UPPER TROPOSPHERIC HUMIDITY OBSERVATIONS FROM METEOSAT AND COMPARISONS WITH ECMWF FORECASTS

Johannes Schmetz and Leo van de Berg

European Space Agency (ESA), European Space Operations Centre (ESOC),
64293 Darmstadt, Germany

ABSTRACT

Global studies of the Earth's environment require continuous, consistent and accurate data monitored over long periods of time and over the whole globe. At least the demand for continuity and consistency is well met by operational meteorological satellite programs.

As an example of how operational satellites can contribute to a global climate monitoring, the development of a climatology for the upper tropospheric relative humidity (UTH) from Meteosat radiance observations in the water vapour channel (WV: 5.7 - 7.1 μ m) is discussed. Since water vapour is the most important greenhouse gas in the Earth's atmosphere and the most variable one, knowledge about the water vapour distribution and its relationship to cloud formation is fundamental to understanding the Earth's greenhouse effect.

Monthly means of the UTH from METEOSAT are compared with ECMWF forecast fields. We find a slight dry bias in ECMWF fields in convective regions and a more severe moist bias in the dry subtropical subsidence regions.

A preliminary analysis of Meteosat UTH data reveals significant diurnal cycles of the upper tropospheric humidity. While diurnal cycles cannot be resolved with TOVS observations, the latter have the distinct advantage of providing a complete global coverage with one instrument. An optimum observing system might require a combination of both geostationary and polar orbiting satellites for UTH observations.

1. INTRODUCTION

A prerequisite for global climate studies are data sets that provide relevant quantities continuously, consistently and accurately over long periods of time and over the whole globe. Presently the demand for continuity is only met by operational meteorological satellite observations. Consistency or homogeneity of the data needs to be improved. Concerning calibration the present situation is better for the infrared instruments aboard polar orbiting satellites, which have onboard calibration, than it is for geostationary satellites.

This paper provides a short description of the upper tropospheric humidity (UTH) observations from METEOSAT. Section 2 introduces the water vapour-climate aspect and underlines the need for UTH observations. Section 3 briefly describes the UTH retrieval and section 4 presents some results and comparisons with the ECMWF forecast model.

2. WATER VAPOUR AND CLIMATE

Water vapour is the most important greenhouse gas in the Earth's atmosphere. More than 70% of the atmospheric grey body optical depth is due to water vapour (Stephens et al., 1992). The generally held view on the role of water vapour in the climate system is that it induces a positive feedback mechanism enhancing the mean global warming due to external forcings (e.g. Manabe and Wetherald, 1967). Cloud fields are directly coupled to the water vapour fields, since cloud formation starts once the humidity exceeds a critical value.

Recent work by Stephens and Greenwald (1991), Shine and Sinha (1991) and Arking (1992) demonstrated with model calculations that all levels of water vapour in the atmosphere contribute to the water vapour greenhouse effect. Figure 1 is based on radiative transfer results and illustrates this fact. The greenhouse effect G is defined here as the difference between the longwave radiative fluxes emerging from the surface F_{sfc} and from the top of the atmosphere F_{toa}:

$$G = F_{sfc} - F_{toa} \qquad [1]$$

In Figure 1 G is plotted as a function of relative humidity (RH) that has been varied in two atmospheric layers between 0 and 4 km (dashed) and between 4 and 12 km (solid), respectively. The RH changes are performed such that the RH takes a fixed value throughout either of the two layers whereas the rest of the atmosphere keeps the original tropical standard atmosphere. For temperatures below 243 K the relative humidity was calculated relative to ice. Figure 1 shows that the greenhouse effect or the trapping of longwave radiation due to water vapour is of the same order of magnitude for relative humidity changes in the lower as well as in the upper troposphere. One should note however that the greenhouse effectiveness of a single H_2O molecule rapidly increases with altitude. For instance, a molecule at 11 - 12 km in a tropical atmosphere is about 100 times more effective than one between 1 and 2 km. Note also that the range of variability of the UTH usually is much higher than the low level humidity. Therefore an adequate humidity climatology of the upper troposphere, including the local variability, is quite important.

3. UPPER TROPOSPHERIC HUMIDITY FROM METEOSAT

The upper tropospheric relative humidity is inferred from the METEOSAT WV-channel (5.7 - 7.1 μ m) as an operational product and it is distributed twice daily via the Global Telecommunication System (Schmetz and Turpeinen, 1988). The WV channel is sensitive to about the upper 3 millimeters of total water vapour; that is typically down to a pressure level of 600 hPa, although precise limits depend on the actual atmosphere. The UTH has the advantage over radiosondes that it provides a global-scale coverage. In the present study we use basically the same retrieval technique as described in Schmetz and Turpeinen (1988). The main features are as follows:

i) a preprocessed radiance data set is used for the retrieval, i.e. we use results of a scene classification for areas of 32x32 pixels (one pixel is about 5 km x 5 km).

ii) the clear-sky WV radiance is used for the retrieval

iii) the relative humidity is inferred through radiance-to-relative humidity look up tables that are obtained by radiative forward calculations using forecast temperature profiles.

iv) the operational WV calibration has not been used; instead we recalibrated the data using archived radiosonde data with a radiative transfer code as it is used operationally (Schmetz, 1989). The difference to the operational calibration is a tighter quality control of radiosonde humidity data, which leads to less noise and generally a somewhat higher (4 - 6%) calibration coefficient. The shift in the calibration is mainly due to a relatively small number of radiosondes that systematically report too high a moisture. Details of this analysis will be presented elsewhere. We also note that there is some uncertainty about the response function of Meteosat-4 (Olivier, 1991, personal communication) that still needs to be resolved.

v) contrary to the present operational UTH product we derive a UTH also in image segment areas that contain high or medium level clouds as long as the cloud classification provides a clear sky radiance. Thus relative humidities have a larger range than the clear-sky climatology that we described previously (van de Berg et al., 1991).

vi) two retrievals per day (1200 and 0000 UT) are used to form monthly means.

4. RESULTS

4.1 Relative humidity

Figure 2 shows the monthly mean UTH for July 1991. We observe minimum relative humidities of less than 10 % in a long belt stretching from the Western South Atlantic Ocean over Africa into the Indian ocean. Striking is the extremely zonal stratification of features which is indicative of a pronounced meridional circulation. The usefulness of WV radiances for monitoring upper tropospheric large-scale circulation has also been shown by Picon and Desbois (1990). The pronounced Hadley circulation is characteristic of the Northern summer as already been noted by van de Berg et al. (1991).

The maximum relative humidities in Figure 2 occur in the ITCZ where deep convection moistens the upper troposphere. Observed maxima are in the expected range of 70 - 80 % which cannot be exceeded since the UTH refers to saturation over water. At high levels ambient relative humidity should refer to ice and at a pressure level of 400 hPa in a tropical atmosphere the ratio of saturation pressure over ice to that over water is around 0.8. Droplet or particle curvature effects, in principle, work in the opposite direction but they are negligible for realistic particles. For instance, the saturation water vapour pressure over a droplet with a 1 μm radius is only 0.1% higher than over a flat water surface. Note also that the restriction to clear-sky WV radiances introduces a dry bias in area averages in cloudy regions.

In order to compare the ECMWF forecast relative humidity with the satellite observations we have produced a comparable product from the ECMWF grid profiles by averaging over the relative humidities at 600, 500, 400 and 300 hPa with weightings that correspond to a mean atmospheric contribution function of the WV channel (Turpeinen and Schmetz, 1989).

Figure 3 shows the ECMWF-UTH. A comparison with Figure 2 reveals that the ECMWF forecast is too moist in the subtropical region and too dry in the ITCZ. The moist subtropics have been noted before in comparisons with microwave inferred precipitable water (Liu et al., 1992; Phalippou, 1992). Recent work at the ECMWF (eyre et al., 1992) has reduced the bias in the Northern hemisphere by using TOVS radiances in the data assimilation.

It has been suggested that insufficient parameterization of water vapour transport through the planetary boundary layer in the subsidence regions is the cause of the high bias in the ECMWF model. One could also conceive that the Hadley circulation in the model is not strong enough or that the water vapour transport out of the tropical systems is exaggerated. This would explain both areas of discrepancy in the subtropics as well as in the ITCZ. Concerning the systematic differences between satellite UTH and ECMWF-UTH it should be noted that the satellite measurements have a much higher sensitivity in dry regions. The high resolving power of the water vapour channel in dry regions is the main difference and potential advantage over IR window observations, that better resolve moist and cloudy areas.

As an important remark we wish to point that the effect of model spin-up of the hydrological cycle seems to be secondary. A comparison of the satellite UTH with model results for the 12h and 36h forcast yields results that are quite similar (maximum difference is 5%). The overall conclusion, namely that the model is too dry in the ITCZ and significantly too moist in the subtropics, is not changed.

4.2 Brightness Temperatures

The comparison of UTH fields in the previous section has the advantage that relative humidity is easy to interpret; however, it has the drawback that the comparison is less rigorous since the folding of a mean contribution with the upper tropospheric relative humidity profile of the ECMWF forecast may introduce geographically varying biases in the model-inferred UTH. A more rigorous approach is the comparison of observed brightness temperatures with those computed with a radiative transfer model using the ECMWF forecasts. This has been done in Figure 4 (satellite) and Figure 5 (ECMWF). We observe an area over the continental ITCZ where the satellite brightness temperature is lower than the calculations. In subtropical regions the calculated brightness temperatures are up to 6K too low, which far exceeds the possible bias due to satellite calibration and temperature forecast errors.

4.3 Adjustment of Humidity Profiles

An attempt has been made to translate the more rigorous brightness temperature comparison in section 4.2 in a bias in the ECMWF forecasts above 500hPa. The following procedure has been adopted: We assume that the relative structure of the relative humidity in the forecast is correct. Then the relative humidity is adjusted by multiplying the upper level humidity values with a factor until observed and calculated brightness temperature agree. The principle is illustrated in Figure 6 where the left panel shows the relative humidity (with respect to water) before and after the adjustment and the right panel shows the corresponding mixing ratios. Note that we do not receive forecast humidities for altitudes higher than 300 hPa. The relative humdity is extrapolated linearly to zero at 100 hPa which is the top of the atmosphere in the radiation model. This may cause problems in tropical regions with a very high tropopause and in cases with an unusually moist stratosphere, however Takayama (1992) verified that the linear extrapolation generally is a reasonable approach.

The adjustment has been applied to the full month of July 1992 using 12 and 24 h forecasts and the corresponding satellite observations. Figure 7 shows the mean adjustment factor (times 100) that needs to be applied to the ECMWF relative humidities on order to obtain agreement in the brightness temperatures. Again we see an area over the continental convective zone where the ECMWF is somewhat too dry whereas in the subtropics we find adjustment factors as low as 0.4.

4.3 Diurnal Variations

The last result we present are diurnal variations in the UTH as observed from Meteosat. Figure 8 shows monthly mean results (July 1992) for four different regional scale areas. As expected we see clear diurnal signals in convective regions. The minimum occurs in the afternoon when convection has attained or approaches its maximum. The preliminary explanation we can offer is as follows: The UTH retrieval uses clear-sky radiances for image segment areas of 32x32 pixels. At the time when convection is around its maximum one can expect enhanced local subsidence which would lead to the observation of warmer clear-sky pixels which are in turn used for the UTH retrieval. The matter needs thorough further study. It is fair to conclude that diurnal variations in the clear-sky water vapour brightness temperatures exist, and this fact may pose a sampling problem when humidity observations are made from polar orbiting satellites.

5. CONCLUSIONS

This paper presented an analysis of UTH fields derived from METEOSAT and a comparison with ECMWF forecast fields. The comparison of UTH fields from satellites with models on a routine basis will provide a stringent test on the various aspects of model performance, such as large-scale dynamics, water vapour transport and convection.

The comparison with the UTH from ECMWF forecasts shows that ECMWF fields are too moist in the subtropical subsidence region and too dry in the ascending branch of the Hadley cell.

Observations from geostationary satellites, like Meteosat, have the advantage of providing high temporal resolution and thus resolving diurnal cycles. A preliminary analysis indicates that significant diurnal cycles exist in the upper tropospheric humidity over certain areas. TOVS observations are clearly superior with respect to onboard calibration and the fact that a single instrument covers the whole Earth. This suggests that an optimum observing system for the upper tropospheric humidity should use radiance measurements from polar orbiting and geostationary satellites jointly for the derivation of longer-term averages.

REFERENCES

Arking, A., 1992: Water vapor and lapse rate feedback: Insight from a one-dimensional climate model. Submitted to the Journal of Climate.

Eyre, J., G. Kelly and A. McNally, 1992: Assimilation of TOVS water vapour information in the tropics. Internal Memorandum of the ECMWF Research Department. 3 p.

Liu, W.T., W. Tang and F.J. Wentz, 1992: Precipitable water and surface humidity over global oceans from Special Sensor Microwave Imager and European Center for Medium Range Weather Forecasts. J. Geophys. Res., 97, C2, 2251 - 2264.

Manabe, S. and R.T. Wetherald, 1967: Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J. Atmos. Sci., 24, 241 - 259.

Phalippou, L, 1992: Comparison between SSM/I and ECMWF total precipitable water. Meteorological Newsletter (ECMWF), No. 57, p.3 - 9.

Picon, L. and M. Desbois, 1990: Relation between METEOSAT water vapor radiance fields and large scale tropical circulation. J. Climate, 3, 865 - 874.

Schmetz, J., 1989: Operational calibration of the METEOSAT water vapor channel by calculated radiances. Appl. Opt., 28, 3030 - 3038.

Schmetz, J., and O.M. Turpeinen, 1988: Estimation of the upper tropospheric relative humidity field from METEOSAT water vapour image data. J. Appl. Meteorol., 27, 889 - 899

Shine, K.P. and A. Sinha, 1991: Sensitivity of the Earth's climate to height-dependent changes in the water vapour mixing ratio. Nature, 354, 382 - 384.

Stephens, G.L., and T.J. Greenwald, 1991: The Earth's radiation budget and its relation to atmospheric hydrylogy. Part 1: Observations of the clear sky greenhouse effect, J. Geophys. Res., 96, D8, 15311 - 15324.

Stephens, G.L., A. Slingo and M. Webb, 1992: On measuring the greenhouse effect of Earth. NATO ASI Series on 'High resolution infrared remote sensing for Earth's waether and climate studies', Paris, 23 - 26 March 1992, To appear.

Takayama, Y., 1992: Accuracy of in-flight calibration of the water-vapour channel of a satellite radiometer by radiance calculation. Int. J. Remote Sensing, 13, 1537 - 1548.

Turpeinen, O.M. J. Schmetz, 1989: Validation of the upper tropospheric humidity determined from Meteosat data. J. Atmos. Oceanic Technol., 6, 359 - 364.

van de Berg, L., A. Pyomjamsri and J. Schmetz, 1991: Monthly mean upper tropospheric humidities in cloud-free areas from Meteosat observations. Intern. J. Climatol., 11, 819 - 826.

Wu, X., J.J. Bates and S.J.S.Khalsa, 1993: A climatology of the water vapor band brightness temperatures from NOAA operational satellites. Submitted to Journal of Climate.

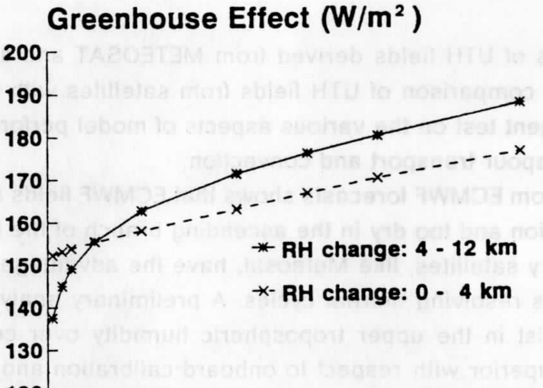
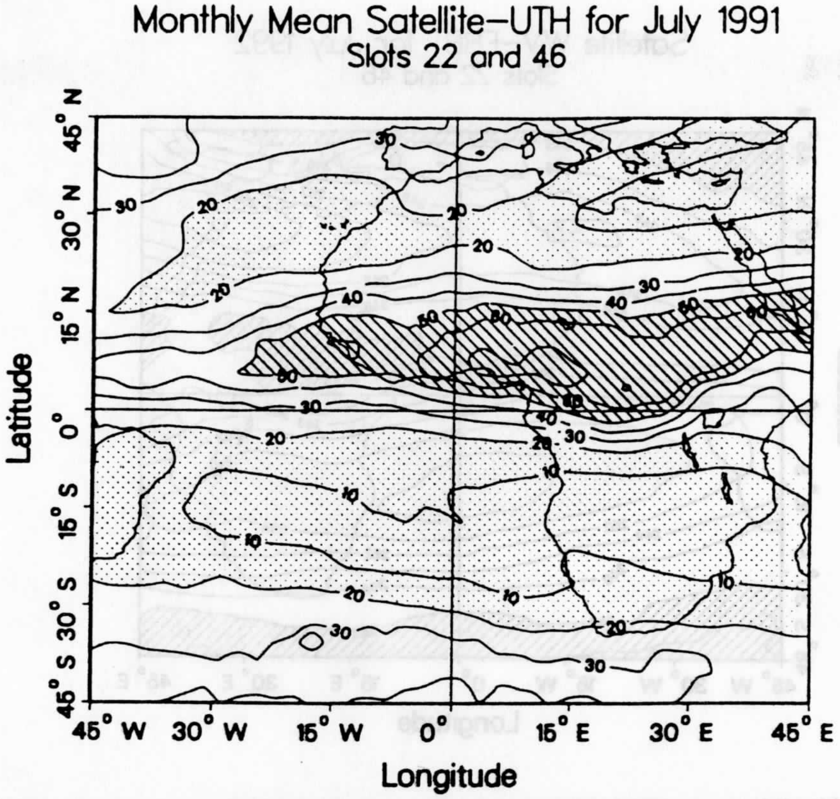
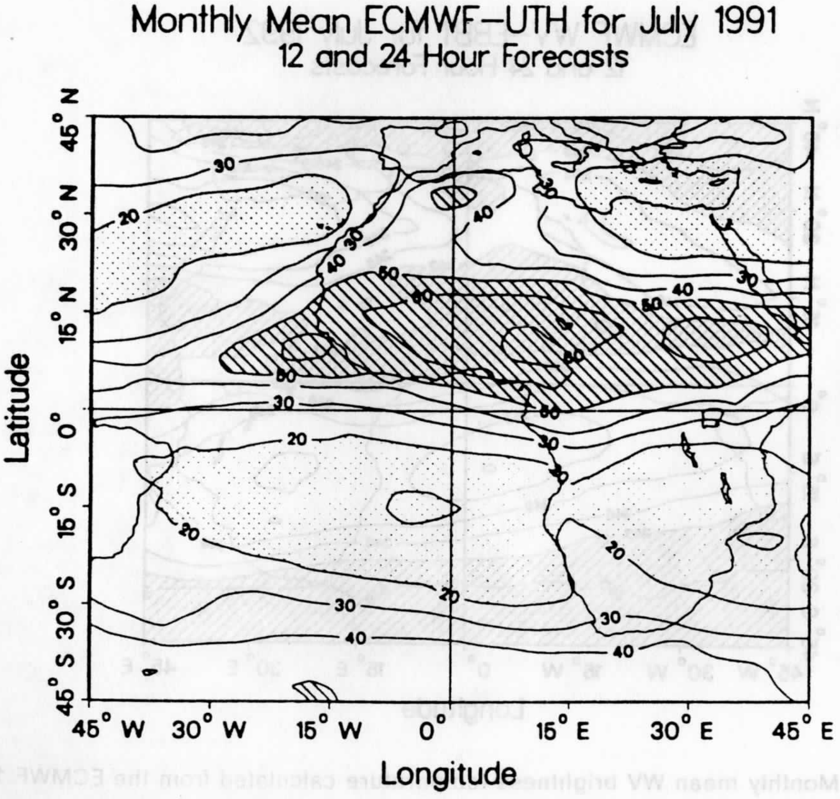


Figure 1: Greenhouse effect, defined as the difference between the outgoing longwave radiation at the surface and at the top of the atmosphere, as a function of relative humidity in the upper (4 - 12 km; solid line) and lower troposphere (0 - 4 km, dashed).



Monthly Mean Satellite–UTH for July 1991
Slots 22 and 46

Figure 2: Monthly mean upper tropospheric relative humidity (UTH) from METEOSAT-4 for July 1991. Values are in %.



Monthly Mean ECMWF–UTH for July 1991
12 and 24 Hour Forecasts

Figure 3: Monthly mean ECMWF UTH for July 1991. Values are in %.

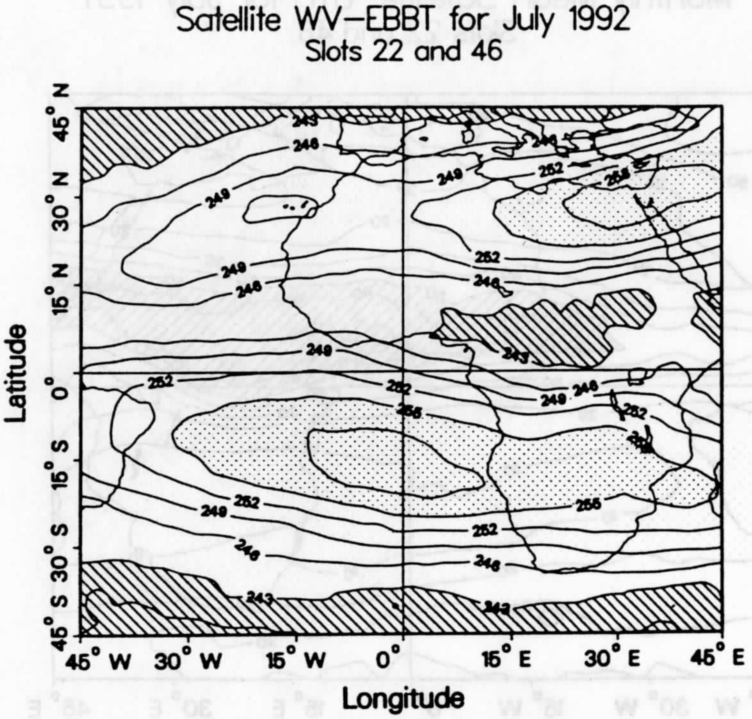

Satellite WV–EBBT for July 1992
Slots 22 and 46

Figure 4: Monthly mean WV brightness temperature from METEOSAT for July 1992.

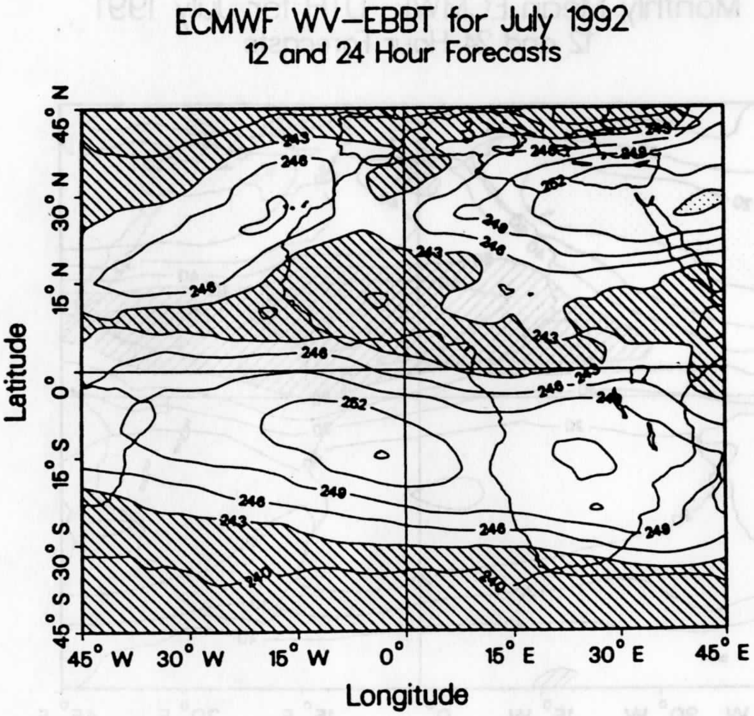

ECMWF WV–EBBT for July 1992
12 and 24 Hour Forecasts

Figure 5: Monthly mean WV brightness temperature calculated from the ECMWF 12 and 24 h forcast profiles for July 1992.

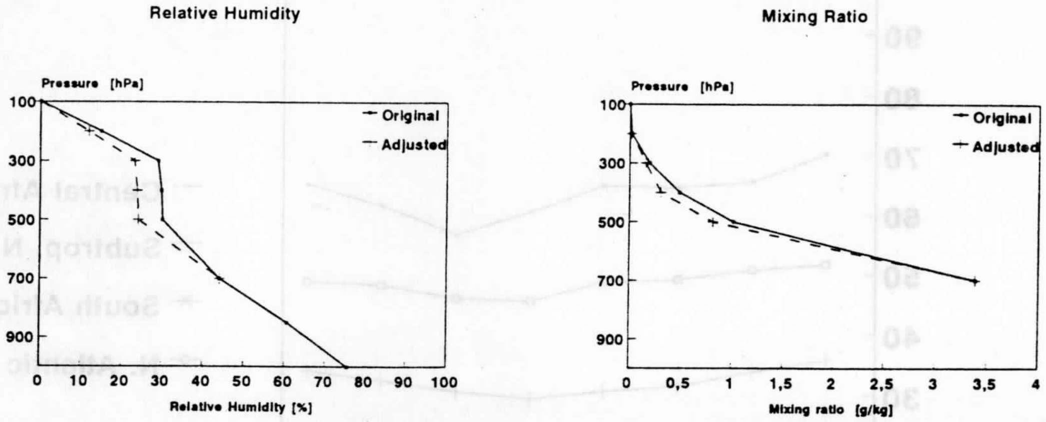


Figure 6: Illustration of the adjustment of forecast humidity profiles by multiplication with a constant factor in order to make the satellite observed brightness temperatures agree with radiative transfer calculations based on the ECMWF forecast. In this example the adjustment factor applied to the relative humidity is 0.8. The brightness temperature for the original profile is 244.3 K and for the adjusted one it is 245.8 K.

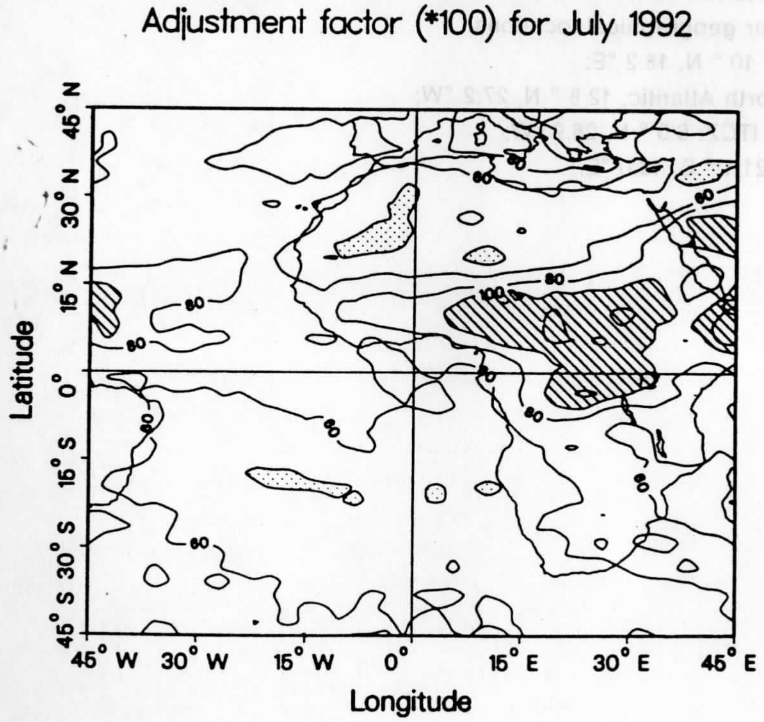


Figure 7: Monthly mean adjustment factors for the ECMWF upper tropospheric relative humidity which is required to obtain agreement between satellite observed and calculated brightness temperatures (July 1992).

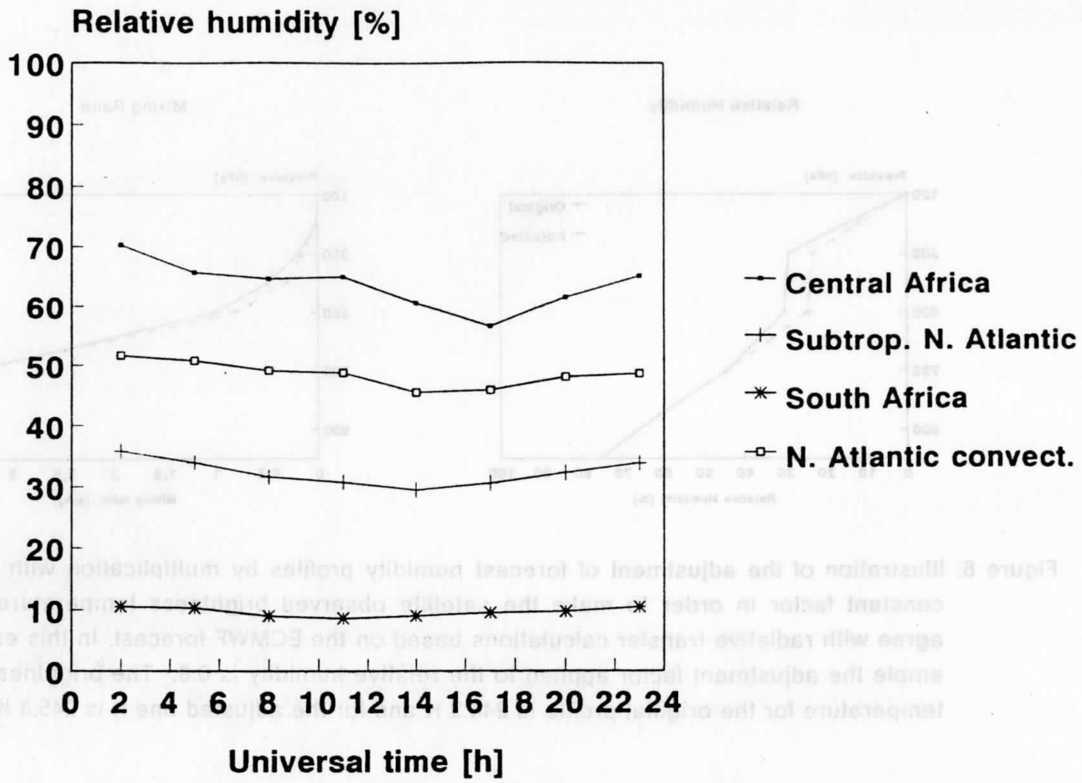


Figure 8: Monthly mean diurnal variation of the satellite observed upper tropospheric relative humidity for four geographical locations:
central Africa: 10 ° N, 18.2 °E;
Subtropical North Atlantic: 12.8 ° N, 27.2 °W;
North Atlantic ITCZ: 6.0 ° N, 26.9 °W;
South Africa: 21.1 ° S, 18.0 °E.

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European Centre for Medium-range Weather Forecasts
Shinfield Park, Reading, RG2 9AX, U.K.

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