ASSIMILATION OF GEOSTATIONARY WATER VAPOUR RADIANCE DATA AT ECMWF

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ABSTRACT

Within a four-dimensional variational (4dvar) assimilation system it is possible to take advantage of the high temporal resolution of geostationary radiance data by assimilation of observations at times other than 00, 06, 12, and 18 Z, thereby providing information about the time evolution of the model fields. In this report the results of initial experiments in the assimilation of Meteosat Water Vapour channel (WV) radiance data within a 4dvar assimilation system are presented. Comparisons are drawn with the direct assimilation of the Meteosat Clear Sky Water Vapour Wind (WVW) product. An initial investigation into the impact of both WV radiance data and WVW's on the assimilation and forecast system is made. Some problems which must be addressed before the assimilation of Meteosat WV channel radiances can be implemented operationally are discussed. Future plans leading to the operational assimilation of the Clear Sky WV radiance product within the ECMWF system are outlined.

1. INTRODUCTION

In the context of Numerical Weather Prediction (NWP), the primary use of Water Vapour (WV) radiances from geostationary satellites has been in the generation of Water Vapour winds. These products, which are produced by tracking cloud features in successive images, have been successfully assimilated for some time. However, since WV channels are sensitive to radiance emitted primarily from the upper troposphere, only a small number of high clouds will be detected in any given image and consequently only a small proportion of the data will be used. Clear sky WV winds can also be produced, in this case by tracking clear sky moisture features. Although these wind products make more use of the available data, difficulties in the height assignment of the wind vector makes their use in NWP more problematic (Velden et al., 1997).

An alternative approach being explored here is the direct assimilation of WV radiances within a variational data assimilation system. With the move on 24th November, 1997, to four-dimensional variational assimilation (4dvar) as the operational system at ECMWF, a new opportunity to exploit WV radiance data from geostationary satellites has become available. Within 4dvar (Rabier et al., 1996) it will be possible to take advantage of the high temporal resolution of geostationary radiance data by assimilating observations at times other than 00, 06, 12 and 18 Z, thereby providing information about the time evolution of the UTH field and therefore indirectly the model dynamics in this region.
Routine monitoring of Meteosat WV brightness temperatures against simulated brightness temperatures, calculated from ECMWF first-guess fields using the fast radiative transfer model, RTTOV, has been carried out from November 1996 until the present. This monitoring will soon be done as part of the operational suite, and will then use the new version of the fast radiative transfer model, RTTOV-5 (Saunders et al., 1998), which is discussed further in §3.1. For the duration of Meteosat-5 and the early period of Meteosat-6 there was very little mean bias between the measurements and simulations. However, since May 1997 a significant bias has developed (fig. 1), the source of which is not well understood. This bias is apparent for both Meteosat-7 and Meteosat-5 (now positioned at 63°E) data.

**Meteosat-5 Tb Globe**

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**Figure 1.** Histogram of the bias between Meteosat-5 and Meteosat-7 WV channel brightness temperatures and those simulated from first guess fields, both before and after bias correction, for a six hour window about 7th January 1999, 12Z.

### 2.1 Investigation of Bias

To investigate the source of the bias described above, a simple study has been carried out in conjunction with EUMETSAT where WV radiances calculated from RTTOV-5 have been compared to those calculated from the fast radiative transfer model SYNSATRAD, developed at EUMETSAT (Tjemkes
and Schmetz, 1997). The comparison used 43 reference profiles selected from the TIGR-2 data set (Matricardi and Saunders, 1999), and was carried out for both the IR and WV channels of Meteosat-7. For the IR channel the synthetic radiiances calculated from RTTOV-5 and SYNSATRAD were within 0.6K for all profiles with SYNSATRAD typically producing brightness temperatures slightly higher than those from RTTOV-5 (fig. 2a) Such good agreement was not however obtained for the WV channel (fig. 2b). For the majority of profiles the difference between the two fast models was less than 1.5K however a significant number showed much larger differences, up to 4K. The greatest discrepancies were for those profiles representative of tropical atmospheres (1-12). The same comparison has been carried out for

NOAA-12 HIRS Channel 12 as part of the GVap Workshop on Upper Tropospheric Humidity (Soden et al., 1999) where a similar pattern was seen. In this case the maximum difference was approx. 3K. Furthermore SYNSATRAD typically reproduces brightness temperatures simulated by the GENLN2 line-by-line model (Edwards, 1992) for NOAA-12 HIRS Channel 12 to greater accuracy than RTTOV-5, both in terms of bias and standard deviation (Soden et al., 1999). The comparison to the line-by-line model has not yet been repeated for the Meteosat-7 WV Channel but none-the-less these results do suggest that at least part of the observed bias may be attributable to RTTOV-5. However, when HIRS-12 radiances are compared to radiances from ECMWF first guess fields, in the Meteosat area, the bias apparent for Meteosat WV radiances is not seen. EUMETSAT have been able to confirm that there was a change in the observed bias during 1997 (Tjemkes, private communication, 1998) and that is most likely attributable to changes in the cluster analysis method (Elliot, private communication, 1998) however there is still some uncertainty over the absolute level of the observed bias and what contribution is the result of a bias in RTTOV-5 itself for this channel. Further work is needed to resolve these issues.

2.2 Bias Correction

Regardless of the source of the bias, these data must be bias corrected before they can be used in the operational assimilation system. The bias correction system currently in use for NOAA TOVS data has been applied to the Meteosat WV radiances. The correction scheme used is a modification of the original scheme described in Eyre (1992). In the new scheme, the air-mass correction is determined on the basis of the following selected model predictors: model thickness 1000 - 500 hPa; model thickness 200 - 50 hPa; model surface skin temperature; and model total column water vapour. The statistics of “observation - first guess” departures are accumulated and a linear regression applied to determine the coefficients of the air-mass bias correction in terms of these predictors. Applying this bias correction procedure to both Meteosat-5 and Meteosat-7 radiance data independently results in good correspondence between the two residual bias fields and results in a composite bias corrected field which is spatially coherent (fig. 3).

It is likely that once the Meteosat WV Channel radiance data are routinely assimilated it may be necessary to re-evaluate the choice of predictors used in the bias correction. With the current choice the bias correction is dominated by the mean offset with little contribution from the air-mass correction predictors. This may reflect a poor choice of predictors or simply that the mean observed bias cannot be easily related to air-mass characteristics. Furthermore, a quality control has been invoked where datum points having first guess departures greater than a specified threshold are not used in the regression. The threshold may need to be relaxed for Meteosat data where a larger bias and therefore also first guess departures are seen. However, at present it is advisable to use the operational correction scheme as applied to NOAA HIRS channel 12 as these data represent measurements of a very similar quantity.
FIGURE 2. Difference between Meteosat-7 IR and WV channel brightness temperatures simulated by RTTOV-5 and SYNSATRAD for 43 reference profiles (SYNSATRAD - RTTOV-5).

2.3 Bias Stability

A further issue that has been highlighted by the routine monitoring of the Meteosat WV radiances is the short term drift in bias on a timescale of two weeks or less. For example the mean bias of Meteosat-5 from 9-12-98 until 20-12-98 varies from just over 2.0K to 4.0K with some instances of changes of more than 1.0K in less than one day. (Note that the change in the mean bias corrected difference on the 9th of December was due to the introduction of a updated bias correction). Since a bias correction is assumed to be valid for a period of at least a month, and it is not practical to bias correct on timescales less than this, the only way to accommodate such variation in the context of operational data assimilation is to increase the measurement errors. This would necessarily decrease the weight of the observations in the assimilation system which is not desirable. Currently the random observation error is assumed to be 2K for the Meteosat WV channel with an assumed mean bias of zero (after bias correction). The stability of the bias will be monitored to assess any requirement for such an increase.
3. DESCRIPTION OF EXPERIMENTS

Three experiments have been set up as part of a preliminary investigation into the impact of Meteosat WV channel radiance data on the 4dvar assimilation system. These are a control, an experiment in which Meteosat radiance data are assimilated directly, and one in which the derived Clear Sky WVW product is assimilated. All three experiments cover the period from the 2nd of July, 1998 to the 13th of July 1998, and are extensions of the Cycle 19 operational ECMWF 4dvar assimilation system.

3.1 Control

The control experiment uses RTTOV-5, the new version of the RTTOV radiative transfer model which is based on 43 atmospheric levels and includes a gradient in humidity up to 0.1hPa. (In the previous version of RTTOV there was a gradient in humidity only up to 300hPa. This was clearly inadequate for the assimilation of WV channel radiance data where the peak of the weighting function is typically around 300hPa.) Both Meteosat-5 and Meteosat-7 Cloud Motion Winds are included as for current operations (Lalaurette et al., 1998). Also, TOVS radiance data and SSMI Total Column Water Vapour data are assimilated, in addition to the conventional in-situ measurements.

3.2 Clear Sky Radiance Assimilation

In the radiance experiment, the segment processed clear sky radiance data from both Meteosat-5 and Meteosat-7 are assimilated. Each datum point received is a segment processed clear sky radiance product comprising 32 x 32 pixels and corresponding to approximately 160 x 160 km at the sub-satellite point (SSP), increasing to a maximum of approximately 250 x 250 km at 50° from the SSP. See Kelly et al. (1996) for further details. No thinning is carried out with the exception that no over-lap is allowed between the two satellites. In the over-lap region, Meteosat-7 data are used for longitudes ≤
30°E and Meteosat-5 data are used for longitudes > 30°E. Before being passed to the main assimilation, the radiance data are preprocessed in a 1dvar retrieval in which those profiles which have an “observation - first guess” difference greater than 8K are rejected, as are those which fail to converge within the 1dvar system.

3.3 Clear Sky Water Vapour Wind Assimilation

In this experiment the clear sky WVW product provided by EUMETSAT is assimilated. Again, data from both Meteosat-5 and Meteosat-7 are used. These data are received every 90 minutes and assimilated in hourly windows. They are thinned (Rohn et al., 1998) and as for the radiance data, no overlap is allowed. Data are not used over land if the height assignment is < 500mb and Meteosat-7 data is not used over land for latitudes > 35°N. Finally, data are only assimilated if they have a quality indicator, assigned by EUMETSAT, greater than 0.8. Note that in this experiment the WVW’s are assimilated as a single level vector using the EUMETSAT height assignment provided. This is a simplistic use of the data which will be improved in the future (Kelly et al., 1998).

4. INITIAL IMPACT INVESTIGATIONS

Although the clear sky radiance product and the clear sky WVW product may be considered to contain similar information, when viewed in the context of a 4dvar assimilation system, they cannot be considered to contain identical information. The information contained in the radiance product about the evolution of the wind field is implicit and depends on the time evolution of the clear sky radiance product rather than its instantaneous state. Conversely, the WVW product contains explicit information, influenced by assumptions implicit in the derivation. Since this derivation relies on explicit tracking of clear sky targets the coverage is not necessarily uniform and there may be areas where it is not possible to produce a wind product. Despite these differences it is possible to make general comparisons and draw preliminary conclusions regarding the relative impact of these two data types.

4.1 Mean Analysis Differences

For each experiment the mean analysis fields have been generated for the period from 4th July 1998 to 10th July 1998. The first two days of each experiment have been excluded to avoid any “spin up” problems while the model adjusts to the new data. Mean difference fields were then generated between the radiance assimilation and the control, and the winds assimilation and the control.

To investigate the impact of each data type on the model dynamics, one field to consider is the vector wind field. Typically where there is an impact from the WVW’s there is often a similar impact from the radiance data. However the radiance experiment does show greater influence in some areas (the Indian ocean for example) which may be related to data coverage in the WVW product. Also, the vertical response is different for the two experiments. In the case of the WVW’s experiment, the data is assimilated at a single level which is dictated by the height assigned to the product by EUMETSAT. Any vertical spreading of information comes primarily from the vertical correlation of the background error in the vector wind field. In contrast, the vertical information provided by the direct assimilation of WV channel radiance data comes both from the weighting function implied by RTTOV-5, and also from the vertical correlation in the background error in specific humidity. These differences result in a different vertical response between the two experiments with the radiance experiment typically showing a larger vertical spread of information extending from 500mb to 200mb or higher and the winds experiment having more localised changes centred around 450mb.
**Figure 4a.** Mean 200mb specific humidity difference for the radiance experiment minus the control, expressed as a fraction of the control humidity, for the period 4th - 10th July 1998.

**Figure 4b.** Mean 350mb specific humidity difference for the winds experiment minus the control, expressed as a fraction of the control humidity, for the period 4th - 10th July 1998.
These features are also apparent in the response of the specific humidity field.Whilst the radiances assimilation shows a large scale moistening in the region 200-300mb (fig. 4a), the winds assimilation shows a smaller scale moistening at lower altitudes, typically 350mb (fig. 4b). At lower altitudes both experiments show significant changes to the moisture field but there is no mean drying or moistening. Fig. 4a also clearly shows the advection of humidity information from the Meteosat area, south of Australia, by the sub-tropical jet. This is consistent with upper tropospheric humidity behaving as a quasi-passive tracer. A similar pattern is seen in the temperature fields with a large scale cooling from 200-300mb from the radiance data but more localised temperature changes resulting from the assimilation of the WVW’s.

It is possible that some of these large-scale temperature and humidity changes may be attributable in part to a non-optimum bias correction. This will be re-evaluated in future experiments. Furthermore, due to the large volume of Meteosat WV channel data being assimilated, some short-comings in the ECMWF humidity analysis have become apparent. These will be discussed further in §4 but until they are rectified it would be unwise to draw anything more than qualitative conclusions regarding the impact of Meteosat WV channel radiance data on the ECMWF system.

3.2 VERIFICATION

One way to verify an assimilation experiment is to compare with observations. For both the radiances assimilation and the winds assimilation the RMS fit of the model first guess to the conventional observations was similar. However, after assimilation of the WV radiances data, the RMS fit of the model first guess to the Meteosat WV data itself was significantly improved. This is encouraging as it demonstrates that the model has drawn well to the radiance data without degrading the fit to the conventional observations. The assimilation of the WVW’s has not, however, significantly altered the RMS fit to the Meteosat WV radiance data.

This is confirmed by a comparison of Meteosat-7 WV imagery, with corresponding simulated images. Fig. 5 shows a section from a Meteosat-7 WV image for the 3rd of July 1998, 00Z (fig. 5a) and simulations based on analysis fields for the same date and time from the radiance assimilation (fig. 5b), the winds assimilation (fig. 5c) and the control (fig. 5d). It can be clearly seen that the assimilation of the Meteosat WV radiances data has made significant corrections to the model state most notably in the region of Madagascar and off the west coast of Africa) which is now in much better agreement with the image than either the winds assimilation experiment or the control.

Also, after assimilation of WV channel radiance data significantly less residual bias remains between the measurements and the first guess fields as shown in fig. 6, further confirming that the model has drawn well to these data. A number of forecasts have been run for each experiment. In all cases the impact is essentially neutral or slightly positive compared to the control. This is very encouraging considering the known problems with the humidity analysis (§4). However, a greater number of samples is required for a more meaningful comparison.
FIGURE 5. A section from a Meteosat-7 WV image for the 3rd of July 1998, 00Z (a) and simulations from corresponding analysis fields after assimilation of Meteosat WV radiance data (b), after assimilation of Meteosat Clear Sky WV winds (c) and from the control experiment (d).
Figure 6. Mean difference between Meteosat-5 and Meteosat-7 WV channel brightness temperatures and those simulated from first guess fields for a period from 2nd July to 13th July 1998, after assimilation of WV channel radiance data. This can be compared with fig. 3.

4. Specific Humidity Analysis

Investigation of the experiments described above has highlighted certain problems with the ECMWF humidity analysis that need to be resolved before Meteosat WV data can be assimilated effectively. In particular, when Meteosat WV radiance data were included in the assimilation, problems with the speed of convergence of the minimisation were noticed. Further investigation of the eigenvectors of the analysis system showed that undue emphasis was being given to specific datum points. These points corresponded to extremely dry model profiles associated with an unrealistic specification of the background error in humidity, corresponding in some cases to an error in radiance space of up to 32K. This should be compared to a specified measurement error of 2K. As the weight that a measurement is given in the analysis system is related to the balance between the background and measurement errors, such an unrealistic specification of background error will be difficult for the assimilation to accommodate. Furthermore, there is no indication that for these data points there are particularly large first guess departures therefore the specified background error is clearly not representative in these cases.

In the current operational system the humidity background error is specified on the basis of an empirical formulation as a function of the temperature $T^b$ and relative humidity $U^b$ of the background:

$$\sigma_b = -0.002T^b - 0.0033|T^b - 273| + 0.25U^b - 0.35|U^b - 0.4| + 0.70$$

$$\sigma_b = \min[0.18, \max(0.06, \sigma_b)]$$
Since the analysed variable is specific humidity, the standard deviation in terms of relative humidity is then converted to specific humidity, taking the variation of $q$ of the equation

$$q = \frac{U e_{\text{sat}}}{\varepsilon - p - U(\frac{1}{\varepsilon} - 1)e_{\text{sat}}}$$

where $U$ is the relative humidity, $\varepsilon = R_{\text{dry}}/R_{\text{vap}}$, $e_{\text{sat}}$ is the saturation water-vapour pressure at the temperature in question and $p$ is pressure. A minimum value is set by $\sigma_b = \max(\sigma_b, 1.25 \times 10^{-8} \text{ kg/kg})$. For pressures less than $p_0 = 800 \text{ hPa}$, and over the sea, the model of background errors described above is modified by

$$\sigma_{\text{mod}} = \sigma_b \left[ 1 - a + a \exp \left( -\frac{(p - p_0)^2}{b} \right) \right]$$

where $\alpha = 0.5(1 - \text{LSM})$ (where LSM = land–sea mask) and $b=12500$. This is intended to prevent excessively large increments. Stratospheric errors are set to the minimum value to inhibit drift.

Tests are currently being carried out to determine the most appropriate method for preventing the unrealistically high background errors that the current formulation allows in some circumstances. Possibilities included restricting the background error to be less than a specified percentage in specific humidity or the use of a cycling specification of humidity background error (Derber and Bouttier, 1999). These options are currently being investigated.

5. SUMMARY AND FURTHER WORK

Meteosat-5 and Meteosat-7 WV radiances are soon to be passively monitored within the operational assimilation system at ECMWF. Preliminary experimentation has clearly shown that the direct assimilation of geostationary WV channel radiance data, within a 4dvar variational assimilation system, may be used indirectly to correct the model dynamics in the upper troposphere. A broadly similar response may be obtained from the assimilation of the associated Clear Sky Water Vapour wind product however differences in data coverage and height assignment will result in differences in impact. Before a full investigation can be carried out there are several areas where improvements are required for optimal use of both the radiance and the wind data. Some problems that will affect the WV radiance data assimilation are as follows. There are known deficiencies in the specification of the 4dvar background error for specific humidity under certain conditions. This will be corrected in the near future. Furthermore, in the specification of the background cost, humidity is uncoupled to other model variables in the current operational configuration. Including a correlation between temperature and humidity in tropical regions would be desirable. Finally, although RTTOV-5 has a more appropriate gradient for the WV channel, there is still room for improvement and this should be investigated. Also, the possible bias in RTTOV-5 for the Meteosat WV channel needs further study. With regard to the WVV product, it would be desirable to develop a more sophisticated method for describing the vertical distribution of information (Kelly et al., 1998) which more realistically represents the thick layer from which the information has come. This will be investigated. Another change planned at ECMWF which will interact with this work is the move to a model with many more levels (~60) which will take place in the near future. Passive IR and WV radiance monitoring will be carried out with this new model. Once these improvements have been completed and more detailed impact studies carried out it is intended that the assimilation of Meteosat WV radiance data will be implemented operationally at ECMWF.
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