Impact of horizontal resolution on the simulation of seasonal climate in the Atlantic/European area for present and future times

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ABSTRACT: The climate response to increasing levels of atmospheric greenhouse gases, prescribed according to the Intergovernmental Panel on Climate Change (IPCC) scenario IS92a, is studied in 2 model simulations. One is a transient response experiment performed with a medium resolution (T42) coupled general circulation model of the atmosphere and ocean (ECHAM4/OPYC) developed at the Max Planck Institute for Meteorology. The other one is a time-slice experiment with the high resolution (T106) ECHAM4 model forced with monthly sea-surface temperatures and sea-ice from the coupled model. For two 30 yr time-slices, representing the present-day climate (1970–1999) and the future climate with an effective doubling of carbon dioxide (2060–2099), the seasonal mean climate statistics obtained from the 2 experiments in the Atlantic/European area are compared with each other and, for the simulations of the present-day climate, with observational data in order to evaluate the impact of the model's horizontal resolution on the simulation of regional climate change as well as on the quality of the simulation of regional climate. As the region of special interest, the Atlantic/European area is chosen. The model's horizontal resolution has a noticeable impact on the assessment of anthropogenic climate change as well as on the quality of the climate simulation at a local level, while at a regional level, that is considering the entire Atlantic/European area, the effect of the horizontal resolution is considerably reduced. The level of uncertainty related to the horizontal resolution actually falls within the range of uncertainty caused by the internal model variability obtained from ensembles of climate predictions. The level of uncertainty at a given location is very small for the near-surface temperature but somewhat higher for the sea-level pressure, in particular in autumn and winter, and relatively high for precipitation, with a marked maximum in summer. While the uncertainties in autumn and winter are mainly accounted for by the marked impact of the horizontal resolution on the dynamical aspects of the model, the high level of uncertainty in summer is related to the pronounced effect of the horizontal resolution on the model's physical parameterizations.

KEY WORDS: Climate change · Europe · General circulation model · Horizontal resolution · Precipitation · Sea-level pressure · Temperature

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1. INTRODUCTION

The possibility of climate change caused by the ongoing rapid increase in various greenhouse gases, with carbon dioxide (CO₂) being considered the most

important one, has been intensively investigated over the last decade. Though the question that an overall warming of the earth's atmosphere will take place is widely accepted within the scientific community, there is still some disagreement regarding the magnitude of the change and precisely how long it may take before the change becomes indisputably noticeable (Houghton et al. 1990, 1996).

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The major tools to assess the anticipated change in climate caused by the increase in greenhouse gases are simulations made with global coupled atmosphere-ocean general circulation models (AOGCMs), where the changes in the concentrations of various greenhouse gases have been prescribed according to typical scenarios provided by the Intergovernmental Panel on Climate Change (IPCC) (e.g. Mitchell et al. 1995). During the last decade, the models used for these scenario simulations have gradually been refined, not only with respect to the physical parameterizations and the resolution, but also with respect to the external forcing mechanisms. While earlier studies were based on models with relatively coarse resolutions of about 5° to 6° (e.g. Manabe et al. 1991, Cubasch et al. 1992), the horizontal resolution is roughly doubled in the current generation of models (e.g. Mitchell & Johns 1997). Some models consider not only CO_2 but also other greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) or tropospheric ozone as well as the direct and indirect effects of sulphate aerosols (e.g. Roeckner et al. 1999, referred to as 'R99' hereafter). In spite of these improvements, the uncertainties in the assessment of future climate change are still quite large. These uncertainties are, for instance, related to a number of atmospheric feedback processes, which are treated differently in the different models. Another source of uncertainty is the heat uptake by the ocean, which affects both the pattern and the delay of the warming induced by the radiative forcing of the greenhouse gases.

Regional climate is, however, often affected by processes on spatial scales that are considerably smaller than the scales typically resolved by the coupled climate models (e.g. Giorgi & Mearns 1991), which are on the order of 300 to 500 km. Hence, AOGCMs cannot explicitly capture the fine-scale structures that characterize climate variables such as the near-surface temperature or precipitation for many regions of the globe. In order to obtain information about the climate on these small scales 3 methods, also called 'regionalization' techniques are currently being used: (1) High resolution and variable resolution so-called 'time-slice' simulations with atmospheric general circulation models (AGCMs), (2) dynamical downscaling with regional climate models (RCMs), and (3) statistical downscaling methods.

The main advantage of the dynamical downscaling approach (e.g. Giorgi et al. 1992, Marinucci & Giorgi 1992, Jones et al. 1997) is that a much higher horizontal resolution, presently of the order of a few tens of km, can be used than in the AOGCMs, since the model domain is considerably smaller. The main limitations of this approach are that the regional information is only available in a particular region of interest and, more

fundamentally, that interactions between the regional and the global scales are excluded. For the time-slice approach (e.g. Bengtsson et al. 1995, Cubasch et al. 1995, Déqué et al. 1998) these arguments are reversed. Scale interactions between the regional and the global scales are included, but the horizontal resolution, currently about 100 km, is considerably coarser than for RCMs, since the entire globe is covered. However, one limitation of both of these methods is that coupled atmosphere-ocean modes cannot develop in these atmosphere-only models. The third method, namely statistical downscaling (e.g. von Storch et al. 1993, Wilby & Wigley 1997), is quite different, since it does not require any additional modelling; instead, statistical methods are used to empirically derive relationships between the regional climate and the large-scale circulation. The crucial question is, however, whether these empirical relationships, which are derived for the present-day climate, are also valid for the future climate.

The time-slice approach is based on the assumption that the large-scale circulation patterns in the low- and high-resolution GCMs are not markedly different from each other. Otherwise the climate state simulated by the high-resolution AGCM could be inconsistent with the underlying sea-surface temperature (SST) and sea-ice forcing originating from the low-resolution coupled model. The main advantages of this approach are that the time-slice simulations are globally consistent and that they capture remote responses to forcing mechanisms which only work realistically at a fine horizontal resolution. This allows, however, the AGCM to develop its own large-scale climatology, possibly violating the aforementioned assumption. Hence, it is important to consider the degree to which the high- and the low-resolution models converge to one climate state. It is generally assumed that with increasing horizontal resolution the simulations converge to one climate state for the explicitly resolved climate variables. This implies that there is a threshold resolution above which the climate state will not change fundamentally but reveal additional details for the finer scales.

In a recent study Williamson (1999) investigated the convergence of atmospheric simulations in a series of experiments in which the grid and the scale of the physical parameterizations were fixed, while the horizontal resolution of the model's dynamical core was increased. He compared the convergence characteristics of these dual-resolution simulations with the standard model, where the resolutions of both the dynamical core and the physical parameterizations were increased together. He found, for instance, that the aspects of the transient flow in the mid-latitudes did not converge with increasing resolution when the scale of the physics was held fixed. Apparently the non-

linear interactions in the dynamics created finer scales, with or without a finer-scale forcing. The lower-resolution scales, i.e., those of the physical parameterizations seemed, however, to converge. These convergence characteristics were shared by both the dual-resolution model and the standard model when the resolution was increased. Stratton (1999) found a similar change in the characteristics of the transient flow in the mid-latitudes between the low- and the high-resolution versions of her AGCM to that of Williamson (1999), namely a distinct shift in skewness of the probability density function of the vertical pressure velocity toward subsidence with increasing horizontal resolution. In addition, the probability of stronger upward motion increased with higher resolution, while that of weaker upward motion decreased. Such a dependency of the simulation of the transient flow in the mid-latitudes on the horizontal resolution of a GCM can lead to differences in the structure of the large-scale circulation patterns at these latitudes with increasing resolution (Stratton 1999).

These 2 studies considered simulations of the present-day climate. In a time-slice experiment, however, both a simulation of the present-day climate and of the future climate are performed with a high-resolution AGCM. For the case in which the differences between the simulations with different horizontal resolutions for the simulations of the present day and of the future climate, which is affected by the anticipated changes in the atmospheric concentrations of the greenhouse gases, vary in certain regions, the climate change signals inferred from the low- and high-resolution models in those regions will deviate. This will, however, add to the level of uncertainty that the predictions of the future climate generally have. May & Roeckner (2001) (referred to as 'MR01' hereafter), who investigated the impact of model's horizontal resolution on the assessment of anthropogenic climate change from a global perspective for annual mean values, found that the large-scale changes in temperature, the zonal wind component, sea-level pressure and precipitation obtained from their time-slice experiment and from the climate change experiment at low resolution that had provided the boundary forcing were broadly similar. In general, except for precipitation, the high-resolution responses were slightly weaker than those simulated in the coupled model due to the fact that the effect of resolution was smaller for the simulated climate in the future, i.e., warmer period compared to the present-day period. On a regional scale, the impact of horizontal resolution was smaller in the Southern Hemisphere than in the Northern Hemisphere, where the deviations in the climate change patterns were mainly accounted for by changes in the characteristics of the stationary waves.

In this study, which is based on the same time-slice experiment as MR01, we focus on one particular region, namely the Atlantic/European area. In contrast to MR01, our study does not only address the simulated changes in climate due to the anticipated changes in the concentrations of the important greenhouse gases, but includes an evaluation of the simulations of the present-day climate against observational data as well. Furthermore we distinguish between the seasons in our study, while in MR01 only the annual mean climate change was considered. Together with the focus on the Atlantic/European region, this gives further insight into the nature of the mechanisms causing the dependency of the simulations of both the present-day and the future climate on the model's horizontal resolution, since during the different seasons different physical processes may be responsible for the deviations between the high- and low-resolution models. During the cold seasons, the formation of precipitation in the Atlantic/European area is, for instance, mainly controlled by the large-scale circulation but primarily governed by convective activity during the warm seasons.

The paper is organized as follows: In Section 2 we describe the time-slice experiment on which our study is based. Subsequently we present the results for the simulations of the present-day (Section 3) and the future climate (Section 4). A summary and the conclusions follow in Section 5.

2. TIME-SLICE EXPERIMENT

The model employed in the time-slice experiment is the ECHAM4 AGCM (e.g. Roeckner et al. 1996a). The model was developed at the Max Planck Institute (MPI) for Meteorology to simulate the global present-day climate and a possible global change in climate due to enhanced emissions of greenhouse gases. It is based on the global forecasting system that is used at the European Centre for Medium-Range Weather Forecasting (ECMWF), but several major changes have been made, in particular to the physical parameterizations in order to make the model suitable for climate simulations. Details on the climate statistics of ECHAM4 in its 'standard' configuration at a horizontal resolution of T42 (corresponding to 64×128 grid points on a Gaussian grid) and 19 vertical levels can be found in Roeckner et al. (1996a).

In the time-slice experiment we used ECHAM4 with a horizontal resolution of T106 (corresponding to 160×320 grid points on a Gaussian grid) and 19 vertical levels. In ECHAM4 most of the free parameters in the physical parameterizations are independent of resolution (but note they were selected at a horizontal resolution of T42) instead of tuning the model by choosing

an optimal set of parameters at the respective resolution. Only the parameterizations of a few processes, which turned out to be extremely scale dependent, were tuned individually at different horizontal resolutions, such as the parameterizations of gravity wave drag, horizontal diffusion and formation of precipitation in stratiform clouds (e.g. Stendel & Roeckner 1998). The empirical multiplicative constant for the surface wind stress due to the gravity wave drag increases, for instance, with resolution, that is 2.5 versus $3.0 \times 10^{-5} \text{ m}^{-1}$ for T42 and for T106, respectively. Further, the damping rate of the smallest waves is stronger for T106 than for T42 with e-folding decay times of 3 and 9 h, respectively. In order to maintain a similar global radiation budget for the different resolutions, the parameters determining the efficiency of precipitation formation and, hence, the lifetime of clouds were adjusted for the different horizontal resolutions. Both the factor governing the efficiency of rain formation and the factor governing the fall velocity of ice crystals are increased for the high resolution. The parameterization of convection does, however, not explicitly depend on the horizontal resolution. Since the convergence of the atmospheric moisture fluxes in the lower atmosphere is enhanced at high resolution, the convective rainfall rate is generally stronger for T106. Thus generally speaking the high resolution does not automatically reduce all the systematic model errors, since some of the physical parameterizations, those tuned at the lower resolution, are possibly scale dependent. Nevertheless the high resolution leads to a more realistic simulation of the present-day climate by ECHAM4 due to the inclusion of a much wider spectrum of spatial scales, and hence the non-linear interactions between them, and a more realistic representation of the topography (Stendel & Roeckner 1998).

We performed 2 simulations with ECHAM4 for the high resolution over a period of 30 yr each. These 2 so-called time-slices were chosen so that one 30 yr period represents the present-day climate and the other one the climate at a time when the atmospheric concentration of CO_2 has doubled. The first time-slice covers the period 1970 through 1999 and the second one the period 2060 through 2089. In each of these time-slices the lower boundary forcing, i.e., monthly mean values of the SSTs and of the sea-ice extent was prescribed as obtained from a climate change simulation performed with a coupled atmosphere-ocean model run with low horizontal resolution. Moreover, the temporal evolution of the concentrations of the important greenhouse gases has been prescribed in the same way as in that climate change simulation (see below). Further details on the experimental design of our time-slice experiment are given in May (1999) (referred to as 'M99' hereafter), and a thorough discussion of the changes in

the mean climate inferred from these 2 time-slices can be found therein as well as in MR01.

The climate change experiment was performed at the MPI for Meteorology. The AOGCM consists of the ECHAM4 AGCM with a horizontal resolution of T42 and 19 vertical levels and an extension (level 3) of the OPYC (Ocean model in isoPYCnic coordinates) model (Oberhuber 1993) including a sea-ice model. OPYC has 11 layers and a varying horizontal resolution: poleward of 36° latitude the resolution is identical to that of the low-resolution AGCM, that is ca 2.8° . At low latitudes, the meridional grid spacing is gradually decreased to 0.5° at the equator in order to allow for a better representation of the equatorial wave guide in the model and, hence, the ENSO (El Niño-Southern Oscillation) phenomenon. Roeckner et al. (1996b) showed that this AOGCM was able to capture many features of the observed interannual variability of the SSTs in the tropical Pacific. This included not only the amplitude, lifetime and frequency of occurrence of El Niño events, but also the phase-locking of the SST anomalies and the annual cycle. The model components are coupled quasi-synchronously and exchange information once daily. Annual mean flux adjustments of heat and freshwater were estimated from a 100 yr spinup of the coupled model. For further details on the coupling technique and the performance of the model, refer to Roeckner et al. (1996b) and Bacher et al. (1998).

The coupled model was used for a control experiment and in the meantime for 3 different time-dependent forcing experiments, which are thoroughly described in R99. At the time when we decided to perform our time-slice experiment, only the greenhouse gas experiment covering the period 1860 through 2100 (referred to as 'GHG' in R99) was available, so that we could only use this particular climate change experiment to extract the boundary forcing for our time-slice experiment.

In that climate change simulation the concentrations of various gases were prescribed as a function of time: the greenhouse gases CO_2 , CH_4 and N_2O and several industrial gases such as chlorofluorocarbons (CFC-11, 12, 113, 114, 115), hydrochlorofluorocarbons (HCFC-22, 123, 141b), hydrofluorocarbons (HFC-125, 134a, 152a), carbon tetrachloride (CCl_4) and methylchloroform (CH_3CCl_3). From 1860 to 1990 the annual mean concentrations of these gases were prescribed as observed and after 1990 according to the scenario IS92a (Houghton et al. 1992). For the industrial gases the IS92a scenario was updated to be consistent with a 'Copenhagen-like' emission scenario (Houghton et al. 1996). Ozone and aerosols, on the other hand, were prescribed in the same way as in the control run, that is as climatological distributions for the present-day

conditions. This time-dependent or ‘transient’ forcing experiment was initialized at year 100 of the control run of the coupled model, nominally year 1860 in the transient experiment. In the control run the concentrations of the greenhouse gases (CO_2 , CH_4 and N_2O) were prescribed as observed in 1990 rather than given pre-industrial values, and present-day observations were used for the ocean spinup and for deriving the flux adjustment (Bacher et al. 1998). As a consequence the climate in the control run and, hence, the initial state of the transient experiment correspond to modern rather than pre-industrial times. Therefore in GHG the initial shift in the concentrations of the greenhouse gases had to be taken into account by enhancing the observed/anticipated concentrations in an appropriate way (see R99 for further details on this procedure).

3. PRESENT-DAY CLIMATE

First we want to investigate the impact of the horizontal resolution on the simulation of the present-day climate in the Atlantic/European region, which is defined as the area between 50°W and 40°E and between 25° and 50°N , respectively. For that purpose we compare the simulations covering the first period (1970–1999) of the respective experiments, i.e., the time-slice experiment and the transient climate change simulation (also referred to as the greenhouse gas experiment) that provides the boundary forcing, with each other as well as with observational data. In the following these simulations are generally referred to as TSL_1 and GHG_1 , respectively (see Table 1). As observational data we use the ECMWF re-analyses (referred to as ERA, see Table 1) for the period December 1978 through January 1994 (Gibson et al. 1997). These are more precisely the analyses for the near-surface temperature and the sea-level pressure and the 24 h forecasts for precipitation. We have chosen the 24 h forecasts instead of the analyses for precipitation in order to avoid the spinup, which causes an underestimation of precipitation by about 15 % in the analyses nearly everywhere (Stendel & Arpe 1997). As for the horizontal resolution we use either T106 or T42 de-

pending on whether we compare the re-analyses with the time-slice or with the greenhouse gas experiment. The significance of the differences between the respective data sets was obtained with a 2-sided *t*-test. As for precipitation we also consider observations for the European land areas provided by the Climate Research Unit, University of East Anglia (CRU), for the period January 1979 through December 1993 (Hulme et al. 1995). These data, which originate from synoptic stations, were interpolated onto a regular grid with a gridpoint separation of 0.5° .

3.1. Near-surface temperature

Fig. 1 shows the seasonal mean values of the temperature at 2 m in the Atlantic/European area for the winter season (December, January and February) for the 3 different data sets as well as the differences between these fields. According to this, the 2 simulations (Fig. 1b,c) reproduce the general structure of the temperature distribution in the Atlantic/European area (Fig. 1a) quite well, in particular the south-north temperature gradient over the Atlantic and the combined south-north and east-west temperature gradient on the European continent. Due to the improved presentation of the orography at the high resolution and due to the finer resolution itself, TSL_1 (Fig. 1b) reveals a lot more regional variations than GHG_1 (Fig. 1c).

The simulations are, however, characterized by a positive temperature bias in most of the area (Fig. 1d,e), and the area mean temperature in the simulations exceeds the ERA by about 3°C (see Table 2). One of the causes for this bias is the experimental design of the transient climate change simulation (R99). Since in the control run of ECHAM4/OPYC, which was used to derive the flux adjustments and provided the initial state for GHG, the concentrations of the greenhouse gases were prescribed as observed in 1990, the initial state of GHG corresponds to the present day, i.e., 1990 rather than pre-industrial times (1860). This had to be taken into account by enhancing the observed/anticipated concentrations of the greenhouse gases in an appropriate way, leading to higher temperatures in the simulation of the present-day climate in GHG than for the ‘real’ present-day climate. Another cause of the positive temperature bias is a systematic error of the coupled model leading to relatively high SSTs and, hence, near-surface temperatures in the western Atlantic (Fig. 1d,e). But also over the land areas the temperatures in the simulations are considerably higher than in ERA. This is partly due to the fact that the model

Table 1. List of data, their acronyms and the periods over which they run

Data	Acronym	Period	Acronym
Time-slice experiment with ECHAM4 (T106)	TSL	Present-day (1970–1999) Future (2060–2089)	TSL_1 TSL_2
Climate change experiment with ECHAM4/OPYC (T42)	GHG	Present-day (1970–1999) Future (2060–2089)	GHG_1 GHG_2
ECMWF re-analyses (T106/T42)	ERA	Present-day (1979–1993)	ERA

Fig. 1. Winter (December, January and February) mean temperatures at 2 m (TEMP2) from (a) ECMWF re-analyses (ERA) and from the simulations of the present-day climate in (b) the time-slice (TSL) and (c) the greenhouse gas experiments (GHG) (see Table 1 for acronyms). The differences between (d) TSL and (e) GHG and ERA are also shown. Units are °C. The contour interval is 2.5°C (a–c) and 1.0°C (d,e). Those gridpoints where the elevation exceeds 1500 m are blanked out

does not produce a realistic snow distribution and partly due to a systematic error in the simulation of the cyclone tracks in ECHAM4 (see Section 3.3). This systematic error, or more precisely its dependency on the

model's horizontal resolution, accounts also for the marked differences between TSL₁ and GHG₁, there being considerably higher temperature in TSL₁ in northern and eastern Europe (see Fig. 5d).

Table 2. Differences between the simulations of the present-day climate in the time-slice (TSL) and the greenhouse gas experiments (GHG) and ECMWF re-analyses (ERA) for different seasons (see Table 1 for acronyms). In addition to the differences in the area mean values we present the root-mean-square (RMS) values of the spatial variance of the difference fields and values of the pattern correlation (COR) between these difference fields. Only those grid points where the elevation does not exceed 1500 m are considered

Meteorological variable	DJF	MAM	JJA	SON
TEMP2 (°C)				
TSL ₁ – ERA	3.0	2.3	2.3	2.4
GHG ₁ – ERA	3.0	1.8	1.4	2.3
RMS(TSL ₁ – ERA)	3.5	2.8	3.3	2.7
RMS(GHG ₁ – ERA)	3.7	2.5	2.4	2.7
COR(TSL ₁ – ERA, GHG ₁ – ERA)	0.90	0.91	0.74	0.97
PRECIP (mm d⁻¹)				
TSL ₁ – ERA	0.17	-0.18	-0.41	0.06
GHG ₁ – ERA	0.20	-0.13	-0.21	0.13
RMS(TSL ₁ – ERA)	0.68	0.56	0.76	0.47
RMS(GHG ₁ – ERA)	0.77	0.47	0.60	0.52
COR(TSL ₁ – ERA, GHG ₁ – ERA)	0.57	0.74	0.77	0.50
MSLP (hPa)				
TSL ₁ – ERA	1.8	-0.1	-1.6	0.5
GHG ₁ – ERA	2.1	0.3	-0.1	1.1
RMS(TSL ₁ – ERA)	3.0	1.8	2.2	1.5
RMS(GHG ₁ – ERA)	3.0	1.5	1.2	1.7
COR(TSL ₁ – ERA, GHG ₁ – ERA)	0.54	0.33	0.02	0.55

The differences between the 2 simulations and ERA vary by season (see Table 2). For both simulations the positive temperature bias is smaller during spring (March, April and May), summer (June, July and August) and autumn (September, October and November) than in winter, in particular for GHG₁. This is partly due to a negative temperature bias in the Baltic Sea in spring and in the North and Baltic Seas as well as in the Mediterranean Sea in summer, indicating that the annual cycle of the SSTs in ECHAM4/OPYC is too weak in these shallow ocean basins. Further, the positive temperature bias is reduced relative to the winter season on the entire European continent during spring and autumn and during summer only in northern Europe. In spring and summer the temperature bias is smaller in GHG₁ than in TSL₁ due to a rather small temperature bias on the European continent during these seasons, in particular during summer. The magnitude of the local deviations between the 2 simulations and ERA (determined with the root-mean-square [RMS] of the spatial variance averaged over the area of analysis) are larger in TSL₁ than in GHG₁ for spring and in particular for summer. The relatively large value during summer is primarily due to the aforementioned relatively small temperature bias on the European continent in GHG₁ during that season. This is also the reason why the distributions of the differences

with ERA as obtained for the 2 simulations in summer are not as similar (the pattern correlation is 0.74) as during the other seasons, with correlations of 0.90 and 0.97, respectively.

3.2. Precipitation

As for the seasonal mean values of daily precipitation during winter, Fig. 2a–c reveal the improvement of the simulation of precipitation at high resolution in various regions due to the better presentation of the orography at the finer resolution. TSL₁ (Fig. 2b) reveals characteristic maxima of precipitation in the vicinity of steep mountain ranges, such as near southeastern Greenland, on the south coast of Iceland and on the west coasts of Norway and Scotland, in agreement with ERA (Fig. 2a) and other observational data (see Fig. 3). In GHG₁, on the other hand, the amount of precipitation in these areas is unrealistically small (Fig. 2c). Both simulations are, however, characterized by a slight underestimation of precipitation over the western Atlantic in the centre of the Atlantic stormtrack.

Although the differences between the 2 simulations and ERA are only very small for the area mean values, i.e., on the order 1 to 2 % (see Table 2), the geographical distributions reveal quite substantial regional differences compared to ERA. For TSL₁ we find, for instance, a general underestimation of precipitation over the southern part of the Atlantic and in southwestern Europe (Fig. 2d), while the high-resolution model produces too much precipitation over the northern part of the Atlantic and on the entire European continent except southwestern Europe. These deviations are associated with a systematic difference in the stormtrack activity, with too many cyclones reaching northern and eastern Europe during winter (see Section 3.3). Another marked difference compared to ERA is the excessive precipitation in the area south of Greenland, reflecting the very broad band of precipitation in the centre of the Atlantic stormtrack in TSL₁ (Fig. 2b). In contrast, ERA reveals a narrow band of precipitation between 35° and 50° N and between 35° and 50° W, respectively (Fig. 2a).

As for GHG₁ (Fig. 2e), the structure of the difference field is similar to TSL₁ on most of the European continent and in the area south of Greenland but different over the rest of the Atlantic, with an overestimation of precipitation over the southern part of the ocean basin and an underestimation over the northern part. As in the high-resolution model, these deviations are related to a systematic difference in the simulation of the stormtrack in the low-resolution model, with too few cyclones over the northern part of the Atlantic and too many over the southern part (see Section 3.3). Further,

Fig. 2. Winter daily precipitation (PRECIP) from (a) ERA and from the simulations of the present-day climate in the (b) TSL and (c) GHG. The differences between (d) TSL and (e) GHG and ERA are also shown. Units are mm d^{-1} . The contour interval is 2.5 mm d^{-1} (a–c) and 1.0 mm d^{-1} (d, e). Also the significance of the differences according to a 2-sided *t*-test is indicated (d, e). Positive (negative) differences exceeding a significance level of 97.5% are marked by the dark (light) shading

the amount of precipitation originating from individual cyclones is too small due to the coarse resolution, which does not allow for a realistic representation of frontal structures in the model. As a consequence, the main differences between TSL_1 and GHG_1 are more precipitation simulated at the high horizontal resolution over the northern part of the Atlantic and northern Europe and less precipitation over the southern part of the ocean basin and southern Europe (see Fig. 6d).

While the 2 simulations are characterized by too much precipitation in the area of analysis during winter and autumn, ECHAM4 underestimates the amount of precipitation during spring and summer (see Table 2). Hence the annual cycle of precipitation is too strong in the simulations. In addition to an underestimation of precipitation over most of the Atlantic, the simulations reveal a negative precipitation bias in all of western and southern Europe during spring and on the entire European continent during summer. It is also on the European continent where the underestimation of precipitation during summer is considerably stronger in TSL_1 than in GHG_1 , accounting for a large part of the much larger bias (-0.41 vs -0.21 mm d⁻¹, see Table 2) in the high-resolution model and, therefore, to a larger error in the annual cycle of precipitation (0.58 vs 0.41 mm d⁻¹) in TSL_1 . During the warm seasons, i.e., spring and summer, the distributions of the differences between the 2 simulations and ERA are rather similar (the pattern correlations are 0.74 and 0.77, respectively), while during the cold seasons, with correlations of 0.57 in winter and 0.50 in autumn, respectively, the 2 simulations reveal rather different difference pattern structures. This indicates that during these seasons, when precipitation primarily occurs in connection with synoptic disturbances and, hence, depends on the dynamical aspects of the model, the differences in the simulations of the large-scale flow patterns at the different horizontal resolutions cause marked differences in the simulation of precipitation. During the warm seasons, on the other hand, when the formation of precipitation is primarily governed by convective activity, the simulation of precipitation crucially depends on the model's physical parameterizations. Apparently the mechanism responsible for the model's dry bias works in the same way in the high- and low-resolution models. This mechanism is an unrealistic drying of the ground on the entire European continent at the beginning of the warm seasons leading to a reduction of evaporation and, hence, of the local formation of precipitation later on. The physical parameterizations involved are the parameterization of soil processes and the parameterization of the vertical fluxes in the planetary boundary layer. Since the ground's capacity for storing water is rather limited (Dümenil & Todini 1992), ECHAM4 not only stores too little water during the

cold seasons but also evaporates too much water at the beginning of the warm seasons. This problem is actually amplified by the model's deficiency in realistically simulating the snow cover in winter. Moreover, vertical moisture fluxes in the planetary boundary layer that are too strong may further accelerate the drying. Due to the finer horizontal resolution, these fluxes are considerably stronger in TSL than in GHG , leading to the relatively large dry bias during the warm seasons in the high resolution model.

The values of precipitation in the re-analyses represent in various regions model results rather than direct observations. That is, firstly, because of the difficulties in obtaining high-quality direct measurements of precipitation and, secondly, because of the lack of direct observations of precipitation in large areas, in particular over most of the North Atlantic. We therefore want to compare ERA directly with in-situ observations of precipitation on the European continent and various islands.

Fig. 3 shows the seasonal mean values of daily precipitation as obtained from ERA and CRU for the different seasons. The 2 data sets reveal very similar distributions of the precipitation, indicating the good quality of the estimates of precipitation over the land areas in ERA. However, presumably due to the even finer resolution, CRU shows more precipitation than ERA in the vicinity of the major mountain ranges, such as in western Norway, western Scotland or northwestern Spain. During autumn and winter, we find, for instance, differences of about 2 mm d⁻¹ in southwestern Norway, corresponding to 20–30 % of the respective seasonal mean values. In contrast, in the other parts of Scandinavia, i.e., Sweden and Finland and also in some parts of central Europe, ERA shows more precipitation than CRU. The aforementioned differences between the 2 data sets occur generally in all seasons, indicating that the systematic error in ERA in the simulation of precipitation does not vary according to season. Over the middle of the North Atlantic, ERA generally underestimates the amount of precipitation (Stendel & Arpe 1997). In particular, in the stormtrack region, the GPCP (Global Precipitation Climatology Project) data set (Huffman et al. 1995) and the Legates data set (Legates & Willmot 1990) give more precipitation during both winter and summer. As for the high latitudes, the Legates data set shows about the same amount of precipitation as ERA during winter but somewhat more precipitation during summer. Hence, the differences between the model simulations and ERA over the European continent are quite robust, and when considering CRU as a reference, the model's bias is slightly larger for all seasons except for summer, when the dry bias is slightly smaller than in ERA. Over the middle part of the North Atlantic, the underestima-

Fig. 3. Seasonal mean daily precipitation from the ECMWF re-analyses (a–d) and from observations for the period 1979–1993 from the Climate Research Unit (CRU) (e–h). Units are mm d^{-1} . Seasons are winter (a,e), spring (b,f), summer (c,g) and autumn (d,h)

tion of precipitation in GHG (see Fig. 2e) is even more severe, when the GPCP data are considered as a reference, while for TSL the overestimation over the northern part of this region (see Fig. 2d) is less pronounced compared to ERA.

3.3. Sea-level pressure

In order to describe the dynamical state of the atmosphere we take a look at the seasonal mean values of the sea-level pressure in winter (Fig. 4). Though the 2 simulations reveal the characteristic pressure pattern with low pressure centred to the west of Iceland and high pressure centred to the west of the Iberian peninsula (Fig. 4b,c), the distributions differ from ERA in several respects.

For TSL₁, the pressure is too high over the western part of the Atlantic and in western and southern Europe, but too low over the northeastern Atlantic and in northern and eastern Europe (Fig. 4d). As a consequence, the high-pressure area over the southern part of the Atlantic is far too strong and centred too far downstream over Spain (Fig. 4b). At the same time, the Icelandic low is slightly too weak, and another area with relatively low pressure is located over the Norwegian Sea. This pressure pattern indicates that in the high-resolution model the transient disturbances are displaced to the east. Moreover, they have a strong tendency to move eastward along a parallel of latitude rather than to occasionally take a southeastern route into the Mediterranean area when reaching the European continent. This can directly be seen from the distributions of the stormtrack activity expressed by the high-frequency RMS deviations of the geopotential height field at 500 hPa. Compared to ERA, TSL₁ is characterized by an underestimation of the stormtrack activity over the western part of the North Atlantic and an overestimation over the eastern part as well as over northern and western Europe (Andersen et al. unpubl.). Apparently the individual cyclones as simulated by the high-resolution model are too intense in these regions and, hence, lead to an overestimation of precipitation (see Fig. 2d). The low-resolution ECHAM4 simulates, on the other hand, pressure to be too high not only over western and southern Europe, but also over the northern part of the Atlantic and Scandinavia (Fig. 4e). This illustrates an underestimation of the intensity of the cyclones in the low-resolution model, while at the same time the transient disturbances have too strong a tendency to move eastward along a paral-

lel of latitude in the exit region of the Atlantic storm-track (Fig. 4c). In this case the distribution of the storm-track activity indicates a general underestimation of the stormtrack activity relative to ERA of up to 20% in the core of the Atlantic stormtrack (Andersen et al. unpubl.). Only over central and eastern Europe is the stormtrack activity as simulated by the low-resolution model larger than in ERA, leading to an overestimation of precipitation over these parts of the European continent (see Fig. 2e). As in other AGCMs (e.g. Doblas-Reyes et al. 1998, Stratton 1999), the importance of the aforementioned 'zonalisation' effect depends on the model's horizontal resolution, since it is enhanced for the high resolution (see Fig. 7d).

Also during the other seasons the high-pressure system over the southern part of the Atlantic is too strong in TSL₁, while on the European continent the deviations from ERA vary considerably by season. In summer TSL₁ shows, for instance, a negative pressure bias everywhere, while in autumn the pressure is too high over the northern part of the Atlantic and Scandinavia, indicating an underestimation of the intensity of the Atlantic stormtrack in TSL₁. As for GHG₁, the deviations from ERA have a very similar structure for all seasons but summer, when GHG₁ is characterized by an additional negative pressure bias over the western Atlantic centred at the British Isles. The deviations of the 2 simulations from ERA and, hence, the systematic errors of the large-scale circulation in the Atlantic/European region have quite different structures in summer (the pattern correlation is close to 0), while for autumn and winter the pattern correlations are about 0.55 (Table 2).

4. FUTURE CLIMATE

Now we want to investigate the impact of horizontal resolution on the simulation of the anthropogenic climate change in the Atlantic/European region. For that purpose we compare the climate change signals defined as the differences between the second (2060–2089) (referred to as TSL₂ and GHG₂, see Table 1) and the first period (1970–1999) derived from the time-slice and from the greenhouse gas experiment. Deviations between the climate change signals are accounted for by different impacts of the model's resolution on the simulations of the future and of the present-day climate, that is

$$\begin{aligned} \text{DIFF} &= (\text{TSL}_2 - \text{TSL}_1) - (\text{GHG}_2 - \text{GHG}_1) \\ &= (\text{TSL}_2 - \text{GHG}_2) - (\text{TSL}_1 - \text{GHG}_1) \end{aligned}$$

Fig. 4. Winter mean sea-level pressure (MSLP) from (a) ERA and from the simulations of the present-day climate in the (b) TSL and (c) GHG. The differences between (d) TSL and (e) GHG and ERA are also shown. Units are hPa. The contour interval is 2.5 hPa (a–c) and 1.0 hPa (d, e). Also the significance of the differences according to a 2-sided *t*-test is indicated (d, e). Positive (negative) differences exceeding a significance level of 97.5% are marked by the dark (light) shading

Therefore, we also compare the deviations between the 2 experiments for the simulations of the present-day and the future climate with each other.

4.1. Near-surface temperature

The two experiments predict a warming in the entire Atlantic/European region during winter (Fig. 5a,b). The warming is relatively strong on the European continent and relatively weak over most of the Atlantic and over the Mediterranean Sea. But we find also a rather strong warming in the high latitudes due to a shrinking of the sea-ice extent in the Arctic and along the east coast of Greenland in the future climate (M99). The very modest warming near the southern tip of Greenland on the other hand could be related to the efficient vertical mixing and hence the large effective heat capacity of the ocean in this area (e.g. Manabe et al. 1991).

The warming predicted on the European continent is considerably stronger in GHG than in TSL, with maximum differences between 2 and 3°C in eastern Europe (Fig. 5c). As a consequence, the change of the mean temperature in the area of analysis is somewhat stronger in GHG than in TSL (3.4 vs 3.2°C, see Table 3). The differences on the European continent are related to the fact that the differences between the temperatures simulated by the high- and low-resolution mod-

els are substantially smaller for the simulations of the future (Fig. 5e) than for the present-day climate (Fig. 5d). This can also be seen from the values of the RMS deviations of the differences between the simulations for different horizontal resolutions, with 1.4 and 1.0°C for the first and the second period, respectively (see Table 4). For the future climate characterized by a strengthening of the zonal component of the large-scale flow over the northern Atlantic (M99), the simulation of the Atlantic stormtrack activity apparently does not depend as much on the horizontal resolution as for the present-day climate (see Section 4.3).

During the other seasons the horizontal resolution is less important for the warming predicted in the Atlantic/European region (see Table 3). The 2 experiments give essentially the same values for the area mean differences as well as for the RMS deviations. In accordance with this, the RMS deviations between the 2 experiments for the simulations of the present-day and the future climate are closer to each other in spring, summer and autumn than during winter (see Table 4).

4.2. Precipitation

Both experiments predict an increase in precipitation during winter over the northern part of the Atlantic and in northern Europe and a reduction further south (Fig. 6a,b). This pattern is the result of 2

Table 3. Differences between the simulations of the future and the present-day climate obtained from TSL and GHG for different seasons (see Table 1 for acronyms). In addition to the differences of the area mean values, we present the RMS values of the spatial variance of the difference fields and values of the pattern correlation between these difference fields. Only those grid points where the elevation does not exceed 1500 m are considered

Meteorological variable	DJF	MAM	JJA	SON
TEMP2 (°C)				
TSL ₂ – TSL ₁	3.2	3.1	3.4	3.3
GHG ₂ – GHG ₁	3.4	3.2	3.3	3.3
RMS(TSL ₂ – TSL ₁)	3.3	3.1	3.5	3.4
RMS(GHG ₂ – GHG ₁)	3.7	3.3	3.5	3.4
COR(TSL ₂ – TSL ₁ , GHG ₂ – GHG ₁)	0.99	0.99	0.99	0.99
PRECIP (mm d⁻¹)				
TSL ₂ – TSL ₁	0.24	0.09	-0.01	0.13
GHG ₂ – GHG ₁	0.15	0.04	-0.01	0.11
RMS(TSL ₂ – TSL ₁)	0.46	0.26	0.17	0.43
RMS(GHG ₂ – GHG ₁)	0.55	0.27	0.22	0.38
COR(TSL ₂ – TSL ₁ , GHG ₂ – GHG ₁)	0.72	0.68	0.60	0.74
MSLP (hPa)				
TSL ₂ – TSL ₁	-0.9	-1.4	-1.2	-0.8
GHG ₂ – GHG ₁	-0.9	-1.3	-1.4	-0.9
RMS(TSL ₂ – TSL ₁)	1.5	1.7	1.4	1.5
RMS(GHG ₂ – GHG ₁)	2.3	1.6	1.6	1.4
COR(TSL ₂ – TSL ₁ , GHG ₂ – GHG ₁)	0.86	0.91	0.92	0.85

Table 4. Differences between TSL and GHG for the simulations of the present-day and of the future climate as well as for the patterns of climate change obtained from TSL and GHG ('ΔTSL – ΔGHG') for different seasons. We present both the RMS values of the spatial variance of the difference fields and values of the pattern correlation between the difference fields for the simulations of the present-day and the future climate in the 2 experiments, respectively. Only those grid points where the elevation does not exceed 1500 m are considered

Meteorological variable	DJF	MAM	JJA	SON
TEMP2 (°C)				
RMS(TSL ₁ – GHG ₁)	1.6	1.2	2.0	0.7
RMS(TSL ₂ – GHG ₂)	1.2	1.1	2.2	0.7
RMS(ΔTSL – ΔGHG)	0.7	0.4	0.4	0.3
COR(TSL ₁ – GHG ₁ , TSL ₂ – GHG ₂)	0.93	0.94	0.99	0.90
PRECIP (mm d⁻¹)				
RMS(TSL ₁ – GHG ₁)	0.65	0.37	0.49	0.47
RMS(TSL ₂ – GHG ₂)	0.59	0.38	0.53	0.51
RMS(ΔTSL – ΔGHG)	0.38	0.20	0.18	0.28
COR(TSL ₁ – GHG ₁ , TSL ₂ – GHG ₂)	0.81	0.85	0.94	0.84
MSLP (hPa)				
RMS(TSL ₁ – GHG ₁)	2.8	2.0	2.5	1.6
RMS(TSL ₂ – GHG ₂)	2.0	1.7	2.2	1.5
RMS(ΔTSL – ΔGHG)	1.2	0.7	0.6	0.8
COR(TSL ₁ – GHG ₁ , TSL ₂ – GHG ₂)	0.92	0.94	0.97	0.85

Fig. 5. Differences of the winter mean temperatures between the simulations of the future and the present-day climate obtained from (a) TSL and (b) GHG. Also shown are (c) the differences between the patterns of climate change obtained from TSL and GHG as well as the differences between TSL and GHG for the simulations of (d) the present-day and (e) the future climate. Units are $^{\circ}\text{C}$. The contour interval is 0.5°C (a–c) and 1.0°C (d,e). The significance of the differences between TSL and GHG at the 97.5% level is indicated by the shading (c–e): dark, positive; light, negative

Fig. 6. Differences of the winter daily precipitation between the simulations of the future and the present-day climate obtained from (a) TSL and (b) GHG. Also shown are (c) the differences between the patterns of climate change obtained from TSL and GHG as well as the differences between TSL and GHG for the simulations of (d) the present-day and (e) the future climate. Units are mm d⁻¹. The contour interval is 0.5 mm d⁻¹ (a-c) and 1.0 mm d⁻¹ (d,e). The significance of the differences between the patterns of climate change at the 99.0% level is indicated by the shading: dark, positive; light, negative

types of changes. Firstly, due to the general warming and due to the general increase in evaporation over the oceans (MR01), the amount of precipitable water in the atmosphere is considerably enhanced. Secondly, the meridional pressure gradient over the North Atlantic is increased (see Section 4.3). As a consequence, individual cyclones are predicted to be more intense (Andersen et al. unpubl.), at the very least due to a positive feedback of the water vapour, giving more precipitation. The increase in the mean precipitation in northern and central Europe as obtained from TSL goes along with an increase in the frequency of heavy precipitation events, while the number of days with light precipitation is reduced (Voss et al. unpubl.). This tendency has, however, also been found in southern Europe, though the mean amount of precipitation in this area is reduced. Both experiments predict an increase in the area mean precipitation in all seasons but summer (Table 3), when the amount of rainfall is reduced in all of Europe except for northern Norway and Sweden.

Despite a general agreement, the 2 experiments reveal a number of differences in several regions. TSL predicts, for instance, a very strong increase in precipitation in the vicinity of the steep mountain range on the Norwegian west coast (Fig. 6a), which cannot be found in GHG (Fig. 6b), and TSL shows a reduction of precipitation near the southeastern tip of Greenland in contrast to GHG. Another obvious difference between the 2 experiments is the relatively strong increase in precipitation in GHG over the northern Atlantic and the rather strong decrease over the southern part (Fig. 6b). As a consequence, the changes in precipitation over the Atlantic to the west of Greenwich are considerably stronger in GHG than in TSL (Fig. 6c). This deviation between the 2 models is related to the relatively strong change in the stormtrack activity predicted by ECHAM4/OPYC due to a rather strong increase in the meridional pressure gradient (see Section 4.3). In Scandinavia, on the other hand, the increase in precipitation is stronger in TSL, but in eastern Europe it is stronger in GHG. Considering the entire Atlantic/European region, the local change in precipitation is stronger in GHG than in TSL during winter, with RMS deviations of 0.55 and 0.46 mm d⁻¹, respectively (see Table 3).

The differences between the changes in precipitation predicted in the 2 experiments over the Atlantic west of Greenwich are by and large due to the relatively strong differences in the simulations of the present-day climate in this area (Fig. 6d). During the first period both the overestimation of precipitation in TSL over the northern part of the Atlantic and the underestimation over the southern part are more pronounced than for the simulations of the future climate (Fig. 6e).

This is related to the stronger dependency of the stormtrack activity on the model's resolution in the simulations of the present-day than in those of the future climate (see Section 4.3). For the entire Atlantic/European region, the local differences between the 2 experiments are stronger for the simulations of the present-day climate than in those of the future climate during winter, with RMS deviations of 0.65 and 0.59 mm d⁻¹, respectively (see Table 4).

During the other seasons, when the large-scale flow pattern is less important for the simulation of precipitation, the deviations between the 2 experiments are relatively strong for the simulations of the future climate (see Table 4). During summer precipitation is, for instance, the main difference between the simulations at different resolution, that is rainfall in the low-resolution model over the entire European continent except for northern Europe is considerably larger for the simulations of the future climate. This is also the season for which the difference patterns between the 2 models for the 2 periods are most similar, with a pattern correlation of 0.94. Since the predicted increase in the area mean precipitation is relatively strong in TSL in winter and spring but the same as in GHG in summer and autumn (see Table 3), the difference between the 2 experiments with regard to the amplitude of the annual cycle (see Section 3.3) is further enhanced in the simulations of the future climate. The local change in precipitation is, however, stronger in GHG in all seasons but autumn.

4.3. Sea-level pressure

Both the high- (Fig. 7a) and low-resolution models (Fig. 7b) predict a decrease in the atmospheric pressure over the northern part of the Atlantic and northern Europe and an increase over the southern part of the Atlantic and central and southern Europe during winter, leading to a strengthening of the meridional pressure gradient in the future climate. For the local change in pressure, we find an intensification of the Icelandic Low, which together with the increase in pressure further south leads to an intensification of the North Atlantic Oscillation (NAO) (e.g. Hurrell 1995). The change of the atmospheric pressure is, however, considerably stronger in GHG than in TSL. The change in the magnitude of the NAO is, for instance, about 6 hPa in GHG compared to 3 hPa in TSL, and for the RMS deviations we find values of 2.3 and 1.5 hPa for the low- and high-resolution models, respectively (see Table 3). Further, the change in the atmospheric pressure field as predicted in GHG is closer to the NAO pattern, since in GHG we can identify significant changes in both centres of action, while in TSL there is

Fig. 7. Differences of the winter sea-level pressure between the simulations of the future and the present-day climate obtained from (a) TSL and (b) GHG. Also shown are (c) the differences between the patterns of climate change obtained from TSL and GHG as well as the differences between TSL and GHG for the simulations of (d) the present-day and (e) the future climate. Units are hPa. The contour interval is 0.5 hPa (a-c) and 1.0 hPa (d,e). The significance of the differences between the patterns of climate change at the 99.0% level is indicated by the shading: dark, positive; light, negative

only an insignificant change in the northern centre. Hence, the geographical distribution of the deviations between the changes in climate predicted in the 2 experiments (Fig. 7c) shows a pronounced negative maximum over the southern part of the Atlantic, indicating the relatively strong pressure increase in GHG, while there are large positive differences to the south-east of Greenland and over northeastern Europe due to a rather strong pressure decrease in GHG in these areas. The strengthening of the meridional pressure gradient over the North Atlantic leads to an increase in the Atlantic stormtrack activity together with a downstream extension of the stormtrack (Andersen et al. unpubl.). In correspondence with the stronger increase in the meridional pressure gradient in GHG relative to TSL, the increase in the stormtrack activity is also larger in the low-resolution model. The intensification and shift of the Atlantic stormtrack is, in turn, accompanied by a strengthening of the extreme near-surface winds in the future climate over the northeastern Atlantic and northwestern Europe (Andersen et al. unpubl.).

A comparison of the deviations between the 2 experiments for the 2 periods (Fig. 7d,e) reveals that the differences between the climate change patterns are mainly due to differences in the simulations of the present-day climate at the different horizontal resolutions. This is the case over the southern part of the Atlantic and in the eastern part of the Mediterranean region, where the positive pressure differences between TSL and GHG are larger for the first period, as well as over the northern part of the Atlantic and in particular near southeast Greenland and over northeastern Europe, where the negative pressure differences are stronger for this period. Apparently the simulation of the large-scale circulation, including the stormtrack activity in the Atlantic/European region, is not as dependent on the model's horizontal resolution for the predicted future climate as for the present-day climate. Or, in other words, the impact of the model's horizontal resolution on the simulation of climate clearly depends on the climate state itself. The 2 experiments actually predict a strengthening of the zonal relative to the meridional component of the large-scale flow over the northern Atlantic in the future climate (M99), so that the zonalisation error of the model, which is enhanced for the high resolution, is less important. Consequently the spatial variance is considerably larger (2.8 vs 2.0 hPa) for the simulations of the present-day climate (see Table 4). In contrast to precipitation, for the sea-level pressure the deviations between the patterns of climate change arise from deviations in the simulations of the future climate. Only during winter, when the simulation of precipitation strongly depends on the large-scale flow, are the deviations between the models at

different horizontal resolutions larger for the simulations of the present-day climate.

5. SUMMARY AND CONCLUSIONS

In this paper we have investigated to what extent the simulation of the seasonal climate in the Atlantic/European region for the present and future times depends on the horizontal resolution of the AGCM employed. We have done that by comparing the simulations of the present-day climate from a high-resolution time-slice experiment (TSL) and a low-resolution transient greenhouse gas experiment (GHG) with observational data and by comparing the changes in climate inferred from these experiments with each other. TSL was performed with the ECHAM4 AGCM with a horizontal resolution of T106, and GHG with the ECHAM4/OPYC coupled model with a horizontal resolution of T42 for the atmospheric component. The lower boundary forcing for TSL, i.e., SSTs and sea-ice, was obtained from GHG.

The evaluation of the simulations of the present-day climate reveals that the finer horizontal resolution both improves and impairs ECHAM4's ability to reproduce certain aspects of the observed climate in the Atlantic/European area realistically. The local maxima of precipitation in the vicinity of the major mountain ranges are, for instance, simulated reasonably well in TSL. Further, the activity of synoptic disturbances is enhanced so that the bias of the atmospheric pressure over the northern part of the North Atlantic and northern Europe is reduced. As a consequence, the amount of precipitation originating from individual cyclones is much more realistic in TSL. The zonalisation error of ECHAM4 is, however, more severe for the high horizontal resolution. Another drawback of TSL is the relatively strong underestimation of precipitation over the European continent during summer. But in general, that is for most of the meteorological variables and most of the seasons considered, the deviations between the model biases in TSL and in GHG are within the range of the internal variability of coupled climate models (Giorgi & Francisco 2000a). The only exception is the considerable enlargement of the dry bias of precipitation during summer, i.e., 30.6% in TSL and 15.6% for GHG.

The 2 experiments reveal a number of the features of future climate change indicated in previous greenhouse warming experiments (e.g. Houghton et al. 1996). These are the larger warming on the European continent than over the Atlantic, the strengthening of the meridional pressure gradient due to a decrease in atmospheric pressure in the northern part of the Atlantic/European region and an increase in the south-

ern part as well as an increase (decrease) in precipitation in the northern (southern) part of this area. Although there is a high degree of similarity between the 2 experiments, there are notable deviations between the climate change patterns obtained from the 2 experiments, leading to a somewhat weaker response (assessed using the spatial variance) in TSL than in GHG, in particular in winter. Further, the areas where the changes in climate are locally significant are in some cases, i.e., for some of the meteorological variables and for some seasons, smaller in TSL than in GHG (see Table 5). As for the sea-level pressure, we find smaller areas with significant changes in TSL in autumn and winter and for precipitation in all seasons except spring. This behaviour is, however, to some extent related to the higher internal variability in TSL, which is related to the finer horizontal resolution, as a wider spectrum of spatial scales can be resolved. The aforementioned relationships between TSL and GHG differ, however, to some extent from the aforementioned estimates of the relative strength based on the values of the spatial variance. Therefore, one has to consider both the magnitude of the local changes and the size of the area with significant local changes when comparing the strength of the responses to the greenhouse gas forcing in the 2 experiments.

The relative differences of the response patterns, defined as the spatial variance of the differences between the climate change patterns obtained from TSL and GHG normalized by the mean spatial variances from TSL and GHG themselves, range from 17–40% for the sea-level pressure to 52–85% for precipitation (see Table 6). Hence, the uncertainties are rather large for the prediction of the local change in precipitation and reduced for the sea-level pressure, while for the near-surface temperature the uncertainties are very small. This has to be expected, since the simulation of precipitation in AGCMs depends both on the simulation of the large-scale circulation and on the physical

Table 6. Ratio of the spatial variances for the differences of the climate change patterns obtained from TSL and GHG, i.e., $[\text{RMS}(\Delta\text{TSL} - \Delta\text{GHG})]^2$ (see Table 4), and for the mean of the climate change patterns obtained from TSL and GHG, i.e., $0.5\{[\text{RMS}(\text{TSL}_2 - \text{TSL}_1)]^2 + [\text{RMS}(\text{GHG}_2 - \text{GHG}_1)]^2\}$ (see Table 3), for different seasons. Only those grid points where the elevation does not exceed 1500 m are considered

Meteorological variable	DJF	MAM	JJA	SON
PRECIP	0.60	0.63	0.85	0.52
MSLP	0.40	0.17	0.18	0.30

parameterizations of the respective models, while the simulation of the sea-level pressure fields is mainly a manifestation of the large-scale flow. For the near-surface temperature, the uncertainty is so small due to the experimental design deviations between the climate change patterns only occurring on the European continent or in the areas covered with sea-ice. The level of uncertainty varies by season. For the sea-level pressure the uncertainties are, for instance, rather large in autumn and winter, due to the marked impact of the horizontal resolution on the dynamical aspects of the model and, hence, the simulation of the large-scale flow during the cold seasons. For precipitation, on the other hand, the high level of uncertainty in summer is related to the pronounced effect of the horizontal resolution on the model's physical parameterizations.

For the sea-level pressure, the deviations between the climate change patterns are generally, i.e., in all seasons, related to relatively strong differences between TSL and GHG in the simulations of the present-day climate in the Atlantic/European region. For precipitation, on the other hand, the effect of the horizontal resolution is stronger in the simulations of the future climate in all seasons but winter. During winter the deviations between TSL and GHG are mainly related to the different characteristics of the Atlantic stormtrack embedded in the large-scale circulation in the high- and low-resolution models, leading to a stronger zonal orientation of the flow over the European continent in TSL. This discrepancy between the high- and low-resolution versions of ECHAM4 is, however, considerably smaller in the simulations of the future climate, which is characterized by a strengthening of the zonal flow component over the Atlantic and Europe. Since during winter the simulation of precipitation is mainly controlled by the large-scale circulation, also for precipitation, the effect of the horizontal resolution is relatively strong in the simulations of the present-day climate, whereas for the other seasons, for which the physical parameterizations are more important for the simulation of precipitation, the differences are larger for the simulations of the future climate.

Table 5. Fraction of the areas where the climate change patterns obtained from TSL and GHG exceed the 99.0% level of significance according to a 2-sided *t*-test which is indicated in Figs. 6a,b (precipitation) & 7a,b (sea-level pressure), respectively. Only those grid points where the elevation does not exceed 1500 m are considered

Meteorological variable	DJF	MAM	JJA	SON
PRECIP				
SIGN(TSL ₂ – TSL ₁)	0.23	0.19	0.20	0.23
SIGN(GHG ₂ – GHG ₁)	0.39	0.18	0.31	0.26
MSLP				
SIGN(TSL ₂ – TSL ₁)	0.19	0.54	0.74	0.30
SIGN(GHG ₂ – GHG ₁)	0.27	0.49	0.75	0.45

The model's horizontal resolution apparently has an impact on the assessment of anthropogenic climate change at a local level, while at a regional level, that is considering the entire Atlantic/European area or sub-regions such as northern and southern Europe, for instance, the effect of the horizontal resolution is considerably reduced. The level of uncertainty related to the horizontal resolution actually falls with the range of uncertainty caused by the internal model variability obtained from ensembles of climate predictions (Giorgi & Francisco 2000b). Given this, the impact of the horizontal resolution on regional climate change is much smaller than the uncertainties arising from different climate models, illustrating the crucial role of the models' physical parameterizations for the prediction of the future climate. According to Giorgi & Francisco (2000b), these uncertainties in regional changes are 3 K or more for temperature and 25% of the present-day values or greater for precipitation. Hence, we can, for our experiment and for the Atlantic/European area, confirm the validity of the basic assumption of the time-slice approach: the overall similarity of the large-scale circulation patterns in the low- and high-resolution GCMs.

In light of the aforementioned differences between TSL and GHG the important question remains: whether the response obtained in TSL is more reliable than the response in GHG, assuming that the boundary forcing provided by GHG is 'perfect'. For the large-scale circulation in the Atlantic/European area, this question is hard to answer, since TSL reveals a rather strong model error in the atmospheric pressure field over the southern part of the Atlantic, while GHG is characterized by a considerable bias over the northern part of the Atlantic and in northern Europe. For precipitation, on the other hand, TSL may give the more realistic response, since due to the better presentation of the mountain ranges in the high-resolution model, the local maxima of precipitation are much more realistically simulated in TSL. A drawback of TSL in this respect may, however, be that in the high-resolution model the overestimation of the amplitude of the annual cycle of precipitation is more severe than for the coarser resolution. But there are a variety of aspects and regions, respectively, that gain from the enhanced horizontal resolution of ECHAM4. The amount and spatial distribution of precipitation in the tropics is, for instance, more realistically simulated in TSL (MR01), and in particular the simulation of the Indian summer monsoon is much more realistic with the high resolution (M99). Hence, the high-resolution model may give a more reliable prediction of the future climate in many respects. However, in order to get the maximum benefit from a relatively costly time-slice experiment, it appears to be necessary to improve those

aspects of the high-resolution model that are impaired as compared to the (standard) low-resolution model. One way to do this would be to further optimize, that is to empirically adjust the physical parameterizations of the high-resolution model. This has been hampered by the prohibitively high computational costs in the past. Another possibility would be to develop and/or use physical parameterizations that can be applied for various horizontal resolutions without any empirical adjustments but taking the different spectra of spatial scales into account.

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LITERATURE CITED

- Bacher A, Oberhuber JM, Roeckner E (1998) ENSO dynamics and seasonal cycle in the tropical Pacific as simulated by the ECHAM4/OPYC3 coupled general circulation model. *Clim Dyn* 14:431–450
- Bengtsson L, Botzet M, Esch M (1995) Hurricane-type vortices in a general circulation model. *Tellus* 47A:175–196
- Cubasch U, Hasselmann K, Höck H, Maier-Reimer E, Mikolajewicz U, Santer BD, Sausen R (1992) Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Clim Dyn* 8:55–69
- Cubasch U, Waskewitz J, Hegerl G, Perlwitz J (1995) Regional climate changes as simulated in time-slice experiments. *Clim Change* 31:273–304
- Déqué M, Marquet P, Jones R (1998) Simulation of climate change over Europe using a global variable resolution general circulation model. *Clim Dyn* 14:173–189
- Doblas-Reyes FJ, Déqué M, Valero F, Stephenson DB (1998) North Atlantic wintertime intraseasonal variability and its sensitivity to the GCM horizontal resolution. *Tellus* 50A: 573–595
- Dümenil L, Todini E (1992) A rainfall-runoff scheme for use in the Hamburg climate model. In: O'Kane JP (ed) *Advances in theoretical hydrology*. Elsevier Science Publishers, Amsterdam, p 129–157
- Gibson JK, Källberg P, Uppala S, Hernandez A, Nomura A, Serrano E (1997) ERA description. ECMWF Re-analysis Project Report Series 1
- Giorgi F, Francisco R (2000a) Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM. *Clim Dyn* 16:169–182
- Giorgi F, Francisco R (2000b) Evaluating uncertainties in the prediction of regional climate change. *Geophys Res Lett* 27:1295–1298
- Giorgi F, Mearns LO (1991) Approaches to the simulation of regional climate change: a review. *Rev Geophys* 29: 191–216

- Giorgi F, Marinucci MR, Visconti G (1992) A $2 \times \text{CO}_2$ climate change scenario over Europe generated using a limited area model nested in a general circulation model. 2. Climate change scenario. *J Geophys Res* 97:10011–10028
- Houghton JT, Jenkins GJ, Ephraums JJ (eds) (1990) Climate change. The IPCC scientific assessment. Cambridge University Press, Cambridge
- Houghton JT, Callandar BA, Varney SK (eds) (1992) Climate change 1992: the supplementary report to the IPCC scientific assessment. Cambridge University Press, Cambridge
- Houghton JT, Meira Filho LG, Callandar BA, Harris N, Kattenberg A, Maskell K (eds) (1996) Climate change 1995. The science of climate change. Cambridge University Press, Cambridge
- Huffman GJ, Adler RF, Rudolf B, Schneider U, Keehn PR (1995) Global precipitation estimates based on a technique combining satellite-based estimates, rain gauge analysis, and NWP model precipitation information. *J Clim* 8:1284–1295
- Hulme M, Conway D, Jones PD, Jiang T, Barrow EM, Turnley C (1995) Construction of a 1961–90 European climatology for climate modelling and impacts applications. *Int J Climatol* 15:1333–1364
- Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269:676–679
- Jones RG, Murphy JM, Noguer M, Keen AB (1997) Simulation of climate change over Europe using a nested regional model. II: Comparison of driving and regional model responses to a doubling of carbon dioxide. *Q J R Meteorol Soc* 123:265–292
- Legates DR, Willmot CJ (1990) Mean seasonal and spatial variability of gauge corrected global precipitation. *Int J Climatol* 10:111–127
- Manabe S, Stouffer RJ, Spelman MJ, Bryan K (1991) Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2 . Part I: Annual mean response. *J Clim* 4:785–818
- Marinucci MR, Giorgi F (1992) A $2 \times \text{CO}_2$ climate change scenario over Europe generated using a limited area model nested in a general circulation model. 1. Present-day seasonal climate simulation. *J Geophys Res* 97:9989–10009
- May W (1999) A time-slice experiment with the ECHAM4 A-GCM at high resolution: the experimental design and the assessment of climate change as compared to a greenhouse gas experiment with ECHAM4/OPYC at low resolution. DMI Scientific Report 99–2, Danish Meteorological Institute, Copenhagen
- May W, Roeckner E (2001) A time-slice experiment with the ECHAM4 AGCM at high resolution: The impact of horizontal resolution on annual mean climate change. *Clim Dyn* (in press)
- Mitchell JFB, Johns TC (1997) On modification of global warming by sulfate aerosols. *J Clim* 10:245–267
- Mitchell JFB, Davis RA, Ingram WJ, Senior CA (1995) On surface temperature, greenhouse gases and aerosols: models and observations. *J Clim* 8:2364–2386
- Oberhuber JM (1993) Simulation of the Atlantic circulation with a coupled sea-ice—mixed layer—isopycnal general circulation model. Part I: Model description. *J Phys Oceanogr* 22:808–829
- Roeckner E, Arpe K, Bengtsson L, Christoph M, Claussen M, Dümenil L, Esch M, Giorgetta M, Schlese U, Schulzweida U (1996a) The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. MPI-Report No. 218, Max Planck Institute for Meteorology, Hamburg
- Roeckner E, Oberhuber JM, Bacher A, Christoph M, Kirchner I (1996b) ENSO variability and atmospheric response in a global coupled atmosphere-ocean GCM. *Clim Dyn* 12: 737–754
- Roeckner E, Bengtsson L, Feichter J, Lelieveld J, Rodhe H (1999) Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. *J Clim* 12:3004–3032
- Stendel M, Arpe K (1997) Evaluation of the hydrological cycle in reanalyses and observations. ECMWF Re-analysis Project Report Series 6, European Centre for Medium-Range Weather Forecasting, Reading
- Stendel M, Roeckner E (1998) Impacts of horizontal resolution on simulated climate statistics in ECHAM4. MPI-Report No. 253, Max Planck Institute for Meteorology, Hamburg
- Stratton RA (1999) A high resolution AMIP integration using the Hadley Centre model HadAM2b. *Clim Dyn* 15:9–28
- von Storch H, Zorita E, Cubasch U (1993) Downscaling of global climate change estimates to regional scales: an application to Iberian rainfall in wintertime. *J Clim* 6: 1161–1171
- Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. *Prog Phys Geogr* 21:530–548
- Williamson D (1999) Convergence of atmospheric simulations with increasing horizontal resolution and fixed forcing scales. *Tellus* 51A:663–673

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