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Some •aspects of systematic error in the ECMWF model

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Abstract

First, systematic errors of short-range and medium-range Z500 forecasts are described along with their changes since the early 1980s. Then systematic cloud error will be described. Finally, the capability of the ECMWF model to simulate the Madden-and-Julian Oscillation is assessed. Copyright © 2005 Royal Meteorological Society

1. Introduction

Two sources of error lead to the development of forecast error: error in the initial conditions and model error. Continuous monitoring at ECMWF reveals that forecast errors have been substantially reduced in recent years (Simmons and Hollingsworth, 2002). This reduction of forecast errors is partly due to improved initial data and partly due to model improvements. In general, however, it is not straightforward to separate the influence of improved analyses from those due to improved model formulations, since models are used in data assimilation schemes to determine the analysis.

A relatively simple way to identify aspects of model error is to focus on *systematic* errors of the forecast. To this end, a particular meteorological aspect (e.g. the mean circulation) is quantified from a large set of forecasts. The model results are then compared with estimates of the truth, which are obtained from observational data (or reanalyses). At the beginning of 2003, it was decided to carry out a comprehensive study of systematic errors in the ECMWF forecasting system. This decision was motivated by the fact that such a systematic major documentation had not been carried out for some time and that the ECMWF model underwent considerable improvements in recent years (e.g. Andersson *et al*., 2003). In the following, we shall discuss some of the outcomes of this extensive study (see also, Jung and Tompkins, 2003; Jung *et al*., 2004; Jung, 2005).

2. Results

2.1. Atmospheric circulation

We start by considering short-range and medium-range systematic Z500 errors of the ECMWF model cycle 23R4. This cycle is one of the key model releases at ECMWF used to carry out the ERA-40 reanalysis (Uppala, 2002). It also forms the atmospheric component of the ECMWF operational seasonal forecast system. This model cycle was in operational use at ECMWF for the medium-range from 12 June 2001 to 21 January 2002. In the framework of the ERA-40 reanalysis project, this cycle has also been used to carry out 10-day reforecast every day from 1960 to 2001. The resolution used is $T_L159(\approx 1.125°)$ with 60 levels in the vertical. The length of the time series allows us to quantify systematic errors with unprecedented accuracy.

Mean systematic Z500 errors of short-range $D+2$ forecasts ($D+n$ denotes a n-day forecast) are shown in Figure 1 for all four seasons. The first thing to notice is that systematic Z500 errors are very similar throughout the annual cycle, both in terms of their spatial structure and their magnitude. The two areas that stand out, in particular, are the North Pacific and the central North American continent. In the North Pacific, an anticyclonic bias has developed by $D+2$, which leads to an underestimation of the midlatitude westerly winds. Over the North American continent, the model has problems at $D+2$ in producing the observed stationary wave structure downstream of the Rocky Mountains. Evidently, this problem is prominent in all four seasons. The relaxation of the 'convective mass-flux limiter' for long time steps introduced in October 2003 led to a significant reduction (the error has been halved) of the North American Z500 bias during the summer months (not shown).

Systematic Z500 errors at $D+10$ are shown in Figure 2. Evidently, the largest systematic errors in the northern hemisphere occur during the winter season (DJF•). Moreover, as for $D+2$ forecasts, systematic Z500 errors at $D+10$ show a very similar structure throughout the annual cycle. The spatial correlation (north of 20°N) between the winter pattern and those in spring, summer and autumn amounts to 0.57, 0.60 and 0.78 respectively. Notice that most of the systematic errors found at $D+2$ also show up at $D+10$ (e.g. North Pacific and North America). It is worth pointing out that the thorough investigation of the systematic error structure of one particular model

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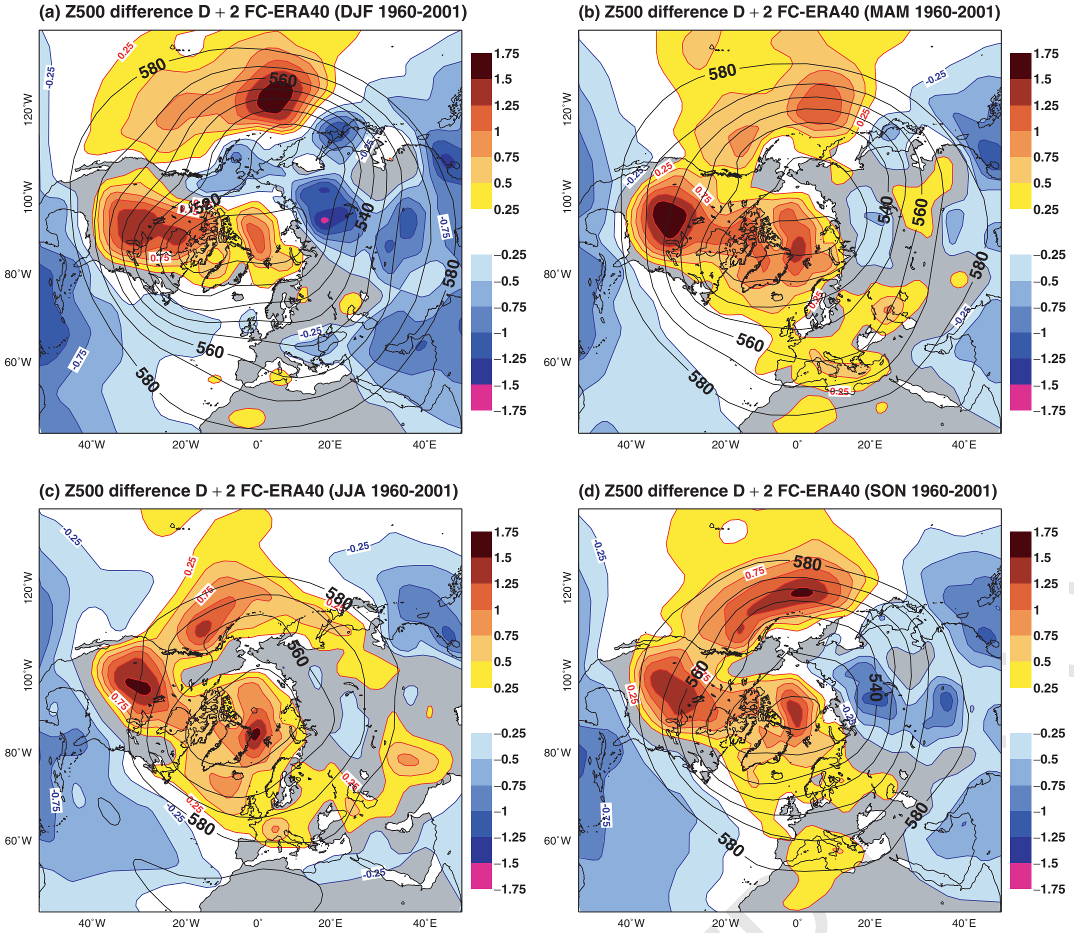

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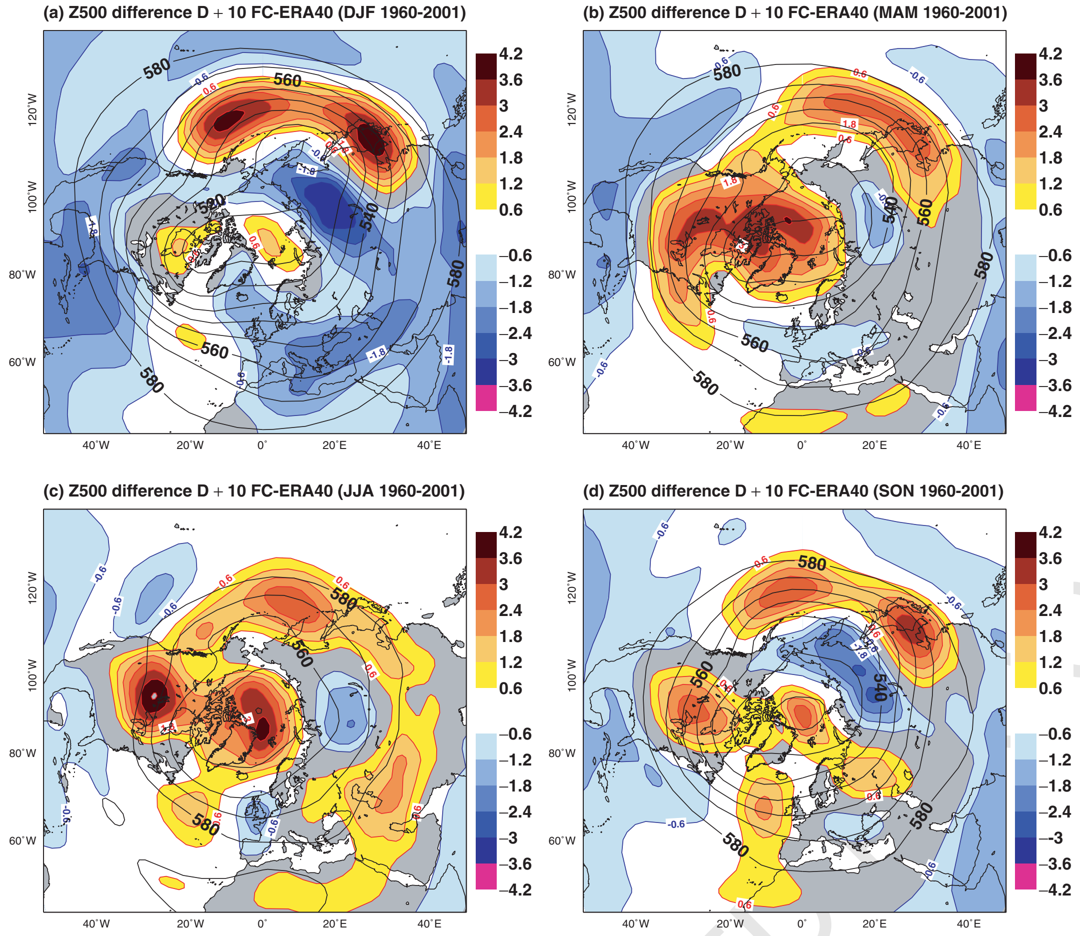
Figure 1. Mean Z500 difference (shading in *dam*) between D + 2 forecast and verifying analysis data for (a) winter, (b) spring, (c) summer, and (d) autumn. Results are based on ERA-40 hindcast and reanalysis data from the period 1960–2001. Also shown is the mean Z500 field from ERA-40 reanalysis data (thin dotted contours in *dam*)

cycle in the far-medium range has been made possible only through the availability of the ERA-40 hindcasts over a long period (40 years in this study). Usually, the operational ECMWF model undergoes changes at least once a year. Therefore, the assessment of systematic errors in medium range usually has to rely on only one realization of each season. As discussed in more detail by Jung (2005), this is problematic since, on average, the skill of Z500 forecasts at D + 10 is relatively low. As a consequence of this loss of predictability, the seasonal mean of all individual forecasts is very similar to the climatology and, therefore, the seasonal-mean forecast error resembles the observed Z500 anomaly, except with opposite sign. This makes it difficult to separate true systematic model errors from the usually quite large 'apparent' systematic error.

Climatological systematic Z500 errors of model cycle 23R4 are described in detail by Brankovic and Molteni (2004). The spatial structure of climatological systematic Z500 error in the North Pacific is very similar to that at D + 10 for the ERA-40 reforecasts; the magnitude at D + 10, however, amounts only to about half that in the extended-range. This shows that systematic Z500 errors continue to grow beyond the medium range. Further experimentation has revealed that the North Pacific Z500 bias in the extended range is largely due to the use of an unrealistic aerosol climatology in north Africa and the Middle East (Rodwell and Jung, manuscript in preparation). This shows that the North Pacific Z500 bias is in part remotely forced. The fact that systematic Z500 errors are also evident in the short range (D + 2, Figure 1) clearly shows that the origin is both remote and local, their relative importance being dependent on the forecast range under consideration.

So far, the focus has been on systematic Z500 error of one particular model cycle (23R4). Next, we discuss how systematic Z500 error has changed in operational ECMWF forecasts since the early 1980s. For the winter season, results have been recently presented by Jung (2005). Here, we go one step further by considering all four seasons. In the following, the magnitude of the mean error component is quantified by computing the spatial standard deviation of the difference between mean Z500 forecast errors (forecast minus analysis) north of 30°N for individual years. The resulting time series for operational D + 2 and D + 5 forecasts are shown in Figure 3. The most prominent feature at D + 2 is the pronounced reduction of systematic Z500


(a) Z500 difference D + 10 FC-ERA40 (DJF 1960-2001)

(b) Z500 difference D + 10 FC-ERA40 (MAM 1960-2001)

(c) Z500 difference D + 10 FC-ERA40 (JJA 1960-2001)

(d) Z500 difference D + 10 FC-ERA40 (SON 1960-2001)

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Figure 2. Same as in Figure 2(a)–(d), except for D + 10 hindcasts. Note the different contour interval

error around the mid to late 1980, which have been traced back to changes in the parametrization of convection and radiation and to a lesser degree gravity wave drag and vertical resolution (Arpe, 1989). Evidently, D + 2 forecasts during the winter season benefited the most from these model improvement. After almost 10 years of little changes of systematic Z500 error at D + 2, mean errors improved substantially in all four seasons since 1999 or so. While the exact reason for this reduction is not known, it is likely that improved parametrizations (see also next section) and an increase of the horizontal resolution to T_L511 ($\approx 0.35^\circ$), which took place in autumn 1999, played key roles.

2.2. Clouds and cloud-related parameters

In recent years, effort has also been expended to improve the representation of moist physical processes in the ECMWF model. However, in general, it is not straightforward to relate improvements of the representation of physical processes (so-called parametrizations) to fields such as geopotential height. This (and their paramount influence on local weather conditions) implies that diagnostics of cloud-related parameters should be preferably included in any detailed study of systematic model error.

Previous assessment of clouds in model cycles used in the late 1990s has revealed that, in general, clouds are well captured, with the following exceptions: The cloud cover is too low in the midlatitudes (in particular too little cloud cover is simulated over Europe in summer) and subtropics; the cloud ice amount is too low, especially in the midlatitudes; the liquid water is too high, especially in the subtropics; the cloud cover in stratocumulus regions is too low; and, finally, there is too much high cloud in regions of tropical deep convection (Jakob, 1999; Hogan *et al.*, 2001; Chevallier *et al.*, 2001; Chevallier and Kelly, 2002).

Here, we can only briefly examine one cloud influenced diagnostic for illustrative purposes, namely, the systematic error in the top-of-atmosphere (TOA) net short-wave budget. For further details, see Jung and Tompkins (2003) and Tompkins *et al.* (2004). Model cycle 26R1 (operational from 29 April to 6 October 2003) and cycle 23R4 are validated against Earth Radiation Budget Experiment (ERBE) measurements in Figure 4 to see if model improvements occurred in the intervening 2-year period.

The older cycle (left column) reveals signs of some of the characteristic errors identified in the literature. The reflectivity is too high in much of the subtropics and in the tropical Pacific and Atlantic due to excessive liquid water in these regions. In contrast, the lack

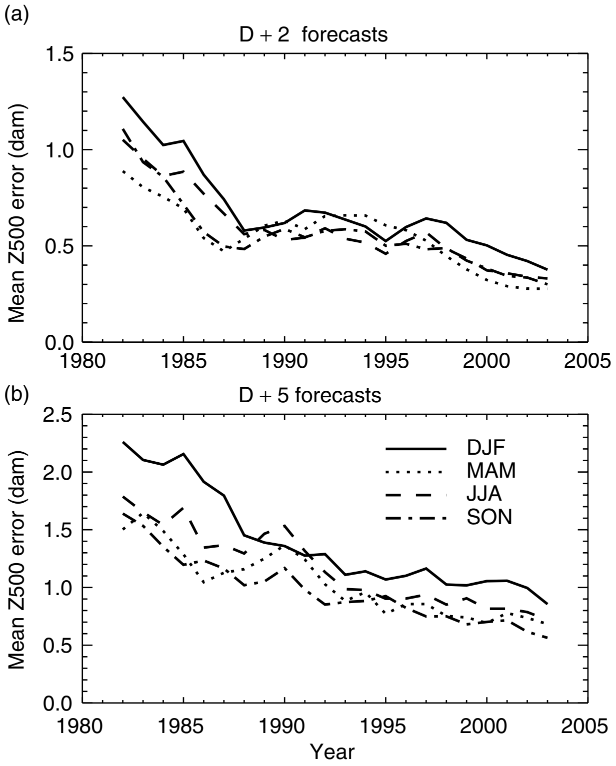


Figure 3. Temporal evolution of wintertime Northern Hemisphere (north of 30°N) mean Z500 errors of operational (a) D + 2 and (b) D + 5 forecasts in winter (solid), spring (dotted), summer (dashed), and autumn (dash-dotted). A three year running average has been used for smoothing. Results are based on the spatial standard deviation of the temporal mean forecast error. Area-weighting has been taken into account

of stratocumulus near the West coast of the Americas and Africa is associated with too little reflectivity. Analysis of cloud cover and liquid water path (LWP) retrievals from other instruments confirms this assessment (not shown). In model cycle 26R1 (Figure 4, right column) observed TOA-SW● characteristics are substantially improved in the tropical and subtropical oceans. A summary of the model revisions to convective, radiative and cloud processes that lead to a reduction in LWP from cycle 23R4 to 26R1 is given in Jung and Tompkins (2003). In contrast, the model still fails to capture stratocumulus adequately. This has been addressed by a new diffusion scheme (not shown), which will be implemented operationally in late 2005 (Tompkins *et al.*, 2004).

2.3. Madden-and-Julian oscillation

So far, we have focussed on systematic errors of the mean. However, model problems may also affect the model's ability to simulate variations around the mean. Here, we shall concentrate on the by far most dominant mode of atmospheric intraseasonal variability in the Tropics, which is associated with continental-scale organization of convection propagating eastward across the Indian and western Pacific ocean. Honouring the discoverers of this phenomenon (Madden and Julian, 1972), this mode is nowadays known as the *Madden-and-Julian oscillation* (MJO). Regarding operational activities at ECMWF, there are at least three reasons why the MJO should be simulated well. First, there is evidence that westerly wind bursts can trigger ENSO● events. Therefore, the skill of ECMWF's seasonal ENSO forecasts may crucially depend on the model's ability to simulate the MJO. Second, there is an indication that medium-range forecast skill in the northern hemisphere extratropics depends on how well the Tropics in general, and the MJO, in particular, are simulated (Ferranti *et al.*, 1990). Finally, the quasi-periodicity of the MJO at periods of 30–60 days implies extended-range predictability that might be utilized in monthly forecasts (Vitart, 2004), which have been produced operationally at ECMWF every week since October 2004.

The MJO has been diagnosed in a set of 6-month long integrations with model cycle 26R1 (at T_L95 with 60 levels in the vertical). The integrations were started on 1 October of each of the years 1960–2001 using observed SST fields. A dramatic shortcoming of the ECMWF model is that it does not produce the observed spectral peak in the 30–60 day range. This can be inferred from Figure 5, which shows average power spectra of tropical velocity potential anomalies at 200 hPa for different longitudes. The ERA-40 reanalysis data show a clear spectral maximum in the eastern hemisphere, particularly between 60 °E and 180 °E. The ECMWF model, on the other hand, merely produces red power spectra with no indication of quasi-periodicity. As pointed out by Jung and Tompkins (2003), the model also has problems in simulating the temporal coherence of slowly eastward propagating anomalies, whereas relatively fast propagating anomalies are more realistically simulated.

Finally, it has been found that in the ECMWF model MJO-related upper tropospheric divergence anomalies are primarily associated with large-scale precipitation (i.e. convection on the gridscale) instead of subgrid-scale convective precipitation (Tompkins and Jung, 2004). Additional sensitivity experiments with an aqua-planet version of the model have revealed that the quasi-periodicity of the simulated MJO depends on the ratio of large-scale to convective precipitation; changes to the model physics that increase the proportion of large-scale precipitation amplify the magnitude and increase the periodicity of the simulated MJO. It is hypothesized that this is because the large-scale cloud scheme is constrained to provide latent heating in phase with any wave that provides forcing for the cloud, a positive feedback along the lines of theories of Conditional Instability of the Second Kind (CISK) (e.g. Lindzen, 1974; Kirtman and Vernekar, 1993). This is consistent with the propagating mode's resemblance to a moist Kelvin wave. The convection scheme is not so constrained and can provide heating out of phase with the wave, possibly even damping the oscillation (Emanuel, 1994). We should emphasize that

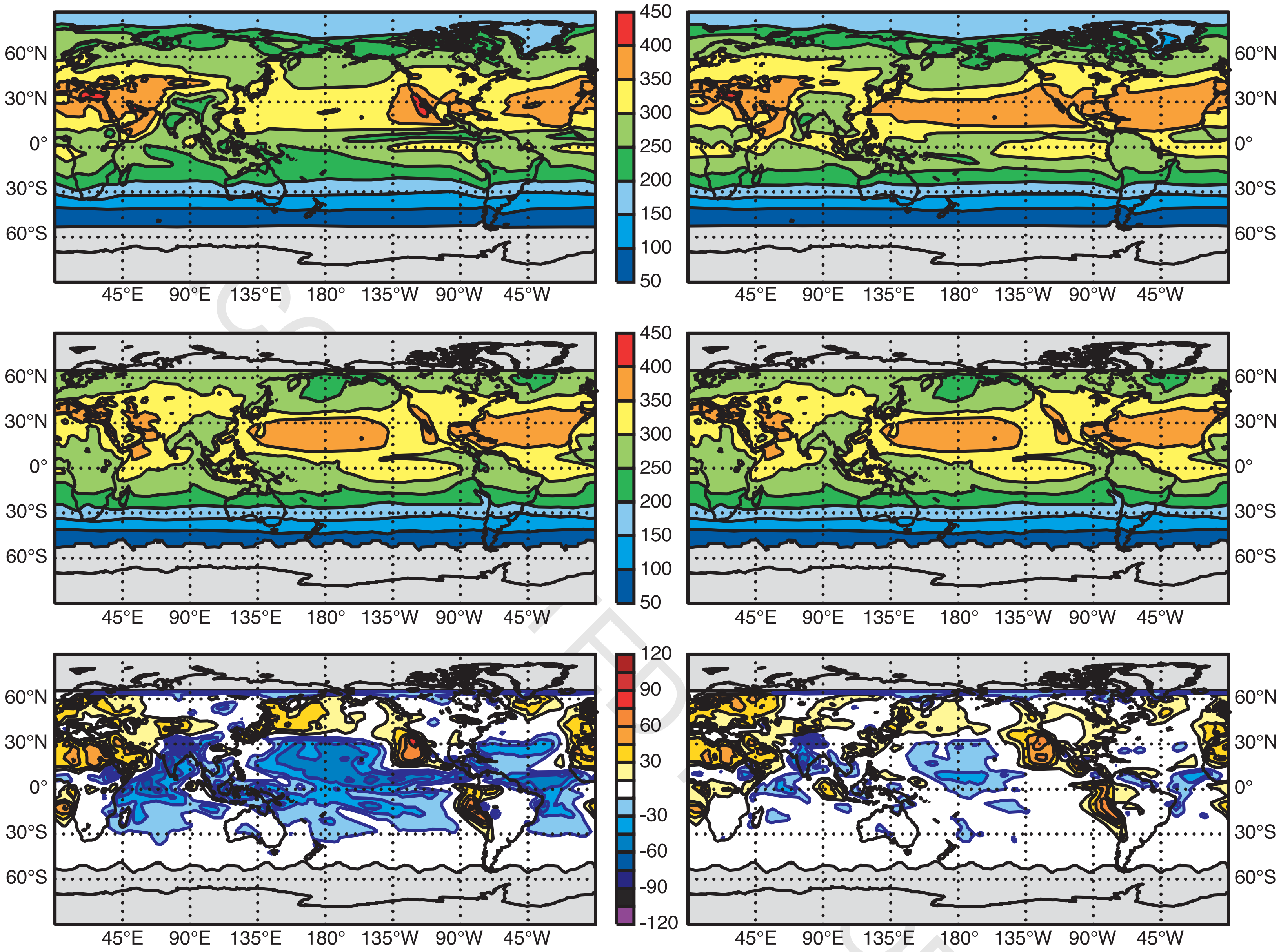
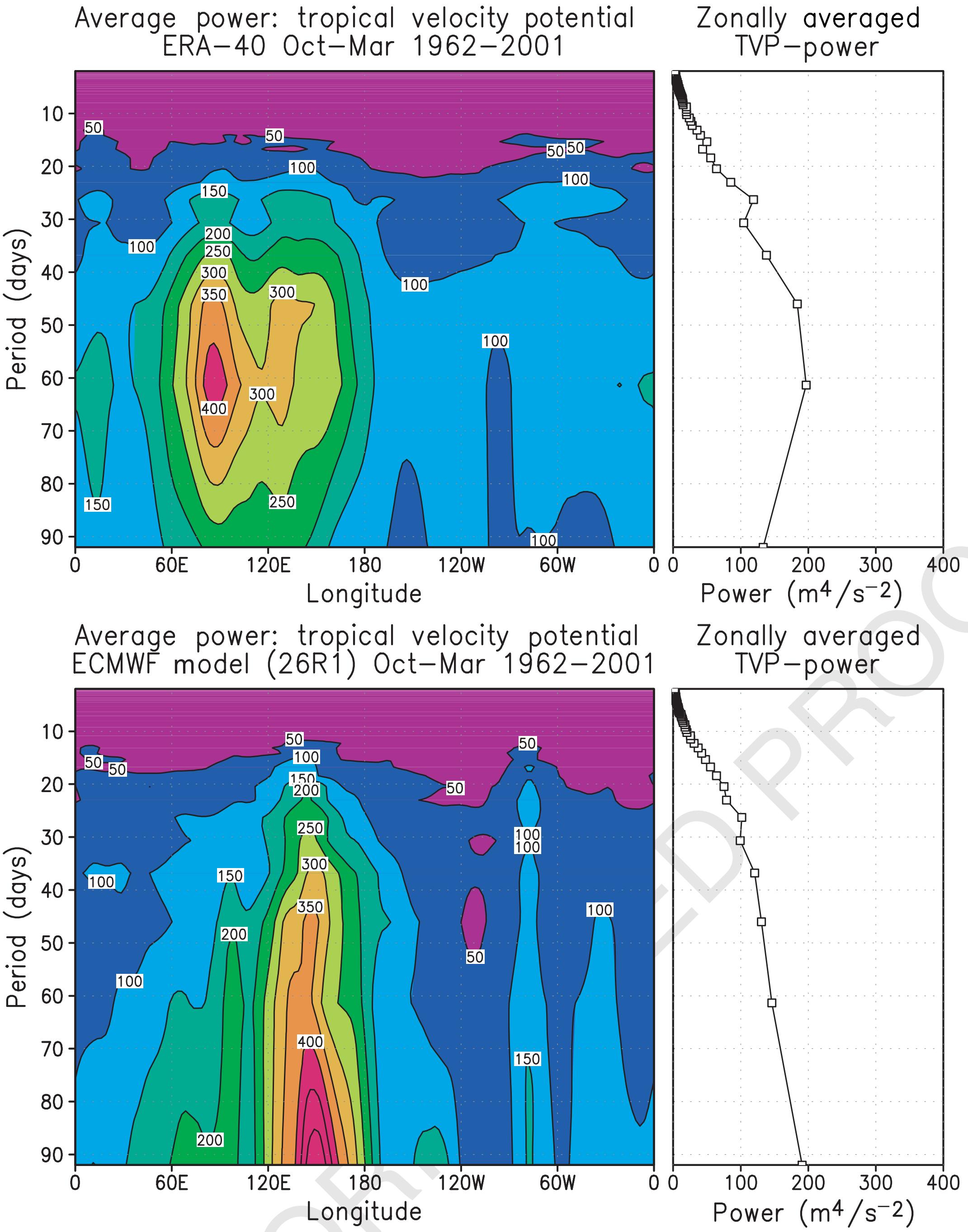


Figure 4. Mean top of the atmosphere downward short-wave radiation (Wm^{-2}) for the period June–August 1987 based on model data (upper panels), observational data from ERBE (middle panels) along with difference: model minus observational data (lower panels). Left: Model cycle 23r4. Right: Model cycle 26r1



Average power: tropical velocity potential ERA−40 Oct−Mar 1962−2001

Zonally averaged TVP−power

Average power: tropical velocity potential ECMWF model (26R1) Oct−Mar 1962−2001

Zonally averaged TVP−power

Figure 5. Average power spectra of tropical (5°S–5°N) velocity potential anomalies at 200 hPa for ERA-40 reanalysis data (upper panels) and climate runs with model cycle 26R1 (lower panels). The average is based on 40 raw spectra for the autumn and winter months from October to March of the years from 1962 to 2001. Zonal averages are shown in the right-hand panels. The mean annual cycle has been removed before the computation of the spectra

we do not claim that this mechanism is necessarily relevant to the real atmosphere, merely that it is key to the model's simulated propagating mode.

Most of the model's deficits in simulating the MJO described above are typical features of earlier model cycles and other atmospheric models as well (Slingo *et al*., 1996). Given the importance of the MJO for medium-range and extended-range forecasting improving the model's capability to properly simulate the MJO has a high priority in the near future. Possible model improvements, however, are likely to require a better understanding of the mechanisms governing the MJO — a widely accepted theory for the MJO is still missing.

3. Further remarks

In this study, some aspects of systematic error in the ECMWF model have been described. The concept of systematic error is a very powerful and straightforward tool to identify the existence of model errors. In general, however, without any further experimentation and diagnosis, it is difficult to infer the exact source of the model problems, giving rise to systematic model error. In this sense, diagnosing systematic model must be seen as only the first (but important) step in a chain to pinpointing and eradicating model error.

From a methodological point of view, the concept of systematic model error is straightforward. There are potential pitfalls, however. First, the datasets used for verification can be associated with considerable uncertainties. This is particularly true for cloud-related parameters and precipitation over the oceans, for example, which are notoriously difficult to observe. Moreover, the estimation of systematic errors is a statistical problem. Therefore, the shortness of time series poses serious problems, at least for some forecast aspects. In this study, we have made use of 40 years of 10-day reforecasts with the same model cycle to infer systematic Z500 errors in the northern hemisphere with, to our knowledge, unprecedented accuracy (see also Jung, 2005).

In the past, long time series for the purpose of model assessment have primarily been obtained by carrying out seasonal integrations for a relatively large number of years (e.g. Brankovic and Molteni, 2004). While this is definitely an important part of every model assessment, it is difficult to separate locally from remotely forced errors (Klinker and Sardeshmukh, 1992). To circumvent this problem, in our opinion, it is very fruitful to augment climate diagnostics by detailed investigations of systematic errors in the short range and medium range, as has been done for Z500 in this study.

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