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Citation for published version:
Iles, C & Hegerl, G 2017, 'Role of the North Atlantic Oscillation in decadal temperature trends' Environmental Research Letters. DOI: 10.1088/1748-9326/aa9152

Digital Object Identifier (DOI):
10.1088/1748-9326/aa9152

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Environmental Research Letters

Role of the North Atlantic Oscillation in Decadal Temperature Trends

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Abstract

Global temperatures have undergone periods of enhanced warming and pauses over the last century, with greater variations at local scales due to internal variability of the climate system. Here we investigate the role of the North Atlantic Oscillation (NAO) in decadal temperature trends in the Northern Hemisphere for periods with large decadal NAO trends. Using a regression based technique we find a best estimate that trends in the NAO more than halved (reduced by 57%, 5-95%: 47-63%) the winter warming over the Northern Hemisphere extratropics (NH; 30N-90N) from 1920-1971 and account for 45% (±14%) of the warming there from 1963-1995, with larger impacts on regional scales. Over the period leading into the so-called warming hiatus, 1989-2013, the NAO reduced NH winter warming to around one quarter (24%; 19-31%) of what it would have been, and caused large negative regional trends, for example, in Northern Eurasia. Warming is more spatially uniform across the Northern Hemisphere after removing the NAO influence in winter, and agreement with multi-model mean simulated trends improves. The impact of the summer NAO is much weaker, but still discernible over Europe, North America and Greenland, with the downward trend in the summer NAO from 1988-2012 reducing warming by about a third in Northern Europe and a half in North America. A composite analysis using CMIP5 control runs suggests that the ocean response to prolonged NAO trends may increase the influence of decadal NAO trends compared to estimates based on interannual regressions, particularly in the Arctic. Results imply that the long-term NAO trends over the 20th century alternately

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masked or enhanced anthropogenic warming, and will continue to temporarily offset or enhance its effects in the future.

1. Introduction

Global temperatures have not warmed uniformly over the last century, instead undergoing periods of enhanced warming and pauses, with greater variability at regional scales. Such variations are expected due to internal variability of the climate system, for example through modes of atmospheric and ocean variability, including the El Nino Southern Oscillation, the Atlantic Multidecadal Oscillation, the Arctic Oscillation and atmospheric blocking (*Hasselmann* 1976; *Hawkins & Sutton* 2009, see *Medhaug et al*., 2017). Atmospheric dynamics accounted for around 40% of the observed winter warming over the Northern Hemisphere extratropical continents from 1965-2000 (*Wallace et al*. 2012), and one third of the winter warming over North America over the last 50 years, with larger or even opposite contributions for some sub-regions (*Deser et al*. 2016b) . Variability of the annular modes is the main source of spread in climate projections up to 2060 in the mid and high latitudes in a large model ensemble (*Deser et al*. 2012). Removing the effect of circulation reduces ensemble spread and improves agreement with observations (*Wallace et al*. 2012; *Deser, et al*. 2016b).

The North Atlantic Oscillation (NAO) is the leading mode of atmospheric circulation variability over the North Atlantic sector, associated with the sea level pressure gradient between Iceland and the Azores. It is related to the position of the jet stream and storm tracks, affecting temperature and precipitation patterns over Eurasia, North American and Greenland, particularly in boreal winter, with impacts on both ecosystems and human activities (*Hurrell et al.* 2003 and references therein). The NAO varies on a wide range of timescales from days to multiple decades (e.g. *Hurrell* 1995; *Hurrell et al*. 2003) and is closely related to the Northern Annular Mode (NAM) or Arctic Oscillation (AO), the leading mode of the entire Northern Hemispheric (NH) cold season circulation throughout the atmosphere (e.g. *Thompson & Wallace* 1998). The winter NAO underwent a multidecadal downward trend from around 1920 to 1970, an upward trend until the early 1990s and downward until 2013 (Figure 1a). Spatial patterns of NH temperature trends during these periods resemble the appropriate phase of the NAO (*Ostermeier & Wallace* 2003 and *Nagato & Tanaka 2012*), but also show some resemblance with the pattern expected from global warming during the latter two periods. The upward trend in the NAM to the 1990s accounted for 30% of the winter warming over the NH extratropics, 50% of the warming over Eurasia and much of the cooling over eastern-Canada to Greenland from 1968-1997 (*Thompson et al*. 2000; *Hurrell*; 1996). Over the recent period of reduced warming, a substantial portion of the winter cooling over the NH continents (*Cohen et al*. 2012; *Saffioti et al*. 2015) and Europe (*Saffioti et al*. 2016) can be accounted for by the NAO or AO, with improved agreement with CMIP5 simulated trends over Europe following dynamical adjustment (*Saffioti et al*. 2016). Over the next 50 years, it is expected that multi-decadal NAO variations will cause a large spread in projections of temperature and precipitation over Europe, at least in the CESM large ensemble (*Deser et al*. 2016a).

Here we systematically quantify the contribution of trends in the winter and summer NAO to decadal temperature trends in the Northern Hemisphere, following the method of *Thompson et al*. (2000), but extended over the entire 20th century. We further remove the NAO contribution to trends, deriving a pattern that is closer to the direct thermodynamic effect of warming. We focus on individual periods of the NAO's maximum decadal trends and compare residual regional temperature changes to CMIP5 simulations of the last century. We then investigate whether the effect of long-term NAO trends may be enhanced via ocean processes (*Deser et al*. 2016a; *Delworth et al*. 2016; *Delworth & Zeng* 2016; *Li et al*. 2013).

2. Data and Methods

2.1 Observational Data

The NAO is generally characterised either using the difference in normalised station based pressure measurements between Iceland and Portugal or the Azores, or as the first Empirical Orthogonal Function (EOF) of sea level pressure over the North Atlantic sector. We use the EOF based index since it captures the full spatial NAO pattern and the seasonal migration of its pressure centres better than the station based index and is less affected by noise induced by small-scale weather features (*Hurrell et al*. 2003). The EOF based index for 1899 onwards was downloaded from the NCAR climate data guide

(CDG) website for the extended winter season (DJFM), when the NAO is strongest, and for contrast the summer (JJA) when the NAO is weaker and shifted to the North-East, and European climate is less dominated by the large scale circulation (*Bladé et al*. 2012; *Hurrell et al*. 2003). EOFs are calculated for the region 20 to 80°N and -90 to 40°E across the whole time period. Some studies use the high summer index (JA) instead of JJA since the July and August NAO are more closely related to each other than that in June (*Folland et al*. 2009; *Bladé et al*. 2012); but we found little difference when basing our analysis on a calculated JA EOF-based index instead (not shown). We also tested sensitivity to using station-based indices, downloaded from NCAR CGD. These are based on stations from Iceland and Portugal for DJFM, and Iceland and the Azores for JJA. In winter results were very similar to those using the EOF based indices. While there were some differences in summer (Figure 1), the effect of the summer NAO (SNAO) on temperature trends remained small.

We used the HadCRUT4.4 observed surface temperature dataset, which contains monthly temperature anomalies from 1850 to present relative to 1961-1990 climatology on a 5° latitude-longitude grid (*Morice et al*. 2012). These are based on station measurements of surface air temperature (SAT) over land and ship and buoy measurements of sea surface temperatures over ocean, with gridboxes not containing data labelled as missing. To calculate seasonal data, we required all months in a given season to be present. Observed sea level pressure (SLP) data is taken from HadSLP2, which contains monthly values on a 5° latitude-longitude grid from 1850-2004. Data are spatially interpolated to give globally complete coverage (*Allan & Ansell* 2006).

2.2 Climate model data

Observational results are compared to climate model simulations from the CMIP5 (Coupled Model Intercomparison Project Phase 5) archive (*Taylor et al*. 2012). SAT from historical 'ALL' forcing runs is used for the period 1850-2005, extended to the present by appending the first few years of the appropriate Representative Concentration Pathway 4.5 (RCP 4.5) simulation, which reaches a radiative forcing of 4.5 Wm^{-2} by 2100 relative to preindustrial conditions (results should not be sensitive to scenario over this short timeframe considered; Kirtman et al. 2013)). The historical 'ALL' runs are forced with observed records of greenhouse gases, anthropogenic aerosols, volcanic aerosols, solar variability, land-use and ozone. Note that over the most recent period, the assumed forcing may not realistically capture low-level volcanic and solar forcing (e.g. *Kaufmann et* al. 2011; *Santer et al*. 2014; 2015) and hence slightly overestimate recent trends. We select all available model runs that have data for both the historical and RCP4.5 periods (38 models, 108 runs; see Table S1). Model data are regridded to the grid of HadCRUT4.4, with missing values in observations masked in simulations to replicate the same coverage.

In order to investigate longer-term impacts of NAO trends on temperature (see Methods and SI) we use SAT and SLP data from CMIP5 control runs, which use forcings fixed at preindustrial levels (Table S1). Data are regridded to a common 2.5° grid.

2.3 Methods

To calculate the influence of the NAO on SAT we regress the standardised time series of the NAO index for a given season on the temperature time series for the same season for each grid cell for the period 1900-2013, using detrended data. This yields a regression coefficient for each grid cell showing the change in temperature per unit change in the NAO (Figure 2c-d), and its significance levels assuming white noise. A requirement of at least 30 years of data per grid cell was used. The same procedure was applied to sea-level pressure, but based on the period 1900-2004, when the dataset based on consistent methods ends (Figure 2a-b).

In order to examine the impact of the NAO on decadal temperature trends, we first select periods of the strongest observed NAO trends of at least 20 years for both seasons. These are shown in Figure 1a-b and Figure S1 and are discussed below. For each year the NAO contribution to temperature is calculated for each grid cell by multiplying the NAO index value by the regression coefficients calculated above. The NAO contribution is then subtracted from the raw temperature anomalies to calculate residual anomalies for each year. Temperature trends are calculated for each grid cell for the raw temperature, residual temperature, and NAO related temperature, and are used if 80% of data are available over a given time period.

NH extratropical (30-90N) and regional temperature time series with and without NAO effects are calculated, using the regions shown in Figure 2c-d and Table S2 (see also Figure S5). The regions are selected to illustrate the maximum possible impact of the NAO on temperature trends based on the interannual regressions above. The contribution of the NAO is calculated based on a regression of the detrended regional mean temperature time series against the detrended NAO index. Calculating trends and NAO contributions on a grid cell basis first and then regional averages gives very similar results (Figure S9). Our method assumes a symmetrical temperature response between positive and negative NAO states. Whilst not strictly true (Hurrell et al. 2003; Heape et al. 2013), Figure S8, which is based on a composite of NAO trend periods of either sign in CMIP5 simulations, suggests any asymmetry is small and unlikely to substantially affect our findings.

Calculating the effect of decadal NAO trends on temperature based on interannual regressions may miss any further response caused by the ocean integrating short-term atmospheric variations, e.g. in temperature and wind forcing (Hasselmann 1976; Thompson 2015); which can enhance the NAO response (*Deser et al*. 2016a). Therefore, we also examine the effect of decadal NAO trends in CMIP5 model control runs. We compare CMIP5 results obtained by applying the method detailed above to results obtained by compositing temperature trends over multiple NAO trend periods and multiple model runs, which should capture longer-term aspects of the response (see Supplementary Methods). We examine NAO trends of varying lengths (11, 16, 21, 25, 31 and 51 years) that cover the range of periods examined in the first part of our analysis. Significance of the difference in results using the two techniques is evaluated using a two sample student t-test that does not assume equal variances.

4. Results

Figures 1a-b show the time series of the winter and summer NAO, for both the EOF and station-based indices. In winter, the two indices are very similar, but in summer there is a noticeable difference, including in the overall trend in some decades, particularly the 1960s to 1980s. This difference may arise because the stations used do not coincide well with the pressure centres of the SNAO, which is shifted to the north-west of its winter counterpart. Therefore the following analysis focuses on the EOF-based index. The periods of decadal NAO trends analysed are shown as trend lines. These are 1920-

1971, 1963-1995 and 1989-2013 for winter, during which periods the NAO index shows a trend of -1.3, +2.4 and -2.3 standard deviations respectively, and 1902-1942, 1936-1960, 1957-1984 and 1988-2012 for summer, with a change of +1.9, -1.2, +1.4 and -2.5 standard deviations over time respectively. These are individual periods of maximum NAO trends that overlap slightly. Results for non-overlapping periods are similar, although NAO trends are weaker for the most recent period (see Figure S3 for DJFM).

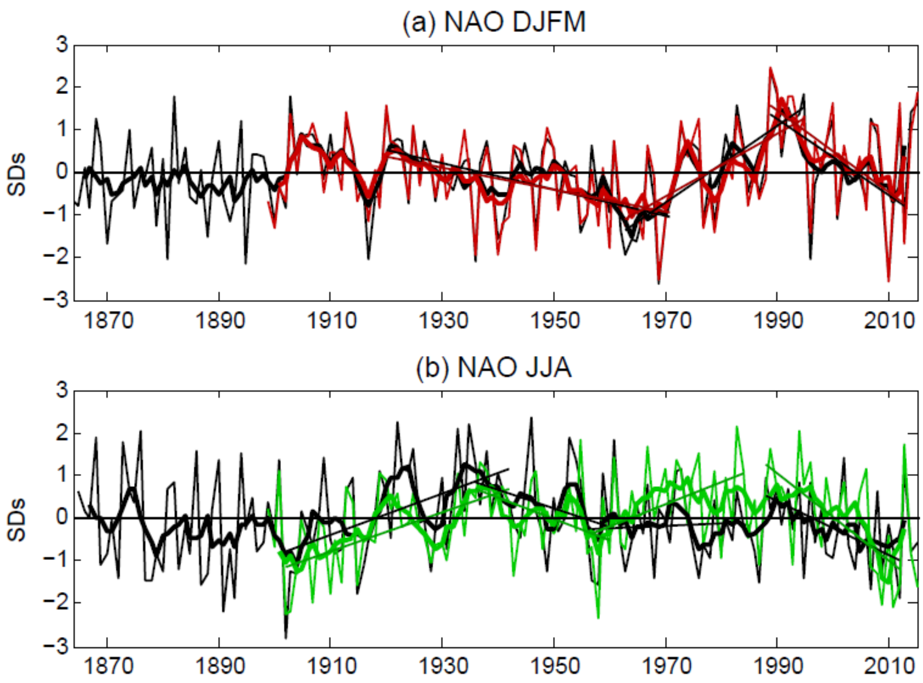

Figure 1: Time series of the NAO index for (a) the extended winter season (DJFM) and (b) summer (JJA). Coloured line represents an EOF based index, and black line the station based index. Thin lines show interannual variations, whilst thick lines are 5 year smoothed. The trend of the NAO index is shown for the periods examined in the paper.

Figure 2 shows the interannual regression of the NAO indices on sea level pressure and temperature for both seasons. The effect of the NAO on seasonal temperatures and temperature trends arises due to the cumulative effects of its synoptic time scale variations. A positive phase of the NAO in winter is associated with anomalously low pressure over Iceland and the North Pole and high pressure over the Azores. This leads to a strengthened storm track angled towards the North-East which brings warm maritime air from the Atlantic over Northern Eurasia, causing a strong warming signal there (*Hurrell et al.*, 2003; *Thompson and Wallace*, 2000). Over Eastern Canada and Greenland cold anomalies are associated with stronger than average northerly winds. A weak warming signal can also be seen over the United States and cooling over the Mediterranean and Middle East, associated with stronger clockwise flow around the subtropical Atlantic high. These patterns, including the effects over Asia, agree with those found by previous studies (see *Hurrell* 1995; *Hurrell et al*. 2003; *Thompson & Wallace* 1998; 2000; *Thompson et al*. 2000; *Deser et al.* 2016a). A negative NAO is associated with opposite pressure anomalies, leading to a more wavy jet stream and a weaker, more zonal storm track. This allows north-easterly anomalous winds to occur over Eurasia bringing cold temperatures to northern Europe. The NAO's effects can extend beyond the Atlantic region through its association with the Arctic Oscillation, and through interactions with other synoptic scale phenomena. For example, interactions with Ural Blocking, the Siberian high and the East Asian Monsoon are thought to extend its influence over Asia (*Luo et al*. 2016; *He et al*. 2017 and references therein), whilst interactions with European blocking allow its influence to reach the Middle East (*Yao et al*. 2016). The SNAO is weaker, with north-eastward shifted pressure centres. It leads to weak temperature anomalies reminiscent of the winter NAO, with significant impacts largely limited to Northern Europe, North America, and the North Atlantic (see *Folland et al. 2009*; *Bladé et al*. 2012).

For the time periods identified above we calculate the contribution of the NAO trends to decadal trends in temperature across the Northern Hemisphere (see Methods). Figure 3 shows the spatial pattern of winter temperature trends for each period, the contribution from the NAO and the residual trends once the NAO has been subtracted. From 1920-1971 there was a cooling trend over northern Eurasia and the eastern United States, with warming elsewhere. The NAO downtrend explains the Eurasian cooling, and part of the North American cooling, with a more uniform warming signal following its removal. From 1963-1995, the upward NAO trend accounts for a large part of the strong warming trend over northern Eurasia and part of the cooling trend over Eastern Canada-Greenland (see also *Thompson et al*. 2000). Finally, during the most recent period (1989-2013), most of the large cooling signal over Northern Eurasia and part of the warming signal over Eastern Canada-Greenland is accounted for by the concurrent NAO downtrend, with a more amorphous warming signal following NAO removal. In summer the contribution of NAO trends to temperature trends is much weaker, with only subtle changes in spatial patterns following NAO removal (Figure S4).

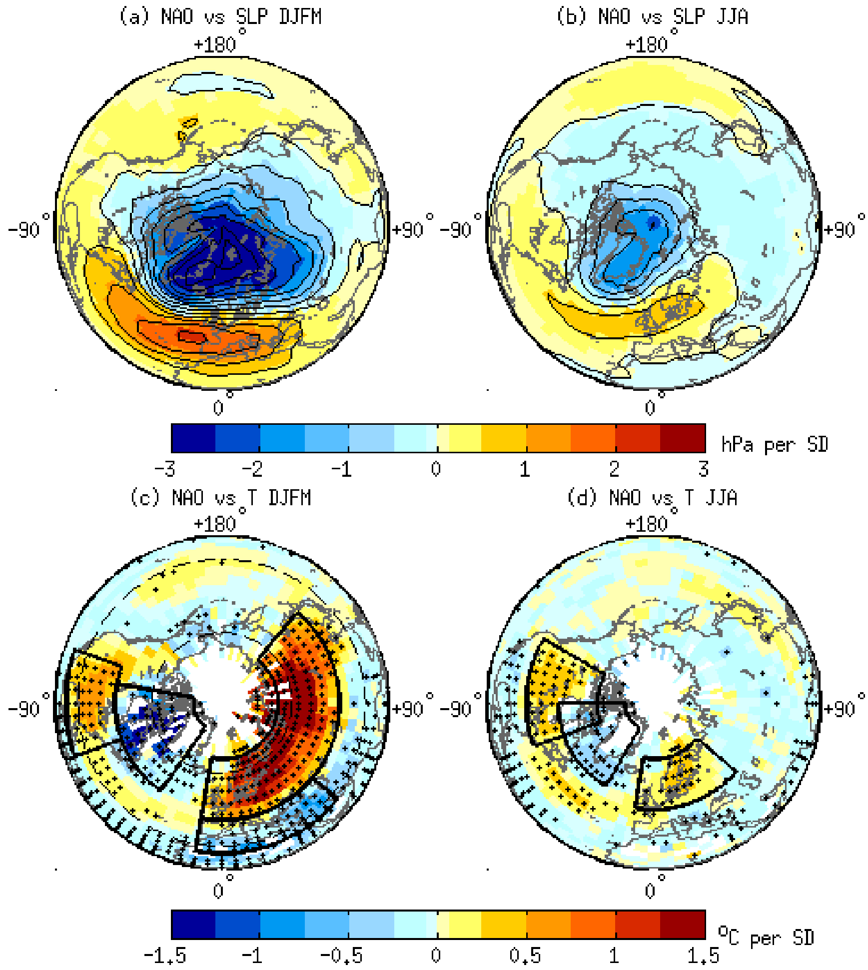

Figure 2: (a, b) The regression of the EOF based NAO index on sea level pressure and (c, d) surface air temperature for DJFM (a, c) and JJA (b, d), expressed in units per standard deviation change in the NAO index. Contour interval is 0.5hPa. Stippling indicates significance at the 0.05 level, and missing data are left blank. Boxes indicate the regions used for analysis and are detailed in Table S2.

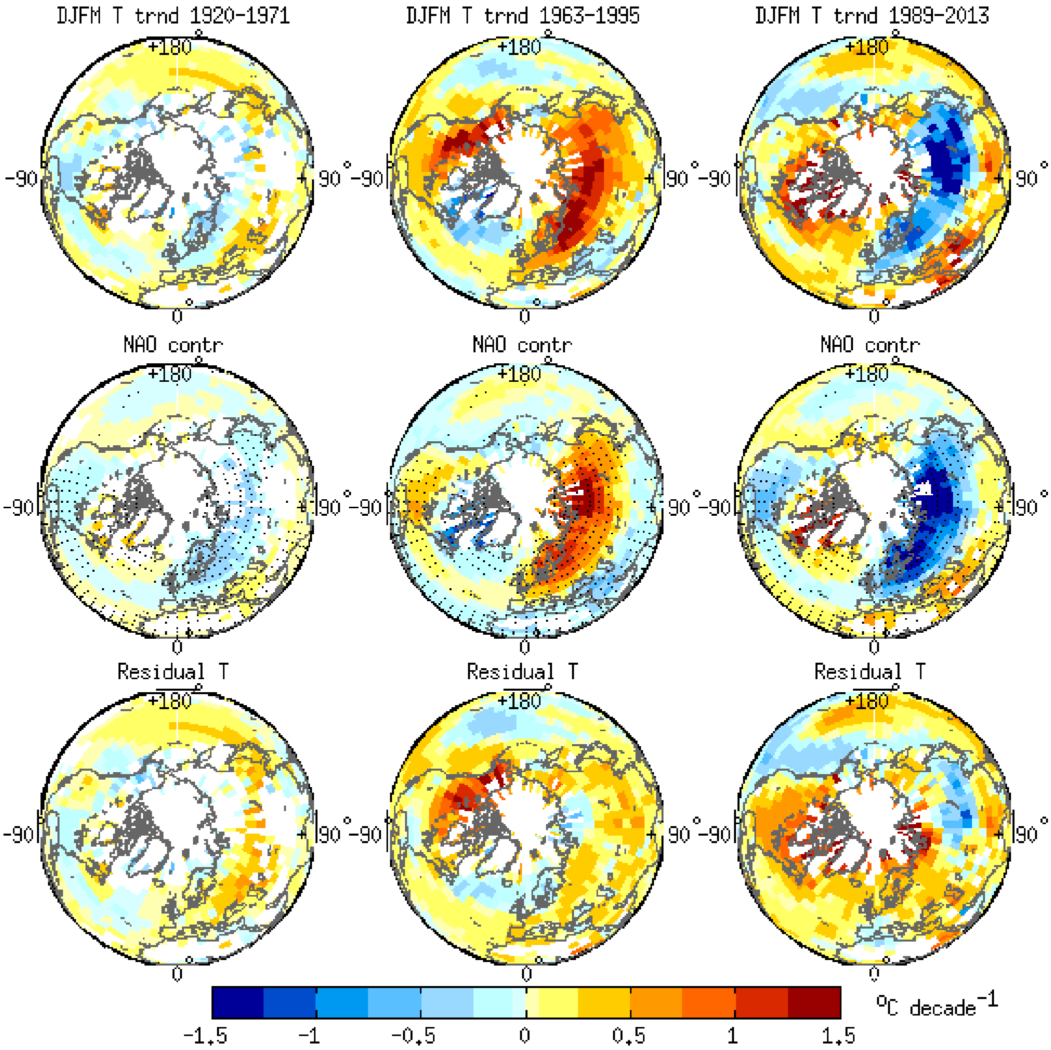

Figure 3: The contribution of the NAO to winter (DJFM) decadal temperature trends. Top row: raw temperature trends, middle row: the contribution of the NAO, bottom row: the residual temperature trend once the NAO contribution has been subtracted. Left hand column 1920-1971, middle column 1963-1995, right hand column 1989-2013. Stipples are the same those in Figure 2 and indicate grid cells with a significant *interannual* relationship between the NAO and temperature. Units are °C per decade.

The impact of NAO-induced temperature trends is strongest at regional scales. Figure 4 shows the contribution of the NAO to temperature trends for the regions shown in Figure 2c (see Methods). In winter, the NAO has a large influence on temperature trends in all of the regions examined. For most regions the downward trend of the NAO has a cooling effect from 1920-1971, contributing to a negative or small positive temperature trend overall, except for Eastern Canada-Greenland and the Mediterranean. From 1963-1995 the NAO makes a substantial contribution to the warming trend seen particularly over Northern Eurasia (contributing 82% of the warming (±15% based on 5-95%

uncertainty range of the NAO vs SAT regression coefficients) or 0.65 (±0.11)°C decade^{-1}), but also over the USA and the Arctic (65 (±23)% and 55 (±28)% respectively) (see also *Thompson et al*. 2000). Over Eastern Canada-Greenland and the Mediterranean, the NAO uptrend causes a cooling trend over this period, with a positive residual trend once the NAO influence is removed. During the most recent period (1989-2013) the negative NAO trend caused a large cooling over northern Eurasia (-0.70 °C decade^{-1}), with a weak residual warming trend of 0.12 (±0.15) °C decade^{-1} following its removal. The NAO reduced the warming trend in the USA and the Arctic over this same period, whilst in Eastern Canada-Greenland and the Mediterranean it greatly enhanced the warming trend, doubling it in the former case, and tripling it in the latter. Averaged over the NH extratropics, the NAO reduced the winter warming trend to 43% (37-53%) of what it would have been from 1920-1970, accounts for 45 (±14)% of the warming signal from 1963-1995, consistent with *Thompson et al*. (2000) and reduces it to 24% (19-31%) of what might have occurred from 1989-2013. Overall, removing the NAO influence yields residual trends that are mostly positive and tend to increase over time (see Figure 4). Comparing with the CMIP5 multi-model mean temperature trends over the same regions and time periods, removing the NAO influence from the observations improves agreement between the observed and model simulated trends in 14 out of 18 cases (6 regions over 3 time periods).

In summer, the contribution of NAO trends to temperature trends is smaller than in winter, and not noticeable if averaged over the NH extratropics (not shown). However, its effects are noticeable over North America and Europe, with opposite sign over Eastern Canada-Greenland (Figure 4g-i). For example, the downward trend in the SNAO from 1988-2012 reduced warming by 32% (13-44%) in Northern Europe and 48% (31-58%) in North America, and enhanced it in Eastern Canada-Greenland by 58% (32-97%). Removing the NAO influence improves agreement of observed temperature trends with CMIP5 multi-model mean simulated trends in 9 of 12 cases. Unlike in winter, the residual trends are not consistently positive or growing over time, suggesting that other factors are at play, including possibly aerosol forcing (*Boucher et al*. 2013)

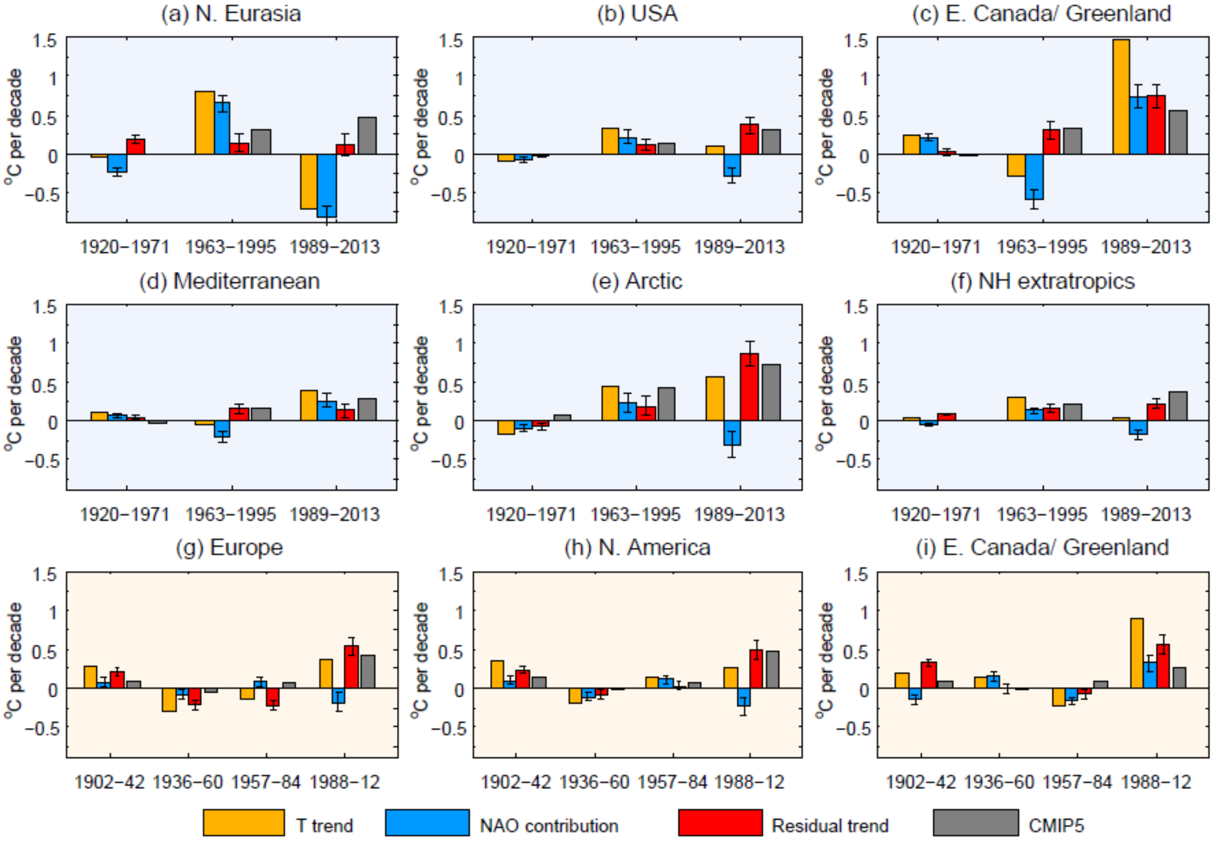

Figure 4: Temperature trend (yellow), NAO contribution (blue) and residual trend once the NAO influence has been subtracted (red) for winter (DJFM) (a-f) and summer (JJA) (g-i) averaged across the regions shown in Figure 2, for the time periods shown in Figure 1a-b. Also shown is the CMIP5 multi-model mean trend for each region (grey). 5-95% confidence intervals for the NAO and residual reflect uncertainty in the regression of the NAO on regional mean temperature.

The analysis is designed to explore the maximum influence that the NAO has had over selected periods of the last century. Therefore, the NAO contributions are smaller if examining other periods. Figure 5, left column shows the contribution of the NAO to the recent warming hiatus period (1998-2013). The hiatus was most pronounced over northern extratropical regions in winter and Figure 5 shows that the NAO accounts for part of the winter cooling trend in these regions. Since the NAO was preferentially in a low phase during this period, the trend starting in 1989 captures the NAO induced winter cooling into the hiatus period best (Figure 3). Figure S6 shows that during the hiatus itself, the remaining NAO trend accounts for 81 (±14)% of the cooling over northern Eurasia, 77 (±16)% of the warming over Canada-Greenland and 87 (± 27)% of the cooling over the NH extratropics. Residual trends are still negative across northern Eurasia and the NH extratropics, in contrast to the multi-model mean, which shows a strong warming trend. Other factors contributing to the cooling in NH boreal winter may include positive pressure anomalies over Eurasia (*Deser et al*., 2017), including an increased frequency of Ural Blocking (*Luo et al*. 2016), with global temperatures influenced by increased Pacific Ocean heat uptake, AMO variability, the recent solar minimum and low level volcanism (e.g. *Flato et al*. 2013 and references therein).

Many detection and attribution studies are based on the period 1950-2005 (Bindoff et al., 2013). While the global contribution of the NAO to winter temperature trends over this period is negligible (4.8 (±7)% of the observed warming; Fig S6), its effect is noticeable on regional scales (Figure 5, right column, S6), contributing 25 (±8)% of the warming over the NH Extratropics and 54 (±10)% of the warming over Northern Eurasia. This suggests that the best estimate of the human contribution from detection and attribution over those regions may be overestimated in winter, but as detection and attribution methods account for climate variability (Hegerl et al. 1997; 2007; Tett et al. 1999), uncertainty ranges should include the true value. In Eastern Canada-Greenland, the NAO has masked a positive trend (Figure S6). Removing the NAO influence brings observed trends closer to the multi-model mean trend (Figure S6). Extending the analysis to 2013 gives similar results although both raw temperature trends and the contribution of the NAO are weaker (not shown).

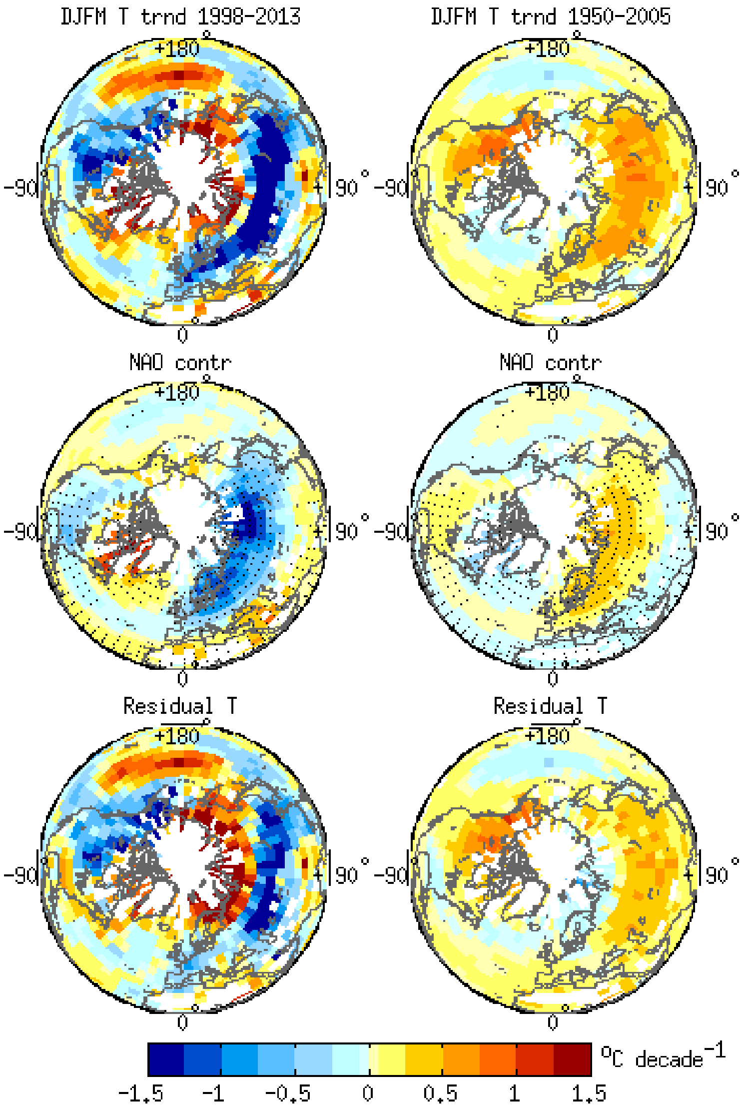

Figure 5: As for Figure 3 but for trends during the hiatus period (1998-2013), when the NAO was consistently low, and the long-term trend 1950-2005.

5. Longer term temperature responses

The analysis so far has been based on the NAO-temperature relationship derived from interannual regressions. However, this approach does not capture the effect of long-term NAO trends on the ocean. For instance, *Delworth & Zeng* (2016) found using the GFDL climate model that a positive NAO trend of longer than 10 years can strengthen the Atlantic Meridional Overturning Circulation (AMOC). Cold, strong westerlies extract heat from the subpolar gyre, increasing deep water formation and speeding up gyre circulation. The resulting increased AMOC circulation warms the extratropics with a delay of about 10 years from the initial NAO forcing, amplified by melting sea ice and snow-related albedo feedbacks, and increased heat flux from ice-free oceans. These effects increase for longer NAO trends, and are opposite for a negative NAO trend.

We use CMIP5 control runs to test whether the long-term NAO trends analysed here might be amplified by the ocean response (see also *Deser et al*. 2016a). We examine the temperature change for a one standard deviation NAO trend, comparing the interannual regression technique to results from a composite technique based on control simulations (see Methods and SI). The difference between the two techniques is shown in Figure 6 for 16, 31 and 51 year trend lengths (for other periods see Figure S7), and the absolute values are shown in Figure S8.

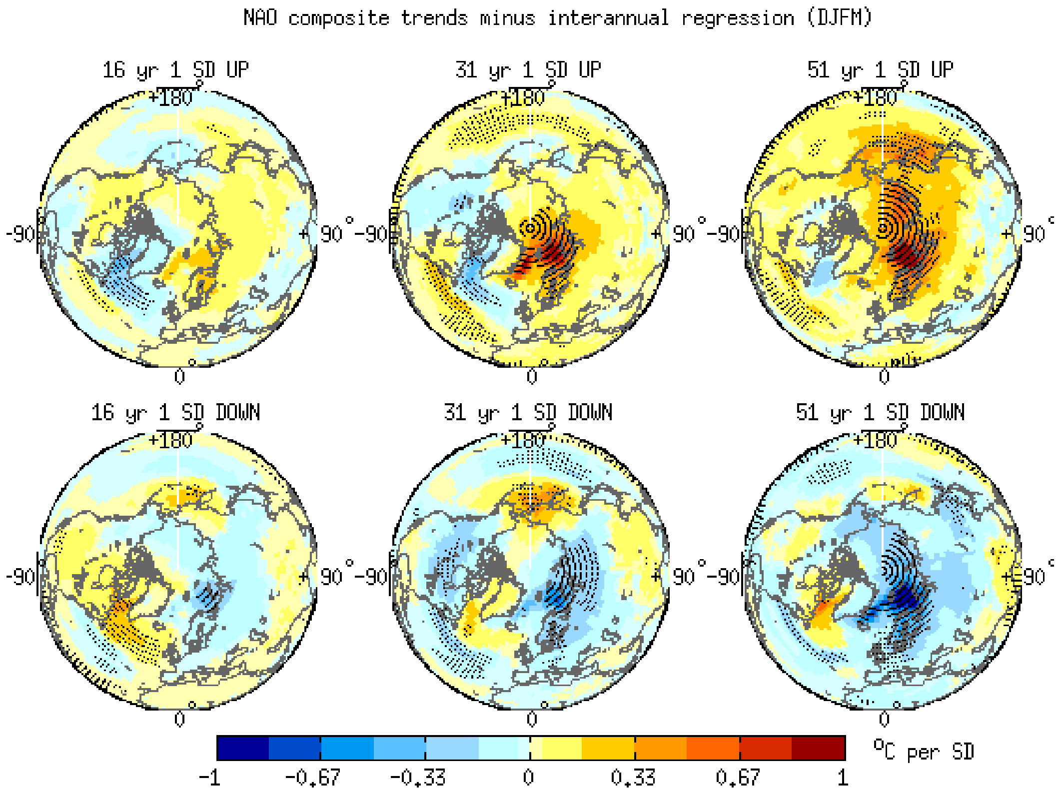

Figure 6: The difference between the NAO vs temperature relationship for a one standard deviation trend in the NAO over the periods considered based on a composite of long-term NAO trends minus the same based on interannual regressions. Both are based on CMIP5 control simulations (see Methods and SI) and are shown for trends of different lengths (16, 31 and 51 years – further periods are shown in Figure S7). Top row is for positive NAO trends, and bottom for negative ones. Stippling indicates a significant difference using a student's T test at the 0.05 level

The composite method results in a larger warming trend, particularly over North-East Russia and the Barents Sea compared to the interannual regression method for positive NAO trends (cooling for downwards NAO trends), which gets stronger, increases in area and becomes more significant as the trend length increases. For 51 year trends the signal extends over much of the Northern Hemisphere, but is strongest in the Barents Sea. A classic tripole pattern response to the NAO can be seen over the North Atlantic for most periods (e.g. *Visbeck et al*. 2003) (note also a small response in the Pacific). The Atlantic response is consistent with the findings of *Delworth & Zeng* (2016) and *Delworth et al*. (2016), and the strengthened warming over the Eurasian high latitudes with *Deser et al.* (2016a) . These results imply that the contribution of the NAO to twentieth century temperature trends is likely to be somewhat larger than that calculated through the interannual regression technique, particularly in the Barents Sea and high latitudes of Eurasia.

Using the composite technique enhances the temperature response particularly in the Arctic (by around 60-90%), but also in Northern Eurasia (14-25%), Eastern Canada-Greenland (5-17%) and the NH extratropics as a whole (by 26-46%) (Figure S9; Table S3). However, the limited observational coverage in the Arctic does not capture such an effect well (compare Figures 3, 6). When explicitly removing the NAO effect using the response of control run-based trends, this tends to overcompensate rather than improve agreement with multi-model mean CMIP5 simulated historical temperature trends in around half of cases (not shown); although results are difficult to interpret given the limited data coverage for the ocean effect.

6. Conclusions

Decadal trends in the NAO have had a large effect on NH extratropical winter temperature trends over various periods since 1900. The NAO reduced warming over the NH extratropics by 57% (47-63%) from 1920-1971, accounted for 45 (±14)% of the warming there from 1963-1995 and reduced warming to 24% (19-31%) of what it would have been from 1989-2013. The largest effects occur in Northern Eurasia, with opposite effects in Eastern Canada to Greenland. After removing trends explained by the NAO, the residual shows a more amorphous pattern of warming in all periods considered, with observed trends in better agreement with CMIP5 multi-model mean trends in most cases. In summer, the NAO influence is weaker, but made a notable contribution to temperature trends in northern North America, Europe and Eastern Canada-Greenland. The NAO also explains some of the boreal winter cooling trend over northern Eurasia and the NH extratropics over the 'hiatus' period itself, although observed residual trends still disagree with the warming simulated by CMIP5 models during this period.

Our method of removing the NAO is based on the temperature response to interannual NAO variations. A composite method analysing the effect of multidecadal NAO trends in CMIP5 control runs yields a stronger temperature response, particularly over the Barents Sea and high latitude Eurasia, and more so for longer NAO trend periods. This is in agreement with previous studies that suggest an influence of the NAO on temperature via changes in the AMOC and sea-ice and snow feedbacks. However, taking into account these longer-term effects does not consistently improve agreement with multi-model mean CMIP5 simulated temperature trends, either due to further variability, missing data in key regions, or errors in the model response to NAO trends.

In conclusion, long-term NAO trends have had a strong effect on winter temperature trends during the 20th century, particularly the most recent ones, and modest effects on some regional summer trends. These results highlight the need to better understand and predict circulation responses, such as that of the NAO, to forcing. Even due to variability alone, our findings highlight long-term uncertainty in future temperature trends.

Acknowledgements

The authors thank David Thompson and Vikki Thompson nee Frith for discussions. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science. We would also like to thank two anonymous reviewers for their helpful comments and suggestions. CI and GH are supported by the ERC funded project TITAN (EC-320691). GH was supported by NCAS and the Wolfson Foundation and the Royal Society as a Royal Society Wolfson Research Merit Award (WM130060) holder.

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