The role of the North Atlantic Oscillation for projections of winter mean precipitation in Europe

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Key Points:

- The North Atlantic Oscillation (NAO) explains half of model spread in southern European winter precipitation change by 2080-2099 for RCP8.5
- Extreme positive NAO winters may increase in frequency in future by up to 35%, due to mean NAO change, but there is large model uncertainty
- Extreme positive NAO winters have more severe future precipitation impacts, with implications for resilience to this type of extreme season

Abstract

Climate models generally project an increase in the winter North Atlantic Oscillation (NAO) index under a future high emissions scenario, alongside an increase in winter precipitation in northern Europe and a decrease in southern Europe. The extent to which future forced NAO trends are important for European winter precipitation trends and their uncertainty remains unclear. We show using the Multimodel Large Ensemble Archive that the NAO plays a small role in northern European mean winter precipitation projections for 2080-2099. Conversely, half of the model uncertainty in southern European mean winter precipitation projections is potentially reducible through improved understanding of the NAO. Extreme positive NAO winters increase in frequency in most models, coincident with mean NAO changes. These extremes also have more severe future precipitation impacts, largely because of background mean precipitation changes. This has implications for future resilience to extreme positive NAO winters, which already can have severe societal impacts.

Plain Language Summary

Variations in atmospheric circulation over the North Atlantic are dominated by the North Atlantic Oscillation (NAO) pattern. A positive NAO phase is associated with a northward shift of the North Atlantic storm track, bringing wetter weather to northern Europe and drier weather to southern Europe. In response to future human-caused increases in greenhouse gas emissions, climate models generally simulate an increase in the winter NAO, alongside an increase in winter precipitation in northern Europe and a decrease in southern Europe. However, it is unclear what role the NAO plays in future European winter precipitation trends. Here we show, using a large number of simulations from different climate models, that the NAO plays a small role in late 21st century northern European winter precipitation changes. Conversely, the NAO plays a sizable role in southern Europe. This is important because it suggests that model-to-model uncertainty in southern European winter precipitation changes could be reduced with improved understanding of the NAO. Winters with a prolonged extremely positive NAO state are generally projected to increase in frequency and have larger precipitation impacts. This has implications for future resilience to these seasonal extremes, which already can have severe societal impacts including flooding and drought.

1 Introduction

The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric circulation variability in the North Atlantic sector and exerts a strong influence on European weather and climate (Hurrell et al., 2003). A positive NAO phase is associated with a stronger eddy-driven jet stream over the North Atlantic and a northward shift of the storm track. In winter, this brings milder and wetter weather to northern Europe, and colder and drier weather to southern Europe. The NAO is associated with the first mode of interannual variability in European winter precipitation (Álvarez-García et al., 2019; Qian et al., 2000; Seager et al., 2020; Zveryaev, 2006).

There are significant societal impacts associated with NAO-induced precipitation variability. On interannual timescales, the NAO has a strong influence on precipitation and river flows in the Iberian Peninsula, with consequent impacts on water availability for hydroelectricity production and intensive agriculture (Trigo et al., 2004). Prolonged winter periods with a predominantly positive NAO state are also connected to the occurrence of catastrophic flood events in northern Europe, with significant impacts on flood economic losses (Zanardo et al., 2019).

On longer timescales, climate models on average project an increase in the winter NAO index by the late 21st century under a high emissions scenario (McKenna and Maycock, 2021), alongside an increase in winter precipitation in northern Europe and a decrease in southern Europe (Douville et al., 2021; Lee et al., 2021). While future atmospheric circulation change has been highlighted as a contributor to regional precipitation projections and their uncertainty (Deser et al., 2012, 2017; Fereday et al., 2018; Seager et al., 2010, 2014; Shepherd, 2014; Zappa et al., 2015), it is currently unclear the extent to which future forced NAO trends are important for European mean winter precipitation trends and their uncertainty. Furthermore, since extreme NAO winters are commonly associated with severe societal impacts, it is important to determine whether the projected mean positive NAO anomaly by the end of the century under high anthropogenic emissions alters the frequency of extreme positive NAO winters and their associated precipitation impacts.

This study aims to determine the role of the NAO for projections of winter mean European precipitation. Specifically, we aim to address:

1. What role do modelled forced trends in the NAO play in projections of European mean winter precipitation and their uncertainty?
2. Do models show an increase in the frequency of extreme positive NAO winters in the future?
3. Do extreme positive NAO winters have more severe precipitation impacts in the future? If so, what role does the NAO play in this (e.g., through changes in the mean NAO)?

2 Methods

2.1 Datasets

We use the Multimodel Large Ensemble Archive (MMLEA; Deser et al., 2020). The MMLEA contains large (16-100 member) initial-condition ensembles for seven Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Table S1; Hazeleger et al., 2010; Jeffrey et al., 2013; Kay et al., 2015; Kirchmeier-Young et al., 2017; Maher et al., 2019; Rodgers et al., 2015; Schlunegger et al., 2019; Sun et al., 2018). While CMIP5 models may have stronger precipitation biases than higher resolution models (Roberts et al., 2019), the MMLEA dataset has various unique benefits. Initial-condition large ensembles provide a more accurate measure of the forced climate response and larger samples of relatively rare extreme winters. Multimodel large ensembles also allow us to examine structural model uncertainty and the robustness of projections (Maher et al., 2021b).

We use historical and Representative Concentration Pathway (RCP) 8.5 simulations from the MMLEA models for the common period 1950-2099. RCP8.5 was chosen because only a small subset of the models is available for other RCPs. The analysis uses monthly mean precipitation and mean sea level pressure (MSLP) data averaged over December to February (DJF).

The models are evaluated using observation-based MSLP data from the NOAA-CIRES-DOE 20th Century Reanalysis version 3 (20CRv3; Compo et al., 2011; Slivinski et al., 2019).

This longer-term dataset was chosen to minimise the sampling errors associated with short observational records. A 1000-member "Observational Large Ensemble" (Obs LE; McKinnon & Deser, 2018) is also used for this reason, which contains synthetic historical trajectories produced by a statistical model based on observed climate statistics. Observed precipitation data is taken from the E-OBS dataset (Cornes et al., 2018). We evaluate the models against the observations over a historical period common to all datasets (1951-2014; year is for January).

All data were regridded onto a common 2° grid using bilinear interpolation for MSLP and a conservative remapping method in Climate Data Operators (Schulzweida, 2021) for precipitation.

2.2 Analysis and statistical methods

Following Stephenson et al. (2006) and Baker et al. (2018), the NAO index is defined as the difference in area-average MSLP between a southern box (90°W-60°E, 20°N-55°N) and a northern box (90°W-60°E, 55°N-90°N) in the North Atlantic. McKenna and Maycock (2021) discuss the advantages of this NAO index definition in detail.

Historical NAO-precipitation and NAO-MSLP patterns (Figure S1a) are constructed from the regression slopes obtained by regressing historical (1951-2014) timeseries of DJF precipitation and MSLP in each grid-cell onto the NAO index timeseries. All timeseries are linearly detrended. For MMLEA models, the patterns are defined separately for each ensemble member and then the ensemble mean is calculated (Simpson et al., 2020). The NAO-congruent part of a precipitation or MSLP anomaly map is obtained by multiplying the historical NAO-precipitation or NAO-MSLP pattern by the NAO index anomaly.

The long-term forced climate response is calculated as the ensemble mean difference between a future period (2080-2099) and a near-present-day period (1995-2014). Precipitation changes are calculated as a percentage of the modelled 1995-2014 climatology. This reduces the influence of model climatological biases: for example, if a model simulates too little precipitation in a region climatologically, it will be unable to simulate a large decrease in precipitation in that region. Since this study concerns the NAO's role in Europe-wide precipitation projections, we calculate the area-average precipitation change over large areas of northern (45°N-72°N, 10°W-30°E) and southern (32°N-45°N, 10°W-30°E) Europe. These regions are defined based on broad areas of wetting to the north and drying to the south in the multimodel mean MMLEA precipitation projections.

95% confidence intervals in a given quantity for a single large ensemble are calculated as follows. For an ensemble of size N, 10^4 bootstrapped ensembles are created consisting of N members each by resampling with replacement whole ensemble members from the original N-member ensemble. Whole timeseries are sampled to preserve their temporal structure. The given quantity is calculated for each of the 10^4 bootstrapped ensembles and confidence intervals are computed from the spread in the bootstrapped estimates of the quantity.

3 Results

3.1 Model evaluation

We first evaluate the NAO-precipitation relationship in the MMLEA models. Overall, there is a high spatial correlation between the modelled and observed NAO-precipitation patterns (Figure S1a). Generally, the simulated relationship is too weak in regions where the observed relationship is strongest (the Iberian Peninsula, northwest UK, and western Norway). For some individual grid-cells in these regions the observed relationship lies outside the inter-member ensemble spread indicating local biases. Averaged over northern Europe, however, the observed relationship falls within the inter-member spread so we cannot conclude there is any systematic model bias (Figure S1b). Conversely, all models except MPI-ESM-LR are unable to simulate a drying in southern Europe as large as observed for a positive NAO index anomaly.

Following Thompson et al. (2017), the model representation of NAO variability is examined by comparing the modelled and observed distributions of historical annual winter NAO index anomaly (Figure S2a). Figure S2b shows that the standard deviation of the observed winter NAO distribution falls within the inter-member spread for every model except CSIRO-Mk3.6 and EC-EARTH, which have too low variability. All MMLEA models have a skewness and kurtosis which is indistinguishable from the observations. CSIRO-Mk3.6, however, has a positive ensemble median skewness, while the observed NAO distribution has an overall negative skewness, consistent with dynamic arguments showing enhanced persistence of negative NAO events (Woollings et al., 2010). The MMLEA models generally simulate 5th and 95th percentile extreme NAO winters of a comparable magnitude to Obs LE with the exception of CSIRO-Mk3.6 (Figure S2a). Considering the minimum and maximum values of the modelled distributions, all models except CSIRO-Mk3.6 can reproduce NAO winters of a similar magnitude to the two most negative and two most positive years for 20CRv3. On these grounds, CSIRO-Mk3.6 and EC-EARTH will not be used in the results relating to extreme NAO winters (Section 3.3).

3.2 Role of the NAO in European mean winter precipitation projections

Figure 1 shows ensemble mean winter precipitation anomalies between the future (2080-2099) and present-day (1995-2014) for northern and southern Europe in the MMLEA models, where these are decomposed into an NAO-congruent part and a residual (Section 2.2). The spatial patterns of precipitation change are generally similar across the models (Figure S3). Figure 1 shows MPI-ESM-LR as an example, chosen because it lies near the centre of the MMLEA and CMIP5/6 intermodel spread in projected NAO index change (McKenna & Maycock, 2021). CanESM2 and the GFDL models lie towards the most negative and most positive end of the NAO projections, respectively.

In all MMLEA models, there is a future increase in total precipitation in northern Europe, which ranges from 10% to 20% of the present-day climatology. The NAO contribution is generally small, but as expected depends on the magnitude of the NAO trend. Specifically, the NAO contributes to almost none of the total precipitation change for models with relatively small to moderate NAO trends (CanESM2, EC-EARTH, CESM1-CAM5, MPI-ESM-LR, CSIRO-Mk3.6) and up to one-third for models with the strongest NAO trends (GFDL-ESM2M, GFDL-CM3). The residual precipitation changes, on the other hand, are generally relatively large and account for the majority of the total precipitation change in all models.

In southern Europe, there is a future decrease in total precipitation in most models. However, there is large uncertainty across models in the magnitude, from no change in CanESM2 to a decrease in precipitation of 25% in GFDL-CM3. The role of the NAO in these precipitation trends is proportionately larger than for northern Europe, contributing up to

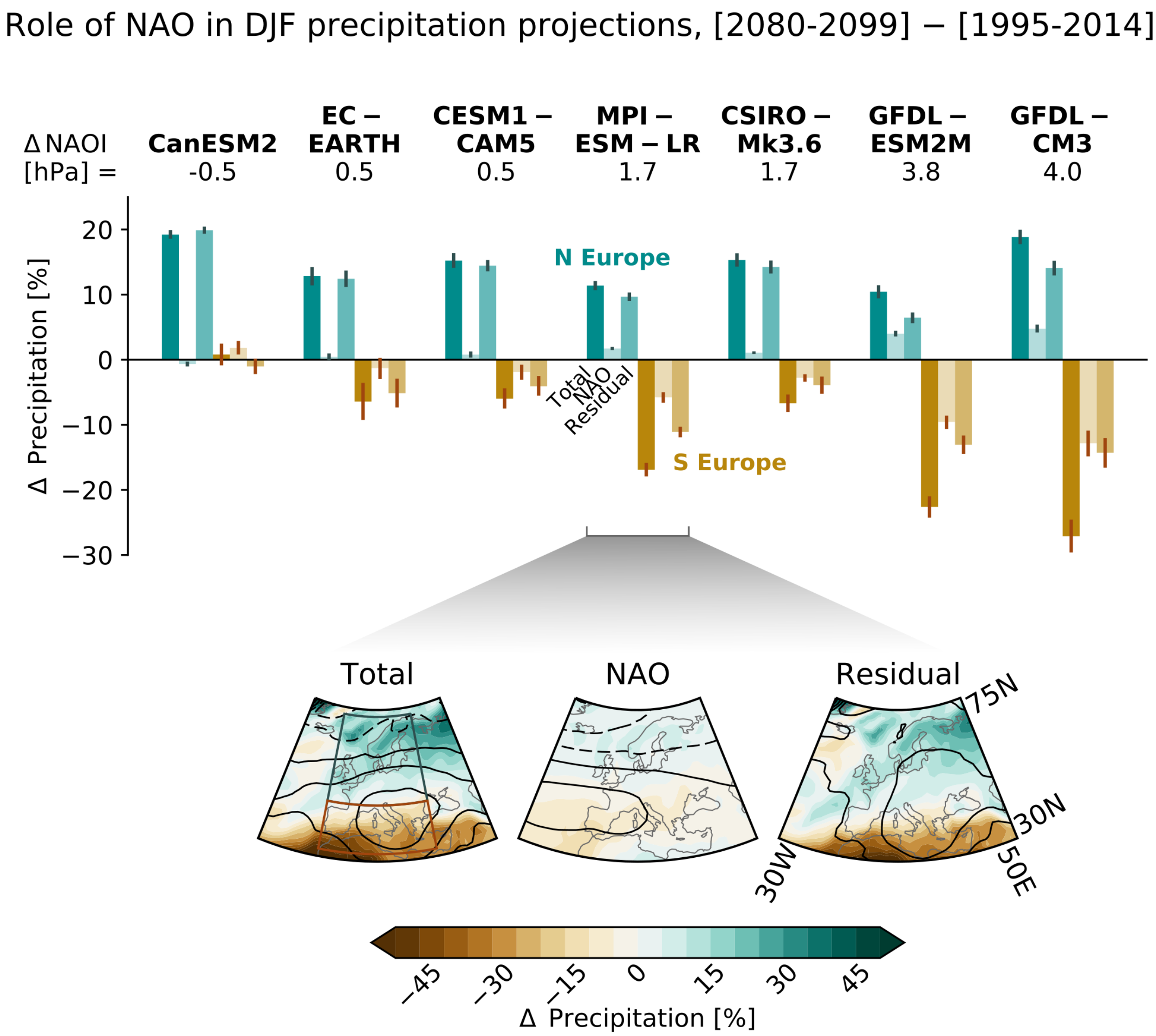

Figure 1. Role of ensemble mean DJF NAO index change (ΔNAOI) in DJF precipitation projections (2080-2099 minus 1995-2014) in northern and southern Europe for the MMLEA models. Bars show area-average precipitation anomalies in northern (blue) and southern (brown) Europe; see lower left map. Left bar: Total precipitation anomaly; Middle bar: NAO-congruent part; Right bar: Residual. Precipitation anomalies are shown as a percentage of the 1995-2014 climatology. Error bars show bootstrapped 95% confidence intervals. Contours on maps show MSLP anomalies from −2 hPa (dashed) to 2 hPa (solid) in 1 hPa intervals.

one-third of the total precipitation change in models with the smallest positive NAO trends (EC-EARTH, CESM1-CAM5) and up to half in models with relatively moderate to large NAO trends (MPI-ESM-LR, CSIRO-Mk3.6, GFDL-ESM2M, GFDL-CM3). The residual precipitation changes in southern Europe all show a drying, but only dominate over the NAO-congruent precipitation change in three models (EC-EARTH, MPI-ESM-LR, GFDL-ESM2M).

We now examine the NAO contribution to model uncertainty in projections of total precipitation change. Similar to Fereday et al. (2018), we calculate the fractional contribution of the NAO to the total intermodel variance in forced precipitation projections as $\sigma_{NAO}^2/\sigma_{TOT}^2$, where $\sigma_{TOT}^2 = \sigma_{NAO}^2 + \sigma_{RES}^2$. This shows the NAO contributes around a fifth and half of the intermodel spread in forced precipitation changes in northern and southern Europe, respectively. For smaller regions centred on the dominant centres of action for the NAO-precipitation relationship (53°N-70°N, 10°W-18°E and 36°N-44°N, 10°W-2°E; Figure S1a), the NAO contributes to a larger proportion (two-thirds) of the model structural uncertainty.

We hypothesise the residual wetting in northern Europe mainly arises from the warming climate and associated increases in specific humidity (Held & Soden, 2006; Manabe & Wetherald, 1980; Trenberth et al., 2003). This is because the residual precipitation anomalies are similar across the models despite different residual northern European circulation anomalies (Figure S3). Furthermore, normalising the precipitation changes by changes in global mean surface air temperature results in residual and total changes in northern Europe that are generally similar in magnitude across the models (around 3-4 %/K and 3.5-4.5 %/K, respectively; Figure S4). In contrast, this is not the case in southern Europe (Figure S4); the residual drying in the Mediterranean may be associated with the residual anticyclonic circulation anomalies which are not NAO-congruent (Figure S3).

3.3 Frequency and precipitation impacts of future extreme positive NAO winters

Anomalous precipitation during extreme positive NAO winters contributes to flooding in northern Europe and meteorological drought in the Iberian Peninsula (Trigo et al., 2004; Zanardo et al., 2019). Figure 2 shows future changes in the frequency of extreme positive NAO winters, defined where the NAO index exceeds the present-day 95th percentile. The model with a negative mean NAO index change (CanESM2) simulates a decrease in frequency of extreme positive

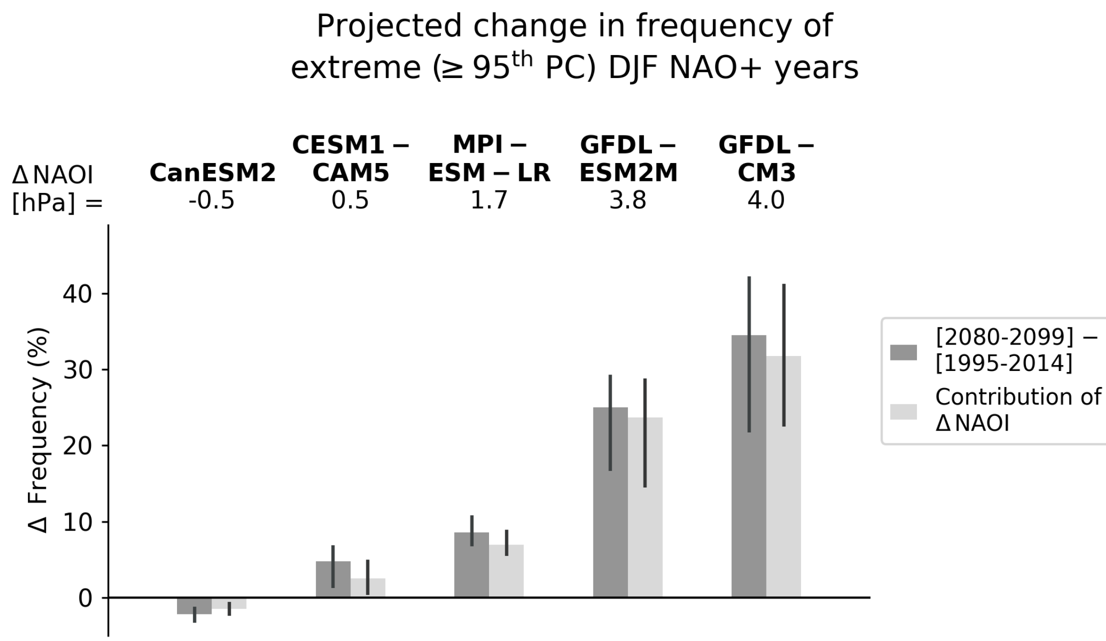

Figure 2: Projected change (2080-2099 minus 1995-2014) in the frequency of extreme positive (≥ 95th percentile for 1995-2014) NAO winters for selected MMLEA models (see Section 3.1). Contribution of ensemble mean DJF NAO index change (ΔNAOI) is calculated by shifting the 1995-2014 distribution of annual DJF NAO index by ΔNAOI. Error bars show bootstrapped 95% confidence intervals.

NAO winters, while models with positive NAO index changes show increases in frequency of up to 35% (GFDL-CM3) – i.e., a 1-in-20 year winter becomes a 2-in-5 year winter. The changes in frequency can be largely explained by the ensemble mean NAO index change (Figure 2; Figure S5). While an increase in NAO variability likely contributes to part of the frequency changes in CESM1-CAM5, changes in NAO variability are not robust across MMLEA models (Figure S5). Changes in the skewness and kurtosis of the annual NAO index distribution are not robust in any model (Figure S5).

Figure 3 shows the future versus present-day precipitation anomalies for northern and southern Europe during extreme positive NAO winters, defined where the NAO index exceeds the 95th percentile for the given period. For the present-day, extreme positive NAO winters are generally associated with 10% higher winter precipitation in northern Europe and 20% lower precipitation in southern Europe (Figure 3). In the future, all MMLEA models project an increase in wet anomaly in northern Europe during extreme positive NAO winters, from two (MPI-ESM-LR, GFDL-ESM2M) to three times as large (CanESM2, CESM1-CAM5, GFDL-CM3). In southern Europe, models with a smaller mean NAO index change project little change in precipitation (CanESM2, CESM1-CAM5), while models with a larger NAO index change (GFDL-ESM2M, GFDL-CM3) project a dry anomaly during strongly positive NAO winters that is around twice as large.

The simplest explanation for this result is that the shift in climatological mean precipitation causes a shift in precipitation associated with NAO extremes. Future changes in the NAO-precipitation relationship and/or NAO variability could also play a role (e.g., Deser et al., 2017; Osborn, 2011).

Figure 4 shows the future minus present-day difference in precipitation during extreme positive NAO winters, decomposed into climatological mean parts and an “other” part. The climatological mean changes include the part due to mean NAO index changes and a residual part (i.e., the NAO-congruent part and residual from Figure 1, respectively). This shows precipitation changes during extreme positive NAO winters are largely consistent with climatological mean changes. In northern Europe, the increase in precipitation is dominated by the mean residual changes, which – as previously discussed – are likely associated with background thermodynamic effects in a warmer climate. Mean NAO changes play a larger role in southern Europe than for northern Europe, contributing to around half of the total precipitation anomaly in models with larger NAO index changes (GFDL-ESM2M, GFDL-CM3).

In CESM1-CAM5 and GFDL-CM3, there is a non-climatological increase and decrease, respectively, in northern European precipitation anomaly during future extreme positive NAO winters, which is different from zero within error; a sizable part of this is explained by an increase and decrease in the NAO-precipitation relationship (p<0.05; not shown), with small contributions from an increase and decrease in interannual NAO variability (Figure S5). Changes in the NAO-precipitation relationship are also responsible for the non-climatological contributions in MPI-ESM-LR west of Norway and in southwestern Europe (Figure 4). However, projected changes in interannual NAO variability (Figure S5) and in NAO-precipitation relationship strength (not shown) are not consistent across the MMLEA models.

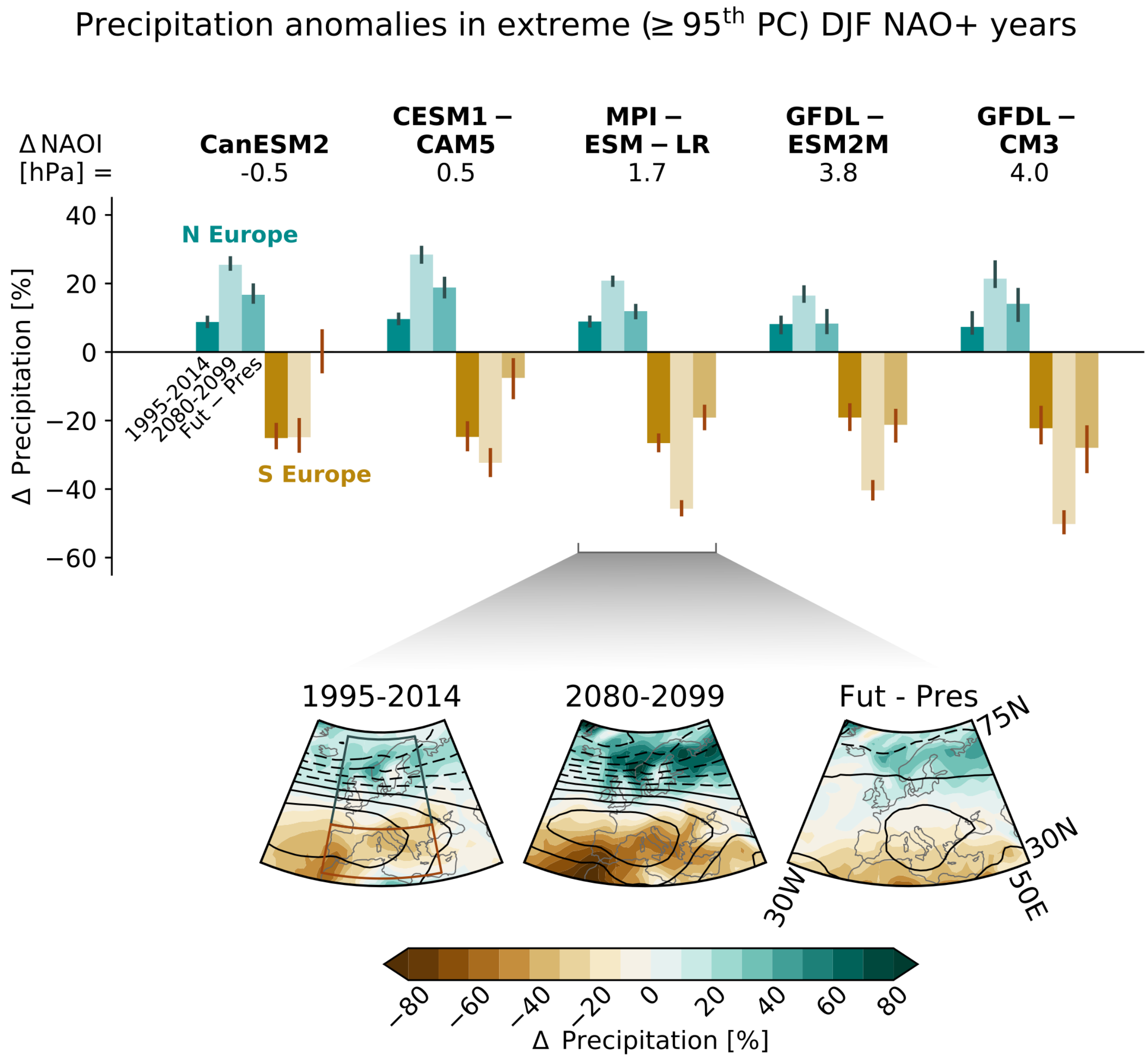

Figure 3: Precipitation anomalies in northern and southern Europe during extreme positive (≥ 95th percentile) NAO winters for 2080-2099 versus 1995-2014 in selected MMLEA models (see Section 3.1). Left bar: 1995-2014 anomaly; Middle bar: 2080-2099 anomaly; Right bar: 2080-2099 anomaly minus 1995-2014 anomaly. Precipitation anomalies are shown as a percentage difference from the 1995-2014 winter climatology and averaged over all extreme positive NAO winters. Error bars show bootstrapped 95% confidence intervals. ΔNAOI is the ensemble mean DJF NAO index change for 2080-2099 minus 1995-2014. Contours on maps (see Figure S6 for all models) show MSLP anomalies from −12 hPa (dashed) to 6 hPa (solid) in 2 hPa intervals.

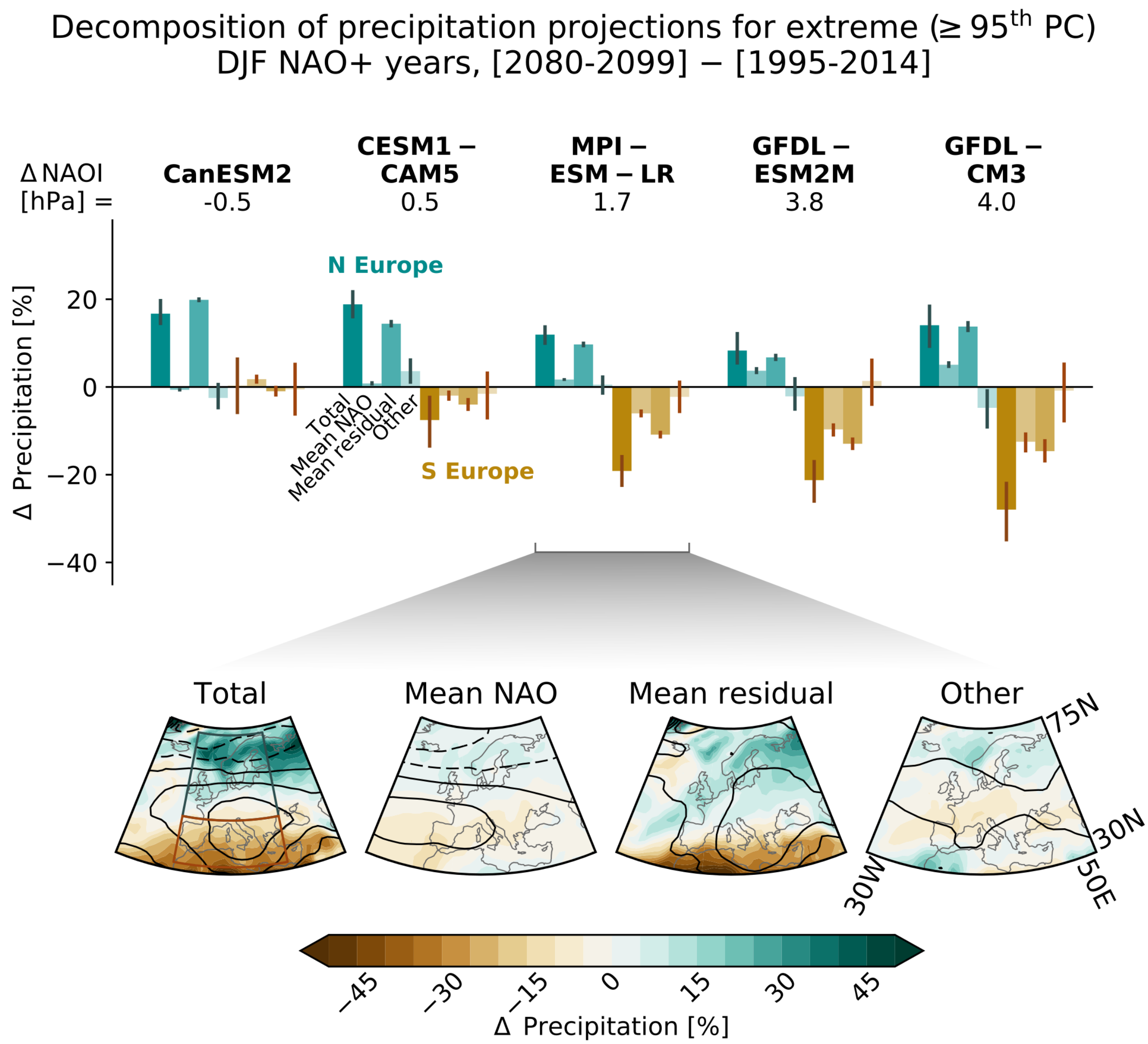

Figure 4: Decomposition of projected precipitation change (2080-2099 minus 1995-2014) during extreme positive (≥ 95th percentile) NAO winters in selected MMLEA models (see Section 3.1). Far left bar: Total precipitation anomaly; Middle left bar: Part from ensemble mean DJF NAO index change (ΔNAOI, NAO part in Figure 1); Middle right bar: Part from ensemble mean residual change (residual in Figure 1); Far right bar: Non-climatological "other" part. Precipitation anomalies are shown as a percentage of the 1995-2014 winter climatology and averaged over all extreme positive NAO winters. Error bars show bootstrapped 95% confidence intervals. Contours on maps show MSLP anomalies from −3 hPa (dashed) to 3 hPa (solid) in 1 hPa intervals.

4 Discussion and Conclusions

This study has examined the role of forced NAO changes for projections of winter mean European precipitation using multimodel initial-condition large ensembles from the MMLEA. We use this smaller multimodel ensemble because the CMIP archives typically do not provide enough ensemble members to isolate forced NAO changes from internal variability (McKenna & Maycock, 2021).

Despite the spread in late 21st century projections of the mean winter NAO index across MMLEA models under the RCP8.5 scenario (McKenna & Maycock, 2021), the qualitative pattern of mean winter precipitation change is very similar with wetting in northern Europe and drying in southern Europe. In northern Europe, the NAO only contributes up to one-third of the precipitation change in a given model and explains one-fifth of the intermodel spread. The NAO plays a larger role in southern Europe, contributing up to half of the precipitation change and explaining half of the intermodel spread. The residual intermodel spread in southern European precipitation change may arise from spread in other aspects of atmospheric circulation change; indeed, a sizable part of the spread in forced MSLP projections over southern Europe is not NAO-congruent (McKenna & Maycock, 2021). The NAO is relatively more important for precipitation change in certain smaller regions, including northwest Europe and the Iberian Peninsula, than at a continental scale.

Stephenson et al. (2006) showed the NAO is not a key factor in European mean winter precipitation projections for an earlier generation of climate models, where only one ensemble member was available per model meaning forced changes could not be distinguished from internal variability. Our analysis using MMLEA suggests Stephenson et al. (2006)'s result is only robust in northern Europe. Differences in future atmospheric circulation change across the CMIP5 models have been found to contribute to 75%-80% of the intermodel spread in projections of mean winter precipitation in southern Europe or the Mediterranean (Fereday et al., 2018; Zappa et al., 2015). The results presented here suggest a large part of the forced component of this spread could be reduced through improved understanding of the NAO.

Second, we examine future changes in the frequency of extreme (1-in-20 year) positive NAO winters, which are often associated with severe societal impacts. The MMLEA models generally project an increase in extreme positive NAO winter frequency, largely due to a positive shift in mean NAO index. The increase can be up to 35%, but large intermodel spread in the magnitude of mean NAO index changes (McKenna & Maycock, 2021) results in large model uncertainty in extreme frequency changes.

Third, we show extreme positive NAO winters have more severe precipitation impacts in future in all MMLEA models. In particular, future extreme positive NAO winters have northern European wet anomalies that are two to three times larger than in the present-day and southern European dry anomalies that are up to two times larger. Mean NAO index changes contribute up to half of the southern European precipitation changes. Across the MMLEA models, however, the most robust Europe-wide contribution is from changes in climatological winter precipitation that are unconnected with the NAO. Specifically, precipitation anomalies during future extreme positive NAO winters amount to NAO-induced precipitation anomalies similar to present-day superposed onto a future background climatology that constructively interferes with the NAO pattern; this coincidence between mean state changes and interannual variability has implications for climate adaptation and resilience to this type of seasonal extreme.

Multiple studies have shown increased precipitation within extratropical cyclones in a warmer climate (e.g., Hawcroft et al., 2018; Kodama et al., 2019; Yettella & Kay, 2017), and since the NAO is associated with changes in the position and intensity of the storm track (Hurrell et al., 2003) we anticipated the NAO-precipitation relationship would strengthen in future. However, such a strengthening is not robustly found in models. Further studies are required to establish the connection between the cyclone-centric view of climate change and the perspective of changes in large-scale circulation and storm tracks.

Model biases could influence this study's results. For example, the MMLEA models may underestimate NAO-congruent changes in southern European precipitation given the too-weak NAO-precipitation relationship in this region. They may also underestimate future increases in northern European precipitation as compared to higher resolution models (Moreno-Chamarro et al., 2021). Multiple Regional Climate Model initial-condition large ensembles are now becoming available (Maher et al., 2021a), which could be used to further examine the influence of these biases. Importantly, models have been shown to underestimate predictable forced NAO variations by a factor of two on seasonal timescales (Baker et al., 2018; Dunstone et al., 2016; Eade et al., 2014; Scaife & Smith, 2018; Scaife et al., 2014) and by a factor of ten on decadal timescales (Smith et al., 2020). If this issue is also present in multidecadal NAO projections, the NAO contribution to future changes in European winter mean precipitation may be underestimated. Future work should examine whether multidecadal NAO projections have a too-low signal-to-noise ratio. Understanding the dynamical mechanisms responsible for intermodel spread in future forced NAO changes will also be important for identifying potential constraints on the spread in southern European mean winter precipitation projections.

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Data Availability Statement

The Multimodel Large Ensemble Archive and Observational Large Ensemble data can be accessed at http://www.cesm.ucar.edu/projects/community-projects/MMLEA/. The GFDL-ESM2M large ensemble data used here can be accessed from the Princeton Large Ensemble Archive through Globus (https://www.sarahschlunegger.com/large-ensemble-archive). 20CRv3 can be downloaded from https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.html and E-OBS from https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php.

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