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Projection of North Atlantic Oscillation and its effect on tracer transport

Sara Bacer[1], Theodoros Christoudias[2], and Andrea Pozzer[1]

[1]Atmospheric Chemistry Department, Max Planck Institute for Chemistry, Mainz, Germany
[2]Computation-based Science and Technology Research Center, The Cyprus Institute, Nicosia, Cyprus

Correspondence to: S. Bacer (sara.bacer@mpic.de)

Abstract. The North Atlantic Oscillation (NAO) plays an important role in the climate variability of the Northern Hemisphere with significant consequences on long-range pollutant transport. We investigate the evolution of pollutant transport in the 21st century influenced by the NAO under a global climate change scenario. We use a free-running simulation performed by the ECHAM/MESSy Atmospheric Chemistry (EMAC) model coupled with the ocean general circulation model MPIOM, covering the period from 1950 until 2100. We find that NAO trends will continue to interchange in the future considering variable length periods, while the overall trend (150 years) is weakly positive. To investigate the future NAO effects on transport we consider carbon monoxide tracers with exponential decay and constant interannual emissions. We find that at end of the century south-west Mediterranean and Africa will see higher pollutant concentrations with respect to the past. On the contrary, central Europe and a wider part of north Europe will benefit from increased pollutant depletion. Therefore, under a global climate change scenario local air quality conditions over Europe and North Africa, influenced by North Atlantic teleconnection activity, will become more extreme.

1 Introduction

The North Atlantic Oscillation (NAO) is the most prominent recurrent pattern of atmospheric variability over middle and high latitudes in the Northern Hemisphere (NH). It refers to a redistribution of atmospheric mass between the Arctic and the subtropical Atlantic. The NAO, defined as the surface pressure difference between the Azores high and Icelandic low, influences weather conditions (Hurrell, 1995). When the Icelandic low and Azores high are relatively stronger, the pressure difference is higher than average (positive NAO phase) and the north-south pressure gradient produces surface westerlies stronger than average across the middle latitudes of the Atlantic towards northern Europe. On the other hand, when the low and high surface pressure are relatively weaker (negative NAO phase) the flow has a reduced zonal component. These meridional oscillations produce large changes in the mean wind speed and direction, heat and moisture transport, surface temperature and intensity of precipitation, especially during boreal winter (Hurrell et al., 2003, and references therein). Several studies (Hurrell, 1995; Visbeck et al., 2001; Hurrell et al., 2003) have associated the westerly flow during positive NAO with warm and moist maritime air and enhanced precipitation over northern-western Europe, and colder and drier conditions over the Mediterranean.

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As the NAO exerts a strong influence on the boreal winter weather, it can also affect the transport of gas pollutants on hemispheric scale. Li et al. (2002) examined the transatlantic transport of anthropogenic ozone and the NAO impacts on the surface ozone in North America and Europe; they found that there are higher northern American ozone concentrations at Mace Head Ireland during positive NAO, when westerly winds across the North Atlantic are stronger. Creilson et al. (2003) also analysed the relationship between the NAO phases and the tropospheric ozone transport across the North Atlantic and discovered that rises of ozone over western Europe are strongly correlated with positive NAO. Eckhardt et al. (2003) studied the relationship between the NAO and transport towards the Arctic and found that concentrations of surface carbon monoxide, originating both from Europe and North America, increase in the Arctic during the NAO positive phases. Christoudias et al. (2012) studied the transport of regionally-tagged idealised tracers in relation to the NAO and found that, during high positive NAO phases, the trace gases emitted from North America are transported relatively far to northern-eastern Europe, while the trace gases emitted over Europe are transported mostly over Africa and the Arctic Circle. Pausata et al. (2012) showed both with station measurements and coupled atmosphere-chemistry model simulations that the NAO affects surface ozone concentrations during all seasons, except in autumn. The sensitivity studies by Thomas et al. (2014) regarding the free tropospheric carbon monoxide concentrations to different atmospheric weather conditions confirmed the NAO control of pollutant distribution and transport over the region of Nordic countries.

A number of studies have focused on the impacts of the NAO on aerosol concentrations. Moulin et al. (1997) analysed the role of the NAO in controlling the desert dust transport into the Atlantic and Mediterranean and suggested that the NAO likely influences the distribution of anthropogenic aerosols. Jerez et al. (2013) investigated the NAO influence on European aerosol concentrations through local atmospheric processes (e.g., precipitation, wind, cloudiness) and found that positive NAO promote higher ground-level aerosol concentrations in southern regions of the Mediterranean during winter. Pausata et al. (2013) proved the influence of the NAO extreme events during the 1990s on the variability of particulate matter concentrations over Europe and indicated the NAO index as a useful indicator for health impacts of pollution.

The aforementioned studies suggest that future NAO phases will be important when projecting the northern American and European pollutant transport over Europe and the Arctic. There are, however, no studies on the influence of the NAO on tracer and pollutant transport under a future scenario, taking into account the global climate change. With this work we aim to study the NAO influence on the pollutant transport in the future.

The NAO is an intrinsic mode of atmospheric variability but there is mounting evidence in the literature that it is unlikely that only stochastic atmospheric processes are the cause of NAO changes. There are a few candidate mechanisms to interpret low-frequency variations such as the North Atlantic (Rodwell et al., 1999) and tropical (Hoerling et al., 2001) sea surface temperature (SST), the sea-ice variations in the North Atlantic Ocean (Mehta et al., 2000) and the stratospheric circulation (Baldwin et al., 2001). Recently, Woollings et al. (2015) have ascribed the NAO variability on interannual-decadal timescales to the latitudinal variations of the North Atlantic jet and storm track, and the NAO variability on longer timescales to their speed and strength changes. In order to explain the upward trend observed from 1960s until 1990s some external forcings have been proposed as responsible. They include the increase of greenhouse gases (Kuzmina et al., 2005), warmer tropical SST (Hoerling et al., 2001) and the strengthened stratospheric vortex (Baldwin et al., 2001). However, there is still no consensus

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and Osborn et al. (1997) asserted that recent variations can not be explained, even when combining the anthropogenic forcing and internal variability. Thus, a conclusive understanding of past NAO variability has still to be reached and the future NAO evolution continues to be an open research topic.

Earth system model simulations with increasing greenhouse-gas (GHG) concentrations can provide projections of the NAO and future trends. Most models have projected a weak positive NAO trend under a global warming climate change scenario. Gillett et al. (2013) found this when considering the mean of 37 CMIP5 models' merged historical and RCP 4.5 simulations for each season, and Stephenson et al. (2006) obtained similar results with 14 models out of 18 studied. However, some studies found the NAO index in a future scenario only weakly sensitive to the GHG increment, with no significant trends (Fyfe et al., 1999; Dorn et al., 2003; Rauthe et al., 2004; Fischer et al., 2009), or even decreasing trends (Osborn et al., 1997). More lately, Pausata et al. (2015) analysed the impacts due to the aerosol reduction (after air pollution mitigation strategies) and GHG increment on the winter North Atlantic atmospheric circulation and obtained a stronger positive NAO mean state by 2030. The dependency of the results on the model used is still unclear (Gillett et al., 2003; Stephenson et al., 2006). Other research questions are still open, regarding which climate processes govern the NAO variability, how the phenomenon varies in time, and what is the potential for the NAO predictability (Visbeck et al., 2001; Hurrell et al., 2001; Woollings et al., 2015).

The distribution and development of gases and aerosols are controlled by atmospheric chemistry and physics, including the transport of air masses integrated over continental scale. A large number of studies have addressed the NAO influence on tracer transport and the future trends of the NAO as disparate topics. However, no study has addressed the NAO influence on the pollutant transport throughout the 21st century using an integrated modelling approach and with a full atmospheric chemistry to account for all potential feedbacks.

The aim of this paper is to study the influence on the pollutant transport due to the NAO in the span of the 21st century using a full Earth system model. We analyse a simulation performed by a coupled atmosphere-chemistry-ocean general circulation model (GCM) in order to: (i) validate the ability of our model system to describe the NAO, (ii) investigate the NAO signal and trend in the future, and (iii) study the NAO influence on the pollutant transport in the past and in the future over the North Atlantic sector. For the analysis, we focus on the carbon monoxide (CO) pollutant, which is directly emitted by combustion sources and has a lifetime of 1–3 months in the atmosphere; thus, it has a sufficiently long atmospheric residence lifetime relative to the timescales of transport.

The paper is structured as follows: Sect. 2 briefly describes the model used and the simulation set-up; Sect. 3 presents the NAO trends of the future projection; Sect. 4 analyses the NAO influence on and the changes of tracer transport. Conclusions and outlook are given in Sect. 5.

2 Methodology

Increasingly, the dynamics and chemistry of the atmosphere are being studied and modelled in unison in global models. Starting with the fifth round of the Coupled Model Intercomparison Project Phase 5 (CMIP5), some of the Earth system models (ESMs) that participated with interactive oceans included calculations of interactive chemistry. It was also a main

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recommendation of the SPARC CCMVal Report (2010), that Chemistry-Climate Models (CCMs) should continue to evolve towards more comprehensive, self-consistent stratosphere-troposphere CCMs. These developments allow for including a better representation of stratosphere-troposphere, chemistry-climate and atmosphere-ocean couplings in CCMs and ESMs used for more robust predictions of climate changes and mutual influences and feedbacks on emitted pollutants (Eyring et al., 2012). The EMAC model was one of the first community models to introduce all these processes (Jöckel et al., 2006).

In this work we analyse a long chemistry climatic simulation performed by the ECHAM/MESSy Atmospheric Chemistry (EMAC) climate model under the "Earth System Chemistry Integrated Modelling" (ESCiMo) initiative (Jöckel et al., 2015). The EMAC model is a numerical chemistry and climate simulation system which uses the Modular Earth Submodel System (MESSy) to describe tropospheric and middle atmosphere processes and their interactions with oceans, land and human influences via dedicated sub-models (Jöckel et al., 2010).

The long chemistry climatic simulation RC2-oce-01 (Jöckel et al., 2015), hereafter referred to as "coupled simulation", simulates the development of the climate covering the period 1950–2100. The simulation is performed by the fully coupled atmosphere-chemistry-ocean model EMAC-MPIOM (Pozzer et al., 2011), using the 5th generation European Centre Hamburg general circulation model (ECHAM5, Roeckner et al. (2006)) as the dynamical core of the atmospheric model and the MESSy submodel MPIOM (Max Planck Institute Ocean Model, Marsland et al. (2003)) as the dynamical core of the ocean model. The simulation resolution uses a spherical truncation of T42 (corresponding to a quadratic Gaussian grid of approx. 2.8×2.8 degrees in latitude and longitude) and 47 vertical hybrid pressure levels up to 0.01 hPa into the middle atmosphere (approximately 80 km with a resolution of ~ 20 hPa (~ 1 km) at the tropopause), referred to as T42L47MA. This vertical resolution is essential in order to take into account the influence of the stratosphere on the NAO variability (Baldwin et al., 2001). Proper representation of the stratospheric dynamics is important for simulating future climate changes and a realistic reproduction of the NAO changes (Shindell et al., 1999). Scaife et al. (2007) further showed that the stratospheric variability has to be reproduced in order for models to fully simulate surface climate variations in the North Atlantic sector. The resolution for the ocean corresponds to an average horizontal grid spacing of 3×3 degrees with 40 unevenly spaced vertical levels (GR30L40). An important feature of the EMAC model is its capability to provide a careful treatment of chemical processes and dynamical feedbacks through radiation (Dietmüller et al., 2016). The model computes gas phase species online trough the MECCA submodel (Sander et al., 2011) and uses prescribed atmospheric aerosols to take into account the interactions with radiation and heterogeneous chemistry. The model incorporates anthropogenic emissions as a combination of the ACCMIP (Lamarque et al., 2013) and RCP 6.0 data (Fujino et al., 2006). A detailed description can be found in Jöckel et al. (2015) and references therein.

A coupled model simulation has been chosen for the following reasons. Coupled GCMs perform better than atmospheric GCM forced with SST in reproducing the spatial patterns of atmospheric low-variability and the NAO phenomenon (Saravan, 2011). Several works have shown that coupled models are able to simulate the main features of the NAO (e.g., Osborn et al. (1997), Stephenson et al. (2006)). Recently Xin et al. (2015) have quantified the contribution of the coupling in the NAO variability, showing that 20% of the NAO monthly variability is caused by the ocean-atmosphere coupling and 80% is due to the chaotic atmospheric variability. Therefore a coupled model is essential for a reasonable projection of future NAO. Our model is one of the first to include a full ocean-atmosphere coupling, stratospheric circulation in conjunction with online chemistry

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and anthropogenic emissions to capture all associated feedbacks, thus providing state-of-the-art simulation capability of the phenomenon and potential impacts.

In order to investigate the transport of pollutants we use passive tracers with emissions modelled after CO emissions for the year 2000 (i.e. no interannual variability) and decay lifetime constant in time. These tracers are well-suited for investigating transport-related effects as no chemical influences or emission variability are included. CO is a good proxy for anthropogenic pollution, as it is mostly emitted by biomass burning and human activities (Pozzer et al., 2007). In particular, we consider two passive CO tracers with a constant exponential decay (e-folding time) equal to 25 and 50 days, referred to as CO_{25} and CO_{50} respectively. For the analysis we focus on the winter (DJF: December-January-February) seasonal means, since the sea level pressure (SLP) amplitude anomalies are larger in winter and the NAO is typically stronger in this period.

3 NAO representation and trends

3.1 NAO representation

In order to define the spatial structure and temporal evolution of the NAO we use Empirical Orthogonal Function (EOF) analysis. We compute the eigenvectors of the cross-covariance matrix of the time variations of the SLP (Hurrell et al., 2003). By definition the eigenvectors are spatially and temporally mutually orthogonal and scale according to the amount of the total variance they explain; the leading EOF (EOF1) explains the largest percentage of the temporal variance in the dataset. The NAO is identified by the EOF1 of the cross-covariance matrix computed from the SLP anomalies in the North Atlantic sector. We compute the EOF1 from winter seasonal SLP anomalies in the North Atlantic sector: 20°N-80°N, 90°W-40°E. The EOF1 spatial pattern is associated with a north-south pressure dipole with its centres of action corresponding to the NAO poles with highest SLP variability. Therefore, the long chemistry coupled simulation reproduces the NAO signal, with the typical north-south dipole structure (Fig. 1, top). EOF1 explains 38.8% of the total variance, in accordance with the results found in literature (e.g., Fischer et al. (2009), Ulbrich et al. (1999)).

In order to detect NAO differences between the past and the end of the 21st century, we define two 30-year-long periods: (A) 1980-2010 and (B) 2070-2100. The EOF1 analysis for the two periods separately is shown in Fig. 1 (centre and bottom). We find that the centres of action of the NAO move northeastward towards the end of the 21st century. This shift is in agreement with the results obtained by Ulbrich et al. (1999) and Hu et al. (2003) for a climate change global warming scenario.

The shift of the NAO centres of action has to be taken into account when examining the temporal evolution of the NAO pattern. The NAO station-based index, defined as the difference of the normalized SLP between one northern station in Iceland and one southern station in the Azores, is fixed in space and does not reflect the spatial variability of the NAO centres of action, over seasonal (Hurrell et al., 2003) or (future) decadal (Ulbrich et al., 1999) scales. Since our model projects a spatial shift of the NAO centres, we will be considering the principal component time series of the leading EOF of SLP (PC1) (Hurrell et al., 2003) as NAO temporal index.

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3.2 NAO trends

To investigate the NAO temporal variability and trends over the simulated period, we compute the linear regression coefficients of the PC1 considering sliding windows. In particular, we define windows of variable length between a minimum of 10 years and a maximum equal to the simulated period of 150 years sliding along the whole time series. We compute the linear slope (trend) for each window and assign the value to the window central year (e.g., the regression coefficient of the PC1 for the period 1980-1990, a 11-year window, is assigned to the year 1985).

First we compute the trends for the past period (A) of the coupled simulation (Fig. 2, top). Similarly, we repeat the analysis considering the "NAO-PC-based index" (NAO Index, data) produced by the Climate Analysis Section of the National Center for Atmospheric Research (NCAR) based on Hurrell et al. (2003) (Fig. 2, bottom). In this way we directly compare our modelled results with the observations. We note that the patterns and slope values are in good agreement, validating the capability of our model to correctly simulate the NAO over the reference period. We distinguish two clear patterns: an upward trend (red shading) which dominates between 1980 and 1991 and a downward trend (blue shading) which dominates from 1992 onwards. The positive trend in the first period corresponds to the one observed from records and largely discussed in the literature (e.g., Hurrell (1995), Visbeck et al. (2001), Gillett et al. (2003)).

For the analysis of simulated longer periods and future trends we apply the same sliding window method, as described previously, to the whole simulation period (Fig. 3). No change in the projected future NAO variability is identified compared to the past, when considering periods shorter than 30 years. For windows of length between 30 and 60 years, upward trends (centred in the 1980s and 2040s) interchange with downward trends (centred in the 2010s and 2060s). On longer window lengths we find that very weak non-statistically significant NAO trends are prevalent. The slope of the overall trend computed for the whole simulation is between 0 and +0.005 at the 95% level of significance.

In summary, our coupled EMAC-MPIOM model predicts a small significant positive trend for the NAO (for the 150 years horizon) in agreement with other studies that have used coupled models (e.g., Gillett et al. (2003), Hu et al. (2003), Stephenson et al. (2006)).

4 NAO effects on tracer transport in the future

In order to analyse the NAO influence on tracer transport we compute the correlation between the PC1 and tracer mixing ratio at the surface level. We consider the passive tracers CO_{25} and CO_{50}, whose emission and decay lifetime are constant, in order to remove influences by chemical production/decomposition variability. In this way the correlation gives information purely on the effect of tracer transport. To identify the future changes in transport pathways related to the NAO, we compute the correlation separately in the two periods (A) and (B). We perform the analysis with the CO_{25} tracer, that undergoes exponential decay with e-folding time equal to 25 days. A supplementary analysis is repeated for CO_{50}, with 50-day e-folding constant, to provide a constrain on the systematic uncertainty associated with the resident time of the tracer in the atmosphere.

In the near-past period (A) (Fig. 4, left) we observe that the PC1 and CO_{25} mixing ratio are significantly correlated over the northern part of the American east coast (between New York and Labrador regions), north-west Baffin Bay region, Arctic,

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north Africa and part of the Iberian Peninsula. Also present is a continuous area of significant anti-correlation encompassing the American central-east coast (near Florida and Cuba), through the central North Atlantic Ocean, towards northern and eastern Europe, and the Black Sea regions. Under positive NAO activity, tracers are depleted over northern Europe while higher concentrations are shifted towards northern Africa and the Arctic. The analysis with CO_{50} leads to similar results (see the electronic supplement), and thus the results can be considered robust under the uncertainties associated with pollutant tracer atmospheric residence lifetimes.

Since the CO concentration over Europe is mostly influenced by emissions from Europe and only partially from North America (the Asian contribution can be considered negligible (Duncan et al., 2008)), we can compare our results with the findings of Christoudias et al. (2012) that used tracers tagged by origin. We find transport patterns (Fig. 4 (left)) similar with the ones of Christoudias et al. (2012) for European emissions. However, our results supersede those in Christoudias et al. (2012) as that study was limited in the period 1960–2010, and was forced by prescribed SST and global atmospheric hydroxyl radical (OH) concentrations (as the removal mechanism for CO depletion).

The future transport changes can be seen in Fig 4 (right). All significantly correlated areas increase in size compared to the past, except for the area at north-west of the Baffin Bay which decreases. The area with positive correlation over the Arctic spreads southwards up to the Scandinavian Peninsula and the one over Africa spreads westwards and northwards, covering further the Iberian Peninsula. Moreover the correlation over north-west Africa and the near ocean becomes stronger with values between 0.6 and 1.0, greater than in the past. Similarly, the area with significant anti-correlation is wider with respect to the past, and a more pronounced gradient between positive and negative correlated regions is formed. The large area with negative correlation over the North Atlantic extends further over northern Europe and the North Atlantic Ocean and develops over new regions, i.e. south Greenland and Baffin Bay. The magnitude of the negative correlation also increases over north-east Europe, south Scandinavian and the North Atlantic Ocean (between Great Britain and Iceland) with values in the range -0.6 and -0.8. Therefore, we find that during period (B), which is mostly characterized by positive NAO trends, the flow over Europe is expected to transport tracers over the Arctic and Africa splitting the European continent in two distinct areas. Again, the analysis considering CO_{50} has produced similar results (presented in the electronic supplement).

Comparing the past and future periods (A) and (B) we investigate how the NAO will influence the transport in the future. We find that the dichotomy between low and high pollutant concentrations (and air quality conditions) will be enhanced at the end of the century. In particular, together with the persistence of positive NAO trends, it can be expected that the south-west Mediterranean and north Africa will suffer from higher pollutant concentrations, while a wider part of north Europe will benefit from lower concentrations of long range pollutants, associated with improved surface air quality. At the same time it seems that the region over the American east coast will be characterized by concentrations of pollutants in a range similar to the past, with respect to the NAO activity.

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5 Conclusions

A free-running simulation performed by the coupled EMAC-MPIOM model has been analysed in order to study the influence of the NAO on future pollutant transport and concentration changes. The simulation takes into account the GHG increment during the 21st century according to the ACCMIP (Lamarque et al., 2013) and RCP 6.0 (Fujino et al., 2006) scenarios. We find that the model is able to reproduce the SLP anomalies and the NAO signal. EOF analysis shows the typical dipole pattern which is identified as the NAO. Moreover, the trends of the modelled temporal index PC1 are comparable with the ones computed with the observations (Fig. 2), giving a further confirmation about the validity of the simulated results.

Similarly to other coupled GCMs, our model (i) simulates a northeastward shift of the NAO centres of action and (ii) projects a very weak but significant positive trend of the NAO in a global warming scenario when considering the full modelled period, suggesting that the anthropogenic forcing has a non-null contribution in the NAO evolution. By analysing the NAO trends in the past period (A), we find that the model reproduces the upward trend observed before the 1990s and the following change downwards in a reasonable way, differently from the models considered by Stephenson et al. (2006). In our model the NAO trends continue to interchange in the future. The investigation about the causes of the positive trend, variability and shift of the NAO is beyond the purpose of this study and already discussed in the literature.

The major aim of this paper is the study of the NAO influence on the tracer transport in a future scenario with respect to the past by means of a coupled atmosphere-chemistry-ocean GCM. To the best of our knowledge this is the first study of the changes in pollutant transport over the 21st century due to the NAO influence. The model-projected positive NAO trend prevalence at the end of the century, would have as consequence that the areas with depleted tracers (i) are wider, spreading northwards over Europe and south Greenland, and (ii) benefit from lower pollutant concentrations, especially over north Europe and south Scandinavian, with respect to the past. Moreover, areas with current high pollutant concentrations will see a marginal increase in size, and the magnitude of concentrations will further increase over north Africa and the Iberian Peninsula. Only the region near the American east coast remains largely unchanged. Overall, under a global climate change scenario we find that local air quality conditions may become more extreme as time goes by, under the influence of the NAO.

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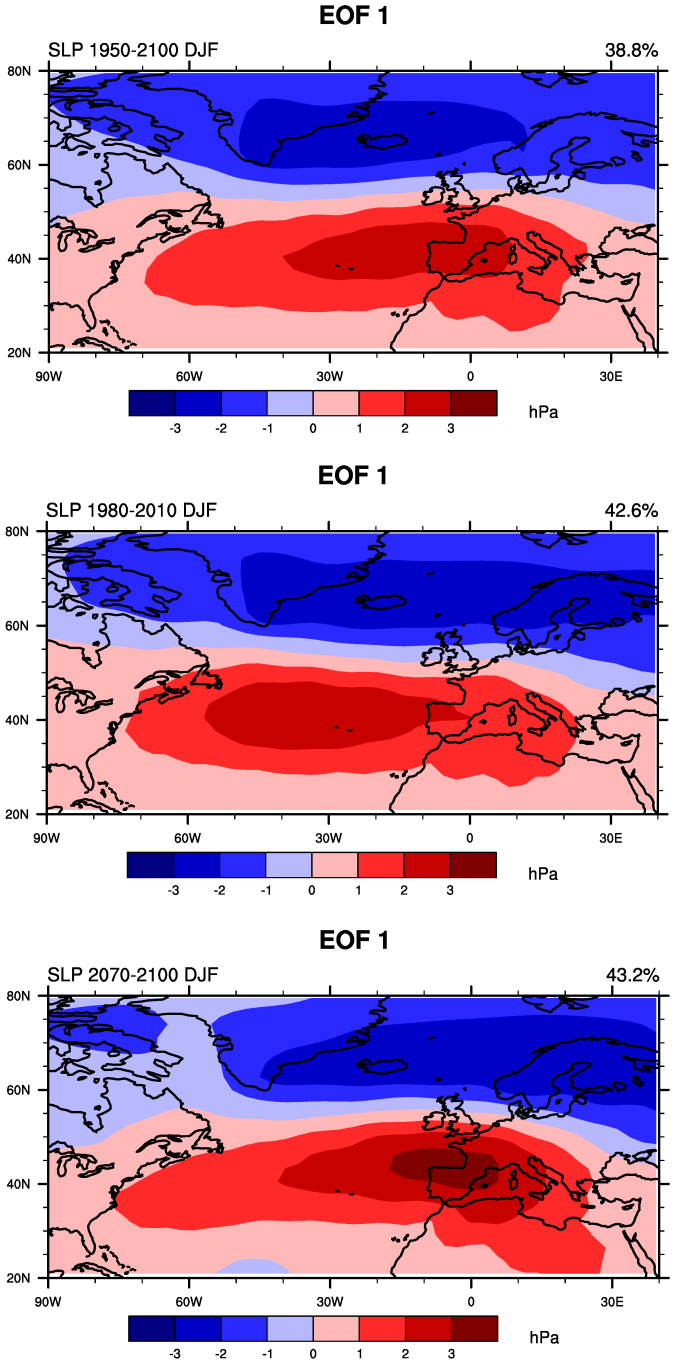

Figure 1. Leading empirical orthogonal function (EOF1) of the winter (DJF) mean sea level pressure (SLP) anomalies in the North Atlantic sector (20°N-80°N, 90°W-40°E) of the coupled simulation considering the full period 1950-2100 (*top*), period (A): 1980-2010 (*centre*), and period (B): 2070-2100 (*bottom*). The percentage at the top right of each figure quantifies the total variance explained. The patterns are displayed in terms of amplitude (hPa), obtained by regressing the SLP anomalies on the principal component time series.

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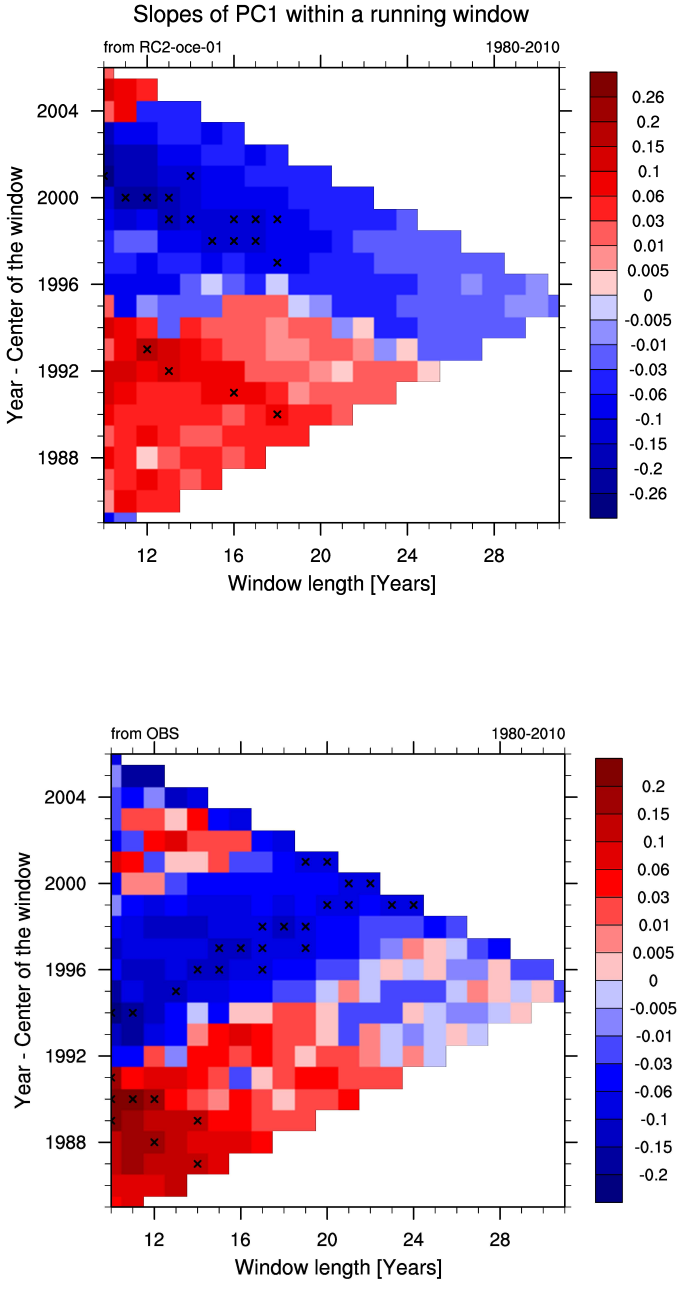

Figure 2. Linear regression coefficients of the PC1 based on coupled simulation data (*top*) and the NAO-PC-based index by NCAR (*bottom*), computed in sliding windows with variable length for the period (A) 1980-2010. Plotted in the x-axis are the window lengths expressed in years, and in the y-axis the central year of the windows. The regression coefficient values are expressed in $\mathrm{hPa}/\mathrm{year}$ (see color legend). Points marked with black crosses indicate 95% level of significance.

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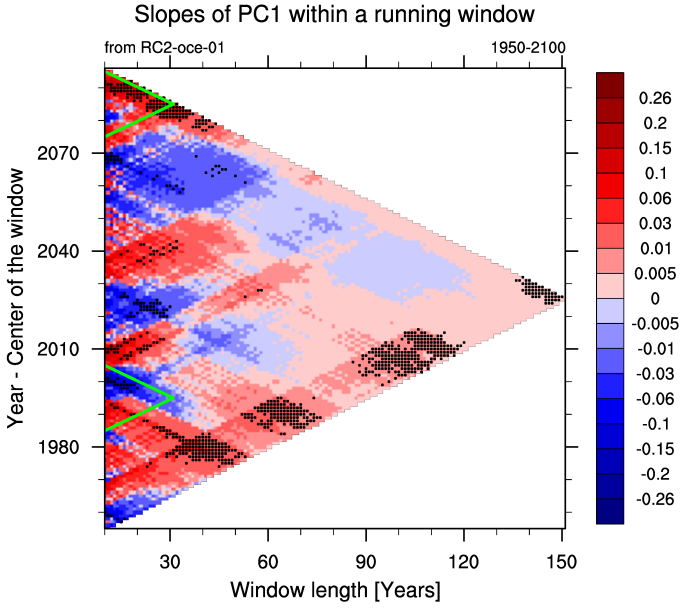

Figure 3. Linear regression coefficients of the PC1 based on coupled simulation data computed in sliding windows with variable length for the whole period 1950-2100. Plotted in the x-axis are the window lengths expressed in years, and in the y-axis the central year of the windows. The regression coefficient values are expressed in $\mathrm{hPa/year}$ (see color legend). Points marked with black crosses indicate the 95% level of significance. The green triangles indicate the areas of the two periods (A) and (B).

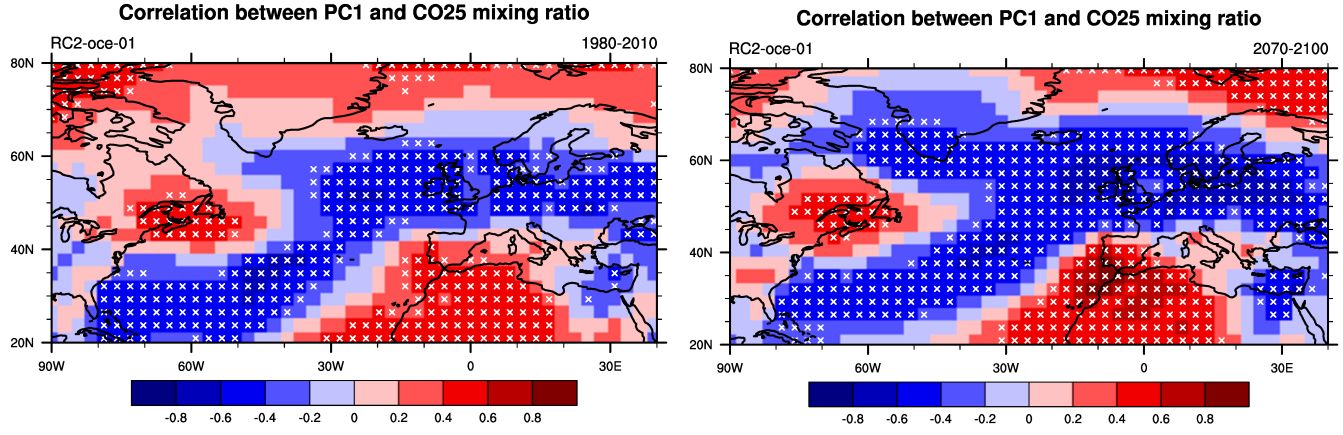

Figure 4. Correlation between the winter seasonal CO_{25} mixing ratio anomalies at the surface level and the PC1 of SLP computed with the coupled simulation data for the past and future periods, (A) (*left*) and (B) (*right*) respectively. Points marked with a white cross indicate local significance at the 95%.