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Analysis and forecast impact of the main humidity observing systems

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Summary

The global analysis and forecast impact of observed humidity has been assessed by means of observing system experiments with the ECMWF 4D-Var data assimilation system. It is found that humidity data have a significant impact extending into the medium range (5-6 day forecasts), with a marked impact also on the wind and temperature fields. This contradicts some previous studies that have shown insignificant impact of humidity observations in general. The current, greater benefit of the humidity analysis may be due to improved model and data assimilation methods, and vastly increased availability of atmospheric moisture observations. The results show that each tested data type provides benefit to the analysis and forecast performance, which indicates that the humidity analysis is effective in extracting information from a wide variety of humidity observations. Data from the microwave sounding instruments (SSMI and AMSUB) dominate the humidity analysis over sea, whereas radiosondes, surface stations (SYNOP) and AMSUB dominate over land. The infrared sounders (GEOS, HIRS and AIRS) dominate in the upper troposphere, at 200-300 hPa.

The lack of absolutely calibrated humidity data makes dealing with biases in observations and model one of the main issues for determining the global moisture distribution and a balanced hydrological cycle. In these experiments, SSMI adds water in the sub-tropical subsidence areas due to a bias with respect to the model. In several locations over land, radiosondes and SYNOP have opposite bias impacts in the boundary layer, resulting in local influence on precipitation when either data set is withheld. The SYNOP data are biased wet and the radiosondes are biased dry with respect to the model.

1. Introduction

In this paper we investigate the impact in numerical weather prediction (NWP) of observed humidity using the 4D-Var assimilation system of the European Centre for Medium-Range Weather Forecasts (ECMWF). We test the separate and combined impacts of the main humidity observing systems. It is generally accepted that the predictability impact of the humidity initial state is far less than that of temperature, wind and surface pressure (Smagorinsky et al. 1970). Recently, Bengtsson et al. (2004a) concluded from an observing system experiment for winter and summer seasons that there was a very limited contribution from humidity observations in general in the ERA-40 reanalysis (Uppala et al., 2005), and that the assimilation of satellite data in fact led to a more poorly balanced global hydrological cycle. Uppala et al. (loc.cit.) concurred that the hydrological cycle of the six hour ERA-40 forecast would have been closer to physical balance from 1973 onwards had humidity observations from satellite not been assimilated, but pointed out that using satellite data improved the water vapour content over tropical oceans in ERA-40. This came at the expense of high initial precipitation rates and lack of balance between precipitation and evaporation as the forecast model shifted to its drier equilibrium state. Bengtsson *et al.* (2004b) had also noted that removing satellite data from the assimilation resulted in drier analyses that were in poorer agreement with independent ground-based GPS measurements.

Nevertheless, using the ERA-40 3D-Var version of the ECMWF forecast system, Bengtsson and Hodges (2005) compared the predictive skill of two sets of forecasts run from initial states generated by assimilations with and without humidity observations, respectively. They found that the two sets of forecasts showed virtually identical prediction skill in both the extra-tropics (500 hPa geopotential) and the tropics (850 and 250 hPa wind). In the tropics, where an impact might have been expected, they found small-scale, unstructured differences in temperature and geopotential, but no noticeable effect on the skill of the wind forecasts. It was argued that humidity fields of sufficient realism are formed by the model through assimilation of temperature and wind data, to the extent that the addition of humidity observations has negligible effect. Furthermore, Bengtsson and Hodges (2005) argued that not even advanced analysis methods, such as 4D-Var, would be able to improve the handling of humidity data, because of the slowness of the feedback processes (involving latent heat sources and their interaction with the wind field). The time scales are of the order of days, which is incompatible with the typical current 4D-Var assimilation window (6 or 12 hours). A slow process can manifest itself in terms of a slow drift in the analysis, e.g. in the evolution of stratospheric humidity (Simmons et al. 1999).

The 4D-Var results presented in this paper show, in contrast to the conclusions of Bengtsson and Hodges (2005), that humidity data can have significant NWP impact extending into the medium range (5-6 days), with a marked impact also on the wind field. The ECMWF humidity analysis has been extensively developed in recent years, and significant progress with respect to the ERA-40 system has been demonstrated. An improved formulation of the background error covariance model for humidity has been derived (Hólm et al. 2002) and implemented[1]. Data from several additional instruments from satellites in both geostationary (METEOSAT and GOES) and polar orbits (AMSU-B and AIRS) have been introduced. The use of radiosonde and surface humidity data has been revised based on current data quality statistics (Nash 2002). The development of the moist physics parameterisations, namely clouds, convection and vertical diffusion, since ERA-40 have been described by Tompkins et al. (2004).

In order to test the NWP impact of observed humidity and the ability of the 4D-Var data assimilation system to extract information from the main types of humidity data, we have performed a comprehensive set of humidity observing system experiments (OSE) using the Hólm et al. (2002) humidity analysis. Eight one-month experiments have been run. In the first seven experiments, one type of humidity data was withheld and in the eighth experiment all humidity data were withheld. The results were evaluated through comparison with a standard assimilation (the control) which used all the available data as in the October 2004 version of the ECMWF operational system[2]. As all tested humidity data were assimilated in the control assimilation this evaluation approach should not prejudice any one of the tested data types unduly.

The new humidity analysis scheme (Hólm et al. 2002) is performed in terms of a normalized relative-humidity variable, which enables an improved description of the humidity background errors. The condensation effects near saturation and the strict bound at zero humidity are also implicitly accounted for. The effort on humidity analysis is motivated by an increasing availability of humidity data, and by the need to improve the assimilation in cloudy and precipitating regions: 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 affects the intensity of the tropical convection, and hence the intensity of the Hadley circulation. ECMWF's current development programme for radiance assimilation in cloudy and precipitating conditions (Marécal and Mahfouf 2003; Chevallier et al 2004; Moreau et al 2004; Andersson et al. 2005; Bauer et al. 2006a; 2006b) relies on an accurate assimilation procedure for humidity.

In this OSE study, the impact of humidity observations is evaluated in terms of analysis and short and medium range forecast performance for humidity, temperature, geopotential and precipitation. The set of

[1] Introduced with version 26r3 of the Integrated Forecasting System (IFS), 7 October 2003
[2] Labelled version 28r4 of the IFS, 18 October 2004

experiments is defined in Section 2, where also the main characteristics of the various humidity observing systems are discussed. Selected analysis and forecast impact results are shown in Sections 3 and 4, respectively. Summary, conclusions and perspectives are given in Section 5.

2. Definition of experiments

A one-month OSE was run from 1-31 July 2003, using the ECMWF 4D-Var data assimilation system (Rabier et al. 2000) with 12-hourly cycling (Bouttier 2001) at T319 horizontal resolution (~60 km) and 60 model levels. Analysis increments at T159 (~120 km) resolution were computed and added to the T319 background fields, using the incremental 4D-Var method (Courtier et al. 1994). The October 2004 version of the integrated forecast system (IFS) was used throughout. Its standard configuration provided the Control assimilation used as reference in all comparisons in the following. In addition, eight observing system experiments were run in the same period. In the first seven experiments one main humidity observation type was withheld, as detailed in Table 1. In the eighth experiment all humidity observations were withheld, that is, the combination of all seven individually tested data sets. The impact of each observing system is investigated in terms of the difference between the Control and the experiment in which that data type had been withheld.

Table 1 Definition of the seven humidity OSEs, the no-humidity experiment (Noq) and the Control assimilation. The Control used all available observations as in the October 2004 version of the ECMWF operational system. Approximate data counts for the withheld data, their main humidity information and typical data coverage are also given.

Experiment Name	***Removed data sets***	***Daily # of withheld data***	***removed # of channels (available)***	***Main humidity information***	***Typical data coverage***
Control	-	-	-	Combination of all those below	Global
NoSSMIq	DMSP-13, 14, 15 Polar orbiting	220,000	7 (of 7) Microwave	Total column, except in clouds/rain	Ice free ocean
NoRSq	Radiosonde specific humidity	21,500	-	Tropospheric humidity profiles with high vertical resolution	Concentrations over N. America, Europe, E. Asia and Australia
NoSYNOPq	2m relative humidity	13,200	-	Boundary layer humidity	Irregular with concentrations in populated regions
NoGEOSq	Geostationary GEOS-9, 10, 12 Meteosat-5, 7	141,500	1 (of 2) Infrared	Upper troposphere, clear air	Within 50 degrees of the Equator, cloud free only
NoAMSUBq	Polar orbiting NOAA-16, 17	131,500	3 (of 5) Microwave	Upper and mid troposphere	Irregular, emissivity dependent over land and ice; good over ice free ocean
NoHIRSq	Polar orbiting NOAA-16, 17	120,000	6 (of 19) Infrared	Mostly upper troposphere, clear air	Cloud free ocean and ice
NoAIRSq	Polar orbiting AQUA	280,000	230 (of 2378) Infrared	Upper and mid troposphere, clear air	Cloud free ocean and ice
Noq	Combination of the above	927,700	-	Almost nil	None

The Control assimilation system uses a large variety of conventional observations (Courtier et al. 1998) and satellite radiances (Thépaut and Andersson 2003), several of which are at least partly sensitive to humidity. All the satellite data considered here have been assimilated directly as radiances (Andersson et al. 1994; Bauer et al. 2002), whereas in earlier studies (Eyre 1993; Gadd et al. 1995; Gérard and Saunders 1999) the humidity information had been retrieved in a separate step prior to assimilation.

We now turn to a brief description of the main humidity observing systems in the order they appear in Table 1. In the first OSE (NoSSMIq) SSMI radiance data were withheld. The SSMI microwave instruments provide radiance data in 7 channels (horizontally and vertically polarized at 19, 37 and 85 GHz and vertically polarized at 22 GHz). These channels show a differential sensitivity to the integrated atmospheric water-vapour content and wind-induced sea-surface roughness (Phalippou 1996). Radiosonde dew-point temperature observations (withheld in NoRSq) are converted to specific humidity (q) using the observed temperature and pressure (Vasiljević et al. 1992). The specific humidity profiles from the RS90 and RS80 sonde types are used at all reported levels below 100 hPa, subject to a temperature threshold which is -80°C for rs90 and -60°C for RS80. All other sonde types[3] are used only up to 300 hPa, subject to temperature being higher than -40°C. The SYNOP 2-metre dew point observations are converted to relative humidity (RH) as detailed by Vasiljević et al. (1992). 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. 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, which provides a complete and frequent coverage within about 50° latitude of the Equator. These data are not used during periods of solar equinox due to intrusion of sun light in the receiver (Köpken et al. 2004, Munro et al. 2004). From AMSUB (English et al. 2000), three of the five available 183 GHz microwave channels are assimilated depending on the land/sea mask and the height of the terrain: channel 5 is used over sea, and channels 3 and 4 are used over sea and land provided the orography is less than 1500 and 1000 m, respectively. The AMSUB window channel 2 is used in quality control checks to detect rain and cloud contamination. 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 (McNally et al. 2006). The withheld infrared data carry ambiguous temperature and humidity information. In these experiments the temperature impact is minimal as a very large amount of temperature sounding data is retained. For each of the tested observing systems, the numbers of withheld data with important humidity sensitivity are listed in Table 1.

Typical data coverage maps of assimilated data for each of the seven tested observing systems were shown in Andersson et al. (2004), and are omitted here for brevity. Summary statements are given in Table 1. 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 (McNally and Watts 2003), and to water clouds and rain (Bauer et al. 2002) 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 (SYNOP and radiosondes) provide an uneven coverage over land, with dense concentrations over parts of North America, Europe, East Asia and Australia.

[3] In the near future, rs92 data will be used like rs90.

3. Analysis impact

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.

3.1 Humidity background errors

Humidity has the least Gaussian and the least homogeneous background errors of all the analysis variables. This is due to the condensation that occurs when saturation is reached and the strict limit at zero humidity. It is suspected that this unaccounted non-Gaussian behaviour has been a major contributor to problems in the humidity analysis (Andersson et al. 2005) and in the ERA-40 hydrological cycle (Kållberg 2002). Developing ECMWF's new humidity analysis (as used here), Hólm et al (2002) adopted the approach of Dee and DaSilva (2003) to recast the humidity analysis problem in terms of a transformed humidity variable for which short-range forecast errors exhibit near-normal distribution. A normalized relative humidity variable was thus chosen as the new control-variable for the revised humidity analysis. The normalization factor is the standard deviation of the relative humidity error, stratified according to the relative humidity itself, with dependence on vertical level. The asymmetries in background error probability density functions for conditions near zero humidity and near saturation are accounted for through a non-linear transformation of the humidity variable (see Hólm et al. 2002 for a description). In terms of either specific or relative humidity, the resulting covariance model implies error standard deviations that are strongly dependent on the atmospheric state. It was shown in Figure 8 of Andersson et al. (2005) that within a typical mid-latitude weather system the modeled relative-humidity background error is lower within the cold-air outbreak and within the saturated frontal-zone region, and higher within the more central regions of the low-pressure system.

A zonal-mean cross section view of the relative-humidity background error standard deviations (%) implied by the Hólm et al. (2002) statistical model are shown here in Figure 1, as diagnosed using a randomisation technique (Andersson et al. 2000). The figure shows short-range forecast uncertainty. Its variations partly reflect the atmospheric humidity variability: There are maxima in the tropical convective regions and at the boundary layer top. The maximum over the Antarctica reflects the poorer data coverage there and the difficulties assimilating satellite sounding data in high terrain and over ice (ambiguity between the effects on the measured radiances of atmospheric moisture and the surface). The minima correspond to the sub-tropical subsidence regions, where the air is very dry, and the uncertainty small. Above the diagnosed tropopause, the standard deviations are explicitly set to very small values in order to prevent extrapolation into the stratosphere of tropospheric analysis increments. The purpose is to effectively switch off the humidity analysis in the stratosphere due to a general lack of humidity observations there (available in near real time).

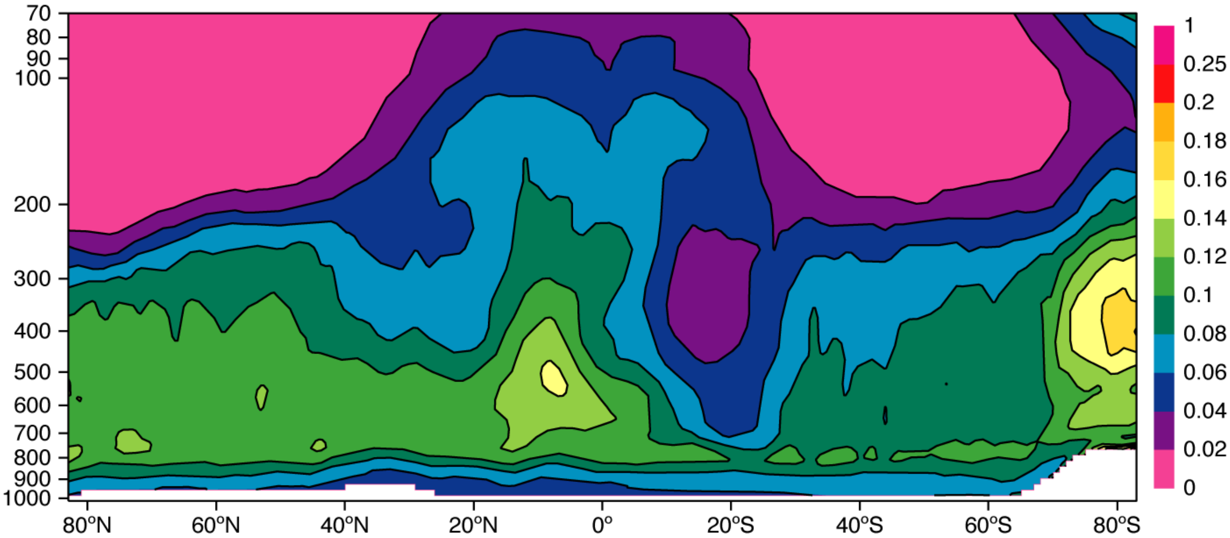

Figure 1 Background error standard deviations for relative humidity (shaded in intervals of 2%), in a zonal-mean cross section view for 20030702-21 UTC, implied by the Hólm et al. (2002) statistical model for humidity errors. Maxima correspond to the boundary layer top, the tropical convective region north of the Equator and the Antarctic region. The minima correspond to the sub-tropical subsidence regions.

3.2 Analysis differences

In Figure 2 we display the analysis impact of each of the seven observation types in terms of the root-mean-square (RMS) of analysis difference with respect to the Control assimilation. These are shown as vertical profiles on pressure levels between 1000 and 100 hPa for three geographical areas: North America (predominantly a land area with dense surface and radiosonde networks), the tropics (dominated by the Hadley circulation) and the Southern Oceans (almost totally reliant on satellite data). The total humidity impact, as provided by the RMS of the Control minus Noq difference, is shown in full black line, for reference. As this represents the largest impact it appears furthest to the right in each panel.

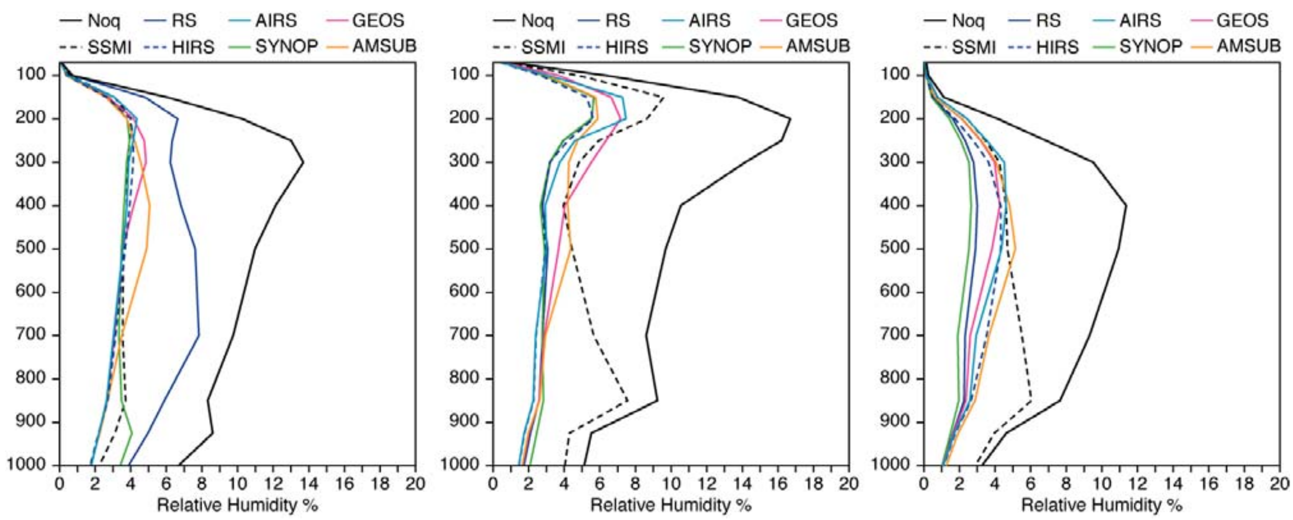

Figure 2 RMS of relative-humidity analysis differences (%) between the Control assimilation and each of the humidity OSEs (see labels), 20030702-20030731, 12 UTC, for three geographical regions: (a) North America (25-60° North, 75-120° West), (b) the tropics (20° North to 20° South) and (c) the Southern Hemisphere mid-latitudes (30-60° South). The rightmost curve in each panel (full line) represents the total impact of observed humidity, i.e. the RMS of Control minus Noq analyses.

The withdrawal of a minor contributing observing system introduces small quasi-random perturbations which evolve during assimilation, where undetected by other data. The curve formed by the left-most point at each level in Figure 2 can thus be interpreted as an indication of the analysis uncertainty, i.e the noise not controlled through assimilation of available data. It appears that the humidity analysis is constrained to within 3 to 4 % in all three regions, except near the top of the deep tropical convection. In land regions with good radiosonde coverage (N. America, left panel), radiosonde data make the largest contribution to the humidity analysis, followed by AMSUB between 600 and 400 hPa, SSMI and SYNOP at 700 hPa and below. In the tropics SSMI entirely dominates in the lower troposphere with a second peak appearing at 200 hPa, presumably through interaction with the convection parameterization of the model. AMSUB makes a significant contribution above 700 hPa, GEOS above 600 hPa and AIRS contributes above 300 hPa. Radiosondes in the tropics have only a small impact confined to the levels below 500 hPa, due to the poor coverage, and the dominance of satellite data at higher levels. The SYNOP data have some impact in the lowest levels. In the Southern Hemisphere mid-latitude region, radiosondes and SYNOP make a negligible contribution as expected from their poor coverage, whereas SSMI dominates in the lower troposphere. HIRS, GOES and AIRS each provide similar contributions to SSMI and AMSUB in the upper troposphere. It should be emphasized that these impacts are with reference to the full system as provided by the Control assimilation. Earlier experiments (McNally and Vesperini 1996) have demonstrated very significant tropical humidity impacts of HIRS data in experiments where SSMI and AIRS data were absent.

The geographical distribution of the RMS relative-humidity analysis differences is highly variable (not shown here for brevity). Maps of the 850 hPa level show that SSMI provides the largest analysis impact of the seven tested observation types. SSMI dominates the low-level humidity analysis in the subsidence regions north and south of the ITCZ, but not within the ITCZ itself, where SSMI and other satellite data are not used due to clouds or precipitation[4]. Radiosondes and SYNOP have locally large impacts in some of the regions with dense coverage: North America, Europe, Central Asia, India and China. Maps of the 300 hPa level (not shown) indicate that SSMI data, although not used in the rainy regions, has considerable influence on humidity at 300 hPa in the ITCZ and in the Indonesian region. The SSMI impact at 300 hPa is also strong in all oceanic storm-track regions. AMSUB has substantial impact in most regions of the globe, over land and ocean. The geostationary data have direct impact on upper-tropospheric humidity in the tropics, whereas HIRS and AIRS impact is most apparent at high latitudes. Radiosondes and SYNOP affect the 300 hPa humidity primarily over central North America, Western Europe and central Asia, both directly and presumably also through interaction with convection by the modified supply of humidity in the boundary layer.

3.3 Biases

Systematic errors in the model and errors in the data contribute to bias in analyses (Dee and da Silva 1998; Dee 2003; 2005). In these experiments (and in ECMWF operations until mid 2006[5]), satellite radiance data are bias corrected for air-mass dependent and scan-angle dependent biases using the method of Harris and Kelly (2001). There have been several reports on persistent observation bias also in radiosondes (e.g. Wang et al. 2002, Nash 2002, John and Buehler 2005). However, radiosonde and SYNOP humidity data are currently not subject to bias correction at ECMWF. Dee and Todling (2000) highlighted the importance of

[4] Subsequently, assimilation of rain-affected SSMI radiances has been introduced (Bauer et al 2006b), in IFS cycle 29r2, June 2005.

[5] Variational bias correction (Dee 2004; McNally et al. 2006) is currently in pre-operational testing, with IFS cycle 31r1, scheduled for implementation in September 2006.

analysis humidity bias in general, whereas Gérard and Saunders (1999) and McNally and Vesperini (1996) showed significant bias impact from the use of SSMI and HIRS data, respectively.

Bias differences between Control and each of the eight experiments are shown in Figure 3, in the form of north-south cross sections, averaged over the study period. Panel (a), Control minus Noq, shows that

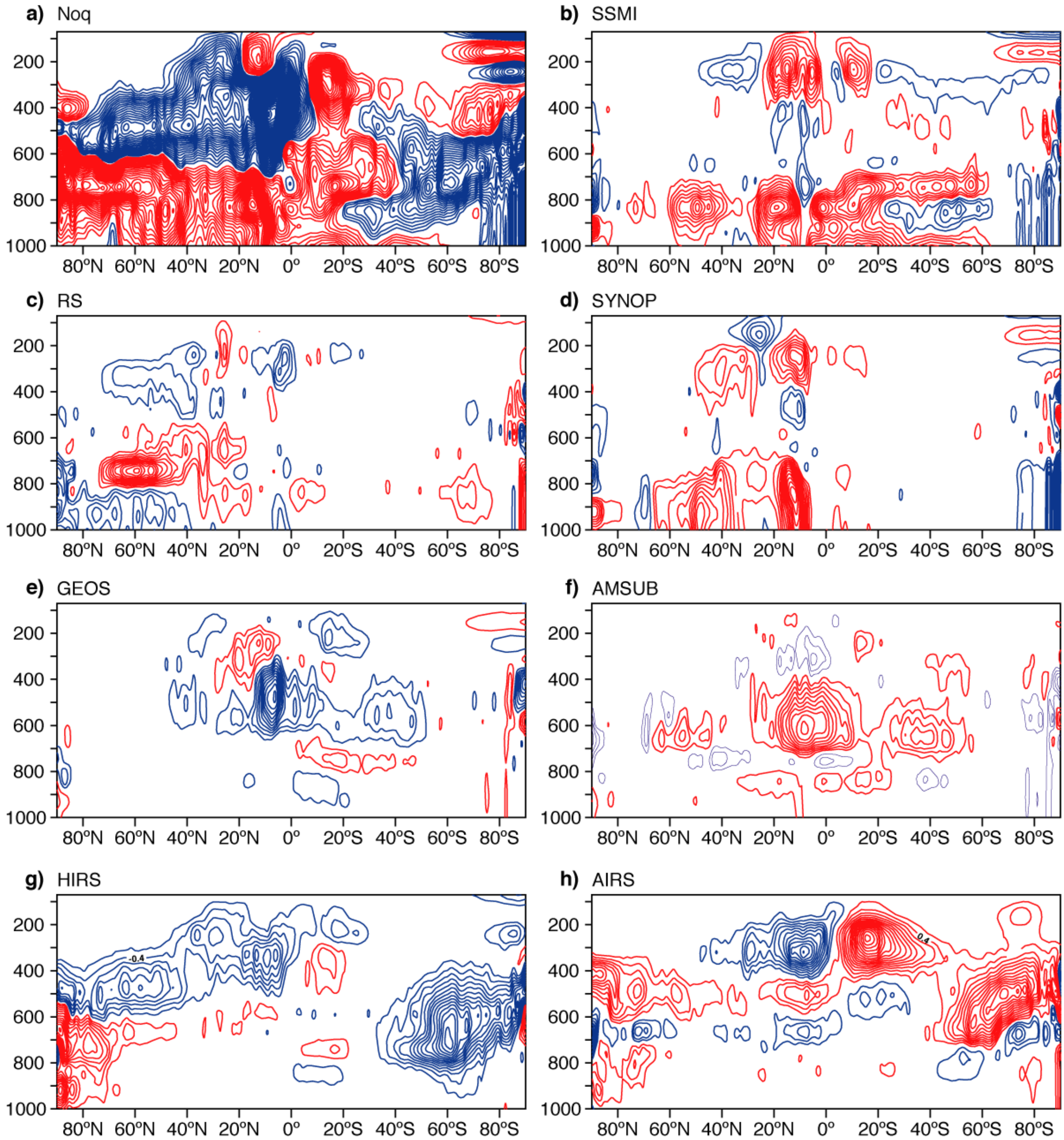

Figure 3 Zonal-mean monthly mean (2-31 July 2003) cross sections of relative-humidity analysis differences (%). The contour interval is 0.2 % with red (blue) indicating that the Control assimilation is moister (drier) than the experiment withholding the data. From top left: Noq, SSMI, radiosondes, SYNOP, GEOS, AMSUB, HIRS and AIRS.

observed humidity substantially modifies the moisture analysis: in the N. Hemisphere and in the tropics by increasing moisture in the lower troposphere and decreasing it at higher levels. Panel (b), Control minus NoSSMIq, shows that SSMI systematically adds moisture (over ocean) in the lower troposphere in the tropics and the northern hemisphere mid latitudes. Geographical maps of the bias (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 precipitation impact (next section) there. Radiosondes and SYNOP, panels (c) and (d), show biases in the boundary layer of opposite sign. These appear over many continental areas and are seen here at the 850, 925 and 1000 hPa levels of the cross-sections. Over parts of Europe and N. America (40-70° N in panel (c)) there is clear indication that radiosondes contribute to a drying of the analysis in the upper troposphere, which is consistent with John and Buehler's (2005) findings that several radiosondes have a upper tropospheric dry biases. While absolute amounts are small, upper tropospheric humidity is important for accurate radiative transfer calculation, and also for the indirect influence on cirrus cloud formation. The assimilation of GEOS and AMSUB data, panels (e) and (f), also leads to localized biases of opposite sign: in this case in the upper troposphere of the ITCZ region. HIRS data (g) influence the mean humidity analysis at high latitudes in both hemispheres, which can be linked to difficulties in cloud detection over sea ice. The AIRS data (h) appear to counteract the HIRS biases, in parts.

Figure 4 shows vertically integrated humidity bias impacts in terms of total column water vapour (TCWV). TCWV is dominated by the moisture content of the warm air in the lower troposphere and at lower latitudes. The mid and upper tropospheric relative-humidity biases seen in Figure 3 contribute very little in terms of TCWV; the plots for GEOS, AMSUB, HIRS and AIRS are therefore omitted. In Figure 4 we can see that the net effect of all assimilated humidity observations (panel a) is to add moisture. Over sea, the TCWV bias impact is almost entirely due to SSMI data.

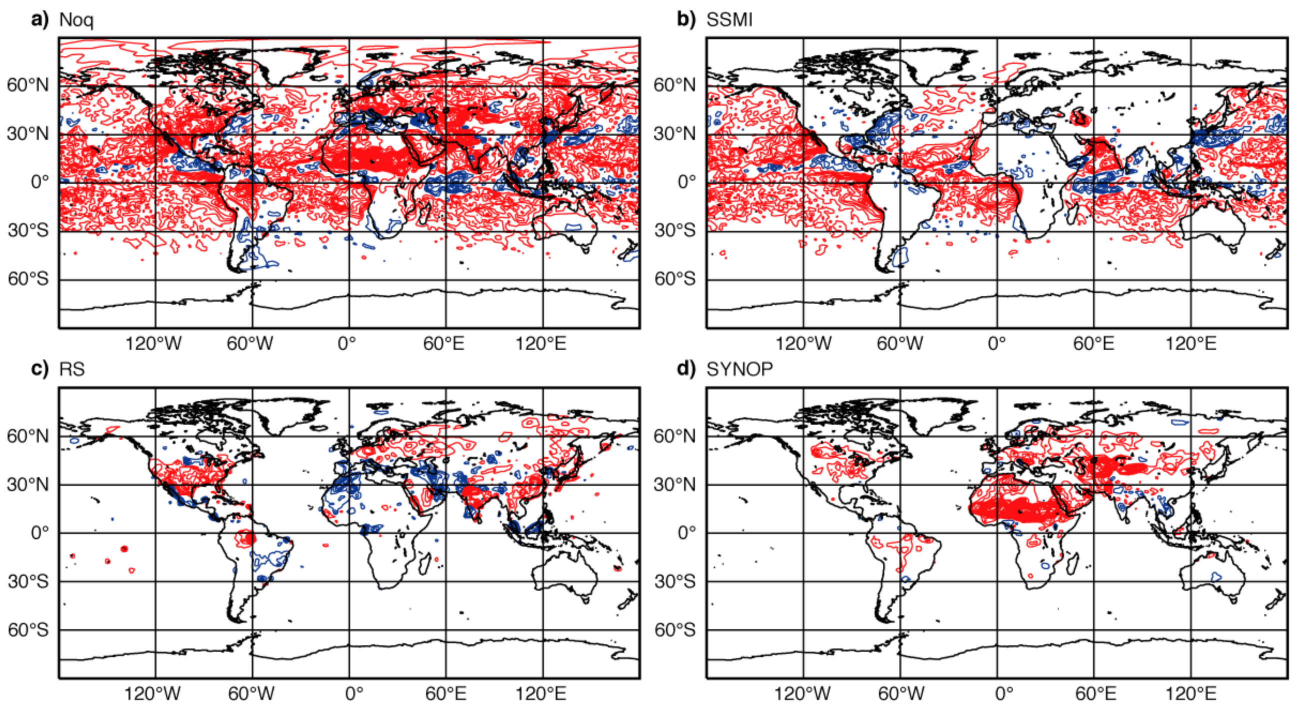

Figure 4 Mean analysis difference for total column water vapour (0.5 kg m-2 contour interval) for (a) Control-Noq, (b) Control-NoSSMIq, (c) Control-NoRSq and (d) Control-NoSYNOPq. The NoGEOSq, NoAMSUBq, NoHIRSq and NoAIRSq (not shown) had negligible impact in terms of TCWV.

Over land, the bias is 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 sonde coverage including parts of North America. SYNOP assimilation adds significant moisture to the Sahel and Sub-Sahara regions of Africa. The humidity increments at the lowest model level are used as input to the soil-water analysis (Drusch and Viterbo 2006). It is likely that the SYNOP impact in this region is through its interaction with the soil moisture analysis.

4. Forecast impact

The forecast impact has been investigated in terms of short-range forecasts of precipitation, and in terms of forecast scores to day ten for relative humidity, wind, temperature and geopotential. We focus on the short to medium range (1 to 5 days) because it is not always possible to obtain significant results for longer ranges with a relatively short study period (one month).

4.1 Short-range precipitation forecast

Precipitation impact for parts of the tropics and North America is shown in Figure 5. Global plots have been produced for each of the eight experiments and some were discussed in Andersson et al. (2004). Here we focus on the total precipitation impact due to observed humidity as provided by the Control minus Noq comparison. Figure 5 shows that the rainfall in the first 12 hours of forecasts is increased in the Western Pacific region 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 difference plot that the location of the ITCZ in the East Pacific has been modified by the assimilation of humidity data. The corresponding map for NoSSMI minus Control (not shown) indicates that nearly all the differences seen over ocean in Figure 5 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 (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.

From Figure 5 we can deduce that assimilation of radiosondes and SYNOP humidity data locally increases the rainfall in the regions where Figure 4 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 precipitation impact of observed humidity is smaller than in the tropics but may nevertheless be important in relative terms; Figure 5 shows reduced precipitation in the western parts of the Atlantic and Pacific oceans, which is due to assimilation of SSMI.

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, documented by Beljaars (2002; 2005) and Kållberg (2002), has now been significantly reduced, through changes to the moist physics parameterizations, and the assimilation system. Due to the spin-down problem assimilation of observed humidity produced up to 50% more tropical precipitation early in forecasts than assimilations without humidity data. It is evident from Figure 5 that the current Control humidity analyses are in much better balance with the forecast model, and do not result in excessive amounts of precipitation initially in forecasts[6].

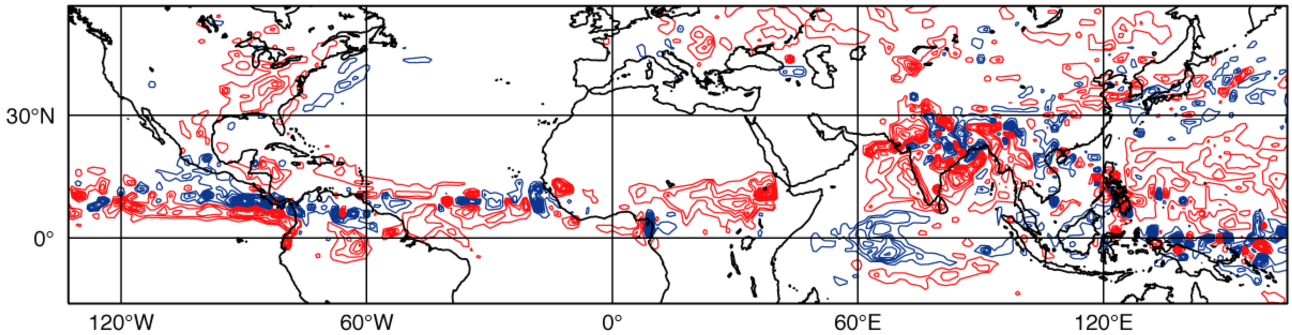

Figure 5 Average daily precipitation difference (20030702-20030731) in 12-hour forecasts from analyses at 06 and 18 UTC, showing Control minus Noq. Red (blue) contours (1 mm/day) indicate that assimilation of observed humidity has increased (decreased) precipitation.

4.2 Forecast verification scores

Differences in latent heat release associated with the above mentioned differences in precipitation result in temperature differences throughout the troposphere (not shown). 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 parameterisation directly changes the wind through its vertical momentum transport. To test the forecast benefit of humidity assimilation, daily ten-day forecasts have been run from the Control and each of the eight experiments. Objective forecast verification scores have been computed for geopotential, temperature, vector wind and relative humidity at pressure levels. The scores shown here are root mean square errors (RMSE), computed with the operational ECMWF analysis as reference.

Figure 6 shows the forecast impact of observed humidity in relative terms, i.e. 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 10. The error bars indicate 90% two-sided confidence intervals. Scores are shown for the Northern Hemisphere extra tropics, the tropics within 20° of the Equator, and the Southern Hemisphere extra tropics, for 1000 hPa geopotential, 500 hPa temperature, 300 hPa vector wind and 850 hPa relative humidity. We see that there is a clear positive impact from assimilating humidity observations in all three regions, and for all four quantities. The humidity forecast impact is initially very large (>15 % in NH and Tr) but falls off rapidly during the first 4 days of forecasts. This is indicative of the fact 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. Our results 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%). The extra-tropical dynamical impact is positive over the entire 10-day forecast range with just one or two near-neutral exceptions. Where the lower bound of the error bar is above

[6] A further 'spin-down limiter' which reduces the analysis increments locally at model grid points with high CAPE (convective available potential energy) was introduced in IFS version 29r2 in July 2005. To be reported elsewhere.

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 day 7 or 8 of forecast.

Table 2 and Table 3 show a break down by observation types of 48-hour forecast impacts in terms of 300 hPa vector wind, 1000 hPa geopotential (extra-tropics) and 500 hPa temperature (tropics). The results are generally consistent with what we have seen above in terms of analysis and forecast impact. The Noq experiment has larger errors than Control in all three regions. The total impact of humidity observations is thus beneficial. Furthermore we can see that the total impact is larger than that of any of the individual observing systems. In the Northern Hemisphere extra-tropics it is radiosondes, AMSUB and HIRS that contribute most. In the Southern Hemisphere, SSMI, AMSUB and GEOS are the main contributors. In the tropics, SSMI, SYNOP and AMSUB contribute clear benefit for 300 hPa wind, whereas SYNOP, GEOS, HIRS and AIRS provide benefit in terms of 500 hPa temperature.

Table 2 Normalized RMS of 48-hour forecast error for 300 hPa vector wind (%), showing differences between the Control and each of the eight experiments, for three geographical areas. Positive values indicate benefit of assimilating the data.

Experiment	N.Hem 300 hPa VW	Tropics 300 hPa VW	S.Hem 300 hPa VW
NoSSMIq	0.6	2.1	1.9
NoRSq	1.3	0.3	-0.1
NoSYNOPq	0.3	1.3	0.1
NoGEOS	0.8	0.5	0.5
NoAMSUB	1.6	1.0	1.0
NoHIRSq	1.2	0.6	0.5
NoAIRSq	0.3	0.8	-0.1
Noq	**4.2**	**6.1**	**4.6**

Table 3 As Table 1 for 1000 hPa geopotential (%) in the extra-tropics, and 500 hPa in the Tropics.

Experiment	N.Hem 1000 hPa Z	Tropics 500 hPa T	S.Hem 1000 hPa Z
NoSSMIq	0.2	-0.1	3.5
NoRSq	0.8	0.5	0.1
NoSYNOPq	0.8	2.6	-0.0
NoGEOS	0.6	0.7	1.2
NoAMSUB	1.7	0.0	0.9
NoHIRSq	0.8	0.7	0.8
NoAIRSq	0.5	0.8	0.3
Noq	**3.3**	**7.3**	**4.9**

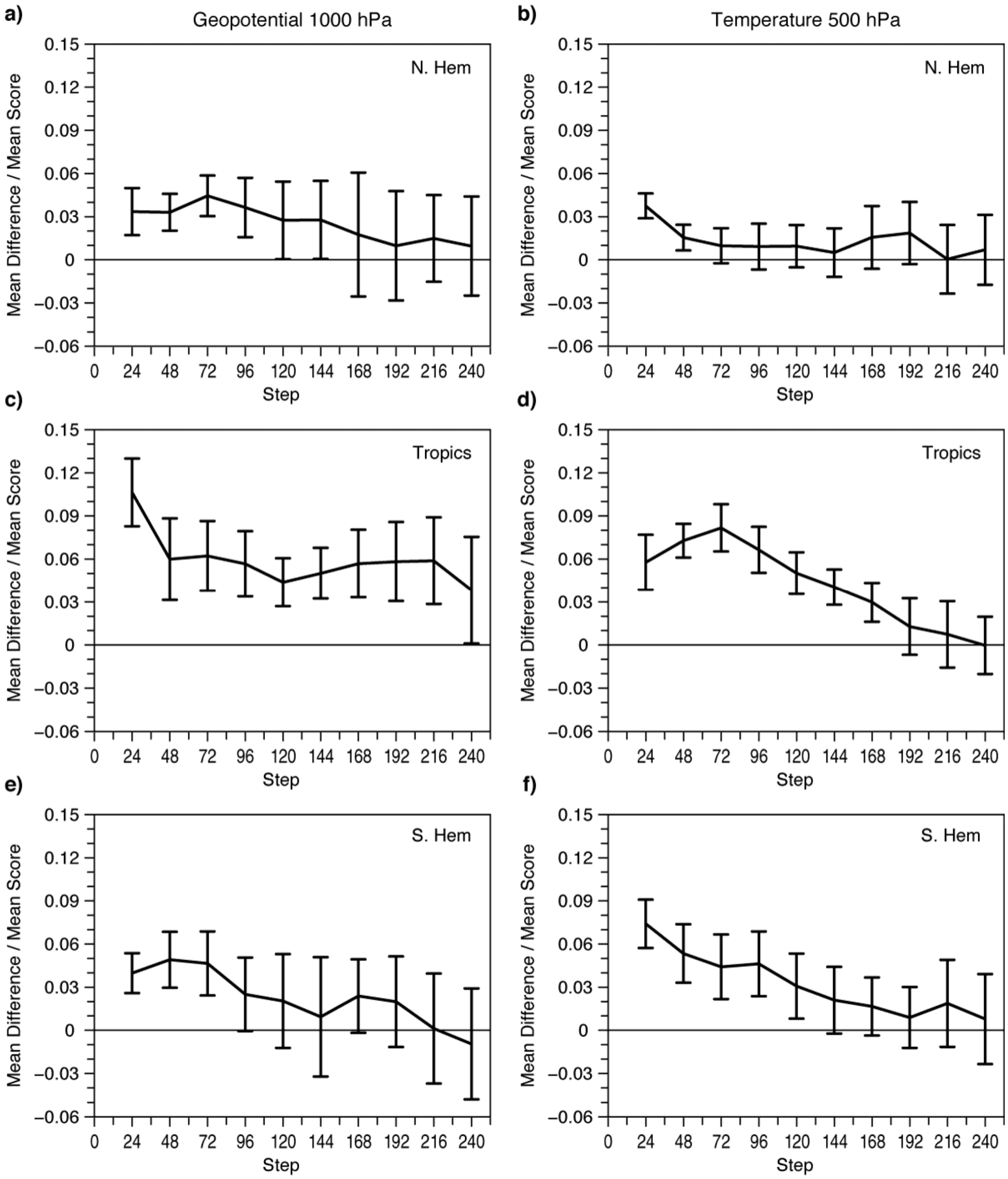

Figure 6 Forecast impact of observed humidity in terms of normalized RMSE, i.e. (Noq-Control)/0.5(Noq+Control), for 1000 hPa geopotential (left) and 500 hPa temperature (right) in three verification areas, as labelled. The error bars represent 90% two-sided confidence intervals.

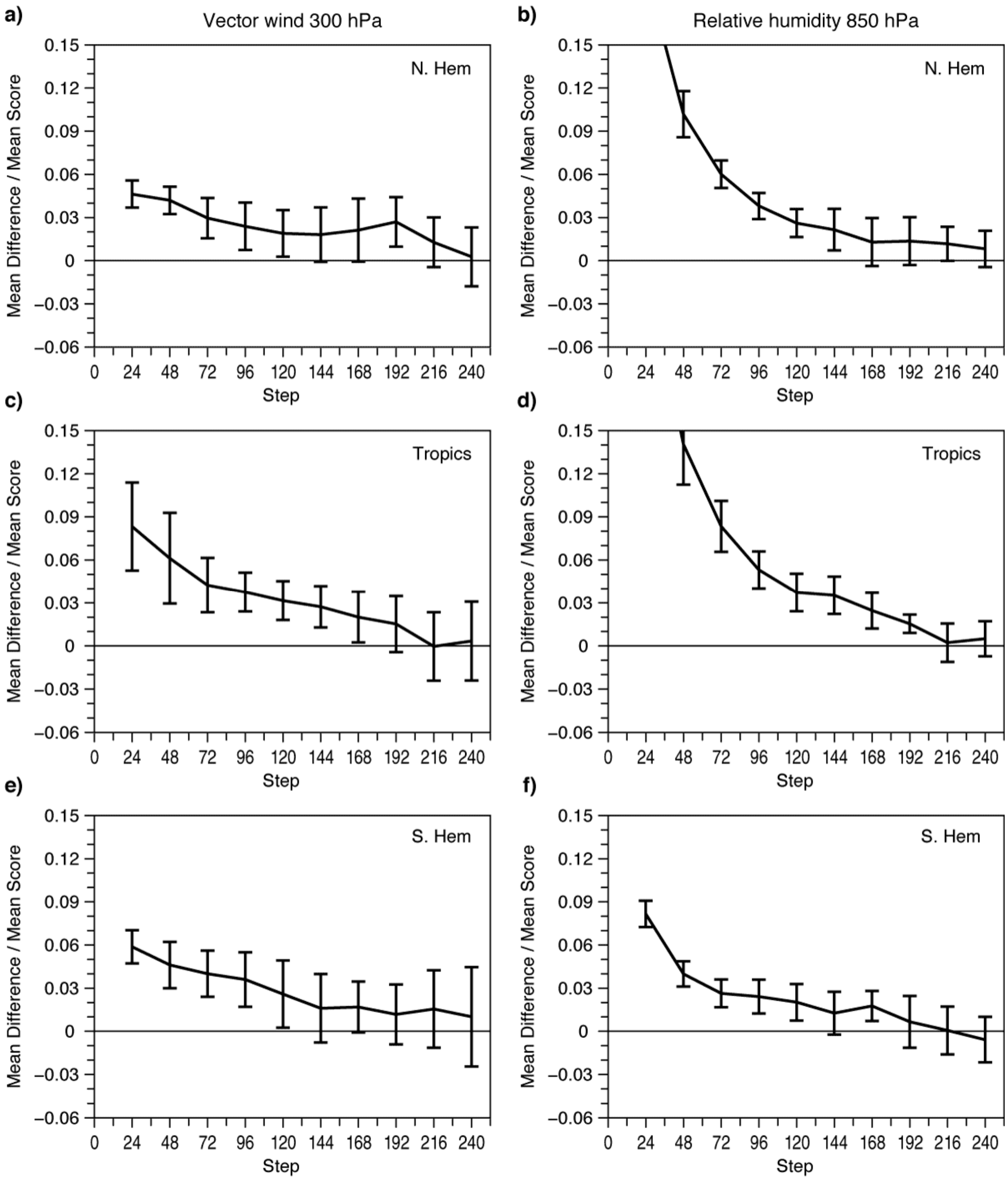

Figure 7 Like Figure 6 but for300 hPa vector wind (left) and 850 hPa relative humidity (right).

5. Summary and conclusions

The analysis and forecast impact of observed humidity has been tested in one-month observing system experiments (OSE) using ECMWF's 4D-Var data assimilation system. The impact of seven main types of humidity observations has been evaluated in terms of differences with respect to a reference system (the Control assimilation), which used all data. As there is some considerable overlap and redundancy between observing systems the impact measured in this way appears much smaller than would have been the case if we had chosen to add the data types one at a time to a reference system without humidity data (Noq). We have chosen to use the full system as reference in this study, as this is the most relevant option for evaluating the performance of ECMWF's assimilation of observed humidity.

Our main result is that humidity data have a significant NWP impact extending into the medium range (5-6 days), with a marked impact also on the wind field. This is in contrast to the results of Bengtsson and Hodges (2005), which used an earlier 3D-Var version of the ECMWF forecasting system and showed virtually identical prediction skill with and without assimilation of humidity observations. We conclude that the introduction of the new humidity analysis (Hólm et al. 2002) and several new types of satellite radiance data (Bauer et al. 2002; Köpken et al. 2004, Munro et al. 2004; McNally et al. 2006), as well as improvements to the physical parameterisations of the model (Tompkins et al. 2004) have contributed to these results. We may also speculate that the 4D-Var technique is superior to 3D-Var in its handling of humidity data, but this requires further investigation. We estimate that the random component of the analysis error is 3 to 5 % relative humidity, and that the bias error has a similar magnitude.

Furthermore, we have found that each data type provides benefit to the analysis and forecast performance. We therefore conclude that the humidity analysis (Hólm et al. 2002) performs well, and is effective in extracting information from a wide variety of humidity observations. Analysis differences between the experiments and the Control showed that: SSMI dominates the humidity analysis over sea, followed by AMSUB; radiosondes, SYNOP and AMSUB dominate over land; and GEOS, HIRS and AIRS dominate in the upper troposphere, at 200-300 hPa. Analysis increments from SSMI peak at 850 hPa, AMSUB at 400-500 hPa, GEOS and HIRS at 300 and AIRS at 200 hPa.

SSMI adds water in the sub-tropical subsidence areas due to a bias with respect to the model. Radiosondes and SYNOP have a tendency to create opposite biases in the boundary layer over land, with local influence on precipitation. The SYNOP data are biased wet and the radiosondes are biased dry with respect to the model.

5.1 Perspectives

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

- The use of HIRS and AIRS infrared radiances continues to be developed (McNally et al. 2006), 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 operations 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.

- In the near future, microwave radiances from new instruments will be assimilated that complement 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, which have specifications similar to the SSMI. While these instruments will not provide additional information on moisture's vertical distribution, 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.

- Since June 2005, SSMI radiances affected by clouds and precipitation are assimilated at ECMWF through a 1D+4D-Var analysis method (Bauer et al. 2006a; 2006b). Similarly to 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 4b) 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.

- There has been a gradual improvement of 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 (e.g. Wang 2002, Miloshevich, 2004, Vömel et al. 2006). Some of the causes have been tackled by improved radiosonde design, for instance, the 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 (e.g. Wang 2002, Miloshevich: 2004, Vömel et al. 2006). Some of these bias correction algorithms should be investigated for use in the ECMWF 4DVar system. Additionally, the dropsonde humidity data, e.g. from United States tropical-cyclone and winter-storm recognisance flights, have improved in quality, and are since December 2005 assimilated at ECMWF when available. 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.

- GPS radio occultation techniques are being developed that may improve humidity information in the upper troposphere and tropopause region (Healy and Thépaut 2006). Ground-based GPS measurements provide total-column humidity information that is used experimentally in NWP assimilation (Poli et al. 2006). Near real-time GPS networks are being coordinated in Europe, N. 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.

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References

Andersson, E., J. Pailleux, J.N. Thépaut, J. Eyre, A. P. McNally, G. Kelly and P. Courtier, 1994: Use of cloud-cleared radiances in three/four-dimensional variational data assimilation. *Q. J. R. Meteorol. Soc.*, **120,** 627—653.

Andersson, E., M. Fisher, R. Munro and A. McNally, 2000: Diagnosis of background errors for radiances and other observable quantities in a variational data assimilation scheme, and the explanation of a case of poor convergence. *Q. J. R. Meteorol. Soc.* **126,** 1455—1472.

Bauer, P., G. Kelly, and E. Andersson, 2002: SSM/I radiance assimilation at ECMWF. Proceedings of ECMWF/GEWEX Workshop on "Humidity Analysis", Reading, U. K., 8—11 July 2002, 167—175.

Andersson, E., E. Hólm and J. N. Thépaut, 2004: Impact studies of main types of conventional and satellite humidity data. Proc. 3rd WMO Workshop on "The Impact of Various Observing Systems on Numerical Weather Prediction", Alpbach, Austria, 9—12 March 2004, Eds. H. Böttger, P. Menzel and J. Pailleux. *WMO/TD* No. **1228**, 32—44.

Andersson, E., P. Bauer, A. Beljaars, F. Chevallier, E. Hólm M. Janisková, P. Kållberg, G. Kelly, P. Lopez, A. McNally, E. Moreau, A. J. Simmons, J.-N. Thépaut and A. M. Tompkins, 2005: Assimilation and modeling of the atmospheric hydrological cycle in the ECMWF forecasting system. *Bull. Amer. Meteorol. Soc.*, **86,** 387—402.

Bauer, P., P. Lopez, A. Benedetti, D. Salmond, and E. Moreau, 2006a: Implementation of 1D+4D-Var assimilation of precipitation-affected microwave radiances at ECMWF, Part I: 1D-Var. *Q. J. R. Meteorol. Soc.*, **132,** in press.

Bauer, P., P. Lopez, A. Benedetti, D. Salmond, S. Saarinen and M. Bonazzola, 2006b: Implementation of 1D+4D-Var assimilation of precipitation-affected microwave radiances at ECMWF, Part II: 4D-Var. *Q. J. R. Meteorol. Soc.*, **132,** in press.

Beljaars, A. C. M., 2002: Some aspects of modeling of the hydrological cycle in the ECMWF model. Proceedings of ECMWF/GEWEX Workshop on "Humidity Analysis", Reading, U. K., 8—11 July 2002, 191—202.

Beljaars, A., 2005: Biases in the ECMWF model. Proc. ECMWF/EUMETSAT workshop on "Bias estimation and correction in data assimilation", Reading 8-11 November 2005, 29—39.

Bengtsson, L., K. I. Hodges and S. Hagemann, 2004a: Sensitivity of large-scale atmospheric analyses to humidity observations and its impact on the global water cycle and tropical and extratropical weather systems in ERA40. *Tellus*, **56A,** 202—217.

Bengtsson, L., Hagemann, S., and Hodges, K.I. 2004b: Can climate trends be calculated from reanalysis data? *J. Geophys. Res.,* **109***,* D11111, doi:1029/2004JD004536.

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

Bouttier, F., 2001:The development of 12-hourly 4D-Var. *ECMWF Tech. Memo*. **348,** pp 21.

Chevallier, F., P. Lopez, A.M. Tompkins, M. Janisková, and E. Moreau, 2004: The capability of 4D-Var systems to assimilate cloud affected satellite infrared radiances. *Q. J. R. Meteorol. Soc.*, **130,** 917—932.

Courtier, P., J.N. Thépaut and A. Hollingsworth, 1994: A strategy for operational implementation of 4D-Var, using an incremental approach. *Q. J. R. Meteorol. Soc*. **120,** 1367—1388.

Courtier, P., E. Andersson, W. Heckley, J. Pailleux, D. Vasiljevic, M. Hamrud, A. Hollingsworth, F. Rabier and M. Fisher, 1998: The ECMWF implementation of three-dimensional variational assimilation (3D-Var). I: Formulation. *Q. J. R. Meteorol. Soc.* **124,** 1783—1807.

Dee, D., 2003: Detection and correction of model bias during data assimilation. Proc. ECMWF Seminar on "Recent developments in data assimilation for atmosphere and ocean", Reading, U.K., 8—12 September 2003, 65—73.

Dee. D. P., 2004: Variational bias correction of radiance data in the ECMWF system. Proc. ECMWF Workshop on "Assimilation of High Spectral Resolution Sounders in NWP", 28 June—1 July 2004, ECMWF, Reading, UK, 97—112.

Dee, D., 2005: Bias and data assimilation. *Q. J. R. Meteorol. Soc*., **131,** xxx—xxx. *In print.*

Dee, D. P., and A. da Silva, 1998: Data assimilation in the presence of forecast bias. *Q. J. R. Meteorol. Soc*., **124,** 269—295.

Dee, D. P., and R. Todling, 2000: Data assimilation in the presence of forecast bias: The GOES moisture analysis. *Mon. Wea. Rev*., **124,** 269—295.

Dee, D. P., and A. M. da Silva, 2003: The Choice of Variable for Atmospheric Moisture Analysis. *Mon. Wea. Rev*., **131,** 155—171.

Drusch and Viterbo, 2006: The ECMWF soil water analysis. *Mon. Wea. Rev*., **134,** xxx—xxx. Accepted

English, S. J., R. J. Renshaw, P. C. Dibben, A. J. Smith, P. J. Rayer, C. Poulsen, F. W. Saunders and J. R. Eyre, 2000: A comparison of the impact of TOVS and ATOVS satellite sounding data on the accuracy of numerical weather forecasts. *Q. J. R. Meteorol. Soc*., **126,** 2911—2931.

Eyre, J. R., G. A. Kelly, A. P. McNally, E. Andersson, and A. Persson, 1993: Assimilation of TOVS radiance information through one-dimensional variational analysis. *Q. J. R. Meteorol. Soc*., **119,** 1427—1463.

Gadd A. J., B. R. Barwell, S. J. Cox and R. J. Renshaw, 1995: Global processing of satellite sounding radiances in a numerical weather prediction system. *Q. J. R. Meteorol. Soc*., **121,** 615—630.

Gérard, É. and R. W. Saunders, 1999: Four-dimensional variational assimilation of Special Sensor Microwave/Imager total column water vapour in the ECMWF model. *Q. J. R. Meteorol. Soc*., **125,** 3077—3102.

Harris, B., and G. Kelly, 2001: A satellite radiance bias correction scheme for radiance assimilation. *Q. J. R. Meteorol. Soc.,* **127,** 1453—1468.

Healy, S. B. and J. N. Thépaut, 2006: Assimilation experiments with CHAMP GPS radio occultation measurements. *Q. J. R. Meteorol. Soc.,* **132,** 605—623.

Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J-F. Mahfouf, A.J. Simmons and J.N. Thépaut, 2002: Assimilation and modeling of the hydrological cycle: ECMWF's status and plans. *ECMWF Tech. Memo*., **383,** pp 55.

John, V. O. and S. A. Buehler, 2005: Comparison of microwave satellite humidity data and radiosonde profiles: A survey of European stations. *Atmos. Chem. and Phys.*, **5,** 1843—1853.

Kållberg, P., 2002: The ERA-40 hydrological cycle. Proc. ECMWF/GEWEX workshop on "Humidity Analysis", Reading, U. K., 8—11 July 2002, 101—105.

Köpken, C., G. Kelly, and J.-N. Thépaut, 2004: Assimilation of METEOSAT radiance data within the 4D-Var system at ECMWF. Assimilation experiments and forecast impact. *Q. J. R. Meteorol. Soc.*, **130,** 2277—2292.

Marécal, V., and J.-F. Mahfouf, 2003: Experiments on 4D-Var assimilation of rainfall data using an incremental formulation. *Q. J. R. Meteorol. Soc.,* **129,** 3137—3160.

McNally, A. P., and M. Vesperini, 1996: Variational analysis of humidity information from TOVS radiances *Q. J. R. Meteorol. Soc.,* **122,** 1521—1544.

McNally, A.P., and P.D. Watts, 2003: A cloud detection algorithm for high spectral resolution infrared sounders. *Q. J. R. Meteorol. Soc.*, **129,** 3411—3423.

McNally, A.P., P.D. Watts, J. A. Smith, R. Engelen, G. A. Kelly, J. N. Thépaut and M. Matricardi, 2006: The assimilation of AIRS radiance data at ECMWF. *Q. J. R. Meteorol. Soc.*, **132,** 935—958.

McNally, T., T. Auligné, D. Dee and G. Kelly, 2006: A variational approach to satellite bias correction. *ECMWF Newsletter,* **107,** 18—23.

Miloshevich, L. M., A. Paukkunen, H. Vömel and S. J. Oltmanns, 2004: Development and validation of a time-lag correction for Vaisala radiosonde humidity measurements. *J. Atm and Oc. Techn.*, **21,** 1305—1327.

Moreau, E., P. Lopez, P. Bauer, A. Tompkins, M. Janisková, and F. Chevallier, 2004: Variational retrieval of temperature and humidity profiles using rain rates versus microwave brightness temperatures. *Q. J. R. Meteorol. Soc,* **130,** 827—852.

Munro, R., C. Köpken, G. Kelly, J.-N. Thépaut, and R. Saunders, 2004: Assimilation of METEOSAT radiance data within the 4D-Var system at ECMWF: Data quality monitoring, bias correction and single-cycle experiments. *Q. J. R. Meteorol. Soc.*, 130, 2293—2313.

Nash, J., 2002: Review of test results on the accuracy of radiosonde relative humidity sensors. Proc. ECMWF/GEWEX workshop on "Humidity Analysis", Reading, U. K., 8—11 July 2002, 117—123.

Phalippou, L., 1996: Variational retrieval of humidity profile, wind speed and cloud liquid water path with the SSM/I: Potential for numerical weather prediction. *Q. J. R. Meteorol. Soc.*, **122,** 327—355.

Poli, P., P. Moll, F. Rabier, G. Desroziers, B. Chapnik, L. Berre, S. B. Healy, E. Andersson and F-Z. El Guelai, 2006: Forecast impact studies of zenith total delay data from European near real-time GPS stations in Meteo-France 4DVar. *J. Geophys. Res.*., **111,** submitted.

Rabier, F., H. Järvinen, E. Klinker, J.F. Mahfouf and A. Simmons, 2000: The ECMWF operational implementation of four-dimensional variational assimilation. Part I: experimental results with simplified physics. *Q. J. R. Meteorol. Soc.* **126,** 1143—1170.

Simmons, A. J., A. Untch, C. Jakob, P. Kållberg and P. Undén, 1999: Stratospheric water vapour and tropical tropopause temperatures in ECMWF analyses and multi-year simulations. *Q. J. R. Meteorol. Soc.*, **125,** 353—386.

Smagorinsky, J., K. Miyakoda and R. F. Strickler, 1970: The relative importance of variables in initial conditions for dynamical weather prediction, *Tellus*, **22,** 141—157.

Tompkins, A. M., P. Bechtold, A. C. M. Beljaars, A. Benedetti, S. Cheinet, M. Janisková, M. Köhler, P. Lopez, and J.-J. Morcrette, 2004: Moist physical processes in the IFS: Progress and Plans. *ECMWF Tech Memo.*, **452,** pp 91.

Uppala, S. M., P. W. Kållberg, A. J. Simmons, U. Andrae, V. da Costa Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hólm , B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. McNally, J.-F. Mahfouf, J.-J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Sterl, K. E. Trenberth, A. Untch, D. Vasiljević, P. Viterbo and J. Woollen, 2005: The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* **131,** 2961—3012.

Vasiljević, D., C. Cardinali and P. Undén, 1992: ECMWF 3D-Variational assimilation of conventional observations. Proc. ECMWF workshop on "Variational assimilation with emphasis on three-dimensional aspects.", Reading, 9—12 November 1992, 389—436.

Vömel, H., H. Selkirk, L. Miloshevich, J. Valverde-Canossa, J. Valdés, E. Kyrö, R. Kivi, W. Stolz, G. Peng, J. A. Diaz, 2006: Radiation dry bias of the Vaisala RS92 humidity sensor. *J. Atm and Oc. Techn.* Submitted.

Wang, J. H., H. L. Cole, D. J. Carlson, E. R. Miller, K. Beierle, A. Paukkunen and T. K. Laine, 2002: Corrections of humidity measurement errors from the Vaisala RS80 radiosonde - Application to TOGA COARE data. *J. Atm and Oc. Techn.*, **19,** 981—1002.