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LETTER

Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes

Reindert J Haarsma[1], **Frank M Selten**[1] **and Sybren S Drijfhout**[1,2]

[1] Royal Netherlands Meteorological Institute (KNMI), PO Box 201, 3730 AE De Bilt, The Netherlands
[2] University of Southampton, National Oceanography Centre, European Way, Waterfront Campus, Southampton, UK

E-mail: haarsma@knmi.nl

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Abstract

We use state-of-the-art global climate models and observations to show that the projected higher pressures over the British Isles due to global warming are part of an atmospheric response to the decelerating Atlantic meridional overturning circulation (AMOC) causing a reduction in the associated northward heat transport, keeping the North Atlantic relatively cool. However, considerable inter-model differences in the projected weakening of the AMOC lead to a large spread in the projected wind changes. Hence, the uncertainty in the projected reduction of oceanic heat transport is a main source of uncertainty in projections of Western European climate change. Better-constrained projections of European summer climate thus rely heavily on a more realistic representation of ocean processes in climate models.

1. Introduction

Global mean temperatures have risen by 0.7 °C since 1950 with a broad scientific consensus that this warming is due to the human-induced rise in greenhouse gas concentrations. The observed warming, however, has been far from uniform, with a pronounced amplification in the Arctic regions; also, temperatures over land warm more rapidly than over the ocean, and the subpolar North Atlantic exhibits a consistent warming minimum (Drijfhout *et al* 2012).

This warming minimum is correlated with a weakening of Atlantic Ocean currents (Drijfhout *et al* 2012, Woollings *et al* 2012). Warm and salty surface waters of the Atlantic Ocean flow northward to subpolar regions via the Gulf Stream. Heat loss to the atmosphere creates cold, salty surface waters that eventually become dense enough to sink. After sinking, the water returns south as deeper, colder water. This Atlantic meridional overturning circulation (AMOC) carries substantial amounts of heat northward, which is gradually released to the overlying atmosphere (Lozier 2012). The climate of Western Europe, characterized by westerly winds and frequent rain-bearing low-pressure systems, depends on the pattern of this heat release (Srokosz *et al* 2012). As a result, changes in the AMOC affect the seasonal climate across Western Europe.

Climate change scenarios for countries in Western Europe usually account for these regional differences, but uncertainties remain large due to the considerable spread in regional temperature, wind and precipitation responses to altered greenhouse gas and aerosol concentrations in the previous and last Coupled Model Intercomparison Project (CMIP) ensembles used in preparation for the Intergovernmental Panel for Climate Change (IPCC) reports.

Drivers of Western European climate change are (1) changes in global mean temperature, and (2) changes in winds (Haarsma and Selten 2012, de Vries *et al* 2012, Woollings *et al* 2012, Haarsma *et al* 2013, van den Hurk *et al* 2013, Zappa *et al* 2013). Many studies have been devoted to understand the spread in global-mean temperature change as measured by climate sensitivity, and model-dependent cloud changes have been identified as the main cause (Dufresne and Bony 2008). In summer the dominant wind changes over Western Europe are governed by higher pressures over the British Isles, which enhance easterly winds and amplify continental warming and drying (Haarsma *et al* 2009). The magnitude of these changes is very uncertain as different models give very different

Table 1. CMIP5 models that have been analyzed. More information is available online at http://cmip-pcmdi.llnl.gov/cmip5.

Model name	Originating	Country
ACCESS1-0	CAWCR	Australia
ACCESS1-3	CAWCR	Australia
CanESM2	CCCMA	Canada
CCSM4	NCAR	USA
CESM1-BGC``	NCAR	USA
CESM1-CAM5	NCAR	USA
CNRM-CM5	CNRM-CERFACS	France
GFDL-CM3	GFDL	USA
GFDL-ESM2M	GFDL	USA
inmcm4	INM	Russia
MPI-ESM-LR	MPI	Germany
MPI-ESM-Mr	MPI	Germany
MRI-CGCM3	MRI	Japan
NorESM1-ME	NCC	Norway
NorESM1-M	NCC	Norway

answers and many processes potentially contribute to these projected changes. Using CMIP5 (Taylor *et al* 2012) models, observations and idealized experiments with a coupled global climate model we focus on investigating the dominant mechanisms behind this uncertainty and the connection with the warming minimum and the changes in the AMOC. The causes of the AMOC changes fall outside the scope of this study and are not investigated.

2. Data and experiments

2.1. CMIP5 models

The set of 15 coupled CMIP5 models used in this study is given in table 1. The forcing is the RCP4.5 scenario. For each model only the data of the first ensemble member is used. The size of this multi-model ensemble was determined by the availability of meridional overturning stream functions uploaded to the CMIP5 database.

2.2. Idealized experiments

For the idealized experiments the coupled climate model EC-Earth (Hazeleger *et al* 2010), version 2.3, is used. The atmospheric component is derived from the Integrated Forecast System (IFS) of the European Centre of Medium range Weather Forecast (ECMWF). The resolution is T159L62. Because of its close connection to the numerical weather prediction model of the ECMWF the main strength is the simulation of the circulation patterns, such as storm tracks and blockings, especially over the North Atlantic and western Europe (Hazeleger *et al* 2010). The ocean component is NEMO and has a resolution of 1 degree. EC-Earth has a cold bias over the North Atlantic that varies between 0.5 °C and 3 °C locally (Sterl *et al* 2012).

Two idealized experiments were designed to investigate causal links between wind changes over Western Europe and atmospheric cooling over the midlatitude North Atlantic associated with a weakened AMOC. The first is a surface cooling experiment in which an artificial surface cooling was applied. The second is a 'hosing' experiment in which an extra freshwater flux was applied to induce a weakened AMOC and reduced northward heat transport in the Atlantic, likewise as observed in the CMIP5 climate change projections. The experimental set-up of these idealized experiments is described below.

2.2.1. Idealized surface cooling experiment

The simulations were performed for pre-industrial concentrations of greenhouse gases. Over the subpolar region (50°–65° N, 25°–40° W) the ocean surface was cooled by extracting 50 W m^2 from the atmosphere-to-ocean turbulent surface heat flux which resulted in a summer sea-surface temperature cooling of about 2 °C. The length of the simulations was eight months starting at 1 January 1850. The ensemble size equals 200. All ensemble members are identical except for random perturbations added to the time derivatives of the prognostic variables in the atmospheric model during the first ten days of the simulations. The control simulation consists of a similar ensemble of 8-month runs but without the idealized cooling.

2.2.2. Hosing experiment

With EC-Earth V2.3 we performed two 50-year simulations both starting in the year 1850. One control simulation used 'standard' historical forcing while in the other an extra fresh water flux of 0.25 Sv was applied to the ocean surface over the region 50°–70° N, 70°–20° W.

3. Results

3.1. CMIP5 analyses

The dominant atmospheric summer circulation change for Western Europe as simulated by the CMIP5 ensemble of models is due to anomalous high pressures over the British Isles (figure 1(a)). It is associated with reduced precipitation, enhanced solar radiation and increased easterly winds, reinforced by the Mediterranean heat-low that also develops in response to global warming (Haarsma *et al* 2009). The high-pressure anomaly is located downstream (east) of an area of reduced North Atlantic warming (figure 1(b)). Associated with this so-called warming hole is a reduction of the turbulent heat released by the ocean to the atmosphere (figure 1(c)).

To test the hypothesis that the Western European atmospheric circulation response in the CMIP5 ensemble is connected to this warming hole, we performed a regression analysis of sea-level pressure onto surface air temperature (SAT) (figure 2(a)). We find that models with a stronger warming hole indeed simulate a stronger pressure response, suggesting that

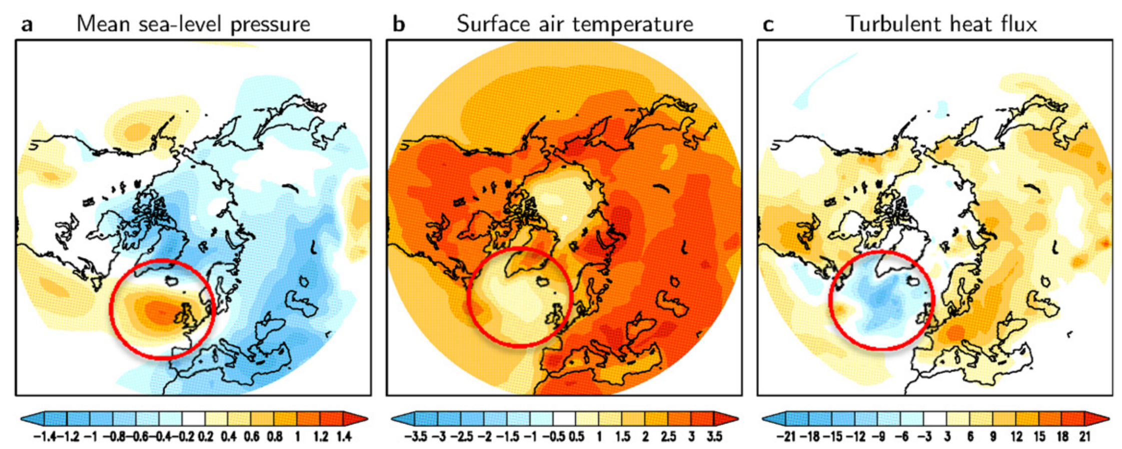

Figure 1. Summer (June–August) mean climate change in RCP4.5 simulations. (a) CMIP5 model mean summer (June–August) change (2071–2100)–(1971–2000) for RCP4.5 in mean sea level pressure (MSLP) (shaded, (hPa)). (b) As (a) but for surface air temperature (SAT) (K). (c) As (a) but for turbulent heat flux (W m^{-2}) (positive upward). The Atlantic high, the warming hole and reduced turbulent heat flux have been highlighted by a red circle in (a), (b) and (c), respectively.

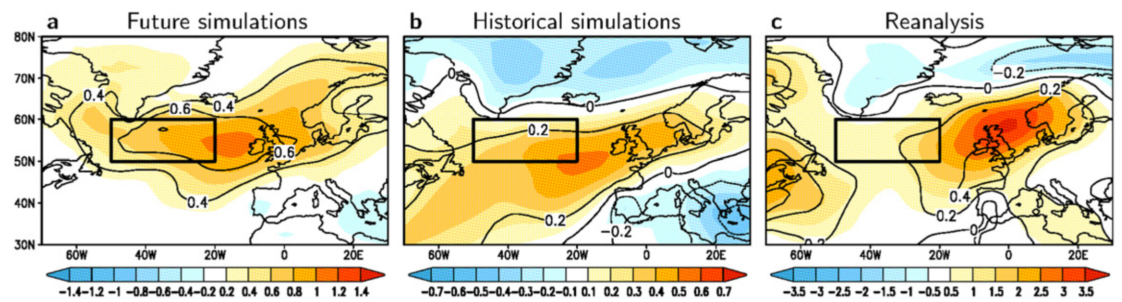

Figure 2. Relation between mean sea level pressure (MSLP) and surface air temperature (SAT) over the sub-polar gyre. (a) Regression (shaded, (hPa K^{-1})) of summer (June–August) MSLP change onto area averaged (20°–50° W, 50°–60° N, black box) SAT change for the (2071–2100)–(1971–2000) CMIP5 RCP4.5 inter-model variations with respect to the ensemble mean climate change and the associated correlation (contours). The anomalous area averaged SAT is computed with respect to the mean Northern Hemisphere (30°–90° N) SAT and is multiplied by a minus sign (cool SAT covaries with high pressure downstream). (b) As (a), but for the low-frequency (9-yr running mean) variability of detrended historical (1850–2000) CMIP5 simulations. (c) As (b), but for the NCEP 20th century (1850–2000) reanalysis.

the inter-model spread in pressure response is caused by differences in heating from the ocean. The location of the anomalous high pressure region downstream of the reduced warming area is consistent with the atmospheric response to a thermal forcing by the ocean (Sutton and Mathieu 2002), where anomalous surface cooling (e.g., due to the warming hole) is balanced by horizontal advection of warmer air (Held 1983). This connection, although weaker, is also found in the low frequency (9-yr running mean) variability of the historical runs performed in CMIP5, for the period of 1850–2000 (figure 2(b)) and in analyses of historical climate fluctuations (NCEP 20th century reanalysis, Compo *et al* 2011) (figure 2(c)). Regression and correlation analyses using surface turbulent fluxes instead of SATs yield similar patterns (figure 3). Because cold SAT anomalies coincide with surface flux anomalies that imply that the ocean is cooling the atmosphere, we conclude that on these low-frequency time scales the ocean forces the atmosphere and not vice versa.

The correlations and regressions in the historical observations are higher than for the historical simulations of the climate models. A possible explanation for this is that current climate models underestimate the impact of the ocean on the atmospheric circulation as has been suggested in earlier studies (Czaja and Blunt 2011, Eade *et al* 2014, Scaife *et al* 2014). So far the regression analysis suggests that cooling of the North Atlantic Ocean induces an anomalous high-pressure system over the eastern North Atlantic.

Future climate-warming scenarios consistently exhibit a weakening AMOC (Cheng *et al* 2013). Polar amplification of global warming reduces the cooling of the salty northward flowing waters by the overlying atmosphere. Moreover, surface waters in the northern North Atlantic become more fresh due to increased precipitation related to an intensified hydrological cycle (Bintanja and Selten 2014) and enhanced Greenland mass loss (Rahmstorf *et al* 2015). Both effects conspire to make the surface waters less dense, which

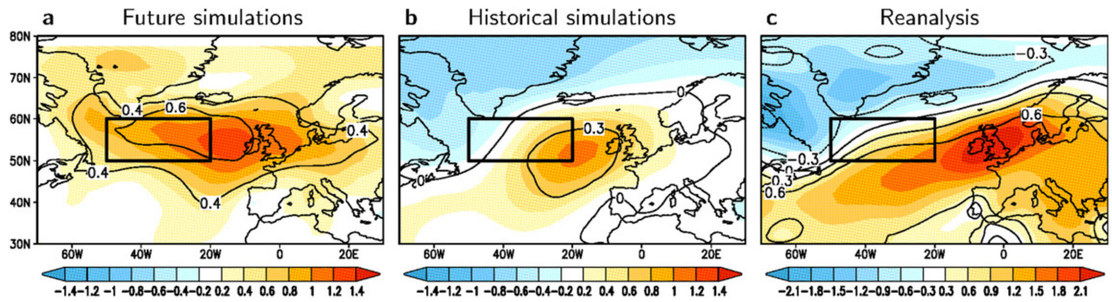

Figure 3. Regression and correlation of MSLP on surface heat flux over the sub-polar gyre. As (a), (b), and (c) in figure 2 but now regressed onto the anomalous turbulent (sensible plus latent) surface heat flux (W m^{-2}) instead of SAT. Downward flux is positive (atmospheric cooling over the sub-polar gyre covaries with positive pressure anomalies downstream).

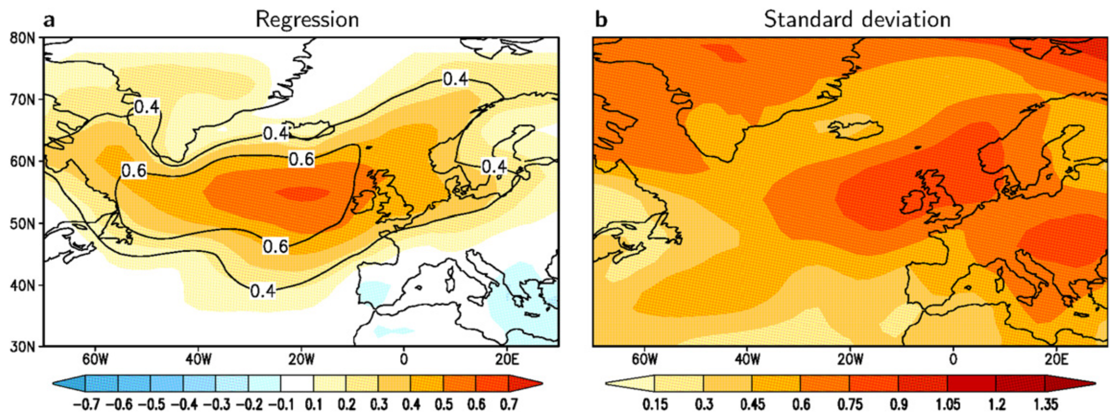

Figure 4. Inter-model relation between projected MSLP change and projected AMOC strength. (a) Regression (shaded (hPa)) and correlation (contours) of MSLP change onto AMOC change for the (2071–2100)–(1971–2000) CMIP5 RCP4.5 inter-model variations. The regression coefficient has been multiplied with minus one times the standard deviation of the inter-model AMOC spread (1.7 Sv) to compare figure 4(a) with figure 4(b). The MSLP is computed for June–August, the AMOC is annual mean. (b) Standard deviation of the inter-model variations in MSLP change (hPa) for the (2071–2100)–(1971–2000) period.

results in reduced sinking of deep water. The weakening of the AMOC tempers the temperature rise over the North Atlantic due to global warming. As a result, the spatial pattern of global warming contains a minimum over the northern North Atlantic, a warming hole, due to decreased northward heat transport by the AMOC.

An index of the AMOC was created by averaging the amplitude of the meridional overturning stream function in the CMIP5 models between 500 and 2000 m depth and between the southern boundary of the Atlantic, around 34° S, and 50° N. This index reflects large-scale changes in the AMOC associated with a long-term, anthropogenically forced trend, which indeed has a basin-scale expression (Drijfhout *et al* 2012).

A regression analysis of projected mean sea level pressure (MSLP) change on projected AMOC index change by the various CMIP5 models (figure 4(a)) reveals a similar pattern as the ensemble mean MSLP change (figure 1(a)), with a high pressure system west of the UK. The ensemble mean decline of the AMOC is 4.0 Sv, which according to this regression would cause a maximum MSLP increase of about 1.4 hPa, which is similar to the ensemble mean MSLP response (figure 1(a)). The maximum in the regression pattern (figure 4(a)) also largely coincides with the local maximum of the inter-model standard deviation of the CMIP5 MSLP responses (figure 4(b)). The uncertainty in the response of the atmospheric circulation over Western Europe is therefore to a large extent determined by the inter-model differences in the response of the AMOC to global warming. More important, however, the regression analysis and ensemble mean response combined strongly suggest that the ocean-induced pressure response is a dominant contributor to atmospheric circulation changes over Western Europe in response to global warming. A similar regression analysis further reveals that the response of enhanced AMOC decline and reduced ocean-to-atmosphere heat release in the North Atlantic sub-polar gyre consists of reduced rainfall and cloud cover and enhanced incoming solar radiation (figure 5).

3.2. Idealized EC-Earth experiments

To further support the hypothesis that projected changes in atmospheric summer circulation over Western Europe can indeed be attributed to the

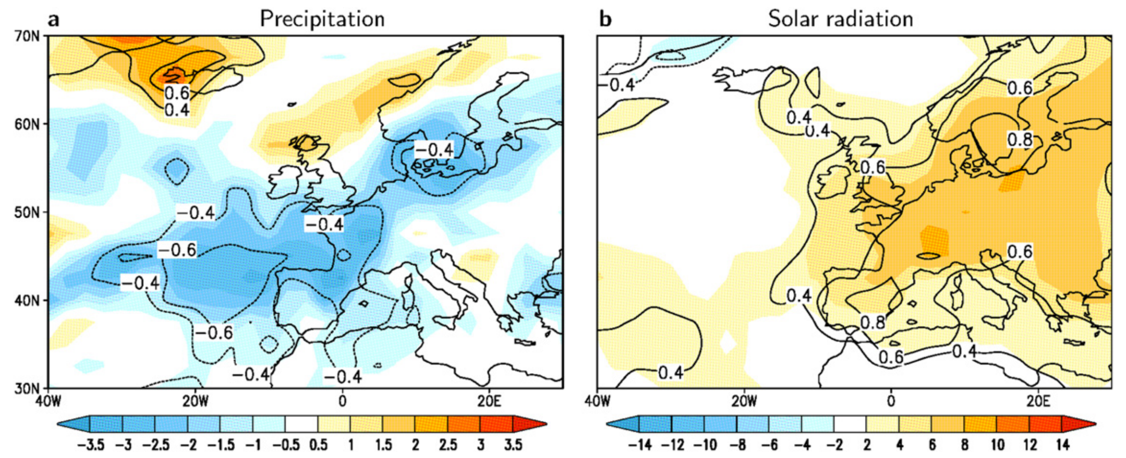

Figure 5. Relation of European climate variables to AMOC variations. (a) Regression (shaded (mm month^{-1})) and correlation (contours) of rainfall change onto AMOC change for the (2071–2100)–(1971–2000) inter-model (CMIP5, RCP4.5) variations. As in figure 4 the regression coefficient is multiplied with minus one times the standard deviation of the inter-model AMOC spread of 1.7 Sv to give the typical magnitudes of precipitation variations related to AMOC variations. (b) As in (a), but for solar radiation (W m^{-2}).

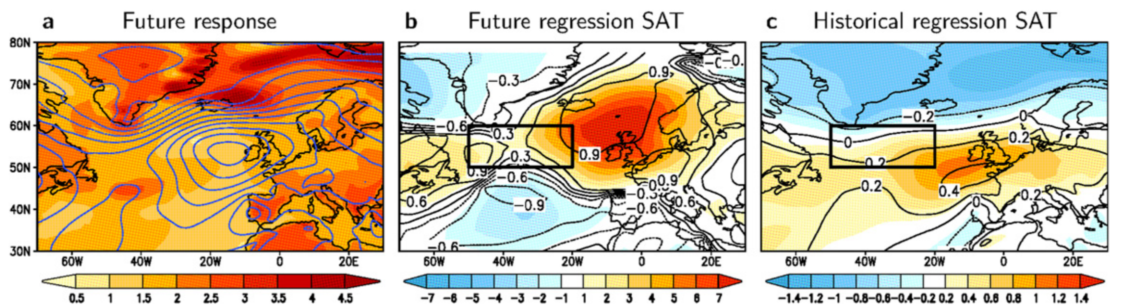

Figure 6. Projected climate change and historical variability in EC-Earth. The CMIP5 analysis was repeated for an eight member ensemble of EC-Earth to verify whether the dynamics in EC-Earth are consistent with the CMIP5 ensemble. (a) EC-Earth ensemble mean projected change (2071–2100)–(1971–2000) in SAT (shaded (K)) and MSLP (contours (hPa)) for RCP4.5. (b) Regression (shaded, (hPa K^{-1})) and correlation (contours) of projected MSLP change onto area (20°–50° W, 50°–60° N) averaged SAT change for the (2071–2100)–(1971–2000) EC-Earth- RCP4.5 inter-ensemble member variations. The anomalous area-averaged SAT is computed with respect to the mean Northern Hemisphere (30°–90° N) SAT and multiplied by minus one. (c) As (b), but for the low-frequency (9-yr running mean) variability of detrended historical EC-Earth simulations.

weakening of the AMOC we performed two idealized experiments with the global climate model EC-Earth (Hazeleger *et al* 2010). EC-Earth reproduces the CMIP5 ensemble mean pressure response (compare figure 6(a) and figure 1(a)) and the covariation of sub-polar gyre temperature variations and pressure variations over the British isles in CMIP5 and the NCEP 20th century reanalysis (compare figures 6(b), (c) and figures 2(a) and (b)).

The first experiment consists of an ensemble of EC-Earth simulations in which an additional idealized surface cooling over the subpolar region was applied. The prescribed cooling is similar to the heat flux anomaly associated with the warming hole in the CMIP5 climate change scenarios (see section 2.2.1 for a detailed description). Figures 7(a)–(c) shows the ensemble mean differences (June–August) between the idealized surface cooling experiment and the control experiment. The regional cooling and accompanying reduction in surface heat flux results in an anticyclone that is somewhat more displaced to the west, but in all other aspects very similar to the ensemble mean MSLP response pattern of the CMIP5 models and the MSLP regression pattern on sub-polar gyre temperature variations in the NCEP 20th century reanalysis. Because of the short duration (eight months) of the cooling experiment the impact is mainly on the mixed layer of the ocean and the change in the AMOC is minor.

The second experiment is a ‘hosing’ experiment (see section 2.2.2 for the description) in which a fresh-water flux is added to the North Atlantic. This results in 50 year in a weakening of the AMOC by 7 Sv from 16 Sv to 9 Sv and is accompanied by a cooling of 2 °C over the North Atlantic subpolar gyre and a reduction in the surface heat flux of about 30 W m^{-2} (figures 7(d)–(e)). This strong reduction in AMOC and cooling of Atlantic SST is in agreement with similar ‘hosing’ experiments (e.g. Vellinga and Wood 2002). Also in this experiment a high-pressure

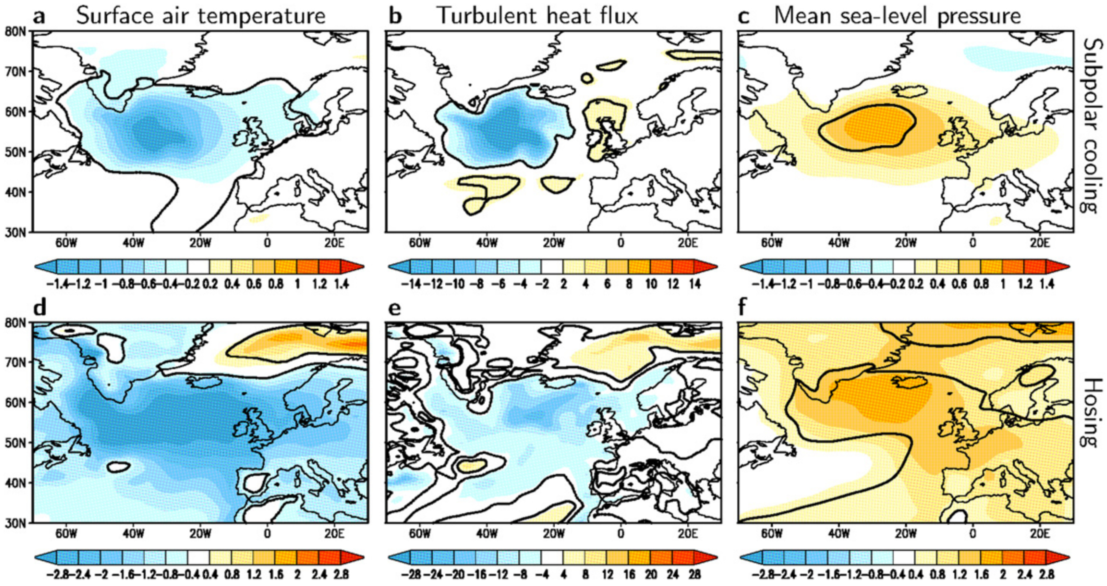

Figure 7. Summer (June–August) responses in the idealized experiments with EC-Earth. Upper panels (a)–(c): subpolar cooling experiment (2.2a). Lower panels (d)–(f): hosing experiment (2.2.b). (a) And (d) SAT (K) response. (b) And (e) turbulent heat flux (W m^{-2}). (c) And (f) MSLP (hPa). The 95% significance is indicated by a black solid contour. The analysis of the hosing experiment was done over the last 10 year of the integration, which is sufficient for statistical significance.

anomaly over the eastern North Atlantic develops (figure 7(f)). Such a link between anomalous heat fluxes in the subpolar gyre and sea-level pressure is consistent with studies that show that in this region ocean anomalies drive the surface turbulent heat fluxes, forcing atmospheric variations on time scales longer than ten years (Gulev *et al* 2013) and sometimes even on shorter timescales (Gastineau *et al* 2013).

Both idealized experiments support the statistically based conclusion of an ocean-induced atmospheric response, consistent with a previously conjectured link between the AMOC and sea-level pressure west of the UK (Sutton and Dong 2012).

4. Discussion and conclusions

Over the North Atlantic, the change in the pressure distribution, with a high over the UK and a low north west of it, bears a strong resemblance to the summer North Atlantic Oscillation (SNAO) (Folland *et al* 2009). The SNAO, however, is not well simulated in CMIP5 models, with implications especially for the Mediterranean drying (Bladé *et al* 2012). Therefore, deficiencies of the climate models in their simulation of the atmospheric circulation and its variability, and the atmospheric response to changes in ocean circulation constitutes an additional source of uncertainty in projected summer circulation changes over Western Europe in addition to the uncertainty in the projected strength of the AMOC. Understanding the atmospheric summer response over Western Europe due to global climate change is therefore intimately connected to the understanding of the response in the ocean circulation, and its impact on the atmospheric circulation.

In CMIP5 models the Atlantic meridional oscillation (AMO) in historical runs is generally underestimated, although there is a large range (Sheffield *et al* 2013, Zhang and Wang 2013). For instance ACCESS1-0 and MPI-ESM-LR correctly simulate the amplitude whereas EC-Earth and inmcm4 underestimate the amplitude by about 50%. In addition figure 5 of Zhang and Wang reveals that there is a large variation in the spatial structure of the AMO simulated by the various models with substantial differences with respect to the observed spatial structure. In particular some models do not simulate the maximum amplitude over the sub polar gyre as in the observations.

This raises the question whether the ability of models in simulating past North Atlantic decadal variability provides information about their response to global warming. Although a full analysis of this question is outside the scope of this research we have analyzed the relation between the historical decadal variability and the future response in the subpolar gyre and it turns out to be weak (figure 8). This suggests that there are essential differences in the driving mechanism of natural AMO variability, which is largely driven by internal ocean dynamics, and the future AMOC response, which is a response of the ocean to changing atmospheric forcing.

From our simulations and subsequent analyses we infer that the decline of the AMOC is the primary cause for the anomalous high-pressure system west of the United Kingdom, which largely determines the wind response over Western Europe to global warming. Our results also suggest that the impact of the

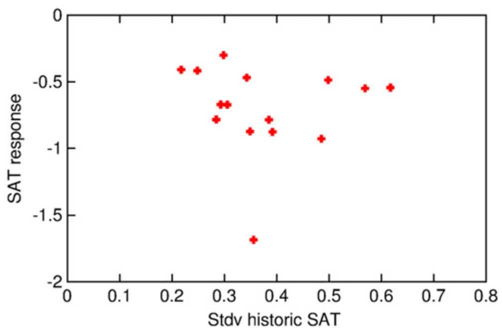

Figure 8. Scatterplot for the averaged value over the warming minimum area (20°–50° W, 50°–60° N, black box figure 2) of the standard deviation of anomalous SAT variations in the detrended historical (1850–2000) CMIP5 simulations (9-yr running mean) and the SAT (2071–2100)–(1971–2000) CMIP5 RCP4.5 change. To remove the effect of differences in climate sensitivity between the models the SAT response is defined as the warming minimum response Δ_{WH} normalized by the Northern Hemisphere (30°–90° N) response Δ_{NH}: $(\Delta_{WH}-\Delta_{NH})/\Delta_{NH}$.

AMOC on the atmospheric circulation is under estimated by CMIP5 models, which is supported by Rahmstorf *et al* (2015). We conclude that uncertainties in the projected reduction of oceanic heat transport constitutes a major source of uncertainty in regional climate projections for Western Europe. Reducing this uncertainty requires more realistic modeling of ocean processes that needs benchmarking against observational data from the RAPID array (Smeed *et al* 2014) and reanalysis products (Balmaseda *et al* 2013).

Author contributions

Reindert Haarsma did most of the analyses and wrote the paper. Frank Selten carried out the idealized cooling and hosing experiments with EC-Earth and analyzed the results. Sybren Drijfhout computed the AMOC index of the CMIP5 models. All authors contributed to the scientific ideas and writing of the article.

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