## Mid-latitude Cyclones and Storms in an Ensemble of European AOGCMs under ACC

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**1. Introduction**

This study investigates the occurrence of mid-latitude cyclones and wind storms under anthropogenic climate change conditions from a multi-model perspective. It thus contributes to the work performed by the ENSEMBLES project (http://ensembles-eu.metoffice.com/index.html) which is supported by the European Commission's 6th Framework Programme. The main objective of ENSEMBLES is to "develop an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, global and regional Earth System models developed in Europe..". The ENSEMBLES approach is based on the assumption that "the prediction of both natural climate variability and the human impact on climate is inherently probabilistic, due to uncertainties in forecast initial conditions, representation of key processes within models, and climatic forcing factors. Hence, reliable estimates of climatic risk can only be made through ensemble integrations of Earth-System Models in which these uncertainties are explicitly incorporated." Thus, within this framework the present study aims at a robust diagnostic of the future occurrence of extreme cyclones under anthropogenic climate change (ACC) based on an ensemble of state-of-the-art global circulation models and at deducing measures of uncertainties of these ACC signals.

Mid-latitude cyclones are a vital part of the general circulation of the atmosphere. In the Northern Hemisphere, these extra-tropical cyclones mostly originate at the discontinuity zones in the atmosphere, the polar fronts of North Pacific and the North Atlantic, influenced by the characteristics of the Northern Hemisphere's long, planetary waves. Typically, surface cyclones travel along these zones of preferred growth conditions (e.g. Pinto et al., 2008) and are steered by the upper troposphere transient eddies of planetary (zonal) wave number 4-8. Some of the cyclones can develop to very intense systems with wind speeds of up to 250 km/h (70ms$^{-1}$) or more. Such developments depend on the environmental large-scale conditions, which are particularly favourable in the boreal winter half year from October to March. These winter storms are one of the most relevant meteorological-hydrological extreme events for central Europe (Cornford 2002, Ulbrich et al. 2003a, 2003b, Fink et al. 2004, Meehl & Tebaldi 2004) on which the focus of this study will be laid. Extreme meteorological conditions generate severe impacts on human facilities and infrastructure, and thus affect general socio-economic conditions (e.g. Leckebusch et al., 2007). Thus, it is necessary to increase understanding of climate change and its impact on society by generating concrete scientific information that can be used for impact studies, thus assisting a transfer of knowledge from the scientific community to decision-makers. In this context, it is of crucial importance to gain information on potential changes in central European storms and corresponding wind patterns under future climate conditions.

It is still uncertain whether the intensity or frequency of North Atlantic extra-tropical cyclones (ETC) has undergone a specific long-term trend in the recent past. There is some evidence from observational data that activity has increased since the 1960s, possibly associated with natural inter-decadal variability. (e.g. Lambert 1996, Serreze et al. 1997, Jones et al. 1999, McCabe et al. 2001, Paciorek et al. 2002, Geng & Sugi 2003). Additionally, different trends have been suggested in the Northern and Southern Hemispheres, the latter experiencing decreasing cyclone activity since the beginning of the 1990s (e.g. Simmonds & Keay 2000). It seems reasonable to investigate the potential future occurrence of ETCs, and their related wind fields, by means of global and regional climate modelling. While most authors have concentrated their studies on the diagnosis of ETCs for one specific model (e.g. Lunkeit et al. 1996, Carnell & Senior 1998, Kharin & Zwiers 2000, Knippertz et al. 2000, Leckebusch & Ulbrich 2004, Pinto et al., 2007), with partially different investigation methods, in this study a multi-model approach applying the same investigation method is performed. Multi-model ensemble studies investigating possible future trends in extreme cyclones were first published e.g. by Lambert and Fyfe (2006) and Leckebusch et al. (2006). A comprehensive overview of scientific results achieved so far can be found in Ulbrich et al. (2008). In order to quantify the confidence and uncertainties in future predictions, we investigated an ensemble of seven atmosphere-ocean coupled global climate

| Model | No of runs | Resolution | 20C | SRES A1B |
|---|---|---|---|---|
| MPI-ECHAM5 | 3 | T63 (ca. 1.9°) | 1961-2000 | 2071-2100 |
| DMI-ECHAM5 | 1 | T63 (ca. 1.9°) | 1961-2000 | 2071-2100 |
| IPSL-CM4 | 1 | 2.5 x 3.75° | 1961-2000 | 2071-2100 |
| FUB-EGMAM | 1 | T30 (ca. 4°) | 1961-2000 | 2081-2100 |
| CNRM-CM3 (ARPEGE Atm) | 1 | Available at 2.85° | 1981-2000 | 2081-2100 |
| BCCR-BCM2 (ARPEGE Atm.) | 1 | Available at 2.85° | 1960-1999 | 2080-2099 |
| HadGEM1 | 1 | 1.25 x 1.875° | 1960-1999 | 2070-2099 |

*Table 1: AOGCMs investigated in this study including the number of available model runs (second column), horizontal resolution, and time periods for the twentieth century (control climate) and future conditions (scenario climate).*

models (AOGCMs). The climate change signal is identified based on the IPCC SRES A1B scenario (cf. Table 1).

**2. Investigation Method and Results**

Extra-tropical cyclones were assessed by applying an objective identification algorithm originally published by Murray & Simmonds (1991), which is organized in 2 steps. Firstly, cyclones are identified by an algorithm based on the search for the maximum of the Laplacian of the mean sea level pressure (ΔMSLP). Under quasi-geostrophic conditions, this is equivalent to the search for extremes of relative vorticity. Secondly, a tracking algorithm is applied, which takes into account the most probable propagation of the cyclone core under the given synoptic situations. ETCs were identified for the control and scenario period of each investigated GCM for the winter half-year (ONDJFM). In order to avoid artefacts, systems localized in areas with a terrain-height above 1500 m asl are excluded (due to underground extrapolation of the MSLP). Additionally, open and closed systems are differentiated: a cyclone is determined to be closed if a true minimum of MSLP is situated in the vicinity of a maximum of ΔMSLP. Furthermore, only systems with a Laplacian above the threshold of 0.1 (0.2) hPa deg.lat.$^{-2}$ for closed (open) systems are considered. If the Laplacian exceeds 0.6 hPa deg.lat.$^{-2}$, a system is classified as strong; otherwise it is classified as weak. Moreover, the only systems considered are at least closed and strong once in their lifetime. Details of the identification, established tracking algorithm, and current settings of the algorithm and its implications can be found in Murray & Simmonds (1991), Leckebusch & Ulbrich (2004), Pinto et al. (2005), Leckebusch et al. (2006). There is no single definition of what constitutes a wind storm event or an extreme wind speed. In accordance with previous studies we define the cyclone systems with a Laplacian of the MSLP above the long year 95th percentile (for the GCMs: of the control run) as extreme cyclones, or as severe winter storms.

The model's simulation of the recent climate is validated against ERA40-Re-analysis data (1961-2000). For all cyclone systems (Figure 1) as well as for the extreme cyclones (not shown) a very good agreement between the ensemble mean (Figure 1b) and ERA40-Re-analysis (Figure 1a) is found respecting cyclone track density. The two well pronounced centres of activity are correctly simulated in terms of position and intensity (number of tracks per winter). It should be noted that the model-to-model variability does not emerge in this ensemble mean perspective. For single models significant deviations from the re-analysis data could be observed. For each model the level of agreement with the ERA40-Re-analysis (which is taken here as an observational data set, though the assimilation is indeed a model simulation) is estimated and used to introduce different weightings for each model for the construction of the ensemble mean climate change signals. First, the weights are constructed via the spatial correlation coefficients between the GCM's and ERA40's cyclone track densities for all recognised cyclones: both the climatological mean track density and its interannual variability pattern are correlated between GCM and ERA40 and the product of both coefficients is taken as weight (w) for each model. In order to recognise more realistic models in the ensemble mean than unrealistic ones, this weighting factor was varied, from w to $w^4$. For these four different weighting factors the ensemble mean for the control period and the ACC signal were calculated. Consequently, the climate change signal is presented in terms of a weighted ensemble mean. In Figure 2, page 15, results for the weighting ($w^4$) are presented as an example.

For all identified and tracked cyclones a decrease in the hemispheric number of tracks is found (cf. Figure 2a), which is in accordance to other studies (e.g. Lambert and Fyfe, 2006). For the changes of extreme cyclones (Figure 2b) a different pattern arises: Indeed the hemispheric total number also decreases, but the horizontal distribution clearly identifies regions of increased frequency of extreme cyclones, and thus winter storms. Two regions show increased numbers of extreme cyclone tracks: the Northeast-Pacific and the Northeast-Atlantic. In both areas the increase is between 10% and 20% compared to the control period. The spatial distribution of the anthropogenic influence is more or less independent of the strength of weighting applied. The weighting leads more to changes of magnitude and statistical significance of the identified changes, e.g. over the Northeast-Atlantic. The more the influence of unrealistic models is decreased the more the statistical significance of the ACC signal is increased.

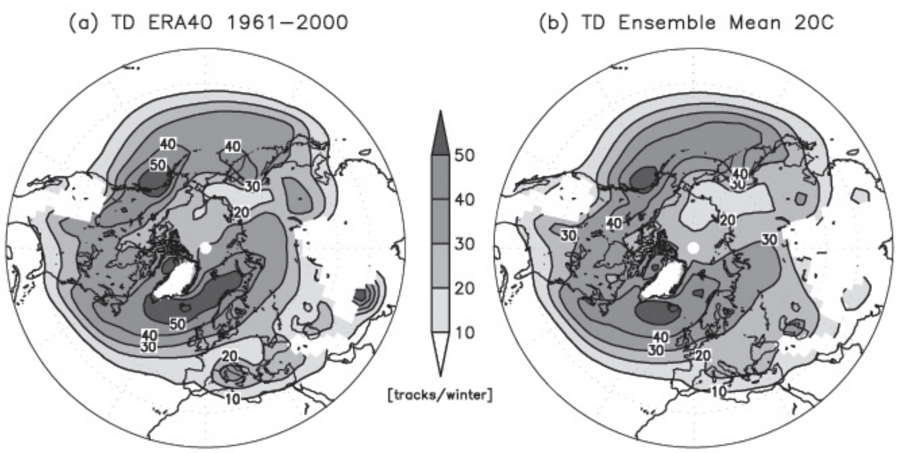


*Figure 1: Cyclone track density for ERA40-Re-analysis (left) and the Ensemble Mean (right). Unit: tracks per winter (ONDJFM). Areas with an altitude above 1500 m are eliminated (without weighting).*

### 3. Conclusion and Future Work

The results presented here reveal the importance of a regional perspective compared to an evaluation on hemispheric level. Although an overall decrease of the number of extreme cyclones is diagnosed, this holds not true for specific hot spots: the Northeast-Pacific and the Northeast-Atlantic affecting western Central Europe. These findings support results achieved with a simple one model-approach (e.g. Leckebusch and Ulbrich, 2004, Bengtsson et al., 2006, Pinto et al., 2007), as well as findings from multi-model studies (e.g. Leckebusch et al., 2006). It should be noted that the model-to-model variability is high, especially for the ACC signal for the extreme cyclones. The statistical significance of the ACC signal is thus reduced, if only one realisation of one model is incorporated. Nevertheless, the overall pattern with increasing number of extreme cyclones over the Northeast-Atlantic and the British Isles remains robust. Furthermore, from this multi-model perspective, it will be possible to deduce measures of uncertainties based on the model-to-model variability which is also assessed in this study but not presented here. Thus, it will be possible to advise the non-scientific community about the possible uncertainty of future climate developments as diagnosed from GCMs, based on the different setups of climate models. Future work will also concentrate on the identification of key reasons for the differing behaviour of "normal" vs. "extreme" cyclones. First results were published for one GCM (Pinto et al., 2008), giving hints for a broader baroclinic area during the intensification phase of extreme cyclones and a potentially increased influence of the equivalent-potential temperature on the storm development under ACC conditions.

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*From Leckebusch et al. page 3: Mid-latitude cyclones and storms in an Ensemble of European AOGCMs under ACC*

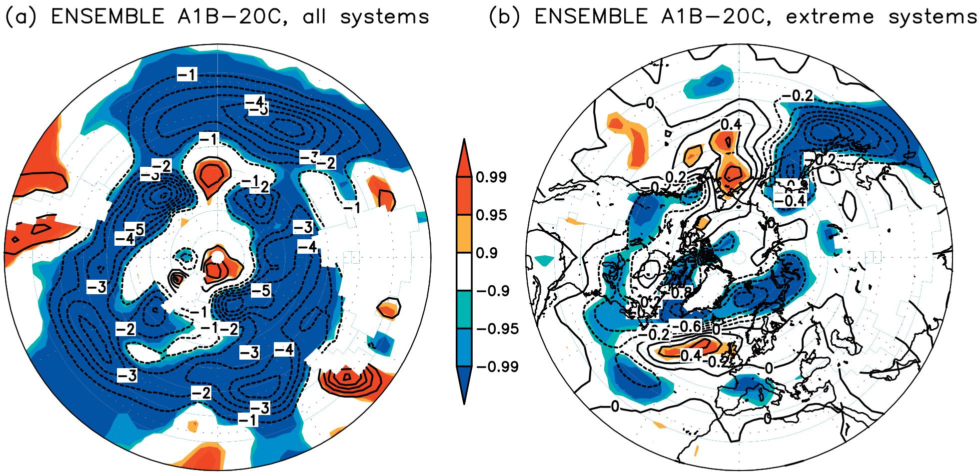


*Figure 2: Ensemble mean climate change signal (IPCC SRES A1B) of the cyclone track density. Left a): All cyclones. Right b): Extreme cyclones. Units: systems per winter (ONDJFM). Areas with an altitude above 1500 m are eliminated. Coloured: Statistical significance above the 90/95/99% level according to a student t-test. The ACC ensemble mean signals are weighted by the quality of each model (for detail see text).*

*From Pokrovsky, page 8: Relationship between the Atlantic multidecadal oscillation and the ice extent in Kara Sea*

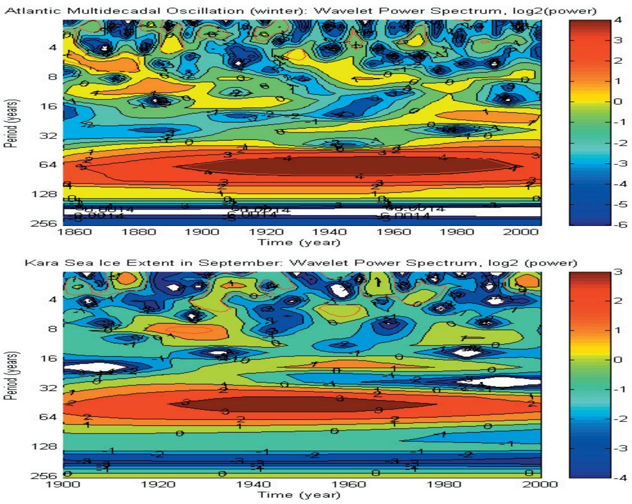


*Figure 1. Coherency in wavelet power spectrum (log2 scale) for climate series of: AMO winter values for 1856-2000 (upper panel) and ice extent September values in Kara Sea (lower panel).*

*From Timmerman, page 10: Perspectives on the remote control of ENSO variability*

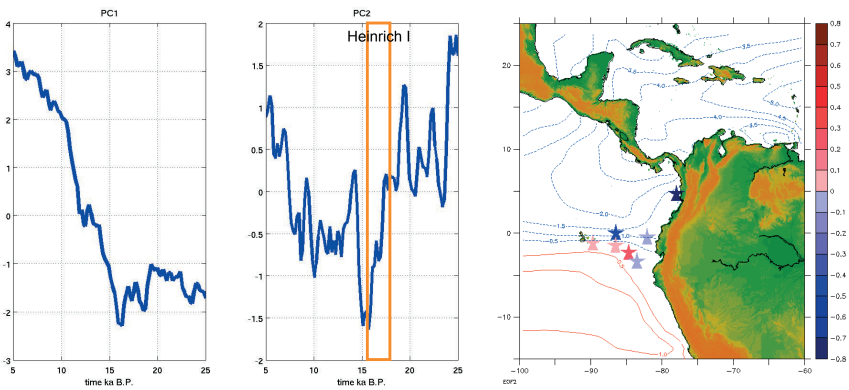


*Figure 1: Left: Principal component of the first EOF of SST derived from Alkenone data from cores V19-27, ME24, V19-30, V21-30, RC11-238, V19-28, JPC32. All data were brought onto the same timescale using cubic spline interpolation. The first EOF mode represents the major deglaciation event. Its EOF (not shown) has the same sign for all core locations; Middle: Principal component of the second EOF of alkenone-derived SST data. This EOF captures the millennial scale events such as Heinrich I, the Bølling Ållerød and the Younger Dryas; Right: Loadings of the second EOF (multiplied by -1) of eastern equatorial Pacific Alkenone-derived SST data (stars) and simulated SSTA response [K] to a shutdown of the Atlantic Meridional Overturning Circulation in the GFDL-CM2.1 model A meridional dipole pattern results from an intensification of the Panama wind-jet due to the SST decrease in the Caribbean, and coupled air-sea feedbacks in the eastern equatorial Pacific  involving the wind-evaporation SST feedback.*