Shifts of means are not a proxy for changes in extreme winter temperatures in climate projections

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Abstract (249 words, max 250)
Changes in severity of extreme weather events under influence of the enhanced greenhouse effect could have disproportional large effects, compared to changes in the mean climate. To explore changes in the tails of the probability density functions (PDFs) of local weather variables, we used a coupled atmosphere/ocean/sea-ice model for two 49-member ensemble runs, for present-day (1961-1990) and scenario (2051-2080) greenhouse gas concentration timeseries. These large ensembles (1470 years each) provide a sufficiently long time series for an analysis of the meteorological circumstances of extremes and changes therein. We have focused on daily-mean surface-air temperatures in winter over the Northern Hemisphere. Over large parts of the continents, changes in the shape of the PDFs contribute at least as much as shifts in the mean to changes in the one-in-10-year temperature events. In coastal areas this is largely attributable to changes in the large-scale circulation, for those types of extremes linked to infrequent wind directions. In other areas, the inhomogeneous mean warming, increasing inland and polewards, affects the tails of the local temperature PDFs. A large-scale circulation anomaly pattern links temperature extremes in widely different regions. Its geographical structure resembles the Northern Hemisphere Annular Mode. In the projected ensemble, this anomaly pattern favours its positive phase, leading to the enhanced probabilities of westerly winds all around the Northern Hemisphere. In some regions the outer ends of the tails of PDFs respond stronger than, or different from, the one-in-10-year extremes, as shown for one-in-100-year events by applying the General Extreme Value analysis.

1 Introduction

Climate model studies in the past decades have indicated possible significant changes in the mean climate under influence of an increased greenhouse effect. Many impact studies of climate change have used such information extensively, assuming implicitly that probability distributions around the mean state would stay unchanged (e.g. ref IMAGE?). However, disproportional changes in climate extremes could have effects different from the impacts of mean climate change (Mearns et al. 1996; Mearns et al. 1997; Knapp et al. 2002). Thus, information on changes at the tails of probability distributions might be of crucial importance. Katz and Brown (1992) showed that climate extremes are sensitive to changes in the shape of the probability distribution function (PDF) of climate variables, which cause the extremes to respond differently from the mean.

In a global warming scenario, two large-scale mechanisms might change the shape of the PDF of daily mean surface-air temperatures (SAT) in winter over the Northern Hemisphere. In the first of these two mechanism, large-scale circulation changes influence local SAT extremes by changing the frequency and/or speed of winds blowing from the directions correlated with these extremes. We will refer to this mechanism as the 'circulation effect'. An important example of such circulation changes is provided by recent enhanced greenhouse effect experiments with Coupled General Circulation Models (CGCMs). These experiments suggest that the Northern Hemisphere's principal pattern of North Atlantic variability, the North Atlantic Oscillation (NAO, Wallace and Gutzler 1981), will, on average, shift towards a more positive phase under global warming (Osborn 2002). In Western Europe, extreme cold winters are associated with a negative NAO, so that a lower frequency of strongly negative NAO indices directly has an impact on the occurrence of cold extremes. Like these CGCMs, the climate model

ECBilt-CLIO that we have used for the experiments presented in this paper shows a shift towards more positive values of a NAO index under global warming (Figure 1). In ECBilt-CLIO the streamfunction Empirical Orthogonal Function (EOF) that most strongly resembles the NAO pattern explains less than 20% of variability in the 1961-1990 period, as opposed to more than 40% for the CGCMs in Osborn (2002). It is the only leading North-Atlantic EOF in ECBilt-CLIO for which the Principal Component (PC) time series shows a trend in the greenhouse simulations.

In the second large-scale mechanism, the temperature of air masses upstream might change. Indeed, the climate change patterns in the lower troposphere as projected by Coupled General Circulation Models (CGCMs), show a geographical heterogeneous warming, which is largest for continental areas and polar regions. The warming increases with latitude, mainly because of the snow/ice-albedo feedback. In addition, the warming is larger for continental areas, compared to the oceans, because of the ocean's larger heat capacity. ECBilt-CLIO reproduces these large-scale features as shown in Figure 2. One might expect that extremes associated with wind directions along SAT gradients would show changes different from the mean. We will refer to this mechanism by the 'temperature gradient effect'. In ECBilt-CLIO, for the greenhouse gas scenario used in this paper, a re-organization of ocean convection near Spitzbergen causes a sudden cooling in the North-Atlantic region in the course of the 21st century (figure 2). This phenomenon has been studied extensively in two recent papers (Schaeffer et al. 2002; Schaeffer et al. 2003) and will not be the focus of the present paper.

The large-scale changes in circulation and horizontal SAT gradient in ECBilt-CLIO under global warming are robust as compared to CGCMs. In this paper, we will study the contributions of these two large-scale mechanisms to changes in SAT extremes.

Experiments by Gregory and Mitchell (1995) showed that the variance of daily-mean SAT might decrease under global warming over Europe in winter. Thus, in this case, the PDF narrows. If the skewness of the distribution remains unchanged, this leads to an extra decrease in frequency of cold extremes and a smaller increase in frequency of warm extremes on top of the changes that are associated with a shift in the mean. We will show that the balance of the large-scale mechanisms mentioned above for specific geographical locations not only narrows the PDF, but in general also changes its skewness.

In a recent paper, Kharin and Zwiers (2000) estimated shifts in extreme temperatures, precipitation and wind speed under global warming. Using 63 years of CGCM data they have determined statistical parameters in the general extreme value (GEV) distribution. These parameters were then used to find extreme values for a return period of 20 years, which is too long to determine from the statistical sample directly. The disadvantage of their approach is that the meteorological circumstances of such extreme events, which were found by statistical extrapolation, can not be reconstructed. This seriously hampers an analysis of the physical mechanisms behind the changes in extreme events. For the present study, we have chosen a different trade-off. By using a climate model, which is simpler in some aspects, but computationally much more efficient, we are able to construct a larger statistical ensemble of extremes, in order to draw extreme events directly and preserve the meteorological relations among variables.

Overall, we are concerned with the question in which regions circulation changes and the temperature gradient effect cause extreme SATs to respond different from the mean. This question will be addressed in section 4 by comparing the geographical pattern of changes in extreme events caused by shifts of the mean with the changes caused by modifications of the shape of the PDF. This will be done for one-in-10 year events, as well as for one-in-100 years events. We then pick one region of interest for a more thorough analysis of one-in-10 year SAT events, for which we come up with some general rules that can be applied to explain the changes seen for other locations. The analysis thus presented should give one an impression to what extent the link between the two large-scale mechanisms and changes in extremes is robust, in the sense that it is applicable to more complex GCMs. First, after shortly introducing the coupled climate model ECBilt-CLIO in section 2, our methodology to address the research questions will be presented in section 3. We conclude with a short discussion in section 5.

2 Model description

The atmosphere is represented by a global spectral quasi-geostrophic model, truncated at T21 (ECBilt, Opsteegh et al. 1998), also referred to as an atmosphere model of ‘intermediate complexity’, with 3 vertical levels. ECBilt was developed for research on the relative importance of the physical feedbacks in the extra-tropics of the climate system on decadal and longer timescales. ECBilt is further used for long simulations in paleoclimatological research and for projections of future anthropogenic climate change in ensemble mode and for many different scenarios. In light of these research applications, ECBilt was developed with specific attention to high computational efficiency. Since the application of this model is in the extra-tropics, a quasi-geostropic approach for the dynamical core of the model was adopted. In addition, physical parameterizations were kept as simple as possible (Opsteegh et al. 1998). A bucket soil-moisture model of uniform depth (15 cm) represents the land surface. Snow-free albedo and forest fraction are derived from satellite imagery. Forest fraction is used in a simple algorithm to lower albedo in case of snow ('snow-masking' by trees). The ocean model (CLIO) is a general circulation model (GCM) with a dynamic sea-ice component and a relatively sophisticated parameterization of vertical mixing (Goosse and Fichefet 1999). The horizontal resolution of CLIO is 3 degrees in latitude and longitude, and there are 20 unevenly spaced vertical levels in the ocean.

The coupled model (ECBilt-CLIO) was recently used to study the influence of mid- to high latitude atmosphere/ocean/sea-ice interactions on climate variability and change (Goosse et al. 2001; Renssen et al. 2001; Goosse et al. 2002; Schaeffer et al. 2002; Schaeffer et al. 2003). The present-day climatology is explored in more detail by Goosse et al. (2001), who showed that the principal mode of variability involving large variations in Arctic sea-ice cover compares favorably with observations. The estimated global climate sensitivity is 1.7 ºC for a doubling of CO_2, which is on the low end of the estimated range (Kattenberg et al. 1996; Gregory et al. 2002).

3 Methodology

3.1 Experiment set-up

After a 1000-year coupled spin-up to approach an equilibrium climate state for greenhouse gas concentrations for the year 1850, the model was forced by the historical pathway of greenhouse gas concentrations from 1850 to 1990. This was followed by a transient climate change experiment from 1990 to 2100, with greenhouse gas concentrations from the IPCC SRES-A1b scenario (IPCC 2000; Schaeffer et al. 2002). We then selected initial conditions from the years 1961 ('present-day') and 2051 ('scenario'). 49 integrations of 30 years length each were performed starting in these years, each with a physically negligible random adjustment of atmospheric initial conditions. These random adjustments lead to different (uncorrelated) atmospheric states within the first month of the simulations. The individual simulations within one such 49-member ensemble represent different evolutions of the climate system for the same external forcing, allowing one to assess the severity of rare weather conditions. Such an assessment is not possible on the basis of observations since the real climate has only one realization and is continually adjusting to the evolving forcings. The first year of each ensemble member is discarded in the analysis, assuming that it takes a while for the atmospheric states to become completely uncorrelated.

3.2 Methodology of analysing extreme events

Using the results of the ensemble-mode experiments, we first calculate the probability density functions (PDFs) of daily mean surface-air temperature (SAT). For each grid cell and month of the year, daily mean SAT values were counted in 'bins' of equal temperature distance, spanning the range from the minimum to the maximum sampled value. The null hypothesis is that the whole PDF simply shifts with the mean, without changing its shape. In this case, the value of the one-in-10-year event will also shift with the mean. However, if the shape of the PDF does change there will be an additional shift in the value of the one-in-10-year extreme. We will assess the relative contributions of changes in the mean and the shape of the PDFs to changes in the value of the one-in-10-year extremes in the following way (see figure 3 for an example for the model grid cell located at 52°N11°E). First, for both the present-day and the scenario ensemble, monthly PDFs for SAT are integrated up to 1/300, to estimate the value of a minimum SAT within a month, that is exceeded with a return period of 10 years (there are 30 days per month in the model). For maximum SAT, one-in-10-year extremes are calculated by integrating PDFs down from 1 to 299/300. Subtracting the value for the 'present-day' ensemble from that for the scenario ensemble gives the change in one-in-10-year maximum and minimum SAT. This analysis is repeated after first subtracting the respective PDF means from both time series. This second calculation provides an estimate of the contribution to changes in the one-in-10-year extreme events due to a change in the shape of the PDFs only.

As a side step in the analysis, we will focus on the tails of the PDFs and assess rarer events. For this purpose, we draw maximum and minimum daily mean SAT for each year (annual extremes). Parameters in the Generalized Extreme Value (GEV) distribution (Zwiers and Kharin 1998; Kharin and Zwiers 2000) are fitted to these data by use of probability weighted moments (Hosking 1990). Using these parameters, we will estimate the changes in extreme values for return periods of 10 and 100 years. As with the PDF analysis, we repeat the exercise after subtracting the means, to isolate the influence of changes in the shape of the PDF. Although the fit turns out to be good for return periods up to 100 years, the sampled annual extremes for some locations deviate significantly from the GEV fit for longer return periods. As also suggested by Kharin and Zwiers (2000), a poor fit for long return periods might be explained by the relatively small sample from which annual extremes are drawn, since the distributions can be expected to approach the GEV distributions asymptotically for large samples. We have tested this assumption by repeating the calculation for extremes drawn from a pool of 5 consecutive years, instead of 1, which improved the fits significantly for most locations and to some extend for a few remaining points. This strongly indicates that the probability distributions tend to converge to the three distribution types that are distinguished in the GEV analysis (Fischer-Tippett I (or Gumbel), II and III distributions). For Northern Hemisphere extra-tropical winter conditions, we have as yet found no reason to believe that extremes for long return periods are caused by a different physical mechanism than more frequent extremes. Using an extended ensemble experiment with the same climate model, van den Brink et al. (2003) did find such indications for wind speed in the North Sea region ('super storms'). In this case long-return-period extremes are drawn from a different parent distribution and two different GEV fits are needed to cover the whole range of events.

4 Changes in extreme events

In ECBilt-CLIO the January minimum SAT extremes from the PDF analysis generally respond stronger than the mean (figures 4a and 4b). As a simple test of statistical significance of the SAT change patterns, we have repeated the analyses using only one, or the other, half of the ensemble members, which did not change any of the patterns shown in figure 4. The PDFs for January SAT generally seem to narrow over regions in which mean SAT increases and broaden in regions of decreased means. In the area of North-Atlantic cooling, PDF-extreme minimum SAT decreases stronger than the mean, while in all other areas these extremes either increase as much as the mean, or more (figure 4b). In addition, the skewness changes, which is illustrated by the different locations of high and low values in the geographical patterns of changes in cold and warm January extremes, which are attributable to changes in the shape of the PDF (compare figures 4b and 4d). PDF-shape changes are especially influential for minimum PDF-extremes at land-sea boundaries, while on the warm side, PDF-shape changes seem to have a particularly strong effect in regions with a continental climate. In sections 4.1 to 4.4 we will look into more detail at the meteorological circumstances under which the extremes occur.

For 10-year return periods, the GEV analysis of annual minima produces patterns of change comparable to the PDF analysis (compare figures 5a and 5b with figures 4a and 4b). Differences can be explained by the fact that in the GEV analysis one extreme value is drawn for each year, which, unlike the PDF analysis, ignores persistence of cold periods. Therefore, in general a 10-year event in the PDF analysis is more extreme than in the GEV analysis. In addition, the GEV annual minima may be drawn from different months in winter than the January extremes in the PDF analysis. In spite of the differences, the GEV analysis produces the same regions in which the changes in PDF shape have a relatively strong impact on 10-year extreme minimum SAT. The pattern of changes in 100-year minima (figure 5c and 5d) largely shows an increase in amplitude, except for Western Europe. Thus, the 100-year minima in general seem to be more sensitive to changes in the shape of the PDF in agreement with Katz and Brown (1992), but the response is qualitatively the same as that of the 10-year minima. The only important exception is western Canada, where 100-year minimum SAT increases less than the mean, which implies that the PDF broadens on the cold side, in contrast to other regions and shorter return-periods. Thus, cold 100-year extremes over western Canada seem to respond to a greenhouse forcing in a qualitatively different way as compared to 10-year extremes. Although this is an interesting model result, we lack a sufficiently large sample to thoroughly analyze the meteorological conditions associated with such 100-year extremes.

The overall patterns from the GEV analysis broadly agree with the results of Kharin and Zwiers (2000), except for the region of changes in ocean deep convection in ECBilt-CLIO. Annual minima increase most strongly over Eastern Europe, east Asia and central and east North America. Some of the differences in patterns, and especially in amplitude might be caused by the fact that there is no diurnal cycle in ECBilt-CLIO, so that we are not able to draw daily maximum and minimum SAT, as in Kharin and Zwiers (2000). Annual maxima increase especially over central and southeast North America, north and northeast of the Tibetan Plateau and the region east of the Mediterranean (not shown), in agreement with Kharin and Zwiers (2000). However, the moderating influence on (boreal summer) warm extremes from increased precipitation in the western USA found by Kharin and Zwiers (2000) does not occur in ECBilt-CLIO.

4.1 Local characterization of extremes in De Bilt

For a closer analysis of (changes) in 10-year extreme events, we start by focusing on the grid point at 52°N 11°E. This is close enough to our institute's hometown for us to further refer to it as 'De Bilt'. In the maritime climate of De Bilt, the local temperature is strongly influenced by the wind direction. Northeasterly winds advect cold continental air masses to the area, whereas southwesterly winds bring relatively warm air masses (reference to Oldenborgh ?). In figure 6, we have plotted the daily mean SAT versus the daily mean wind direction for the whole sample of 42630 January days. In an attempt to achieve an optimal correlation, we have also experimented with plotting daily mean SAT against wind direction averaged over a number of days preceding that day. Although in theory advection of anomalous cold, or warm, air masses results in local anomalies with some delay from the moment wind starts to blow from the direction concerned, these plots did not show a markedly higher correlation between temperature and wind direction. Figure 6 confirms that in ECBilt-CLIO cold extremes in winter are correlated with easterly winds, bringing cold air masses from the continental climate upstream. The relationship is more outspoken for more extreme low SAT. Warm January days are correlated with southwesterlies. The correlations are higher for higher windspeeds (see circles in figure 6).

4.2 Changes in extremes in De Bilt

In De Bilt the warming of the cold extremes is more profound than the mean warming and the warm extremes warm less (see figures 3 and 4). The PDF of wind direction in De Bilt in figure 7 shows that the frequency of easterlies decreases in the scenario ensemble, while the prevailing westerlies become more frequent. The frequency of warm southwesterlies does not change. The number of occurrences of easterlies in the control climate is much lower than that of westerlies. Therefore, since easterlies are correlated with cold SAT extremes, a shift in frequency from easterlies to westerlies has a disproportional strong influence on the occurrence of cold SAT extremes, as compared to mean SATs, which are correlated with the more frequent westerlies. The reduced occurrence of infrequent cold easterly winds in the scenario ensemble contributes to the depletion of the cold tail. For the PDF in figure 7 and all other PDFs presented below, we have repeated the analyses using only one, or the other, half of the ensemble members, which did not influence the response of the PDFs to greenhouse forcing. Thus the changes in the location and shape of the PDFs as discussed in the text are statistically significant.

To shed light on the possible contribution of changes in the wind speed to changes in the shape of the SAT PDF, we calculated the mean wind speed for 12 classes of wind directions for both ensembles, as well as the mean wind speed of the 5 percent strongest and weakest winds (figure 8). The mean wind speed has slightly increased for the westerly directions and slightly decreased for easterly directions. The most marked change is a reduced probability of strong easterly winds. This might have made an additional contribution to the depletion of the cold tail, since the cold extremes most strongly correlate with strong easterlies.

For the same 12 classes of wind directions, we have calculated the PDFs of SAT coinciding with winds from those directions (figure 9). The mean value of SAT coinciding with easterlies has increased more than the mean for westerly directions. This can be explained by the anomalous temperature gradient pointed inland (figure 2), which forms part of the temperature gradient effect. In addition, the temperatures in the cold tail (lower percentile in figure 9) of the easterlies have increased as well. Thus, the air masses advected from the East in the projected ensemble are warmer, which contributes to the depletion of the cold tail.

Summarizing, for the De Bilt grid point both impacts of large-scale circulation on local extremes seem to work in the same direction as the temperature gradient effect. This results in a disproportionally large warming for extreme cold days as compared to the mean. The analysis in this section for De Bilt somewhat resembles that of Gregory and Mitchell (1995), who showed that the frequency of eastern winds decreases in an equilibrium 2xCO_2 simulation for a grid point in South England in a atmospheric GCM coupled to a mixed-layer ocean.

4.3 Impact of large-scale circulation changes

The SAT values for the one-in-10-year cold extremes in De Bilt are correlated with a larger-scale pattern of SAT anomalies (figure 10a). This pattern was obtained by averaging SAT over all extreme cold cases in De Bilt and subtracting the mean of all January days. The pattern resembles that of temperature anomalies associated with the negative phase of the North Atlantic Oscillation (NAO, Wallace and Gutzler 1981), or the Northern Hemisphere Annular Mode (NAM, Wallace 2000). The negative phase of the NAO is associated with anomalous easterlies in Western Europe, as is the case for the cold extremes in De Bilt. The SAT-anomaly pattern in figure 10a suggests that cold extremes in De Bilt are the result of the redistribution of heat, transporting cold-air anomalies from northeast Asia to Western Europe. The cold 10-year extremes in the scenario ensemble are characterized by the same large-scale SAT-anomaly pattern (not shown), thus probably by the same mechanism.

The pattern of mean anomalies in the stream function on cold extreme days in De Bilt with 10-year return period (figure 10b) also resembles the structure associated with the NAO (Wallace and Gutzler 1981). The differences with the NAO-index pattern in figure 1 can be explained by the emphasis that is now laid on local cold days and easterlies in De Bilt. This is in contrast to the Empirical Orthogonal Function (EOF) analysis of streamfunction variability shown in figure 1, which is applied to the whole North Atlantic region and all simulation days.

The amplitude of the 2nd EOF in the principal component (PC) analysis in figure 1b shows a trend towards more positive values. The 2nd EOF as shown in figure 1a is the only leading North-Atlantic streamfunction EOF that shows any trend in ECBilt-CLIO. In line with Ulbrich and Christoph (1999), for a comparable greenhouse gas scenario, this trend is modest as compared to natural variability of the NAO index, as given by the spread in NAO index at any given point in time.

The NAO timeseries does not show an increase in ensemble variance. This means that in ECBilt-CLIO the NAO index shifts to more positive values, whereby strong negative values simply shift with the mean. This might explain why in the GEV analysis annual-minimum SAT values with a 100-year return period show the same response as 10-year events (see figures 5b and 5d).

The shift to more positive values of the NAO index partly explains the changes in the mean streamfunction over the North Atlantic in figure 11. Ulbrich and Christoph (1999) found that a spatially fixed NAO index as also used in our analysis does not capture the full change in storm track intensity. The remaining part of the changes in the latter can be explained by changes in spatial structure of the principal modes of variability. The North-Atlantic sector part of the change in mean streamfunction (figure 11) strongly resembles the NAO-like 'De Bilt cold-day pattern' (figure 10b). This suggests that the global pattern of changes in the mean streamfunction might serve to explain changes in the shape of the local SAT PDF by large-scale circulation. To this end, the mechanism found for De Bilt can be generalized for other locations: If a gridcell lies in a region of high gradient in streamfunction change (figure 11), then the SAT extremes correlated with the wind direction with the lowest probability in the control ensemble will be affected by a change in the shape of the PDF.

There are several points in figure 4, showing a change of SAT PDF, other than De Bilt for which this rule applies. The warm extremes in central to east Siberia (point 2 in figure 11) are linked to easterlies, bringing relatively warm air masses from the Pacific Ocean. Changes in streamfunction over this region suggest a mean decrease in easterly wind frequency and/or speed. In agreement with the general rule, the PDF in gridcell 2 narrows on the warm side (figure 4d). For west Canada (point 4 in figure 11, cold extremes in figure 4) the situation is comparable to De Bilt and the PDF of SAT narrows on the cold side. The response over the Labrador Sea (point 6, warm extremes) is comparable to east Siberia. In all these gridcells the tail of the PDF of SAT depopulates for those extremes that are correlated with wind directions showing lowest probability in the wind direction PDFs.

4.4 Impact of changes in temperature gradient

The general large-scale circulation rule as presented in the previous section can not explain the changes in SAT PDF shape on the cold side for the regions of the Bering Strait (point 3) and Labrador Sea (point 6), nor on the warm side for the Bering Strait and central Canada (point 5). For the Bering Strait region, the SAT PDF narrows on both sides (figure 4), but the PDFs of wind direction and wind speed do not change (not shown). For this region, cold extremes are associated with north-northwesterly polar winds, while warm extremes are correlated with Pacific Ocean southeasterlies. SAT change shows a strong gradient in both these directions, because of both the Land/Sea and the North/South contrasts (see figure 3). In figure 12, we see that, indeed, the temperature of air masses advected by winds from northwest to northern direction rises more and from the southeast rises less than the mean. In addition, the PDF of temperatures narrows on the cold side for northwest-northerlies. The pattern of anomalous SAT correlated with local cold or warm extremes shows only a localized wave train (not shown), confirming that large-scale circulation changes are of little influence.

For the Labrador Sea region, the frequency of warm east to southwesterlies become less frequent (see also previous section) and cold west-northwesterlies become more frequent. The depletion of the warm tail is further enhanced by the temperature gradient effect. For the cold west to northwestern direction, the temperature of both mean and extreme cold winds increases so strongly, that the temperature gradient effect overcompensates the impact of the increase in frequency of cold westerlies.

In central Canada again the temperature gradient effect is dominant. The balance of preferred wind direction tips over from east to southwest in a bimodal wind direction PDF. This bimodality is caused by planetary waves triggered by the Rocky Mountains, which is also apparent in regions near other large mountain chains. However, both wind directions are linked to warm extremes in a quite diffuse distribution, so that this does not have as large an effect on the occurrence of warm extremes as does the change in temperature gradient.

The processes in ECBilt-CLIO for especially central Canada and the Labrador Sea region show that the balance between the impacts on local extremes of changes in the large-scale circulation and the temperature gradient effect is delicate and therefore probably model dependent.

5 Conclusions and discussion

The experiments with the ECBilt-CLIO climate model show that in an enhanced greenhouse climate, cold and warm extreme surface-air temperature in the Northern Hemisphere winter respond different from the mean. In general, changes in the shape of the probability distribution of SAT contribute as much to changes in extremes as a shift of mean temperatures. This change in shape not only involves the variance, but also the skewness of the distribution.

For coastal areas, a large-scale change in mean wind direction causes disproportionally large changes in extremes associated with infrequent wind directions. In Western Europe this occurs because of a shift towards a preferred positive phase of the North Atlantic

Oscillation. Globally, at Northern Hemisphere mid-latitudes the mean wind direction becomes more predominantly west in ECBilt-CLIO. Thus cold extremes on the western side of the Eurasian and North American continents, associated with infrequent easterlies, are likely to warm more than the mean temperatures. Likewise, warm extremes on the eastern sides, also associated with easterlies, are likely to warm less than the mean.

In addition to the impacts of large-scale circulation changes in coastal areas, extremes in all regions are subject to changes in geographical temperature gradient. Since in the long-term mean the air over land warms faster than over oceans, extremes in coastal areas associated with winds from directions perpendicular to air/sea boundaries are also likely to respond different from the mean. Finally, the stronger warming of polar regions as compared to the (sub)tropics means that in all areas extremes associated with north or south wind directions respond different from the mean.

The mechanisms of the impact on extremes of the large-scale patterns of changes in temperature gradient and changes in circulation are plausible. This means that in climate change impact studies it is not advisable to assume that changes in extremes equal changes in mean, especially for non-linear systems for which the impact of changes in extremes is different than the impact of changes in the mean climate.

Based on statistical GEV analysis, we found no strong indications that extremes with return periods in the order of 100 years respond qualitatively different from more frequent one-in-10 year extremes. However, since our model is simpler than state-of-the-art CGCMs, more thorough research on this issue is warranted. If a change in the variance occurs for a preferred pattern of large-scale circulation variability, this might have an influence on events with long return periods that causes these extremes to respond different as compared to more frequent events. One might further speculate that in a enhanced greenhouse world new modes of variability are generated with a low probability, thereby possibly effecting only rare events.

Although strong local differences between CGCM projections remain to exist, the large-scale change in geographical gradient of surface-air temperature under global warming is fairly robust (Houghton et al. 2001). Concerning large-scale circulation changes, recent CGCM experiments show strong agreement to the extent that the NAO shifts towards more positive values under global warming (Osborn 2002), in agreement with ECBilt-CLIO. Thus, one can have confidence in the projected patterns of change in extreme events by GCMs, under influence of these two large-scale mechanisms. However, there are indications that stratosphere dynamics is relevant for the response of the NAO to external forcings (Shindell et al. 1999). The latter is not well-represented in all models, including ECBilt-CLIO. In addition, there is some disagreement between CGCMs projections of changes in the Arctic Oscillation, the larger-scale Northern Hemisphere version of the NAO (Zorita and Gonzáles-Rouco 2000).

Apart from large-scale changes, local physical feedbacks might influence the occurrence of extreme events. The most influential local physical feedback in winter is the snow-albedo feedback, while in summer depletion of soil moisture in summer might cause changes in PDF shape. We did not analyze the contribution of these processes to changes in extremes, mainly because they are crudely represented in the model. We have stressed aspects of the two large-scale mechanisms in winter, since we know these to be best represented in the model.

The balance between the two large-scale mechanisms determines to what extent extremes respond different from the means for a specific region. This balance is model dependent to an unknown degree, because the location and amplitude of changes are influenced by the horizontal and vertical resolution of climate models, as well as by local physical feedbacks, thus physics parameterization schemes. Therefore, a wide intercomparison of CGCM projections of changes in extreme events seems highly advisable.

Figure Captions

Figure 1 Pattern and change in amplitude of NAO-like variability pattern in the climate model ECBilt-CLIO. The analysis is based on a 10-member ensemble experiment (Schaeffer et al. 2002). (a) Covariance between the 1961-1990 DJF-mean 800 hPa streamfunction and the 2^{nd} Empirical Orthogonal Function (EOF) as diagnosed over the simulation period 1961-1990 for all ensemble members for the North-Atlantic sector. (b) Principal component time series of the DJF-mean 800 hPa streamfunction projected on the 2^{nd} EOF for the individual ensemble members between 1961 and 2100 (21-year running mean).

Figure 2 Change in mean surface-air temperature (°C) for the 2051-2080 scenario ensemble with respect to the 1961-1990 control ensemble.

Figure 3 Probability distribution of January daily mean surface-air temperatures for the control (black) and the scenario (gray) ensembles for the grid cell centered at 52°N 11°E. The vertical lines extending up from the horizontal axis indicate means (middle), cold 10-year return value (left) and warm 10-year return value (right).

Figure 4 Changes in January extremes for the scenario ensemble with respect to the control for (a) cold 10-year return value, (b) cold 10-year return value minus mean, (c) warm 10-year return value and (d) warm 10-year return value minus mean. All return values (in °C) were calculated with the PDF analysis.

Figure 5 Changes in cold annual extremes for the scenario ensemble with respect to the control. (a) 10-year return value, (b) 10-year return value minus mean, (c) 100-year return value, (d) 100-year return value minus mean. All return values (in °C) were calculated with the GEV analysis.

Figure 6 Daily mean surface-air temperature in January for De Bilt plotted against daily mean wind direction for the control ensemble. Circles refer to the 33% strongest, squares to the 33% medium and crosses to the 33% weakest winds. The horizontal dashed lines mark the one-in-10 year cold and warm events.

Figure 7 Probability distribution of January daily mean wind direction for the control (black) and the scenario (Gray) ensembles for De Bilt.

Figure 8 Mean wind speed for 12 classes of wind directions for present-day (closed circles) and scenario (open circles) ensembles for De Bilt. The middle lines indicate the difference of mean wind speed with respect to the control ensemble. Upper and lower lines indicate distance of the mean of the 5 percent strongest and weakest winds to the respective ensemble means.

Figure 9 Mean surface-air temperature for 12 classes of wind directions for present-day (closed circles) and scenario (open circles) ensembles for De Bilt. The middle lines indicate the difference of mean wind speed with respect to the control ensemble. Upper and lower lines indicate distance of the mean of the 5 percent strongest and weakest winds to the respective ensemble means.

Figure 10 Anomalous January surface-air temperature (°C) (a) and mean streamfunction (10^7 $m^2.s^{-1}$) (b) on cold days in De Bilt with return period of 10 years for the control ensemble, with respect to the control climatology.

Figure 11 Changes for the scenario ensemble with respect to the control for mean January streamfunction (10^7 $m^2.s^{-1}$).

Figure 12 Mean surface-air temperature for 12 classes of wind directions for present-day (closed circles) and scenario (open circles) ensembles for Bering Strait. The middle lines indicate the difference of mean wind speed with respect to the control ensemble. Upper and lower lines indicate distance of the mean of the 5 percent strongest and weakest winds to the respective ensemble means.

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