gratefully acknowledged.

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TECHNICAL PROCEEDINGS OF THE TENTH INTERNATIONAL ATOVS STUDY CONFERENCE

Boulder, Colorado

27 January - 2 February 1999

Edited by

J. Le Marshall and J.D. Jasper

Bureau of Meteorology Research Centre, Melbourne, Australia

Published by

Bureau of Meteorology Research Centre

PO Box 1289K, GPO Melbourne, Vic., 3001, Australia

December 1999