Biases in the ECMWF model

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1. Introduction

A basic assumption in many data assimilation systems is that the underlying model is bias free. However, models have systematic errors and it is not always clear how damaging this is in data assimilation. Model development is oriented towards reduction of such errors, but will never lead to a perfect model (see Jung and Tompkins, 2003 for a comprehensive review of the evolution of systematic errors in the ECMWF system). In this paper, systematic errors in the ECMWF model are discussed for the short range. Temperature and moisture are discussed by comparing with the analysis, but also by comparing with radio sonde data. It is important to have a well calibrated reference for errors, because there is a risk that the analysis is contaminated by systematic model errors that propagate through the first guess. Moisture errors are also relevant in the context of spin-up[1], which is an imbalance between the model equilibrium and the observations of moisture. Systematic moisture increments go along with spin-up of precipitation during the first stages of the forecasts. Through anomalous latent heat release during the first guess/analysis cycling, spin-up may also be damaging for the analysis of tropical winds.

Another aspect of systematic errors is the surface boundary condition. Surface temperature is an important boundary condition and is also important as a background for the use of satellite channels that are sensitive to the lower troposphere and the surface. The quality of the land surface temperature in the ECMWF model will be discussed. The latter relies heavily on the parametrizations in the land surface model. Over the ocean the sea surface temperature is assumed to be constant during the forecast. The SST analysis which is adopted from NCEP is fairly accurate, but lacks a diurnal cycle. A simple model will be presented to model the diurnal cycle, which is of particular importance in low wind speed areas over the ocean.

2. Temperature

Figure 1 shows the zonal mean temperature field (contours) and the day-1, day-2 and day-5 differences of the forecast and the analysis (shaded), averaged over the month of August 2005. The differences are fairly small in the troposphere and grow to a little over 1 K in the stratosphere. These errors are rather robust and are qualitatively consistent with radio sonde statistics of the 12-hour forecasts (Fig. 2). The comparison with radio sondes indicates that the sondes are 0.5 to 1K warmer than the 12-hour forecasts in the lower stratosphere (100 to 10 hPa). This is unlikely to be due to errors in sonde observations because the best quality observations have been selected and the effect of solar elevation on the observation is negligible for

[1] The word spin-up is used for upward and downward changes. Precipitation spin-up in the ECMWF model is mostly a decrease of precipitation with forecast time.

this sonde type. The most likely reason for the discrepancy is a model bias. Even the analysis is probably contaminated by the model bias because the day-1 minus analysis differences are smaller than the 12-hour forecast errors with respect to sondes.

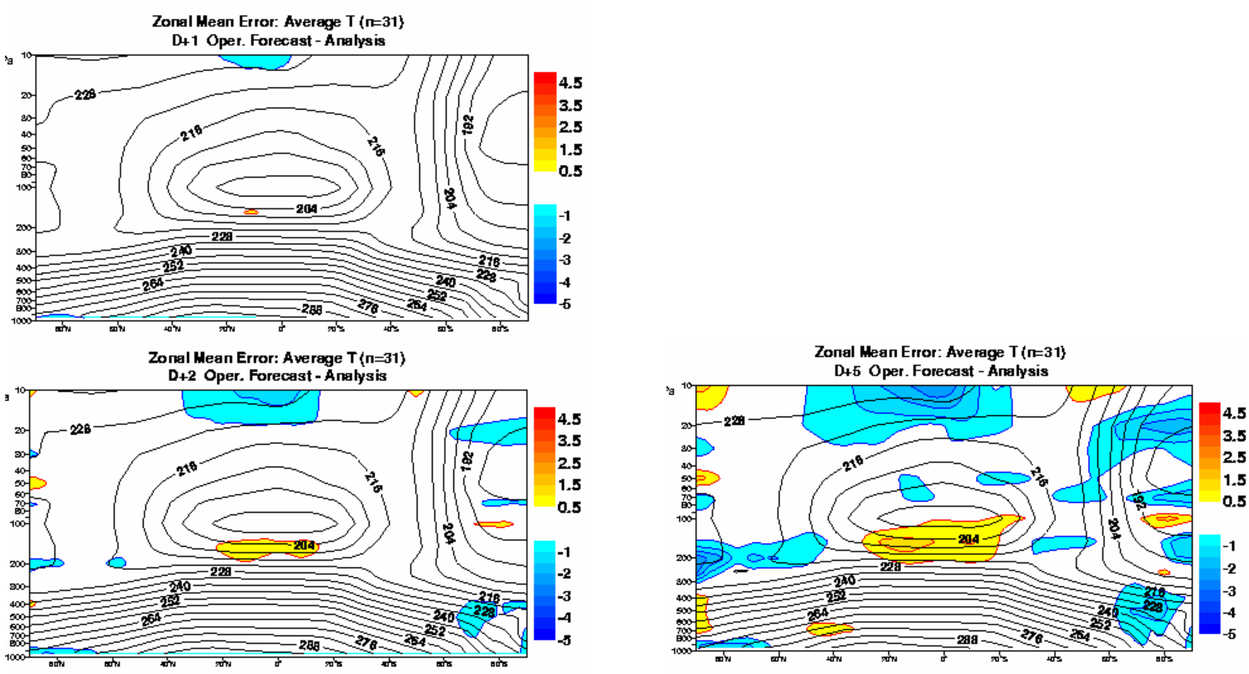


Figure 1 Zonal mean analyzed temperature (contours) and difference between day-1, day-2 and day-5 forecasts and the analysis (shading) averaged over the month of August 2005.

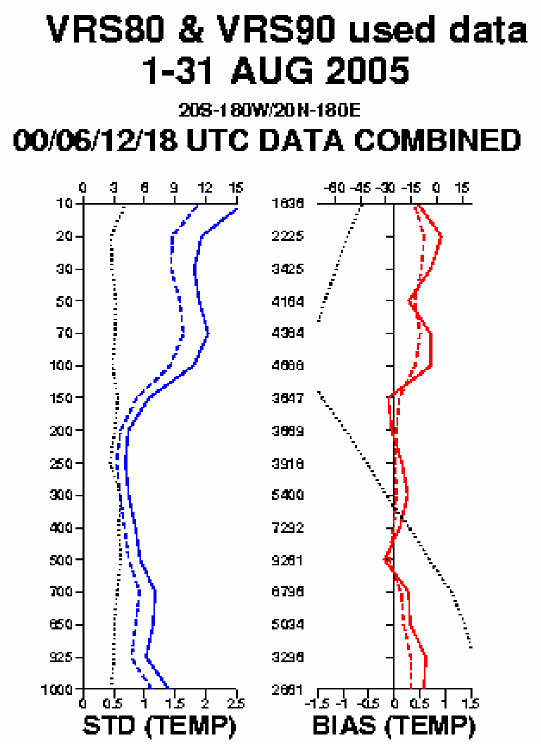


Figure 2 Sonde statistics (Obs-FG) for August 2005 in the latitude band of 20°N to 20°S. The left figure shows the RMS difference; the right hand figure shows the bias. Good quality sondes are used only; effects of solar radiation on the observation can be shown to be negligible.

The reason for the stratospheric bias in the tropics remains unclear. The active processes in this part of the atmosphere are: long wave cooling, short wave heating and dynamics (slow ascending motion, leading to cooling). The equilibrium temperature is the result of a balance between these processes. The tendencies due to long wave cooling and short wave heating increase from about 2K/day at 10 hPa to typically 10 K/day at 1 hPa. The residual of the radiative processes is small (about 1 to 2 K/day) and has to be balanced by the vertical motion. Jung and Tompkins (2003) suggest that the ascent may be too strong during the data assimilation cycling leading to a stratospheric cold bias. Such a too strong Brewer-Dobson circulation would be consistent with the ERA-40 result that the age of the stratospheric air is too young (Uppala et al. 2005).

3. Atmospheric moisture

Monthly zonal mean relative humidity differences between day-1, day-2 and day-5 forecasts and the verifying analyses are shown in Fig. 3. The differences are generally small in the zonal means (the contour interval of the colour shading is only 1%). The main features are a too moist upper tropospheric outflow from the ITCZ, a too dry mid troposphere in the Northern Hemisphere, and a too moist atmosphere over Antarctica compared to the analysis. However these differences are small and it is questionable whether the analysis can be used as an absolute reference. Even the best modern radio sondes are not absolutely calibrated within 5%, so it is difficult to draw firm conclusions.

Relative humidity is strongly influenced by vertical motion, and also the evolution of relative humidity during the first days of the forecast can be interpreted in terms of vertical motion. Figure 4 shows the zonal mean vertical motion and the difference of the day-1 / day-2 forecasts and the analysis. The figure indicates that the Hadley circulation is about 20% stronger in the analysis than in the day-1 and day-2 forecasts. This is believed to be associated with the spin-up of precipitation. Precipitation in the model decreases during the early hours of the forecast and is believed to maintain a too active hydrological cycle during the analysis/first guess cycling.

Maps of monthly mean day-1 to analysis differences of vertically integrated water vapour for August 2005 indicate a drift of less than 2% in most places (not shown). However, there is drift in the vertical moisture structure in some locations as indicated by Fig. 5. Examples are the Western Atlantic and the Caribbean and the Western Pacic where boundary layer moisture (925 hPa) increases during the first 24 hour of the forecast and humidity decreases above the boundary layer (700 hPa). These changes are significant and are supported by radio sonde observations (not shown). The indicated areas have considerable precipitation and also show significant spin-up in the sense that precipitation decreases during the first two days of the forecast (Fig. 6). The precipitation is associated with upward vertical motion and the decrease in precipitation is associated with a decrease in the strength of vertical motion (not shown).

It is not obvious to relate the errors in vertical moisture structure to a particular process. Three model components should be considered: (i) boundary layer diffusion including shallow convection, (ii) deep convection, and (iii) advection. In the areas indicated above with a moistening in the boundary layer and a drying in the mid-troposphere, the parametrized deep convection is the most likely candidate. However, the dynamics, especially the vertical motion should not be ignored, because vertical motion has a strong direct effect on humidity. Very little is known about the uncertainty in vertical motion because it is impossible to verify directly.

In general it can be concluded that the systematic errors in moisture are not very large in view of the measuring uncertainty.

4. Spin-up

In the previous section it was shown that precipitation spin-up is non-negligible and that it is associated with spin-up in moisture structure. This has been a persistent problem in the ECWMF operational system and also in ERA-40. Spin-up is the result of an imbalance between the analyzed state of the atmosphere and the atmospheric state that is favoured by the model. The moisture structure is the most important aspect in relation to precipitation spin-up. Precipitation spin-up is of course unrealistic, and can be damaging to the tropical winds because the anomalous heat release during the data assimilation / first guess cycling can drive erroneous winds.

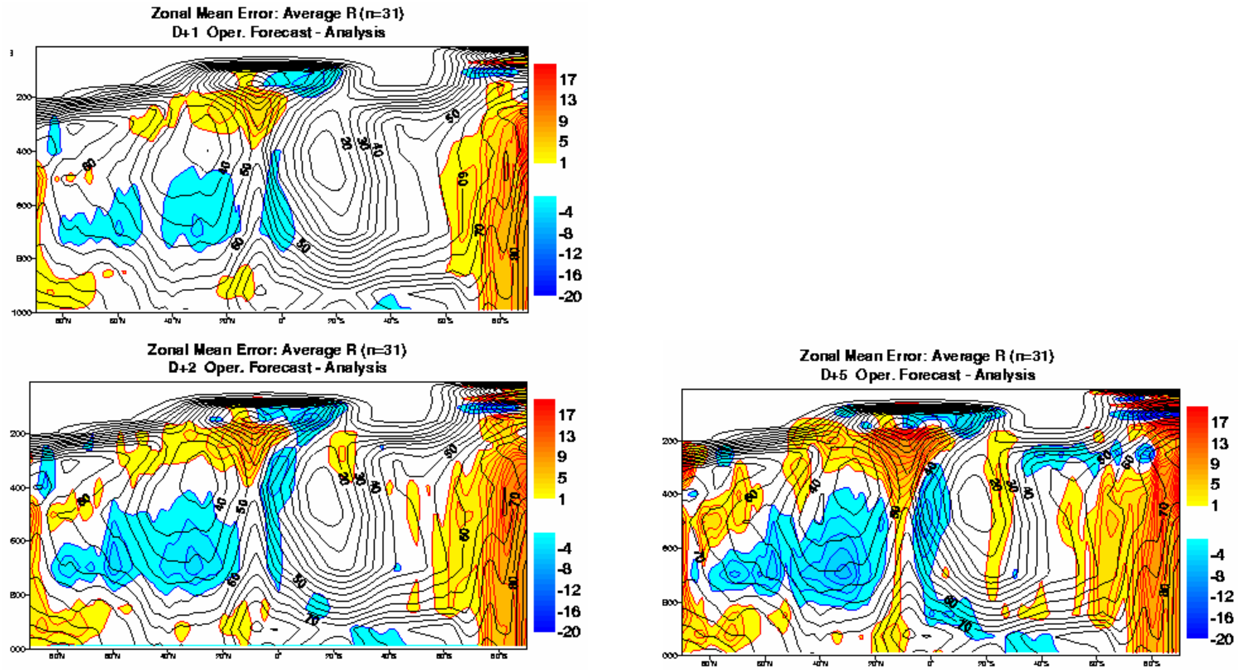


Figure 3 Zonal mean analyzed relative humidity RH in % (contours) and difference between day-1, day-2 and day-5 forecasts and the analysis (shading) averaged over the month of August 2005.

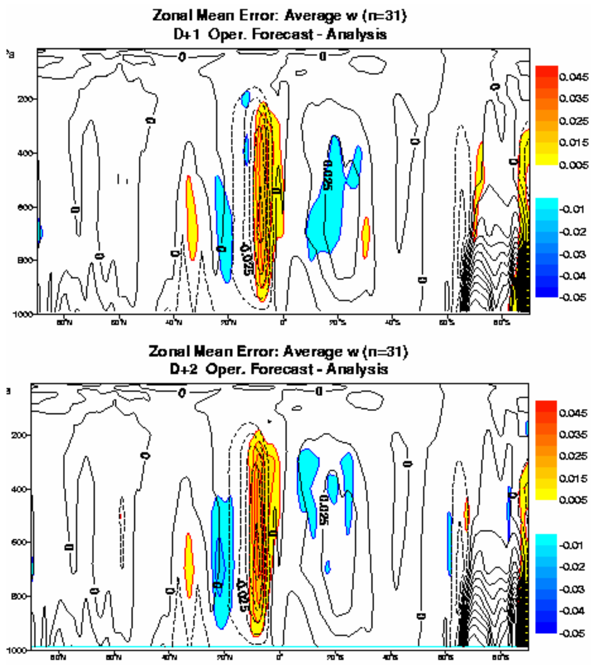


Figure 4 Zonal mean vertical velocity in the analysis in Pa/s (contours) and difference between day-1 and day-2 forecasts and the analysis (shading) averaged over the month of August 2005.

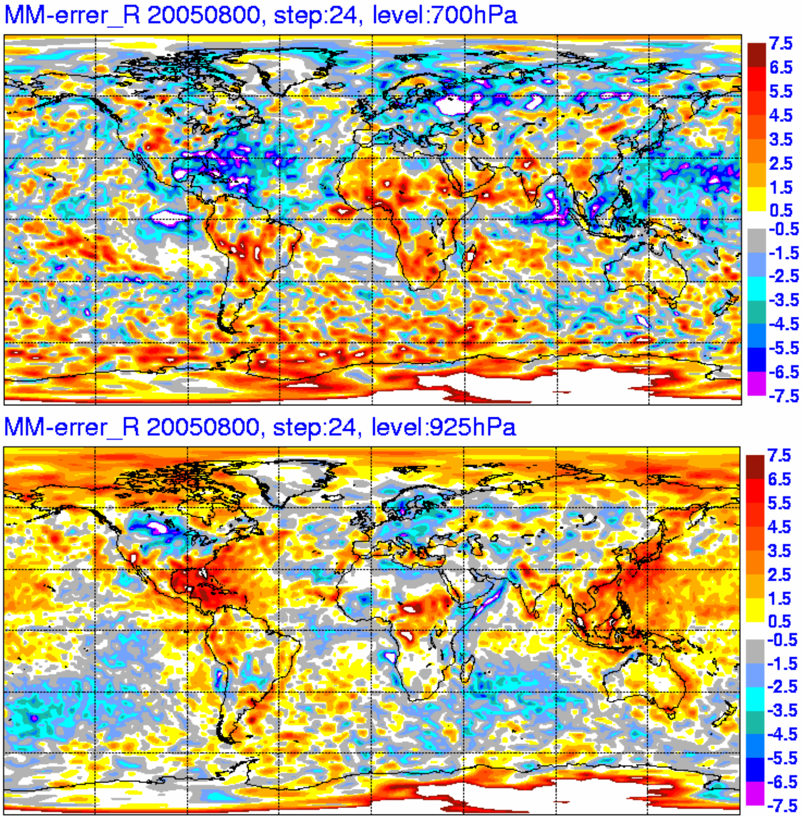


Figure 5 Monthly mean difference for August 2005 between relative humidity of the daily 24-hour forecasts and the verifying analysis for the 700 hPa level (top panel) and the 925 hPa level (bottom panel).

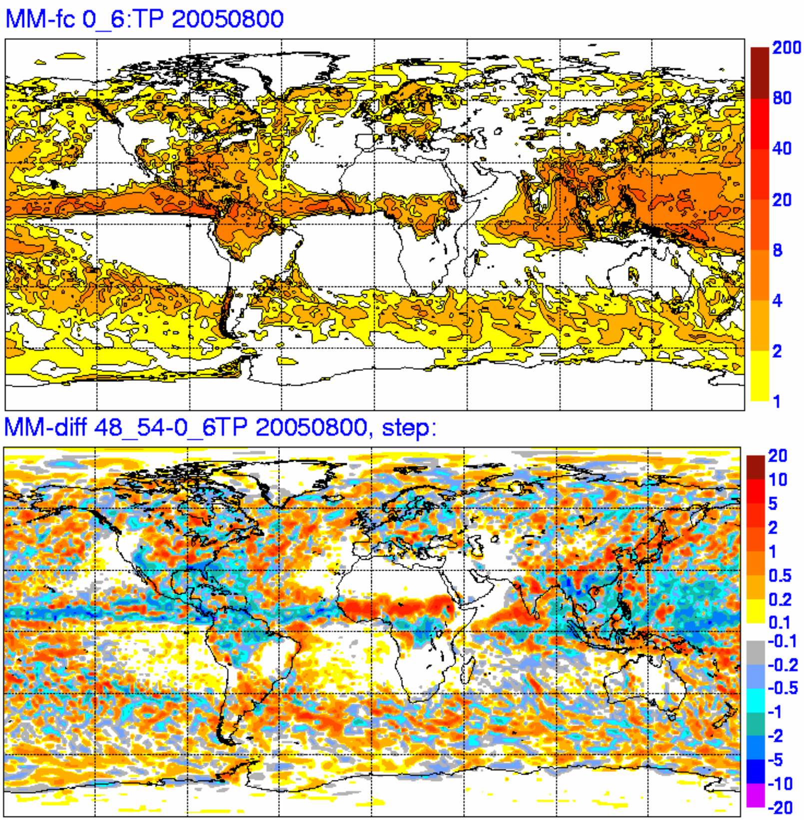


Figure 6 Total precipitation averaged over the daily 6-hour forecasts from 12 UTC (top panel) and the difference between the 48- to 54-hour forecasts and the 6-hour forecasts from 12 UTC (bottom panel).

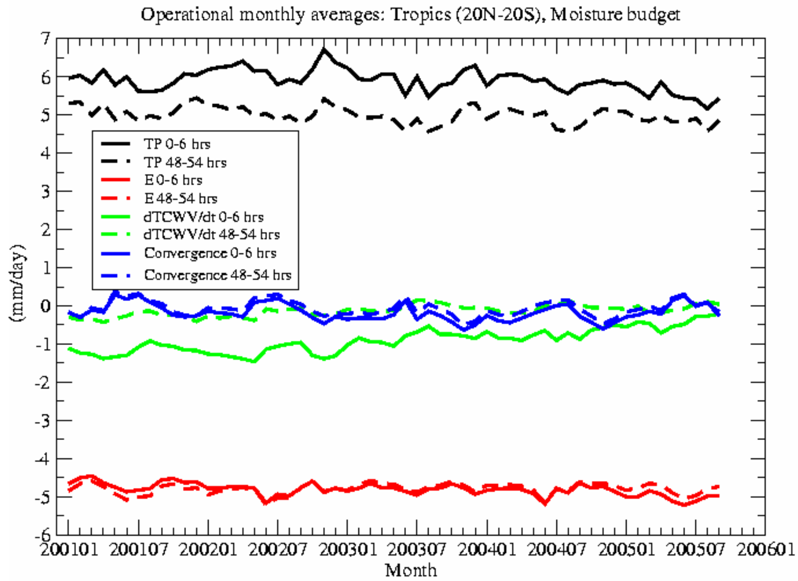


Figure 7 Various terms in the moisture budget equation for the tropical band of 20°N to 20°S from monthly averages of the operational 12 UTC forecasts in the 0- to 6-hour forecast range (solid) and the 48- to 54-hour range.

We now consider the evolution of spin-up in the operational ECMWF system from January 2001 to August 2005. Many model and data assimilation upgrades have been implemented and it is interesting to see which of these changes had impact on spin-up. The following budget equation for the vertically integrated moisture (TCWV) in the tropical band of 20^{o}N to 20^{o}S is considered:

$$\frac{dTCWW}{dt} = -P - E + Conv$$

with *P* for precipitation, *E* for evaporation and *Conv* for moisture convergence, all averaged over the latitude band from 20^{o}N to 20^{o}S. Downward fluxes of P and E are defined positive. Figure 7 shows the different terms in the budget as monthly averages from the 0- to 6-hour forecasts and from the 48- to 54-hour forecasts, daily initialized at 12 UTC. The difference of the terms from the 0 to 6 and the 48 to 54 forecasts is shown in Fig. 8. Precipitation shows clear signs of spin-up with the 48- to 54-hour precipitation 0.5 to 1 mm/day lower than the 0- to 6-hour forecasts. The maximum spin-up occurs around 2002 with notably less spin-up (although still non-negligible) in recent months. Precipitation spin-up is predominantly associated with a reduction of total column water vapour during the first 6 hours of the forecasts. In recent months, the total column water vapour drift is actually close to zero. Spin-up in evaporation is small but non-zero. It evolves from an increase of evaporation with forecast range (more negative) in 2001 to a decrease in 2005. The reason is that the analysis has become drier over time resulting in more ocean evaporation early in the forecasts. Moisture convergence turns out to be small for this latitude band and shows little sign of spin-up.

Figure 8 also shows the operational model changes with some of their main features, starting with CY23R4, which was used for ERA-40. It should be remembered however that ERA-40 used 3DVAR whereas the operational system uses 4DVAR, which may have implications for spin-up. The remarkable result is that the reduction of spin-up over time seems to be achieved by gradual small steps and not by a few distinct system changes. One would for instance expect that the introduction of the new moisture analysis (CY26R3) or the assimilation of rainy radiances (CY29R2) to have a clear impact. Also the introduction of major convection changes (more active parametrized convection) with CY28R1 was in principle a good candidate for impact on spin-up characteristics. However, none of these changes are clearly visible in Fig. 8. Perhaps one of the very few changes that shows a modest reduction in spin-up is the introduction of revised numerics in the time stepping of cloud and convection schemes with CY28R3. Not included in the list of model changes in

Fig. 8 are changes to the satellite data coverage and changes to the satellite bias corrections. Some data assimilation changes may also have had implications to the relative weight of first guess and observations. It is clear however, that over time a better balance has been achieved between model and observations.

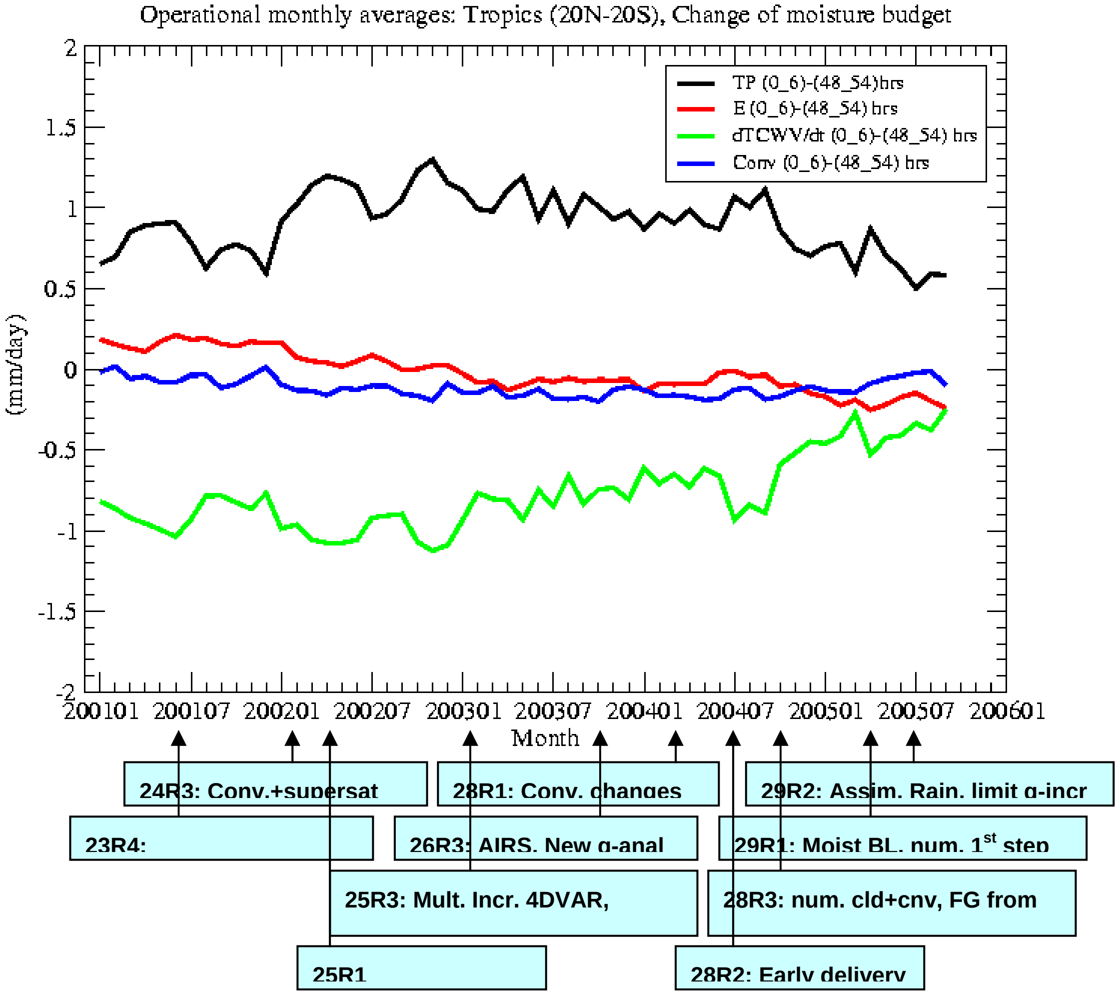
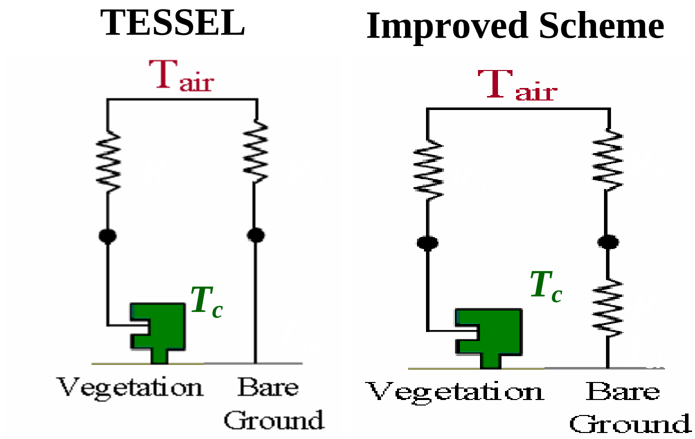


Figure 8 Difference between the 0- to 6-hour and the 48- to 54-hour forecasts of the various terms in the moisture budget equation (difference between solid and dashed curves of Fig. 7).

5. Land surface temperature

Satellite channels with sensitivity in the lower troposphere are not used over land because the emissivity and the temperature of the land surface are not well known. The radiative land surface temperature (called skin temperature in the ECMWF model) shows large errors as documented by Trigo and Viterbo (2003). Errors of mid-day skin temperatures over North Africa are diagnosed from the Meteosat window channel and can be as large as 10 K. The skin temperature is controlled by land surface parameters and surface fluxes (see Van den Hurk et al. 2000 for a description of the Tiled ECMWF Scheme for Surface Exchanges over Land, TESSEL). Over the Sahara, the latent heat fluxes can often be neglected, so the available net radiation at the surface is simply partitioned between ground heat flux and sensible heat flux. The ground heat flux is predominantly controlled by the skin temperature, the coupling of the skin layer with the soil and the soil properties. The skin temperature is mainly controlled by the aerodynamic coupling between the lowest model level and the surface. In the TESSEL scheme, this is determined by wind speed and the surface roughness lengths for momentum and heat. Vegetation and bare soil tiles are used as a simple way to represent sub-grid heterogeneity, and are coupled independently to the lowest model level (see Fig. 9). Trigo and Viterbo (personal communication) suggest to improve the skin temperature by introducing an additional friction velocity dependent (u_*) resistance for the bare soil tile as illustrated in Fig. 9. This works very well for the

Western Sahara as illustrated by the Meteosat verification in Fig. 10. However, it is well known that the aerodynamical coupling varies strongly from location to location dependent on land cover.



$$R_s = \frac{1}{a + bu_*^2}$$

Figure 9 Aerodynamic coupling between the lowest model level and the vegetation and bare soil surface tiles of TESSEL (left). The improved scheme has an additional resistance (right), which is represented in the formula with a dependence on friction velocity u and empirical coefficients a and b.*

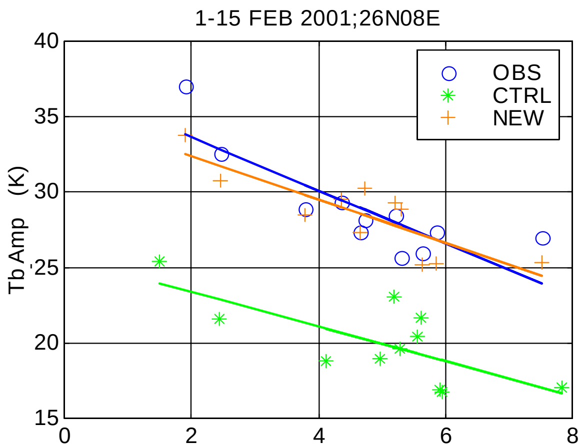


Figure 10 Midday brightness temperatures at the top of the atmosphere in the Meteosat window channel as a function of wind speed for an area around 26°N / 8°E. Observations are shown (o) together with short range forecasts with TESSEL (*) and the improved scheme (+). The model brightness temperatures are computed using the RTTOV radiation scheme.

The challenge is to find a formulation that works globally in all possible environmental conditions.

Another aspect of the surface temperature is the soil temperature profile, which is entirely determined by the land surface parametrization with small increments from SYNOP level data assimilation in cases of stable stratification. From a few countries in Europe, soil temperature observations are received on a routine basis. These are used for verification. Figure 11 shows a time series of the 6 UTC and 15 UTC observations averaged over all German stations together with co-located model output (short range forecasts) for two depths. The model follows the seasonal and synoptic variability very well. However, in summer a systematic bias exists with model temperatures too low by a few degrees. For the depth of 20 cm, the bias is 3 to 5 K. At a depth of 5 cm, the diurnal cycle is strong and the bias can be well above 5 K for day time in the warm spells. These biases are substantial and robust as they represent averages over many stations and a large area. The reason for the bias is not very clear. The thermal coupling of the atmosphere to the surface as part of the surface energy balance is likely to be a key player. It should be realized that these biases are embedded in a large diurnal cycle. The day to night difference of the skin temperature can easily reach 15 K.

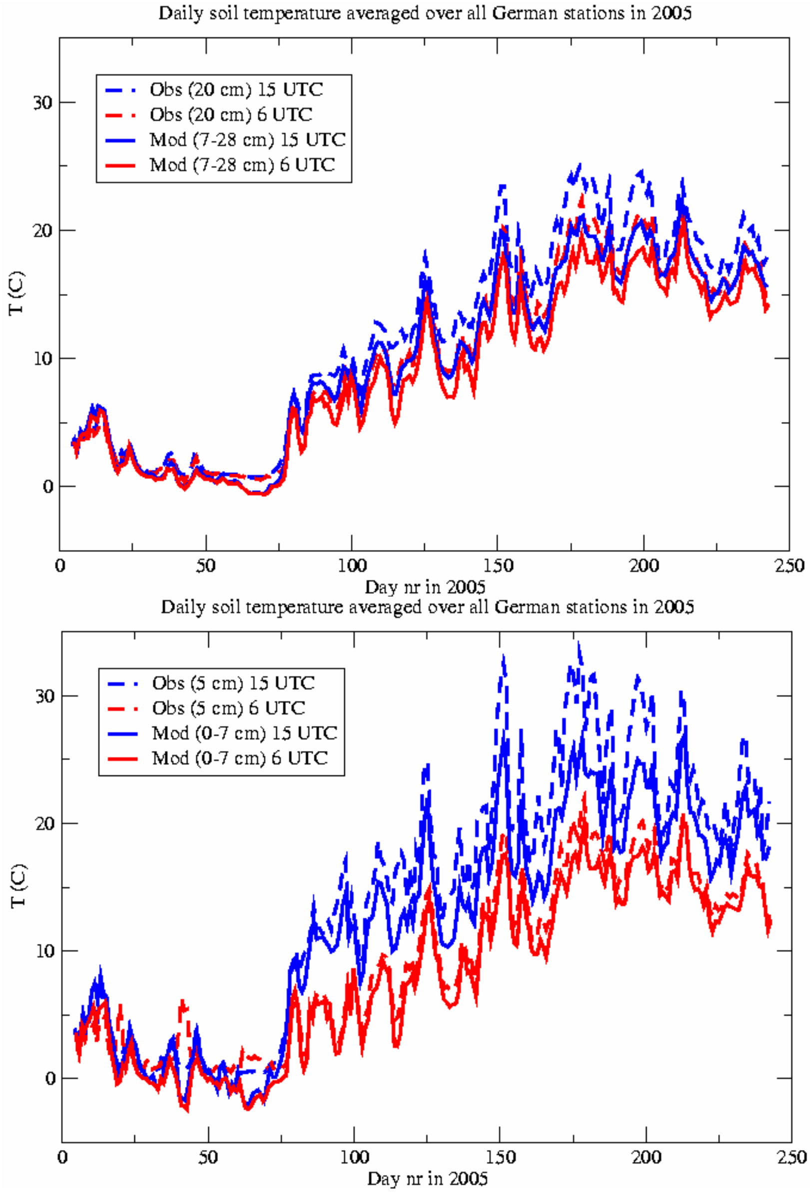


Figure 11 Soil temperatures observed (dashed) and modelled (solid) averaged over all stations in Germany for 6 UTC (red) and 15 UTC (blue) from January to August 2005. The upper panel shows the 20 cm deep observations and the lower panel the 5 cm deep observations.

6. Ocean skin temperature

In the ECMWF system the sea surface temperature is adopted from the daily NCEP analysis and kept constant during the forecast. This SST represents the ocean bulk temperature, typically 1 to 2 m deep. The bulk temperature is a sensible choice for an SST analysis, because it is more robust and persistent than the surface temperature and can be calibrated with ship and buoy observations. However, the ocean surface temperature can be different from the bulk temperature in particular in areas with low winds where the mixing between surface and bulk is weak (Fairall et al. 1996). The warm layer effect due to solar heating in the top metre of the ocean is probably the most important effect. The colour panel in Fig. 12 shows an example of ocean skin temperature difference between 12 and 20 UTC, derived from geostationary satellite observations (Wu et al. 1999) and averaged over 3 days (20-22 May 1998). The difference is typically 1 to 2 K in the low wind speed area. The panels (a) and (b) of Fig. 12 show the result of the simple warm layer model by Zeng and Beljaars (2005) and the wind speed respectively. The model has been used as part of the ECMWF system in a 96 hour forecast for this particular case. The result clearly indicates that it is possible to simulate the diurnal cycle as a perturbation with respect to the NCEP bulk SST. Although the impact of the warm layer on the ECMWF model climate is small (Beljaars 1997), the representation of the diurnal cycle may be relevant for the interpretation of satellite channels that are sensitive to the ocean surface temperature.

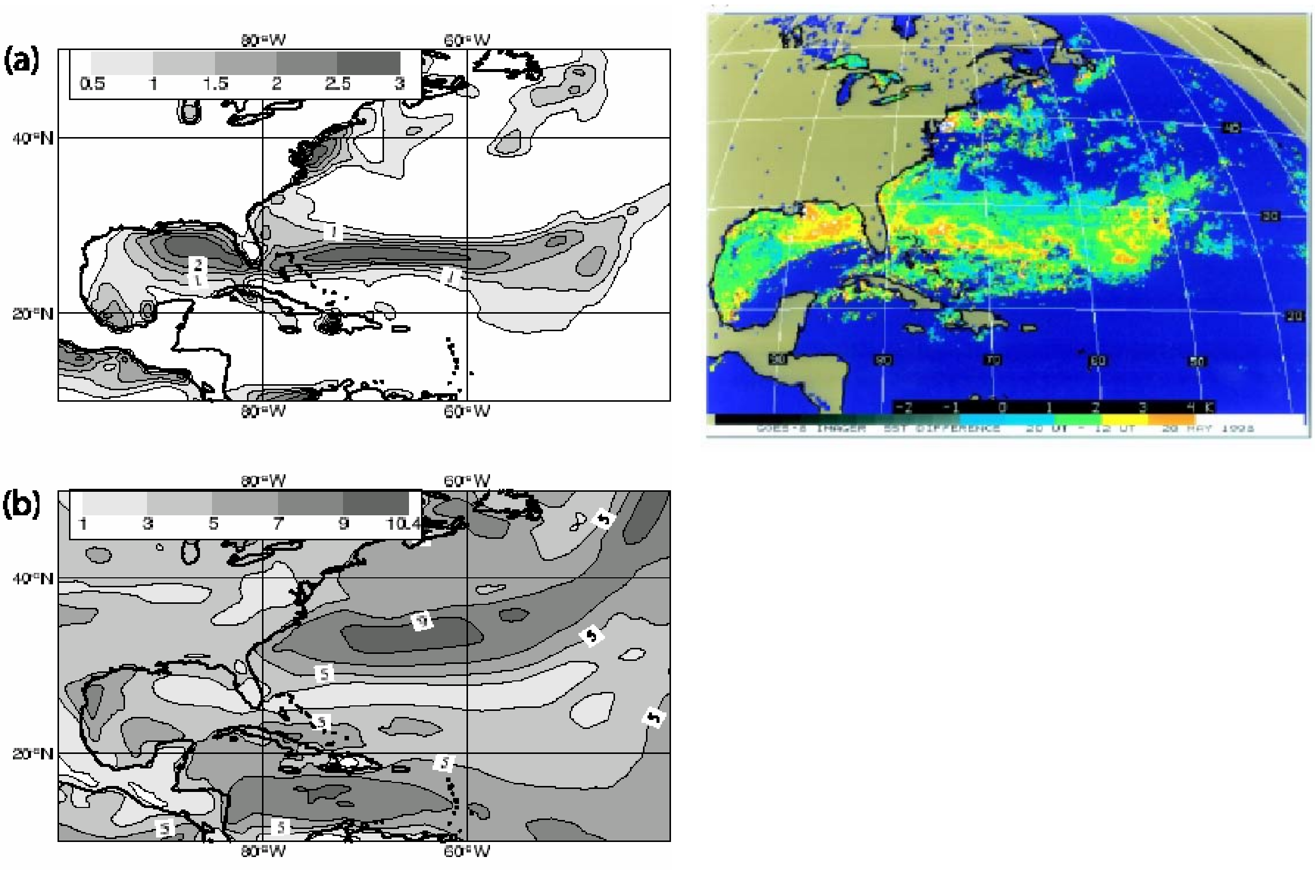


Figure 12 Ocean skin warm layer effects. Panel (a) shows the modelled ocean skin temperature difference between 12 and 20 UTC averaged over 3 days (20-22 May 1998) from a 96-hour model integration including the simple warm layer parametrization by Zeng and Beljaars (2005). Panel (b) shows the wind speed. The colour panel shows the observed difference from Wu et al. (1999).

7. Literature

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