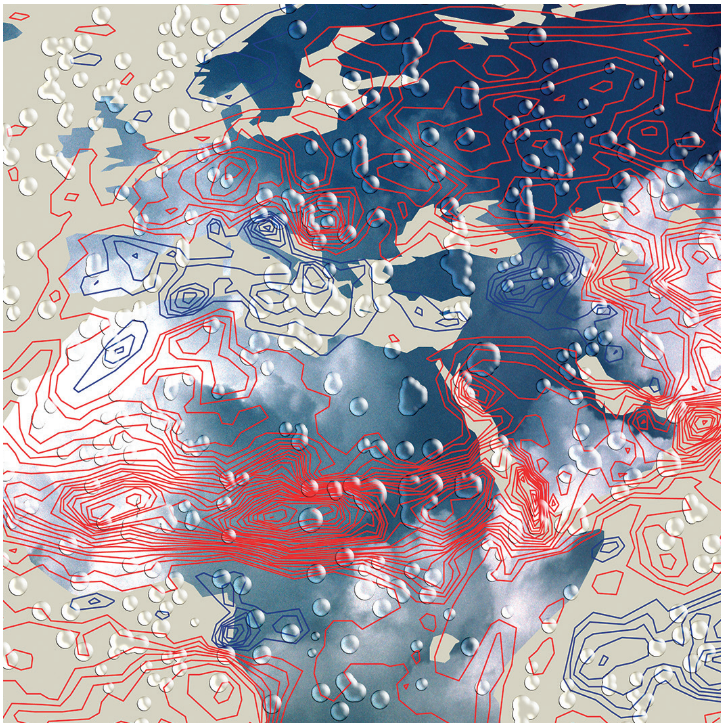
# ECMWF Feature article

from Newsletter Number 109 – Autumn 2006

METEOROLOGY

# Analysis and forecast impact of humidity observations



www.ecmwf.int/en/about/news-centre/media-resources
doi:10.21957/wx38tjlh7z

*This article appeared in the Meteorology section of ECMWF Newsletter No. 109 – Autumn 2006, pp. 11–15.*

# Analysis and forecast impact of humidity observations

Erik Andersson, Elías Hólm, Peter Bauer, Anton Beljaars, Graeme Kelly, Tony McNally, Adrian Simmons, Jean-Noël Thépaut, Adrian Tompkins

We have found that humidity observations have a significant impact on analyses and forecasts extending into the medium range (5–6 days), with a marked impact also on the wind field. This is in contrast to *Bengtsson & Hodges* (2005) who found only small-scale, unstructured temperature differences in the tropics, and no noticeable effect on the skill of the wind forecasts. They explained that the model is capable of forming realistic humidity fields through assimilation of temperature and wind data, to the extent that the addition of humidity observations has negligible effect. Furthermore, in the ERA-40 reanalyses the assimilation of satellite data led to a more poorly balanced global hydrological cycle. ECMWF has improved its humidity assimilation and moist-physics parametrizations (namely clouds, convection and vertical diffusion), and demonstrated that the hydrological cycle is now significantly better balanced with respect to the ERA-40 system. Consequently we decided it was now time to reassess the impact of humidity observations on analyses and forecasts.

In October 2003 an improved statistical model of humidity background errors was implemented (*Hólm et al.,* 2002); this is an important component of the analysis scheme as it determines how the humidity information is distributed away from observation points. Subsequently, data from several additional instruments on satellites in both geostationary (METEOSAT and GOES) and polar orbits (AMSU-B and AIRS) have been introduced. Also the use of radiosonde and surface humidity data has been revised based on current data quality statistics. This concerted effort on humidity analysis is motivated by the increased availability of humidity observations, and by the need to improve the assimilation in cloudy and precipitating regions. Some of the areas where moisture is particularly important are as follows.

- The latent heat release from strong convective events can modify the jet-stream aloft and influence subsequent down-stream developments.
- The moisture content of the air on the warm side of a frontal zone can influence the rate of development of baroclinic systems.
- In the tropics, the supply of low-level humidity can affect the intensity of the tropical convection, and hence the intensity of the Hadley circulation.

### The humidity observing systems

Our humidity impact experiment was run from 1–31 July 2003, using the 4D-Var assimilation system with 12-hourly cycling at T319 horizontal resolution (~60 km), 60 model levels and analysis increments at T159 (~120 km) resolution. The October 2004 version of the forecast system was used throughout. Its standard configuration, which uses a large variety of conventional observations and satellite radiances, provided the *'Control'*. In the experiment *'Noq'* all humidity observations were withheld. See *Andersson et al.* (2006) for a more detailed report on the separate impacts of each of the main humidity observing systems.

First, we describe the main humidity observing systems, in the order they appear in Table 1.

- ***Polar orbiting microwave radiances.*** The SSMI microwave instruments provide radiance data in seven channels. These channels are sensitive to the integrated atmospheric water-vapour content and to wind-induced sea-surface roughness.
- ***Radiosonde specific humidity.*** Radiosondes provide dew-point temperature observations which are converted to specific humidity using the observed temperature and pressure. The humidity profiles from Vaisala's RS90 and RS80 sondes are used at all reported levels up to 100 hPa, subject to a temperature threshold which is -80°C for RS90 and -60°C for RS80. All other sondes are used only up to 300 hPa, subject to the temperature being higher than -40°C.
- ***Two-metre relative humidity.*** The SYNOP two-metre dew-point observations are converted to relative humidity. These data are used over land, but not over sea, during local daytime only (i.e. solar elevation angle greater than zero). The removal of night-time SYNOP data is motivated by poor representativity of the data in stable surface-layer conditions.

 doi:10.21957/wx38tjlh7z

- ***Geostationary IR radiances.*** From geostationary satellites, clear-sky radiance data from the 6.3 µm water-vapour channel of each of five platforms (GOES-9, 10 and 12 and METEOSAT-5 and 7) are used. These data provide a complete and frequent coverage within about 50° latitude of the equator.
- ***Polar orbiting microwave radiances.*** From AMSUB, three of the five available 183 GHz microwave channels are assimilated depending on the land/sea mask and the height of the terrain.
- ***Polar orbiting IR radiance.*** From the infrared sounding instruments (HIRS and AIRS) it is primarily the 6.3 µm band that carries humidity information. For HIRS this corresponds to channels 11 and 12, and for AIRS it comprises channels 1290–1843. The infrared satellite data carry ambiguous temperature and humidity information.

The satellite systems provide very good coverage over the oceans, with gaps in cloudy and precipitating regions depending of the sensitivity to clouds in the infrared, and to water clouds and rain in the microwave measurements. The geostationary radiances and some of the higher-peaking channels of AIRS, HIRS and AMSUB are used also over land. The conventional data (SYNOPs and radiosondes) provide an uneven coverage over land, with dense concentrations over parts of North America, Europe, East Asia and Australia.

| Humidity measurement dataset | Daily number of data | Number of channels (available) | Main humidity information | Typical data coverage of used data |
|---|---|---|---|---|
| SSMI, DMSP-13, 14, 15<br>Polar orbiting microwave radiances | 220,000 | 7 (of 7) | Total column, except in clouds/rain | Ice free ocean |
| TEMP<br>Radiosonde specific humidity | 21,500 | – | Tropospheric humidity profiles with high vertical resolution | Concentrations over North America, Europe, Eastern Asia and Australia |
| SYNOP<br>2m relative humidity | 13,200 | – | Boundary layer humidity | Irregular with concentrations in populated regions |
| GEOS, Meteosat 5,7, GOES-9, 10, 12<br>Geostationary IR radiances | 141,500 | 1 (of 2) | Upper troposphere, clear air | Within 50° of the equator, cloud free only |
| AMSUB, NOAA-16, 17<br>Polar orbiting microwave radiances | 131,500 | 3 (of 5) | Upper and mid troposphere | Irregular, emissivity dependent over land and ice; good over ice free ocean |
| HIRS, NOAA-16, 17<br>Polar orbiting IR radiances | 120,000 | 6 (of 19) | Mostly upper troposphere, clear air | Cloud free ocean and ice |
| AIRS, AQUA<br>Polar orbiting IR radiances | 280,000 | 230 (of 2378) | Upper and mid troposphere, clear air | Cloud free ocean and ice |

**Table 1** Humidity observing systems used in ECMWF data assimilation. Approximate data counts, the main humidity information and typical data coverage are also given.

## Analysis bias differences

The analysis impact of any data type depends on the data coverage, the frequency of the data and their accuracy. The impact also depends on the specification of background errors in the assimilation scheme, and on the existence of any systematic deficiencies and biases in the forecast model and observations. In these experiments, satellite radiance data are corrected for air-mass dependent and scan-angle dependent biases. There have been several reports on persistent observation bias also in radiosondes. However, radiosonde and SYNOP humidity data are currently not subject to bias correction at ECMWF.

Differences between the *Control* and the *Noq* experiments are shown in Figure 1, in the form of north-south cross-sections, averaged over the study period. This shows that the humidity observations substantially modify the moisture analysis: in the northern hemisphere and the tropics there is an increase in moisture in the lower troposphere and a decrease at higher levels. Geographical maps of the differences (not shown) indicate that the moisture is added in the subsidence regions, where the background fields are biased dry. The added moisture is advected to the ITCZ region by the trade winds, leading to an impact on precipitation in that region (see Figure 3 which is described later). Detailed investigations showed that over many continental areas the radiosondes and SYNOPs contribute biases in the boundary layer with opposite sign. Over parts of Europe and North America (40–70°N) radiosondes contribute to a drying of the analysis in the upper troposphere, which is consistent with published literature showing that several radiosondes have upper-tropospheric dry biases. While absolute amounts are small, upper-tropospheric humidity is important for accurate radiative transfer calculations, and also for the indirect influence on cirrus cloud formation.

Figure 2 shows the impact of the humidity observations on the total-column water vapour (TCWV) in terms of the mean analysis difference between *Control* and *Noq*. TCWV is dominated by the moisture content of the warm air in the lower troposphere and at lower latitudes. The mid- and upper-tropospheric differences in relative humidity seen in Figure 1 contribute very little in terms of TCWV. In Figure 2 we can see that the net effect of all assimilated humidity observations is to add moisture. Over sea, the TCWV differences are almost entirely due to SSMI data, whereas over land, the differences are due to the combined effects of radiosonde and SYNOP data. Although we have seen that radiosondes have a drying effect in the boundary layer and in the upper troposphere, the net effect in terms of TCWV is a slight moistening in most regions with good radiosonde coverage, including parts of North America. Also SYNOP assimilation adds significant moisture to the Sahel and Sub-Sahara regions of Africa. As the humidity increments at the lowest model level are used as input to the soil water analysis, it is likely that the impact of SYNOPs in this region is through its interaction with the soil moisture analysis.

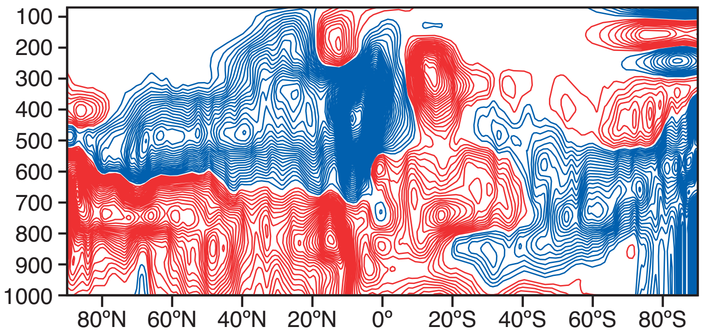



**Figure 1** Zonal-mean monthly mean (2–31 July 2003) cross-sections of relative-humidity analysis differences (%). The contour interval is 0.2 % with red (blue) indicating that the *Control* assimilation is moister (drier) than the *Noq* experiment which withholds the humidity data.

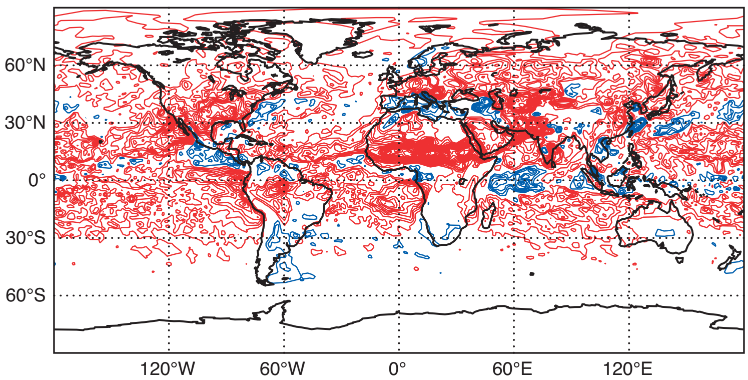



**Figure 2** Mean analysis difference (*Control*–*Noq*) in total-column water vapour. The contour interval is 0.5 kg $m^{-2}$ with red (blue) indicating that the *Control* assimilation is moister (drier) than the *Noq* experiment which withholds the humidity data.


doi:10.21957/wx38tjlh7z

## Short-range precipitation forecast

The impact of the humidity observations on precipitation for parts of the tropics and North America is shown in Figure 3. This shows that the rainfall in the first 12 hours of the forecasts is increased in the Western Pacific due to the assimilation of humidity data. Within the ITCZ there is no significant difference in precipitation intensity in these experiments, but it is evident from the differences that the assimilation of humidity data has modified the location of the ITCZ in the East Pacific. Nearly all the differences seen over the ocean in Figure 3 are due to SSMI. The spreading of humidity impact from clear-sky to precipitating areas is due to transport and physical processes in the model, and is also due to extrapolation by the analysis. The latter effect is determined by the analysis structure functions (i.e. the background error covariance matrix) which currently does not recognize the two regimes, and whether there should be de-correlation of humidity increments across cloud and precipitation boundaries.

More detailed investigations showed that assimilation of radiosondes and SYNOP humidity data locally increases the rainfall in the regions where Figure 2 showed that these data on average add moisture: parts of North America, Europe, India, and in particular central Africa where SYNOP data add moisture to the boundary layer and the soil moisture analyses. In the mid-latitude storm-track regions, the net impact of observed humidity on precipitation is smaller than in the tropics but may nevertheless be important in relative terms. Also Figure 3 shows reduced precipitation in the western parts of the Atlantic and Pacific oceans, which is due to assimilation of SSMI data.

In ERA-40 and in earlier versions of the ECMWF forecasting system there was a rapid adjustment during the first day of forecasts of the tropical rate of precipitation, becoming almost constant at lower rates thereafter. This so-called ‘spin-down’ problem has now been significantly reduced, through changes to the moist physics parametrizations and the assimilation system. Due to the spin-down problem the assimilation of observed humidity observations produced up to 50% more tropical precipitation early in the forecasts than assimilations without humidity data. It is evident from Figure 3 that the current *Control* humidity analyses are in good balance with the forecast model, and compared to the *Noq* analyses they do not result in excessive amounts of precipitation in the early stages of the forecasts.

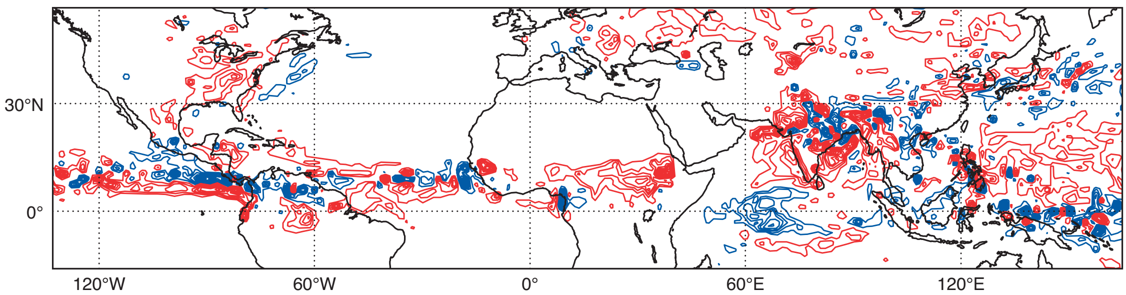



**Figure 3** Average daily precipitation difference (2–31 July 2003) in 12-hour forecasts from analyses at 06 and 18 UTC, showing *Control* minus *Noq*. The contour interval is 1 mm/day with red (blue) contours indicating that the assimilation of observed humidity has increased (decreased) precipitation.

## Forecast verification

Differences in latent heat release associated with the above mentioned differences in precipitation result in temperature differences throughout the troposphere. In forecasts, the large-scale fields of geopotential and wind are influenced where the evolution of weather systems is affected by changes in the moisture distribution. Furthermore, the convection parametrization directly changes the wind through its vertical momentum transport. To assess the benefit to the forecasts of humidity assimilation, ten-day forecasts have been run daily for the *Control* and *Noq* experiments. The scores shown here are root mean square errors (RMSE), computed with the operational ECMWF analysis as reference.

Figure 4 shows the forecast impact of observed humidity in relative terms: values of RMSE(*Noq*)-RMSE (*Control*) normalized by the mean of the two RMSEs. Positive values of this score mean that the *Noq* forecast errors are larger than those of the *Control*, which indicates a beneficial impact of assimilating humidity observations. Conversely, negative values of the score would indicate deterioration. The scores are plotted as a function of forecast range from day 1 to day 10, with the error bars indicating 90% two-sided confidence intervals. Scores are shown for the northern hemisphere extratropics, the tropics within 20° of the equator, and the southern hemisphere extratropics, for 300 hPa vector wind and 850 hPa relative

doi:10.21957/wx38tjlh7z

humidity. We see that there is a clear positive impact from assimilating humidity observations in all three regions. The humidity forecast impact is initially very large (>15 % in the northern hemisphere and tropics) but falls off rapidly during the first four days of the forecasts. This indicates that the humidity field is strongly forced by the dynamics and exchanges with the surface. The improved humidity initial conditions lead to modified precipitation, which in turn affects the dynamical fields (e.g. through latent heat release and convective momentum transfer).

The results in Figure 4 show that the dynamic impact of observed humidity is largest in the tropics (6 to 9%), and it is larger in the southern (3 to 6%) than in the northern hemisphere (2 to 4%). Where the lower bound of the error bar is above the zero line, the positive impact is significant with at least 95% confidence, which is the case for the first 4 to 5 days of our experiments. In the tropics we see a very significant impact on the upper-tropospheric wind field (8% at day 1) and temperature field (6% at day 1) which remains significant and positive to days 7 or 8 of the forecast.

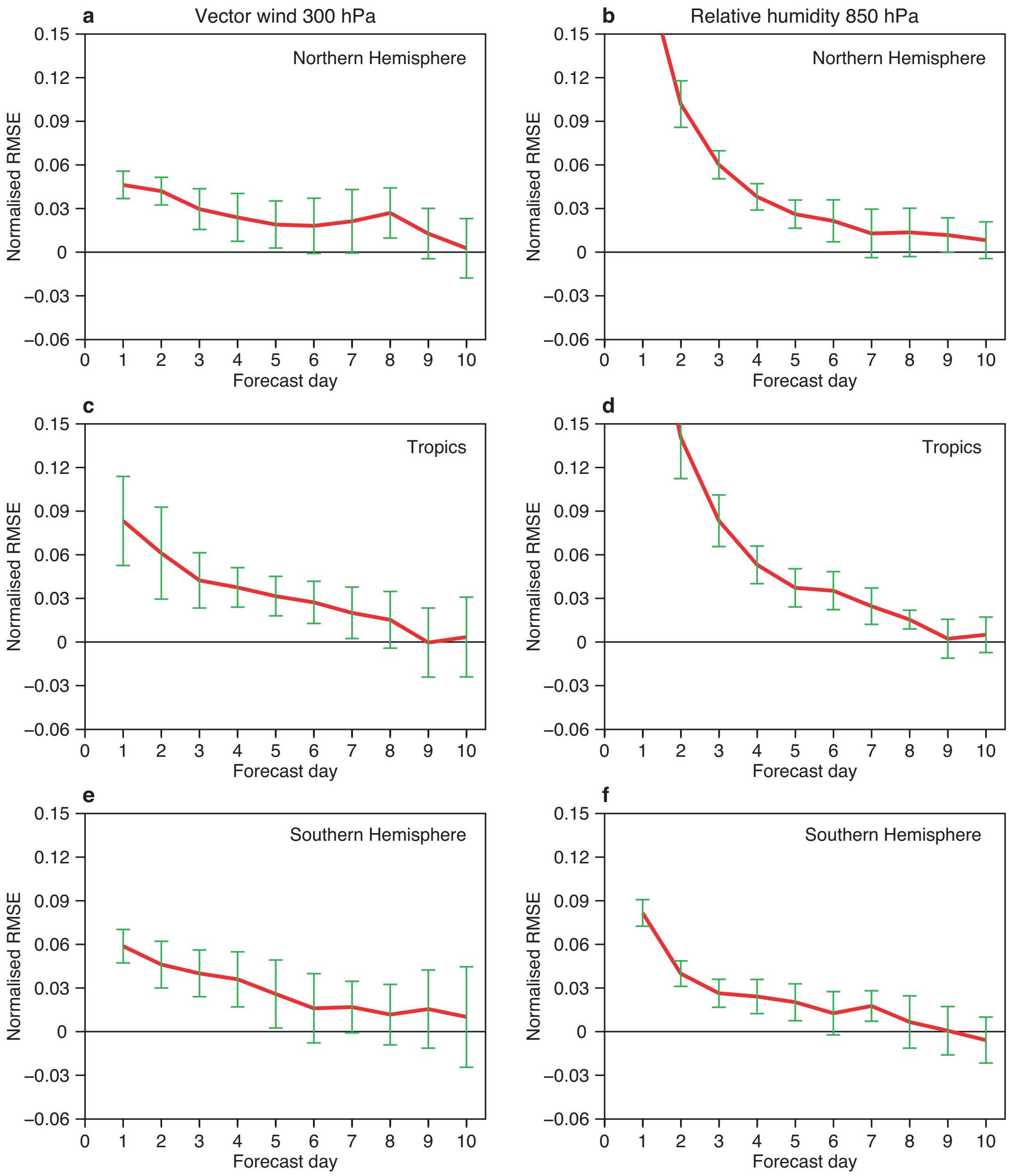



**Figure 4** Forecast impact of observed humidity in terms of normalized RMSE for 300 hPa vector wind (left) and 850 hPa relative humidity (right) in the northern hemisphere extratropics, tropics and southern hemisphere extratropics. The error bars indicate 90% two-sided confidence intervals. The normalised RMSE is given by {RMSE(*Noq*)–RMSE(*Control*)}/{0.5[RMSE(*Noq*)+RMSE(*Control*)]}.


doi:10.21957/wx38tjlh7z

## Perspectives

Several additional sources of moisture information can be exploited in the near future to bring further benefit to the humidity analysis.

- ***Infrared radiances (HIRS, AIRS and MSG).*** The use of infrared radiances (HIRS and AIRS) continues to be developed (e.g. to better account for the influence of clouds and aerosol on the measurements). The long-term provision of high-spectral resolution infrared data (like AIRS) is ensured through U.S. and European programmes (the CrIS and IASI instruments, respectively). Furthermore, the first in the Meteosat Second Generation (MSG) series of geostationary satellites was launched in August 2002 providing frequent data in one additional water vapour channel. These data have been assimilated in ECMWF operational system since June 2005. Currently, infrared radiances are given reduced weight in the analysis; the observation errors are significantly inflated (up to 2 K) to offset known deficiencies in the use of the data. For example, correlations of observation error between channels and within swaths of data are ignored. The distribution in the vertical of the analysis increments is another delicate problem. In step with improvements in these areas, more weight will be assigned to what are intrinsically high-quality radiance measurements, resulting in a more robust and important influence upon the humidity analysis.
- ***Microwave radiances from new instruments.*** Microwave radiances from new instruments will be assimilated in a way that complements the existing imager-sounder combination. These are the Special Sensor Microwave Imager Sounder (SSMIS) that combines SSMI with AMSU-A/B type channels, the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer (AMSR-E) onboard the AQUA satellite; all these instruments have specifications similar to the SSMI. While these instruments will not provide additional information on the vertical distribution of moisture, their orbit configuration will greatly improve the data coverage. The data from these instruments is currently monitored and is expected to be actively assimilated later in 2006.
- ***SSMI radiances.*** Since June 2005, SSMI radiances affected by clouds and precipitation are assimilated at ECMWF through a 1D+4D-Var analysis method. As with the SSMI data in clear areas, the impact on the moisture analysis is significant. The bias impact of the clear-sky data (as seen in Figure 2) has in later experimentation been partly compensated by the assimilation of rain-affected SSMI data. The optimal combined use of clear and cloudy data is strongly dependent on the definition of moisture background errors inside and outside clouds, the horizontal structure functions, and the current methodology of first retrieving the cloud/rain-affected TCWV through 1D-Var. Developments towards a direct 4D-Var assimilation of rain-affected SSMI radiances are underway.
- ***Radiosonde and aircraft humidity sensors.*** There has been a gradual improvement in the accuracy of radiosonde humidity sensors, and recent years have seen the introduction of the Vaisala RS90 and RS92 sondes into operational use. The number of stations using the latest types of sonde is increasing. However, there remains a clear need for bias correction, which can be the result of calibration errors, time-lag errors, sensor icing errors, sensor aging or contamination, or radiative sensor heating effects. Some of the causes have been tackled by improved radiosonde design; for instance, the RS90 and RS92 introduced a pulse-heated twin sensor design to eradicate sensor icing and improve sensor time-lag errors. Other error sources have been addressed by post-processing bias correction techniques. Humidity sensors suitable for commercial aircraft are being developed in order to add humidity to AMDAR reports in the future, and enhance the humidity profiling capability over land.
- ***Global Positioning System humidity data.*** GPS radio occultation techniques are being developed that may improve humidity information in the upper troposphere and tropopause regions. Ground-based GPS measurements provide total-column humidity information that is used experimentally in NWP assimilations. Near real-time GPS networks are being coordinated in Europe, North America and Japan, and real-time European data has been received at ECMWF since March 2004. The use of these new data types in assimilation will be explored in the coming years.

Good quality humidity analyses are becoming even more important as the resolution of the forecasting system increases. The emphasis is on convective and severe precipitation events, which requires accurate depiction of the global distribution of moisture.

## Further reading

**Andersson, E., E. Hólm, P. Bauer, A. Beljaars, G.A. Kelly, A.P. McNally, G.A. Kelly, A. Simmons** & **J.-N. Thépaut,** 2006: Analysis and forecast impact of the main humidity observing systems. *ECMWF Tech. Memo. No. 493.*

**Bengtsson, L.** & **K.I. Hodges,** 2005: On the impact of humidity observations in numerical weather prediction, *Tellus,* **57A,** 701–708.

**Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J-F. Mahfouf, A.J. Simmons** & **J.-N. Thépaut,** 2002: Assimilation and modelling of the hydrological cycle: ECMWF's status and plans. *ECMWF Tech. Memo. No. 383.*



 doi:10.21957/wx38tjlh7z