Some aspects of modelling of the hydrological cycle in the ECMWF model

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1 Introduction

Moist processes are important for the modelling of clouds, precipitation, radiation and latent heat release. Furthermore, data assimilation relies heavily on the moisture field, not only as a background field for the moisture analysis but also in the retrieval of temperature information from satellite channels that are affected by moisture.

So how good are the moisture fields in the ECMWF model? The moisture field depends on physical parametrizations which can have substantial uncertainties, but it also depends on the large-scale motion, particularly the vertical motion. Strong sensitivity of atmospheric moisture to parametrization has been demonstrated in earlier work with the ECMWF model by e.g. Tiedtke et al. (1988) and Gregory (1996) for sensitivity to shallow convection, Tiedtke (1993) for sensitivity to cloud parametrization, Jakob and Klein (1999) for sensitivity to microphysics, and by Beljaars and Viterbo (1998) for the impact of boundary layer top entrainment and air-sea transfer.

This paper does not provide a full review on all modelling aspects that affect moisture. Instead a few examples of verification will be presented to give some insight on the realism and quality of the ECMWF model.

2 Comparison to analysis, and evidence of spin-down in tropical precipitation

An obvious way of assessing the model is by looking at systematic errors as differences between forecasts and analyses. The monthly averaged difference for the month of April 2002 is shown in Fig. 1 for day 1, day 2 and day 5 forecasts. The main difference is in the tropics where the model is drier than analysed. This is associated with a spin-down of precipitation in the tropics (Fig. 2) and a spin-down of the Hadley circulation as can bee seen from the systematic difference in vertical velocity (ω) between forecasts and analysis (Fig. 3). Because of the additional latent heat release in the tropics during the first 12 hours of the forecasts, the Hadley circulation is stronger in the analysis than in the forecasts. It is important to note that the differences in relative humidity (Fig 1) between forecasts and analysis are up to about 5%, which is fairly small. At this stage it is difficult to say whether the model or the analysis is biased, because most current observing systems do not have an absolute calibration within 5%. In spite of the small imbalance in moisture between model and forecasts, the spin-down is damaging to the analysis as it maintains a too active hydrological cycle during the data assimilation.

3 Boundary-layer moisture over the oceans

Boundary-layer moisture is an important aspect of the model for two reasons: Firstly, together with surface wind speed it controls the surface evaporation, secondly, boundary-layer moisture is the dominant contribution to vertically integrated (total-column) water vapour (TCWV). The latter aspect is important in the context of microwave satellite observations, which provide good estimates of TCWV. An example is given in Fig. 4 where the model first guess (top) is compared to 1D-Var retrievals (Phallipou (1996)) and to a model-independent retrieval using the algorithm of Alishouse *et al.* (1990). The patterns in the three panels are remarkably similar suggesting that the observations have a high degree of realism and that the physics and the dynamics of the model do a reasonable job. However, there is again a small systematic difference between the observations and the model. The difference is about $0.5 kg/m^2$ in the global average, corresponding to about 2% of the global mean of $27 kg/m^2$. Such a mismatch is small and may be due to a model bias or due to a bias in the observing and retrieval systems.

Boundary-layer moisture is an indirect indicator for the activity of processes at the top of the boundary layer. If we think of the marine boundary layer as a reasonably well-mixed reservoir with fluxes from the surface and fluxes at the top, then the mixed-layer equilibrium value of specific humidity is determined by both processes. Since air-sea transfer is fairly well known, errors in boundary-layer specific humidity are most likely associated with errors in inversion interaction (e.g. through shallow convection). Field campaigns provide a valuable source of data to verify boundary-layer moisture. Often these observations are not used in the data assimilation, so they are particularly valuable for model validation. An example is the IMET ocean buoy system operated by the Woods Hole Oceanographic Institute (Weller and Anderson (1996)). In Figs. 5 and 6, the saturation specific humidity at the sea surface minus the observed specific humidity at 3.2 m height is compared with short-range forecasts of the ECMWF model. One of the so-called PACS buoys is located in the Pacific at $3^o S 125^o W$; the IMET-Stratus buoy is located in a nearly permanent stratocumulus area at $20^o S 85^o W$. Fig. 5 displays a time series over 17 months with 6-hour intervals. In general the correspondence is quite good, with the model being slightly too dry (i.e. the difference with the ocean surface being too large). This is more pronounced during the last five months when the sea-surface temperature drops gradually and the humidity difference with the ocean drops because warm moist air is advected over the relatively narrow cold tongue in sea-surface temperature that develops near the PACS buoy. The reason for these larger discrepancies in stably stratified situations over the ocean are not known. Comparison of the wind speed and surface fluxes (not shown) indicates very good agreement. This suggests that convection parametrization provides a realistic level of boundary-layer ventilation — otherwise bigger errors would be seen in near-surface moisture.

Also the time series (Fig. 6) for 17 days of hourly data from the IMET-Stratus location shows very good agreement between model and observations. It can again be concluded that the entrainment at the top of the cloudy boundary layer must be reasonable — otherwise near-surface moisture would be more biased.

The boundary-layer specific humidity is of course only one aspect of TCWV. The second major factor controlling TCWV is the boundary-layer depth. During the EPIC experiment, radiosondes were launched from a ship near the IMET-Stratus buoy. A comparison of averaged sondes and model profiles is shown in Fig. 7. The most noticeable characteristic of these profiles is the sharp inversion which is the result of a subtle balance between large-scale subsiding motion and turbulent entrainment at the top of the cloud layer in the inversion. The model inversion is less sharp than the observed one and the model boundary-layer is lower than observed. This has consequences for TCWV because in this situation, TCWV is to a good approximation equal to the boundary-layer depth multiplied by the boundary-layer specific humidity. So relative errors in both parameters cause the same relative error in TCWV. Still the inversion structure is remarkably well captured, which implies that the model manages to maintain a reasonable balance between vertical advection and entrainment processes

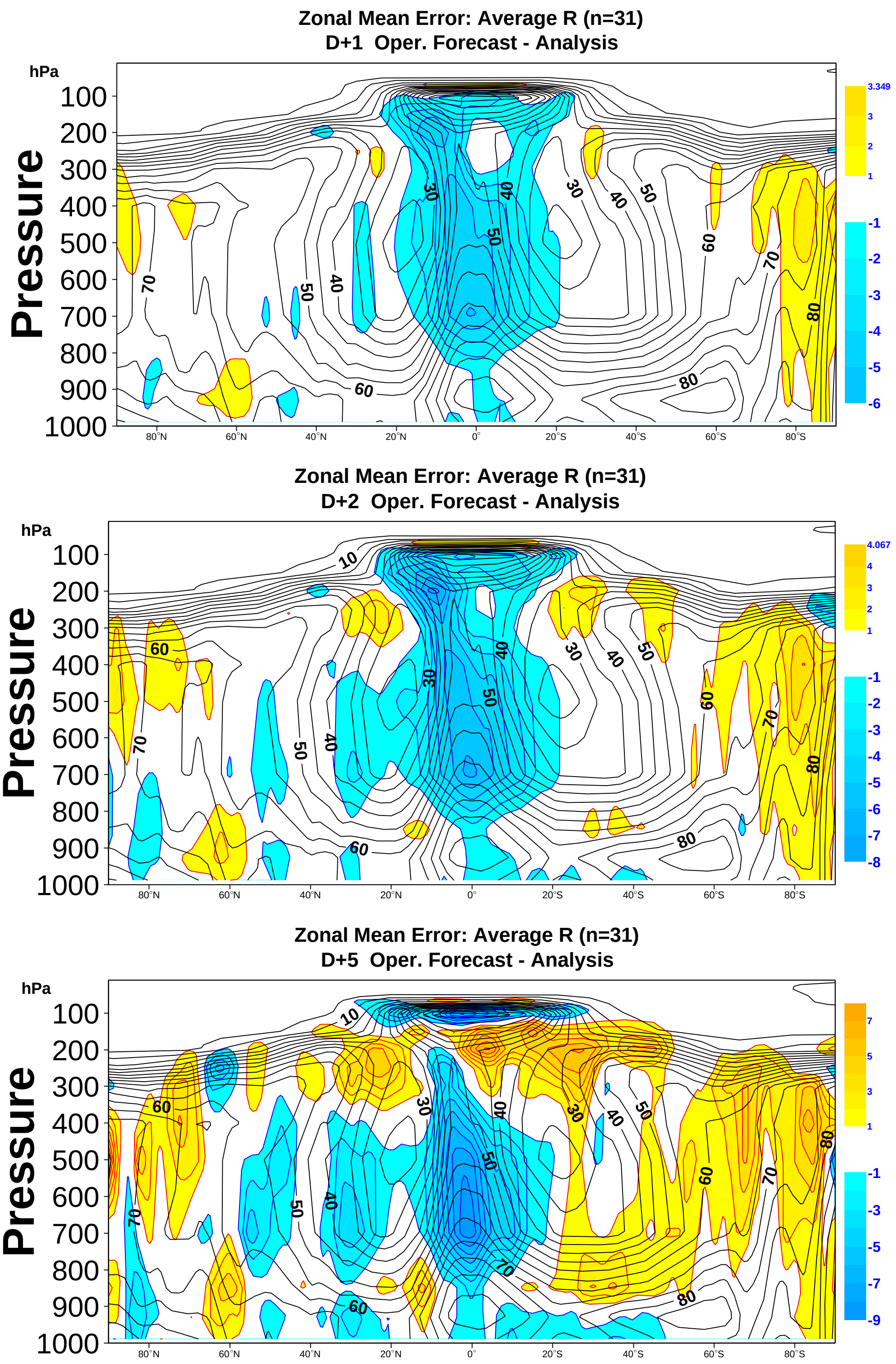

Figure 1: Colour coded differences in relative humidity (%) between day 1 (top), day 2 (middle) and day 5 (bottom) forecasts and verifying analyses averaged over the month of April 2002 from the operational system. The averaged relative humidity (%) from the analysis is represented as a background field in black contours (contour interval 5%).

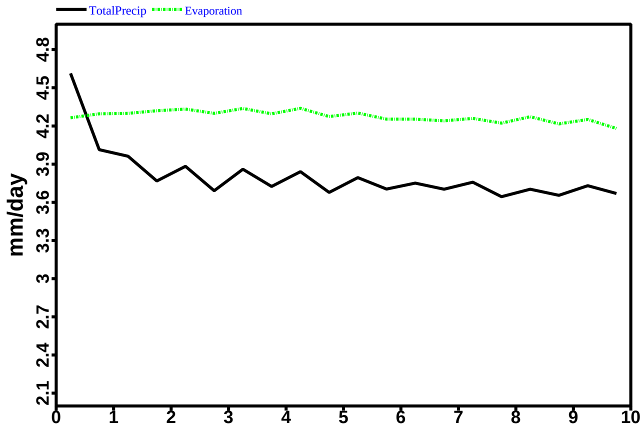

Figure 2: Evolution of precipitation (black line) and evaPoration (green) in the tropical band between 30^oN and 30^oS during the 10-day forecasts from the operational system, averaged over the month of April 2002, in mm/day.

despite the limited vertical resolution, the long integration time steps and shortcomings of the parametrization.

4 Boundary-layer moisture over land, and the influence of the land surface

Boundary-layer moisture over land is very much affected by land surface processes through evaporation from the surface. This sensitivity has frequently been evident during work on the land surface scheme see e.g. Viterbo and Beljaars (1995) and Van den Hurk et al. (2000)). Summer precipitation over land is strongly influenced by land evaporation, which involves a positive feedback: high precipitation leads to more soil moisture, which enhances evaporation feeding back into high precipitation (Beljaars et al. (1996)). To control this positive feedback it is necessary to have a good soil moisture data assimilation scheme. Significant work has been done in the past (Viterbo and Courtier (1995) and Douville et al. (2000)) to optimize the use of SYNOP observations. Currently the EU-funded ELDAS project is underway to improve further the use of SYNOP data and to accommodate other data sources: radiation, precipitation, surface skin temperatures from satellites and future microwave data.

An area where the contrast between dry and moist is probably more pronounced than anywhere else is at the edge of the ITCZ over Africa. Over a distance of a few hundred kilometres boundary-layer moisture varies dramatically due to changing soil moisture conditions. From operational verification it is known that the ECMWF model has the northern edge of the ITCZ over West Africa displaced slightly too far south. Also the cirrus outflow tends to be underestimated. To illustrate the sharp gradient in boundary-layer moisture a time series of 2m specific humidity is shown for 4 latitude bands over Ghana (Fig. 8). The choice of time and place is inspired by the availability of heat flux observations near Tamale (Ghana) during December 2001. Figure 9 shows a comparison of observed heat fluxes with 12-36 hour forecasts in 3-hourly intervals. The good correspondance suggests that the partitioning of sensible and latent heat fluxes is reasonable, which implies that soil moisture also must be realistic. The north-south gradient in specific humidity is remarkable, both in model and observations. At the most southern band, the model is too dry, which is consistent with a slightly too southerly positioning of the rain in the model. In the middle two bands (at the transition from dry to wet), the station to station variability is very large. However, it was found that the gridpoint to gridpoint variability in the model is not significantly higher there than it is in the most northerly or most southerly area. The reason for the variability in the observations is most likely the patchiness of the rain, which is not faithfully reproduced by the model. This illustrates some of the difficulties and challenges posed by modelling and assimilation of atmospheric moisture and soil moisture. Globally uniform structure functions will certainly not apply in areas with such strong gradients in mean and variability.

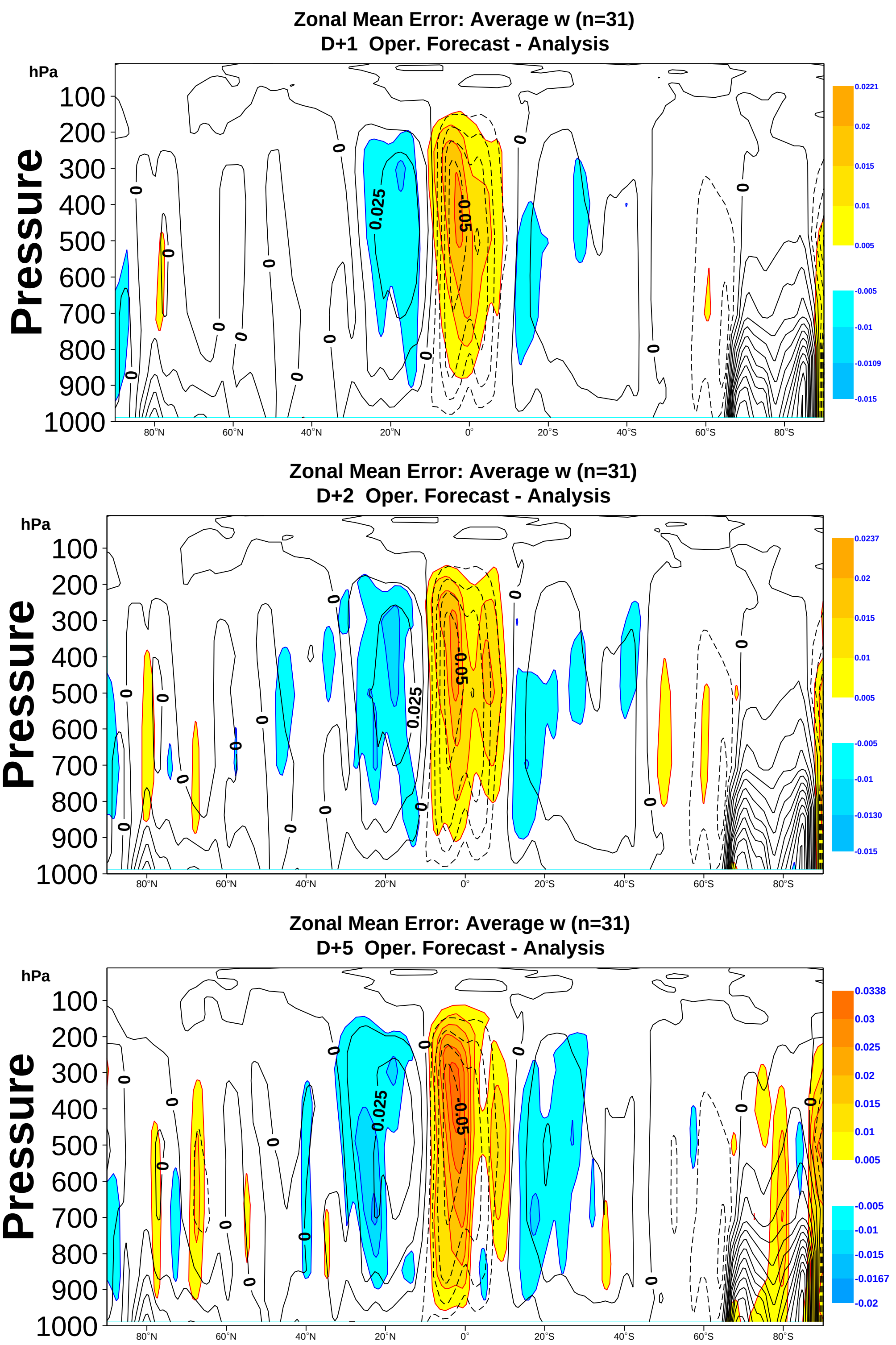

Figure 3: Colour coded differences in vertical velocity (Pa/s) between day 1 (top), day 2 (middle) and day 5 (bottom) forecasts and the verifying analyses averaged over the month of April 2002 from the operational system. The averaged analysis is plotted as a background field (contour interval 0.025 Pa/s). The shading of the difference starts at $\pm 0.005\,Pa/s$ with a contour interval of $0.005\,Pa/s$.

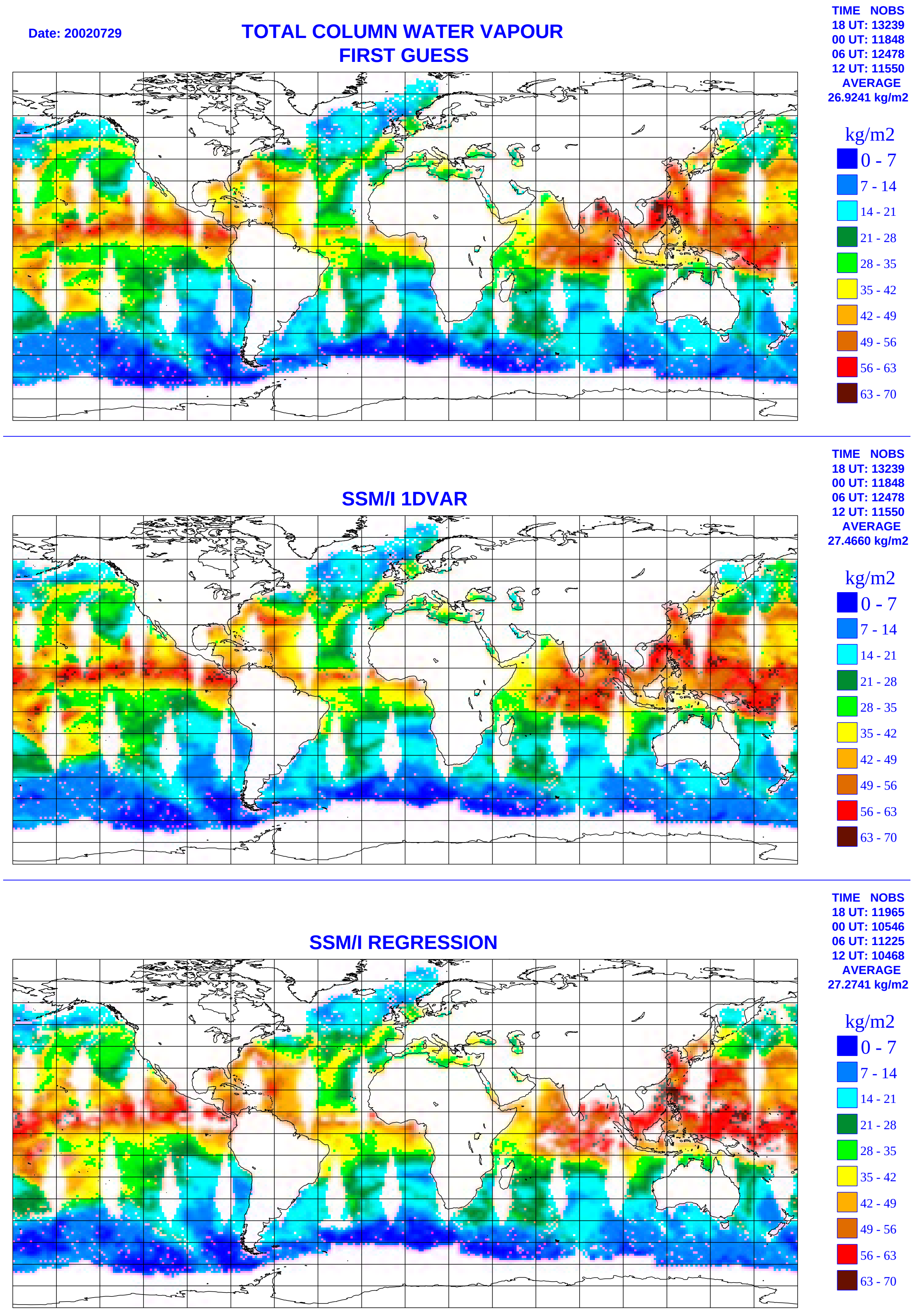

Figure 4: Total-column water-vapour (kg/m^2, see legend) from the model first guess (top), the 1D-Var retrieval (Phallipou (1996), middle), and a model-independent retrieval algorithm (Alishouse *et al.* (1990), bottom) for 29 July 2002.

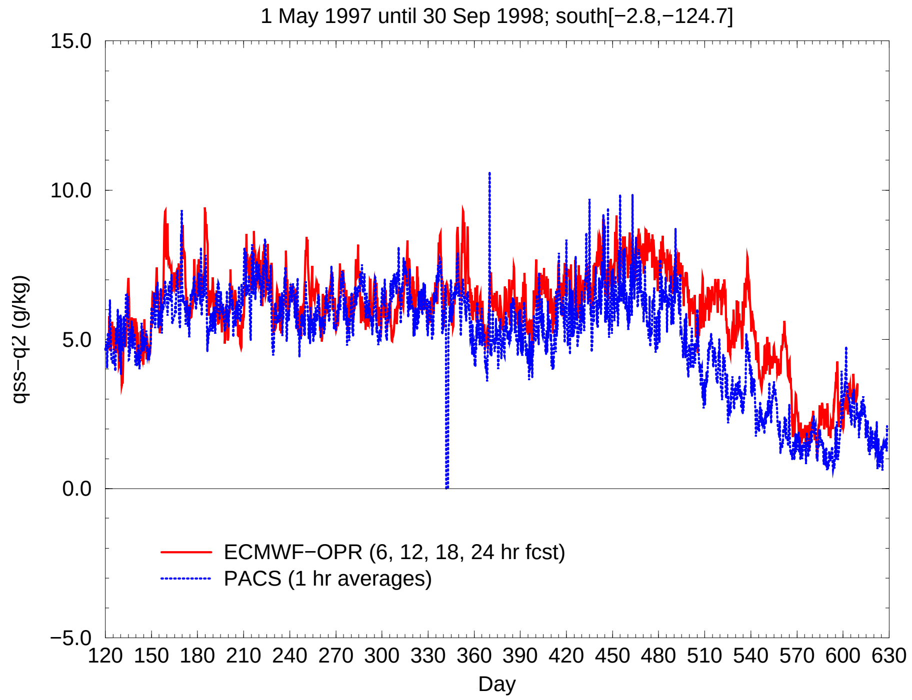

Figure 5: Time series over 18 months with 6-hour intervals of specific-humidity difference between the ocean surface and the 3.2 m level for the PACS buoy location $3^oS\,125^oW$. The model curve (red) is from daily forecast steps 6, 12, 18 and 24 hours. The buoy data (shown in blue) was kindly provided by the Woods Hole Oceanographic Institute.

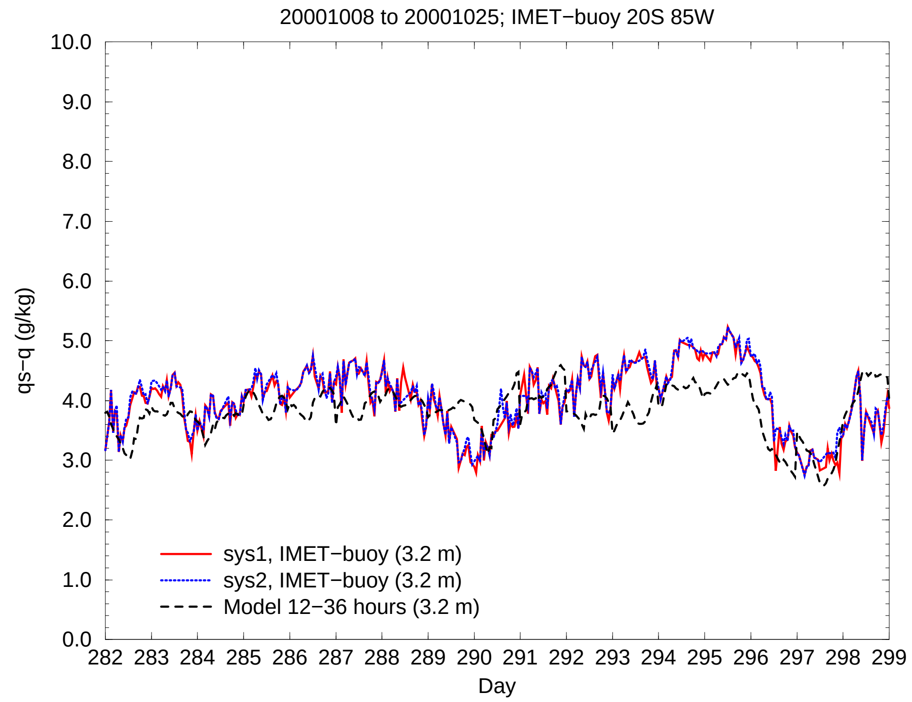

Figure 6: Time series over 17 days with one-hour intervals of specific humidity difference between the ocean surface and the 3.2 m level for the Stratus location $20^oS\,85^oW$. Two observing systems are shown (blue and red lines), giving virtually identical results. The model curve (black dashed line) is from daily forecast steps 12 to 36 hours. The buoy data was kindly provided by the Woods Hole Oceanographic Institute.

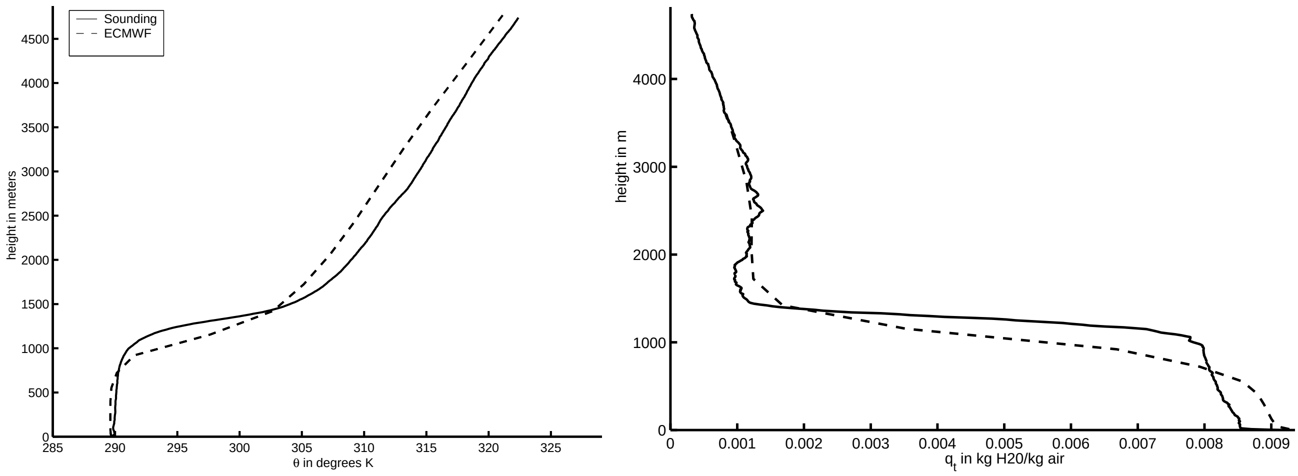

Figure 7: Average of radiosonde observations (full lines) during 6 days of potential temperature and specific humidity at the Stratus location $20^oS\,85^oW$. The corresponding averages of short-range forecasts (dashed) are also shown. The figure was kindly provided by Chris Bretherton, University of Washington.

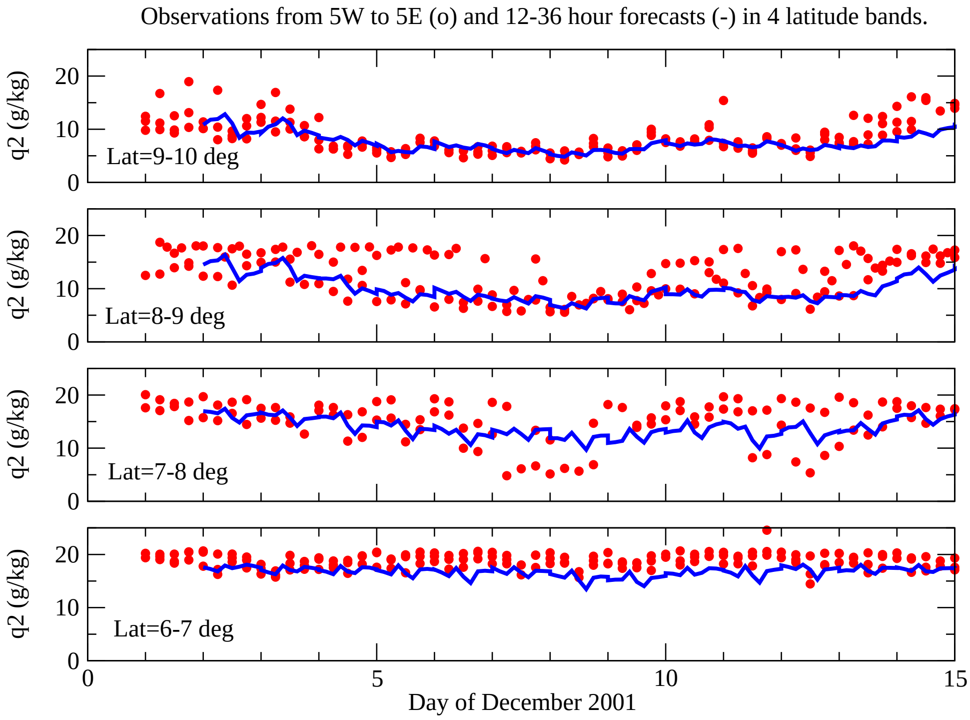

Figure 8: Time series for 2 weeks in December 2001 of 2m specific humidity in 4 latitude bands of 1^o averaged from 5^oW to 5^oE. All the SYNOP stations in these bands are represented by the individual dots. The solid line represents the model averaged over the appropriate latitude band (12 – 36 hour daily forecast have been used with 3 hour intervals).

5 Comparison to radiosondes over the western Pacific

The ARM programme maintains a few locations with very advanced high-quality observations. ECMWF collaboration with the ARM programme has already given interesting results. Christian Jakob (ARM fellow at BMRC, Australia), has compared output of the ECMWF model column for Manus ($147.4^oE\,2.1^oS$), and Nauru ($166.9^oE\,0.5^oS$) in the Western Pacific with radiosonde observations. The profiles are averaged according to precipitation classes as seen in the model during the one-hour period before the observation. The four panels

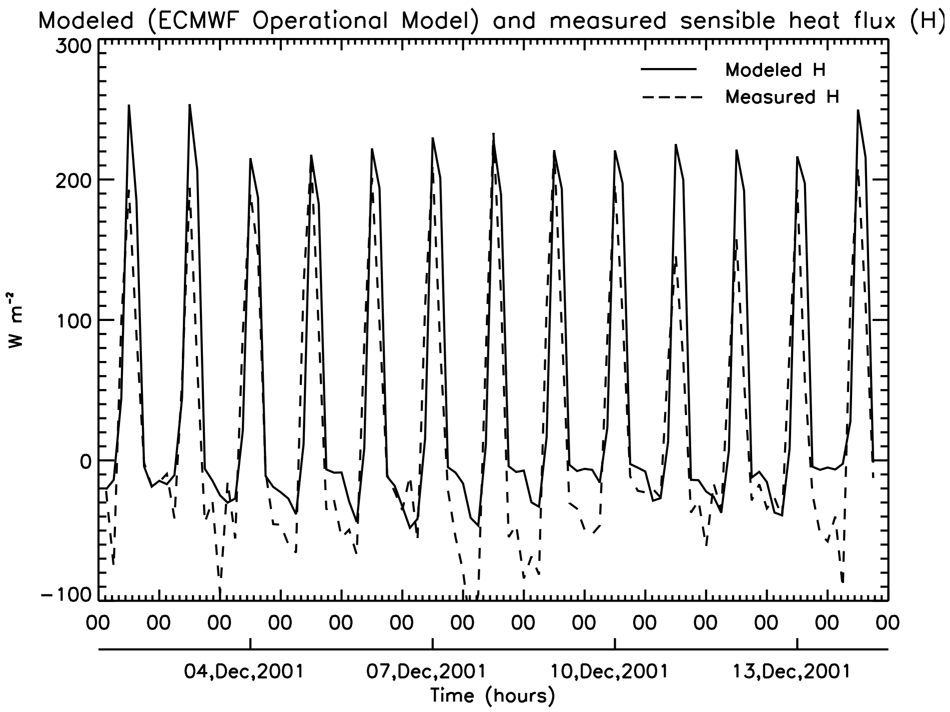

Figure 9: Time series for 2 weeks in December 2001 of observed surface heat flux (dashed) and modelled flux (solid) at Tamale (Ghana, $0.7^o W\, 9.4^o N$). The model data is from 12 – 36 hour forecasts of the operational ECMWF model. This figure was kindly provided by Dirk Burose, University of Wageningen.

in Fig. 10 show observed moisture profiles, modelled moisture profiles, and their differences all stratified according to precipitation rate. The 4th panel shows the precipitation frequencies in the different classes. A few conclusions can be drawn:

- The model rains too frequently. Although one has to be careful comparing a grid-average to a single point (as is well known from precipitation verification studies, Cherubini *et al.* (2001)), the difference is so large that the signal might be real - especially as the model is overestimating even the frequency of the larger precipitation amounts. The problem is larger at Nauru (the drier site in reality) than at Manus.
- The model shows a much smoother transition in RH from not rainy to rainy cases than the data. This is less obvious at Nauru, but here the sample size in the observations (see blue bars) for rain events is very small. At Manus, where the sample is bigger, there only seems to be a difference between rain and no-rain cases in the data. The model, however, shows substantial variation in humidity dependent on the amount of rain.
- Boundary-layer moisture in the model seems to respond too much to rain. This may be related to the convection parametrization, but also to the efficiency of evaporation. Experience with the parametrization of precipitation fraction (Jakob and Klein (1999)) shows that boundary-layer moisture is sensitive to the evaporation of precipitation and to the fractional area over which this process occurs.
- Overall the model seems to be too dry (except in the boundary layer), which might be consistent with too much rain. In the classic Kuo convection scheme, the key parameter was how much of the moisture convergence would go into rain and how much into moistening the atmosphere. The more advanced mass flux parametrizations provide this implicitly through microphysics and the detrainment terms.

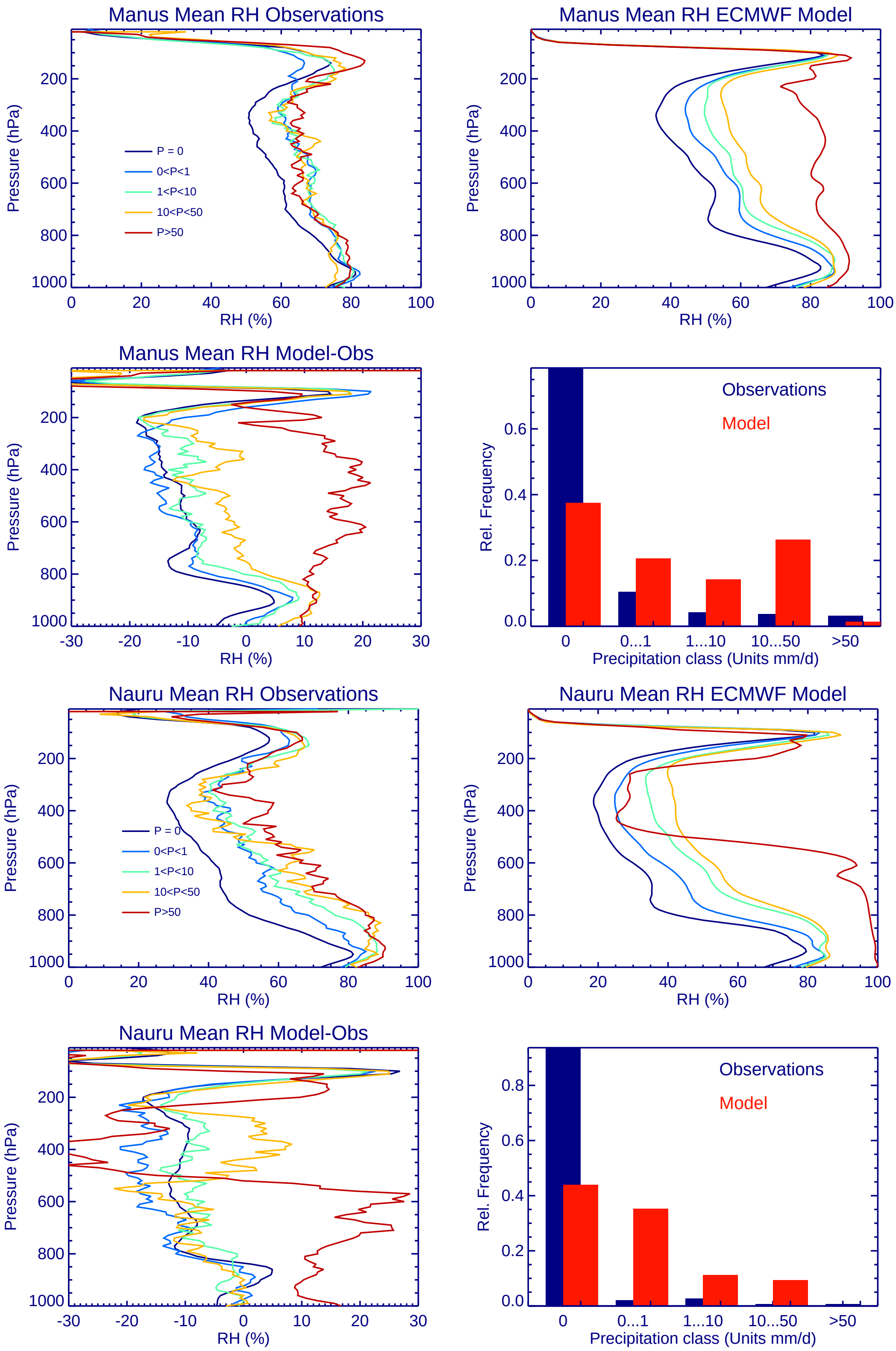

Figure 10: Radiosonde versus model comparison covering two years with averaging according to precipitation rate classes from the model during 1 hour before the observation. The top 4 panels are for Manus (147.4^oE 2.1^oS), the bottom panels for Nauru (166.9^oE 0.5^oS). The 4 panels show observed relative humidity, modeled relative humidity, difference in relative humidity between model and observation and precipitation frequency. The precipitation classes are: 0, 0-1, 1-10, 10-50 and $>$ 50 mm/day. This figure was kindly provided by Christian Jakob, BMRC, Melbourne.

6 Concluding remarks

In this paper a few examples have been shown of the capability of the ECMWF model to represent atmospheric moisture. Operational analyses and different observing systems have been used as reference. The general feeling is that the model uncertainty in moisture is of the same order as the uncertainty in the observations. The tropical spin-down during the first 12 hours of the forecasts represents a mismatch between analysis of moisture and the model climate, but the imbalance is within the absolute calibration accuracy of current moisture observing systems. Therefore, the spin-down can presently be reduced only by 'empirical bias correction'. Research quality data from field campaigns has already demonstrated its value for model improvement, and will become increasingly important in optimizing models and analysis systems.

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