TECHNICAL MEMORANDUM

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Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model

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Abstract

The sensitivity to horizontal resolution of Northern Hemisphere extratropical cyclone characteristics during the wintertime (Dec–Mar) is investigated using a set of seasonal forecasts (1982–2001) with the ECMWF model. Three different horizontal resolutions (T_L95, T_L159 and T_L255) are employed. In order to test the realism of the simulations the model results are compared with those obtained from ERA-40 reanalysis data. The cyclone tracking is accomplished by applying an automatic tracking scheme to 6-hourly mean sea level pressure data. It is shown that many of the key-characteristics of extratropical cyclones in the ECMWF model are highly sensitive to horizontal resolution, with the low-resolution version (T_L95), for example, simulating only about 60% of the reanalyzed total number of extratropical cyclones. Regions found to be particularly sensitive include the North Pacific, the Arctic, Baffin Bay and the Labrador Sea as well as the Mediterranean Sea. For the latter region it is shown that even the relatively high-resolution version of the model (T_L255) underestimates the number of cases of Genoa cyclogenesis significantly. Furthermore, it is shown that in some regions, such as the entrance regions of the major Northern Hemisphere storms, model deficits are insensitive to increases in horizontal resolution. The same analysis has been repeated for the high-resolution operational ECMWF analysis (2000–04) truncated at different total wavenumbers (T_L95, T_L159, T_L255 and T_L511) in order to separate dynamical effects of differences in resolution from those due to pure spectral truncation. It is found that the dynamical effect of changing horizontal resolution dominates over the truncation effect for intense cyclones, whereas the truncation effect dominates for shallow cyclones.

1 Introduction

Extratropical cyclones represent one of the key-features of the atmospheric circulation. They are responsible for a significant amount of the poleward transport of heat, moisture and momentum in the atmosphere. Moreover, they have large impacts on society, primarily due to their capability of producing severe weather events (e.g., Buizza and Hollingsworth 2002, Jung et al. 2004).

Forecasting extratropical cyclones represents one of the main challenges on time scales from days to decades and atmospheric general circulation models (AGCMs) provide the main tools to accomplish this task. The realism of AGCMs depends on a variety of factors including horizontal resolution. Increasing horizontal resolution generally leads to a more realistic explicit representation of small-scale features like, for example, frontal zones and orography and is therefore desirable. However, increasing horizontal resolution is by no means the only way to improve AGCMs. Given limited computer resources, model developers have to decide how much of the computer resources to spend on resolution and how much on other model aspects. Therefore, it is necessary to understand how sensitive AGCMs are to changes in horizontal resolution.

The sensitivity to horizontal resolution has been extensively studied in the past (e.g., Tibaldi et al. 1990, Boyle 1993, Williamson et al. 1995, Brankovic and Gregory 2001). However, the focus has been on the sensitivity of the mean climate to horizontal resolution. A common conclusion of these studies is that the largest changes occur when increasing the horizontal resolution from T21 (triangular truncation at total wavenumber 21) to T42; further increases lead to relatively minor changes (resolutions up to T159 have been studied).

In the above studies the sensitivity of extratropical cyclones—or more precisely transient waves—to horizontal resolution has also been investigated by considering bandpass-filtered time series on a grid point basis (sometimes referred to as the Eulerian perspective). As pointed out by Hoskins and Hodges (2002), however, a more detailed picture of extratropical cyclone characteristics can be obtained by tracking individual cyclones and diagnosing a large set of such tracks along with derived quantities such as the number of cyclones, cyclone deepening rates or the number of cases of cyclogenesis.

The tracking of extratropical cyclones in observational (e.g., Roebber 1984, Sinclair 1994, Serezze 1995, Gulev et al. 2001) and model data sets (e.g., Koenig et al. 1993, Blender and Schubert 2000) is common practice, particularly in the climate community. To our knowledge, however, little previous work has been done (e.g., Slingo et al. 2003, Martin et al. 2004) to quantify the sensitivity of simulated extratropical cyclones characteristics to horizontal resolution using extratropical cyclone tracking diagnostics. This might come somewhat as a surprise given that processes, which are crucial during the lifecycle of extratropical cyclones, operate near the truncation scale of AGCMs (e.g., orographic and diabatic forcing).

One aspect of the sensitivity of (automatically-tracked) extratropropical cyclones to horizontal resolution has been investigated by Blender and Schubert (2000). They carried out one seasonal integration for the winter season 1992/93 with the ECHAM4 model using a relatively high horizontal resolution of T106. For subsequent cyclone tracking the original T106 fields were truncated at different horizontal resolutions (T21, T42, T63 and T84). Blender and Schubert (2000) show that the number of identified cyclones decreases with decreasing resolution. It should be pointed out, however, that this sensitivity only reflects the pure influence of spectral truncation. (Truncating fields to a lower resolution might reduce the number of cyclones simply because small-scale particularities of the sea level pressure fields are less well represented.) The sensitivity of simulated adiabatic, diabatic and orographic processes to horizontal resolution is not accounted for by this approach.

The aim of this study is to quantify the sensitivity of extratropical cyclone characteristics to horizontal resolution taking the possible resolution-dependence of model dynamics, physics and orography into account. To this end we carry out seasonal integrations with the ECMWF model at three different horizontal resolutions. Extratropical cyclone characteristics are derived using an automatic tracking scheme. The focus is on the winter season (December through March).

The paper is organized as follows. In the next section the methods used in this study will be given including a description of the ECMWF model, the experimental setup and the technique used for extratropical cyclone tracking. Then the results will be given. Finally, the results of this study are summarized and discussed.

2 Methods

2.1 Data

The sensitivity of extratropical cyclone characteristics to horizontal resolution is studied using the atmospheric model component of the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). Specifically, numerical experimentation is based on model cycle 29r1, which was used operationally at ECMWF from 5 April to 27 June 2005 to carry out medium-range weather forecasts. In total, three different resolutions were tested. The lowest horizontal resolution employed, which is operationally being used at ECMWF for seasonal forecasting, is T_L95. The second resolution considered is T_L159, which corresponds to the resolution used to carry out monthly forecasts (Vitart 2004). The highest horizontal resolution being investigated is T_L255, which is also the resolution of the ECMWF ensemble prediction system for medium-range weather forecasts at the time of writing (Molteni et al. 1996). The experiments at T_L95 and T_L159 were carried out using 60 levels in the vertical. For the high-resolution run at T_L255, 40 vertical levels were used in order to reduce the computational burden. Notice, however, that the 40 level version of the model differs from the 60 level version primarily in the stratosphere; the vertical resolution in the troposphere is comparable (Untch and Simmons 1999).

For each of three resolutions 6-month long integrations were started on 1 October of each of the years 1982–2001, a total of 20 integrations for each resolution. All results presented in this study are based on the months of December–March only (the first two months were discarded), in order to ensure independence of the different experiments from the initial conditions. Atmospheric initial conditions are based on ERA-40 reanalysis data

Table 1: Main characteristics of the datasets used in this study. Values of the resolution given in parentheses are approximate values in degrees latitude/longitude.

Abbreviation	Note	Cycle	Resolution	Levels	Period
ERA-40	Reanalysis	23R4	T_L159 (1.125)	60	1982–2001
EC-T95	Model run	29R1	T_L95 (1.875)	60	1982–2001
EC-T159	Model run	29R1	T_L159 (1.125)	60	1982–2001
EC-T255	Model run	29R1	T_L255 (0.700)	40	1982–2001

(Uppala et al. 2005). Observed sea surface temperature fields were used as lower boundary condition. The performance of earlier model cycles in simulating the observed climate is described elsewhere (e.g., Jung and Tompkins 2003, Brankovic and Molteni 2004, Jung 2005).

In order to evaluate the realism of the ECMWF model at different horizontal resolutions, ERA-40 reanalysis data (Uppala et al. 2005) are used as the truth. Abbreviations and main characteristics of the datasets used in this study are summarized in Tab. 2.1.

The datasets described above are augmented by operational ECMWF analysis fields for the period 2000–04, which are available at T_L511 (about 40 km resolution). The analysis data were also truncated at the resolution used in the seasonal integrations (T_L95, T_L159 and T_L255). Notice, however, that the underlying dynamics, physics and orography used is basically the same at all truncations. The investigation of the analysis data at different truncations, which closely follows the methodology introduced by Blender and Schubert (2000), allows us to separate the pure impact of spectral truncation (i.e., the smoothness of the fields on small spatial scales) from that due to different dynamics, physics and orography. Hereafter, we shall use the abbreviations AN-T511, AN-T255, AN-T159 and AN-T95 for the analysis data at different spectral truncations.

2.2 Cyclone tracking

For the cyclone tracking of all model experiments, ERA-40 reanalysis and operational analysis data we used 6-hourly SLP (sea level pressure) output. Cyclone tracking of all data sets has been performed using the numerical tracking algorithm of Zolina (2002), which has been used for the tracking extratropical cyclones in NCEP/NCAR reanalysis data (e.g., Zolina and Gulev 2002, 2003). This algorithm was developed on the basis of a reference dataset of storm tracks for the 42 winters of the period 1958–1999 (Gulev et al. 2001), which was obtained using the semi-manual software of Grigoriev et al. (2000). In the automatic method by Zolina (2002) the tracking is performed on a polar orthographic projection which has 181×181 points with the center on the North Pole. This projection significantly enlarges polar and midlatitudinal regions in comparison to the tropics, allowing for more effective cyclone identification and tracking. Interpolation of the $2.5^o \times 2.5^o$ degree data (the original SLP data on the Gaussian grids were first interpolated onto a common regular $2.5^o \times 2.5^o$ grid) onto the polar orthographic grid was carried out using the modified method of local procedures (Akima 1970), which is very accurate and does not create any intermediate artificial extrema. The interpolation of the original data onto a common $2.5^o \times 2.5^o$ grid ensures that similar spatial scales are identified for each data set. Moreover, the original automatic tracking scheme has been optimized for SLP on a $2.5^o \times 2.5^o$ grid.

The pre-processing of the SLP data includes the dynamical interpolation of the 6-hourly SLP fields onto shorter time steps (1-hourly). This involves the numerical solution of $dSLP/dt = \mathbf{u} \cdot \nabla SLP$, where $\mathbf{u}$ denotes the cyclone propagation vector (since the time derivative and the gradient are known $\mathbf{u}$ can be obtained). The solution gives SLP fields at a higher temporal resolution. One important feature of this method is that SLP patterns (cyclones) are allowed to propagate, which is not necessarily the case for purely linear interpolations schemes. For the present study the performance of the dynamical interpolation scheme has been considerably improved, using several years of SLP data from the ECMWF model (at T_L159) with a temporal resolution of 1 hour (1-hourly data have been archived during the model run). Using 1-hourly snapshots the dynamical interpolation scheme was tuned. Validation of the so adjusted automatic tracking code showed that the error in the total number of Northern Hemisphere cyclones is less than 1%; regionally the errors do not exceed 5%; and no significant changes in the cyclone lifecycle are evident.

The tracking procedure begins with the identification of cyclones through the analysis of the local SLP minima ($<$ 1025 hPa). This step involves several iterations and includes the analysis of SLP derivations computed from the 17 neighbouring points, determination of the impact area and the analysis of SLP characteristics within this impact area. The tracking procedure itself starts from the so-called method of the closest neighbours, also employed as initial step in the schemes of Murray and Simmonds (1991), Koenig et al. (1993), Sinclair (1997), Hodges (1994), Hodges and Hoskins (2001) and others. This steps provides a first guess of cyclone migration. Further identification of the tracks involves the 3-pass analysis of cyclone propagation velocities, sorting of the crossing trajectories and separate analysis of the stationary cyclones. Unless stated otherwise *all* tracked cyclones were used for further analysis including short-lived, quasi-stationary systems.

Characteristics of cyclone activity are computed from the output of the tracking scheme (coordinates, time and corresponding SLP values in the cyclone centers). To characterize the spatial distribution of cyclone activity we used a grid, developed by Zolina and Gulev (2002), which has $5^o \times 5^o$ grid cells south of 70^oN and variable grid cell sizes from $10^o \times 5^o$ to $15^o \times 8^o$ north of 70^oN, including the circle rounded at 88^oN. This grid partly accounts for the uncertainties of mapping associated with orientation of cells (Taylor 1986). According to Zolina and Gulev (2002) cyclone activity can be characterized by the cyclone frequency (the number of the pressure minimum events, counted by an Eulerian observer within the box during the chosen time interval) and the number of cyclones (the number of SLP minima passing the box during the time interval, with multiple entries being ignored). Sometimes these quantities are called the cyclone density and track density (e.g. Sinclair 1994). For the datasets used in this study it has been found that the basic conclusions (including regional features) are the same for the two parameters. Hence, only results for the number of cyclones are shown. Zolina and Gulev (2002) quantified systematic and random uncertainties associated with fast cyclones (i.e., cyclones passing the grid cells faster than the time step of the tracking). For 6-hourly output used in this study these uncertainties were found to be small. For proper mapping all cyclone numbers are given per $218000\,km^2$ (i.e., the area of a 5-degree box at 45^oN).

Besides the spatial fields of cyclone numbers and frequencies, we analysed for each cyclone the characteristics of the cyclone lifecycle. Cyclone intensity was quantified as the minimum central pressure during the cyclone lifecycle. Cyclone lifetime has been estimated as the number of k-hourly intervals, forming the cyclone trajectory, k being the time resolution of the tracking. Note that the accuracy of the lifetime is approximately equal to $\pm k/2$ hours (Gulev et al. 2001). Maximum deepening rates, δp, are given by the maximum SLP reduction during 6 hours for the lifecycle of the extratropical cyclone. Following Roebber (1984, 1989) and Serreze (1995), all deepening rates were normalized by $\delta p_{norm} = \delta_p(\sin\phi/\sin\phi_{ref})$, where ϕ_{ref} is a reference latitude (45^oN). This geostrophic adjustment accounts for a latitude-dependent storm vorticity change.

3 Results

In order for the reader to become more familiar with extratropical cyclone tracking diagnostics in Fig. 1 all extratropical cyclone tracks for the winters of the period 1998–2000 are shown for ERA-40 reanalysis data and the numerical experiments carried out at different resolutions. The first thing to notice is that the total number

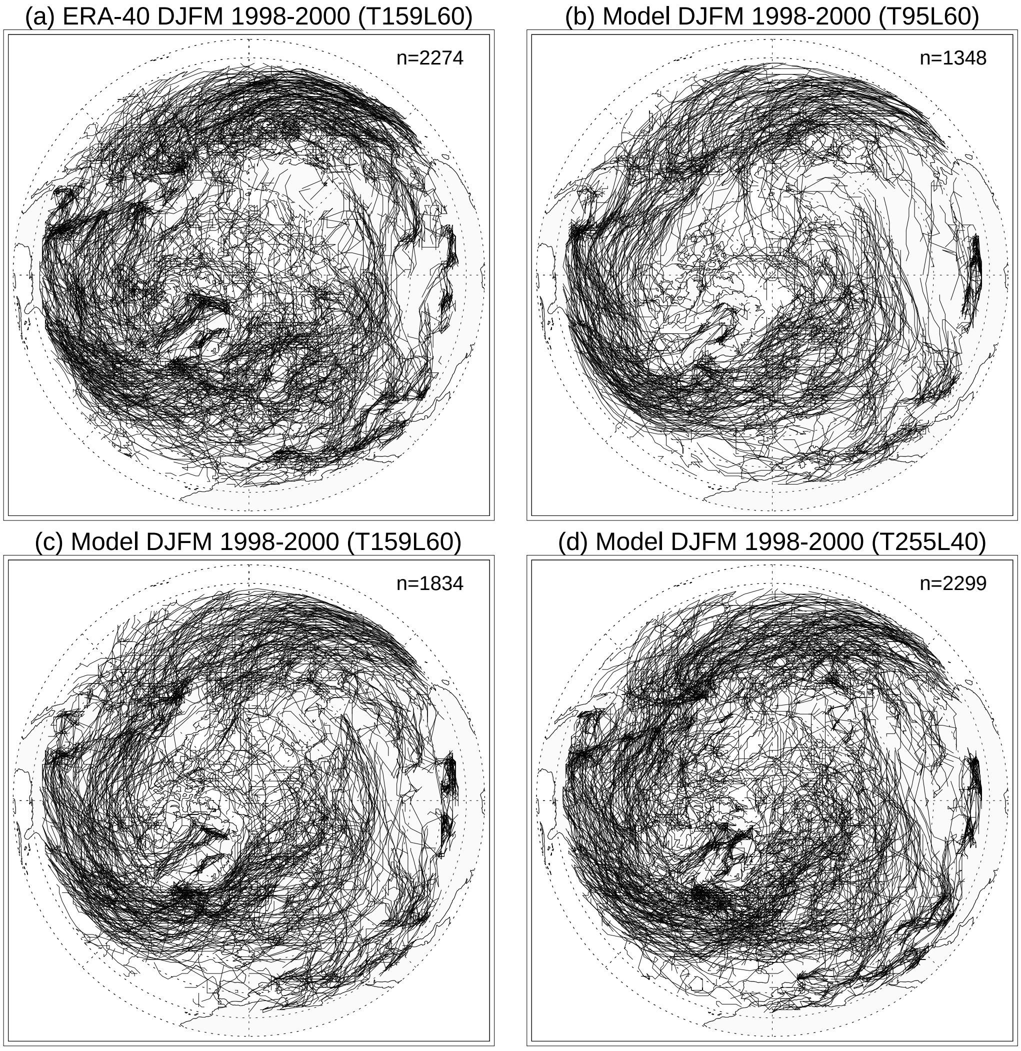

Figure 1: Extratropical cyclone tracks for the three winters (DJFM) of the period 1998–2000: (a) ERA-40 reanalysis data, (b) EC-T95, (c) EC-T159, and (d) EC-T255. The total number of Northern Hemisphere cyclones for the same period is given by n.

of simulated Northern Hemisphere cyclones increases with increasing resolution. Whereas only about 60% of the reanalyzed extratropical cyclones are simulated at T_L95, the total number of cyclones is quite realistic if a resolution of T_L255 is employed. From Fig. 1 it is also evident that the resolution dependence shows regional differences. In the EC-T95 experiment, for example, the North Atlantic storm track and its north-eastward extension is much more confined than in the observations. Furthermore, the lower-resolution model underestimates the number of cyclones in the Arctic, over north-eastern Canada, the Baffin Bay and Labrador Sea as well as in the Mediterranean. Increasing horizontal resolution is clearly beneficial in terms of reducing the above-mentioned problems. However, even at a relatively high resolution of T_L255 there is some indication that the number of cyclones in some areas such as the Mediterranean Sea is underestimated. In summary, Fig. 1 suggests that extratropical cyclones in seasonal forecasts with the ECMWF model are sensitive to the horizontal resolution. Throughout the remainder of this section this sensitivity will be investigated in more detail using the full 20-year data sets.

Time series of the total number of Northern Hemisphere cyclones for winters for the period 1982–2001 are

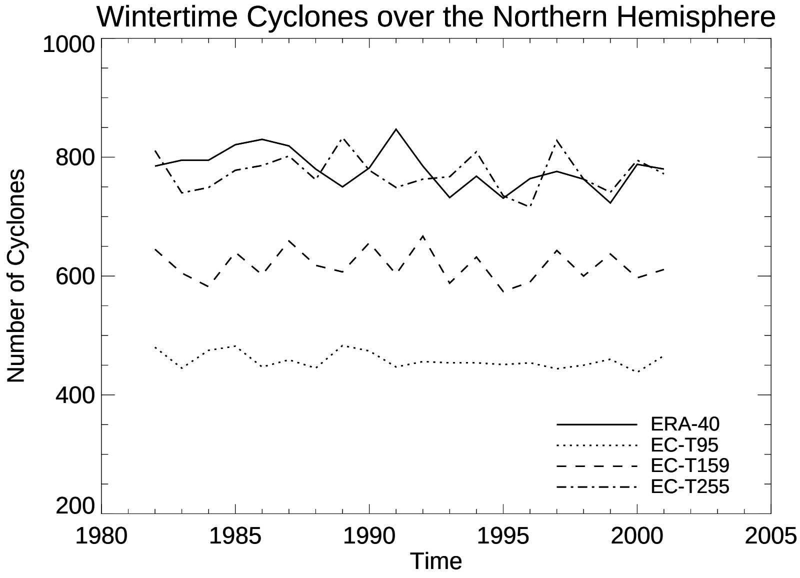

Figure 2: Time series of the total number of wintertime (DJFM) extratropical cyclones in the Northern Hemisphere: ERA-40 (solid), EC-T95 (dotted), EC-T159 (dashed), and EC-T255 (dash-dotted).

shown in Fig. 2. Evidently, the finding described above, that is, increasing the resolution from T_L95 to T_L255 increases the total number of cyclones dramatically, is a robust feature given that interannual variations are much smaller than long-term mean differences. Moreover, there is some indication that the magnitude of simulated interannual variations increases with increasing resolution as well. Finally, none of the three experiments, which were driven by observed SST anomalies, simulates the observed interannual variations suggesting that there is little predictability of the total number of Northern Hemisphere cyclones on seasonal time scales.

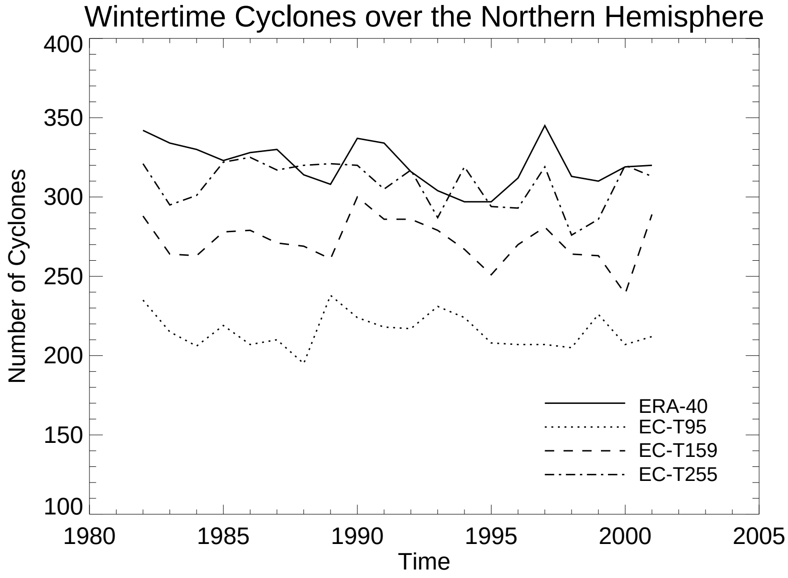

Figure 3: As in Fig. 2, except for cyclones with lifetimes of 2 days or longer which migrated a minimum distance of 1000 km. Notice the different range of the ordinate compared to that in Fig. 2.

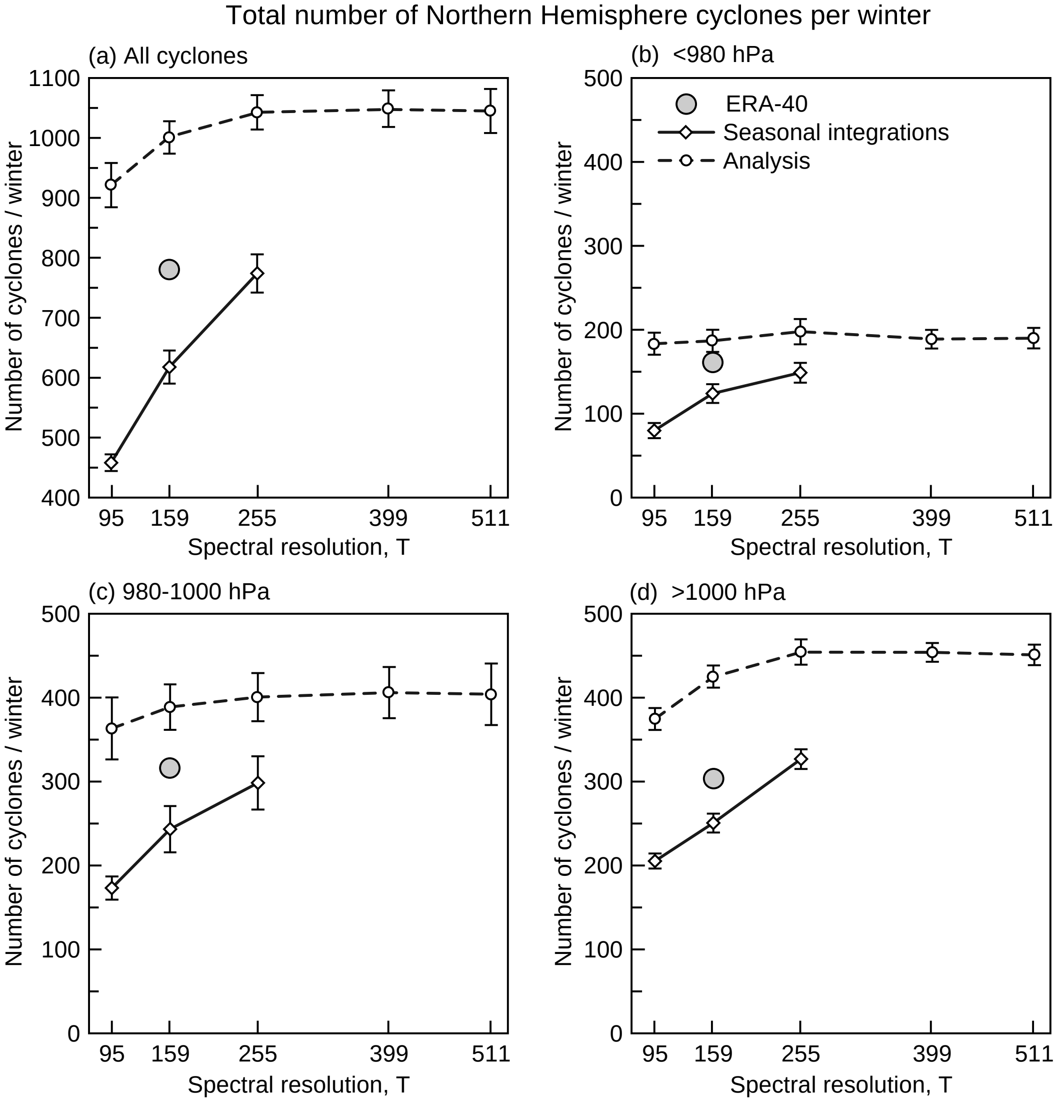

Figure 4: Total number of Northern Hemisphere cyclones per winter as a function of total wavenumber for four different cyclone intensity classes: (a) all cyclones, (b) minimum SLP less than 980 hPa, (c) minimum SLP in the range 980–1000 hPa, and (d) minimum SLP larger than 1000 hPa. Results are shown for ERA-40 reanalysis data (black dot), seasonal integrations at different resolution (solid) and operational analysis data truncated at different total wavenumbers (dashed). Also shown are 95% confidence intervals.

The above results are based on considering all tracked cyclones, including short-lived and stationary systems. One might argue that the resolution effect is most pronounced for exactly those systems (e.g., orographic effects). In order to test this hypothesis the above analysis has been repeated considering only those cyclones whose lifetimes were 2 days or longer and which traveled a minimum distance of 1000 km. In this way the results of this study are also more directly comparable to those from previous studies focussing on long-lived, migratory systems (e.g., Hoskins and Hodges 2002, Bengtsson et al. 2005). Time series of the total number of long-lived and migratory systems over the Northern Hemisphere at different horizontal resolutions are shown in Fig. 3. Clearly, the sensitivity to horizontal resolution descibed above includes long-lived, migratory systems (see also below for more details)!

The increase of the number of Northern Hemisphere cyclones with increasing horizontal resolution is further

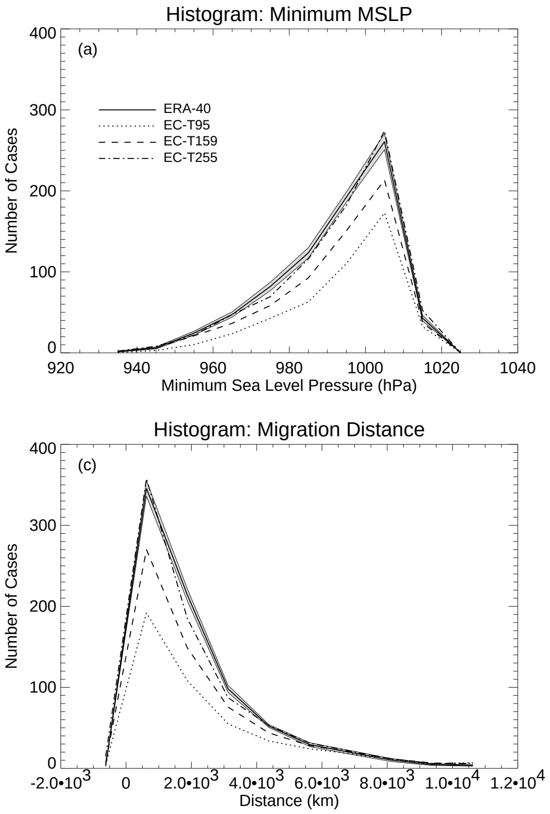

Figure 5: Average number of wintertime extratropical cyclones over the Northern Hemisphere versus (a) minimum SLP (hPa), (b) maximum deepening rate (hPa/6hr), (c) migration distance (km), and (d) lifetime (days). Histograms are shown for ERA-40 (solid), EC-T95 (dotted), EC-T159 (dashed), and EC-T255 (dash-dotted). Results are based on averaging individual histograms over all 20 winters (DJFM). For ERA-40 data, 95% confidence intervals are also shown (shaded).

illustrated in Fig. 4 for different classes of minimum SLP (cyclone intensity). In relative terms, in turns out that the more intensive the cyclones are the stronger the sensitivity to horizontal resolution becomes. For shallow cyclones ($>$ 1000 hPa), for example, the total number of cyclones increases by a factor of about 1.5 when the resolution is increased from T$_L$95 to T$_L$255; for the most intensive cyclones ($<$ 980 hPa), on the other hand, the total number increases by about a factor of 2.0.

In order to disentangle the dynamical/physical effects of horizontal resolution from those due to pure spectral truncation, Fig. 4 also shows the number of cyclones obtained for the high-resolution analysis (the “truth”) along with those obtained from the spectrally truncated SLP analyses (dashed lines). For the most intensive cyclones the truncation effect cannot explain the sensitivity of the total number of extratropical cyclones described above. For shallow extratropical cyclones, on the other hand, the truncation effect clearly dominates over the dynamical/physical effects of horizontal resolution.

We note in passing that the high-resolution SLP analysis contains significantly more extratropical cyclones than SLP fields obtained from the ERA-40 reanalysis (Fig. 4). This conclusion holds for the whole spectrum of intensities and is most likely due to the higher resolution used in the operational analysis system (T_L511) rather than due to differences in model formulation.

Next, we turn our attention to parameters more representative of the lifecycle of extratropical cyclones. Average histograms of minimum SLP, maximum deepening rate (negative values are possible, if a cyclone moves into

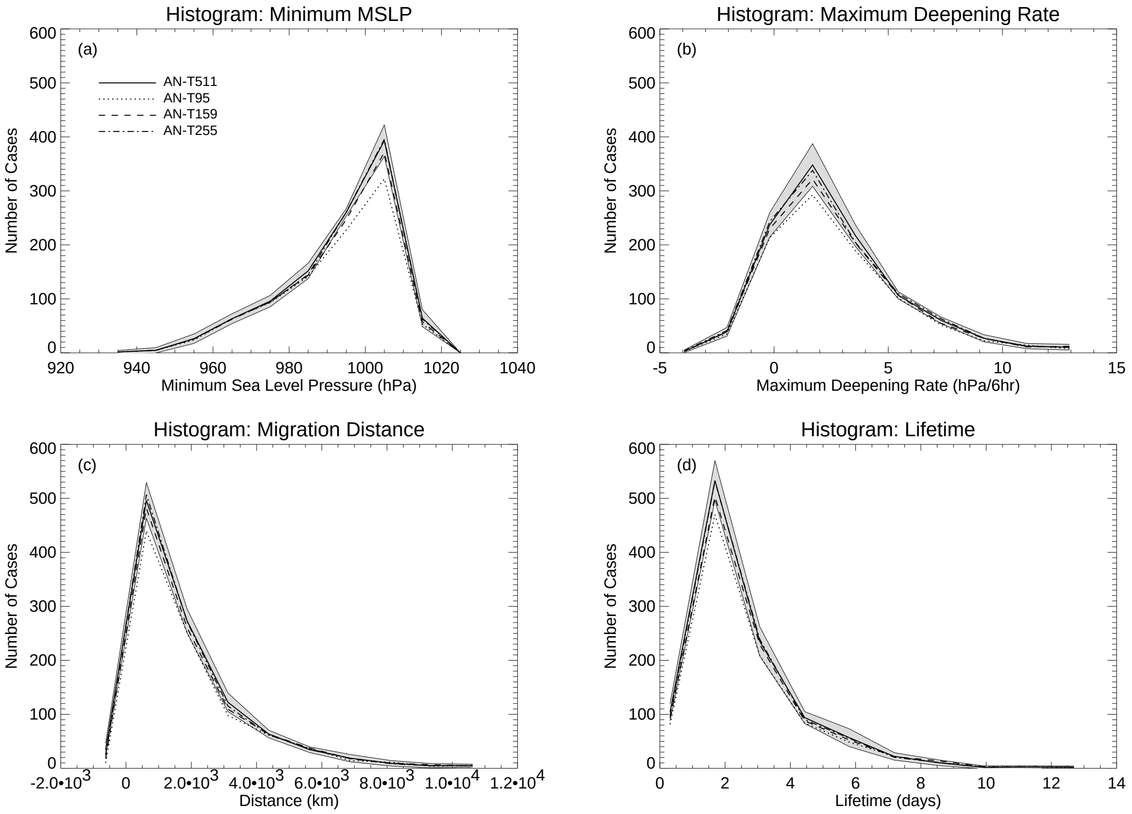

Figure 6: Same as in Fig. 5, except for operational analysis data for winters of the period 2000–04 truncated at different total wavenumbers: AN-T511 (solid), AN-T95 (dotted), AN-T159 (dashed) and AN-T255 (dash-dotted).

a region with higher ambient SLP), migration distance[1], and lifetime of all tracked extratropical cyclones are shown in Fig. 5. Evidently, the horizontal resolution affects the number of cyclones for a wide range of minimum SLP, deepening rates, migration distances and lifetimes. However, for very long-lived (longer than about 6 days) and far moving (more than about 6000 km) cyclones, the resolution effect seems to be less important. It is also worth pointing out that convergence to the histograms obtained from the reanalysis data is achived for the EC-T255 model.

The histograms for the operational high-resolution analysis truncated at different total wavenumbers (Fig. 6) are virtually indistinguishable from each other within the range of uncertainty, except for AN-T95, which produces too few cyclones of moderate intensity, maximum deepening rate, migration distance and lifetime. This suggests that the above conclusion is in fact due to dynamical/orographic aspects associated with the use of different horizontal resolutions during the course of the integrations.

The above diagnostics describe extratropical cyclone characteristics on a hemispheric scale. In order to identify possible regional differences of the sensitivity of the number of extratropical cyclones to horizontal resolution, spatial maps are presented in Fig. 7 for the Northern Hemisphere. The major storm tracks over the North Atlantic and North Pacific ocean are clearly evident for ERA-40 data (Fig. 7a). Enhanced cyclonic activity is also evident over North America, the Arctic sea, Europe, the Mediterranean Sea and southern parts of the Asian continent. The EC-T95 model underestimates the number of extratropical cyclones almost everywhere, particularly in high latitudes (Fig. 7b). This underestimation is particularly prominent on the southern flank

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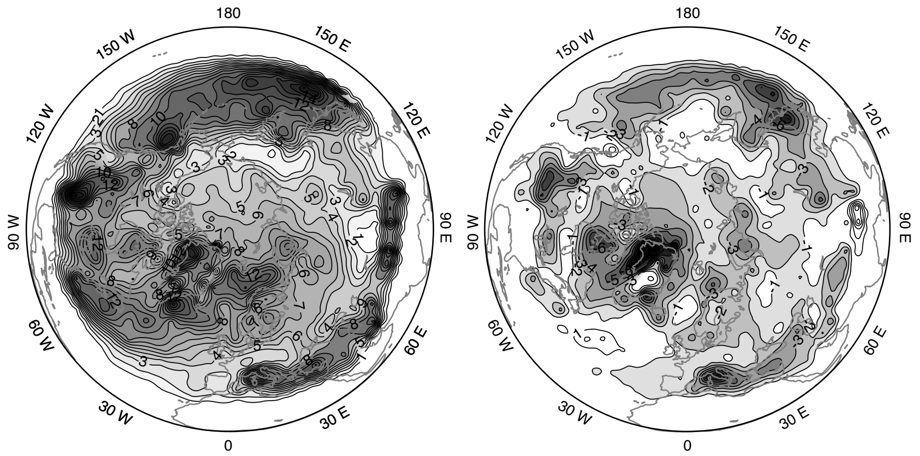
[1] The migration distance for each track was obtained by taking the sum of all distances between adjacent cyclone positions.

Number of Cyclones per Year

(a) ERA-40 (b) EC-T95 minus ERA-40



(c) EC-T159 minus ERA-40 (d) EC-T255 minus ERA-40

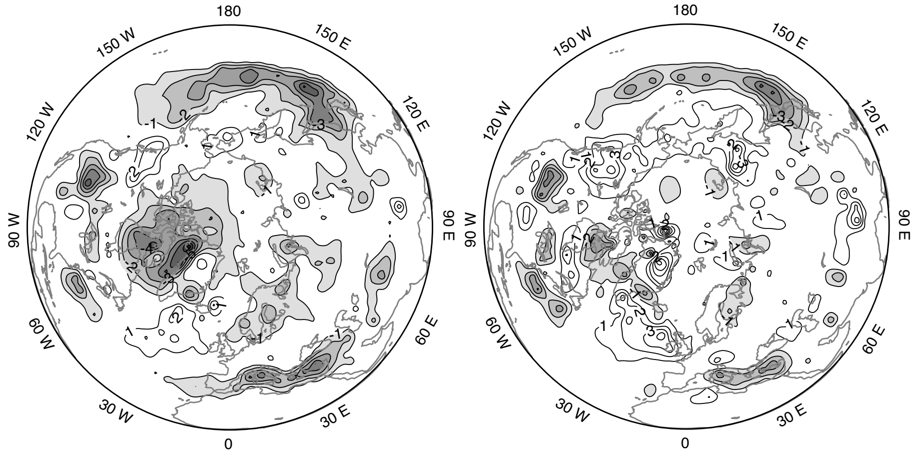


Figure 7: (a) Number of cyclones per winter for ERA-40 reanalysis data. Also shown are differences between simulated and ERA-40 data: (b) EC-T95 minus ERA-40, (c) EC-T159 minus ERA-40, and (d) EC-T255 minus ERA-40. The results are based on winters of the period 1980–2001. The contour interval is 1 cyclone/winter. In (c)–(d) differences below -1 *cyclone/winter are shaded; no shading is used for positive differences.*

of the North Pacific storm track, in the Gulf Stream area, over the western North American continent, over northeast Canada as well as the Baffin Bay and Labrador Sea, over the Arctic, Europe and the Mediterranean. Increasing horizontal resolution improves the model performance considerably. However, even at a resolution of T_L255 (for which the total number of cyclones is realistic, see above), regionally, model problems are still evident (Fig. 7d), most notably over the North Pacific ocean, where the storm track is located too far in the north, and in the Mediterranean Sea. In the Gulf Stream area the underestimation of cyclones is more or less independent of resolution, at least for the resolutions considered in this study. (As argued below, this might be a consequence of the use of relatively coarse-resolution SST fields, L. Bengtsson 2005, personal communication.)

In order to better understand the results described above, it is useful to consider also the sensitivity of cyclogenesis to horizontal resolution (Fig. 8). The main regions where cyclogenesis takes place are either associated with orography (e.g., Rocky Mountains and the Alps) or with zones of strong near-surface baroclinicity such as the Gulf Stream and Kuroshio Current region (Fig. 8a, see also Hoskins and Hodges 2002). EC-T95 under-

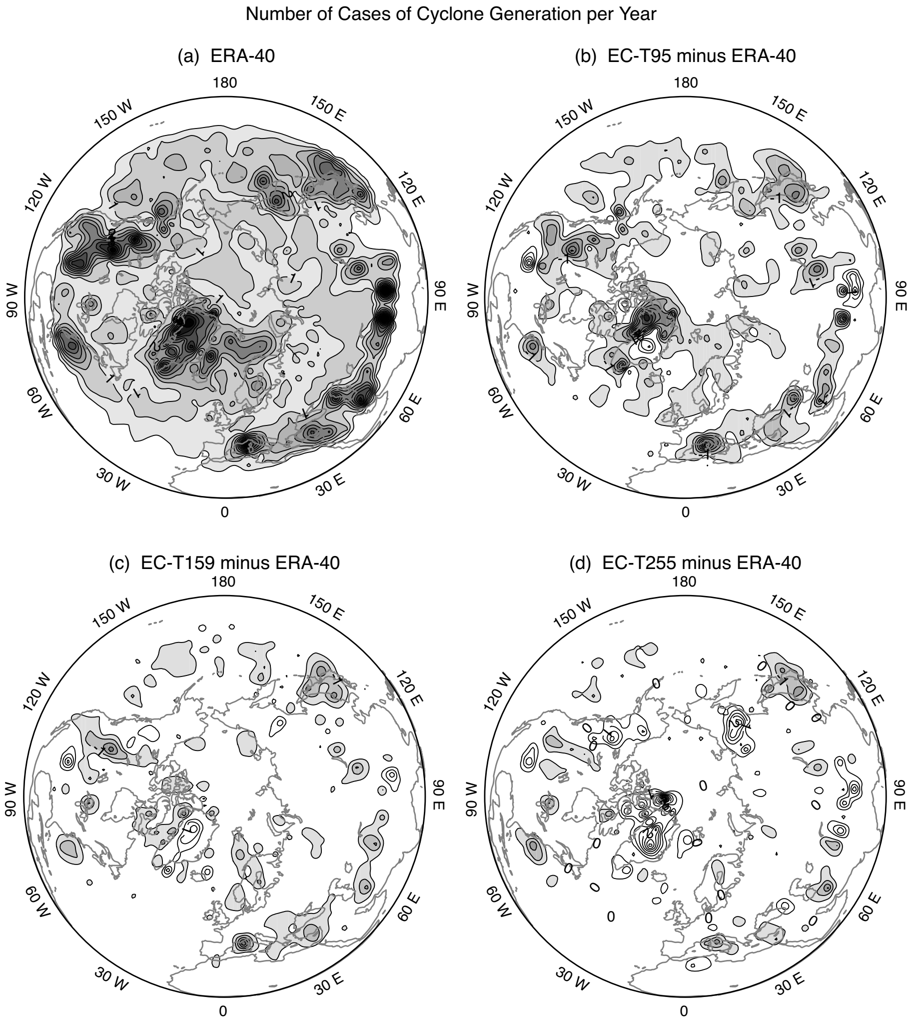


Figure 8: Same as in Fig. 7, except for the number of cases of cyclogenesis per winter. The contour interval is 0.5 cyclones/winter. In (c)–(d) differences below -0.5 *cyclones/winter are shaded; no shading is used for positive differences.*

estimates the number of cases cyclogenesis in all these areas. However, the underestimation of cyclogenesis is not only confined to these region. In relative terms, the underestimation of the cases of cyclogenesis is equally dramatic in the North Pacific, over northwest Europe and in the northeast North Atlantic. Increasing horizontal resolution generally leads to an improvement of the model performance, except for the major baroclinic zones off the east coasts of the North American and Asian continent. Furthermore, Fig, 8 clearly shows that even for EC-T255 the number of cases of cyclogenesis in lee of the Alps is significantly underestimated.

In order to be able to distinguish between dynamical effects and those due to pure spectral truncation the above analysis has been repeated for the high-resolution analysis and the truncated SLP fields (Fig. 9). The largest differences (underestimation) in the number of cyclones between AN-T95 and AN-T511 are found over Greenland and the Rocky Mountains suggesting that the truncation effect plays a role in the vicinity of steep orography (see also Fig. 10 for the number of cases of cyclogenesis). In all other regions mainly dynamical effects are responsible for the sensitivity to horizontal resolution. This is particularly true for higher total wavenumbers (around T_L95), which is in line with our finding that the truncation effect is most pronounced at lower total wavenumbers (Fig. 4).

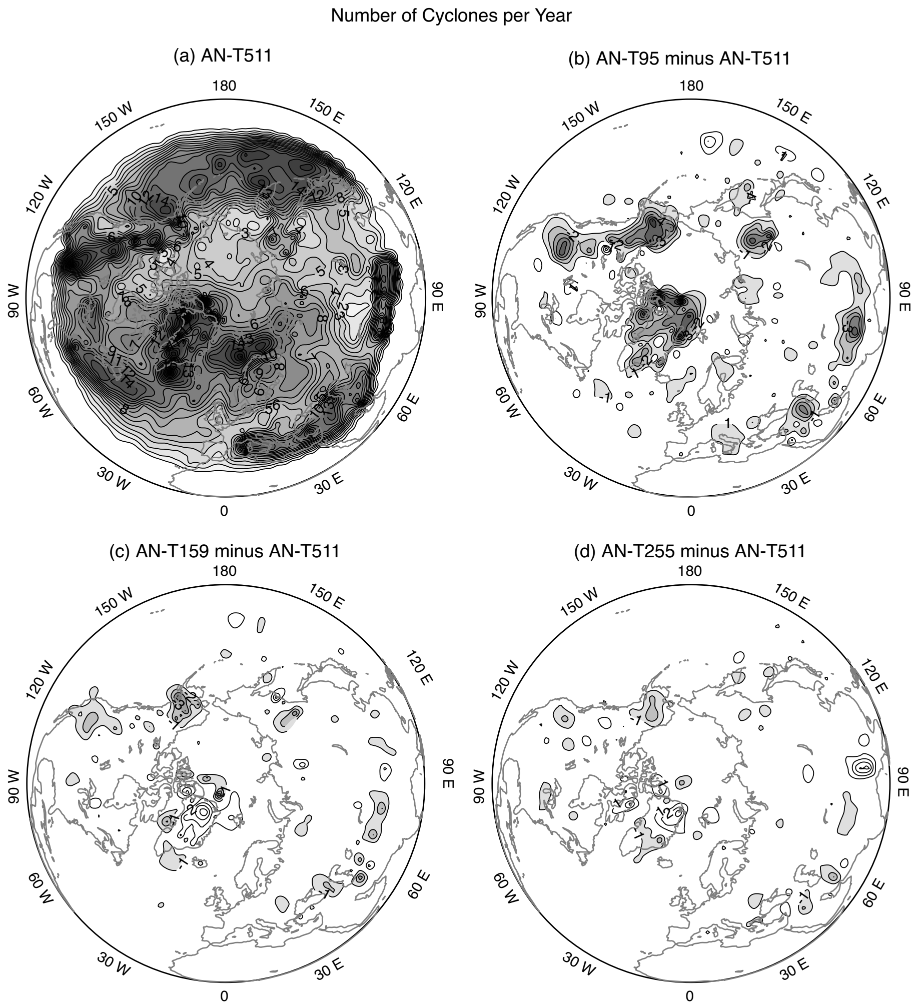


Figure 9: As in Fig. 7, except for (a) AN-T511 and the differences between (b) AN-T95 and AN-T511, (c) AN-T159 and AN-T511 as well as (d) AN-T255 and AN-T511.

4 Summary and Discussion

The sensitivity to horizontal resolution of the ECMWF model in simulating extratropical cyclones during wintertime has been investigated using a large set of seasonal integrations. It has been shown that the low-resolution version of the ECMWF model produces only about 60% of the observed number of cyclones in the Northern Hemisphere. Moreover, large regional model deficits have been found. In general, increasing horizontal resolution leads to substantial improvements. However, even at a relatively high resolution of T_L255 (about 80km) the ECMWF model shows significant short-comings in areas such as the Mediterranean Sea. By using the high-resolution (about 40km) operational ECMWF analysis for the period 2000–04 and truncating the SLP fields at different resolutions it has been shown that the underestimation of intense extratropical cyclones is the result of differences in the dynamics, physics and orography being explicitely resolved at higher horizontal resolutions; for shallow extratropical cyclones, on the other hand, it has been found that the truncation effect dominates.

In this study only the sensitivity to horizontal resolution has been studied. It would be desirable to investigate also the sensitivity to vertical resolution. Increased vertical resolution might be beneficial in representing, for

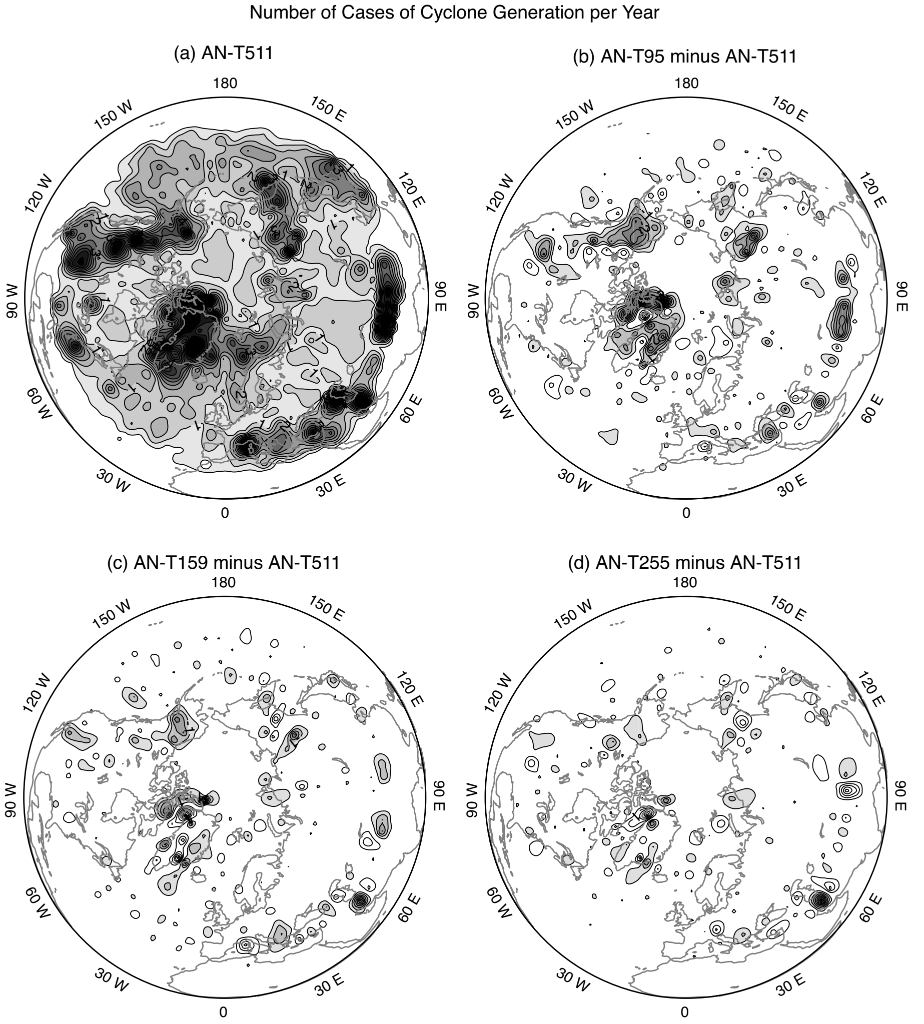


Figure 10: Same as in Fig. 9, except for the number of cases of cyclogenesis per winter. The contour interval is 0.5 cyclones/winter. In (c)–(d) differences below -0.5 *cyclones/winter are shaded; no shading is used for positive differences.*

example, vertical shear. Such an investigation will be left for future studies.

There is some discussion about which fields to use for the tracking of extratropical cyclones. Our results are based on SLP fields. As pointed out by Hoskins and Hodges (2002), vorticity at the 850 hPa level is better at describing smaller-scale systems. (This comes at the price of larger uncertainties associate with the identifcation and tracking of such small-scale features, though.) It is likely that the sensitivity of extratropical cyclone characteristics to horizontal resolution described in this study, becomes even more pronounced if vorticity extrema are being tracked. It is also worth pointing out, that the tracking was performed for SLP fields (of different horizontal resolution) on a common 2.5×2.5 grid. This was done to ensure that similar spatial scales are identified for each data set. Moreover, the automatic tracking scheme has been developed for SLP data on a 2.5×2.5 grid. Finally, it is worth mentioning that the observations do not allow to constrain SLP analyses on spatial scales much smaller than several hundreds of kilometer (for which the model first guess plays a major role). By using a common 2.5×2.5 grid, hence, it is ensured that only the observable scales are compared. It is very likely, however, that the resolution effect described in this study would be even more pronounced if tracking had been performed using the original grids.

A comparison of different reanalysis datasets using objective feature tracking of extratropical cyclones has recently being carried out by Hodges et al. (2003). They found that, overall, tracking statistics correspond very well in the Northern Hemisphere. At the first glance their conclusion seems to contradict the results of this study given that the different reanalyses were carried out with models at different resolutions. However, reanalyses, in contrast to seasonal integrations, are largely contrained by the available observations, at least in the Northern Hemisphere. Therefore, the influence of horizontal resolution might be a second-order effect. In fact, Hodges et al. (2003) found larger differences between different reanalysis products in the Southern Hemisphere, where the first guess–and therefore model formulation—has a larger impact on the resulting analysis.

Our findings have a variety of implications. Firstly, climate simulations designed to investigate possible future changes under increasing greenhouse gas concentrations are usually carried out with relatively low-resolution atmospheric circulation models (coupled to models of the other climate system components). In this context our T_L95 integration has to be considered as being of relatively high horizontal resolution. Given that extratropical cyclones represent one of the key-ingredients of the atmospheric general circulation, the underestimation of synoptic activity in the low-resolution model raises the question as to whether low-resolution atmospheric circulation models are able to realistically simulate the response of extratropical cyclones to increasing greenhouse gas concentrations. Possible changes of storm tracks under increasing greenhouse gas concentrations have been studied by Bengtsson et al. (2005) using the ECHAM5 coupled model. They found a realistic representation of extratropical cyclone characteristics, despite of the relatively coarse resolution of the atmospheric model used (T63). This raises the question as to whether atmospheric models tuned to be particularly skilful in medium-range weather forecasting, such as the ECMWF model, have deficits when it comes to extended-range integrations at relatively low horizontal resolution. It would be useful, therefore, to repeat the analysis described in this study for different weather prediction and climate models.

The results of this study suggest that locally resolution may be even a significant factor in the performance of short-range and medium-range weather forecasting. In this context it is worth pointing out that even T_L255 version of the ECMWF model, which—at the time of writing—is being used operationally to carry our operational ensemble forecasts, underestimates the number of cases of Genoa cyclogenesis in the Mediterranean Sea. This is a significant short-coming and gives support to the decision by ECMWF to increase the horizontal resolution of its ensemble prediction system in the near future.

What are the causes for the underestimation of the total number of extratropical cyclones at low horizontal resolutions? A more realistic representation of the orography at higher horizontal resolutions is clearly beneficial in regions such as the Mediterranean Sea (cyclogenesis in lee of the Alps), around Greenland and the Rocky Mountains. However, our results can only partly be explained by orography (see, e.g., the Arctic, northeast Canada and Europe in Fig. 7). It is conceivable that the lower-resolution versions of the ECMWF model generates too little extratropical cyclones because of excessive dissipation on meso and sub-synoptic scales (see, Janssen 2004, for a discussion of kinetic energy spectra of the ECMWF model). In fact, there is observational evidence for the existence of an inverse energy cascade from meso and sub-synoptic scales towards larger spatial scales (Nastrom and Gage 1985). Therefore, too little kinetic energy near the truncation level could lead to an underestimation of synoptic activity. We are planning to investigate the role of dissipation in a future study. However, there is clearly a limit to how well small-scale processes can be resolved, for example, by T_L95 models. Therefore, we are also planning to investigate whether the use of a recently developed stochastic parametrization scheme improves the simulation of extratropical cyclones in seasonal integrations with the T_L95 version of the ECMWF model. In this new scheme, which has been developed by Shutts (2005), the streamfunction tendency arising from unresolved or poorly resolved physical processes is backscattered to scales near the truncation level. (The dissipative effect of the semi-Lagrangian advection scheme is also taken into account.) This streamfunction tendency is proportional to the square root of the dissipation rate associated with numerical dissipation, mountain drag as well as deep convection; the spatial structure of the forcing is given by a cellular automaton (see Shutts 2005, for details). In fact, it is promising that the use of this new scheme in the T_L95 version of the ECMWF model leads to a more realistic simulation of blocking (Palmer et al. 2005) and weather regimes (Jung et al. 2005) in the North Pacific region.

From the diagnostics described in this study it is difficult to clearly separate the resolution effect of dynamical and physical processes from that of orography. To better understand the sensitivity of dynamical and physical processes to horizontal resolution, it is planned to repeat the experimentation described in this study using an aqua-planet version of the ECMWF.

One of the main conclusions of this study is that increasing horizontal resolution leads to a better simulation of extratropical cyclones. However, there are exceptions such as in the Gulf Stream area, where the underestimation of the number of cyclones shows no sensitivity to horizontal resolution. It is conceivable that increasing resolution beyond T_L255 will erradicate this problem. Alternatively, this problem might arise from the use of relatively coarse resolution SST fields leading to an underestimation of temperature gradients and therefore the baroclinicity in the Gulf Stream region (L. Bengtsson 2005, personal communication). The influence of the smoothness of SST fields used will be addressed in a forthcoming study.

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