Is greenhouse gas forcing a plausible explanation for the observed warming in the Baltic Sea catchment area?

Jonas Bhend[1)2)] and Hans von Storch[1)3)]

[1)] Institute for Coastal Research, GKSS Research Centre, Max-Planck-Strasse 1, D-21502 Geesthacht, Germany
[2)] International Max Planck Research School on Earth System Modelling, Bundesstraße 53, D-20146 Hamburg, Germany
[3)] Meteorological Institute, University of Hamburg, Bundesstraße 55, D-20146 Hamburg, Germany

We investigated whether anthropogenic forcing is a plausible explanation for the observed warming in the Baltic Sea catchment area. Therefore, we compared the most recent trends in the surface temperature over land with anthropogenic climate change projections from regional climate model simulations. We analyzed patterns of change with different spatio-temporal resolutions. The observed annual area-mean change in the daily-mean temperature was consistent with the anthropogenic climate change signal. This finding was robust to the removal of the signal of the North Atlantic Oscillation. In contrast to the annual area-mean change, we found little consistency in both annual cycle and spatial variability of the observed and projected changes.

Introduction

Extensive evidence of a large-scale anthropogenic climate change has been collected during the last decades (for a review *see* Barnett *et al*. 2005 and Hegerl *et al*. 2007). Recently, the human influence on regional-scale climate has come into focus, and a number of studies conclude an anthropogenic warming in different sub-continental scale regions (Spagnoli *et al*. 2002, Zhang *et al*. 2006). For the Baltic Sea catchment area, however, a rigorous assessment of an anthropogenic influence is not yet available (The BACC author team 2008). Thus, this study aims at contributing to the discussion of an observable human influence on near surface temperatures in the Baltic Sea catchment area.

In order to answer the question whether the observed climate change is partly anthropogenic or not, we most often use the "detection and attribution" approach (Hasselmann 1993, Hasselmann 1997, Allen and Tett 1999). This approach consists of two steps. Detection of an external influence is claimed when we can show that the observed change is statistically different from natural internal variability. In the second step — the attribution — we try to identify the most plausible mix of forcings to explain the detected change. On a regional scale, two factors inhibit early detection. First, the variability increases with decreasing aggregation and thus the signal-to-noise ratio of externally-forced changes generally decreases with the decreasing spatial extent of the region under consideration

(Stott and Tett 1998, Zwiers and Zhang 2003). Second, uncertainties in the model-simulated variability and response to external forcings at smaller spatial scales cause further limitations. In order to be able to investigate an anthropogenic influence when formal detection fails, we propose a different approach (*see* also Bhend and von Storch 2008).

We compare observed changes in screen temperatures with the response to anthropogenic forcing, in our case changing greenhouse gas (GHG) and aerosol concentrations in the atmosphere, estimated from model simulations. Since a large fraction of the variability of temperature in northern Europe is linked to the North Atlantic Oscillation (NAO; van Loon and Rogers 1978, Lamb and Peppler 1987, for a review *see* Wanner *et al*. 2001), we also compare the changes after removing the fingerprint of the NAO from both the observations and the anthropogenic change estimates. Hypothesizing that the anthropogenic signal in the NAO is low, we expect an increase in correspondence of the observed and expected change after removing the NAO signal.

By comparing observed changes with the estimated response to a given forcing mechanism, we offer the possibility to falsify the hypothesis that the observed change is mostly related to this mechanism. Thus, we are looking for the consistency of the observed change with the change related to an *a-priori* known forcing. This consistency check could be thought of as a sort of "attribution without detection". In this setup, the recent change is given. The expected signal, however, is unknown and has to be estimated from model simulations.

The spatial resolution of present-day general circulation models (GCMs) is inappropriate for the simulation of the climate in a region with complex terrain and land–sea distribution, such as the Baltic Sea catchment area. One of the most obvious limitations is the unrealistic ice-cover in the Baltic Sea in global-scale models. Thus, we use a set of simulations with a coupled regional atmosphere–ocean model, from which we estimate the anthropogenic signal. Since there are only a few simulations with this model setup available, we cannot derive a reasonable estimate of the variability of the response to anthropogenic forcing (based on sufficiently many independent realizations). Therefore, we do not frame our examination as a formal statistical test with the null hypothesis "the observed change is drawn from the set of scenarios". We collect plausibility arguments from the quantitative comparison of the few scenarios with the observed change instead. Even if inferior to a full statistical test, our method generates instructive results, especially in cases where only few data exist.

If we conclude that the observed change is not consistent with the assumed forcing mechanism, then three possible reasons may be thought of: The simulated response to anthropogenic forcing is wrong, the assumed mechanism is overridden by another mechanism not accounted for in the simulations, or the signal-to-noise ratio of an anthropogenic change is too low and thus a large fraction of the observed trend is due to natural variability. On the other hand, if we find consistency of the observed change with the assumed forcing mechanism, we conclude that the assumed forcing is a plausible explanation of the observed change. Note, however, that consistency is not equivalent to the rejection of the "detection" hypothesis, "the observed change is drawn from a set of changes due to natural variability".

Materials and methods

Observed temperature trends

The observed changes are computed based on the monthly-gridded temperature data set CRU TS 2.1 of the Climatic Research Unit (Mitchell & Jones 2005). These data are available over land on a regular latitude × longitude grid with 0.5° resolution for the period from 1901 to 2002. We define recent change as the trend over the last 30 years available, i.e. 1973–2002, and we estimate the slope of the regression line using least squares. The domain of interest is the Baltic Sea catchment area (Fig. 1).

Climate change scenarios

We use a set of simulations with the Rossby Centre regional Atmosphere–Ocean model (RCAO) of
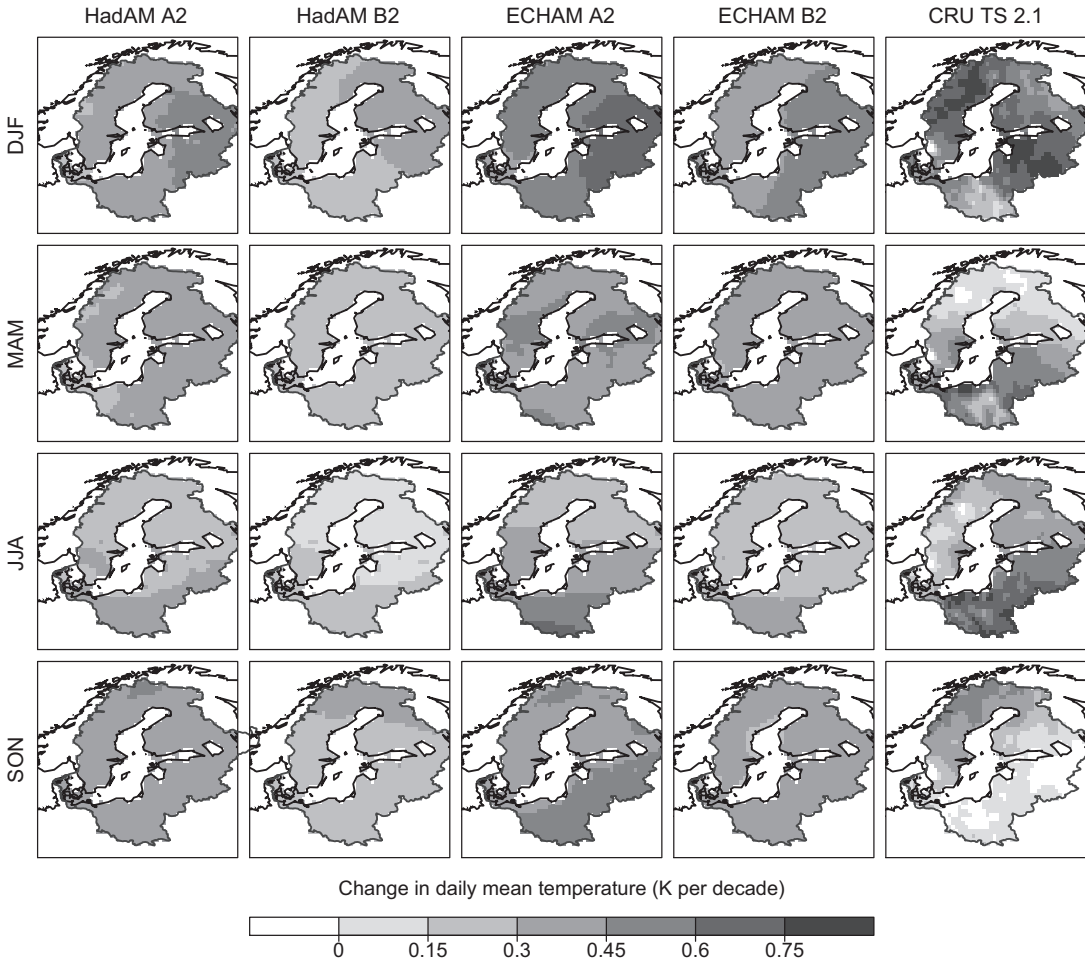
Fig. 1. Seasonal anthropogenic climate change signal for daily mean temperature in the Baltic catchment according to the different climate change simulations with the RCAO model (first four columns) and the observed trend for 1973–2002 according to the CRU TS 2.1 data set (rightmost column).

the Swedish Meteorological and Hydrological Institute (Kjellström 2004, Räisänen *et al*. 2004). The set of simulations includes six time-slice experiments of 30 years driven with two different global models, the HadAM3h (Gordon *et al*. 2000) and the ECHAM4/OPYC (Roeckner *et al*. 1999). For each of the two different GCMs, one simulation with GHG and aerosol concentrations for the period 1961–1990 and two simulations for the period 2071–2100 using GHG and aerosol concentrations from the SRES A2 and B2 scenarios are available.

The response to anthropogenic forcing for a certain period would ideally be estimated from transient climate model simulations with and without anthropogenic forcing. However, as the low signal-to-noise ratio of the anthropogenic change on the regional scale would require a very large ensemble of transient simulations, which is presently not available, we estimate the anthropogenic signal from time slice experiments. In order to be able to do so, we have to make assumptions on the evolution of the anthropogenic signal. First, we assume that the spatial pattern of the response does not depend on the temporal evolution of the forcing. This hypothesis is supported by different analyses of global scale simulations (e.g. Meehl *et al*. 2007: fig. 10.8). Second, we assume a linear development from 1961–2100, and thus we presumably

overestimate the anthropogenic signal in the last decades of the 20th and the first decades of the 21st century. However, compared with the differences between the single realizations (due to different forcing and different driving GCMs) this possible overestimate is negligible.

We define the anthropogenic signal as the difference between the future (2071–2100) and control (1961–1990) period mean climate. The resulting signal is further linearly scaled to change per decade. In accordance with the GCM and emission scenario used, we refer to the respective anthropogenic change estimates as HadAM A2 and B2 and ECHAM A2 and B2.

NAO representations and NAO signals

We use a station-based NAO index, which is defined as the difference in normalized monthly sea level pressure (SLP) between Reykjavik and Gibraltar (Jones *et al.* 1997). The NAO index in the set of regional climate model simulations has been derived accordingly from the respective SLP fields. The reference period for the normalization of SLP time series is 1961–1990. The variability in the dimensionless NAO index based on observations is higher than the variability based on the two different 1961–1990 representations in the regional model simulations with a standard deviation of 1.46 in the observations and 1.14 (1.09) in the HadAM (ECHAM) simulation.

The fingerprint of the NAO is defined as the fraction of the variability in monthly and seasonal mean temperature that co-varies with the respective NAO index. We regress the detrended temperature time series on the detrended NAO index for each grid box separately using ordinary least squares estimation of the parameters of the linear regression. The slope of the regression is the NAO fingerprint. We remove the NAO fingerprint from the observations by subtracting the fingerprint times the trend in the NAO index from the trend in the observations. From the climate change projections, we remove the NAO fingerprint by simply subtracting the respective NAO fingerprint times the difference in the average NAO index for the periods 1961–1990 and 2071–2100.

Pattern correlation

The comparison of the observed (O) and expected (E) patterns of change is carried out using pattern correlation. As the human influence on climate leads to both a change in the mean climate as well as a change in the spatial and/or temporal patterns, we use uncentered pattern correlation as described in Eq. 1:

$$R(O, E) = \frac{\sum_i O_i E_i}{\sqrt{\sum_i O_i^2 \sum_i E_i^2}} \; . \tag{1}$$

Here $R(O, E)$ is the pattern correlation coefficient, O and E refer to the observed and expected pattern of change, respectively, and i represents the dimensionality of the pattern. We investigate patterns with different spatio-temporal resolution. These include the mean annual temperature changes both as area averages (O_{ann}, E_{ann}) and as spatially 0.5°-distributed fields ($O_{ann,x}$, $E_{ann,x}$), and the seasonally and monthly resolved annual cycles of the change, again as area averages (e.g. O_{seas}, O_{mon}) and as spatially distributed fields (e.g. $O_{seas,x}$, $O_{mon,x}$). For the respective pattern correlation coefficients, the shorthand $R_{seas,x}$ is used for $R(O_{seas,x}, E_{seas,x})$.

Results

The observed change in annual near surface temperature (O_{ann}) for the Baltic Sea catchment area was 0.37 K per decade. The respective anthropogenic climate change signal (E_{ann}) ranged from 0.24 to 0.45 K per decade (for HadAM B2 and ECHAM A2, respectively). The observed change lies inside the range of expected changes and thus we conclude consistency of O_{ann} with E_{ann}. However, due to the strong inter-annual variability, the trend component in the observed 30-year time series accounted for only 11.7% of the total variance. After the signal of the NAO had been removed from both the observations and climate change simulations, we found a reduction of O_{ann} to 0.32 K per decade and slight reduction in E_{ann} to 0.24–0.43 K per decade.

The annual cycle of the average anthropogenic change for the Baltic Sea catchment area
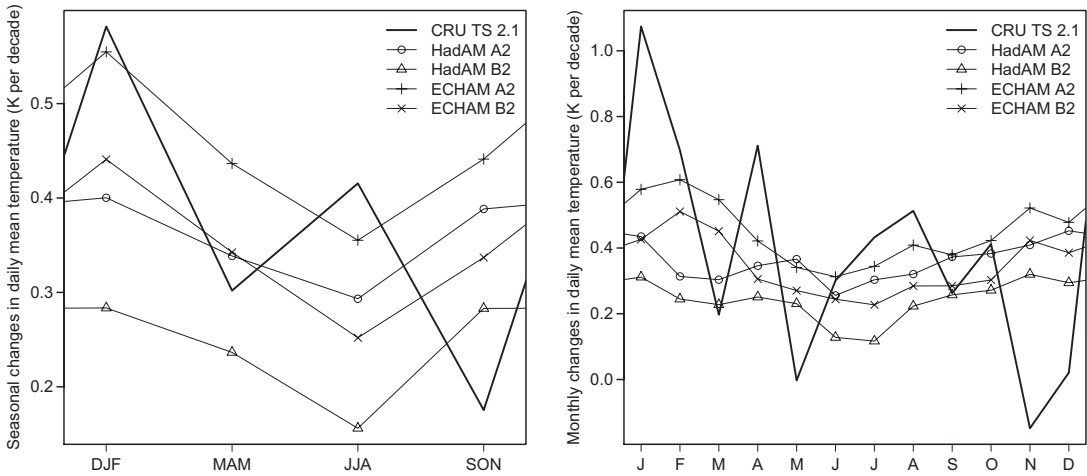
Fig. 2. Seasonal (left-hand-side panel) and monthly (right-hand-side panel) area mean changes in near surface temperature for the Baltic catchment. The observed trends for 1973–2002 are represented by the thick line, the different anthropogenic change estimates derived from a set of simulations with the RCAO model are represented by the thin lines and different symbols.

was characterized by a stronger warming in E_{seas} in winter (DJF) than in summer (JJA, *see* Fig. 2). In contrast to E_{seas}, the annual cycle of the observed warming showed smallest warming in autumn. The differences between the expected and observed patterns increased when we increased the temporal resolution and compared O_{mon} with E_{mon}. The anthropogenic change estimates derived from simulations driven with ECHAM showed a pronounced annual cycle in E_{mon}, with strongest warming in February and weakest warming in June and July. The simulations driven with HadAM showed a slightly different pattern with smaller amplitude than the annual cycle of E_{mon} in ECHAM A2 and B2.

We found a pronounced spatial variability in the pattern of observed changes ($O_{seas,x}$), with enhanced warming in the northern part of the Baltic Sea catchment area in winter (DJF) and autumn (SON) and in the southern part in spring (MAM) and summer (JJA). In the anthropogenic change estimates, however, the spatial variability was much smaller and the annual cycle of the area mean changes dominated the combined spatio-temporal pattern (Fig. 1).

The pattern correlation coefficients for the different indices of surface temperature change and different anthropogenic change estimates used were highest for the annual change with

full resolution ($R_{ann,x}$), with values around 0.97 (Fig. 3). When investigating the annual cycle, we found the highest pattern correlation scores for $R_{seas,x}$ with values greater than 0.9. With increasing spatial and temporal details, the pattern similarity decreased. If the pattern of change was analyzed after the fingerprint of the NAO had been removed from both observations and climate change scenarios, we found a slightly reduced pattern similarity compared with the pattern correlation with the full signal.

Discussion

The observed change in the annual near-surface temperature in the Baltic Sea catchment area is consistent with the anthropogenic change estimates derived from regional climate model simulations. For the annual area mean change, we assessed the consistency by comparing the magnitude of the simulated change with the corresponding observed trend. The magnitude of the observed trend was, however, strongly dependent on the trend length used. With an increasing trend length, the magnitude of the most recent trend decreased almost linearly from 0.37 K per decade for 30-year trends to 0.06–0.07 K per decade for 70-year and longer trends (for
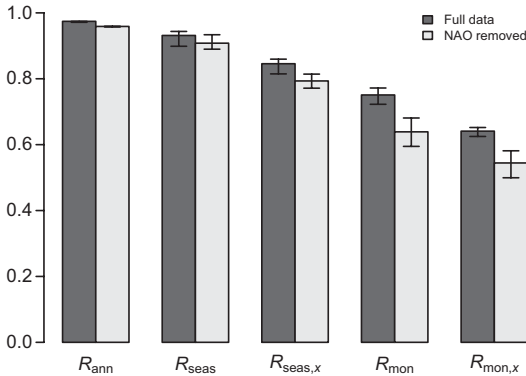
Fig. 3. Uncentered pattern correlation between different patterns of observed trends for 1973–2002 and the respective anthropogenic change patterns. The spatio-temporal resolution increases from left to right. The shaded bars indicate pattern correlation between the observations and the mean anthropogenic change signal of all four different members investigated, the whiskers denote the spread of pattern correlation of the observed change with the individual anthropogenic change signals.

a review of trends of different length in sub-regions and at individual stations *see* the BACC author team 2008). The observed decrease in magnitude of the most recent trends with the increasing trend length could be due to the weaker anthropogenic signal in the earlier parts of the 20th century, or due to the decreasing influence of natural variability with increasing trend length. The most recent 30-year and 40-year trends in the surface temperature are consistent with the anthropogenic change estimate: 50-year trends in the annual area-mean temperature of 0.23 K per decade lie slightly below the lowest anthropogenic change estimate (HadAM B2, 0.24 K per decade). We should note, however, that the anthropogenic change estimates are most likely biased high due to the assumption of a linear development of the anthropogenic signal between 1961 and 2002. From the above-presented evidence we conclude that the anthropogenic forcing is a plausible explanation for the observed annual area-mean trend and that this finding is robust to the choice of the trend length. Without reference to an estimate of natural variability and additional forcings, however, we are not able to rule out alternative explanations. This is a major limitation of the method presented here.

The annual cycle in the climate change scenarios (E_{seas}) was different from the annual cycle in O_{seas}. The observations showed larger amplitude between the minimum and maximum seasonal warming and a different structure with minimal warming occurring in SON instead of JJA as in the scenarios (left-hand side panel in Fig. 2). Increasing the temporal resolution resulted in a noisier pattern in the observations, whereas the simulated annual cycle of changes remained smooth (right-hand side panel in Fig. 2). The lower amplitude in the simulated annual cycle of the temperature change could result from deficiencies in the representation of the large-scale circulation variability related to the NAO and atmospheric blocking in the driving GCM (D'Andrea *et al.* 1998, Osborn 2004, Stephenson *et al.* 2006). Furthermore, the differences in O_{mon} from month to month point towards a low signal-to-noise ratio of an anthropogenic change in monthly area-mean temperatures. Part of the observed variability in the annual cycle could be due to random variations and thus not explicable by the response to external forcing. We conclude that anthropogenic forcing is an insufficient explanation for the observed annual cycle in seasonal and monthly temperature changes in the Baltic Sea area.

The pattern similarity decreased with the increasing spatial and temporal resolution (Fig. 3). Consequently, the signal-to-noise ratio of an anthropogenic change decreased with the increasing spatio-temporal detail. This is in line with findings of various authors (e.g. Stott & Tett 1998, Zwiers & Zhang 2003). We conclude that either the anthropogenic climate change signal is large scale (compared with the size of the domain under investigation) or the RCM used is not able to simulate regional details with sufficient quality — given GHG concentrations as the sole forcing.

By removing the NAO signal from the data before the analysis resulted in a slight reduction of the pattern correlation. We found that the signal-to-noise ratio of an anthropogenic change was reduced by removing the NAO signal. This indicates that our initial assumption of a negligible anthropogenic effect on the NAO may be incorrect. This conclusion is in line with that of Gillett *et al.* (2002), who showed that the

observed increase in the NAO index during the last decades of the 20th century is not attributable to natural variability alone and thus a significant part of the observed changes in the NAO is anthropogenic. However, anthropogenic forcing of the NAO remains a matter of debate, as present-day GCMs are not yet able to reproduce fully the observed NAO variability (Osborn 2004, Stephenson *et al*. 2006).

Conclusions

It is often assumed that the observed regional climate change is at least partly anthropogenic. As a plausibility check, we proposed a simple consistency analysis. We therefore compared the most recent observed changes in near-surface temperatures with an estimate of the anthropogenic signal as proposed by a set of regional climate model simulations. By comparing the annual area-mean change in the surface temperature in the Baltic catchment, we found a good correspondence with the available climate change scenarios. The magnitude of the annual change was also similar after the NAO signal had been removed from both observations and simulations.

In order to further estimate the level of detail to which observed regional features could be explained by anthropogenic change, we assessed the pattern similarity of climate change patterns with a different spatio-temporal resolution. In all the cases, the similarity of observed and expected patterns of change decreased with the increasing level of detail. Whether the loss in similarity with the increasing spatial resolution was due to limitations in our ability to simulate the small-scale structures of the climate change pattern, or a consequence of the climate change signal being in fact a large-scale phenomenon, we do not know. Nevertheless, it was shown that anthropogenic forcing is a plausible explanation for the observed area-mean changes in the annual temperature in the Baltic catchment. In contrast, anthropogenic forcing only partly explained the annual cycle of the observed change. Of course, we cannot exclude the possibility that both additional external forcings and internally-generated variability may have been similarly powerful in explaining the observed changes. Unfortunately, there are no comprehensive regional simulations on alternative forcing mechanisms available yet.

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