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Resolution dependence of orographic torques

A.R. Brown

Research Department

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Abstract

An evaluation of the performance of the Lott and Miller subgrid orography parametrization scheme is made by examining the variation with resolution of the orographic torques (resolved and parametrized) in short-range global runs of the ECMWF Integrated Forecast System. As the spectral resolution is increased from T95 to T511, the magnitudes of the resolved torques increase while those of the parametrized torques decrease. In general the changes in the total orographic torques are reasonably small, but an important exception is between 20 °N and 50 °N in winter. Here the total orographic torque decreases significantly with increasing resolution. Through examination of errors in the modelled angular momentum budgets, it is suggested that the problems lie primarily at the low resolution end, where the parametrized orographic torques seem to be excessive. Furthermore, recent work with the NCEP reanalysis data by Huang *et al.* suggests that this result is not unique to the ECMWF system.

1 Introduction

The importance of the representation of the effects of subgrid-scale orography for the quality of performance of numerical weather prediction (NWP) and climate models is well established. Early schemes (e.g. Palmer *et al.* 1986; McFarlane 1987) concentrated on the effects of propagating linear hydrostatic gravity waves, and gave drag primarily in the stratosphere. More recent developments have included representations of flow blocking and other processes leading to drag in the lower troposphere (e.g. Kim and Arakawa 1995; Lott and Miller 1997; Scinocca and McFarlane 2000; Webster *et al.* 2003).

A number of different techniques have been used in the development and evaluation of these parametrization schemes. One valuable approach has been the use of budget studies on data from NWP analyses and short-range forecasts. For example, Swinbank (1985) showed that the surface torques did not balance the flux convergence in the vertically integrated angular momentum budget, particularly in the northern hemisphere in winter. This provided motivation for the introduction of early gravity wave drag schemes. Later studies examining model drifts over two-timestep integrations supported the change to more low-level and less stratospheric drag (Klinker and Sardeshmukh 1992; Milton and Wilson 1996). More recently, Huang *et al.* (1999) inferred from drifts in the global angular momentum that the surface parametrized orographic torque in their model was excessive.

One problem with the budget approaches is that they provide a rather indirect method of evaluating the performance of the orographic parametrizations, and it can be difficult to discriminate between problems associated with the representation of orography and problems with other aspects of the model. Hence other approaches have involved improving and using understanding of flow over and around orography, concentrating in particular on the drag and momentum fluxes. For example, parametrizations of the momentum fluxes associated with propagating gravity waves are strongly guided by theoretical work (e.g. Bretherton 1969). Observational campaigns (e.g. PYREX, Bougeault *et al.* 1997) have also provided much useful data, including estimates of surface pressure forces and momentum flux profiles which have been used (e.g. Lott and Miller 1997) in the validation of parametrization schemes. Results from high-resolution model simulations, both idealized (e.g. Stein 1992; Kim and Arakawa 1995; Olafsson and Bougeault 1997) and case-study based (e.g. Clark and Miller 1991), have also been widely used to guide recent parametrization developments, particularly with regard to the representation of low-level wave effects and flow blocking. The basic philosophy is that the parametrized momentum fluxes in a large-scale NWP model, which does resolve the orography, should match those explicity resolved in a high-resolution model.

This paper aims to take the model-based approach one step further, by evaluating the parametrized orographic torques by using the NWP model itself across a range of resolutions. As the resolution is increased, more of the orography will be resolved and the parametrized momentum fluxes associated with subgrid orography are expected to decrease. Ideally, the parametrization should ‘switch off’ in such a way that the total orographic surface torque (resolved plus parametrized) is independent of resolution. However, this is a stringent test of both the parametrization scheme and of the method of characterizing the subgrid orography. Some results illustrating a qualitatively reasonable handover from parametrized to resolved drag were presented by Lott and Miller (1997), although their study was limited to the Pyrenees and only spectral resolutions of T106 and T213 were considered. Here we use global simulations, and cover a wider range of resolutions (T95 to T511) so that the fractional changes in the resolved and parametrized torques are larger. Of course, no information is gained through this technique on whether the parametrization of the torques associated with scales unresolved at any of these resolutions is performing adequately. Accordingly it will be used in conjunction with examination of the angular momentum budget.

The plan for the remainder of this paper is as follows. Details of the datasets used and processing performed are given in section 2. Section 3 presents the results, and finally conclusions are given in section 4.

2 Datasets and processing

Datasets for the present study were obtained from the European Centre for Medium-Range Weather Forecasts Integrated Forecast System (IFS). The IFS is used at a variety of resolutions for different purposes. In the present study, spectral resolutions of T95 (triangular truncation at wave number 95), T159, T255 and T511 are used. These correspond to grid spacings on the linear reduced Gaussian grid (Hortal and Simmons 1991) of around 210 km, 125 km, 80 km and 40 km.

At each resolution, the mean orography on the target grid is derived from a 2’30” version the GTOPO30 data set (Gesch and Larson 1998). The orography is then spectrally fitted. Smoothing is applied in spectral space with a ∇^4 operator, where damping by a factor of 5 is applied to the smallest scales. The subgrid orography is characterized through the standard deviation, slope, anisotropy and orientation (Baines and Palmer 1990). These fields are computed from the 2’30” data after subtraction of the mean orography, and are used by the parametrization scheme of Lott and Miller (1997). This scheme provides a representation on the stress associated with propagating gravity waves and with low-level flow-blocking due to subgrid orography.

Processing was carried out on data from forecasts run from 12Z on each day of January 2001 and July 2001. These forecasts were initialized with the operational T511 4-D variational assimilation analysis, interpolated as required. The T95 and T159 runs were performed using a recent cycle of the IFS (26r1). However, the T255 and T511 data were obtained from the operational archives of Ensemble Prediction System control run and of the main deterministic model run respectively. This data was therefore created using the IFS cycles that were used operationally – 23r3 in January 2001 and 23r4 in July 2001. Nevertheless it is not believed that the cycle differences have a significant impact on the present results, as most of the differences between cycles are associated with the data assimilation system and therefore not of relevance for comparisons of forecast only runs. In support of this argument, tests at T159 confirmed that the differences in the surface torques in forecasts performed with cycles 23r4 and 26r1 were very small.

For all of the cases, instantaneous global fields of the horizontal wind components on all model levels and of the surface pressure were retrieved from the 12Z analysis (T+0), and from the forecasts at ranges 6, 12, 18 and 24 hours (T+6, T+12, T+18 and T+24). Six hour averages of the parametrized surface stresses were retrieved at times T+6, T+12, T+18 and T+24. These fields were then used to postprocess the terms in the budget of relative angular momentum (strictly just the principal component thereof) described below.

The relative angular momentum per unit mass is defined through, $m_r = ua\cos\phi$, where u is the zonal wind component, a is the radius of the Earth, and ϕ is the latitude. Vertically integrating the equation for the rate of change of m_r, averaging zonally (denoted by [ ]) and rearranging (e.g. Swinbank 1985; Peixoto and Oort 1992) leads to

$$
\begin{aligned}
-\frac{\partial}{\partial t}\left[\int_0^{p_*} m_r \frac{dp}{g}\right] \quad = \quad & \frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}\left(\left[\int_0^{p_*} m_r v \frac{dp}{g}\right]\cos\phi\right) + \left[p_* \frac{\partial h}{\partial \lambda}\right] \\
& + (a\cos\phi)\left[\tau_*^{sso}\right] + (a\cos\phi)\left[\tau_*^{bl}\right] - f a\cos\phi\left[\int_0^{p_*} v \frac{dp}{g}\right]
\end{aligned}
\qquad (1)
$$

Here p_* is the surface pressure, λ is the longitude, v is the meridional wind component, τ_*^{sso} and τ_*^{bl} are the zonal components of the parametrized surface orographic and boundary layer stresses (positive in the sense to decelerate a westerly flow) and f is the Coriolis parameter. A term involving the action of the Coriolis force on the vertical velocity is negligibly small and has been omitted.

The term on the left-hand-side of Eq. 1 (TEND), is minus the average rate of change of vertically integrated relative angular momentum per unit horizontal area. The terms on the right hand side represent the meridional angular momentum flux convergence (AMFC), the resolved orographic pressure torque (RES), the parametrized subgrid-scale orographic torque (SSO), the boundary layer torque (BL), and Coriolis effects (COR). All of these terms have been post-processed from the six hourly data. Vertical integrals were calculated from the surface to the top of the model – at 0.1 hPa in the T95, T159 and T511 configurations which used 60 levels, but at 10 hPa in the T255 40 level configuration used by the Ensemble Prediction System. Where possible the calculations were done on the reduced Gaussian grid. However, as it is irregular in latitude-longitude, fields were transformed into spectral space for the calculation of the horizontal derivatives and the resulting spectral fields were then transformed back to the reduced Gaussian grid. Some comments on the accuracy and representiveness of the calculated terms (which will be integrated over 10 degree latitude bands) are given in section 3.1.

3 Results

Some aspects of the full calculated angular momentum budgets (including their accuracy and comparison with previously published results) will be discussed in section 3.1. A detailed examination of the resolution dependence of the surface torques then follows in section 3.2. Finally, section 3.3 briefly examines the impacts of the torque differences on the forecast evolution.

3.1 Relative angular momentum budgets

Figure 1 shows the angular momentum flux convergence and surface torque terms in the relative angular momentum budgets integrated over 10 degree latitude bands and averaged over the first day of each of the 31 forecasts for Jan and July 2001 at both T511 and T159. The tendency and Coriolis terms are generally small (typical magnitudes of 1 or 2×10^{18} Nm, although the magnitude of the tendency term does approach 5×10^{18} Nm in some latitude bands in the tropics) and are omitted for clarity. The crosses give an indication of the accuracy of the budget calculations by showing the residuals i.e. the discrepancy between the calculated left and right-hand sides of the budget equation. There are a number of reasons why these residuals may not be zero. These include the presence of a small explicit diffusion term in the model which is not accounted for in the budgets, and also the fact that the post-processed terms are not all calculated exactly consistently with the models finite difference discretization (e.g. the momentum flux convergence calculation has no knowledge of the model's semi-Lagrangian advection scheme). Some inconsistency will also be introduced by the use of true averages over all model time steps for some of the terms (tendency and parametrized stresses), but averages over instantaneous values six hours apart for others (momentum flux convergence, resolved orography and Coriolis),

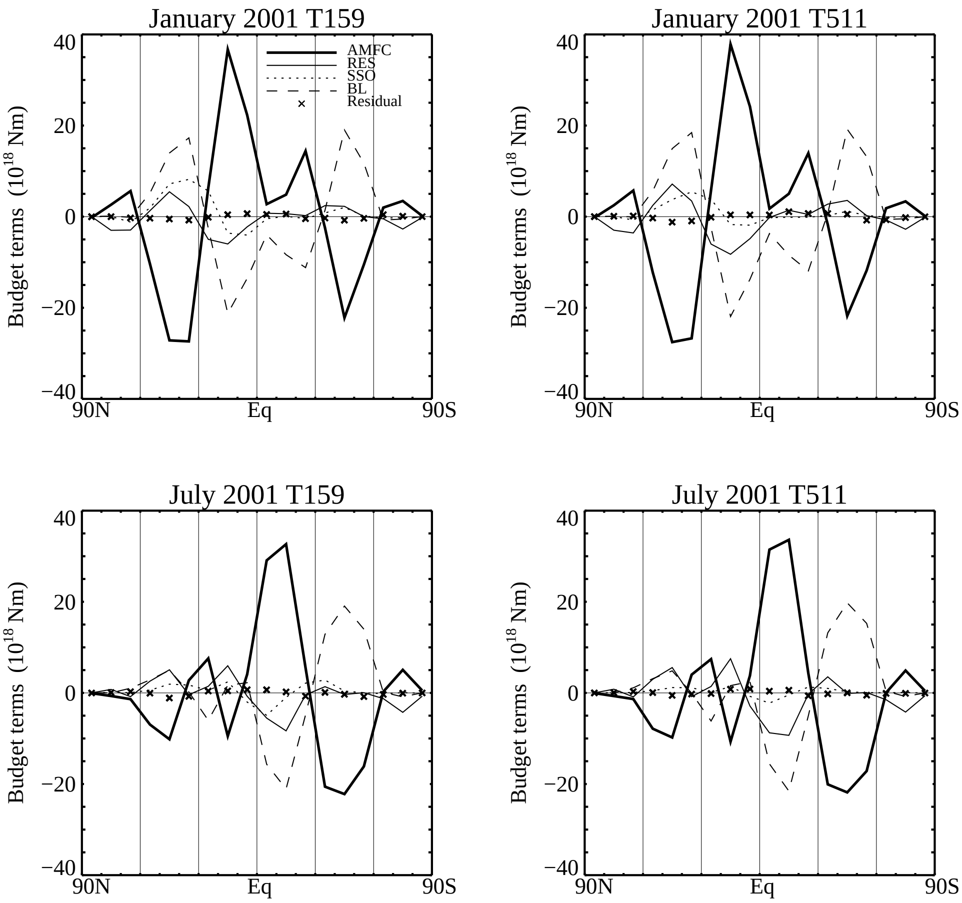

Figure 1: January and July 2001 relative angular momentum budgets at T159 and T511. In each case the terms in the budgets have been integrated over 10 degree latitude bands and averaged over the first 24 hours of each of 31 forecasts.

although tests showed that switching to three-hourly sampling had only a small impact on the results, primarily affecting the Coriolis term[1]. In spite of these issues, the residuals are generally small compared to the boundary layer, orographic and momentum flux convergence terms, suggesting that the results for these terms are reasonably reliable. Furthermore, as an extra check on the reliability of resolved orography term, it was recalculated from some of the datasets by vertically integrating the pressure gradient term calculated in the same way as in the full model. It can be shown analytically that this should give identical results to the surface-based method, although Swinbank (1985) found significant differences between the results of the two methods, which he attributed to finite difference errors. Encouragingly, the discrepancies between the results of our two independent calculations of the term were found to be very small, both at T511 and T159.

Looking first at the T159 January budget, the expected approximate balance is found between the surface torques (which add angular momentum in the tropics and remove it in the extra-tropics) and the angular momentum flux convergence term (which does the reverse). The behaviour of the surface torques is also in good agreement with that from previous studies. For example, Huang *et al.* (1999) presented results from the NCEP reanalysis (Kalnay *et al.* 1996), averaged over December to February of all of 1968 to 1996 (and showed reasonable agreement with the short-record observational estimates of Newton (1972)). Qualitatively their results appear very similar to those in Fig. 1, and, in spite of comparing long averages to the present single month results, the quantitative agreement (after scaling to match our 10 degree latitude bands and sign convention) is also reasonable. For example, the present boundary layer torque maximum value at 45 °S (19×10^{18} Nm per 10 degree latitude band) and minimum value at 15 °N (-21×10^{18} Nm) are within about 10% of the Huang *et al.* values, although the maximum value at 25 °N of around 17×10^{18} Nm is around 25% larger in the present results. The maximum and minimum values in the resolved mountain torques ($\pm 5 \times 10^{18}$ Nm) at 45 °N and 15 °N are also in very good agreement. The maximum parametrized mountain torques at 45 °N also appear to be comparable at around 7×10^{18} Nm per 10 degree latitude band, although it appears that the present results show rather more negative torques near the Equator. Interestingly, the Huang *et al.* results are consistent with Fig. 1 in showing that between 20 °N and 30 °N, the resolved and parametrized orographic torques have opposite signs, with the former acting to increase angular momentum while the latter acts to decrease it.

The July results again show the transport of angular momentum out of the tropics (10 °N to 30 °S), with this loss being balanced through the boundary layer and resolved and parametrized orographic torques. The largest magnitudes of orographic torques occur in this region. To the south of it (away from Antarctica) the primary balance is between the flux convergence term and the boundary layer torque, and the orographic terms are small. North of 10 °N there is a complicated pattern, with a double maximum in resolved mountain torque and the boundary layer torque varying with sign (such that it opposes the resolved mountain torque at around 25 °N). Once again, these results are in very good agreement with those (June to August 1968 to 1996) presented in Huang *et al.*.

It is immediately apparent from Fig. 1 that the various terms in the January and July budgets do not change very strongly with resolution (other than a change in the relative importance of resolved and parametrized orography). The resolution dependence of the surface torques will be examined in more detail in the next section. However, it is worth looking more closely at this point at the resolution dependence of the angular momentum flux convergence term. This is because the main balance in the budget is between this term and the surface torques, and resolution-independent surface torques is only an appropriate goal if this term is essentially independent of resolution. Indeed, Palmer *et al.* (1986) suggested that early general circulation models did not show a requirement for subgrid orographic drag parametrization precisely because their coarse resolution meant that they also underestimated the poleward eddy momentum flux.

[1]It is for this reason that the focus has been on the relative angular momentum budget, as uncertainties in the small Coriolis term are of relatively little consequence. However, corresponding uncertainties in the net poleward mass transport can make the residual in the total angular momentum budget much larger. Exactly the same surface torque terms appear in either budget.

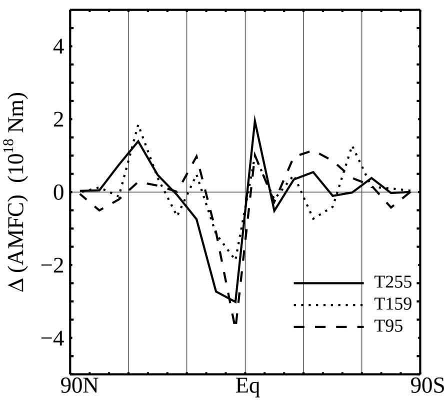

Figure 2: January 2001 average T255, T159 and T95 angular momentum flux convergence (AMFC) differences from T511 values.

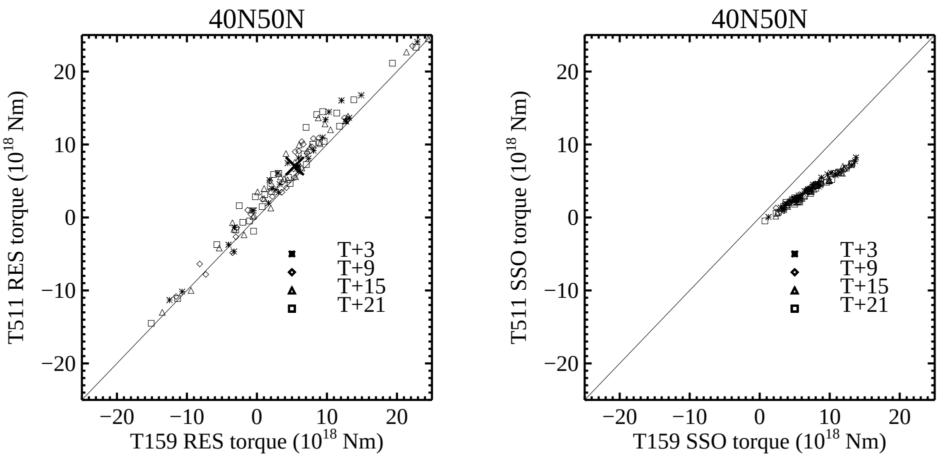

Figure 3: Scatterplots of T511 versus T159 resolved and parametrized orographic torque on the 40 °N to 50 °*N latitude band for January 2001. Results for all of the 31 days are shown for each of 4 forecast ranges.*

Fig. 2 shows the changes with resolution in the angular momentum flux convergence integrated over 10 degree latitude bands for January 2001. The lines show differences from the T511 result, and are generally in anti-phase with the T511 result (shown in Fig. 1). For example, just north of the Equator where the T511 result is positive, the difference plot shows negative values, indicating that T255, T159 and T95 do have smaller values for the flux convergence. However, here and elsewhere, the fractional changes are small (and not always monotonic). It is concluded that even T95 has sufficiently high resolution to provide a reasonably credible representation of the momentum flux.

3.2 Surface torques

The resolved orographic torques show considerable variability, particularly in mid-latitudes. An example of this can be seen in Fig. 3 which shows scatterplots of January 2001 T511 versus T159 resolved and parametrized orographic torques for the 40 °N to 50 °N latitude band. Separate data points are plotted for each 6 hour forecast

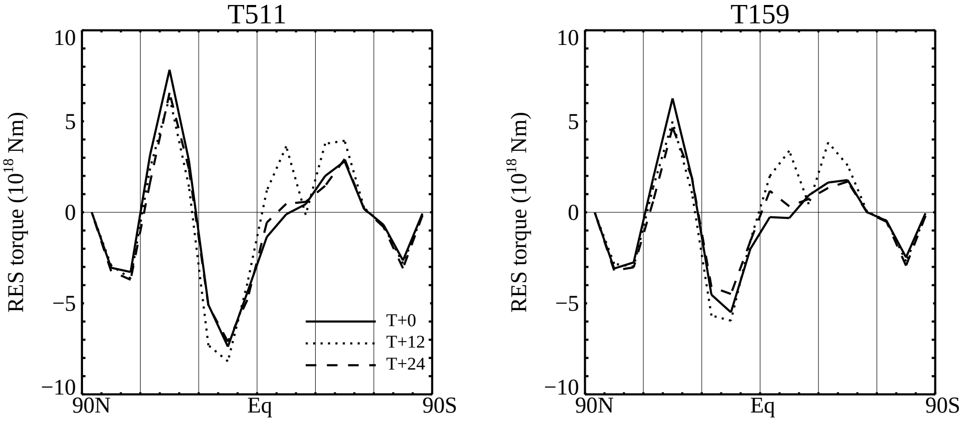

Figure 4: T511 and T159 January 2001 average resolved orographic torques on 10 degree latitude bands at T+0, T+12 and T+24.

period (labeled according to the midpoint time as T+3, T+9, T+21 and T+21) on each day. The T511 resolved values show a large spread about the mean value, even varying in sign. Time series of the resolved torque (not shown) indicate that the variations are typically on a time scale of a few days. The parametrized torques show a smaller spread, and are almost exclusively positive. As the parametrized torques depend on the low-level wind, the lack of negative values suggests that the negative resolved torques are not due to reversal of the wind across the mountains. Instead it seems likely that they are caused by the pressure perturbations associated with synoptic systems which impinge on the mountains. The same effect appears to be captured at T159, as the T159 resolved torques show very similar variability to that seen at T511. As expected, the T159 parametrized torques tend to be larger, and it appears that the magnitude of the average difference in parametrized torque is larger than that in resolved torque. The handover from resolved to parametrized torque will be discussed in more detail below (Figs. 5 to 8).

Averaging over a month, a diurnal cycle in the torques is discernible in some latitude bands. For example Fig. 4 shows the average resolved orographic torques for January 2001 at forecast ranges T+0, T+12 and T+24 hours. At T511, the torques in two bands in the southern hemisphere are significantly greater at T+12 (and also at T+6, not shown) than at T+0. This is probably associated with daytime heating over the land to the east of the Andes relative to the ocean to the west. The T+24 results lie very close to the T+0 ones in the southern hemisphere and topics, indicating that there is little drift in the resolved torques over a 24 hour period. In the northern hemisphere the drift is rather larger, with the resolved torque on the 40 °N to 50 °N latitude band decreasing by around 1×10^{18} Nm over 24 hours. The T159 results are qualitatively very similar, although the drifts in the resolved torque over 24 hours are slightly larger in the tropics.

It does not appear that any significant drifts are being introduced at T159 through the use of an interpolated analysis (which conceivably could give unrealistic results in orographic regions at early times). This was shown be performing further T159 forecasts for January 2001, initializing with ERA-40 reanalyses (Simmons and Gibson 2000), which are also at T159 and hence did not require interpolation. These tests did not show any systematic reduction in the magnitudes of the torque changes over 24 hours. Furthermore, many of the objective verification scores for the 10 day T159 forecasts run from the interpolated operational 4-D variational assimilation analysis were slightly higher than those from the 3-D variational assimilation analysis from ERA-40.

Figure 5 shows scatterplots of the difference in parametrized orographic torque on 10 degree latitude bands

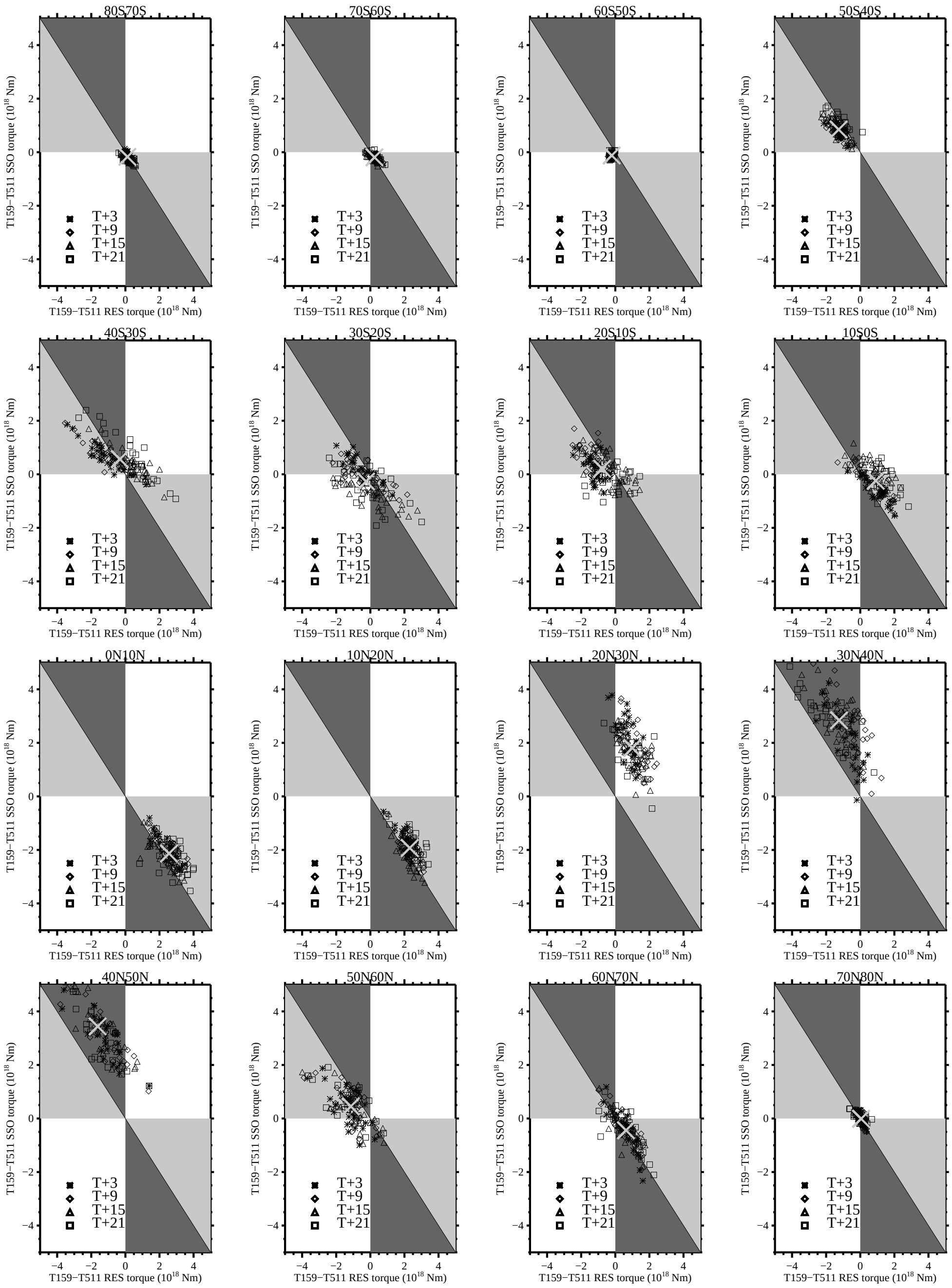

Figure 5: Scatterplots of SSO torque differences between T159 and T511 versus RES torque differences for January 2001. For each latitude band, the results for all of the 31 days are shown for each of 4 forecast ranges. The large crosses indicate the average results over all days and times.

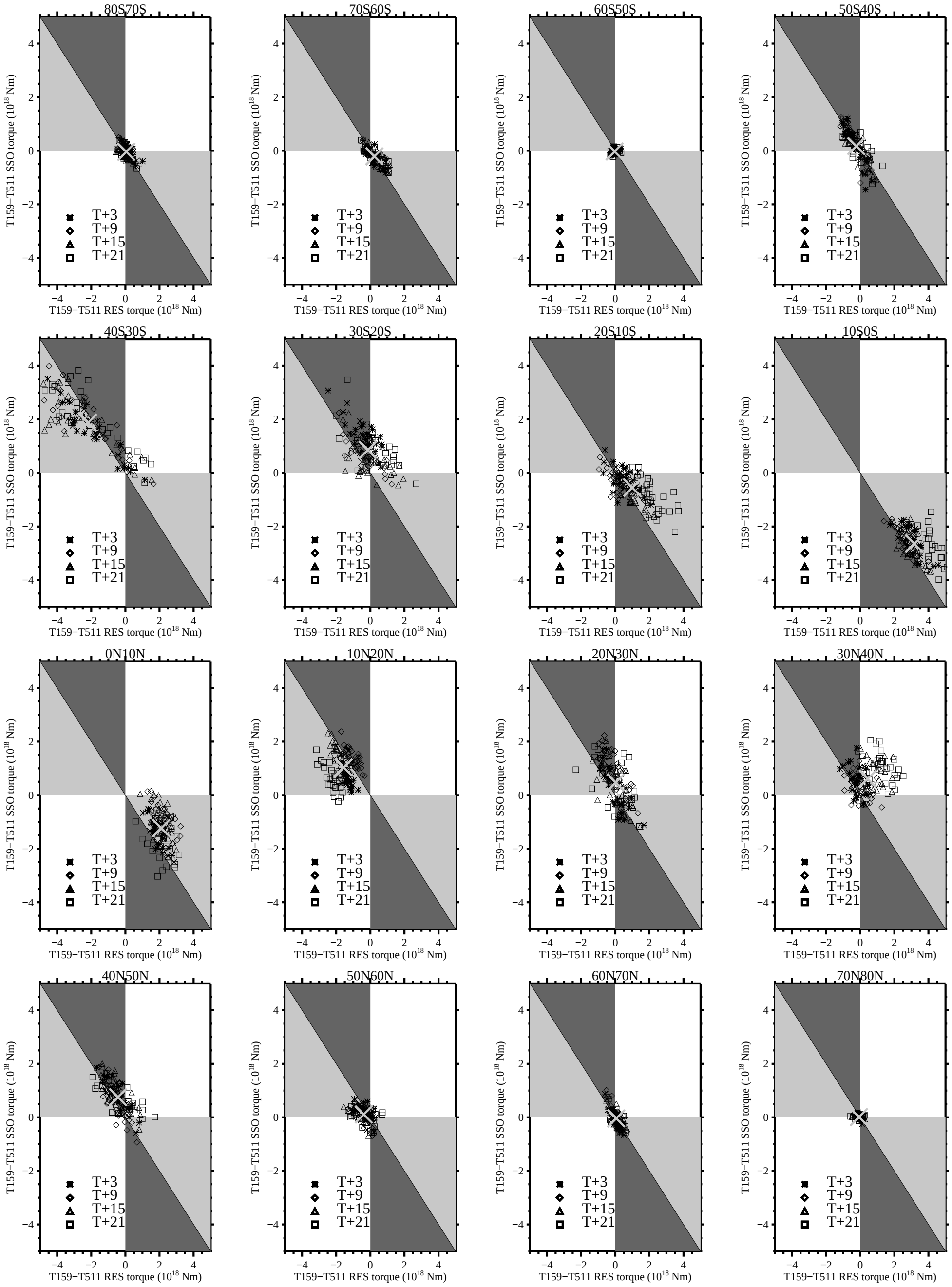

Figure 6: As Fig. 5, except for July 2001.

between T159 and T511 versus the difference in resolved torque. As in Fig. 3, separate data points are plotted for each 6 hour forecast period for each of the 31 days of January 2001. Additionally the large cross indicates the average across all days and times. Points lying on the diagonal running from top left to bottom right indicate that the difference in parametrized torque is equal and opposite to the difference in resolved torque i.e. total orographic torque constant. Points in the shaded regions have the differences of opposite signs. Where the shading is dark, the magnitude of the parametrized torque difference is bigger than that of the resolved difference (i.e. the parametrization overcompensates for the change in resolved torque). Conversely, where the shading is light, the magnitude of the parametrized torque difference is smaller than that of the resolved difference (i.e. the parametrization undercompensates for the change in resolved torque). Points in the unshaded regions have resolved and parametrized torque differences of the same sign.

In general, both the averages and the individual points lie reasonably close to the diagonal that indicates constant total torque. The most notable exceptions are in the latitude bands between 20 °N and 50 °N. In all three of these bands the magnitude of the mean difference in parametrized torque exceeds that of the mean difference in resolved torque. For 30 °N to 40 ° and 40 °N to 50 ° all of the torques are positive, and the result is a larger total orographic torque at T159. For 20 °N to 30 °N the resolved torques are negative while the parametrized ones are positive. Moving from T511 to T159 actually causes both torques to change in the same sense (as the resolved torque becomes less negative while the parametrized torque becomes more positive), again with the result that the total orographic torque is increased.

The increased orographic torque at T159 compared to that at T511 for the bands between 20 °N and 50 °N is seen not just in the mean, but also for almost every individual data point in the scatter plots. Furthermore, separate averages over the month for each of the 4 different forecast ranges (not shown) showed little or no significant drift of the signal with time.

As an aside it is noted that if the spread in resolved torque differences were much greater than that in parametrized torque differences, then this would indicate greater variability in the total torques at higher resolution. This in turn could provide motivation for introducing a stochastic element to the parametrization to increase the variability of the torques at low resolution. However, Fig. 5 shows that spread in parametrized torque differences is typically comparable to that in the resolved torques. Hence no compelling evidence of the need for a stochastic parametrization at these resolutions is found. At still lower resolution it is speculated that some of the variability seen in the resolved torques in the present study might be lost, and that such a parametrization might be useful.

Figure 6 shows scatterplots of the resolved and parametrized orographic torque differences for July 2001. Once again most of the points lie reasonably close to the diagonal indicating constant torque. Notably the results from the 20 °N to 50 °N latitude bands stand out much less strongly as outliers than was the case in Fig. 5 (although there is still some increase in total torque at lower resolution in the 30 °N and 40 °N band).

In order to investigate further and quantify the variation of the orographic torques with resolution, the results obtained across a wider set of resolutions will now be examined by additionally considering the T255 and T95 data. This analysis will be restricted to the monthly mean results. Figure 7 and 8 show the January and July 2001 results for the differences of the T255, T159 and T95 resolved, parametrized and total orographic torques from the T511 values. Additionally the changes in boundary layer torque are shown.

Looking first at the January results, the variations of the resolved and parametrized torques with resolution can be seen to be monotonic in almost all latitude bands. However, between 20 °N and 50 °N, the rate of decrease of the resolved torque as the resolution is made coarser is considerably slower than the rate of increase of the parametrized torque (as previously seen when comparing just the T511 and T159 results). The total orographic torques are therefore greater at coarser resolution, exceeding the T511 values by around 4×10^{18} Nm per 10 degree latitude band at T95, by around 2×10^{18} Nm at T159 and by between zero and 1×10^{18} Nm at T255.

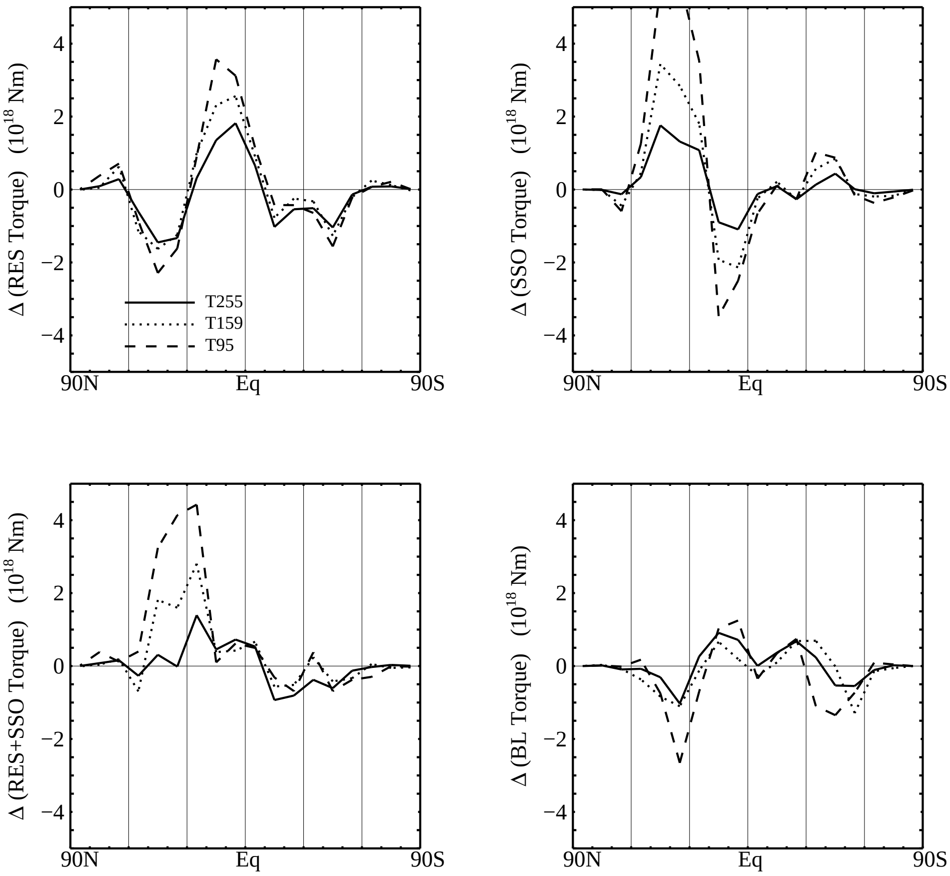

Figure 7: January 2001 average T255, T159 and T95 RES, SSO, RES+SSO and BL torque differences from T511 values.

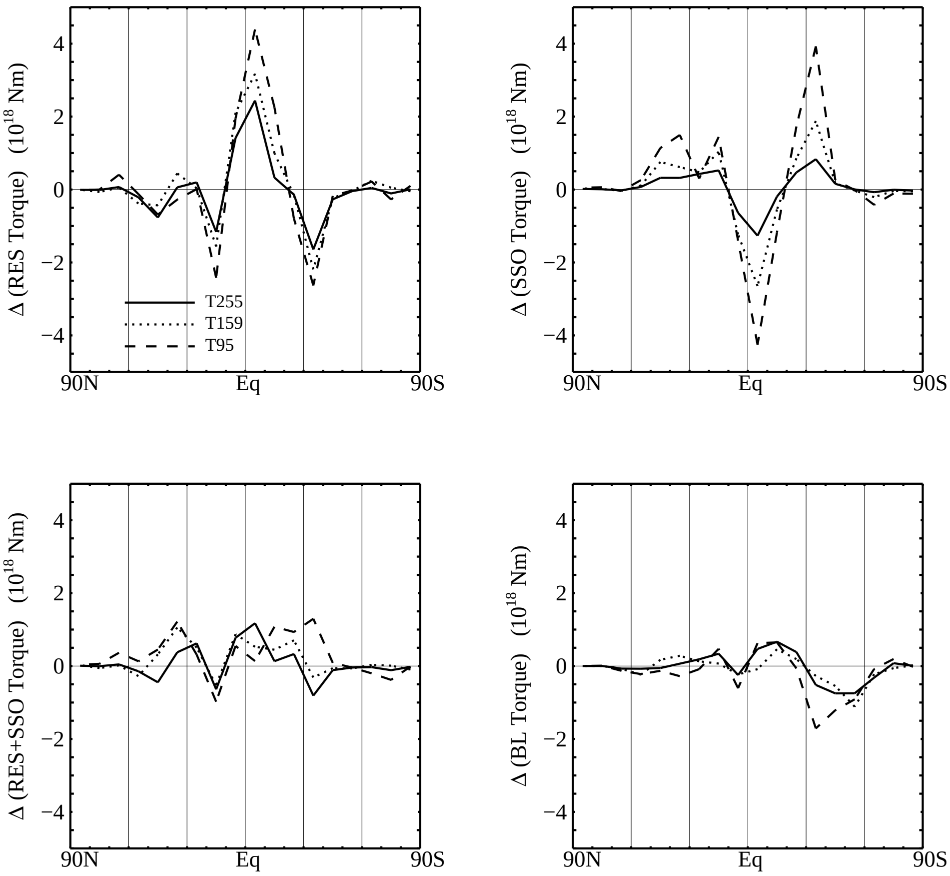

Figure 8: As Fig. 7, except for July 2001.

In the tropics and southern hemisphere the signal in the total orographic torques is much weaker (typical differences from T511 values of only around 0.5×10^{18} Nm) and not always monotonic. However, it appears that, unlike in the 20 °N to 50 °N bands, the parametrization is slightly undercompensating for the resolved changes, as the total torque differences tend to be positive where the torques are negative and vice versa. Interestingly, the different behaviour between 20 °N and 50 °N appears to arise because the fractional changes with resolution of the resolved torques are smaller than elsewhere (and not because the fractional changes in the subgrid torques are larger).

Some changes are also seen in the boundary layer torques, with the magnitudes decreasing slightly as the resolution is decreased. Primarily this is probably because of a loss of variance, particularly at T95. However, it is likely that there is also some interaction with the parametrized orographic stress. In principle it would preferable if this were not the case, as the scales handled by the boundary layer scheme will be completely unresolved for all of the resolutions studied. However, most of the parametrized orographic drag is associated with flow blocking and is applied below the assumed subgrid mountain tops, reducing the low-level wind speeds and hence the magnitude of the boundary layer stress. Changes in the parametrized orographic torque (e.g. when changing resolution) may therefore partially be opposed by changes in the boundary layer torque, although tests at T159 in which the parametrized orographic torque was completely removed found that the boundary layer response typically only recovered around 15% of the torque. Furthermore, it is clear from Fig 7, that the boundary layer stress torque changes with resolution (whether due to variability changes or interactions with the orography scheme) only compensate to a limited extent for the total orographic torque changes between 20 °N and 50 °N. Hence the total surface torques (orographic plus boundary layer) in all three bands increase with decreasing resolution.

The July results (Fig. 8) also show monotonic changes in the resolved and parametrized orographic torques. The changes in total orographic torque with resolution are typically small compared to those seen in January (maximum magnitudes of around 1×10^{18} Nm per 10 degree latitude band), and not always monotonic. However, as the resolution is decreased there is a tendency for the parametrized stress to change too quickly at around 35 °N, leading to an increase in total orographic torque, while it changes too slowly from around the Equator to 20 °S, making the total torque become less negative.

3.3 Errors in angular momentum evolution

The results presented in the previous section have shown that the total orographic torque does show some resolution sensitivity, with significantly larger values being obtained between 20 °N and 50 °N in winter at coarser resolution. In this section, an attempt is made to use the errors in the modelled angular momentum evolution to infer whether the problem is with the low resolution orographic torques being too large, or with the high resolution torques being too small. However, due to the difficulty of isolating problems with orographic torques from problems with other terms in the angular momentum budgets, the results will be suggestive rather than definitive.

E_r is defined to be the average rate of change away from analysis (i.e. forecast rate of change minus rate of change in analysis) in the vertically integrated relative angular momentum on a 10 degree latitude band. The top panels in Fig. 9 show this quantity calculated over 24 and 120 hour forecasts for January 2001. Results are shown for T95, T159 and T511 and additionally for an extra series of simulations performed at T159 but with the Lott and Miller parametrization switched off (T159 NO SSO). Comparison of the results from this last series with the standard T159 results is useful in order to give an indication of the level of sensitivity of the results to the orographic parametrization.

Looking first at the T+24 forecast results, the relative angular momentum decreases between 20 °N and 50 °N

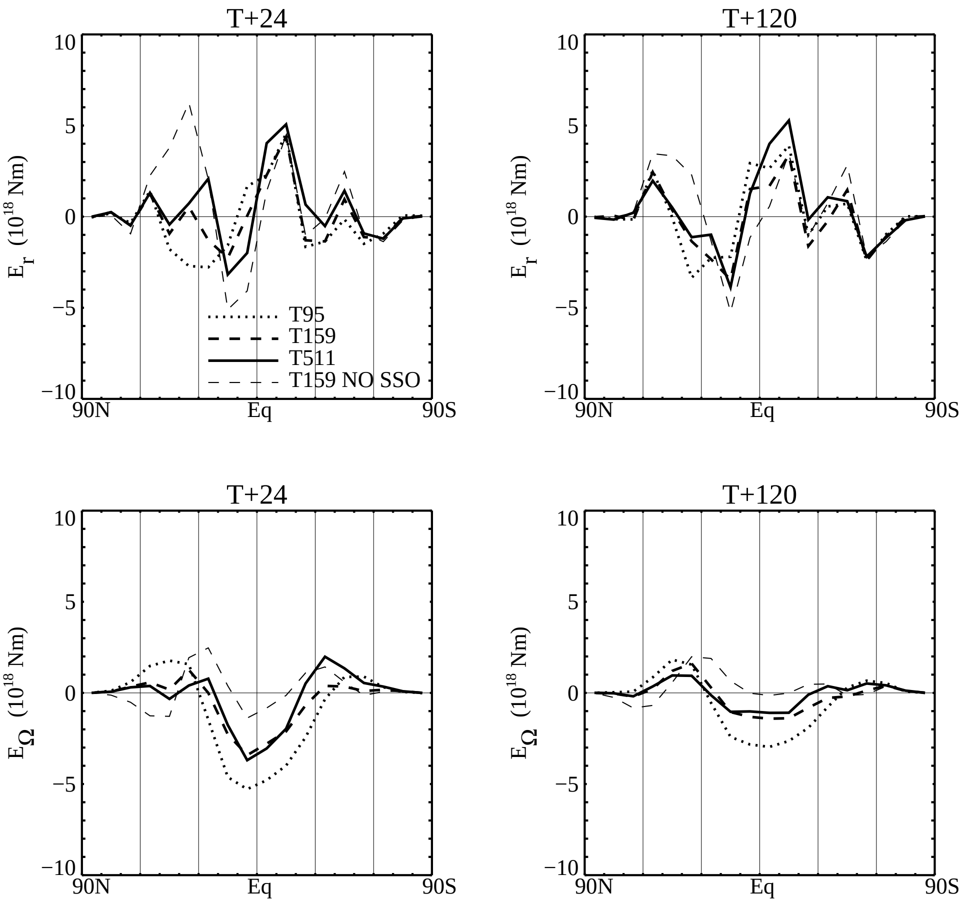

Figure 9: E_r and E_Ω, rates of change away from analysis of vertically-integrated relative and $\Omega-$angular momentum in 10 degree latitude bands, averaged over 24 and 120 hour forecasts for January 2001. Results are shown for T95, T159 and T511, and additionally for an extra set of T159 forecasts (T159 NO SSO) performed with the Lott and Miller orographic parametrization switched off.

as the resolution is degraded, consistent with the torque changes already identified. Also as expected, removal of the orographic parametrization results in a large increase in angular momentum. In this region, E_r is slightly positive at T511, slightly negative at T159, and more significantly negative at T95. It is therefore seems probable that the parametrized orographic torques are too large at T95. However some caution is required, as comparable magnitudes of E_r are obtained in other latitude bands (e.g. around 15 °S) in which the orographic torques are small. This implies that the errors in other terms in the angular momentum budget can be significant, and the possibility that they are contributing to the values of E_r between 20 °N and 50 °N cannot be ruled out.

The results for E_r averaged over 120 hour forecasts are qualitatively similar, with T95 still tending to lose angular momentum relative to T159 and T511 between 20 °N and 50 °N . However the differences between the different resolutions are rather smaller than before, and even T511 now shows negative values of E_r between 20 °N and 40 °N.

As well as causing changes in the evolution of the relative angular momentum, changes in the orographic torques also have an impact on the global mass distribution. As the Ω-angular momentum per unit mass varies only with latitude ($m_\Omega = \Omega a^2 \cos^2\phi$, where Ω is the rate of rotation of the Earth), this in turn causes changes in the distribution of Ω-angular momentum. E_Ω is defined to be the rate of change away from analysis in the total (after vertical and horizontal integration) Ω-angular momentum in 10 degree latitude bands. The bottom panels in Fig. 9 show this quantity averaged over 24 and 120 hour forecasts for January 2001. In the 24 hour forecast results, T511 and T159 both show negative values of E_Ω in the tropics and smaller magnitude positive values elsewhere. These signals are caused by a net mass poleward mass transport relative to that seen in the analyses, and correspond to erroneous zonal mean pressure signals of around -0.2 mb/day in the tropics and $+0.2$ mb/day at high latitudes. Over 120 hours the average signals are qualitatively similar, although generally smaller in magnitude, indicating that the adjustment is most rapid in the first 24 hours of the forecast.

Evidence that the E_Ω signals are sensitive to the orographic parametrization comes from the comparison of T159 and T159 NO SSO. T159 NO SSO shows more positive values between 40 °N and 40 °S, with on average a net mass transport into that region (although in the T+24 panel E_Ω remains negative close to the Equator, indicating that the non-zero values are clearly not solely due to the orographic parametrization). Outside this region, T159 NO SSO shows decreased values of E_Ω. Furthermore, although the magnitude of the signal in the Northern hemisphere does not appear to be particularly large compared to that in the the tropics, this is primarily due to the cosine-squared factor in the m_Ω definition, and a big signal is seen in the zonal mean pressure. North of around 40 °N it is significantly reduced when the orographic parametrization is removed, now showing erroneous changes relative to analysis of about -0.5 mb/day (over both the 24 and 120 hour forecasts).

Compared to T159 and T511, the T95 results show larger errors, with a bigger loss of Ω-angular momentum in the tropics, and a bigger gain elsewhere. These changes are in the opposite sense to those obtained when the orographic parametrization is removed at T159. Hence these results are consistent with the suggestion that the larger orographic torques at T95 are leading to larger errors.

4 Conclusions

An evaluation of the performance of the subgrid orography scheme in the ECMWF IFS has been made by examining the variation of the surface orographic torques in short-range forecasts (from each day of January and July 2001) across a range of resolutions (T95 to T511). It has been shown that the changes with resolution in the other terms in the relative angular momentum budget are generally small compared to those in the resolved and parametrized orographic torques, and hence seeking constant total orographic torque is an appropriate goal. An advantage of this approach, compared to performing a detailed budget analysis at a single resolution, is that it provides a more direct way of evaluating the performance of the orographic parametrization which is less sensitive to errors in other parametrization schemes.

Although the day to day torques were found to be very variable, the average changes over a 24 hour forecast were found to be small, and no evidence was found of problems associated with the use of an interpolated analysis for the lower resolution forecasts. Increasing the model resolution was shown to increase fairly monotonically the magnitudes of the resolved orographic torques, while decreasing the parametrized ones (due to the changes in the ancillary fields characterizing the subgrid orography). In general the handover was found to be reasonably successful, with a relatively weak sensitivity of the total orographic torque to resolution. However, between 20 °N and 50 °N in winter (where the absolute values of the torques are at their largest), the parametrized torques were found to respond much more strongly to resolution changes than the resolved ones. This led to total orographic torques at T95 which were approximately 40% larger than the T511 values of around 10×10^{18} Nm per 10 degree latitude band.

Analysis of errors in the angular momentum budgets has suggested that it is the parametrized torques in the low resolution simulations that are excessive. Interestingly, Huang *et al.* (1999) concluded from drifts in the global angular momentum that the parametrized orographic torques in the NCEP reanalysis were also excessive. Hence it is possible that there may be a general problem in coarse resolution models. As advocated by Huang *et al.*, further review of the orographic parametrizations used in climate models (which would typically use resolutions of close to T95), would seem to be appropriate.

More work is required in order to investigate further and attempt to reduce the resolution sensitivities identified in the previous study. As a short term measure, a simple tuning down of the subgrid parametrization (e.g. by reducing the maximum permitted blocked layer depth which, at three standard deviations, is arguably excessive) at low resolution might be appropriate. However, the same change at T511 might make the torques too small in that case. Furthermore, the fact that the sensitivity of the orographic torque to resolution between 20 °N and 50 °N appears to be different to that elsewhere also suggests that simple scaling alone cannot be a complete solution.

One useful avenue of further research will be to look more closely at the torques on individual mountain massifs, rather than on complete latitude bands. This will remove complications associated with adding possibly opposing signals from different mountain ranges. It may also make it easier to characterize the flow and so, for example, assess whether the resolution dependence varies with the flow conditions (e.g. incident wind strength and stability). If so, then that may indicate problems with the parameter dependence of the parametrization scheme.

It will also be useful to examine the behaviour of the orographic torques at still higher resolutions which capture explicitly more of the true dynamics. Preliminary tests with the global IFS at T799 have indicated a continuation of the trends already identified, although T799 will still be insufficient to model many of the flow features known to occur in mountainous regions. Still more powerful would be the routine diagnosis and comparison of torques from global models and much higher resolution nested mesoscale models.

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