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Natural climate variability and climate change in the North-Atlantic European region; chance for surprise?

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Long-term variability in the North Atlantic Oscillation (NAO) and the Atlantic thermohaline ocean circulation (THC) are both shaping the European climate on time scales of decades and longer. Possible linear and non-linear changes in the characteristics of these natural climate modes due to global warming are an important source of uncertainty in long-term regional projections of future climate changes.

Keywords: CLEAR, natural climate variability, climate change, atmosphere, ocean

1. Introduction

The current projections of future climate changes due to the man-made release of greenhouse gases are based on comprehensive coupled three-dimensional numerical models. An extensive summary and discussion on the state of the art of these models is given in the reports of the intergovernmental panel on climate change (IPCC) [1,2]. All of these comprehensive climate models predict consistently an increase in global surface temperature in the range of 1.5–4.5 °C for a man-made doubling of the CO_2 concentration. However, because of the enormous complexity of such projections, major uncertainties remain. Some of these are related to the inability of the models to correctly represent all the physical processes that govern the climate system, others are related to the unknown future anthropogenic CO_2 and aerosol releases or to unknown future large volcanic eruptions. In addition, uncertainties arise due to unexpected nonlinear changes in the internal dynamics of the climate system [3]. Uncertainties exist on all spatial scales and they are generally larger, the smaller the length scale is and the longer the time scale of the projection is. In this paper we focus on two climatic processes which can introduce uncertainty in projections, these are the North Atlantic Oscillation and the Atlantic thermohaline ocean circulation which are important for both the past and future North Atlantic and European climate.

2. The North Atlantic Oscillation

Analyses based on global data sets indicate that multi-annual to decadal climate oscillations occur with distinct large-scale spatial patterns, referred to as teleconnections [4]. The most widely known is the El Niño Southern Oscillation (ENSO) phenomenon. It occurs every 3–7 years in the equatorial Pacific region and has a profound climatological, ecological and economical impact far beyond that region.

For the European climate the direct influence of ENSO is comparatively small. But there exists a number of other climate patterns that are important for Western Europe: the North Atlantic Oscillation (NAO) is the dominant one. It is particularly strong during the winter season and is associated with a variability in the strength of the westerly wind across the Atlantic. The NAO is typically measured with an index (figure 1A) that represents a normalized pressure difference between Iceland and the Azores or Iceland and Portugal [5].

During positive NAO phases the westerlies across the Atlantic are stronger than in the long-term mean and hence more relatively warm oceanic air is transported towards the European continent [6]. This leads to warmer than average winter temperatures in Europe (figure 2). During negative phases of the NAO the mild westerlies are reduced, winter temperatures are below normal and Western Europe experiences a more continental climate. Both the cold European winters in the 60s as well as the warm winters of the late 80s were associated with negative and positive phases of the NAO, respectively. The NAO is associated with surface temperature anomalies on both sides of the Atlantic, but with opposite signs (figure 2). Winter temperatures in the northern Alpine ridge vary with the NAO, but with substantially smaller amplitudes than in Northern Europe [7]. Many other atmosphere, ocean, terrestrial and marine ecological parameters vary in concert with the NAO. Some examples are the North Atlantic storm track [8,9], precipitation over parts of Europe [5] snow cover and duration over the Alpine ridge [10], thickness of the total ozone layer over the Alpine region and Europe [11] and the length of the growing season

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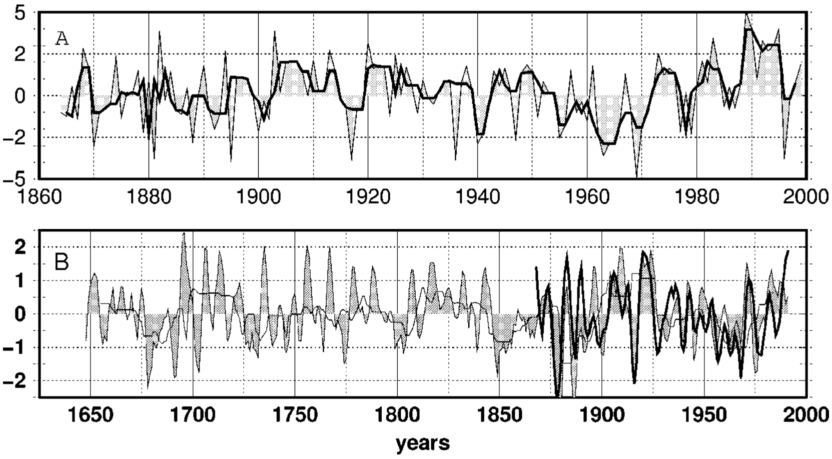

Figure 1. (A) Winter NAO index based on the observed pressure difference between Iceland and Portugal for the period 1859/60–1998/99. Data are a December–March average and each station is normalized relative to the period 1864–1983. The thick line is a 3 year median. For details see [5]. (B) Annual proxy NAO index based on ice accumulation rates from western Greenland [38] for the last 350 years and instrumental annual NAO index for the last 150 years. Both indices are normalized, a linear trend and the high frequency part are removed, using a triangular 1,2,3,2,1 filter, thin line is a 15 year median.

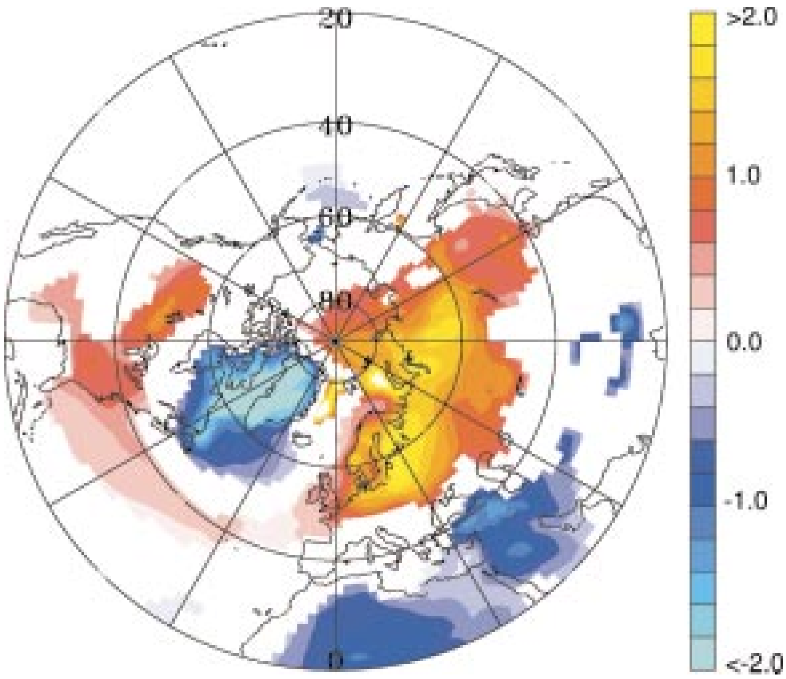

Figure 2. Temperature anomaly (°C) associated with a positive phase (+1 standard deviation in the NAO index) of the NAO oscillation. Calculation are based on 2 m winter temperature derived from NCEP reanalysis data [66] and averaged from December to March for the period 1959–1998. Only statistically significant values with correlation coefficients >0.3 or <−0.3 are shown. Clearly visible is the temperature dipole between Europe–Eurasia and eastern Canada–Greenland.

in parts of Europe [12]. Even the Norwegian electricity production and oil consumption [13] was shown to be correlated with the NAO index (see also [14]).

Although this seesaw in cold/warm winters between Iceland and Northern Europe has long been known [15,16], a comprehensive knowledge of the mechanisms responsible for this climate oscillation is still lacking. There is modeling and observational evidence that NAO is a natural mode of variability that can occur as a purely internal-atmospheric process [17]. Such variations could explain the observed coherent spatial structure, but it is unlikely that they are a source of energy for the observed variability on interannual or longer time scales [18]. One way low frequency variability can arise is due to coupling of the atmosphere with the underlying ocean. There are clear indications that the temperature at the surface [19] as well as in the uppermost ocean layer [20] vary with the NAO. Coupled interaction with the wind-driven gyre circulation [21] and the large-scale thermohaline circulation [22] can also result in variability that resembles the NAO, and the sea surface temperature (SST) in the North Atlantic seems to have a controlling effect [23,24]. It was also suggested that the NAO is a component of a more hemispheric pattern referred to as Northern Hemisphere Annular Mode (NAM) or Arctic Oscillation (AO) [25]. Such ideas point to the role of the stratosphere within the climate system, and have been confirmed by statistical analysis showing that the strength of the polar vortex varies in concert with the tropospheric NAO or AO pattern [26,27]. Hence, chemical and dynamical processes that affect the stratospheric circulation such as volcanic eruptions, ozone depletion or greenhouse gases, e.g. [28,29] can also affect the NAO (AO) long-term variability.

3. NAO and climate change

Decadal climate variability such as the NAO can substantially mask or enhance a man-made warming trend in the Northern Hemisphere and can make the detection of the global warming a difficult task. Over the last 30 years both the NAO and ENSO have been predominantly in a positive phase [30]. Since both have an imprint on the extra-tropical Northern Hemisphere temperature this positive bias contributed to the observed temperature trend for the last 30 years. One might argue that the anthropogenic contribution to the observed global temperature trend is smaller than assumed and that most of the trend is simply due to a coincidence of these natural climate modes (compare with [31]).

However, such an interpretation does not take into account the possibility that the release of greenhouse gases itself can affect the mean state and the probability distribution of the natural climate modes. Idealized studies [3] as well as observational evidence [32] suggest that the climate system exhibits preferred states, so-called regimes. One of these is comparable to the positive NAO climate pattern. The response of a non-linear system to slow external forcing is not necessarily a change in its mean state (e.g., global temperature) but may also consist of a shift towards a predominant occurrence of one particular climate regime [3].

Most of the current models used to calculate global change projections are not yet able to correctly simulate past observed variability in climate patterns like the NAO and are therefore unlikely to predict possible non-linear changes associated with them. Only a few recent studies have explored possible anthropogenically-induced changes in the low frequency behavior of multi-annual patterns. The simulated ENSO variability in a future climate depends on the model used. Some model indicated little changes [33] while others predict significantly different variability [34]. The latter study used a high-resolution coupled ocean-atmosphere model to show that ENSO variability can shift more towards El Niño conditions if greenhouse gas forcing increases (see below). Similar predictions for future NAO responses [35] suggest a north-eastward shift of the NAO pattern towards Europe with an increase in storm activity but only a slight increase in the mean NAO index. However, other simulations suggest that the AO (NAO) moves toward a more positive regime in a future climate [29] if the climate model included a realistic stratosphere (see also [36]). Although the results are still controversial, they seem to suggest that a change in the variability of the AO or NAO can lead to a distinct regional response in a future European climate and hence can have a profound effect on the regional assessment.

An important source of information on the dynamics of the climate system is the comparison of NAO and ENSO indices based on observational data with their paleoclimatic reconstructions. Because of the scarcity or absence of observational data before 1850, proxy indicators are required in order to estimate past values of such indices. Corals, lake sediments and tree rings have been proposed to reconstruct ENSO indices, see, e.g. [37]. Similarly, proxy NAO indices have been estimated based on paleoclimatic data from ice cores [38], tree rings [39], multi-proxy data sets [40] or documentary data [41]. Since the atmospheric mean flow and the moisture transport to western Greenland varies with the NAO index [42], ice accumulation rates determined on a western Greenland ice core can be used to reconstruct a proxy index. For the last 350 years this index suggests (figure 1B) that prolonged phases with positive or negative NAO states have occurred and that the NAO is a highly intermittent climate oscillation with coherent temporal variability only active during limited periods of time [38]. Limitations in the temporal resolution do not permit the identification of extreme NAO events, but a similar reconstruction based mainly on tree ring data including Moroccan trees suggests that the high NAO index values in the first half of the 90s have been exceptional in the last 700 years [40]. If true, this supports the idea that global change has started and is expressed in the modification of the natural climate variability.

4. The ocean thermohaline circulation

Whether or not global warming induced by man-made increase of the concentrations of greenhouse gases in the atmosphere will substantially affect the ocean thermohaline circulation (THC) is a question that has triggered much investigation. Paleoclimatic indicators show, that the North Atlantic climate has been far from stable during the last ice age [43,44]. An example is given in figure 3 which shows the estimated temperature changes in Greenland (Summit) based on variations in the isotopic composition of the ice for the last 100 000 years [45,46]. In addition to the long-term temperature increase from the last ice age and the current warm period (the last 10 000 years are referred to as the Holocene) the Greenland temperature shows large fluctuations with typical return times of 2000–3000 years. The detailed mechanism for these Dansgaard-Oeschger events [45] is not yet understood. They seem not to occur during the current warm phase and cannot be directly linked to changes in the geometry of the Earth's orbit around the sun. There are strong indications from many other paleoclimatic archives that a reduction in the Atlantic thermohaline ocean circulation and hence a reduced northward heat transport is a key

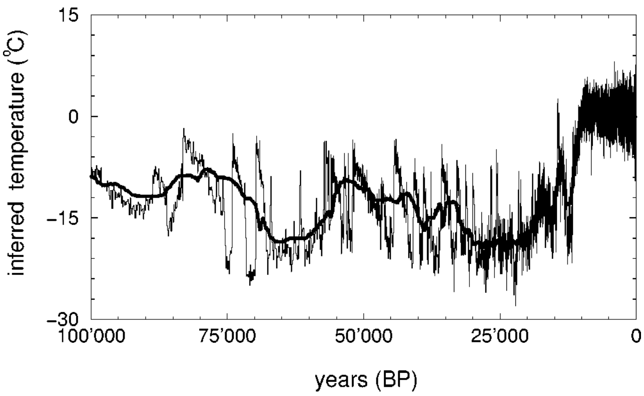

Figure 3. Temperature variability in Greenland for the last 100 000 years. The temperature change is inferred from the isotopic ratio δ^{18}O measured on the GRIP ice core record drilled at Greenland summit [45,46]. The comparatively stable last ∼10 000 years correspond to the warm Holocene, the period 10 000 BP to ∼10 000 to the last glacial with the last glacial maximum around 25 000. Earlier data have lower resolution and thick line indicates a 300 year median.

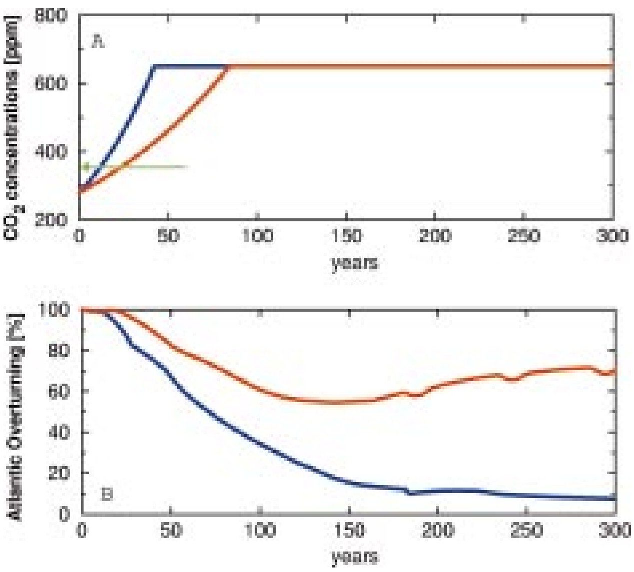

Figure 4. Global warming experiment based on a zonal averaged climate model [51,52]. (A) The assumed CO_2 emission pathway with 1% (grey line) and 2% (bold line) increase per year. The arrow indicates CO_2 concentration (370 ppm) in 2000. (B) response of the thermohaline circulation (maximum Atlantic overturning).

player (see, e.g. [47]). Although the typical return time of these events is several thousand years, high-resolution measurements from Greenland ice cores suggest that a switch from one climate state to the other occurred within few decades only [48]. This suggests that the North Atlantic climate system can change substantially within time scales that are comparable to human life times and prompts the question, whether such rapid changes in the strength of the THC could occur in a anthropogenically modified climate [43,49,50].

5. The THC and global change

Projections of future climate change calculated by all but one of today's coupled ocean-atmosphere numerical models indicate that the strength of the Atlantic THC will be reduced [49,51–53]. The exception is a recent study [54] that will be discussed below. One of the reasons for the reduction of the THC is the enhanced fresh-water cycle that brings more precipitation into the North Atlantic ocean basin. Together with the temperature effect, this leads to a reduced sea surface water density and therefore less deep water formation. Long-term integrations with a zonally averaged climate model indicate, that the thermohaline circulation may even completely shut down within the next 100–200 years, if certain threshold values of released greenhouse gas concentrations are passed [52]. The remarkable finding is, that the response of the Atlantic heat pump is not simply a function of the maximum greenhouse gas concentration reached, as illustrated in figure 4. It is also dependent on the emission history of greenhouse gases. In general, a faster release leads to a higher probability that the THC is irreversibly reduced. Qualitative features of these simple model results, like the rate-sensitive response have been confirmed in more complex models [55,56], whereas other models produce different results [57]. The details of these experiments remain model and parameter sensitive, and hence prevent predictions of the threshold values.

A complete shut-down or even a substantial reduction of the thermohaline circulation can have a significant impact on European weather although the detailed response is still unclear. It seems likely that the European continent would experience a "reduced warming" [53] and that summer precipitation would be reduced [55]. Three-dimensional coupled climate models currently suggest that the reduction in warming of the annual mean European temperature is ∼1–3 °C, but regional differences can be large. By far the strongest response can be expected in the northern North Atlantic sea surface temperature which can even become colder than today [51]. Model results from [58] suggest that the projected annual mean surface temperature over Europe will increase by 4–5 °C for a doubling of the CO_2 concentration and that the THC is only slightly reduced. However, a complete shut-down of the THC, caused by a fourfold increase of the CO_2 concentration, would "only" increase the temperature by 7–8 °C instead of 8–10 °C expected from a linear response.

It is interesting to note that similar amplitudes in European temperature shifts were observed during the Younger Dryas (∼12700 years BP) [59], a climate event also believed to be associated with a shut-down of the THC [60].

6. A stabilizing feedback for the THC

Changes in the thermohaline circulation strongly influence the atmosphere and its natural climate patterns. In turn, changes in the mean state of the natural atmospheric patterns can feedback onto the mean ocean circulation. A recent study using the coupled, high-resolution ECHAM4 climate model [54] indicates that greenhouse gas induced changes in the natural variability of the climate system can influence the stability of the THC. This model suggests, in contrast to a wide range of other models, that the THC is only slightly affected by global warming. The warmer climate favours near-permanent El Niño conditions [34], which in turn increase the freshwater export from the Atlantic to the other ocean basins. Surface waters in the tropical Atlantic therefore become saltier and denser. When these waters are advected northwards into the sinking regions of the northern North Atlantic, they tend to compensate the decrease of sea surface density which results from the warming and increased local precipitation. This represents a stabilizing feedback on the THC. Observational evidence based on two different sets of reanalysis data supports a link between ENSO and Atlantic fresh water export [61] and suggests, that in today's climate the disturbance is strongest in the tropics and has a typical amplitude of about 0.05 Sv (1 Sv $= 10^6$ m^3 s^{-1}) for one standard deviation of the Southern Oscillation Index. This amplitude has little effect on the strength of the today's North Atlantic thermohaline circulation since El Niño and La Niña events occur with similar frequency. However, simulations with a simplified climate model suggest that the freshwater anomalies are sufficient to significantly disturb the THC, if the mean state of the system is shifted into a more El Niño or La Niña-like basic state (figure 5). The strength of the THC increases roughly 10–20% for an El Niño-like freshwater disturbance that lasts several decades and is comparable in amplitude to today's interannual ENSO variability (0.1 or 0.2 Sv).

There is paleoclimatological evidence that the ENSO system was in a more La Niña-like state during the Last Glacial Maximum [62]. This tends to reduce the THC because of a reduced freshwater export from the tropical Atlantic (lower lines in figure 5) during La Niña and is consistent with observational studies that the Atlantic THC was generally weaker than today [63]. For sufficiently large freshwater perturbations (e.g., 0.2 Sv equivalent to extreme La Niña conditions) lasting longer than 70 years the model simulates even a complete shut-down of the THC. This can be taken as an indication that changes in the tropics have the potential to trigger climate variations in the high latitudes of the Atlantic, which is of importance for both paleoclimatic [64,65] as well as for future climate change scenarios [54].

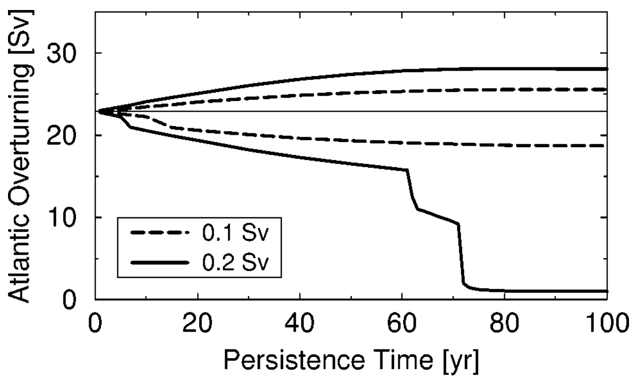

Figure 5. Maximum change in North Atlantic deep water formation rate as a response to a ENSO-like tropical freshwater disturbance based on a zonal averaged climate model [61]. The disturbance lasts 1, 2, 3... up to100 years (persistence time). Freshwater is exchanged between the Atlantic and the Pacific at four different rates (±0.1 and ±0.2 Sv). Upper lines correspond to a transfer of freshwater from the Atlantic to the Pacific, representing a shift towards more positive El Niño events. Lower lines result from additional freshwater transport from the Pacific to the Atlantic, representing a shift towards La Niña years. The thin line indicates the unperturbed overturning.

7. Conclusions

The aim of this paper is not to speculate on a most likely scenario for the future European climate a century hence, but to illustrate some chances for surprise. Most likely scenarios are developed and discussed in detail in the series of the IPCC reports [1,2]; they suggest that climate will continue to warm due to anthropogenic forcing in the future with about 2 °C increase in mean surface temperature in the year 2100. On a more regional scale the response can differ for example due to additional external forcing, such as anthropogenically released aerosols, but also due to changes in the internal dynamics of the climate system. For the European region the North Atlantic Oscillation is a process that strongly shapes the climate on a regional scale. The projection of the future European winter climate and related environmental parameters will depend on whether a regime shift in the NAO (AO) will take place. The same is true for a possible shut down of the Atlantic thermohaline circulation. Assuming that an anthropogenically modified future climate is associated with a shift towards a more positive NAO mean state, the regional modification would be stronger Atlantic westerlies, colder eastern Canadian and milder European winters. From today's NAO variability the temperature difference between a typical positive and negative NAO winter is known and amounts to $\sim$3–4 °C for the central and northern European near surface temperature (figure 2). These amplitudes, although not extreme, are of importance for regional climate assessments.

Regional response patterns can often be quite contrary to intuition and expectations based on simple, qualitative arguments. For example, most projections indicate stronger warming in higher latitudes than in mid latitudes which implies, using simple physical arguments, a reduction of the mean meridional temperature gradient and hence, due to the thermal wind balance, a weakening of the mean westerly winds. However, a reduction of the THC (or similarly a shift towards positive NAO regimes) would lead to a relative cooling over the northern North Atlantic ocean and suggests an opposite effect on the temperature gradient in the region relevant for Europe, and hence an increase in westerly winds.

A number of model studies support the possibility of anthropogenically induced shifts in natural variability, but so far it remains unclear how likely these scenarios are under the currently assumed projections. This is due to the limited knowledge of the processes involved and their crude representation in numerical models, but also due to the fact that the climate system itself is a system that contains many non-linear processes, which makes long-term prediction difficult. Some improvement can be expected form the use of ensemble predictions with the goal to derive estimates of the probability of certain changes, e.g. [23]. Such extensive model simulations will also improve the future quality of integrated assessments of regional climate change. A better understanding now, will reduce the chance for unpleasant surprises in the future.

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