Response of the Physical Aspects Section of the Research Department of ECMWF to the WCRP consultation on Model Evaluation and Improvement

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1 Introduction

This note has been prepared by the Physical Aspects Section of the Research Department at ECMWF. ECMWF is an operational centre for medium range weather forecasting, monthly forecasting, seasonal forecasting and ocean wave forecasting. The operational system is also used for re-analysis projects (ERA-15, ERA-40 and ERA-Interim). ECMWF operates a state of the art global atmospheric model with an integrated data assimilation system. For monthly and seasonal forecasting the atmospheric model is coupled to an ocean model. Resolution varies from T159 (110 km) for the seasonal system to T799 (25 km) for the 10-day deterministic forecasts. A resolution upgrade to T1279 (15 km) is currently under test and will become operational late 2009 or early 2010. Intermediate resolutions are used for monthly forecasting and for the ensemble prediction system. Given these application, ECMWF is interested in atmospheric processes like radiation, convection, clouds, precipitation, and turbulence, but it also includes all aspects of atmospheric dynamics, monsoons, troposphere-stratosphere exchange, ocean and land interactions, snow modelling, and sea-ice feedbacks. Through a recent European Project, ECMWF is getting increasingly involved in comprehensive earth system modelling. A prototype system has been developed for the modelling and assimilation of aerosols, greenhouse gases and reactive gases.

The Physical Aspects Section is responsible for the maintenance and further development of the package of parametrized processes in the ECMWF model covering a wide range of resolutions, applications and time ranges. It is therefore faced with the same questions as the ones asked in the WCRP-questionnaire. The basic question is: How to implement the best possible physics into a large scale model and obtain good results? This is by no means trivial, because good physics does not necessarily give good results in a full model because of compensating errors and poorly understood interactions. This issue is often referred to as the implementation bottle neck.

2 Approaches to model development

Although no general systematic procedures for parametrization development exist, two complementary approaches can be distinguished:

A Bottom-up. In this approach a process is studied with detailed observations and/or dedicated models (e.g. Large Eddy Simulation and Cloud Resolving Models, Line by Line Radiation Models, Limited Area Models that resolve fine scale orography) for specific cases. Then, a parametrization is developed in the context of a single column model applied to the same cases and finally, the results are applied to a full three dimensional model. This is the method followed by working groups like GCSS, GLASS and GABLS resulting in a comprehensive data base of cases that can be used. The big advantage of this approach is that detailed information is available about processes providing information on how the processes function.

B Top-Down. In this approach evaluation of model output inspires the choice of schemes or the optimization of a limited number of parameters. This approach relies heavily on the availability of verification material. Observations or analyzed observations play a big role and come in a broad variety, e.g. as NWP analysis data, satellite derived data like top of the atmosphere radiation, surface based observations like radiosondes and SYNOP's and merged products like precipitation. NWP centres are in a particularly good position to use observations, because they continuously confront short range forecasts with observations through the data assimilation system. The fact that short range forecast errors often have the same signature as errors in the model climate justifies the "seamless modelling approach" as a model development strategy. Short range forecasts also have the advantage that they can be verified in the deterministic range whereas climate simulations needs to be averaged over sufficiently long periods of time to have a representative climate.

Model development groups at NWP and climate modelling centres combine the bottom-up and top-down approaches, which often leads to conflicts. New ideas that look good on the process level do not necessarily perform sufficiently well to be viable in the 3D modelling context. Furthermore, the number of people active in the implementation of new or improved schemes is very limited. Because progress is slow, success unpredictable, and results are not always publishable, work on parametrization is not very popular. Also agencies tend to avoid funding of such infrastructural work.

WCRP is asking now how to organize the science community such that the best possible science is integrated into state-of-the-art NWP and climate models? The simple answer is to bring the process groups (e.g. GCSS, GLASS, GABLS) together with model evaluation groups (as in WGNE). In practise these are very different communities. Many of the scientists in the process study groups do not have access to a large scale modelling environment and many of the scientist involved in model diagnostics do not know the details of the parametrization schemes they are using. Moreover most of the parametrized processes can be considered as a specialism of their own (e.g. land surface modellers tend to come from a different science community than cloud modellers). The aim to establish direct working relationships between process scientist and model diagnosticians is a good idea but may not always work in practise.

However, WCRP can facilitate the interaction by providing well organized and easily accessible data sets, test cases, and verification procedures. The value of good data sets should not be underestimated. We can not expect models to be better than the data we verify them with, and every model parameter that can not be verified is likely to be inaccurate.

ECMWF has long experience in model development and also recently good progress has been made with the representation of parametrized processes. Some of the recent developments are described in Balsamo et al. (2008), Bechtold et al. (2008), Jung et al. (2009), Morcrette et al.

(2007) and Tompkins et al. (2004). However, there are still many outstanding issues. In the following section a list of deficiencies is given with suggestions how they can be addressed with emphasis on how the community can help. This list is by no means exhaustive and changes in time. It is a snapshot of some current issues in the ECMWF system which might inspire WCRP coordination.

3 Deficiencies of the ECMWF model

3.1 Upper tropospheric lower stratospheric temperature bias

The upper troposphere/lower stratosphere in the ECMWF system shows a systematic cold bias, which is has been rather persistent over many model versions. The error is largest in the summer hemisphere. This is an example where short range forecast errors have a similar signature as the errors in the climate of the model although the magnitude is rather different (see Fig. 1). Verification is non-controversial in this case because it is believed that the error in the verifying analysis is much smaller than the forecast error. It is known that the temperature in this region is sensitive to dynamics and radiation. The radiation scheme as such is believed to be accurate, but uncertainties exist with respect to **trace gases, humidity, tropospheric clouds and optical properties of these clouds. Progress would benefit from better data sets for the latter quantities**.

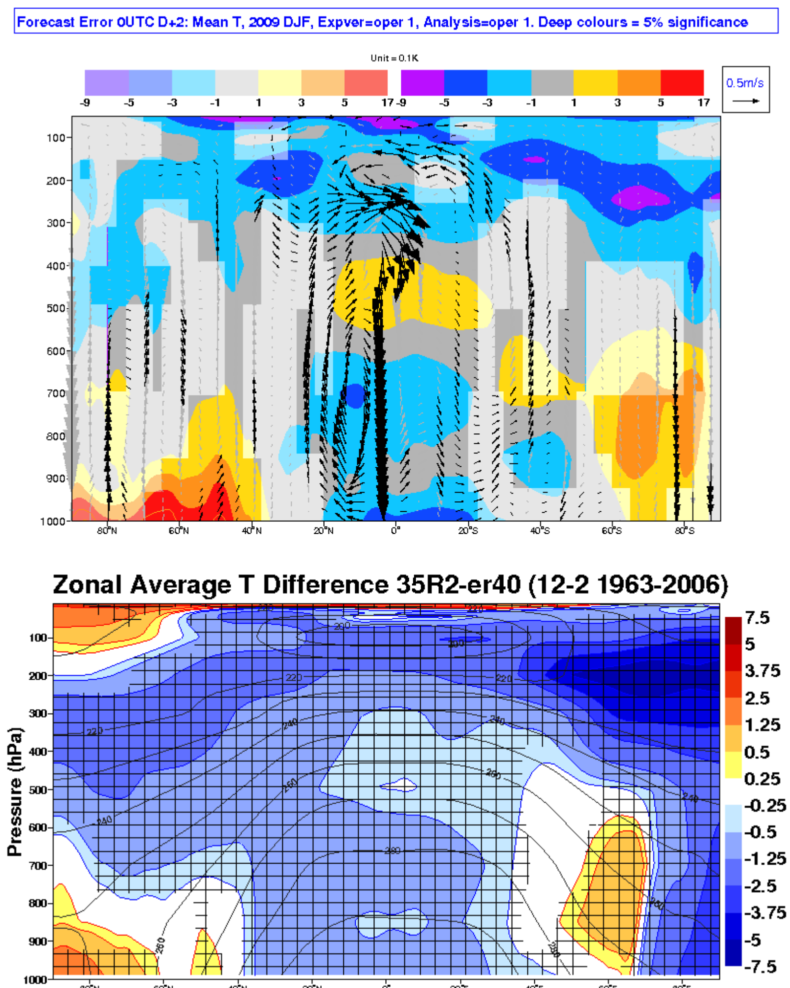

Figure 1: Zonal mean temperature errors of the DJF model climate (bottom) and DJF averaged day-2 forecasts (top).

3.2 Diurnal cycle of convection

The diurnal cycle of convection is in error by about 3 hours, the model convection being too early in the day (see Fig. 2; Bechtold, 2009). Quite a bit of effort has been put into this, without much success. However, CRM simulations are reported to be capable of producing the correct diurnal cycle, provided they are performed with very high resolution (e.g. 500 m). This is encouraging. The fact that high resolution is a pre-requisite suggests that the transition from shallow to deep convection is a an important player. How to design a convection parametrization that handles the diurnal cycle correctly is not clear because it is not known what the key ingredients are.

Therefore, a detailed diagnostic study of the output of a CRM simulation of the diurnal cycle would be most welcome. The purpose of such a study would be to clarify the key mechanisms in convection that control the diurnal cycle.

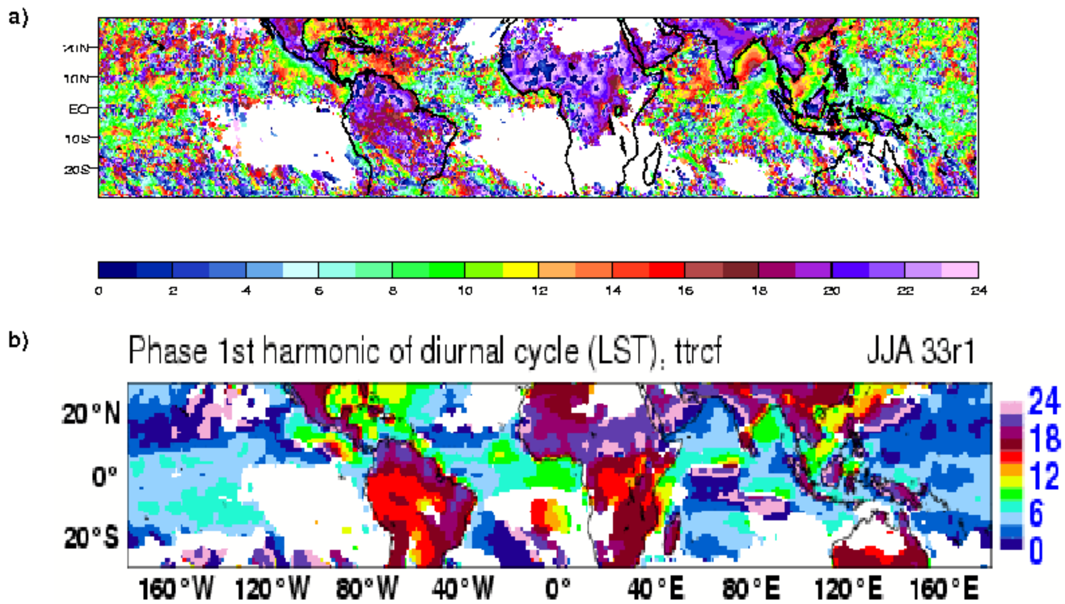

Figure 2: Local time of maximum precipitation, observed (top) and modelled (bottom).

3.3 Winter time near surface temperature over land

The model climate for winter shows substantial errors with a complicated pattern (see fig. 3). Substantial improvements have been achieved recently by improving the density and snow fraction formulations. In the past sensitivities have been demonstrated due to stable boundary layer diffusion, cloudiness (winter stratus), thermal coupling of the vegetation to the underlying soil, soil properties, and soil moisture freezing (for an overview see Beljaars et al. 2007). All these processes affect the winter climate over land, when the near surface temperature is controlled by a subtle balance of relatively small energy fluxes. It is also expected that the representation of wetlands needs improving. **More study is needed in this area. A necessary condition for progress is to develop data sets documenting the energy fluxes over continental areas in winter.**

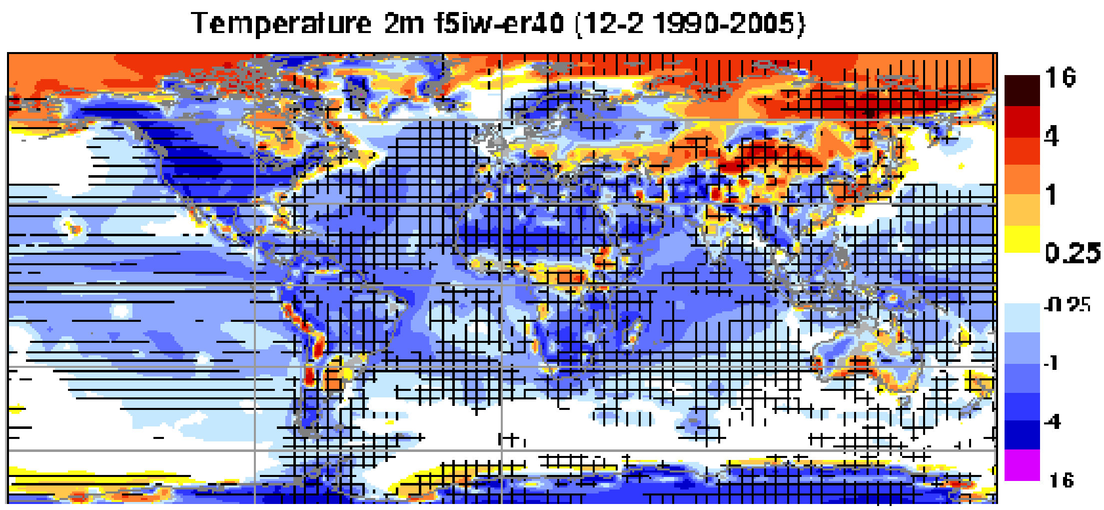

Figure 3: Temperature error of the climate of the model at 2m level for DJF.

3.4 Clouds, radiation and aerosols

The dominant part of the radiation errors are caused by incorrect inputs to the radiation scheme, i.e. errors in clouds, aerosols and possibly trace gases. The ECMWF scheme still uses climatological aerosols, but prognostic aerosols are under development. First their direct effect will be explored, later indirect effects will be studied.

Whether a particular cloud scheme provides the correct radiative effect in a model is still very difficult to assess. Models tend to be very different on this aspect. Although different models may attain similar top of the atmosphere and surface radiative budgets, this may be achieved with rather different water/ice content, cloud cover, and cloud optical properties. Reducing the uncertainty and inter-model differences and achieving the correct feedbacks is a major challenge. More recently effects of aerosols on clouds are also considered, leading to even more uncertainty.

The way forward in this area of research is to make maximum use of the observational material to narrow down the uncertainties. These uncertainties include the basic three-dimensional distribution of cloud, liquid and ice water contents and precipitation (both frequency and magnitude), their optical properties and how these characteristics vary temporally, geographically and by meteorological regime. In particular, mixed-phase processes are generally poorly represented in models. Spatial (sub-grid) heterogeneity and how this is linked to different physical processes in the atmosphere is another aspect of GCM cloud parametrizations that would benefit from observations. New profiling observations from cloud radar and lidar (ground based and satellite based) should be exploited to the full (see e.g. Fig. 4). Because of the importance of cloud radiative effects, such observations should also be combined with radiation observations. Each observation instrument has its limitations and two key activities are (1) to understand these limitations and error characteristics, and (2) to make the most of the synergy between different instruments/observables in order to reduce uncertainty.

The complexity of the observations and the complexity of the modelling issues make it necessary to have a close collaboration between scientists working on the data and algorithms and model developers. An active working group providing a platform for such a collaboration could be beneficial.

Satellite radar and lidar are providing a wealth of "global" information on cloud and precipitation profiles. However, the network of ground based remote sensing observations (ARM, CloudNet) still have a significant role to play in providing a wide range of synergistic observations of cloud, precipitation aerosol and radiation. There should be increased emphasis on extracting useful science from these observations. To structure data access and comparison with models, CEOP could consider to adopt the University of Reading CloudNet project.

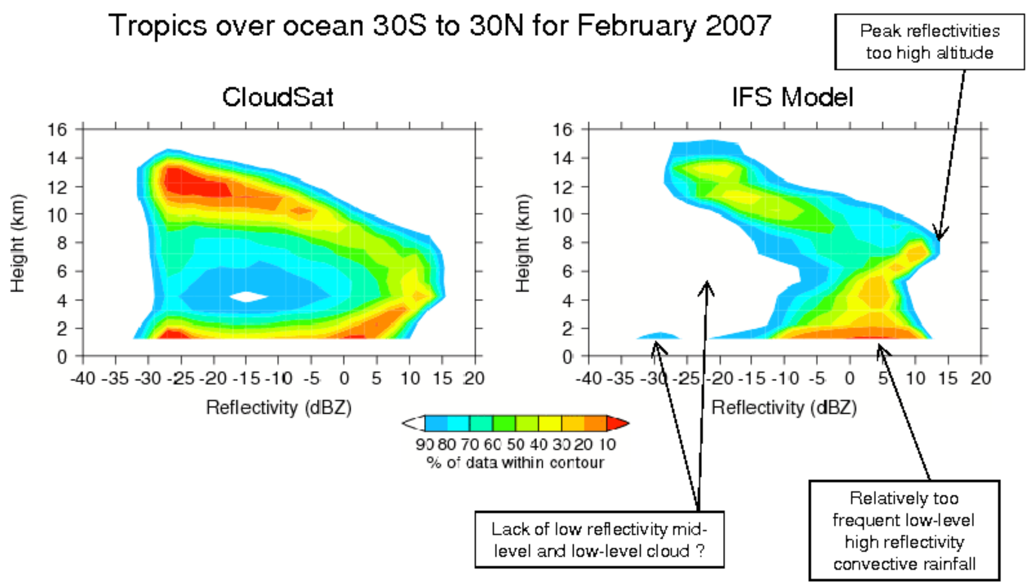

Figure 4: Relative occurrence in colour shading as a function of height and reflectivity for CloudSat observations (left) and the model equivalent of simulated reflectivity (right) from short range forecast co-located with the observations.

3.5 Land surface model processes and land data assimilation

Land surface modelling and data assimilation of soil moisture, snow, vegetation characteristics is an active area of research at ECMWF (see Drusch et al. 2007 for an overview). Attempts are made to have a realistic model combined with good data assimilation where the latter is focusing on the introduction of new sources of data (e.g. ASCAT and SMOS). Model consistency between land surface fluxes and stocks for multivariate assimilation is a requirement. The relevant variables are: heat fluxes, screen level parameters, soil moisture, brightness/skin/soil temperatures, snow mass, snow melting and river discharge.

Data assimilation can provide a synergy between model development and observations. Assimilation clearly exposes model problems as illustrated in Fig. 5. Snow water equivalent and soil moisture show a systematic seasonal cycle indicating that the model is not in balance with the data. In summer, data assimilation adds water to the soil, which might indicate that the effective soil water reservoir is too small.

Progress in this area of research depends crucially on the availability of good data to assimilate (satellite data) and on verification using flux tower data, runoff observations, basin budget studies, and in-situ soil moisture observations. Many relevant working groups are already active (e.g. GLASS working groups GSWP, PILPS, ISMWG and LANDFLUX).

Extending one of the working groups to data assimilation and benchmarking could create a platform for coordination of such activities. It is also believed that an intercomparison of data assimilation systems would be timely.

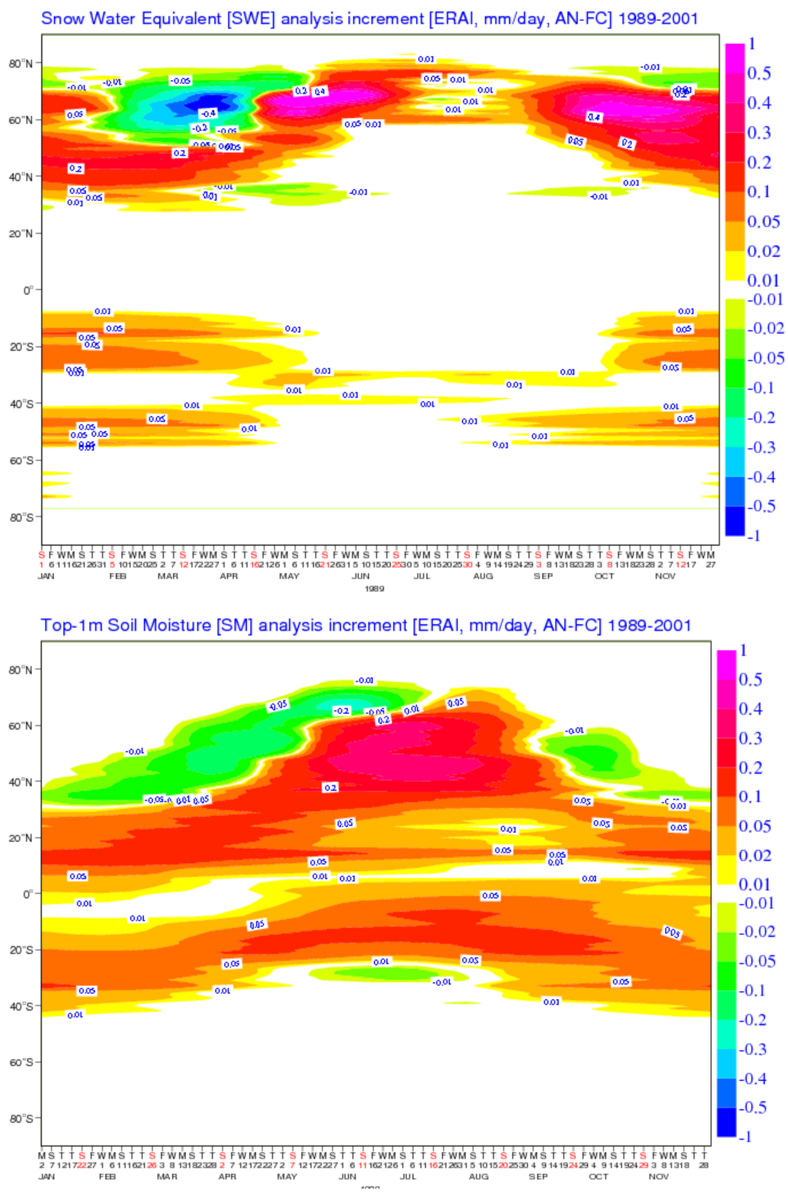

Figure 5: Latitude/time Hovmoller diagram of monthly snow (top) and soil moisture (bottom) increments in ERA-Interim. The snow analysis is based on SYNOP observations of snow depth and the NOAA NESDIS snow cover product. Soil moisture is inferred from short range forecast errors of near surface temperature and relative humidity using SYNOP observations.

3.6 Tropical circulation

A good mean tropical climate and variability are difficult to achieve. ECMWF has recently made substantial progress on tropical variability (Bechtold 2008; see also Fig. 6). Although MJO-like variability is produced, it is still too weak and has not quite the correct phase speed. Also systematic biases exist: the Indian Monsoon is too strong, the Western Pacific precipitation is too high and the equatorial near surface winds show an Easterly bias. These model biases are sensitive to basically all aspects of the parametrization package, so it is difficult to make recommendations. However, simulations at cloud resolving resolution over large areas are becoming possible now on the largest computer systems. **A coordinated activity to analyze such large simulation data sets could lead to progress. The aim should be to understand the key ingredients of the MJO using the detailed simulations. With a better understanding it should be possible to include the relevant sensitivities in parametrization schemes. Experience with the convection sensitivity to environment moisture is a recent example. Producing and sharing CRM-resolution data sets covering large areas might be beneficial to a wider community e.g. groups that develop (stochastic) schemes to estimate uncertainty in parametrized models. Such schemes are needed in modern ensemble prediction and data assimilation systems to represent model uncertainty.**

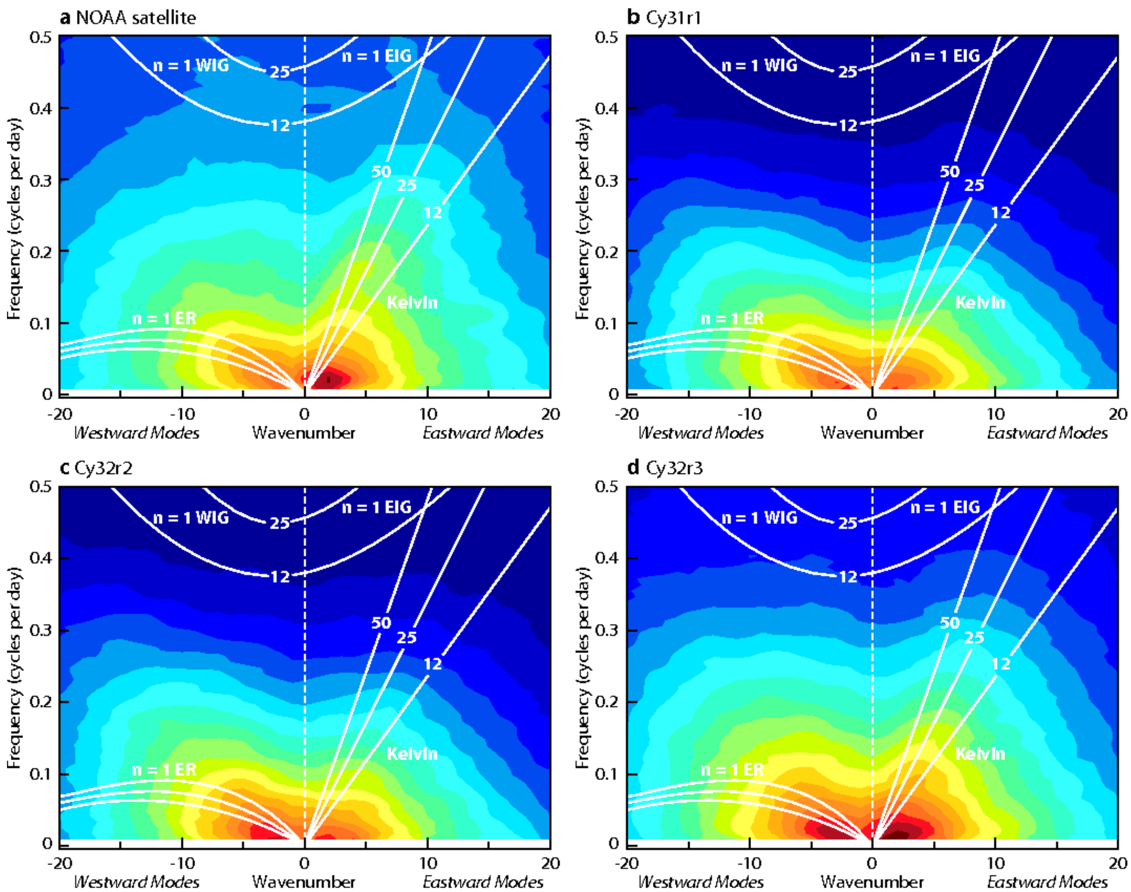

Figure 6: Frequency wavenumber diagram of OLR, as observed (a), with the ERA-Interim cycle 31R1 (b), after introduction of McRad changes according to Morcrette et al. (2007) in cycle 32R3 (c), and after the introduction of major convection changes according to Bechtold et al. (2008) in cycle 32R3 (d).

3.7 Dry boundary layer

Although less well known, the representation of the dry boundary layer in NWP and climate models still has a number of systematic errors. Near surface temperature in winter over continental areas is know to be very sensitive to the amount of diffusion. This is obviously an important topic for climate models because the strongest climate signals are seen in winter over the NH continents. The GABLS project is currently focusing on this. Models tend to have very diffusive schemes to compensate for other deficiencies.

Less well documented are errors in boundary layer wind fields as illustrated in Fig. 7 for the ECMWF system. One of the sources of these particular errors is stable diffusion. However, also wind direction is systematically biased in general and in particular in situations with cold or warm air advection over the ocean (see Brown et al. 2005).

GABLS could progress in a number of new directions: (i) meso-scale variability in relation to stable diffusion, (ii) baroclinic boundary layers, and (iii) momentum transport and the simulation of wind.

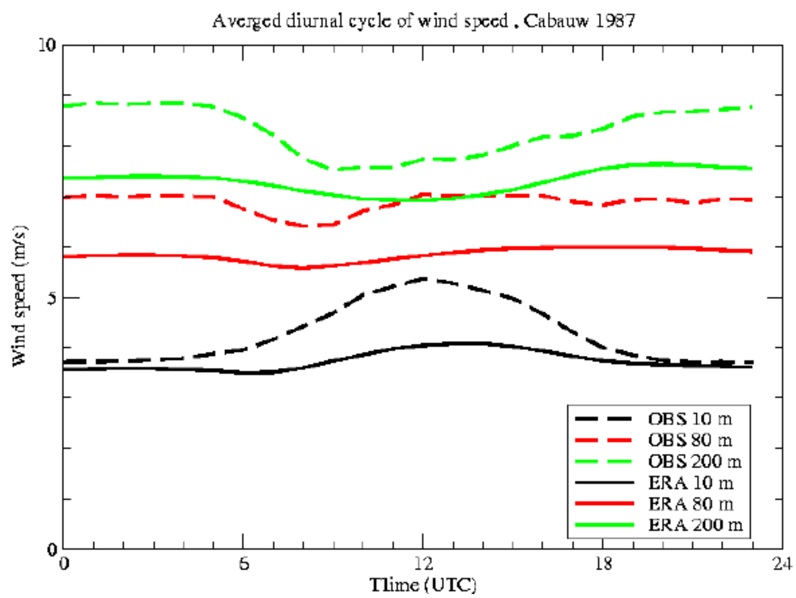

Figure 7: Mean diurnal cycle of wind speed at 10, 80 and 200 m above the surface for the year of 1987 at Cabauw in The Netherlands. The solid lines are from the ERA-40 system; the dashed lines are the tower observations

3.8 Boundary layer clouds

It is well know that boundary layer clouds (stratocumulus and shallow convection) play an important role in the climate system. Models have seen a substantial improvement with the early implementations of shallow convection schemes (e.g. Tiedtke 1988) and a lot of progress has been made more recently on stratocumulus clouds (e.g. Köhler et al. 2005). Boundary layer clouds play a key role in the vertical mixing processes and in the interaction with radiation. Parametrization of these processes will remain necessary even at a CRM resolution of 1 km.

However, many aspects of the representation of boundary layer clouds in the ECMWF model show problems: the transition between stratocumulus and shallow cumulus clouds is not well modelled, drizzle is excessive, cloud shape in the trades is not correct (maximum cloud cover at the top of shallow cumulus rather than at the bottom), the boundary layer shows a dry bias over land, trades are too reflective.

The way forward is not obvious. ECMWF is currently working on the implementation of the scheme by Neggers et al. (2009), which has been developed with the GCSS approach using LES data and a wide range of single column cases. The effect of this scheme on moisture (drying/moistening of the subcloud/cloud layer) is very different from the operational scheme (see Fig. 8), indicating that the new scheme is much less active. Past experience confirmed by recent experimentation indicates that a reduction of the shallow convection activity has a negative impact on NWP performance. This may be related to the role of shallow convection in extratropical cyclones. **Although we don't have a clear recommendation here, it is felt that far too little attention is paid to extratropical dynamics and its interaction with clouds, radiation, convection and boundary layer processes.**

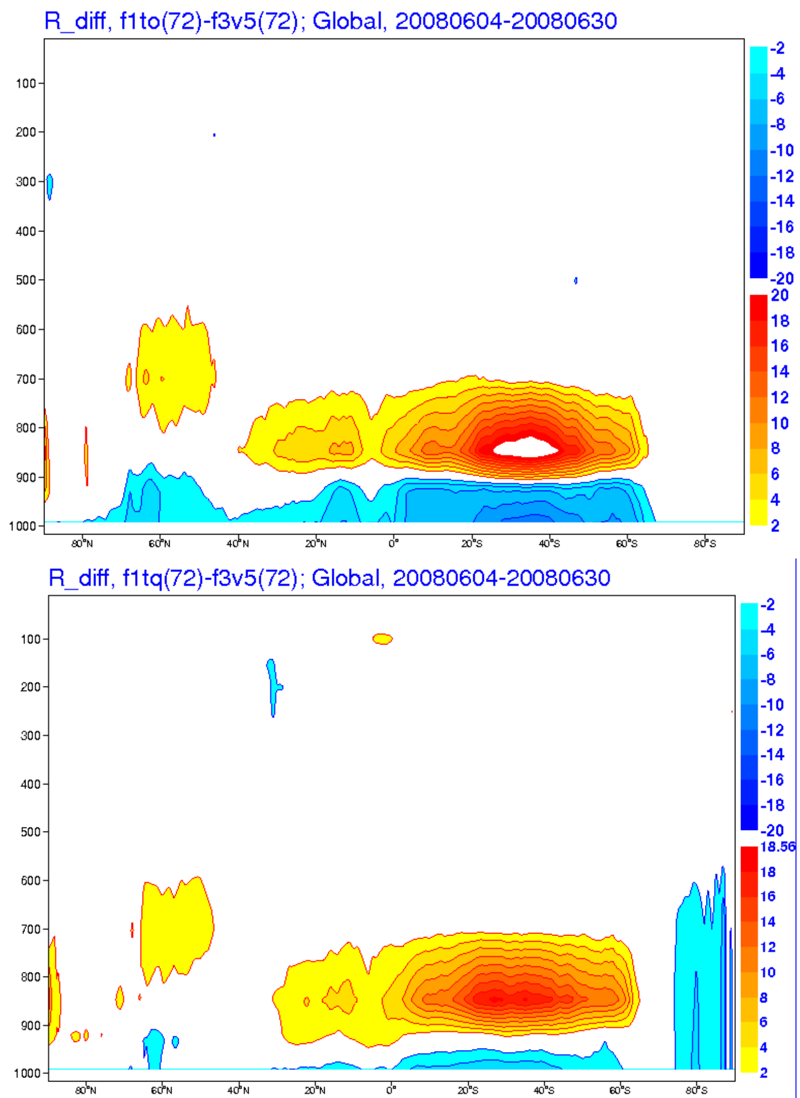

Figure 8: Effect of shallow convection on relative humidity in % (model with shallow convection minus model without shallow convection). The effect of two schemes is shown: the operational scheme CY32R3 (top panel) and the Neggers scheme (bottom panel).

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