# METEOSAT cloud-cleared radiances for use in three/four-dimensional variational data assimilation

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**ABSTRACT**

Variational analysis offers a simple way of utilising the cloud clear radiances from the Meteosat water vapour channel. It is relatively fast and accurate to compute the equivalent radiances from a model guess using a fast radiative transfer model. This departure is then used in the minimisation process of the analysis. Results of the initial computations to examine the feasibility of their use in the variational analysis will be discussed.

## 1. INTRODUCTION

At present numerical weather prediction (NWP) models make little use at upper level of the water vapour (WV) channel on geostationary satellites. The cloudy regions provide the best tracking targets (Holmlund, 1993), however these only represent a small region of this imagery due to the fact that the radiance is emitted from the upper part of the troposphere. Wind vectors can be produced from the clear regions but these segments yield some deep layer mean motion and not the wind at a particular level. These "pure" WV winds are difficult to use in NWP. This study investigates whether it may be better to use the radiance directly in the analysis. Figure 1 shows the relationship between the resolution of the Meteosat satellite (pixel), the Meteosat segment processing and ECMWF operational forecast model.

A humidity product (UTH) has been produced from the Meteosat WV segments (32x32 pixels) for some years (Schmetz and Turpeinen, 1988) and some effort was made use of the UTH product NWP (Zhang et al., 1988). The impact was small and may be partly due to the old ECMWF data assimilation system using the Optimum Interpolation (OI) scheme.

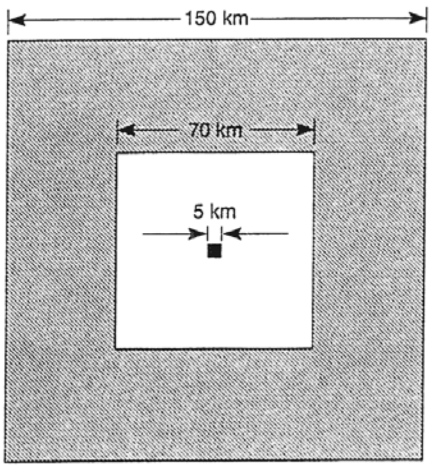



**Fig. 1** Schematic representation of resolution of Meteosat imagery (5 km pixel), ECMWF model (T213 ~ 70 km) and Meteosat segment processing (~ 150 km).

Variational analysis offers a much better way of utilising the clear radiances. The fundamental difference with OI is that the variational scheme computes the observation from the model rather OI analyses the model variables from the retrieved observation, and the latter method is not so straight forward with satellite radiance measurements. Cloud clear radiances from the polar satellites, TOVS (TIROS Operational Vertical Sounder) are currently in operational use and are a good reference when studying possible use of radiances from geostationary satellites.

## 2. VARIATIONAL DATA ASSIMILATION

The direct use of TOVS cloud-cleared radiances in the ECMWF variational data assimilation scheme will be briefly summarised. A more detailed description is found in Anderson, 1994. The scheme uses a fast radiative transfer model and its adjoint. Radiances are used together with all other data.

In a three-dimensional variational formulation (3D-Var), horizontal as well as vertical consistency in the use of the radiances is ensured. Mass, wind and humidity are analyzed simultaneously under certain balance constraints which control the level of gravity waves in the analysis. The scheme thus combines retrieval, analysis and initialisation in one step. In a four-dimensional formulation (4D-Var), time consistency, as given by the evolution of the forecast model and its adjoint, acts as an additional constraint.

We follow the general variational approach to the assimilation of data into an NWP system (Talagrand, 1988) by minimizing the cost-function $J(x)$ with respect to the atmospheric state $x$, where $J(x)$ measures the degree of mis-fit to the observations and to the background information. If the errors involved have Gaussian distributions, then the optimal penalty function is a sum of quadratic terms:

$$
\begin{aligned}
J(x) &= J_o + J_b \\
J_o &= [y - H(x)]^T O^{-1} [y - H(x)] \\
J_b &= (x - x_b)^T B^{-1} (x - x_b)
\end{aligned}
\qquad (1)
$$

where $x_b$ is the background with estimated error covariance $B$, $y$ represents the observations with estimated error covariance $O$, and $H$ is the observation operator (or "forward" operator) which computes model equivalents of the observed quantities at the observation points. The matrix $O$ should in addition to the observation error also include the representativeness error, i.e. the error in the forward operator. Eq.1 applies to a wide range of problems. It has the same form in one as well as three and four-dimensional applications. In the case of TOVS radiances, $H$ specifically represents the radiative transfer model which calculates radiances from the state vector of the forecast model. In 4D-Var, $H$ includes a model integration from the time of the background to the time of the observation (Thépaut, 1993). 3D-Var is thus, in theory as well as in practice, equivalent to a 4D-Var without model integration.

The computation of the radiance cost function is organized like that for conventional data (Vasiljevic et al., 1992), with the addition the horizontal observation error correlations can be taken into account (Pailleux, 1989; 1992). However, data from different satellites are assumed to be uncorrelated. Part of the observation error is due to errors in the radiative transfer model which to some extent introduces error correlations between all radiance data. The radiance observation error correlation function can be specified to be Gaussian with a length scale of 350 km. Half of the observation error only is assumed to be correlated.

The forward operator $H$, is the product of all the operations necessary to go from the control variable $x$ to model radiances at observation points. The operator $H$ is continuous in $x$. It may be linear or nonlinear and it ought to be differentiable in general but it does not have to be differentiable for *all* v for example differentiable between model levels but not differentiable exactly *at* a model level. Once model radiances have been computed, the cost function and its gradient with respect to radiances can be calculated. Then the adjoint operators are applied in the reverse order to yield the gradient of the cost-function with respect to the control variable. The $J_o$ computation is followed by the computation of $J_b$ and its gradient (Heckley et al.,1992), and the whole procedure is repeated until the minimisation has reached convergence, or the maximum number of iterations has been reached.

## 3. SIMULATION USING THE ECMWF FORECAST

A short period, early in the forecast was chosen to look and validate the spacial distribution and time evolution of the simulated Meteosat WV data and estimate the benefit to both 3D and 4D-VAR. The current operational T213 forecast model at ECMWF has 31 vertical levels from the surface to 10 hPa and contains temperature, wind, humidity, and cloud properties (liquid water, ice and cloud fraction) on these levels. The horizontal resolution of the model grid is approximately 70 km. Simulated Meteosat water vapour radiances were calculated using the RTTOV forward model (Eyre, 1991) package at each model grid point. The forecast model was run from the operationally ECMWF analysis for 24 hours and the output was converted into simulated clear-sky Meteosat radiances from the 10th hour every hour until the 17th hour. All these calculations where performed taking into account the satellite direct path ensuring that no limb corrections were required. The model gridded radiances were then remapped to the Meteosat image projection and interpolated to 5 km resolution. In regions where neither medium- nor high-level clouds are present a direct comparisons can be made.

Figure 2. shows a comparison of Meteosat WV image with the 10-hour forecast (see also Table l. for the correspondence between colour and brightness temperature). An effort was made to show the cold cloudy regions in shades of grey in the observed image but some cloud is still in the colour ranges and can be identified by its textural appearance. Using the colour scale the blue areas refer to the dry regions and the red/yellow are the areas where there is high upper level humidity. The first impression in the comparison is that the model appears dryer than the atmosphere, however there is good correspondence between atmospheric features such as frontal regions and dry slots.

The resolution of the global image (Figure 2) is too poor and difficult to observe specific meteorological features, hence some zoomed areas are shown. In the global image a very sharp dry slot was observed over Europe. A region, centred over the Mediteranean was extracted from the global data and remapped to polar stereographic. Figure 3(a) shows this same 10-hour forecast comparison as in Figure 2. and in Figure 3(b) the forecast comparison a further eight hours later. There is good correspondence between all major features though the forecast appears to have a little more blue in the centre of the image. In the eight hour period the forecast has moved the trough directly ahead of the sharp dry slot over Italy from the Adriatic to be over Greece. The sharp dry slot also moves down into the Mediterranean. These features can also be followed well in the Meteosat imagery.

Another further comparison is shown in the Southern Hemisphere in Figures 4. In this example there is a frontal system lying across the top of the imagery (shown by the white cold cloud) and a dry slot that folds itself into the centre of the vortex. The process continues during the forecast period and this process is again well validated by the Meteosat WV imagery.

**Table 1** Colour scale for conversion to temperature for all relevant figures.

| | | |
|---|---|---|
| BLUE/NAVY | 260 - 249 | °K |
| BROWN/GREEN | 248 - 239 | °K |
| RED/YELLOW | 237 - 229 | °K |
| GREY/WHITE (clouds) | 228 - 213 | °K |

## 4. WEIGHTING FUNCTIONS

In order to further understand the nature of the observed radiance in the Meteosat WV channel three model profiles and radiances normalized weighting functions are shown in Figure 5a-c. Figure 5d is a remapped section of the Meteosat imagery (same case as discussed above) with the profile locations marked. The first profile, chosen in a dry region of the image, has low values of upper level humidity. The weighing function is broad and low (~ 450 hPa) in the atmosphere. The second profile is relative moist in the upper levels and hence all upwelling radiation from below is absorbed. The weighing function is sharp and the peak occurs at 360 hPa. The last profile is one that contains some upper level humidity but not enough to absorb all the radiation from below and the outward emitted radiation contains contribution from upper and mid-levels of the troposphere. This produces the ‘double peaked weighting function’. In the past similar weighting functions have been discussed and it was found that if tracked the resulting wind vector could be very difficult to interpret (Laurent et al. 1990).

## 5. SEGMENT PROCESSING FOR CLEAR RADIANCES

The production of CMW from Meteosat is described in detail in Schmetz et al., 1994. The water vapour and infrared channel imagery (2500 lines and 2500 elements) are processed in segments of 32x32 pixels (refer to Fig.l). If the radiance in each segment is cloud free in the water vapour channel then a mean clear radiance is produced for each segment for most of the inner region of the image. Figure 6 shows the full image and an image averaged to segment resolution with the segment locations yielding clear radiances. Note that it is only the very cold cloudy regions that fail.

Next at each segment location synthetic brightness temperatures were calculated from the ECMWF operational analysis. A contour analysis of the differences observed minus computed is shown in Figure 7. It was pleasing that does not appear to be an increasing difference with increasing nadir angle or with latitude. In fact most of the large differences appear over land, e.g. the negative differences (dry bias of model) over Northern and Central Africa, where the TOVS radiance data are not used. Similar comparisons in previous work (Schmetz and van de Berg, 1994, Laurent 1990) showed a different picture of the model bias, but were performed at the time when TOVS radiances were assimilated only in the Northern Hemisphere, while in the current 3D-Var system they are assimilated over the sea. A further examination of the differences with the forecast and observed imagery indicates that the largest errors are usually due to small phase error in the forecast which would be corrected with active use of these data in the analysis.

Figure 8 contains a scatter plot of the observed and calculated brightness temperatures for the case of Figure 7. The relevant statistical results are shown in Table 2 for all data (first row) and for data after quality control (second row). The quality control removes pair of brightness temperatures differing by more than ±6°K and was found to be necessary in using of TOVS due to cloud contamination and using extreme model profiles. A similar comparison can be made between observed and calculated clear radiances for TOVS channel 12 on NOAA 14 which is a similar to the Meteosat WV channel. This gives, after q/c, a mean about -2.0°K and a standard deviation of 3.5°K.

**Table 2** Statistic of observed minus calculated brightness temperatures.

| | Mean (°K) | Stand. dev. (°K) | No. |
|---|---|---|---|
| **No q/c** | 0.04 | 4.2 | 2732 |
| **q/c ±6°K** | 0.40 | 2.8 | 2478 |

**(a)**

**(b)**

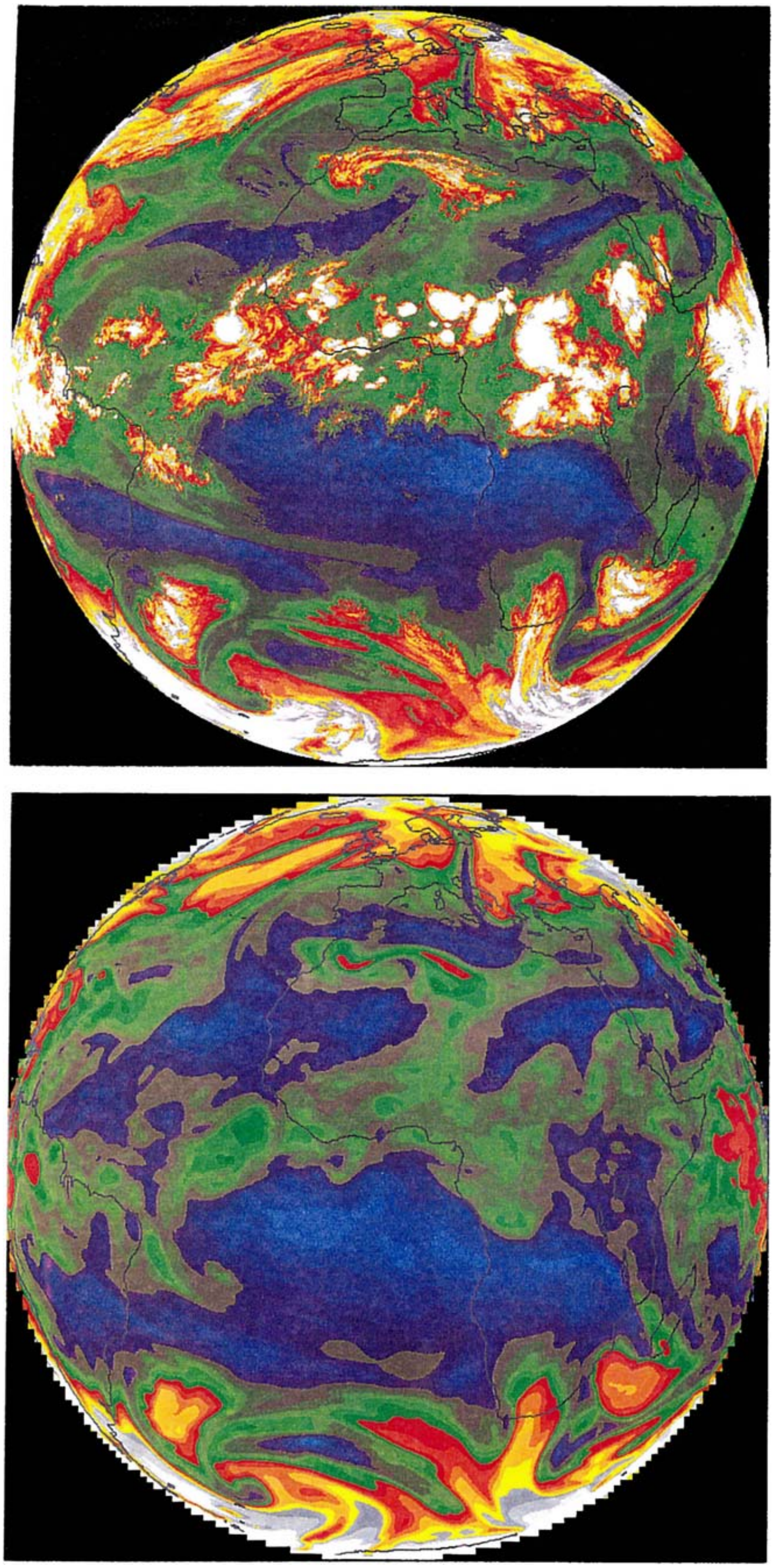


**Fig. 2** WV brightness temperatures on 28/05/96 **(a)** observed by Meteosat-5 at 22 GMT and **(b)** computed from the ECMWF 10 h forecast field valid at the same time.

(a)

(b)

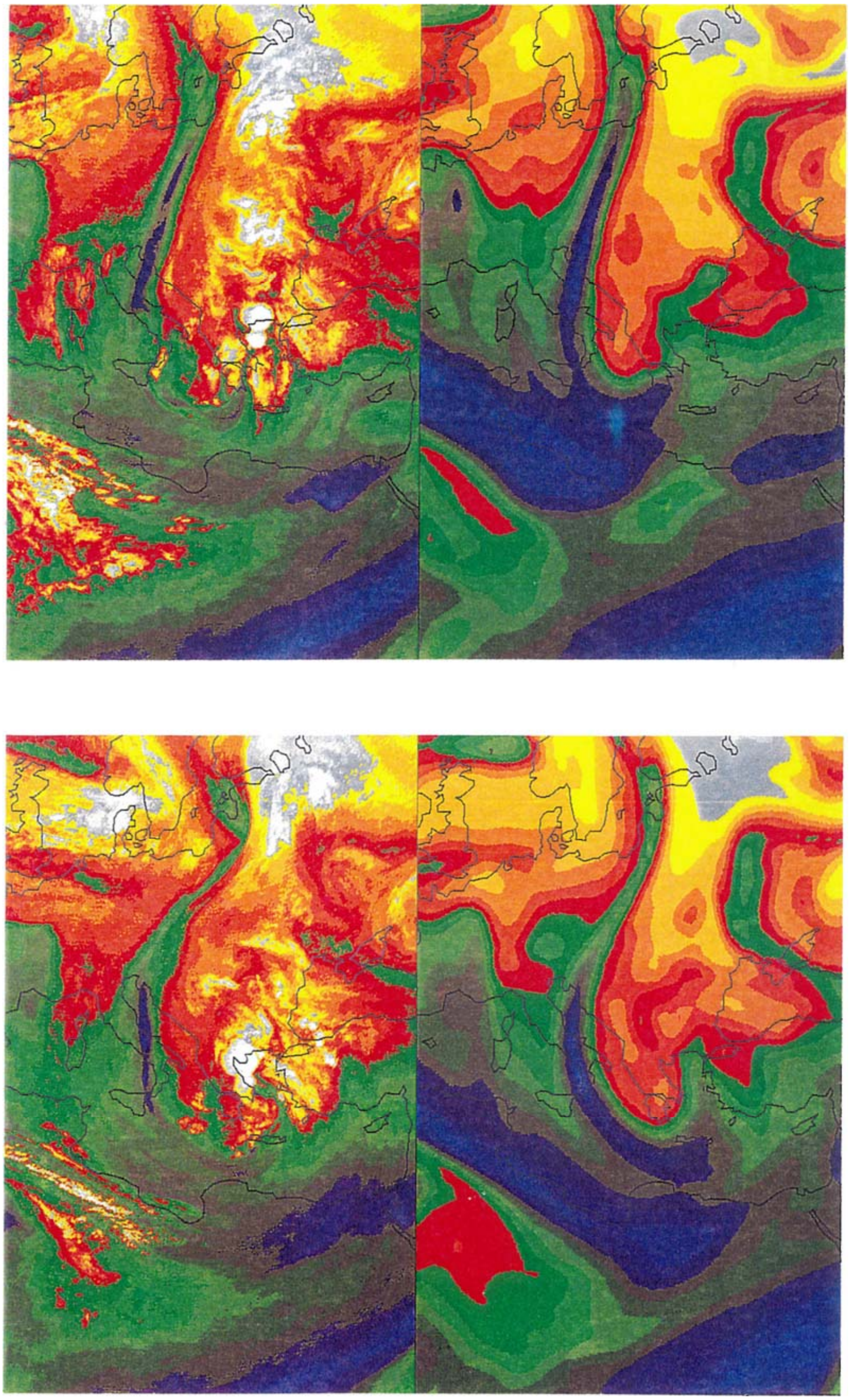
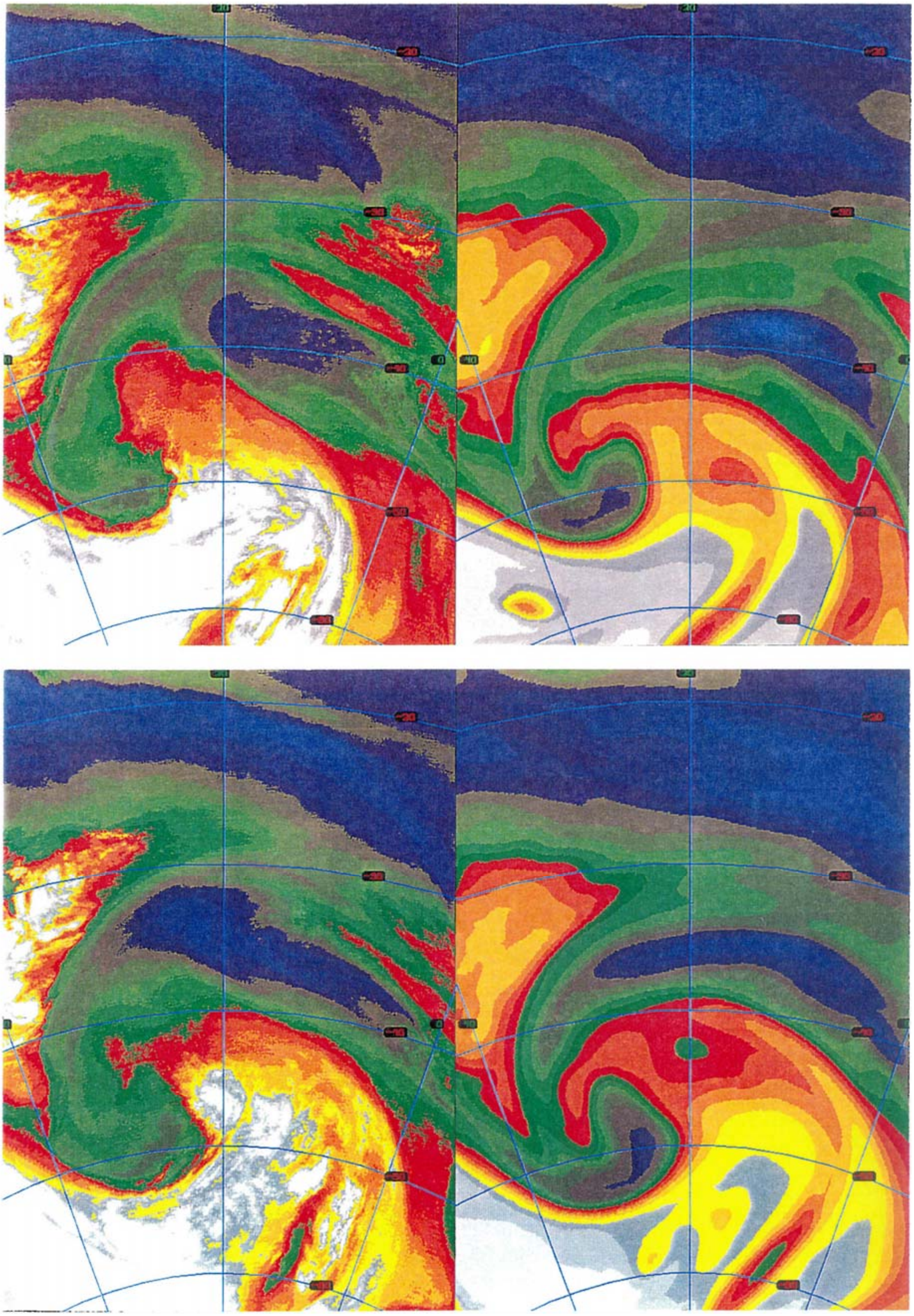


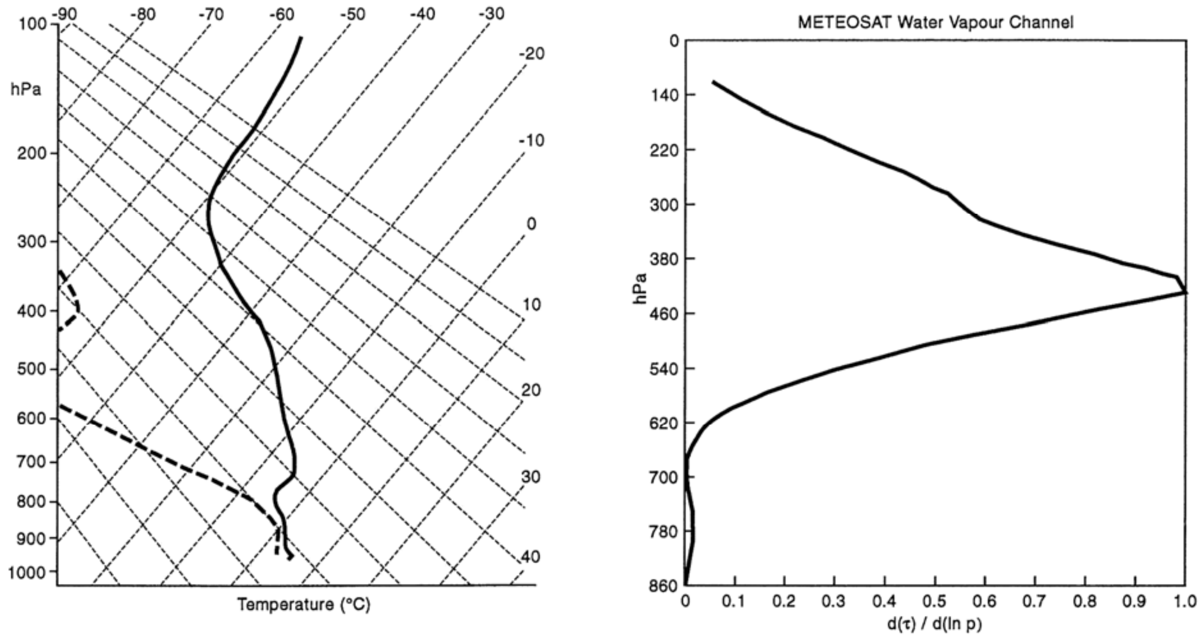
**Fig.3** Temporal evolution of WV brightness temperature for area centred over the Mediteranean, as seen by Meteosat (left) and as computed from the ECMWF forecasts (right). **(a)** On 28/05/96 at 22 GMT (10h forecast) and **(b)** on 29/05/96 at 05 GMT (17h forecast).



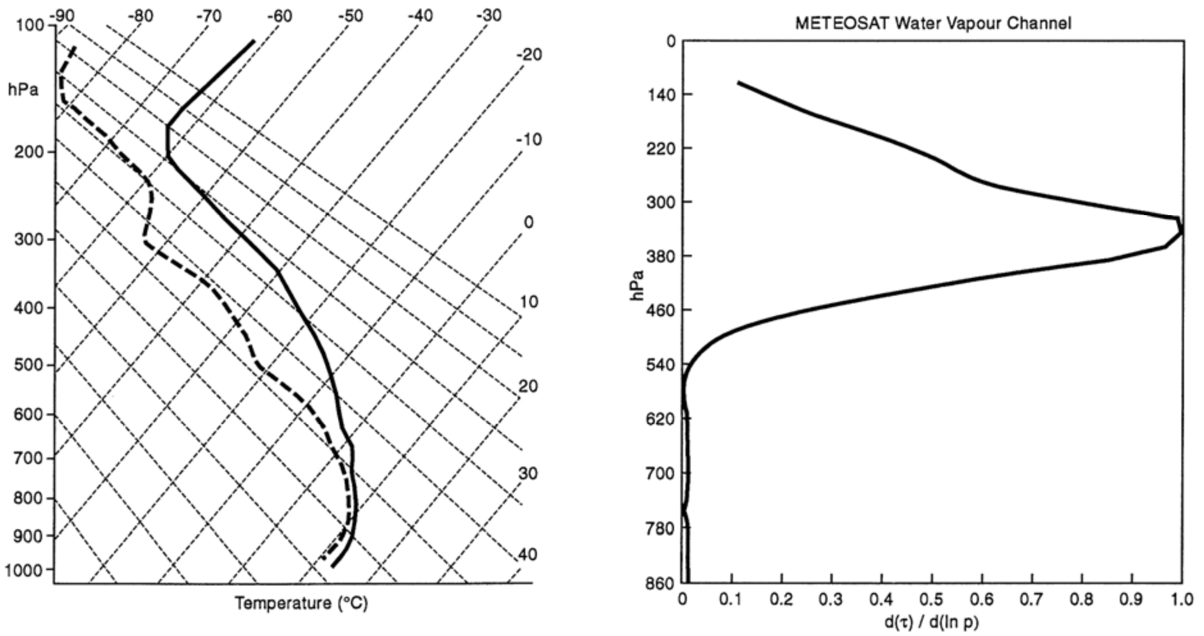
(a)

(b)

**Fig.4** As Fig.3 but for selected area in the Southern Hemisphere.

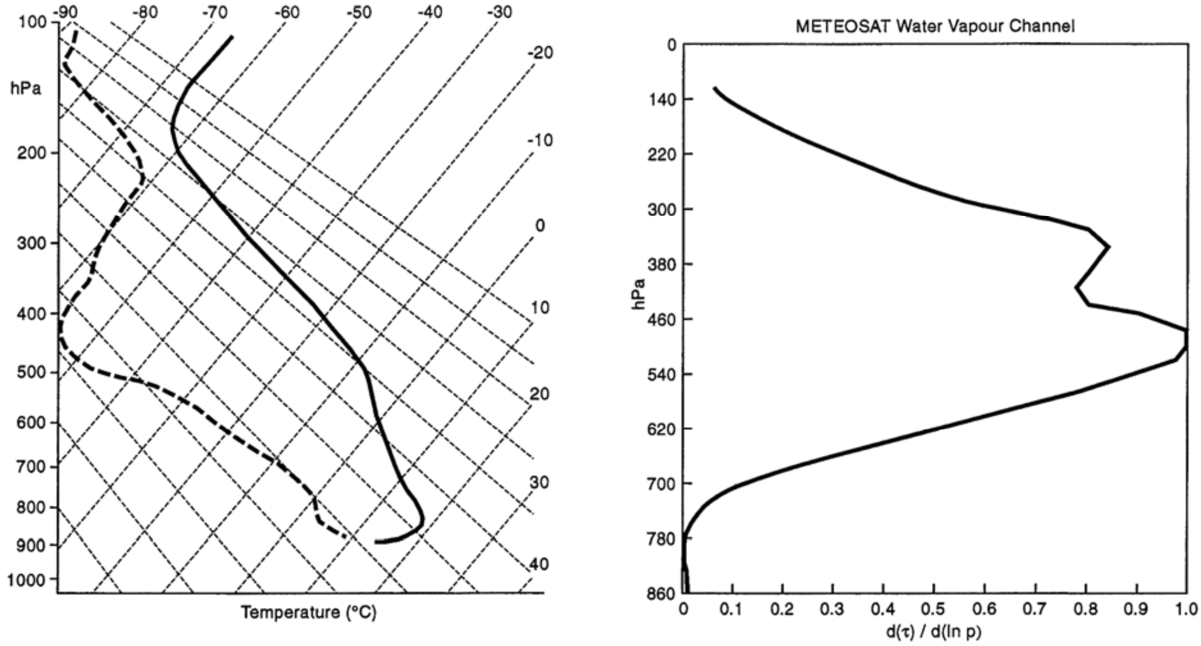



**(a)**




**(b)**

**Fig.5 (a) (b) (c)** Three model profiles of dew point (dashed line) and temperature (continuous line) on 29/05/96 at 00 GMT; below each profile the corresponding weighting functions of the Meteosat-5 WV channel is shown. **(d)** Location of the grid points used for the calculations.




**(c)**

**(d)**

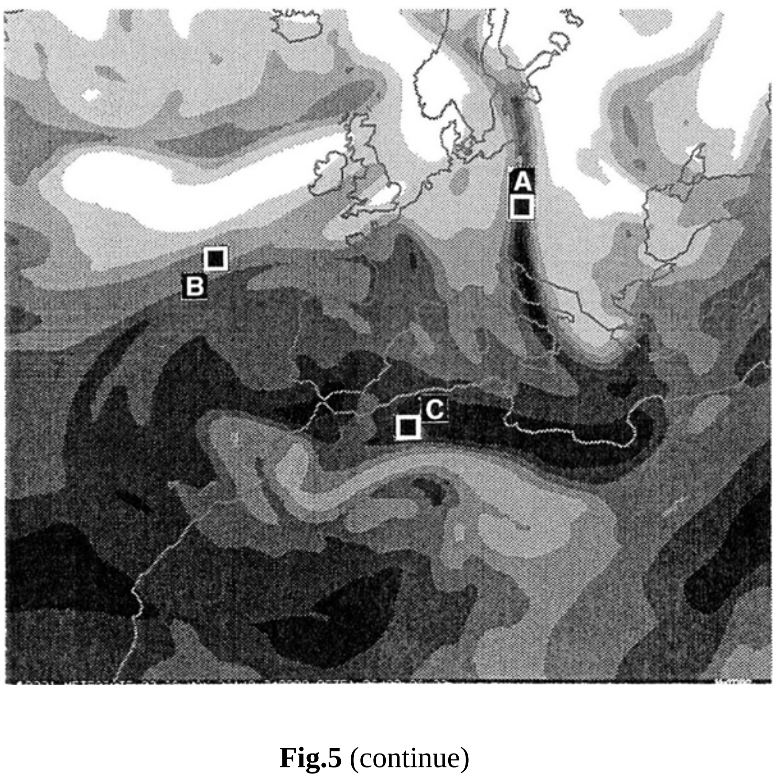



**Fig.5** (continue)

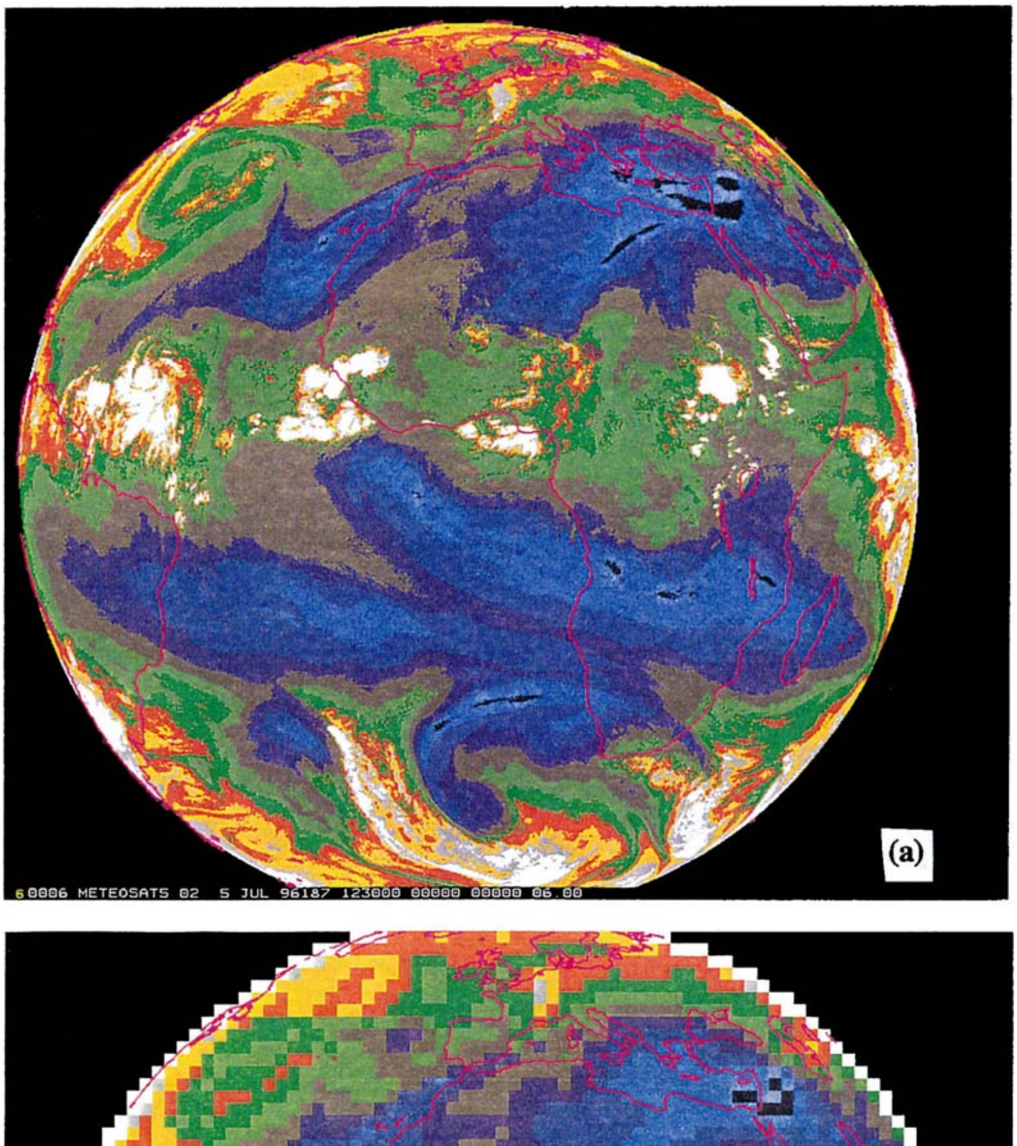



**Fig. 6 (a)** Full resolution Meteosat Water Vapour image and **(b)** segmented image with results from the cloud-clearing algorithm.

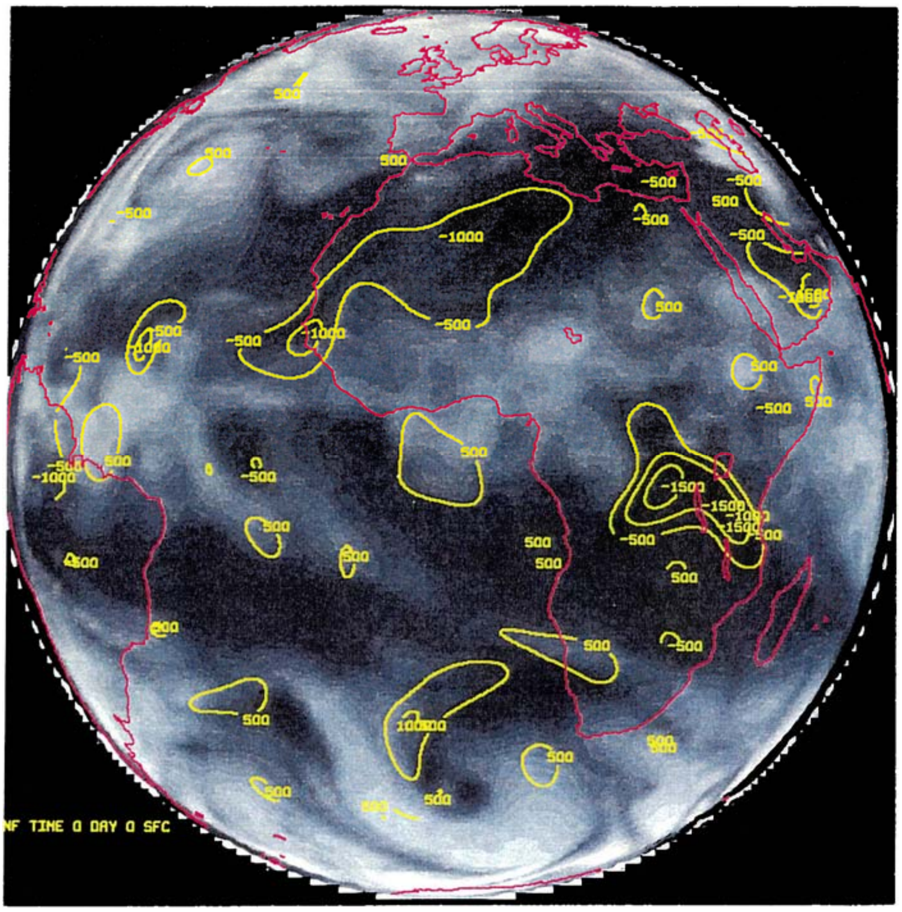



**Fig. 7** Brightness temperatures computed from the ECMWF analysis on 05/07/96 at 12 GMT plus contour of difference observed minus calculated brightness temperature (°K times 100).

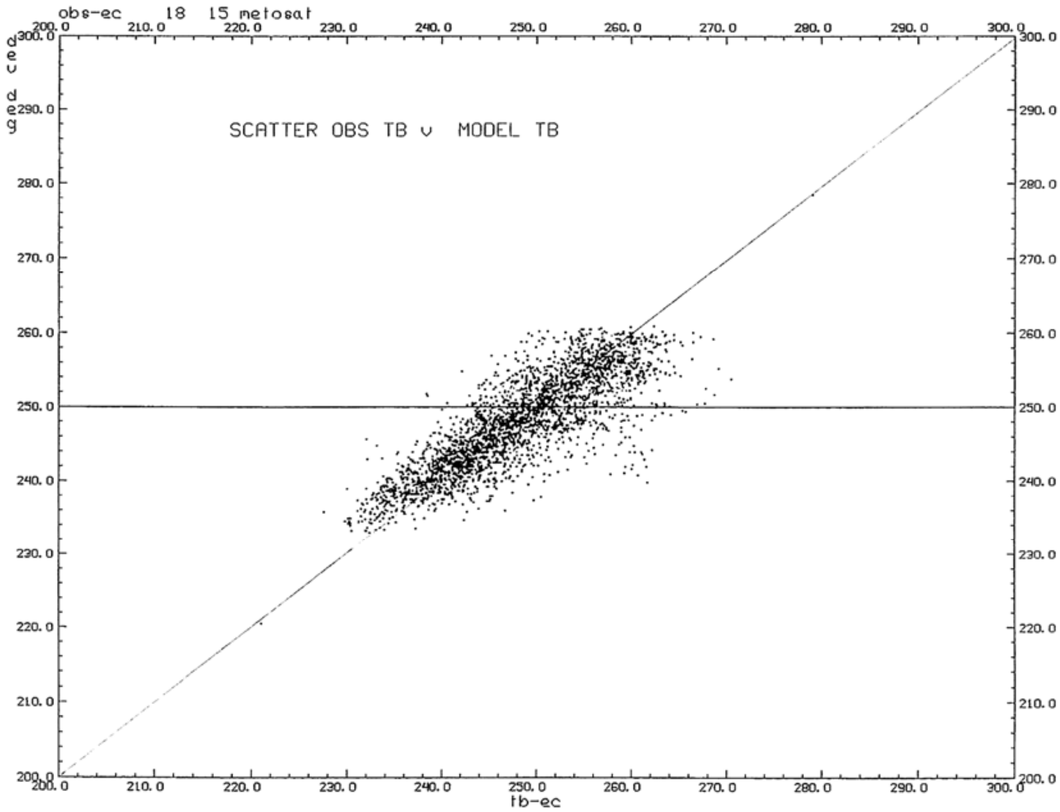



**Fig. 8** Observed versus computed brightness temperatures on 05/07/96 at 12 GMT.

## 6. CONCLUSIONS

From this initial study it is clear the direct use of these clear upper level water vapour radiances from Meteosat is feasible and an important source of new data to improve the data assimilation.
With its use in 4D-Var, the full potential of half hourly measurements offers a real chance of correcting the atmospheric motions of the forecast model during the assimilation period.
Data from this channel is now available on GOES and HIMIWARI and could provide a near global coverage.

## 7. ACKNOWLEDGEMENTS

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