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On the relation between extremes of midlatitude cyclones and the atmospheric circulation using ERA40

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[1] Analyzing ERA40 data there is evidence that extreme intensified midlatitude cyclones are related to the large-scale atmospheric circulation in winter and to a minor degree for spring and autumn. Regionally different circulation patterns are related to extreme intensified cyclones, e.g., cyclones in northern Europe are linked to a slightly rotated NAO-like pattern whereas for southern Europe a blocking-like pattern over central to northern Europe is observed. In the Pacific a north-south dipole pattern is related to extremes in cyclone intensity. In summer these relationships, however, collapse. In winter, depending on the considered region, changes in the meridional temperature gradient, the land-sea temperature contrast, and to some extent changes in static stability modulate the lower to middle tropospheric baroclinicity, being important in the intensification process. **Citation:** Raible, C. C. (2007), On the relation between extremes of midlatitude cyclones and the atmospheric circulation using ERA40, *Geophys. Res. Lett.*, *34*, L07703, doi:10.1029/2006GL029084.

1. Introduction

[2] In the midlatitudes the day-to-day variability is dominated by the passage of high and low pressure systems. The impact of extreme midlatitude cyclones on society and economy was impressively demonstrated over the last decade with, e.g., the storm Lothar over central Europe in December 1999 or the flooding event in August 2005 in the Central Alps, also caused by cyclonic activity [*Beniston*, 2006]. Thus, the investigation of extremes and the related underlying processes comes more and more to the fore not only in science but also in insurance companies, water managements, and hydroelectric power companies [*Mailier et al.*, 2006].

[3] A seminal study manually estimated a climatology of low pressure systems and cyclone tracks [*Köppen*, 1881]. Now-a-days, Eulerian measures, e.g., band-pass filtered 500 hPa geopotential height [*Blackmon*, 1976] and Lagrangian methods, i.e., cyclone detection and tracking [*Blender et al.*, 1997; *Hodges et al.*, 2003; *Simmonds et al.*, 2003], are used to characterise synoptic scale variability. Using the classical Eulerian measure, *Orlanski* [1998] showed that high-frequency eddies in the major midlatitude storm track areas are highly correlated with the stationary atmospheric circulation.

[4] Changes in mean and extreme cyclone characteristics is one focus in future climate projection studies. *Leckebusch and Ulbrich* [2004] found a northward shift of cyclone tracks and an intensification of North Atlantic cyclones in greenhouse gas scenario simulations using the A2 and B2 emissions. However, no significant changes in cyclone intensity were detected by *Kharin and Zwiers* [2005], using another climate model but similar emission scenarios. *Salathé* [2006] showed for the North Pacific that cyclones intensify with strong implications on precipitation at the west coast of the United States. Beside future changes, simulated cyclones for a prolonged cold period in the past centuries undergo substantial changes. *Raible et al.* [2007] found a southward shift of cyclone activity in the Northern Hemisphere and an intensification in particular in winter, resembling proxy evidence [*Jong et al.*, 2006]. Other studies focus on trends in cyclone characteristics, using reanalysis data sets. *Gulev et al.* [2001] identified an upward trend in most of the cyclone characteristics of the midlatitudes except for the eastern Pacific and the continental America region. They also find a strong relationship to the major teleconnection patterns of the basins, the North Atlantic Oscillation (NAO) and the Pacific North America (PNA) pattern. Comparing ERA40 and NCEP/NCAR, *Wang et al.* [2006] found a positive trend of the strong cyclones in the high-latitude North Atlantic and the midlatitude Pacific and a significant negative trend over the midlatitude Atlantic, whereas *Simmonds and Keay* [2002] showed that only the trend of the Pacific cyclone intensity is statistically significant. These trends have also implications on other variables as cyclones in winter are a major source of precipitation, e.g., for the Mediterranean.

[5] For future climate changes and trends in mean and extreme cyclone characteristics, it is essential to understand the basic relations of cyclones and the mean flow. Thus, this study focuses on the connection of extremes in northern hemispheric, midlatitude cyclone intensity with atmospheric circulation patterns, utilizing the ERA40 data set. Moreover, implications for precipitation and wind speed are presented.

2. Data and Analysis Techniques

[6] The European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis data sets (ERA40) provides the basis for the analysis, presented in this study [*Uppala et al.*, 2005]. The reanalysis data set covers the period from 1959 to 2001. The ECMWF uses its operational median-range forecasting system with a horizontal resolution of T159 and 60 vertical levels to generate the ERA40. For this study data are interpolated to a resolution of 2.5 $\times$ 2.5 in longitude and latitude, using a 6-hourly temporal interval (main observation times: 00, 06, 12, 18 UTC) for the cyclone tracking algorithm.

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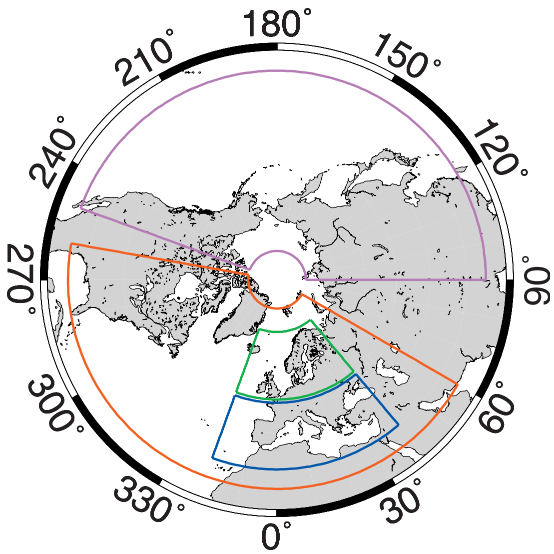

Figure 1. Definition of the four regions to derive the corresponding cyclone intensity (CI) indices: North Atlantic (red), North Pacific (magenta), northern Europe (green), and southern Europe (blue).

[7] To characterize midlatitude cyclones, a tracking scheme [*Blender et al.*, 1997] is applied to the 1000 hPa geopotential height (Z1000). Low pressure systems are identified as minima of Z1000 within a neighborhood of eight grid points. To neglect weak and unrealistic minima a mean gradient of at least 20 gpm/1000 km in a 1000 km neighborhood and a minimum life-time of one day are required. A cyclone should also exceed a minimum gradient of 30 gpm/1000 km at least once during its life-cycle. Minima are connected to cyclone trajectories by a next-neighbor search within 1000 km. Changes due to different reanalysis data are discussed by *Hodges et al.* [2003], *Wang et al.* [2006], and *Trigo* [2006].

[8] The mean gradient of Z1000 around a cyclone center per 1000 km is used as an intensity measure for one time step of a cyclone trajectory [*Raible and Blender*, 2004; *Raible et al.*, 2007]. This gradient of Z1000 is geostrophically adjusted to the reference latitude of 60°N. Thus, the cyclone intensity represents the geostrophic wind rather than the pure geopotential gradient. Extremes in cyclone intensity (CI) are defined by the 90% percentiles of the distribution of the cyclone intensity, using all time steps of all identified cyclone trajectories. These percentiles are estimated for all seasons (December to February, DJF; March to May, MAM; June to August, JJA; September to November, SON) and different regions (Figure 1) leading to time series of CI indices for all seasons and all regions separately.

[9] To study the relationship between extremes in cyclones and the atmospheric circulation a classical correlation analysis technique is applied to ERA40.

3. Relationship Between Extreme Cyclone Intensity and the Mean Flow

[10] Extremes in CI for the midlatitude vary strongly with region and season. CI indices of the different regions are presented in Figure 2 for winter. The CI of the Pacific is stronger than of the Atlantic (Figure 2a). Similarly, the CI of northern Europe and its variability are enhanced compared with southern Europe in winter (Figure 2b). Seasonally, the CI is slightly decreased in spring and autumn with a strong reduction of extreme CI of approximately 30% in summer (not shown). Significant trends from 1958 to 2001 are not observed in the CI indices, except for the Pacific (Figure 2a), in which a positive trend to more intense cyclones for winter is detected (99.4% confidence level). Note that the trend but also the low-frequency behavior of the CI indices for the Atlantic and the Pacific are similar to findings by [*Simmonds and Keay*, 2002], using a different definition of CI in NCEP/NCAR reanalysis.

[11] Correlating the CI indices with the 500 hPa geopotential height field (Z500), distinct patterns are found in winter (Figure 3). Extremes in CI of the North Atlantic are related to a NAO-like pattern (Figure 3a), which is rotated counterclockwise with centers of action over south-western Greenland and central Europe. This resembles findings of *Lim and Simmonds* [2002] and *Trigo* [2006] showing that extreme Atlantic cyclone events tend to form and move within the eastern part of the Atlantic. The correlation pattern between CI index of northern Europe and Z500 (Figure 3b) is similar to the one using the North Atlantic CI index, except for the northern center, being located between Greenland and Iceland. This suggests that these extreme cyclones originate from there and that the simultaneously occurring ridge over Central Europe is important to generate these extremes. Both relationships have a quasi-barotropic structure in winter as the correlation with the Z1000 suggests (not shown), meaning that intense baroclinic events develop vertically as expected. For southern Europe, the correlation pattern reverses sign showing a typical negative NAO-type pattern (not rotated), but the correlation coefficients are weaker than for the CI index of northern Europe (Figure 3c). The correlation of CI index for southern

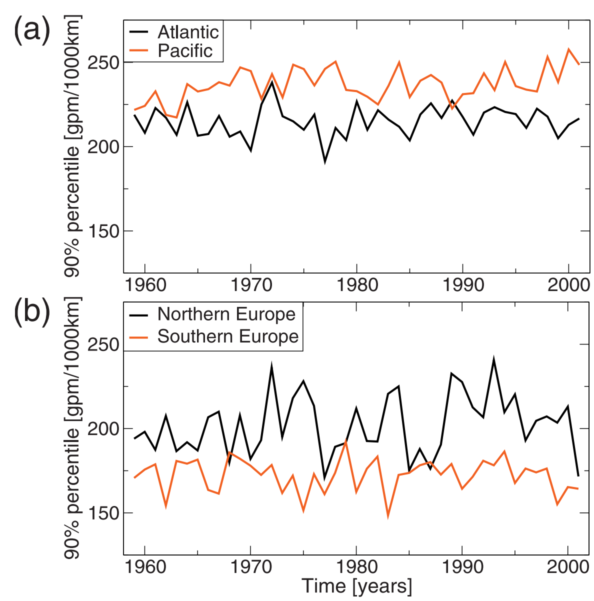

Figure 2. Time series of the 90% percentile of 1000 hPa geopotential height gradient around a cyclone center per 1000 km (CI index) for (a) the Atlantic and Pacific sector and (b) northern and southern Europe in winter.

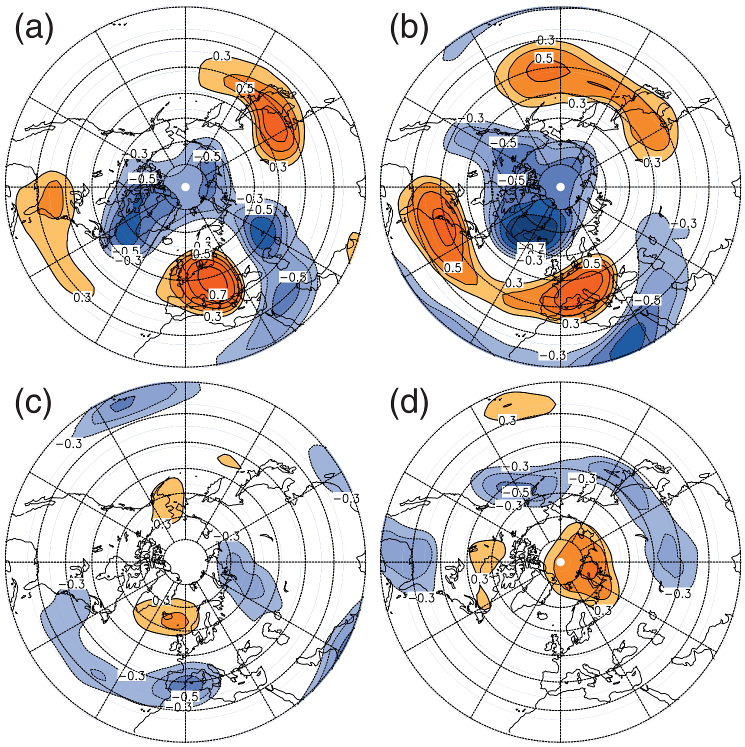

Figure 3. Correlation pattern of the 500 hPa geopotential height with (a) North Atlantic, (b) northern Europe, (c) southern Europe CI index, and (d) North Pacific in winter (shading interval 0.1, contour labels 0.2, starting at ±0.3).

Europe with Z1000 exhibits a similar pattern, again being a hint for a quasi-barotropic structure. In the Pacific, a north-south dipole is found, with centers north of Hawaii and from Kamchatka to the Aleutian Islands (Figure 3d). Only the northern center of action near the Aleutian Islands has a quasi-barotropic structure in winter analysing Z1000. However, the correlation with Z1000 shows also a positive connection with the Siberian High area for stronger than normal CI in the Pacific. In spring and autumn the relationship is diminished and in summer. No correlations are found between the CI and atmospheric circulation patterns (not shown). Probably this is due to the fact that the CI and the mean flow are weaker in summer than in winter.

[12] To show processes involved in intensification of midlatitude cyclones in winter, the focus is set on the meridional temperature gradient, the land-sea temperature contrast, static stability, the baroclinicity, as represented by the maximum Eady growth rate [*Eady*, 1949], and the diabatic component, illustrated by the latent heat flux.

[13] Correlating the CI indices with the 850 hPa temperature leads to the expected patterns (Figure 4), which fits to the 500 hPa geopotential height (Figure 3). For the North Atlantic and northern Europe CI index the correlation with temperature reveals a similar pattern with positive correlations over Florida and northern Europe and negative ones over the Hudson Bay and the eastern part of the Mediterranean (Figures 4a and 4b). This structure implies that the meridional temperature gradient is enhanced in the western part of the Atlantic and reduced over Europe, but the temperature gradient between Greenland and Northern Europe is enhanced. Correlating the southern Europe CI index with temperature shows a weaker pattern (Figure 4c). For the Pacific CI index, negative correlations are found north to 35°N over land, increasing the meridional and the land-sea temperature gradient in particular in the genesis region of the Pacific midlatitude cyclones (Figure 4d). Note that these temperature gradients could also be affected by cyclones themselves through, e.g., advection processes, but note that simulations of climate states with an enhanced meridional temperature gradient suggest an intensification of CI [*Raible et al.*, 2007].

[14] These temperature relations are linked to baroclinicity. The correlation patterns of the Atlantic and the northern Europe CI index with the maximum Eady growth rate at 700 hPa show a positive connection with the midlatitude storm track area in particular with the genesis region near Newfoundland and over northern Europe (Figures 5a and 5b). The connection at the genesis region is not only positively influenced by the increased temperature gradient but also by a decrease in static stability between 300 hPa and 700 hPa (not shown) as suggested by *Walland and Simmonds* [1999]. Over northern Europe there is no significant connection to the static stability, thus the increased temperature gradient between Greenland and Northern Europe seems to be responsible for the increase in baroclinicity and thus an increase in cyclone intensity. Using the southern Europe CI index, the correlation pattern is more localized with increased maximum Eady growth rate over the Mediterranean in the case of stronger than normal extremes in CI (Figure 5c). This relation with maximum Eady growth rate deteriorates vertically. Note that for the southern Europe CI index the static stability seems to play a minor role as no significant correlations are observed over this area. In the Pacific, the correlation patterns are similar

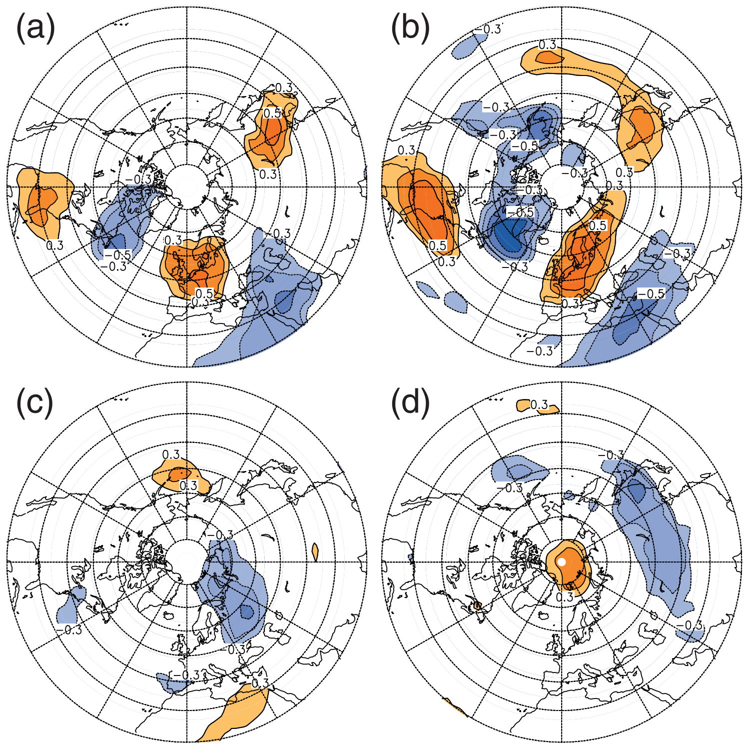

Figure 4. Same as Figure 3 but for the 850 hPa temperature.

as for the Atlantic showing positive correlations in a band of 30–40°N (Figure 5d). As for the Atlantic the static stability is an important factor for the baroclinicity at the genesis regions near Japan and the Aleutian Islands. Thus, both, the temperature gradients and the static stability, have an impact on the baroclinicity and therefore the cyclone intensity. These relations with the maximum Eady growth rate in the Atlantic, northern Europe, and the Pacific are found throughout the lower to middle troposphere up to 500 hPa. Note that the maximum Eady growth rate seems to be a

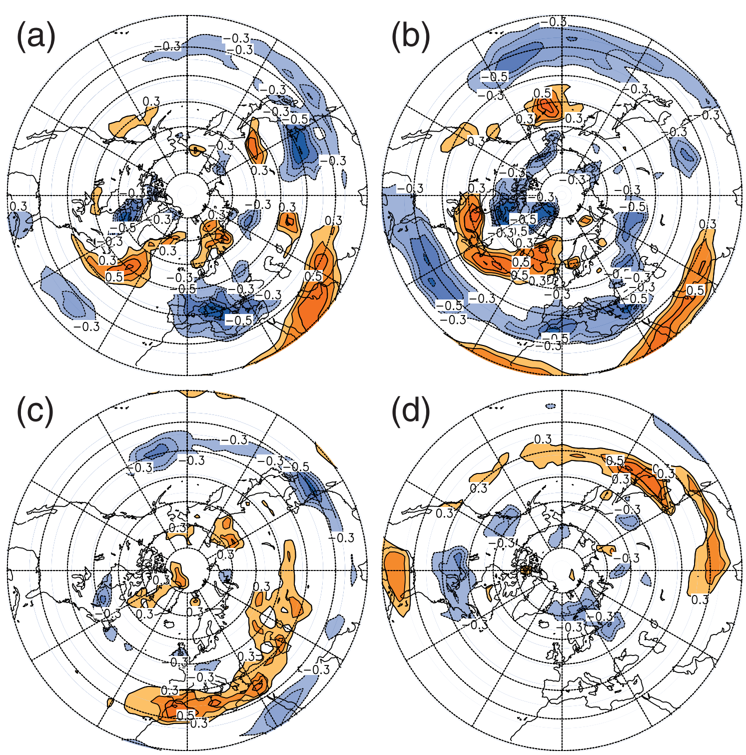

Figure 5. Same as Figure 3 but for the maximum Eady growth rate in 700 hPa.

reasonable indicator for the major storm tracks of extreme cyclones, as the strongest positive correlations (Figures 5a and 5d) are found in the areas of highest values of Eady growth rate.

[15] The diabatic component (surface latent heat flux) seems to play a minor role. The correlation of the Atlantic, Pacific and the northern Europe CI index exhibits a positive relation at the genesis regions in both basins (Newfoundland and Japan/Kamchatka), but over the rest of the midlatitude storm track area, there are no significant correlations (not shown). For the intensification of the Mediterranean cyclones the correlation analysis shows also no significant connections. As it is well established that diabatic processes are important in the intensification of individual cyclones [*Stoelinga*, 1996], a possible reason for this lack of correlation lies in the high variability of heat and moisture fluxes of midlatitude cyclones.

[16] Changes in CI have also impacts on extremes in wind speed and precipitation (defined as 90% percentile of 6-hourly data). Applying the correlation analysis, a strong connection is found between CI indices of the Atlantic and northern Europe over central to northern Europe (not shown). Over the Pacific, a connection to extremes in wind speed in the central part of this basin is primarily found. The southern European CI index is correlated with wind speed extremes in the Mediterranean. This also illustrates that this definition of the CI by the geostrophic adjusted gradient is a useful measure besides others suggested by *Simmonds and Keay* [2000], *Gulev et al.* [2001], *Leckebusch and Ulbrich* [2004], or *Wang et al.* [2006]. Precipitation extremes show a similar behavior as wind speed extremes in all regions (not shown). Again all these relations are found in winter, and less pronounced in spring and autumn, whereas these connections are not developed in summer, suggesting that in summer other processes, e.g., convection, play an important role in generating extremes in precipitation and wind speed.

4. Conclusions

[17] Extremes in cyclone characteristics and their relation to the mean flow are analyzed, using the ERA40 data set. In most of the areas, extremes in cyclone intensity are unchanged in the ERA40 period from 1958–2001. This is in contrast to *Gulev et al.* [2001] and *Wang et al.* [2006] who found significant trends in cyclone characteristics, using different definition of cyclone intensity. One exception is the Pacific, in which a significant upward trend is identified, resembling former studies [*Simmonds and Keay*, 2002]. They used depth as a measure of cyclone intensity, which also takes the size of cyclone into consideration [*Simmonds and Keay*, 2000].

[18] In different regions, extremes in CI have an imprint on the mean flow, which partly confirms prior results [*Gulev et al.*, 2001]. For the Atlantic, northern Europe, and the Pacific the meridional temperature gradient, land-sea temperature contrast, the static stability, the lower to middle tropospheric baroclinicity, and partly the latent heat flux at the corresponding genesis regions of the midlatitude storm tracks play an important role to generate extremes in CI. In southern Europe a more localised behavior is found, which resembles the different character of Mediterranean cyclones. Despite the ongoing discussion of whether teleconnection patterns will change in the future or not [*Hoerling et al.*, 2001; *Gillett et al.*, 2003; *Schneider et al.*, 2003; *Raible et al.*, 2005; *Stephenson et al.*, 2006] our study gives some hint to understand the basics relation between extremes and low-frequency atmospheric modes. But not only atmospheric circulation patterns are affected, there is also an impact on the spatial distribution of extremes in precipitation and wind speed by the CI. Thus, this study illustrates that cyclone characteristics and the mean flow are important to estimate changes in extremes for the future.

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