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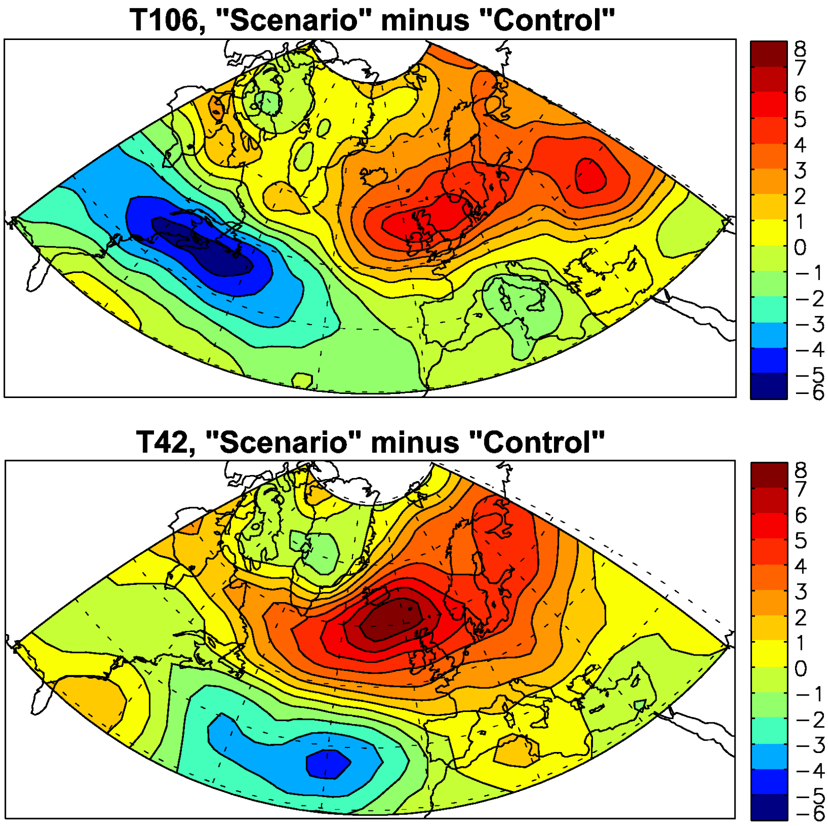

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Changes in the storm climate in the North Atlantic / European region as simulated by GCM time-slice experiments at high resolution

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ABSTRACT

The differences in sea level pressure, 500 hPa high frequency variability and high wind speed statistics in the North Atlantic / European region between a 30 year present-day and a 30 year scenario time slice experiment with increased concentrations of greenhouse gases are investigated for the ECHAM4 atmospheric GCM in T106 horizontal resolution. The results are compared to the underlying transient simulation with a coupled ocean-atmosphere model in T42 resolution.

The T106 present-day simulation shows a stronger high frequency variability in the middle troposphere than the corresponding T42 simulation. In spite of this and despite its higher resolution and shorter time step the extreme near surface wind speeds in the T106 resolution are comparable to those in T42 resolution.

In the time slice scenario simulation as well as in the corresponding part of the transient simulation the Atlantic storm activity is generally shifted east and northwards relative to the present-day simulation. The associated extreme surface winds are somewhat enhanced over Northern Europe in the scenario run. A consistent change is seen in sea level pressure with general decreases of high latitude pressure and increased mean westerlies to the north of approximately 50°N.

The 30 year scenario minus present-day changes of sea level pressure and storm track are found to be statistically significant at the 1% level. Furthermore, the main features of the changes of sea level pressure can not be explained by multi-decadal internal climate variability in the North Atlantic region. It is therefore concluded that these changes are due to the imposed greenhouse gas forcing.

1 Introduction

Concerns about the consequences of anthropogenic climate changes has increased in the public and scientific debate during the last decades. Especially the global effects of the increased concentration of CO_2 and other greenhouse gases in the atmosphere is a matter of constant discussions, and a great deal of scientific effort has been put into the investigation of this problem (see e.g., IPCC, 1996, 2001). In the recent years the focus on regional climate and extreme weather conditions has increased gradually, because changes of e.g. the frequency, strength and distribution of tropical and extra-tropical storms may cause damage exceeding those related to the climate warming itself (see e.g., Kunkel et al., 1999). An increase in the most intensive near surface winds will strongly enhance the storm related damages. Dorland et al. (1999) estimated that damage from storms in the Netherlands will increase by 80% if the maximum wind gust increases by 2% in a future climate (20% of the increase is due to economic growth). Results from the STOWASUS-2100 project (Stowasus-Group, 2001) show that regional increases by up to 10% in extreme wind speeds in the North Sea and Norwegian Sea can result in increases of the highest surges and wave heights by approximately the same percentage.

It is uncertain what the changes in severe storms in a warmer climate – if any – will be. Changes in the extra-tropical storm activity are, however, related to changes in the long-term mean atmospheric flow. The following potential changes in the atmospheric background flow characteristics are simulated by most global coupled atmosphere-ocean climate models (O-A-GCMs):

- Decreased horizontal temperature gradients in the lower troposphere related to a relatively strong warming over the far northern regions in winter (DJF). The polar near surface warming leads to a reduction of the baroclinicity in the lower part of the troposphere. From an isolated point of view this change should lead to a reduced intensity of extra-tropical storm activity, according to theory of baroclinic instability (Holton, 1992) as argued by Branscome and Gutowski (1992); Hall et al. (1994).

- While the baroclinicity in the lower part of the troposphere decreases, an increase is simulated in the upper troposphere, since temperatures in the tropical regions increase more than the corresponding temperatures near the poles where they actually decrease at high altitudes. This change in the background flow causes – again from an isolated point of view – an increase in extra tropical storm activity.
- Increased amounts of moisture available for condensation. The content of water vapour in the lower part of the atmosphere is generally increased as temperature increases, and this is also the case in global warming scenarios with climate models. Latent heat released in connection with condensation in extra-tropical low pressure systems will lead to increased conversion rates of potential to kinetic energy and thereby to faster development rates relative to what would happen in a dry atmosphere (e.g., Kuo and Low-Nam, 1990; Kuo et al., 1991; Gutowski et al., 1992; Langland et al., 1996). Therefore, one can expect increased amounts of water vapour available for condensation to result in more intensive extra tropical storms. Moreover, this effect may tend to be particularly important to the development of relatively small-scale phenomena like polar lows (Sardia and Warner, 1983).
- Decreasing static stability. Another feature which seems common to many climate models is an increasing lapse rate to the north of approximately 50°N. This means that the static stability decreases at high northern latitudes, when the concentrations of greenhouse gases are increased. An increased lapse rate impacts the process of baroclinic instability, since the horizontal scale of the most unstable (i.e. growing most rapidly) atmospheric wave becomes smaller. Furthermore, these smaller scale weather systems grow faster (see, e.g., Holton, 1992) when the static stability decreases. Thus the isolated effect of the simulated decrease in static stability is a shift towards smaller scale and more intensive low pressure systems at high latitudes.

One may be tempted to assume implicitly that changes in atmospheric long term background conditions is the main cause of changes in extra-tropical storm activity. This point of view is quite wrong, as it can be argued that the background flow (and its change) is a consequence just as much as a cause of the actual extra-tropical storm activity and the associated eddy heat and momentum transports. A complete description of the problem must therefore consider the mutual balance between the equator-to-pole heating gradient, the pole-ward eddy heat and eddy momentum flux convergence (and associated indirect circulations), which all determine the meridional temperature gradient and thus the strength of the eddies (e.g., Lindzen and Farrell, 1980; Hoskins and Valdes, 1990; Zhang and Wang, 1997; Hall et al., 1994)

Arguing along similar lines (e.g., Branscome and Gutowski, 1992; Held, 1993; Zhang and Wang, 1997) it is important to note that water vapour – in addition to the enhancing effect – also plays a very important indirect role which tends to weaken the extra-tropical storm activity. This is because an increasing tropical/extra-tropical humidity gradient (related to the Clausius-Clapeyron relationship) will make meridional vapour transport by the cyclones more efficient. Thereby the number and possibly the intensity of cyclones that are needed to maintain a certain pole-ward heat transport is reduced. In the above item list of background flow changes the first should lead to decreased extra tropical storm activity while the last three are favourable for increased activity. Theoretical considerations, diagnostic budget calculations and idealised model experiments can help to judge and understand their relative importance. Concerning the different changes in meridional temperature gradient at low and high altitudes (item 1 and 2) it has been suggested by Held and O'Brien (1992), using an idealised quasi-geostrophic model that eddy heat flux is more sensitive to low than upper level mean temperature gradient. The implication could be a net decrease in storm activity regarding these two items as indicated in the results by, e.g., Branscome and Gutowski (1992).

The above considerations concerns the zonal mean change and are relevant to the overall level of extra-tropical storm activity. From a regional impact perspective, however, climatic changes in the position and strength of the quasi-stationary planetary waves could be very important as modulators of the zonal mean changes, although it must still be kept in mind that causality is complicated as these large scale waves interact with the smaller scale transient eddies (i.e., the storms). It is thus well known that the large scale flow anomalies – as the so called North Atlantic Oscillation (NAO) – interact and are mutually dependent on organized variations in the small scale high frequency eddies (e.g., Nakamura et al., 1997, and references therein). There has been a number of empirical studies (e.g., Hurrell and van Loon, 1997; Rogers, 1997; Kaas and Schmith, 1996; Schmith et al., 1998) identifying these physical relationships.

As for observational evidence, a large number of investigations have estimated the storm activity back in time either from direct observations or inferred from measurements of *SLP*. Several papers report an increase in the north-east Atlantic storm activity and associated changes in the NAO during the last decades (Schinke, 1993; Stein and Hense, 1994; Haak and Ulbrich, 1996; Lambert, 1996; Kaas and Schmith, 1996; WASA-Group, 1998; Schmith et al., 1998), but some of these investigations indicate that a longer lasting and/or stronger trend is needed to finally disprove that the recent trend can be explained by natural inter-decadal variability.

The discussion above clearly shows that an understanding of possible changes in extra-tropical storm activity in a warmer climate is far from simple. It is generally accepted that coupled atmosphere-ocean climate models constitute the best tools available for estimating this change, because, in principle, such models do include basic non-linear feedback mechanisms. It is of relevance to consider models with high spatial resolution because many of the fundamental processes – particularly for extreme developments – take place on relatively small horizontal scales.

The changes of the storm activity in an atmosphere with increased CO_2 concentrations have been investigated for a number of GCM experiments. Most simulations show an increase in the storm activity in the eastern North Atlantic and in western Europe (Hall et al., 1994; Carnell et al., 1996; Lunkeit et al., 1996; Beersma et al., 1997; Cubasch et al., 1997; Schubert et al., 1998; Ulbrich and Christoph, 1999; Knippertz et al., 2000), while some find a weakening of the storms over western Europe (Schubert et al., 1998).

The resolution – e.g., T42 – of the GCMs which are normally used to investigate climate changes is probably inadequate to simulate extreme weather events realistically. To overcome this problem high resolution 'time slice experiments' with AGCMs in high resolution have been used (Bengtsson et al., 1995, 1996) to study tropical storms. In this context time slice experiments are based on a long-term transient climate sensitivity simulation which is first performed with a coupled atmosphere-ocean model at low resolution. The simulated sea surface temperatures (SSTs) for smaller time intervals – corresponding to present and anticipated future climate conditions – are then used as lower boundary conditions in a set of high resolution atmospheric GCM simulations.

Moreover, as climate contains rather slow internal variations, the time slice simulations have to be sufficiently long to identify any changes forced by increased greenhouse effect. Beersma et al. (1997) analyzed the North Atlantic extra-tropical storm activity in the same simulations previously used by Bengtsson et al. (1996) to study tropical storms. These simulations only covered a 5-year control run and a 5-year scenario run with increased concentrations of greenhouse gases. They found that the differences in extra-tropical baroclinic activity between the simulations were less than the typical observed difference between two 5-year periods with high and low NAO index. They thus concluded that longer simulations were needed to obtain statistically robust estimates of potential future changes in North Atlantic storm activity. Here we present an analysis of storm activity in the Northern Atlantic as simulated in two 30 year time-slice experiments with a high resolution (T106) GCM. The motivations for this study are:

- To investigate if a resolution of T106 adds information relative to T42 in simulating extreme baroclinic events.
- To calculate the difference between the scenario and the present-day simulations in terms of North Atlantic storm activity.

The paper is organized as follows: after a short description of the experimental design in section 2, the storm climate is analyzed in section 3 by considering sea level pressure, storm track intensity and extreme wind speed. Differences between the present-day run and ECMWF re-analysis (ERA) are discussed as well as the differences between the underlying coupled simulation in T42 resolution and our T106 simulations. Further, the changes between the present-day and the scenario run are investigated. In section 4 the statistical significance of the changes is investigated while section 5 discusses the possible role of interdecadal natural climate variability. This is followed by a discussion in section 6 and a summary and conclusion of the paper in section 7.

2 Experiment

The model used in the time-slice experiment is the ECHAM4 AGCM (Roeckner et al., 1996a) in T106 resolution, corresponding to a Gaussian grid of 320×160 points (1.125°×1.125°), with 19 vertical levels. The SSTs and sea ice extent were interpolated month by month from a transient run with increasing greenhouse gases (CO_2, CH_4, NO_2, and CFC's) using the ECHAM4/OPYC coupled ocean-atmosphere model in T42 resolution (Roeckner et al., 1999). There was no direct or indirect aerosol forcing in the experiments. Two 30-years time slice experiments were performed: 1970 to 1999 and 2060 to 2089. From 1970 to 1990 observed concentrations of greenhouse gases were used. After 1990 concentrations as described in the IPCC scenario IS92a (IPCC, 1996) were used. The two time slices represent present day climate and a climate with approximate equivalent doubling of the CO_2 concentration relative to present day. A detailed description of the experiment and general changes between the present-day and scenario runs can be found in May (1999) and in May and Roeckner (2001). It should be noted that the change in net radiative forcing solely due to increased concentrations of greenhouse gases from the first to the second time slice is very similar to the corresponding net change for the recent Special Report on Emission Scenarios (SRES) marker scenario A2 (IPCC, 2001) when the increased concentrations of greenhouse gases and the (small) change in direct and indirect aerosol forcing of A2 are included. In this way the time-slices constructed here may be considered a proxy for the A2 marker scenario.

3 The storm climate

The analysis is performed on the boreal winter (November to March) climate in the northern part of the North Atlantic and in Europe. The region is located from 30 to 80°N and from 90°W to 50°E. The boreal winter is chosen as this is the time of most frequent and intense mid-latitude storms in the Northern Atlantic.

The data used consist of average winter mean sea level pressure (*SLP*), 6 hourly 500 hPa height fields and 12 hourly maximum value of wind speed at the 10 m level.

3.1 The T106 simulation for present-day climate compared to the ECMWF Re-analysis

3.1.1 Sea level pressure

The *SLP* in the T106 simulation agrees quite well with the *SLP* in the ERA (Gibson et al., 1997) (Fig. 1a+b). Both the Icelandic low and the Azores high are well simulated, although the Azores high and the Icelandic

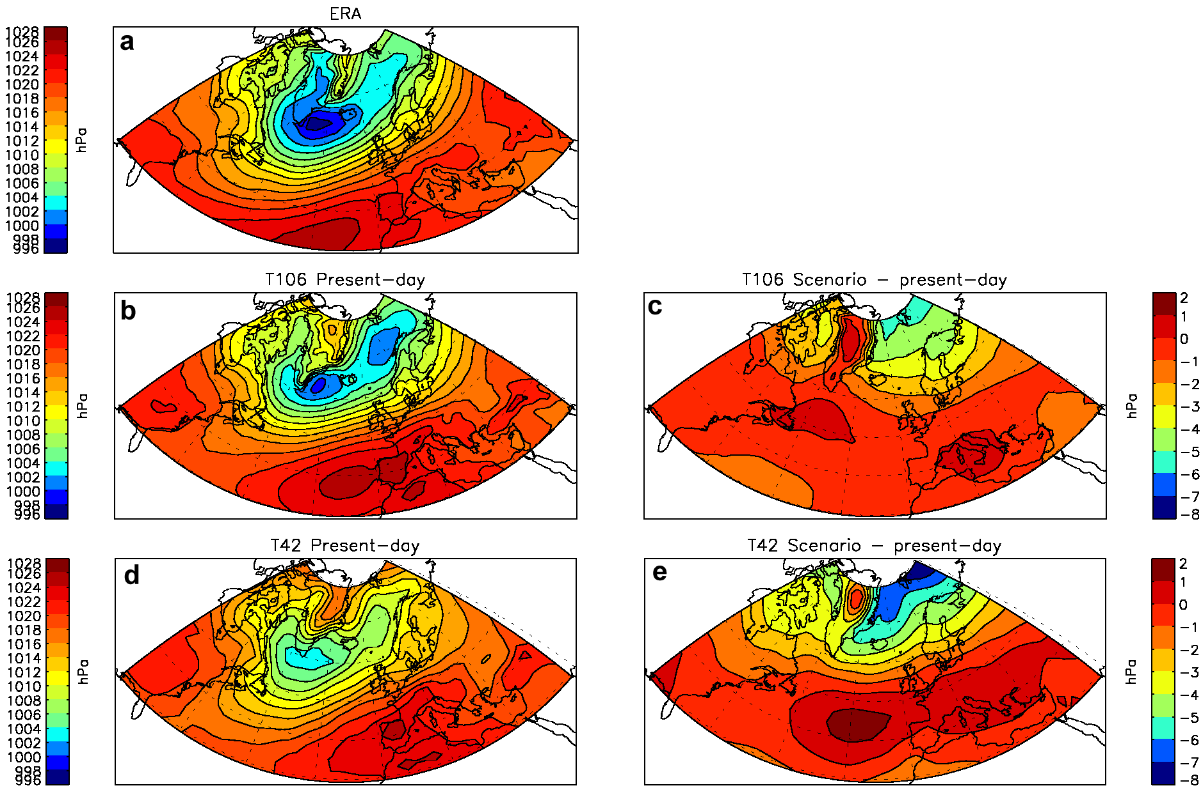

Fig. 1: The winter (NDJFM) mean value of the sea level pressure (hPa) from a) the ERA data, b) the present-day run in T106 resolution, c) the difference between the scenario and the present-day run in T106 resolution, d) the present-day run in T42 resolution and e) the difference between the scenario and the present-day run in T42 resolution.

low are shifted somewhat to the north east. The difference over Greenland is artificial and related to the extrapolation of surface pressure to sea level.

The variability of the *SLP* was investigated by applying an EOF analysis on the monthly *SLP* for the winter (NDJFM). The first EOF (the NAO pattern) of the T106 simulation (not shown) has the same structure as seen in observations with two centres of maximum variability. The centres are, however, displaced towards the east in the simulation, with centres in Northern Scandinavian and just west of Portugal. The first EOF describes 30% of the inter-monthly variability of *SLP*.

3.1.2 Storm tracks

The standard deviation of the 2.5 to 6 day bandpass filtered 500 hPa geopotential height (std_{500}) is often used as a measure of the baroclinic activity (Blackmon, 1976). This is here referred to as the storm track intensity.

In the ERA data the storm track is most intense from the eastern North America around Newfoundland towards the north-east to the North Atlantic around Iceland (Fig. 2a+b). The maximum value of 75 m is situated above Newfoundland. Both the location and the form, i.e. the bending towards north-east just south of Greenland, of the storm track is well simulated by the ECHAM4 model, although the maximum value over Newfoundland is too low by 7 m (~10%). In the northern part of the investigated area, the std_{500} is about equally large in ERA and ECHAM4. In the southern part, however, it is weaker.

3.1.3 Winds

The ERA 10m winds are not suitable for validating the ECHAM4 simulations because they mainly reflect the behaviour of the boundary layer scheme in the assimilating model. An alternative approach could have been to compare the geostrophic winds in ERA to those in the ECHAM4 simulations. However, when it comes to extreme events any differences would probably, again, reflect nothing else but differences between the two models. This is because over ocean very few or no conventional data are available for data assimilation, and regarding the satellite mass field (i.e., temperature) data entering the reanalyses the resolution (mainly in the vertical) is far two coarse to describe the details in the baroclinic structure of very intensive depressions. Hence, the local details of such intensive systems are basically created by the ERA assimilating model.

3.2 Differences between the present-day and scenario simulations in the T106 resolution

3.2.1 Sea level pressure

In the scenario run in T106 resolution the *SLP* is gradually reduced relative to the present-day run northward of about 55°N, reaching a 6 hPa reduction at the northern boundary of the region (Fig. 1c). This enhances the meridional pressure gradient from 50 to 70°N. The *SLP* over Greenland increases by 2 hPa but

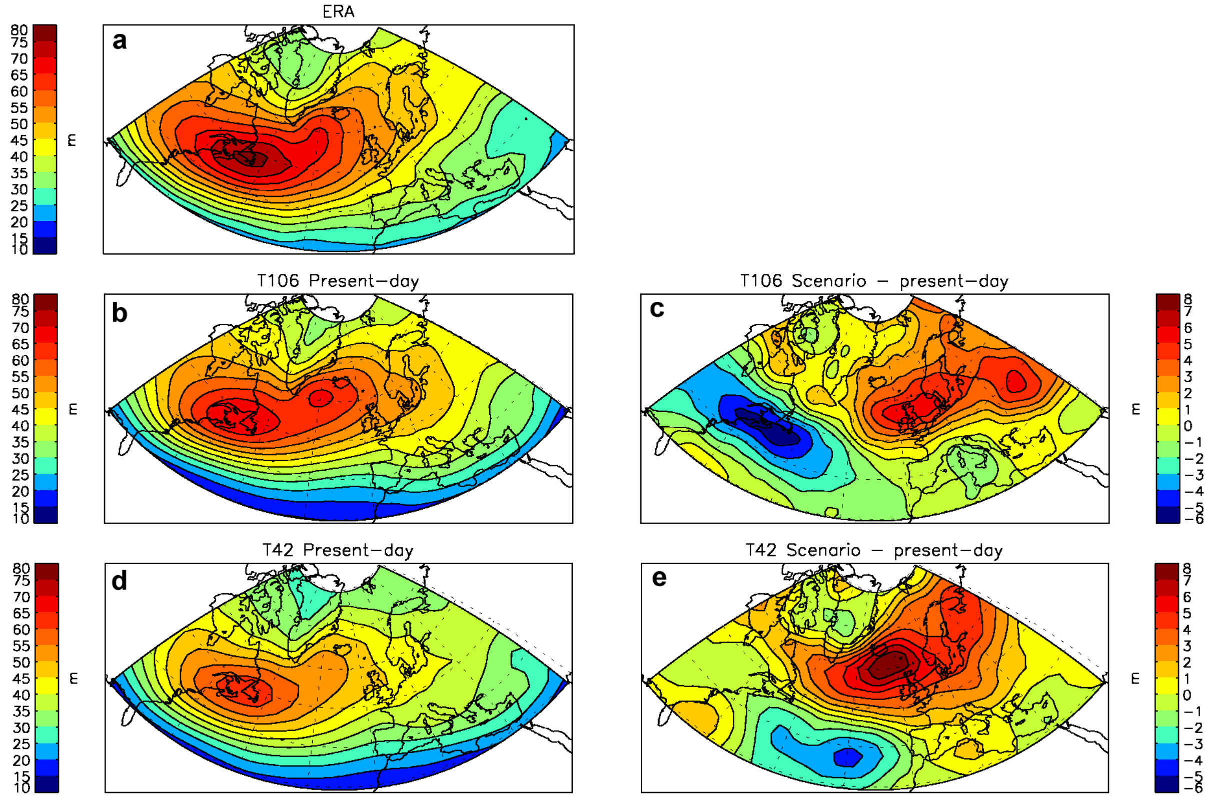

Fig. 2: The winter (NDJFM) storm track intensity (the 500 hPa short term variability) from a) the ERA data, b) the present-day run in T106 resolution, c) the difference between the scenario and the present-day run in T106 resolution, d) the present-day run in T42 resolution and e) the difference between the scenario and the present-day run in T42 resolution. Unit: m.

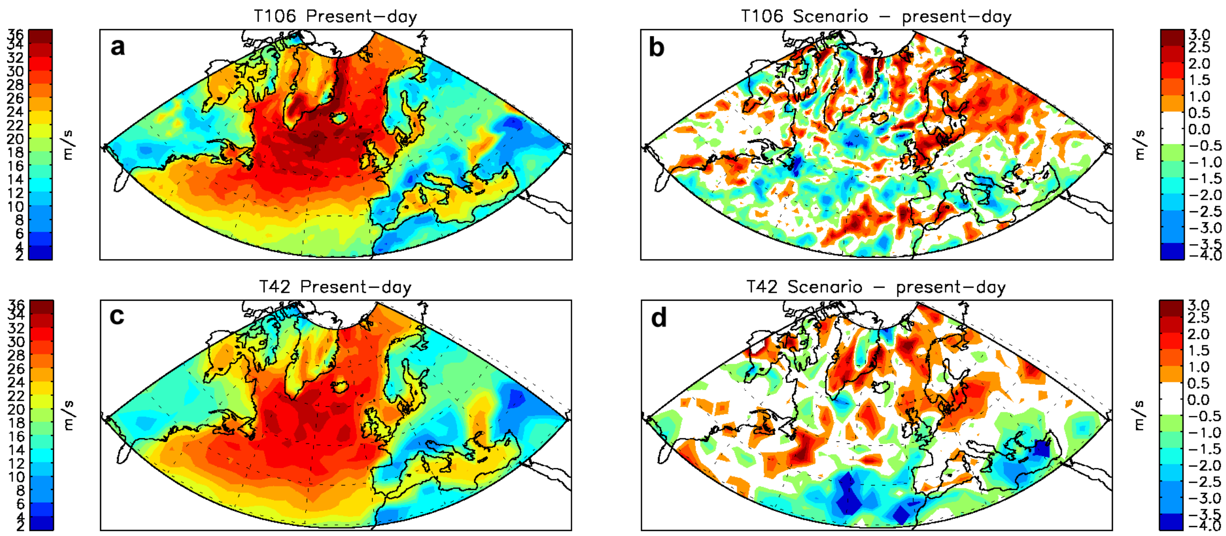

Fig. 3: The mean value of the 10m max wind speeds exceeding the 0.1% percentile level for a) the present-day run in T106 resolution, b) the difference between the scenario and the present-day run in T106 resolution, c) the present-day run in T42 resolution and d) the difference between the scenario and the present-day run in T42 resolution. Only values from winter (NDJFM) are included. Unit: m/s

this is an artefact due to the extrapolation of surface pressure to sea level. A small (2 hPa) increase in the *SLP* is seen over Newfoundland and over the Mediterranean.

3.2.2 Storm tracks

In the scenario run there is a decrease of the std_{500} values over Newfoundland and the Atlantic Ocean south of 50°N and increased values over most of northern Europe (Fig. 2b), especially over the North Sea and Britain and north of the Black Sea, where values are increased with 6 m's. These changes can be viewed as a downstream (i.e. north-eastward) displacement/extension of the storm track. Over the Mediterranean there is a weak reduction in std_{500}. The simulated changes are consistent with the changes in the *SLP* with an increase in the pressure gradient over Scandinavia and the Arctic Atlantic Ocean. An enhancement of the storm activity over the North Sea and western Europe is found in several GCM experiments (see e.g., Lunkeit et al., 1996; Beersma et al., 1997; Cubasch et al., 1997; Ulbrich and Christoph, 1999; Knippertz et al., 2000). In some studies (Hall et al., 1994; Schubert et al., 1998; Lunkeit et al., 1998) this is interpreted as a downstream displacement of the storm track.

3.2.3 Surface winds

As a measure of the extreme winds the mean value of all individual 10m maximum winds exceeding the 0.1 % percentile level was used for each grid point. This corresponds to the mean value of the 8 highest wind speeds from the simulations.

The changes in the wind speeds reveal a much more noisy pattern than the changes in the std_{500}, but some similarities can be seen: In the area, where the std_{500} is increased (i.e., northern Europe), there is a small (1 - 2.5 m/s) increase in the extreme wind speeds (Fig. 3b). Correspondingly there is an overall small reduction in the extreme wind speeds in those areas where the std_{500} decreases (i.e., over the Atlantic Ocean off the Newfoundland coast and in Southern Europe). Over the Atlantic Ocean west of Portugal the wind speed increases although the 500 hPa variability is reduced.

The percentage changes in extreme winds between the scenario and the present-day run are shown in Fig. 4a. It is seen that the extreme 10m maximum winds show a somewhat similar pattern as in Fig. 3b with increased values in the northern Europe and over the Atlantic west of Portugal. These increases locally reaches more than 10% at which level they tend to become statistically significant (not shown). The widespread smaller "patchy" changes are generally not significant. Decreased values are found in the Mediterranean area and over the Atlantic east of Newfoundland.

3.3 Differences between the simulation in T106 resolution and T42 resolution

In this sub-section the results from the model in T106 resolution are compared to the results from the coupled simulation in T42 providing oceanic boundary conditions to our T106 simulations. A description of the changing storm climate in the T42 simulation is given in Ulbrich and Christoph (1999) and Knippertz et al. (2000).

3.3.1 Sea level pressure

In both the scenario and in the present-day run the T106 simulation has stronger westerlies than the T42 simulation and with isobars directed more in the east-west direction (Fig. 1b+d). Both models agree on the enhanced meridional pressure gradient in the scenario runs with lower pressure in the northern part of the region and higher pressure in the southern part, including the Mediterranean area. Especially over Scandinavia and over the Greenland/Norwegian Sea the meridional pressure gradient is enhanced. The model in T42 resolution places the region of pressure increase close to

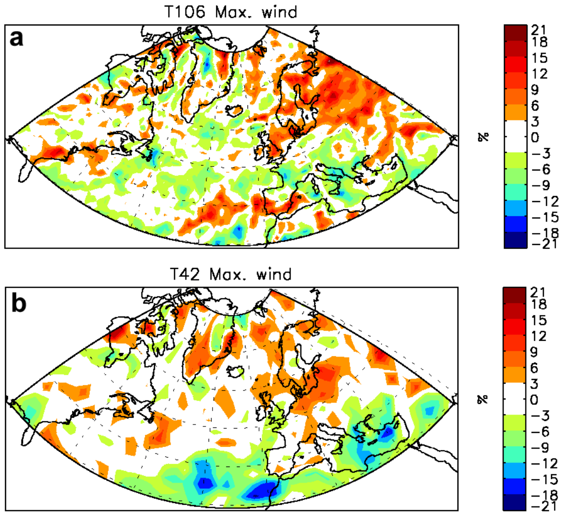

Fig. 4: The relative changes of the extreme winds relative to the present-day run for a) the geostrophic winds in T106-resolution, b) the 10m maximum winds in T106-resolution, c) the geostrophic winds in T42-resolution, d) the 10m maximum winds in T42-resolution. The extreme winds were calculated as the mean value of the 0.1% strongest winds.

the Azores while the model in T106 resolution has the largest pressure increase over the Atlantic out of Newfoundland and in the Mediterranean area. The difference seen on the Greenland ice sheet is due to the extrapolation of surface pressure to sea level.

More detailed comparisons between the model in T42 and T106 resolution are provided in May (1999) and May (2001).

3.3.2 Storm tracks

Both the T42 and the T106 present-day simulations show a correctly located maximum of std_{500} near Newfoundland (Fig. 2). The simulated maximum is, however, about 6 m (~10%) weaker in the T42 than in the T106 simulation, which was already somewhat too weak. The secondary maximum south west of Iceland in the T106 simulation is not seen in the T42 simulation, and there are large areas where the variability is between 10 and 20 percent larger in the T106 simulation.

Though both simulations in T106 and T42 resolution agree on enhanced std_{500} over northern Europe in the scenario run, they show different patterns. While the simulation in T106 resolution has a SW-NE see-saw pattern with decreasing values over Newfoundland, the changes in the simulation in T42 resolution are more directed in the N-S direction with increasing values south-east of Iceland and decreased values over the Atlantic Ocean between 30°N and 45°N.

The weak reduction in std_{500} in the Mediterranean simulated in the T106 resolution scenario run is not seen in the T42 resolution, where the changes are close to zero.

3.3.3 Surface winds

The largest difference between T106 and T42 in the extreme 10 m wind speed is the 5 to 10 m/s higher values

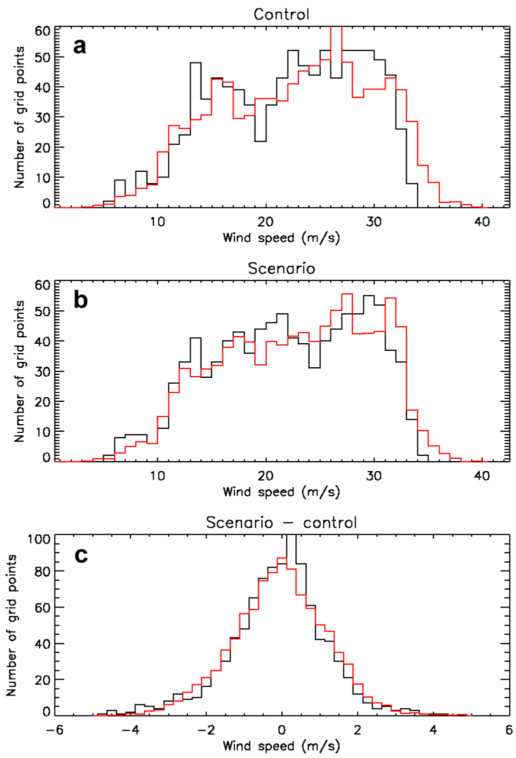

Fig. 5: Histogram of the mean value of the 10m maximum winds exceeding the 0.1% percentile for both the T42 (black lines) and the T106 (red lines) resolutions. a) the present-day runs, b) the scenario runs and c) the differences between the scenario and the present-day runs. The number of grid points from the T106 resolution is scaled to the numbers in the T42 resolution.

in the T106 simulation just off the east coast of Greenland (Fig. 4b). This could partly be due to orographic effects, since the eastern slope of the Greenland ice sheet is considerably steeper in the T106 simulation. In the remaining central and northern part of the area the T106 extreme winds are about 5-7% stronger than at T42.

In the southern part of the ocean area the T42 extreme 10 m winds are stronger than the T106 winds. This is consistent with the differences in mean *SLP* and std_{500}.

Regarding the differences between scenario and control simulations, the T42 change over northern Europe seems to be smaller than at T106 in spite of the apparent larger change in *SLP* and in std_{500} at T42 resolution. The reason for this is unclear, and we do not believe it is due to the strict choice of percentile since the corresponding patterns of change for the average over the weaker 1.0 percentile (not shown) are qualitatively similar to those in Fig. 3.

The differences in extreme 10 m winds can also be displayed as occurrence in different classes. Fig. 5 shows the distribution for the model both in T42 and T106 resolution for the entire selected area. The distributions for the two model resolutions are relatively similar both for the present-day and the scenario runs, but generally with more grid points exceeding 32 m/s in the T106 resolution. The higher density of very strong winds above 35 m/s in the T106 resolution is mainly located along the Greenland east coast and could be due to the orographic effects mentioned above. The difference in distibution function between the scenario and control is generally small with a weak tendency for “more change” (positive as well as negative) in the T106 resolution.

4 Statistical significance of the responses in sea level pressure and storm tracks

The statistical significance of the changes in *SLP* and in std_{500} were calculated using the Mann-Whitney test, which is a non-parametric test (see e.g., von Storch and

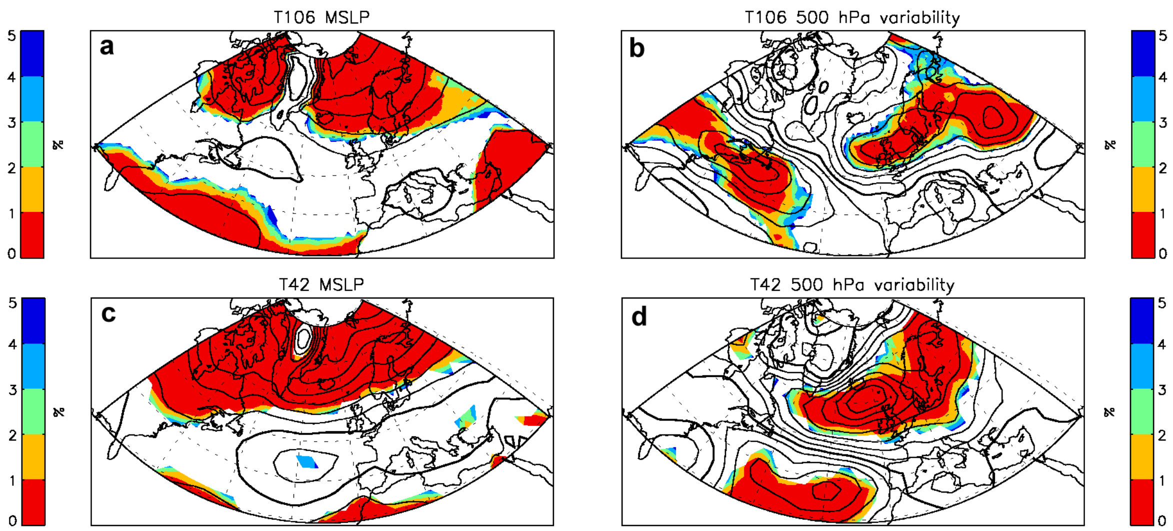

Fig. 6: Statistical significance of the changes in sea level pressure and storm track for a) and b) the T106-resolution, c) and d) the T42-resolution. The significance were calculated by applying Mann-Whitney test for each point. The colour scale applies to the significance levels of the changes, while the contour lines are the changes between scenario and present-day run. Contour intervals are 1 hPa for the sea level pressure and 1 m for the storm track. The contour lines with zero value are thick.

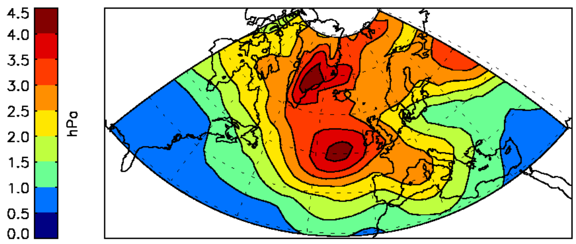

Fig. 7: The maximum difference in sea level pressure (hPa) between any two 29-year mean values for each grid point. The data are from a 300 year long control simulation with the coupled ECHAM4-OPYC model. The atmospheric model is in T42 resolution.

Zwiers, 1999). The null hypothesis, that the mean values from the scenario and the present-day runs were equal, was tested against the alternative hypothesis of different means. This was done for each grid point for the values of the 29 winters from each run.

The results are shown in Fig. 6 for *SLP* and std_{500} for different significance levels. A substantial part of the *SLP* changes (scenario minus present-day) are significant of a 1% level both in the T106 and in the T42 resolution. Areas of statistical significant changes (on a 1% level) for the std_{500} and the *SLP* cover approximately the areas where the corresponding differences (scenario minus present-day) are largest in both resolutions.

5 Long term variations

The atmospheric flow in the North Atlantic region is known to variate on different time scales. The most pronounced large scale phenomenon is the NAO, i.e. the variations in the *SLP* difference between the northern and southern part of the North Atlantic, (see e.g., Hurrell, 1995; Cook et al., 1998), which accounts for more than one third of the overall variability of the *SLP* (Cayan, 1992). During periods with a strong meridional pressure gradient (high NAO-index) the mid-latitude westerly winds are enhanced and the storms become stronger and more frequent (Rogers, 1990). As the NAO-index varies on time scales up to decades, the 2×5 years of time slice simulations analysed by Beersma et al. (1997) were too short, as the changes associated with the greenhouse warming were of the same order of magnitude as the internal variability seen in the ERA – and other – data. To test if our much longer simulations suffer from the same problem of long term internal climate variability we investigate the variations of a 300 year long control run from the OPYC-ECHAM4 coupled model (Roeckner et al., 1996b). As the same model was used for generating the SSTs for the time slice it is assumed that the long term internal variability for the coupled run and for the time slice experiment are reasonably alike. For each grid point 29-year mean values of the *SLP* were calculated from the 300 year control run. This was done with 1 year increments, i.e., in total 300-29+1 mean values were found. The maximum difference between any two 29-year mean values for each grid point is shown in Fig. 7. Maximum values of 4.3 hPa are found over Southern Greenland and west of Ireland. (The local maximum above Greenland could be due to extrapolation of surface pressure to sea level.) These numbers can be compared to the scenario minus present-day differences of the *SLP* (Fig. 1c+e). There are widespread scenario minus present-day changes exceeding the corresponding maximum differences between any two 29-year mean values for the 300-year simulation. In the T42 simulation this is the case for the changes in the area north of 60°N, except Greenland. For the T106 simulation this includes changes over Scandinavia, the sea north of Iceland and northern Canada. It is thus very unlikely that these scenario minus present-day changes should be caused by long term internal variability.

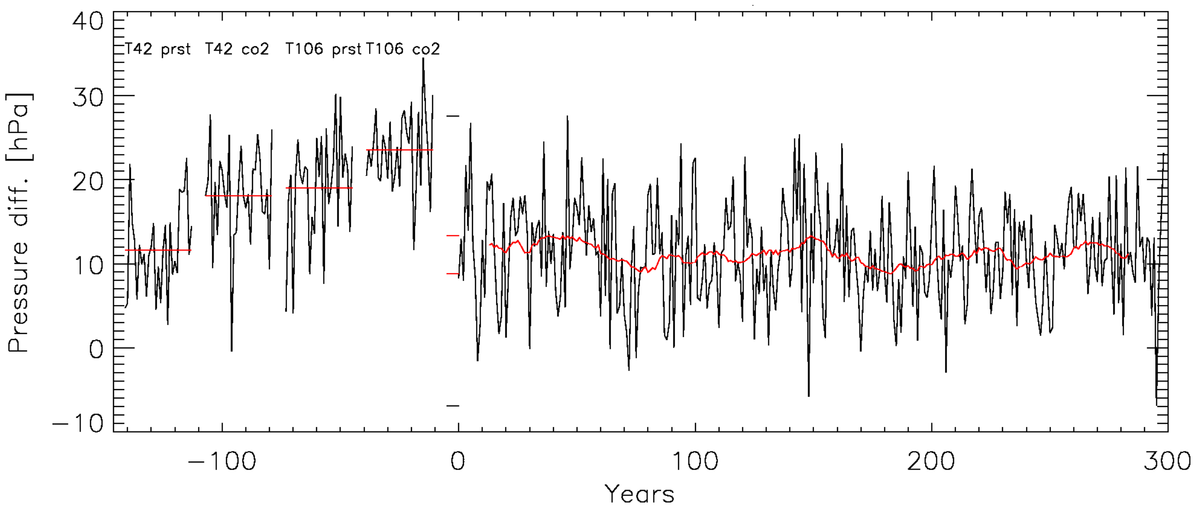

Fig. 8: Pressure difference between areas in southern Europe (5W-10E,40N-50N) and in the northern Norwegian Sea (5W-10E,70N-80N). The pressure difference is shown as mean winter (NDJFM) values for T42 present day, T42 scenario, T106 present day, T106 scenario and from the 300 years T42 control run. The red lines show the mean values for the 30-year runs and the 29-year running mean for the 300-year control run. The marks at 0-year indicates the extreme values for the 300-year control run and the extreme values for the 29-year running mean from the same run.

To describe changes in storm activity a potentially more fundamental parameter than local pressure anomalies is that of meridional pressure gradients. To investigate if long term variability could be responsible for the scenario minus present-day changes in the storm climate the pressure gradient in the 300-year control simulation was compared to pressure gradients in the T42 and T106 simulations. The pressure difference between areas over south-western Europe (5°W - 10°E, 40°N-50°N) and over the Greenland Sea (5°W-10°E, 70°N-80°N) were calculated for each winter (NDJFM). The areas were chosen so that they represent the meridional pressure gradient over Europe in both the T42 and in the T106 runs. The mean value for the 29 winters of the 30-year runs were calculated as well as the 29-year running mean of the 300-year control run. The results are shown in Fig. 8. For both the T42 and the T106 simulations the changes (6.4 and 4.6 hPa, respectively) between the scenario and the present-day run are larger than the difference between the minimum and the maximum of the 29-year running mean from the 300-year control run (4.5 hPa). Furthermore, the average pressure gradient in the T42 scenario simulation is more than 4.5 hPa larger than in any individual 30 year period of the 300 year control simulation. Since the number of independent 30 year slots in the 300 year time series is 10 a conservative estimation is that it is less than 10 percent likely that the changes in regional meridional pressure gradient between the scenario and the present-day runs could be due to inter-decadal natural variability.

6 Discussion

We found in the previous section that the overall enhancement of the near surface westerlies between 50 and 70°N in the North Atlantic region is a consequence of the forcing since the change exceeds the maximum inter-thirty year variability. In support of this conclusion we note that the enhancement is a regional manifestation of an overall - and highly significant - increased meridional surface pressure gradient around 60°N. This can be seen clearly from Fig. 9 where the global field of long term mean *SLP* and its difference in the two time slice simulations is shown for the calendar months DJF and JJA. This strongly indicates that the increased westerlies in the North Atlantic region in winter reflects a hemispheric forced change, since the zonal mean component of the 30 year changes in Fig. 9 far exceeds possible climate anomalies due to non-forced atmospheric variability. The equivalent and quite similar Southern Hemisphere changes, particular in the southern winter (JJA), further supports the conclusion that the simulated changes in the zonal mean flow are forced. The general feature with decreased Arctic and Antarctic winter surface pressure is supported by most other coupled atmophere-ocean models, see, e.g., Fig. 9.12 in IPCC (2001).

We note that the simulated *SLP* change in the Northern Hemisphere in DJF projects quite strongly on the so called Arctic Oscillation (AO) pattern (see e.g. Fyfe, 1999) while the difference in the southern hemisphere in JJA even more clearly mimics the Antarctic Oscillation (AAO) pattern. It is difficult to judge which basic mechanisms may lead to greenhouse forced changes in the AO (and AAO) in the future, but it has been suggested by Shindell et al. (1999) that forced changes in the stratosphere may change the characteristics of the dynamic wave interactions between the stratosphere and the troposphere in such a way as to strengthen the AO, i.e., decrease/increase the surface pressure in the arctic/sub-tropical areas. Another possible mechanism leading to increased AO is a thinning/melting of the Arctic sea ice. From the atmospheric point of view this will act as a large lower boundary heating anomaly. Such a heating anomaly tends to decrease the surface pressure via mechanisms equivalent to those in monsoon circulations. An enhanced release of latent heat at high latitudes associated with enhanced high latitude winter precipitation simulated by most modern GCMs (IPCC, 2001) also constitute a major anomalous atmospheric heat source which may in part explain an increase in the simulated AO and possibly in the AAO.

The discussion on changes in the *SLP* is relevant because there is a relationship between (variations in) this parameter and the position/strength of the storm activity (Rogers, 1990, 1997; Kaas and Schmith, 1996; Schmith et al., 1998). To verify that this relation is also seen globally in our simulations we have plotted the global fields of simulated std_{500} and its change in the months DJF and JJA. In both hemispheres there is a general poleward shift in the storm activity, particularly in the cold season, associated with the increased meridional pressure gradient. But on top of this general picture there are also regional details in both hemispheres demonstrating the relationship between enhancement of strong pressure gradients and enhanced storm activity.

We argued in the introduction that the availability of more moisture for release of latent heat in strong baroclinic developments may decrease their horizontal scale. We have developed a simple local measure to estimate potential changes in the intensity of the inner core of intensive lows simulated at the T106 resolution. The calculation of the index at a given time consists of three steps:

1) a calculation of the Laplacian of the *SLP* ($\nabla^2(SLP)$);
2) a resetting to zero of the value obtained in 1) in all grid points which are not local pressure minima; and
3) a final scanning where a given grid point is assigned maximum value of the result of step 1) and 2) in a surrounding area of 500 times 500 km.

In this way, for a given time, the parameter is approximately a measure of the geostrophic vorticity of the most intensive neighbouring low. For each grid point we have calculated the average of the 20 largest values of the index in the scenario and in the present day simulation. The differences between these fields (not shown) has no overall change in the intensity of the most intensive lows. This means that there is no indication that the inner cores of the baroclinic systems are systematically enhanced in the scenario. We underline that this finding is based specifically on the ECHAM4 model. May (2000) has shown that this model at T106 horizontal resolution is inferior in its ability to simulate tropical storms relative to ECHAM3 at the same resolution (Bengtsson et al. (1995)). This indicates that some processes in ECHAM4 related to release of latent heat and/or the feedback of this heat to the dynamics of model may be too inefficient to fully describe the effect of the diabatic forcing of intensive systems. The reason for this behaviour may be related to the physical parameterisation but the problem would need further investigation. It is noted that this potential weakness may influence our basic findings regarding future changes in extreme extra-tropical storms.

7 Summary and conclusions

The storm track intensity (band-pass filtered 500hPa height variability), time average of mean sea level pressure and near surface extreme wind speeds (average speed over the 0.1 percentile threshold) are investigated

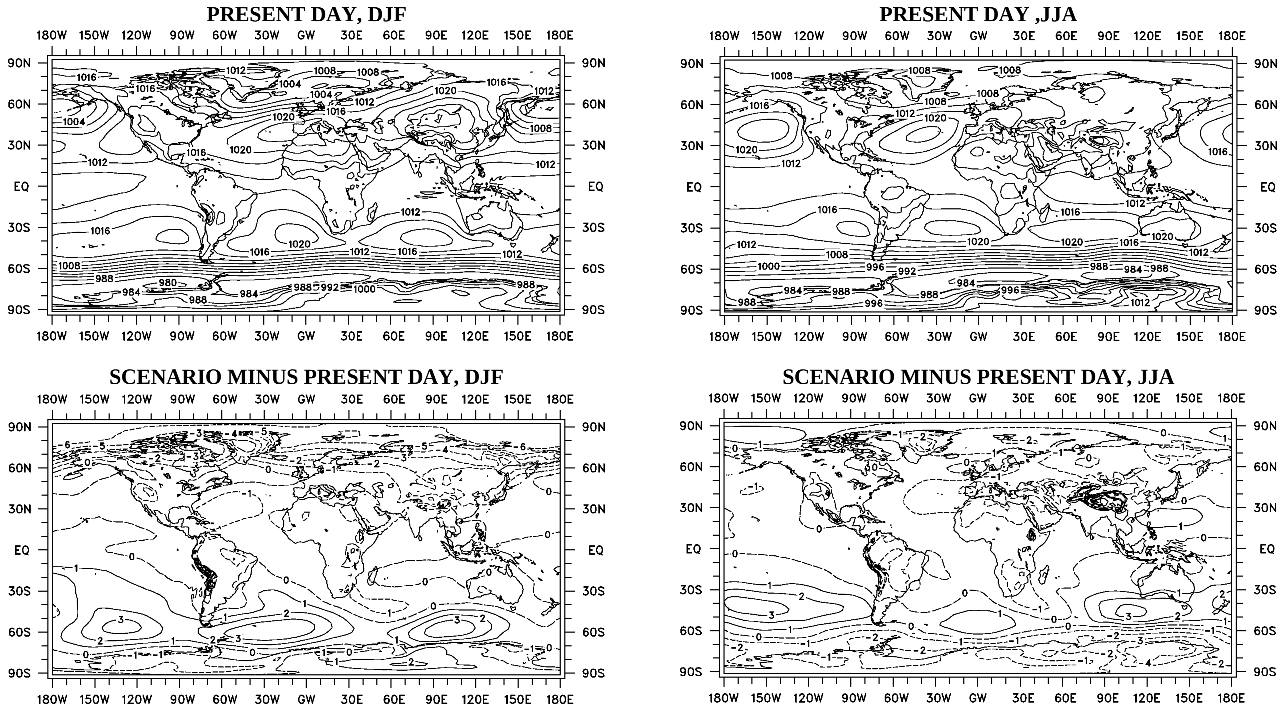

Fig. 9: Long term mean sea level pressure in the 30 year time slice simulations at T106 resolution. Top left: the present day simulation in DJF. Top right: as top left, but for JJA. Bottom left: difference between scenario and present day simulation in DJF. Bottom right: as bottom left, but for JJA

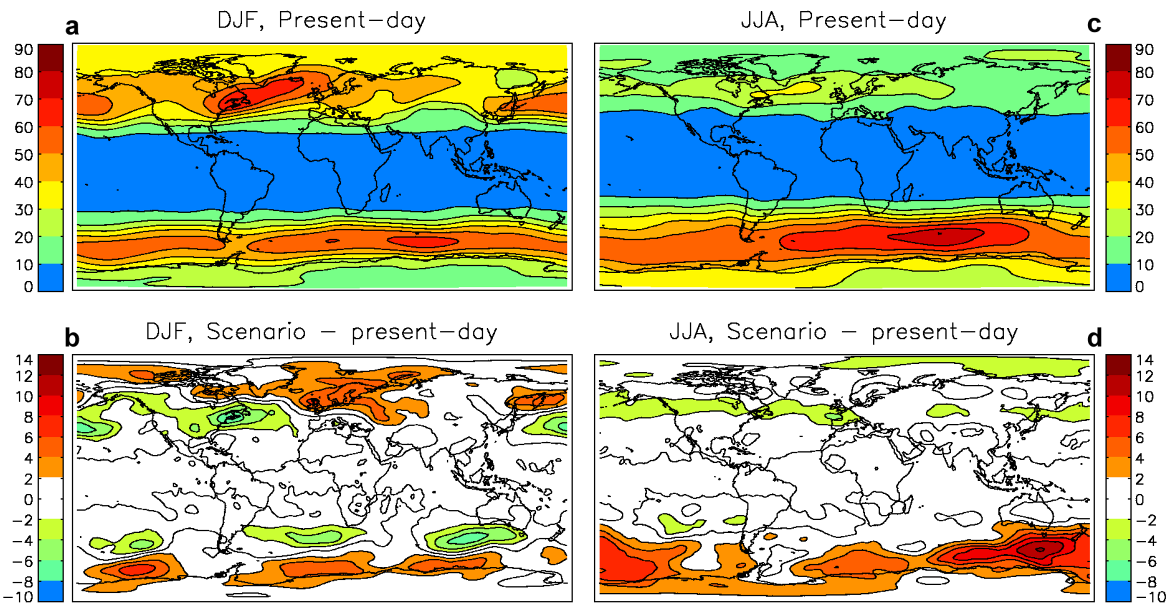

Fig. 10: Storm activity (500 hPa short term variability) from the simulation with the model in T106 resolution. a) Present day simulation for northern hemisphere winter (DJF). b) Scenario minus present-day simulation (DJF). c) Present day simulation for (JJA) d) Scenario minus present-day simulation for (JJA).

in the winter season (NDJFM) in the North Atlantic region for a present day and a greenhouse gas scenario time-slice simulation with the ECHAM4 AGCM at T106 horizontal resolution. The analysis includes a comparison of the T106 data with the corresponding coupled atmosphere ocean simulations (ECHAM4/OPYC) at atmospheric T42 horizontal resolution providing oceanic boundary conditions (SSTs and sea ice) for the time slice simulations. Furthermore, the model data are compared to ECMWF re-analyses (ERA). From our analyses we conclude:

At T106 resolution the model tends to weakly underestimate the standard deviation of the 500 hPa band pass filtered height fields in the present day by compared to ERA. The underestimation of the storm track is more severe at T42 resolution – generally 10-20% weaker than at T106. The climatologic sea level pressure is simulated fairly close to the ERA data, although the isobars over western Europe at T106 model resolution should be slightly more northward and the centre of the Icelandic low pressure system at T42 is 6-7 hPa too high. In the central and northern Atlantic the magnitude of the extreme wind speeds at the 10 meter level are 5-7% stronger at T106 than at T42 resolution.

As for the differences between the scenario and control time slice simulations, the main statistically significant feature is a moderate downstream shift/extension of the Atlantic storm track and an overall zonalization (i.e., enhanced westerlies) of the mean flow between 50 and 70°N. This large scale change generally leads to small increases in the extreme wind speed statistics in northern Europe. Locally the increase in extreme wind speed is more than 10%, however, the pattern of change is highly patchy, and locally relatively few of these changes are significant at a reasonable level. We anticipate that the noisy signal is due to a combination of relatively short length - 2 times 30 years - of the simulations and our high choice of threshold for extreme winds: 0.1 percentile corresponds to only 8 data points within 30 winters. Also the underlying T42 coupled simulation shows a downstream shift/extension of the storm track and an associated enhancement of the time mean westerlies between 50 and 70°N. Generally the T42 changes are somewhat more pronounced than in the T106 model, although this is not the case for 10 m extreme winds.

Based on an additional analysis of the inter-thirty year variability in the coupled 300 year T42 control simulation it is excluded that the overall climate change in sea level pressure - i.e. an enhanced meridional pressure gradient around 60N - could be due to inter-decadal variability. In other words it must be due to the greenhouse gas forcing. This is further supported by a global inspection of the change in the sea level pressure and in the 500 hPa high frequency variability. These changes are closely interrelated and illustrate that the North Atlantic increase in meridional pressure gradient is a regional manifestation of a hemispheric signal characterised by a poleward shift in the storm activity. This signal is also - with some modification - visible in the southern hemisphere winter. Since most recent simulations with coupled atmosphere ocean models show the increase in the winter meridional pressure gradient we conclude that it is likely that the future storm activity over Europe will show a moderate increase.

From an additional investigation of the low pressure systems it is concluded that the ECHAM4 model at T106 resolution show no systematic tendency towards increased inner core intensity of the strongest lows. It is argued that an apparent weakness in the ability of the ECHAM4 T106 model to simulate intensive latent heat driven systems as tropical storms may impact the results presented here, since in a warmer climate one may expect a stronger impact of latent heat release in extra-tropical storms.

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