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An assessment of the North Atlantic Oscillation in the Late Pliocene and its impact on European climate

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Abstract. The North Atlantic Oscillation (NAO) heavily influences European climate and weather and is projected to change with future warming. Despite it's strong links to climate, there has not yet been an analysis of the NAO using the most recent climate model simulations of the Late Pliocene. Using data from the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2), the NAO and North Atlantic atmospheric circulation are analysed. In winter an increased meridional sea level pressure gradient contributes to an increase in the multi-model mean NAO index. However, this is model dependent with only a few models displaying changes in the NAO index. Using forcing factorisation simulations, the differences in sea level pressure are found to be driven by non-CO_2 boundary conditions such as ice sheets and orography. These changes in the NAO also relate to shifts in the zonal winds, with North Atlantic Westerlies being more poleward in winter, and more equatorward in summer. When examining European climate, Northern Europe is on average wetter in the Late Pliocene compared to the pre-industrial, but this is not linked to a difference in NAO behaviour. The simulations examined all show increased mean precipitation over Northern Europe in the Late Pliocene compared to the pre-industrial. Shifts in the distribution of wettest month rainfall are not linked to any change in the NAO index. This could imply changes in Northern European Late Pliocene precipitation extremes, but that these differences are may not be related to differences in the NAO. These shifts in rainfall distributions demonstrate the importance of considering multiple models when examining variability, especially in a palaeoclimate context.

1 Introduction

1.1 The Late Pliocene

The Late Pliocene (specifically Marine Isotope Stage KM5c, 3.205 Ma) climate has been the focus of the second phase of the Pliocene Model Intercomparison Project (PlioMIP2) (Haywood et al., 2020, 2024), and palaeoenvironmental reconstructions using proxy data (e.g. Foley and Dowsett, 2019; McClymont et al., 2020). PlioMIP2 comprises of outputs from of 17 atmosphere-ocean coupled climate models that aim to simulate the Late Pliocene climate in a consistent manner. In the core Late Pliocene experiment, CO_2 concentrations were set to 400 ppmv and the Antarctic and Greenland ice sheets were reduced in size compared to modern. Palaeogeography was similar to the modern, however key differences such as the closures of some Northern Hemisphere ocean gateways (Baring Strait, Hudson Bay and Canadian Archipelago) and changes to vegetation

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cover also drive the change in the climate. The PlioMIP2 multi-model mean (MMM) simulates global annual mean surface air temperatures of 3.2°C above pre-industrial and a global annual precipitation 7% above than pre-industrial (Haywood et al., 2020).

Studies of the Late Pliocene climate have improved our understanding of the climate system and how it responds to a range of forcings. The majority of Late Pliocene modelling studies focus on the long-term mean state. However, changes to large-scale circulation such as the westerly winds (Li et al., 2015), the Intertropical Convergence Zone (Han et al., 2021), Hadley cell circulation (Pontes et al., 2022), sea ice (de Nooijer et al., 2020) and the Atlantic Meridional Overturning Circulation (AMOC) (Zhang et al., 2021; Weiffenbach et al., 2023) may impact modes of variability and the occurrence of extreme events. This change in simulated variability by climate models may have implications for the way that models are compared to each other and to proxy reconstructions.

Some studies have examined higher frequency (monthly or daily) variability in the Late Pliocene. Pontes et al. (2022) and Oldeman et al. (2021) report a reduction in El-Niño Southern Oscillation (ENSO) variability across the PlioMIP2 ensemble. Changes in circulation patterns have been linked to alterations in extreme precipitation in the American North Pacific Coast (Menemenlis et al., 2021). Considering the North Pacific mid-latitudes, Oldeman et al. (2024) report a reduction in the variability of sea level pressure (SLP) in response to an implementation of Late Pliocene non-CO_2 boundary conditions in CCSM4-Utr. However, despite changes to the tropical Pacific, the Pacific Decadal Oscillation remains similar to pre-industrial conditions in the Late Pliocene (Canal-Solis et al., 2025). Examining these differences in variability, and the drivers of them is key to understanding climate extremes in the Late Pliocene which may have implications for the way the Late Pliocene is considered or viewed as an analogue for future climate states. Previous studies have focused on the Pacific basin but there has been less study of North Atlantic variability in the Late Pliocene from the latest phase of PlioMIP, and its possible implications for circulation and climate patterns in Europe.

1.2 North Atlantic variability

The leading mode of variability in the North Atlantic is the North Atlantic Oscillation (NAO), which characterises the variability in surface pressure gradients over the North Atlantic (Hurrell, 1995). In a positive phase, there is an enhanced pressure gradient over the North Atlantic associated with a stronger North Atlantic jet stream (Woollings et al., 2010). In winter, this creates warmer, wetter conditions over northwestern Europe and cooler drier conditions to Southern Europe. During a negative phase, the pressure gradient weakens displaying an equatorward jet stream, cooler and drier conditions in northwestern Europe and wetter, warmer conditions in southern Europe (Hurrell et al., 2003). In the Northern Hemisphere summer, the location of the high pressure centre shifts northeast, closer to Ireland. Like the winter NAO, in summer the westerly winds sit equatorward during a negative phase (Dong et al., 2013).

The NAO exerts a strong influence on European climate and hence on agriculture (Kim and McCarl, 2005) and energy supply (François, 2016; Jerez et al., 2013). Therefore, predicting the behaviour of the NAO has many potential socio-economic benefits. Recent advancements have been made in the long-range prediction of the NAO (Riddle et al., 2013; Scaife et al.,

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2014), however there is still uncertainty regarding how the NAO will respond to a warming climate with potentially large consequences for impacts on European weather (Smith et al., 2025).

From observations of present day climate (1950-2020), the wintertime jet stream has been strengthening along with a trend in sea level pressure that resembles a more positive NAO (Blackport and Fyfe, 2022). This impacts trends in European precipitation, with reanalysis data showing a stronger relation to jet stream speed compared with climate model simulations (from the Climate Model Intercomparison Project Phase 6 (CMIP6) (Blackport and Fyfe, 2022)).

Models representation of the NAO creates a challenge in understanding how it may behave in the future. Currently models underestimate variability in the North Atlantic region (Kravtsov, 2017; Schurer et al., 2023), which has been attributed to model representation of stratosphere-troposphere interactions (O'Reilly et al., 2019). This also extends to future projections where climate models are likely underestimating internal variability (O'Reilly et al., 2021), which has implications for climate extremes. Due to high levels of internal variability in models, is it difficult to identity a robust change in the future NAO due to internal variability being larger then forced response (McKenna and Maycock, 2021). Despite this, studies have suggested that the NAO will become more positive under high-emission scenarios (Mitevski et al., 2025; Smith et al., 2025). This has been shown to account for some of the projected differences in winter precipitation in Southern Europe, but is not significant for projected northern European precipitation (McKenna and Maycock, 2022).

The NAO is a key driver of extreme events such as heatwaves, storms and cold spells (Li et al., 2020a; Horton et al., 2015; Zanardo et al., 2019). Therefore, understanding how the NAO might change in response to external forcing is important both for future climate, but also for understanding the occurrence of extreme events of the Late Pliocene in the European region.

1.3 Late Pliocene North Atlantic Oscillation

The NAO began to operate 60 Myr ago with the expansion of the North Atlantic Ocean (Song et al., 2025), and so has existed across a range of climate states. Examining the NAO, the jet stream and their impacts on European hydroclimate in the Late Pliocene may provide insight into how longer term forcings might impact North Atlantic variability and European hydroclimate. By using the Late Pliocene, we can assess the behaviour of the NAO in a warm climate state that has been validated against proxy data.

Previous studies of the Pliocene have noted changes to the North Atlantic circulation. Haywood et al. (2000) noted a strengthening of the North Atlantic pressure centres along with increased precipitation over North West Europe, indicative of a more positive NAO. Hill et al. (2011) examined the NAO in the Pliocene using the HadCM3 model and found an increased strength in the Iceland Low in the Pliocene compared to the pre-industrial control simulation, which would create a more positive NAO. This strong Iceland low was related to reduced variability in the North Atlantic (Hill et al., 2011). However, the majority of these changes were due to Pliocene orography, particularity the lowering of the Rocky Mountains, which is not included in the PlioMIP2 boundary conditions (Haywood et al., 2016). The NAO can also impact sea ice (Wang et al., 2025). However, studies with PlioMIP1 models do not show a relationship between decadal NAO patterns and sea ice extent (Howell et al., 2016).

There are proxy records of the NAO during the wider Pliocene Epoch. From analysis of annual sedimentary layers Muñoz et al. (2002) find NAO-like periodicity around 2.8 Ma. Tree rings also provide an opportunity to study annually resolved

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temperature variability based on isotope analysis (Csank et al., 2013). Tree ring data from the Canadian Arctic indicates that the NAO was present during the Pliocene (Hill et al., 2011).

The NAO has also been examined in other palaeo periods. This generally reveals that in warmer climates the NAO has a larger amplitude compared to cooler climates where the NAO amplitude is weakened (Zhao et al., 2026). Likewise in climate model simulations of the Last Glacial Maximum, the majority of models simulate reduced winter NAO variability (Rehfeld et al., 2020).

Late Pliocene NAO has not been examined using the PlioMIP2 ensemble which includes an updated palaeogeography from previous studies leading to a better match between modelled and reconstructed sea surface temperatures (SSTs) in the North Atlantic (Haywood et al., 2020). This difference in simulated SSTs and signifiant changes to boundary conditions in this region such as the Canadian Archipelago, Baltic sea and Greenland Ice sheet could have large impacts on North Atlantic Circulation. There are indications of a stronger wintertime North Atlantic jet during the Late Pliocene (Buchan et al., 2026), which is likley related to NAO behaviour. From PlioMIP2 outputs, the mean change in precipitation displays a wettening of northern Europe and a drying of Southern Europe compared to pre-industrial control simulation (Haywood et al., 2020). This resembles a more positive NAO pattern.

This study aims to examine the NAO in the Late Pliocene, what boundary conditions are responsible for any differences and if there is any impact of the NAO on European climate. Understanding these changes may provide an enhanced understanding of the behaviour of the North Atlantic Oscillation in a warmer climate and also provide a perspective on the drivers of European climate. To achieve this data from the PlioMIP2 ensemble is used. The data and analysis methods are described in section 2. Section 3 discusses the changes and drivers of sea level pressure, changes to zonal wind patterns and the NAO in the Late Pliocene. An initial assessment of shifts in the distribution of precipitation over Europe is also presented. The significance of the results and suggestions for future research are presented in Section 4.

2 Data and Methodology

2.1 PlioMIP2 data

We use outputs from the 17 models run as part of PlioMIP2 which are listed in Table 1. We follow the PlioMIP2 naming convention of Ex^c, where c is the CO_2 concentration and x is a combination of o (Late Pliocene orography, including land sea mask and vegetation changes) and i (Late Pliocene ice sheets). This means E^{280}, is a simulation with pre-industrial CO_2 (280 ppmv), orography and ice sheets (the PlioMIP2 pre-industrial experiment) and Eoi^{400} is a simulation with Late Pliocene CO_2 (400 ppmv), orography and ice sheets (the PlioMIP2 Late Pliocene experiment).

The Late Pliocene experiments feature a reduced extent of the Greenland and Antarctic ice sheets as well as the closure of some key ocean gateways (Bering Strait, Canadian Archipelago and the Torres Strait) (Dowsett et al., 2016). CO_2 levels are set to 400 ppmv, but all other greenhouse gases are kept as the pre-industrial value (Haywood et al., 2016). The large scale changes in response to these boundary conditions are reported in Haywood et al. (2020).

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Table 1. Models from PlioMIP2 used in this study and their atmospheric resolution. The models marked with a star (*) use the pre-industrial control simulation (E^{280}) land sea mask for the Late Pliocene (Eoi^{400}) experiments.

Model ID	Atmosphere Resolution	Reference
CCSM4	0.9 × 1.25	Feng et al. (2020)
CCSM4-UoT	0.9 × 1.25	Chandan and Peltier (2017)
CCSM4-Utr	2.5 × 1.9	Baatsen et al. (2022)
CESM1.2	0.9 × 1.25	Feng et al. (2020)
CESM2	0.9 × 1.25	Feng et al. (2020)
COSMOS	3.75 × 3.75	Stepanek et al. (2020)
EC-Earth3.3	1.125 × 1.125	Zheng et al. (2019)
GISS2.1G	2.0 × 2.5	-
HadCM3	2.5 × 3.75	Hunter et al. (2019)
HadGEM3*	1.875 × 1.25	Williams et al. (2021)
IPSLCM6A	2.5 × 1.26	Lurton et al. (2020)
IPSLCM5A2	3.75 × 1.875	Tan et al. (2020)
IPSLCM5A	3.75 × 1.875	Tan et al. (2020)
MIROC4m	∼ 2.8 × 2.8	Chan and Abe-Ouchi (2020)
MRI-CGCM2.3*	∼ 2.8 × 2.8	Kamae et al. (2016)
NorESM1-F	1.9 × 2.5	Li et al. (2020b)
NorESM-L	∼ 3.75 × 3.75	Li et al. (2020b)

We also use data from forcing factorisation experiments [Eo^{280}, Ei^{280}, Eo^{400} and Ei^{400}] from the models CCSM4-UoT, COSMOS and HadCM3 to understand how boundary conditions drive simulated changes. The recommended set up of these experiments are provided in Haywood et al. (2016). To assess the models performance in simulating sea-level pressure, we refer to data from NOAA–CIRES–DOE Twentieth Century Reanalysis version 3 (NOAA CR20). 100 years of data (1900-1999) were used, and linearly detrended to remove longer term forced trends to be more comparable with the stationary climate E^{280} simulations. There are uncertainties arising in reanalysis data from sparse measurements and fewer observations in the earlier part of the sample period meaning it is not a perfect comparison to the control simulations included here.

2.2 Analysis

For the analysis, we take the final 100 years of each simulation regridded to 1° by 1° to allow for comparison between models and to construct a MMM. To define the NAO, we take a station based approach and use the difference in sea-level pressure (SLP) between two boxes, a lower pressure northern box, and a higher pressure southern box. Following Mitevski et al. (2025), the winter (December, January February (DJF)) NAO is defined as the difference in SLP between the Azores (35°N - 40°N,

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30°W - 20°W) and Iceland (60°N - 70°N, 25°W - 10°W). Due to the shift in the high pressure system in summer (June, July, August (JJA)), the southern box is taken as 45°N - 55°N, 25°W - 10°E, and the Northern box remains the same as the winter (60°N - 70°N, 25°W - 10°W). This station based metric provided a similar result to using the leading empirical orthogonal function (EOF1) (Figs. S1 and S2). To understand the drivers of the change in SLP we follow the Lunt et al. (2021) linear-sum factorisation to separate out the influence of CO_2, ice sheets and orography. Due to the nature of the PlioMIP2 experimental design (Haywood et al., 2016), it is not possible to fully separate out the orography and ice sheets as changing the ice sheet will impact the orography.

To examine changes to North Atlantic circulation we use the the zonally averaged zonal wind speed in the North Atlantic region (15°N – 75°N, 60°W – 0°E, defined by Woollings et al. (2010)). Three pressure levels (200, 500 and 850 hPa) are used as these levels are common to all the models examined. The latitude of the jet stream is defined as the latitude of maximum zonal wind speed, and the speed is taken as the maximum zonally averaged zonal wind speed. A cubic spline interpolation is used around the maximum to achieve a latitude precision of 0.1°.

To understand the impact of the NAO on European climate, we examine how temperature and precipitation vary in the strongest and weakest NAO years. This is done by taking the years with the 10 highest and 10 lowest NAO indexes for all models and then constructing a MMM. Following McKenna and Maycock (2022) the change in European precipitation and temperature, and the contribution to the change, is found. This is done by regressing the temperature/precipitation data onto the NAO index in the pre-industrial control simulation to understand how the temperature/precipitation varies in response to the NAO. These correlations are shown in Figs S4 and S5. These relationships are then multiplied by the difference in the NAO index to understand how much of the simulated change is driven by the NAO. There are some limitations with this method given that the data used features single runs rather than ensembles of the same models, so there is less data to construct the regression.

Finally to assess the shift in the distribution of precipitation over Europe, a northern (45°N - 72°N, 10°W - 30°E) and southern region (32°N - 45°N, 10°W - 30°E) are defined based on the pattern of change in precipitation between the Late Pliocene and the pre-industrial. Here only the climatologically wettest month in the pre-industrial simulation for each region is examined. The area-weighted precipitation values are then taken and compared between periods.

3 Results and interpretation

3.1 Changes to North Atlantic Sea level Pressure

Over the North Atlantic, the pre-industrial MMM is in general agreement with the reanalysis data (Fig. 1) although differs in detail. In the winter months, the MMM simulates a pressure that is too high over North Africa and too low over Northern Europe. This leads to a stronger simulated pressure gradient than in the reanalysis data. In the summer months, the MMM is higher than the reanalysis over the northern North Atlantic region. There is a spread among the models with regards to the representation of modern day climate, with the individual difference between the models and the reanalysis data shown in Figs.

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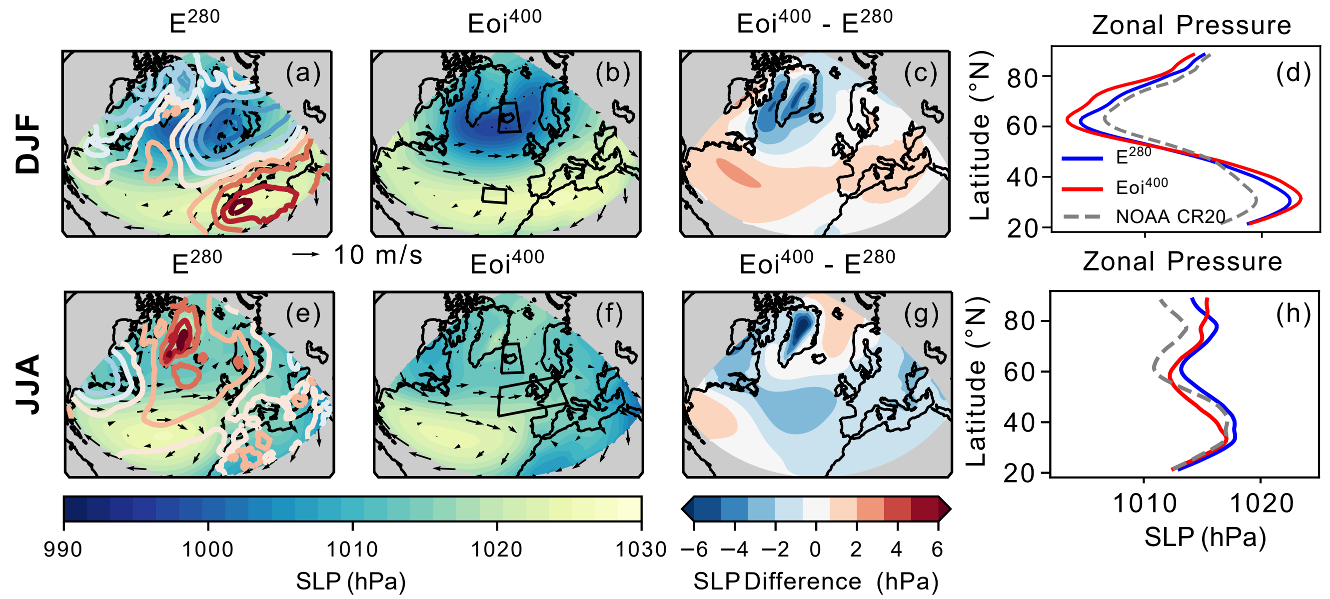

Figure 1. Multi-model mean sea level pressure (SLP) in the pre-industrial simulation (E^{280}), Late Pliocene Simulation (Eoi^{400}) and the difference (Eoi^{400}-E^{280}). The contours in a and e show the difference between E^{280} and the NOAA CR20 reanalysis data following the colour scheme of pannels c and g. The arrows note the strength and direction of the 850 hPa wind field. Panels d and h show the multi-model mean zonal pressure for E^{280} (blue), Eoi^{400} (red) and NOAA CR20 reanalysis (dashed grey). Panel a-d show data for December, January, February (DJF) mean and panels e-h show the June, July, August (JJA) mean. The areas used to define the NAO index are shown by the black boxes in panels b and f.

6 and 7. Differences may be due to the models representation of the North Atlantic or uncertainties in the reanalysis data, particularly from the earlier part of the reanalysis period, or changes to the reanalysis data through time not accounted for by the linear detrending.

In winter months, the largest differences between Eoi^{400} and E^{280} are seen in the western part of the North Atlantic Basin (Fig 1c) with weaker changes seen in the regions used to calculate the NAO index. In the summer months there is a large decrease in sea level pressure to the west of Ireland consistent with the region used to define the summer time NAO. This summer pattern is opposite to that projected by higher (abrupt 2×,4× and 8× CO_2) CO_2 simulations (Mitevski et al., 2025).

Comparing the zonal pressure gradients across the two time periods, in the winter months, the pressure gradient is stronger in the Late Pliocene than the pre-industrial simulations with both a strengthening of the Azores high and a deepening of the Icelandic low, although the largest differences in pressure are seen in the western North Atlantic. This increase in the pressure gradient in winter is consistent with a more positive NAO index. There is a less pronounced gradient change in the summer months, but comparing the spatial pattern and the position of the boxes used to calculate the NAO index (Fig 1f), the deepening of the high pressure system would suggest a more negative NAO index in the mean state.

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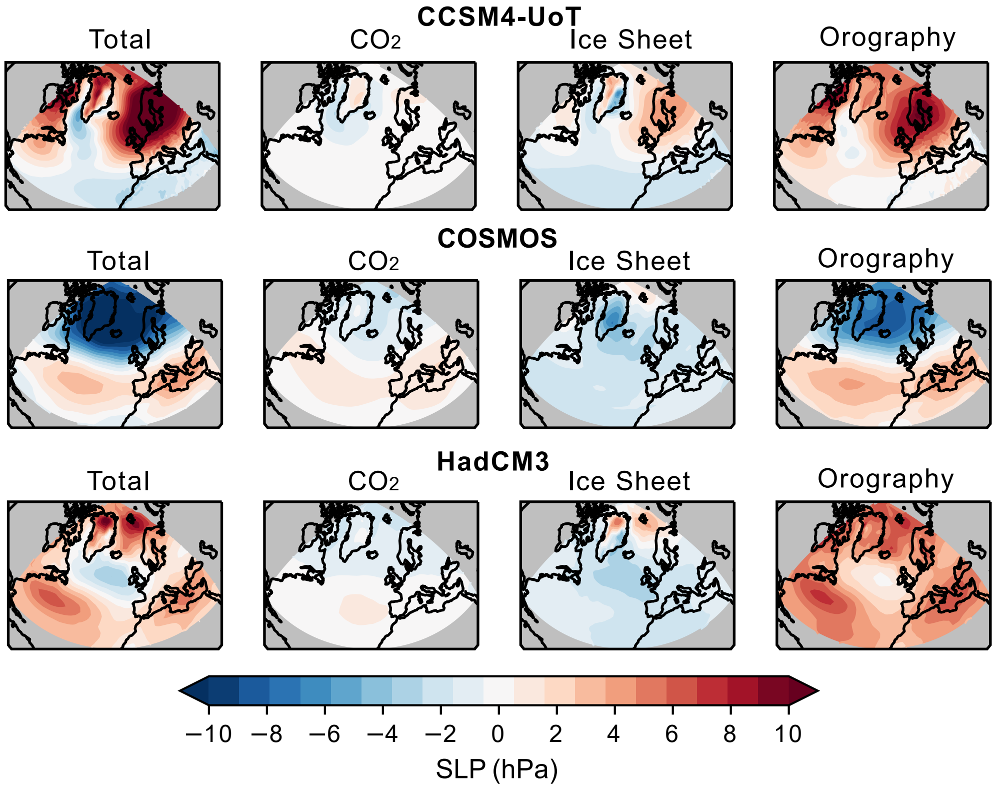

Figure 2. Change in the December, January, February sea level pressure (SLP) between the Late Pliocene and pre-industrial along with the contribution from CO_2, ice sheets and orography from three PlioMIP2 models.

Following the linear sum forcing factorisation method (Lunt et al., 2021), the contribution of different Late Pliocene boundary conditions on SLP can be found. As the full suite of forcing factorisation experiments is needed to achieve this, this analysis is carried out with CCSM4-UoT, COSMOS and HadCM3 where the required simulations are available. In the winter months, the total change in SLP is diverse across the three models used, with CCSM4-UoT and COSMOS having opposite responses (Fig 2). One consistency across these models is the small contribution from CO_2 forcing, with the majority of the change being forced by the ice sheet and orography boundary conditions. This is similar in the summer (Fig 3), with the ice sheet forcing contribution lowering pressure over the North Atlantic across the three models, but orography having a different influence depending on the model. In both summer and winter months, the majority of model differences are created by the orography boundary conditions, which suggests that changes to the land sea mask and vegetation patterns have a large impact on North Atlantic circulation. The small contribution from CO_2 also indicates that the Late Pliocene is not a suitable analogue for future shifts in the NAO under CO_2 driven warming. Nevertheless, it highlights the importance of considering the drivers of change, and how experimental setup and model uncertainties contribute towards uncertainty in understanding circulation in the North Atlantic region.

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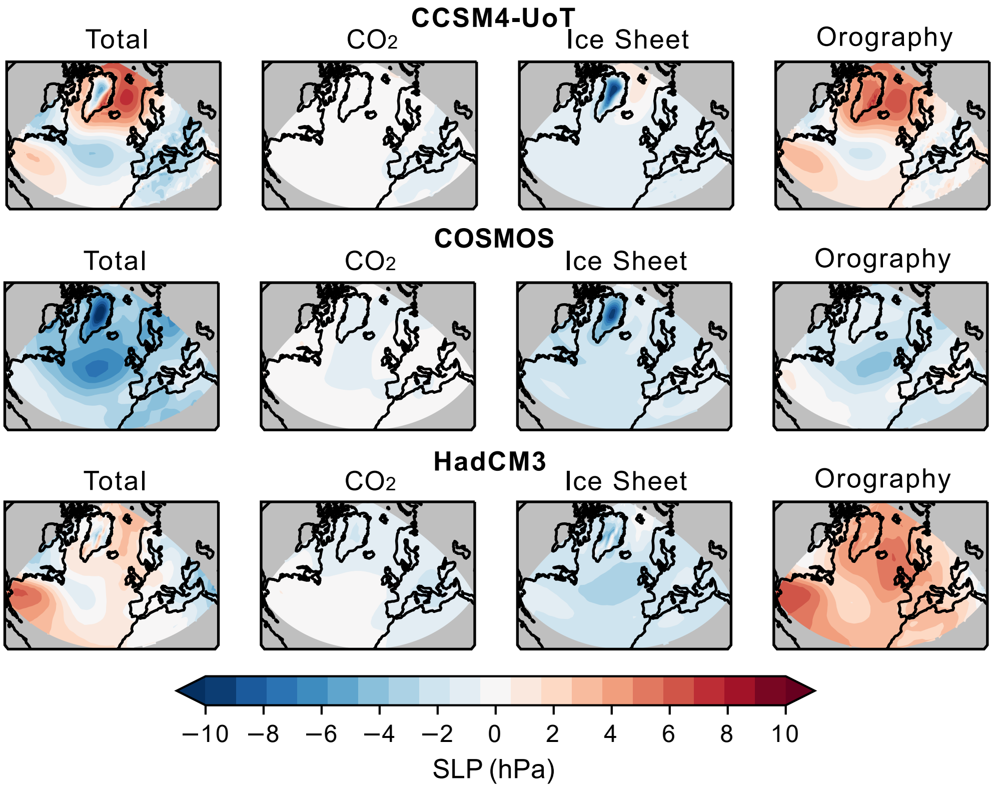

Figure 3. Change in the June, July, August sea level pressure (SLP) between the Late Pliocene and pre-industrial along with the contribution from CO_2, ice sheets and orography from three PlioMIP2 models.

As COSMOS includes dynamic vegetation in each of the runs (Stepanek et al., 2020), it is also not directly comparable to the other models that use static vegetation as feedbacks between climate and vegetation can lead to larger changes in surface temperature (O'ishi et al., 2021). This may also be influenced by feedbacks between altered circulation and changes in vegetation, which are not captured when using prescribed vegetation.

Changing the Greenland ice sheet impacts North Atlantic circulation. By implementing Late Pliocene ice sheets, the orography of Greenland is changed. Greenland orography has been noted as being important for the position of the North Atlantic jet (White et al., 2019). The large response to orography is expected given that orography is one of the main drivers in increasing AMOC strength in the Late Pliocene (Weiffenbach et al., 2023), which leads to increased sea surface temperatures in the North Atlantic. Hill et al. (2011) also note that the NAO responds most strongly to changes in orography, with the height of the Rocky Mountains being noted as being particularly important.

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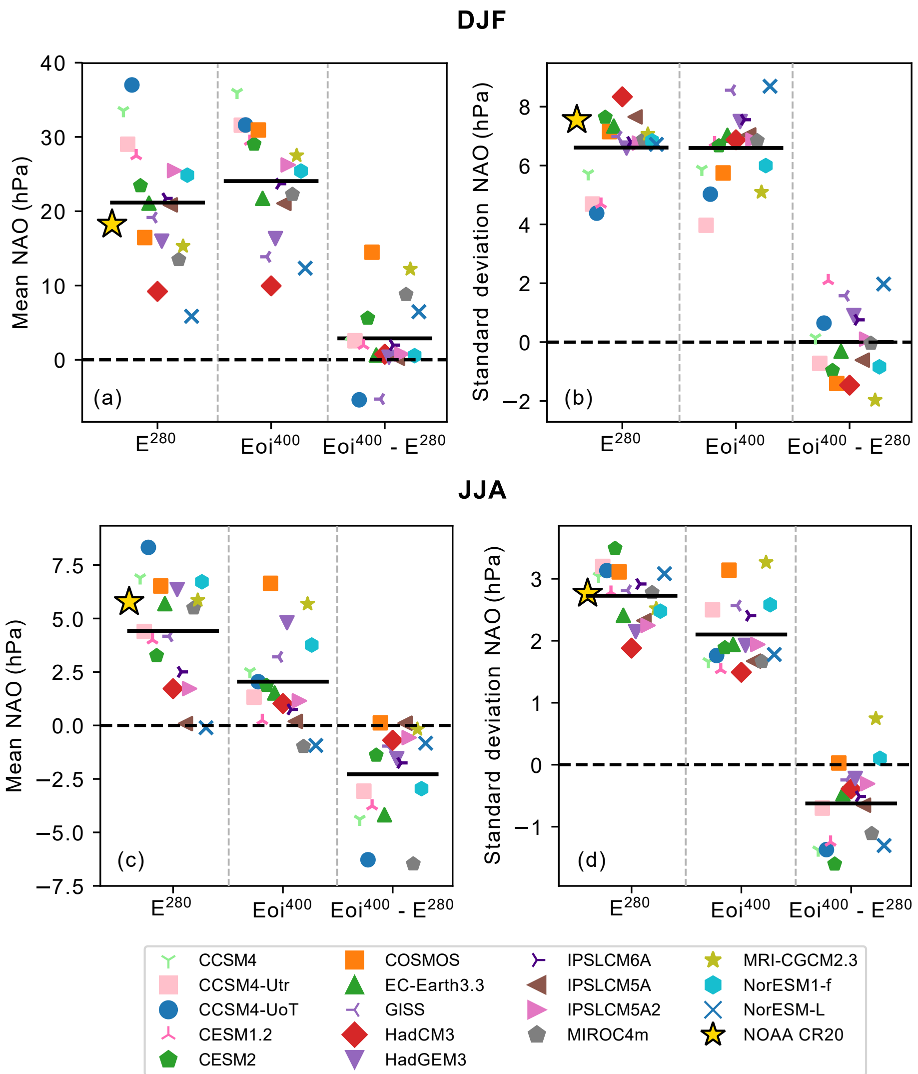

Figure 4. Mean North Atlantic Oscillation (NAO) (left) and standard deviation (right) for pre-industrial (E^{280}), Late Pliocene (Eoi^{400}) and the difference (Eoi^{400} - E^{280}). The black bars represent the multi-model mean with each model labelled. The horizontal position of the models has no meaning, they are shown alphabetically left to right. The star shows the value in NOAA CR20. The top panels indicate December, January, February (DJF) and the bottom panels are for June, July, August (JJA).

3.2 NAO behaviour in the Late Pliocene

Considering the change in the meridional gradient of the zonal pressure over the North Atlantic in winter, a more positive mean NAO index would be expected. When examining the MMM mean NAO index from the PlioMIP2 models, the NAO is more positive on average (Fig 4). However, there is large model spread in this value. Six of the models examined show little

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difference in the NAO index. Five models show larger positive changes (COSMOS, MRI-CGCM2.3, MIROC4m, NorESM-L and CESM2) and CCSM4-UoT and GISS2.1G display a more negative mean NAO index in the Late Pliocene simulation compared to the pre-industrial control. These changes are expected when compared to the spatial pattern of SLP differences in each model (Fig. S8). Previous studies have linked increasing CO_2 to a more positive NAO index (Mitevski et al., 2025), although as mentioned in section 3.1, the main driver of Late Pliocene SLP is not CO_2.

In the summer months, the Late Pliocene has a weaker mean NAO index than the pre-industrial, which is consistent across the majority of the PlioMIP2 models examined. This is likely due to the deepening of SLP off the coast of Ireland, where the summer NAO region is defined, caused by changes to ice sheets and orography. This is not consistent with future projections, which also suggest a more positive summer NAO under higher CO_2 conditions (Mitevski et al., 2025). But again, the majority of the SLP differences are driven by non-CO_2 boundary conditions.

As there is only one ensemble member per model within the PlioMIP2 ensemble, it is difficult to calculate the internal variability of the model to assess if these changes in the mean state are robust, or if they sit within the bounds of the internal variability of the model. As noted for future NAO, only some models simulate a change that is outwith its range of internal variability (McKenna and Maycock, 2021). There may also be other, longer-period modes of variability, such as the Atlantic Multi-decadal Oscillation that could be modulating the results seen here.

There is little agreement amongst models in regards to changes in the variability of the NAO in winter. However, most models show a small reduction in variability in summer. This range in response across models highlights the importance of examining multiple models when examining variability, as even under a climate with strong forcings, there are still inconsistent model responses. It also shows why it is important to consider variability as the change in variability may impact European climate, which in turn could influence how the climate is recorded in proxy data.

3.3 North Atlantic circulation changes

Following the relationship between the NAO and the jet stream over the North Atlantic (Woollings et al., 2010), with a positive NAO being related to stronger wind speeds over the North Atlantic, changes to zonal wind speeds are included here.

In the winter months at all three pressure levels (200, 500 and 850 hPa) the majority of models show poleward shifted westerlies (Fig. 5. At 200 hPa, due to strong wave breaking patterns in the North Atlantic, CCSM4-UoT and CESM1.2 show large jumps in the latitude of maximum zonal wind speed. To improve understanding of changes in North Atlantic circulation, daily data could be used to improve the definition of the jet stream including tilt and allow for the eddy driven jet to be identified. However, this is not currently possible with the available simulations of the Late Pliocene at a multi-model ensemble level. Similarly, the majority of models show faster westerly winds at 200 and 850 hPa. This poleward, faster jet is consistent with a more positive NAO. At 850 hPa, CCSM4-UoT and GISS2.1G displays slower westerly winds, differing from the rest of the ensemble, and this is consistent with the opposite response also shown in the NAO index change (Fig. 4) and SLP pattern (Fig. S8). Comparing the changes in the westerly winds to the NAO index we see that in winter months, the models that show a positive change in the mean NAO index also display poleward (Fig. S10) and faster (Fig. S11) westerly winds. This is expected, as during a positive phase of the NAO, the jet stream and storm tracks are intensified and shifted poleward, often

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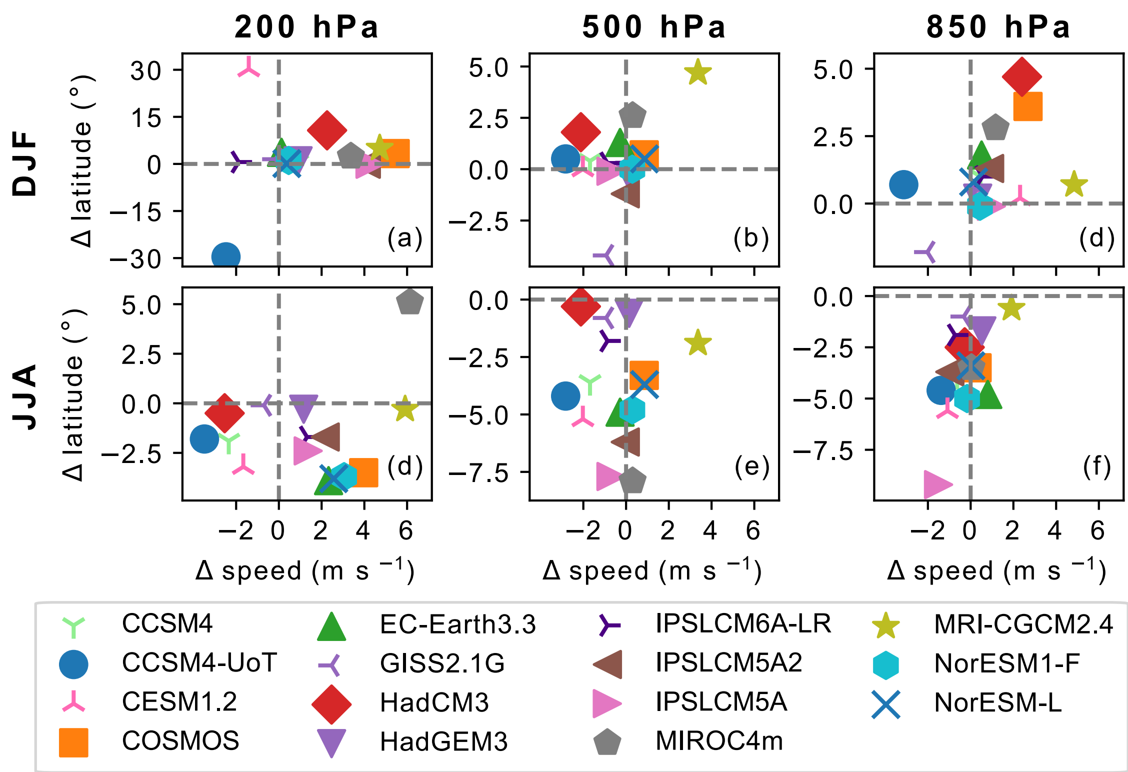

Figure 5. Change to the North Atlantic zonal wind speed and position in December, January February (DJF) and June, July, August (JJA) at three pressure levels (200 hPa, 500 hPa and 850 hPa). The dashed lines indicate position of zero change.

bringing wetter weather to Northern Europe. The models that display the stronger relationship between the latitude of the westerly winds and the NAO (COSMOS, MRI-CGCM2.4 and MIROC4m) are also some of the lowest-resolution models in the ensemble, indicating that model resolution may play a significant role in the representation of North Atlantic circulation in climate models, as found in previous studies (Roberts et al., 2020; Athanasiadis et al., 2022; Haarsma et al., 2019).

Consistent with changes to the summertime NAO (Fig. 4), the zonal wind speeds are more equatorward in the Late Pliocene compared to the pre-industrial simulations, although there is less model agreement in the change of zonal wind speed (Fig 5). In summer the models that show a decrease in the mean NAO index also show a southward shifted jet (Fig. S10), but the relationship with speed is less clear (Fig. S11). The East Atlantic pattern (EA) has also been noted as having an important role in controlling the position of the jet stream (Woollings et al., 2010). However, we do not include that here. When examining the amount of variance explained by the EA there are no significant differences between the Late Pliocene and pre-industrial (Fig. S3).

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3.4 Impact of NAO on European climate in the Late Pliocene

As the NAO and westerly winds impact European climate (Hurrell et al., 2003), any change to these circulation patterns could lead to differences in the climate over Europe. Here we consider changes to European winter time climate as the NAO is strongest during this time.

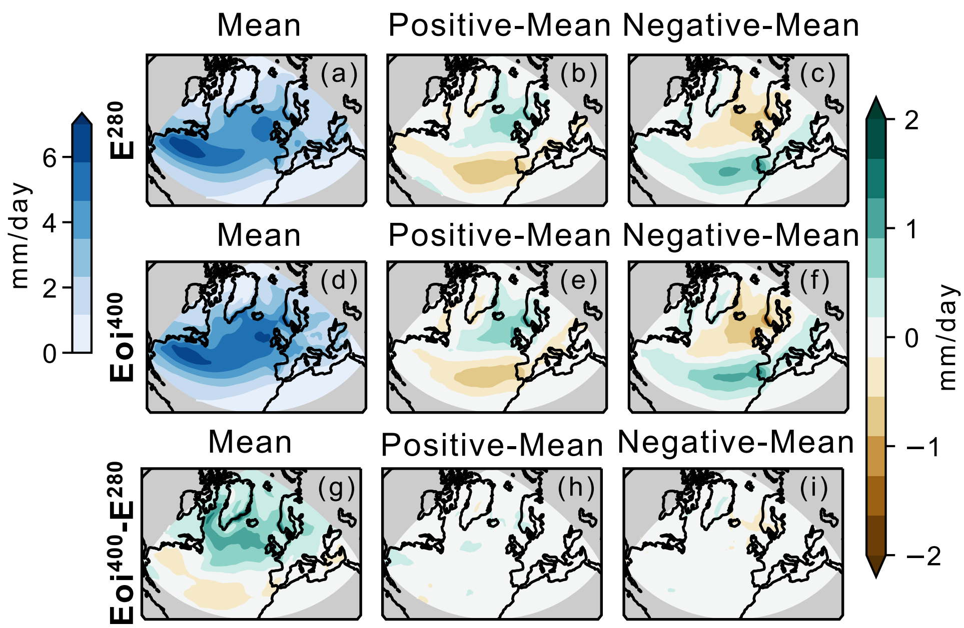

Figure 6. Multi model mean, December, January, February precipitation for the (a) pre-industrial simulation (E^{280}), (b) Late Pliocene simulation (Eoi^{400}) and (g) the difference between them (Eoi^{400}-E^{280}. Panels (b) and (e) show the difference between the 10 strongest NAO years and the mean, and Panels (c) and (f) show the difference between the 10 weakest NAO years. Panels (h) and (i) show the difference between the Eoi^{400} and E^{280} extreme NAO years.

Under future climate projections, it is expected that in winter months, northern Europe will see increased precipitation with southern Europe seeing a decrease (Zappa et al., 2015; McKenna and Maycock, 2022). This is also consistent with the future changes in the projected NAO. Considering the change to the mean state precipitation over the North Atlantic and Europe in the Late Pliocene (Fig 6g), Northern Europe has increased precipitation whereas Southern Europe has little change when compared to the pre-industrial simulation. Examining the impact of the ten most extreme NAO years, the pre industrial simulation shows the expected pattern associated with positive and negative phases of the NAO (Fig 6b and c). The mean state change also resembles the rainfall pattern seen in the more positive NAO years. This relationship between the extremes of the NAO index are similar in the Late Pliocene suggesting that the relationship between European precipitation and the NAO remains in the

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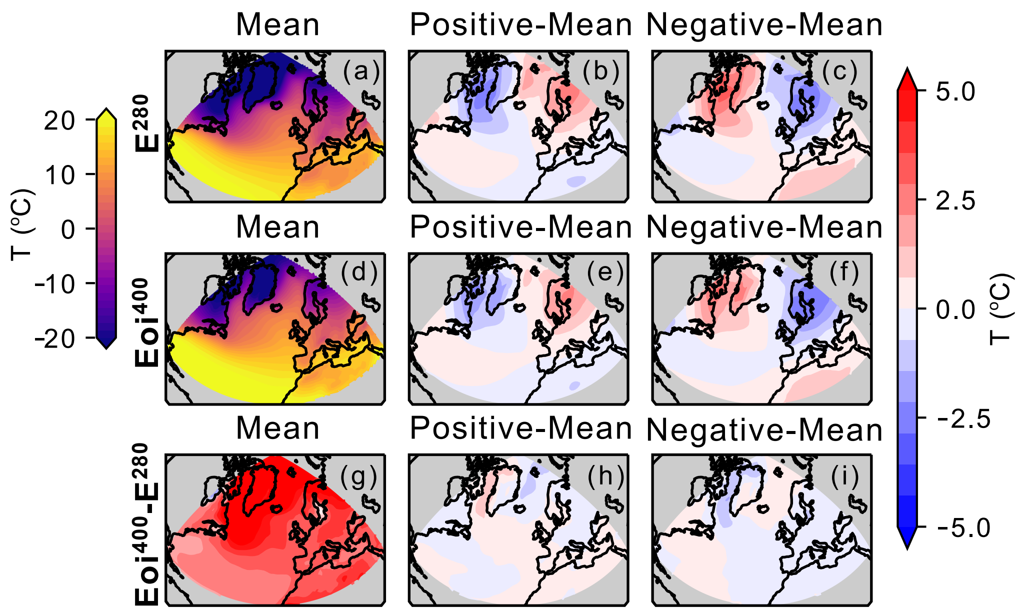

Figure 7. Multi model mean, December, January, February near-surface air-temperature for the (a) pre-industrial simulation (E^{280}), (b) Late Pliocene simulation (Eoi^{400}) and (g) the difference between them (Eoi^{400}-E^{280}. Panels (b) and (e) show the difference between the 10 strongest NAO years and the mean, and Panels (c) and (f) show the difference between the 10 weakest NAO years. Panels (h) and (i) show the difference between the Eoi^{400} and E^{280} extreme NAO years.

Late Pliocene. A similar pattern is seen with winter temperatures, but the mean state change shows a general warming and does not follow a classical pattern of NAO influence (Fig 7).

As the NAO still exerts an influence on European climate it highlights the importance of considering differences in the mean state, and variability from a multi-model perspective as changes in the NAO may impact European climate. This also shows how likely it may be to see an expression of NAO when comparing modelled change to palaeoenvironmental reconstructions like those presented in Salzmann et al. (2008) and Salzmann et al. (2013).

Following the method by McKenna and Maycock (2022), the impact of the change in the NAO on temperature and precipitation can be evaluated. For both winter time precipitation and temperature, the change in the NAO has little impact on the simulated differences (Fig 8). This is expected in the MMM as less than half of the models show a large shift in the NAO index (Fig 4). However, even the models with a larger change in the NAO index (CESM2, COSMOS, MIROC4m, MRI-CGCM2.3 and NorESM-L) still show that the majority of precipitation differences are driven by non-NAO related factors (Fig S12). These results are expected as this method only considers the relationship between the NAO in the pre-industrial control and many other factors such as altered land cover will affect the precipitation pattern over the European region. To fully understand

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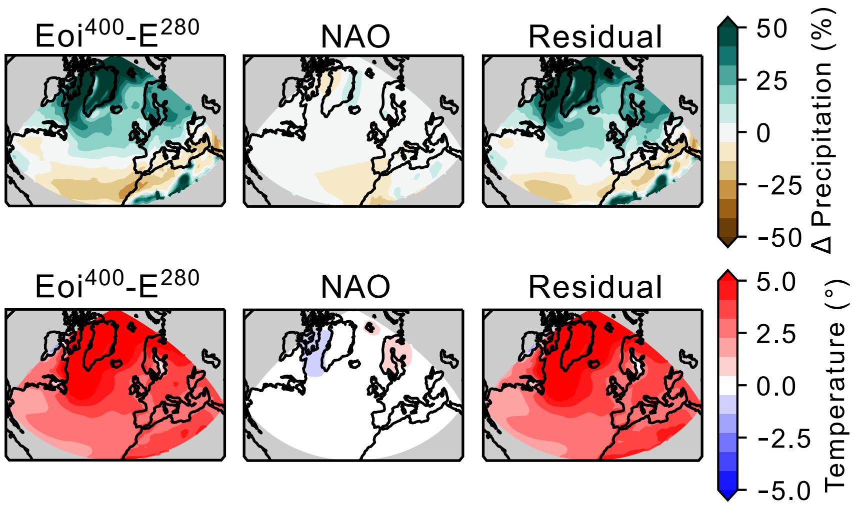

Figure 8. Multi-model mean, December, January, February precipitation (top row) and temperature (bottom row) change between the Late Pliocene and the pre-industrial simulations (Eoi^{400}-E^{280}) showing the total change, the change due to a shift in the North Atlantic Oscillation (NAO) and the residual changes. The NAO contribution is calculated by multiplying the relationships been the NAO and precipitation/temperature (Figs. S4 and S5) by the change in the NAO index. Individual model responses are in Figs S12 and S13.

the role of the NAO on European climate, and the impact of wider changes, more analysis including dynamical vegetation simulations and daily outputs would be required.

Despite these uncertainties, it is clear that there are mean state changes in precipitation and temperature over the European region which may be visible in vegetation proxy data. By comparing model outputs to geological vegetation reconstructions it may be possible to see the implications of longer term changes on the climate in terms of altered distributions of biomes.

An important element to consider when comparing models to proxy data is that there may be shifts in the distribution of the variables, such as precipitation and temperature, which may affect the mean state. Here we examine the distribution of precipitation values in the climatologically wettest month over Northern and Southern Europe (Fig 9). In Northern Europe all the models show increased precipitation in northern Europe although the magnitude of this change varies across the ensemble. It is clear that there are more instances of extreme precipitation in the Late Pliocene as this distribution shifts higher, with the mean of some models being higher than the most extreme values in the pre-industrial simulation (e.g. COSMOS, MRI-CGCM2.3 and EC-Earth3.3). Similarly there are less dry extremes in northern Europe compared to the pre-industrial. This result is limited by the amount of data used, and longer runs, or ensemble runs, would allow for this result to be more robust. In Southern Europe, there is less change in the mean state. Although negative on average there are no significant shifts towards more or less precipitation extremes. In order to fully understand the reasons behind these shifts, it may be necessary to consider daily model output.

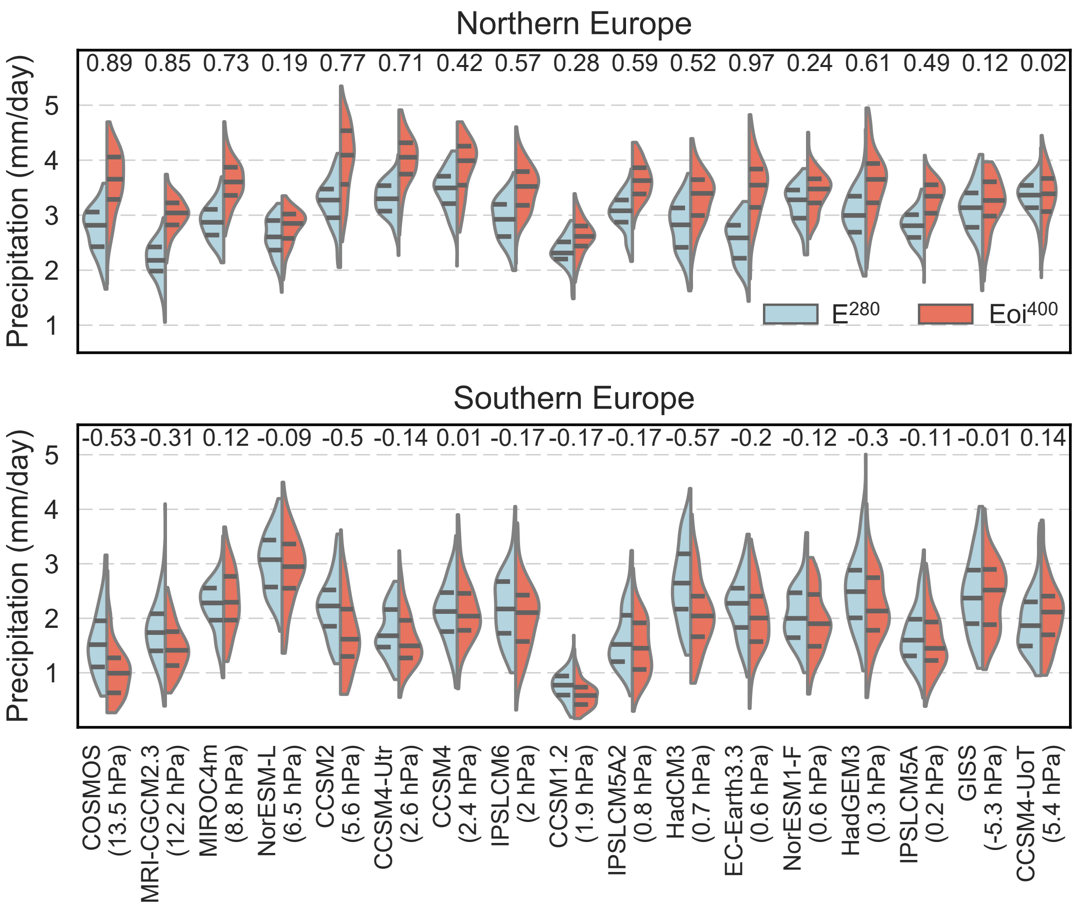

Figure 9. Precipitation distributions during the climatologically wettest months for each model in the pre-industrial (E^{280}) and Late Pliocene (Eoi^{400}) simulations. The change in the mean precipitation is noted above each model and the change in the NAO index for each model is noted.

3.5 Potential for data model comparison

One motivation to examine past climates is the availability of data to compare to climate models. It may therefore be possible to examine the proxy record to further our understanding of circulation and variability in the Late Pliocene. Palaeoenvironmental reconstructions of vegetation may provide opportunities to examine mean state changes, such as the more positive NAO observed in some PlioMIP2 models. Vegetation reconstitutions are relativity abundant in Europe (Salzmann et al., 2008). However, they are from a large window of time in the Pliocene and may not reflect the specific conditions during KM5c. Changes to vegetation are also controlled by many factors beyond temperature and precipitation. Therefore, disentangling the drivers of the change to relate to the climate simulations is challenging. It is also likely that the magnitude of the differences here may not be large enough to drive variations in biome distribution.

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High temporal resolution proxy data would provide an opportunity to assess the performance of climate models at seasonal time scales. Gaining such well-dated high resolution data is challenging, although some records have been used to assess changes in North Atlantic circulation. Tree ring data, varves and bivalves have all been used as records of seasonal changes in the Pliocene and have been related to changes in North Atlantic circulation (Hill et al., 2011; de Winter et al., 2024; Muñoz et al., 2002). Expanding on this data set to produce more annual records would deepen our understanding of seasonal scale variability in the Pliocene. For any differences to be robustly identified, multiple records that are dated to specific orbital windows would be needed so that the results could be compared to climate simulations.

Even if well dated high temporal resolution data sets are created, it would be challenging determine what the causes of change to variability. Although it may be possible to see NAO signals in the data and compare to the range of models presented here to understand what, if any, models are able to reproduce the change in recorded variability and why. This would provide an opportunity to assess Pliocene climate simulations to allow for a more robust understanding of variability.

4 Conclusions and future directions

From examining outputs from the PlioMIP2 ensemble it is determined that differences in North Atlantic SLP between the Late Pliocene and the pre-industrial simulations are driven by non-CO_2 boundary conditions. These differences in the SLP gradient lead to changes in the NAO index. In winter months, on average the, NAO is more positive in the Late Pliocene. However, the majority of models do not show a shift in the NAO index. In the summer months there is more agreement between the models with a less positive NAO index being displayed across the ensemble. This is mainly driven by the influences of the orography boundary condition (including land sea mask and vegetation) to the high pressure centre off the coast of Ireland. There is no large difference seen in the variability between the Late Pliocene and the pre-industiral. In order to further understand if the variability changes are significant, longer or multiple ensemble runs would be needed as the changes observed in the PlioMIP2 data set are likely within the range of internal variability of the models.

The change in the NAO index is likely to impact the way the westerly winds behave in the Late Pliocene with a more positive NAO index being related to a poleward and faster jet stream. This is expected under future climate, but the drivers of these changes are different from the future which limits the use of the Late Pliocene as an analogue for future North Atlantic circulation. This is also the case for differences in precipitation distribution over Europe and this may be heavily influenced by changes in vegetation patterns.

To fully understand how the climate of Europe is changing in response to larger scale features, it may be necessary to consider daily data. This would also provide a better explanation of changes to and drivers of extreme events over the region which has implications for model intercomparisons and data model comparisons.

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Data availability. PlioMIP2 model outputs (with the exception of GISS2.1G and IPSLCM6A) can be downloaded from https://www.globus.org/ (Last access 01/06/2026). Please contact Julia Tindall (J.C.Tindall@leeds.ac.uk) for access. GISS2.1G and IPSLCM6A can be downloaded from the Earth System Grid Federation (ESGF) (https://esgf-node.ornl.gov/search, last access 29/06/2026)

Author contributions. AECB led the study, conducted the formal analysis of the data and wrote the initial draft of the paper. AECB, AMH, JCT, AMD and DJH discussed the analysis and interpretation of the data. All authors contributed to the preparation of the paper.

Competing interests. The authors declare that they have no conflict of interest.

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Preprint. Discussion started: 12 August 2026

References

Athanasiadis, P. J., Ogawa, F., Omrani, N.-E., Keenlyside, N., Schiemann, R., Baker, A. J., Vidale, P. L., Bellucci, A., Ruggieri, P., Haarsma, R., Roberts, M., Roberts, C., Novak, L., and Gualdi, S.: Mitigating Climate Biases in the Midlatitude North Atlantic by Increasing Model Resolution: SST Gradients and Their Relation to Blocking and the Jet, Journal of Climate, 35, 6985 – 7006, https://doi.org/10.1175/JCLI-D-21-0515.1, 2022.

Baatsen, M. L. J., von der Heydt, A. S., Kliphuis, M. A., Oldeman, A. M., and Weiffenbach, J. E.: Warm mid-Pliocene conditions without high climate sensitivity: the CCSM4-Utrecht (CESM 1.0.5) contribution to the PlioMIP2, Climate of the Past, 18, 657–679, https://doi.org/10.5194/cp-18-657-2022, 2022.

Blackport, R. and Fyfe, J. C.: Climate models fail to capture strengthening wintertime North Atlantic jet and impacts on Europe, Science Advances, 8, eabn3112, https://doi.org/10.1126/sciadv.abn3112, 2022.

Buchan, A. E. C., Haywood, A. M., Tindall, J. C., Hunter, S. J., Dolan, A. M., and Hill, D. J.: The Late Pliocene jet stream: Changes and drivers of the mean state and variability, Climate of the Past, 22, 861–877, https://doi.org/10.5194/cp-22-861-2026, 2026.

Canal-Solis, K. V., Tindall, J. C., Oldeman, A. M., Haywood, A. M., Abe-Ouchi, A., Baatsen, M. L., Chan, W.-L., Feng, R., Hunter, S. J., Li, X., Stepanek, C., and Zhang, Z.: Asymmetric Pacific variability in the Pliocene: An unchanged PDO relative to a suppressed ENSO, Global and Planetary Change, 253, 104 932, https://doi.org/10.1016/j.gloplacha.2025.104932, 2025.

Chan, W.-L. and Abe-Ouchi, A.: Pliocene Model Intercomparison Project (PlioMIP2) simulations using the Model for Interdisciplinary Research on Climate (MIROC4m), Climate of the Past, 16, 1523–1545, https://doi.org/10.5194/cp-16-1523-2020, 2020.

Chandan, D. and Peltier, W. R.: Regional and global climate for the mid-Pliocene using the University of Toronto version of CCSM4 and PlioMIP2 boundary conditions, Climate of the Past, 13, 919–942, https://doi.org/10.5194/cp-13-919-2017, 2017.

Csank, A. Z., Fortier, D., and Leavitt, S. W.: Annually resolved temperature reconstructions from a late Pliocene–early Pleistocene polar forest on Bylot Island, Canada, Palaeogeography, Palaeoclimatology, Palaeoecology, 369, 313–322, https://doi.org/10.1016/j.palaeo.2012.10.040, 2013.

de Nooijer, W., Zhang, Q., Li, Q., Zhang, Q., Li, X., Zhang, Z., Guo, C., Nisancioglu, K. H., Haywood, A. M., Tindall, J. C., Hunter, S. J., Dowsett, H. J., Stepanek, C., Lohmann, G., Otto-Bliesner, B. L., Feng, R., Sohl, L. E., Chandler, M. A., Tan, N., Contoux, C., Ramstein, G., Baatsen, M. L. J., von der Heydt, A. S., Chandan, D., Peltier, W. R., Abe-Ouchi, A., Chan, W.-L., Kamae, Y., and Brierley, C. M.: Evaluation of Arctic warming in mid-Pliocene climate simulations, Climate of the Past, 16, 2325–2341, https://doi.org/10.5194/cp-16-2325-2020, 2020.

de Winter, N. J., Tindall, J., Johnson, A. L. A., Goudsmit-Harzevoort, B., Wichern, N., Kaskes, P., Claeys, P., Huygen, F., van Leeuwen, S., Metcalfe, B., Bakker, P., Goolaerts, S., Wesselingh, F., and Ziegler, M.: Amplified seasonality in western Europe in a warmer world, Science Advances, 10, eadl6717, https://doi.org/10.1126/sciadv.adl6717, 2024.

Dong, B., Sutton, R. T., Woollings, T., and Hodges, K.: Variability of the North Atlantic summer storm track: mechanisms and impacts on European climate, Environmental Research Letters, 8, 034 037, https://doi.org/10.1088/1748-9326/8/3/034037, 2013.

Dowsett, H., Dolan, A., Rowley, D., Moucha, R., Forte, A. M., Mitrovica, J. X., Pound, M., Salzmann, U., Robinson, M., Chandler, M., Foley, K., and Haywood, A.: The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction, Climate of the Past, 12, 1519–1538, https://doi.org/10.5194/cp-12-1519-2016, 2016.

https://doi.org/10.5194/egusphere-2026-4616
Preprint. Discussion started: 12 August 2026

Feng, R., Otto-Bliesner, B. L., Brady, E. C., and Rosenbloom, N.: Increased Climate Response and Earth System Sensitivity From CCSM4 to CESM2 in Mid-Pliocene Simulations, Journal of Advances in Modeling Earth Systems, 12, e2019MS002 033, https://doi.org/10.1029/2019MS002033, e2019MS002033 2019MS002033, 2020.

Foley, K. M. and Dowsett, H. J.: Community sourced mid-Piacenzian sea surface temperature (SST) data, https://doi.org/10.5066/P9YP3DTV, 2019.

François, B.: Influence of winter North-Atlantic Oscillation on Climate-Related-Energy penetration in Europe, Renewable Energy, 99, 602–613, https://doi.org/10.1016/j.renene.2016.07.010, 2016.

Haarsma, R. J., García-Serrano, J., Prodhomme, C., Bellprat, O., Davini, P., and Drijfhout, S.: Sensitivity of winter North Atlantic-European climate to resolved atmosphere and ocean dynamics, Scientific Reports, 9, 13 358, https://doi.org/10.1038/s41598-019-49865-9, 2019.

Han, Z., Zhang, Q., Li, Q., Feng, R., Haywood, A. M., Tindall, J. C., Hunter, S. J., Otto-Bliesner, B. L., Brady, E. C., Rosenbloom, N., Zhang, Z., Li, X., Guo, C., Nisancioglu, K. H., Stepanek, C., Lohmann, G., Sohl, L. E., Chandler, M. A., Tan, N., Ramstein, G., Baatsen, M. L. J., von der Heydt, A. S., Chandan, D., Peltier, W. R., Williams, C. J. R., Lunt, D. J., Cheng, J., Wen, Q., and Burls, N. J.: Evaluating the large-scale hydrological cycle response within the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2) ensemble, Climate of the Past, 17, 2537–2558, https://doi.org/10.5194/cp-17-2537-2021, 2021.

Haywood, A., Tindall, J., Burton, L., Chandler, M., Dolan, A., Dowsett, H., Feng, R., Fletcher, T., Foley, K., Hill, D., Hunter, S., Otto-Bliesner, B., Lunt, D., Robinson, M., and Salzmann, U.: Pliocene Model Intercomparison Project Phase 3 (PlioMIP3) – Science plan and experimental design, Global and Planetary Change, 232, 104 316, https://doi.org/10.1016/j.gloplacha.2023.104316, 2024.

Haywood, A. M., Valdes, P. J., and Sellwood, B. W.: Global scale palaeoclimate reconstruction of the middle Pliocene climate using the UKMO GCM: initial results, Global and Planetary Change, 25, 239–256, https://doi.org/10.1016/S0921-8181(00)00028-X, 2000.

Haywood, A. M., Dowsett, H. J., Dolan, A. M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M. A., Hunter, S. J., Lunt, D. J., Pound, M., and Salzmann, U.: The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: scientific objectives and experimental design, Climate of the Past, 12, 663–675, https://doi.org/10.5194/cp-12-663-2016, 2016.

Haywood, A. M., Tindall, J. C., Dowsett, H. J., Dolan, A. M., Foley, K. M., Hunter, S. J., Hill, D. J., Chan, W.-L., Abe-Ouchi, A., Stepanek, C., Lohmann, G., Chandan, D., Peltier, W. R., Tan, N., Contoux, C., Ramstein, G., Li, X., Zhang, Z., Guo, C., Nisancioglu, K. H., Zhang, Q., Li, Q., Kamae, Y., Chandler, M. A., Sohl, L. E., Otto-Bliesner, B. L., Feng, R., Brady, E. C., von der Heydt, A. S., Baatsen, M. L. J., and Lunt, D. J.: The Pliocene Model Intercomparison Project Phase 2: large-scale climate features and climate sensitivity, Climate of the Past, 16, 2095–2123, https://doi.org/10.5194/cp-16-2095-2020, 2020.

Hill, D., Csank, A., Dolan, A., and Lunt, D.: Pliocene climate variability: Northern Annular Mode in models and tree-ring data, Palaeogeography, Palaeoclimatology, Palaeoecology, 309, 118–127, https://doi.org/10.1016/j.palaeo.2011.04.003, special Issue: Climate and seasonality in a Pliocene warm world, 2011.

Horton, D. E., Johnson, N. C., Singh, D., Swain, D. L., Rajaratnam, B., and Diffenbaugh, N. S.: Contribution of changes in atmospheric circulation patterns to extreme temperature trends, Nature, 522, 465–469, 2015.

Howell, F. W., Haywood, A. M., Otto-Bliesner, B. L., Bragg, F., Chan, W.-L., Chandler, M. A., Contoux, C., Kamae, Y., Abe-Ouchi, A., Rosenbloom, N. A., Stepanek, C., and Zhang, Z.: Arctic sea ice simulation in the PlioMIP ensemble, Climate of the Past, 12, 749–767, https://doi.org/10.5194/cp-12-749-2016, 2016.

Hunter, S. J., Haywood, A. M., Dolan, A. M., and Tindall, J. C.: The HadCM3 contribution to PlioMIP phase 2, Climate of the Past, 15, 1691–1713, https://doi.org/10.5194/cp-15-1691-2019, 2019.

Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, Science, 269, 676–679, 1995.

https://doi.org/10.5194/egusphere-2026-4616
Preprint. Discussion started: 12 August 2026

Hurrell, J. W., Kushnir, Y., Ottersen, G., and Visbeck, M.: An Overview of the North Atlantic Oscillation, pp. 1–35, American Geophysical Union (AGU), ISBN 9781118669037, https://doi.org/https://doi.org/10.1029/134GM01, 2003.

Jerez, S., Trigo, R. M., Vicente-Serrano, S. M., Pozo-Vázquez, D., Lorente-Plazas, R., Lorenzo-Lacruz, J., Santos-Alamillos, F., and Montávez, J. P.: The Impact of the North Atlantic Oscillation on Renewable Energy Resources in Southwestern Europe, Journal of Applied Meteorology and Climatology, 52, 2204 – 2225, https://doi.org/10.1175/JAMC-D-12-0257.1, 2013.

Kamae, Y., Yoshida, K., and Ueda, H.: Sensitivity of Pliocene climate simulations in MRI-CGCM2.3 to respective boundary conditions, Climate of the Past, 12, 1619–1634, https://doi.org/10.5194/cp-12-1619-2016, 2016.

Kim, M.-K. and McCarl, B. A.: The agricultural value of information on the North Atlantic oscillation: yield and economic effects, Climatic Change, 71, 117–139, 2005.

Kravtsov, S.: Pronounced differences between observed and CMIP5-simulated multidecadal climate variability in the twentieth century, Geophysical Research Letters, 44, 5749–5757, https://doi.org/10.1002/2017GL074016, 2017.

Li, M., Yao, Y., Simmonds, I., Luo, D., Zhong, L., and Chen, X.: Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018, Environmental Research Letters, 15, 114 003, 2020a.

Li, X., Zhang, Z., Zhang, R., Tian, Z., and Yan, Q.: Mid-Pliocene westerlies from PlioMIP simulations, Advances in Atmospheric Sciences, 32, 909–923, https://doi.org/10.1007/s00376-014-4171-7, 2015.

Li, X., Guo, C., Zhang, Z., Otterå, O. H., and Zhang, R.: PlioMIP2 simulations with NorESM-L and NorESM1-F, Climate of the Past, 16, 183–197, https://doi.org/10.5194/cp-16-183-2020, 2020b.

Lunt, D. J., Chandan, D., Haywood, A. M., Lunt, G. M., Rougier, J. C., Salzmann, U., Schmidt, G. A., and Valdes, P. J.: Multi-variate factorisation of numerical simulations, Geoscientific Model Development, 14, 4307–4317, https://doi.org/10.5194/gmd-14-4307-2021, 2021.

Lurton, T., Balkanski, Y., Bastrikov, V., Bekki, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Contoux, C., Cozic, A., Cugnet, D., Dufresne, J.-L., Éthé, C., Foujols, M.-A., Ghattas, J., Hauglustaine, D., Hu, R.-M., Kageyama, M., Khodri, M., Lebas, N., Levavasseur, G., Marchand, M., Ottlé, C., Peylin, P., Sima, A., Szopa, S., Thiéblemont, R., Vuichard, N., and Boucher, O.: Implementation of the CMIP6 Forcing Data in the IPSL-CM6A-LR Model, Journal of Advances in Modeling Earth Systems, 12, e2019MS001 940, https://doi.org/10.1029/2019MS001940, e2019MS001940 10.1029/2019MS001940, 2020.

McClymont, E. L., Ford, H. L., Ho, S. L., Tindall, J. C., Haywood, A. M., Alonso-Garcia, M., Bailey, I., Berke, M. A., Littler, K., Patterson, M. O., Petrick, B., Peterse, F., Ravelo, A. C., Risebrobakken, B., De Schepper, S., Swann, G. E. A., Thirumalai, K., Tierney, J. E., van der Weijst, C., White, S., Abe-Ouchi, A., Baatsen, M. L. J., Brady, E. C., Chan, W.-L., Chandan, D., Feng, R., Guo, C., von der Heydt, A. S., Hunter, S., Li, X., Lohmann, G., Nisancioglu, K. H., Otto-Bliesner, B. L., Peltier, W. R., Stepanek, C., and Zhang, Z.: Lessons from a high-CO_2 world: an ocean view from $\sim$ 3 million years ago, Climate of the Past, 16, 1599–1615, https://doi.org/10.5194/cp-16-1599-2020, 2020.

McKenna, C. M. and Maycock, A. C.: Sources of Uncertainty in Multimodel Large Ensemble Projections of the Winter North Atlantic Oscillation, Geophysical Research Letters, 48, e2021GL093 258, https://doi.org/10.1029/2021GL093258, e2021GL093258 2021GL093258, 2021.

McKenna, C. M. and Maycock, A. C.: The Role of the North Atlantic Oscillation for Projections of Winter Mean Precipitation in Europe, Geophysical Research Letters, 49, e2022GL099 083, https://doi.org/10.1029/2022GL099083, e2022GL099083 2022GL099083, 2022.

Menemenlis, S., Lora, J. M., Lofverstrom, M., and Chandan, D.: Influence of stationary waves on mid-Pliocene atmospheric rivers and hydroclimate, Global and Planetary Change, 204, 103 557, https://doi.org/10.1016/j.gloplacha.2021.103557, 2021.

Mitevski, I., Lee, S., Vecchi, G., and Orbe, C.: More positive and less variable North Atlantic Oscillation at high CO2 forcing, npj Climate and Atmospheric Science, 8, 171, https://doi.org/10.1038/s41612-025-01051-7, 2025.

Muñoz, A., Ojeda, J., and Sánchez-Valverde, B.: Sunspot-like and ENSO/NAO-like periodicities in lacustrine laminated sediments of the Pliocene Villarroya Basin (La Rioja, Spain), Journal of Paleolimnology, 27, 453–463, 2002.

O'ishi, R., Chan, W.-L., Abe-Ouchi, A., Sherriff-Tadano, S., Ohgaito, R., and Yoshimori, M.: PMIP4/CMIP6 last interglacial simulations using three different versions of MIROC: importance of vegetation, Climate of the Past, 17, 21–36, https://doi.org/10.5194/cp-17-21-2021, 2021.

Oldeman, A. M., Baatsen, M. L. J., von der Heydt, A. S., Dijkstra, H. A., Tindall, J. C., Abe-Ouchi, A., Booth, A. R., Brady, E. C., Chan, W.-L., Chandan, D., Chandler, M. A., Contoux, C., Feng, R., Guo, C., Haywood, A. M., Hunter, S. J., Kamae, Y., Li, Q., Li, X., Lohmann, G., Lunt, D. J., Nisancioglu, K. H., Otto-Bliesner, B. L., Peltier, W. R., Pontes, G. M., Ramstein, G., Sohl, L. E., Stepanek, C., Tan, N., Zhang, Q., Zhang, Z., Wainer, I., and Williams, C. J. R.: Reduced El Niño variability in the mid-Pliocene according to the PlioMIP2 ensemble, Climate of the Past, 17, 2427–2450, https://doi.org/10.5194/cp-17-2427-2021, 2021.

Oldeman, A. M., Baatsen, M. L. J., von der Heydt, A. S., van Delden, A. J., and Dijkstra, H. A.: Mid-Pliocene not analogous to high-CO_2 climate when considering Northern Hemisphere winter variability, Weather and Climate Dynamics, 5, 395–417, https://doi.org/10.5194/wcd-5-395-2024, 2024.

O'Reilly, C. H., Weisheimer, A., Woollings, T., Gray, L. J., and MacLeod, D.: The importance of stratospheric initial conditions for winter North Atlantic Oscillation predictability and implications for the signal-to-noise paradox, Quarterly Journal of the Royal Meteorological Society, 145, 131–146, https://doi.org/10.1002/qj.3413, 2019.

O'Reilly, C. H., Befort, D. J., Weisheimer, A., Woollings, T., Ballinger, A., and Hegerl, G.: Projections of northern hemisphere extratropical climate underestimate internal variability and associated uncertainty, Communications Earth & Environment, 2, 194, 2021.

Pontes, G. M., Taschetto, A. S., Sen Gupta, A., Santoso, A., Wainer, I., Haywood, A. M., Chan, W.-L., Abe-Ouchi, A., Stepanek, C., Lohmann, G., et al.: Mid-pliocene el niño/southern oscillation suppressed by pacific intertropical convergence zone shift, Nature Geoscience, 15, 726–734, 2022.

Rehfeld, K., Hébert, R., Lora, J. M., Lofverstrom, M., and Brierley, C. M.: Variability of surface climate in simulations of past and future, Earth System Dynamics, 11, 447–468, https://doi.org/10.5194/esd-11-447-2020, 2020.

Riddle, E. E., Butler, A. H., Furtado, J. C., Cohen, J. L., and Kumar, A.: CFSv2 ensemble prediction of the wintertime Arctic Oscillation, Climate dynamics, 41, 1099–1116, 2013.

Roberts, C. D., Vitart, F., Balmaseda, M. A., and Molteni, F.: The Time-Scale-Dependent Response of the Wintertime North Atlantic to Increased Ocean Model Resolution in a Coupled Forecast Model, Journal of Climate, 33, 3663 – 3689, https://doi.org/10.1175/JCLI-D-19-0235.1, 2020.

Salzmann, U., Haywood, A. M., Lunt, D. J., Valdes, P. J., and Hill, D. J.: A new global biome reconstruction and data-model comparison for the Middle Pliocene, Global Ecology and Biogeography, 17, 432–447, https://doi.org/10.1111/j.1466-8238.2008.00381.x, 2008.

Salzmann, U., Dolan, A. M., Haywood, A. M., Chan, W.-L., Voss, J., Hill, D. J., Abe-Ouchi, A., Otto-Bliesner, B., Bragg, F. J., Chandler, M. A., et al.: Challenges in quantifying Pliocene terrestrial warming revealed by data–model discord, Nature Climate Change, 3, 969–974, https://doi.org//10.1038/nclimate2008, 2013.

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., Eade, R., Fereday, D., Folland, C. K., Gordon, M., Hermanson, L., Knight, J. R., Lea, D. J., MacLachlan, C., Maidens, A., Martin, M., Peterson, A. K., Smith, D., Vellinga, M., Wallace, E.,

https://doi.org/10.5194/egusphere-2026-4616
Preprint. Discussion started: 12 August 2026

Waters, J., and Williams, A.: Skillful long-range prediction of European and North American winters, Geophysical Research Letters, 41, 2514–2519, https://doi.org/10.1002/2014GL059637, 2014.

Schurer, A. P., Hegerl, G. C., Goosse, H., Bollasina, M. A., England, M. H., Smith, D. M., and Tett, S. F. B.: Role of multi-decadal variability of the winter North Atlantic Oscillation on Northern Hemisphere climate, Environmental Research Letters, 18, 044 046, https://doi.org/10.1088/1748-9326/acc477, 2023.

Smith, D., Dunstone, N., Eade, R., Hardiman, S., Hermanson, L., Scaife, A., and Seabrook, M.: Mitigation needed to avoid unprecedented multi-decadal North Atlantic Oscillation magnitude, Nature Climate Change, 15, 403–410, https://doi.org/10.1038/s41558-025-02277-2, 2025.

Song, Z., Nie, J., Dai, P., Lin, Z., Guo, J., Lan, J., Li, X., Lin, Q., Yin, Z., Yang, J., et al.: Origin and evolution of the North Atlantic Oscillation, Nature Communications, 16, 2142, https://doi.org/10.1038/s41467-025-57395-4, 2025.

Stepanek, C., Samakinwa, E., Knorr, G., and Lohmann, G.: Contribution of the coupled atmosphere–ocean–sea ice–vegetation model COSMOS to the PlioMIP2, Climate of the Past, 16, 2275–2323, https://doi.org/10.5194/cp-16-2275-2020, 2020.

Tan, N., Contoux, C., Ramstein, G., Sun, Y., Dumas, C., Sepulchre, P., and Guo, Z.: Modeling a modern-like $p\mathrm{CO_2}$ warm period (Marine Isotope Stage KM5c) with two versions of an Institut Pierre Simon Laplace atmosphere–ocean coupled general circulation model, Climate of the Past, 16, 1–16, https://doi.org/10.5194/cp-16-1-2020, 2020.

Wang, C., Su, H., Zhai, C., Zheng, J., Yu, S., Mo, H., Wang, Y., and Jiang, L.: Recent slowing of Arctic sea ice melt tied to multidecadal NAO variability, Nature Communications, 16, 8504, https://doi.org/10.1038/s41467-025-63520-0, 2025.

Weiffenbach, J. E., Baatsen, M. L. J., Dijkstra, H. A., von der Heydt, A. S., Abe-Ouchi, A., Brady, E. C., Chan, W.-L., Chandan, D., Chandler, M. A., Contoux, C., Feng, R., Guo, C., Han, Z., Haywood, A. M., Li, Q., Li, X., Lohmann, G., Lunt, D. J., Nisancioglu, K. H., Otto-Bliesner, B. L., Peltier, W. R., Ramstein, G., Sohl, L. E., Stepanek, C., Tan, N., Tindall, J. C., Williams, C. J. R., Zhang, Q., and Zhang, Z.: Unraveling the mechanisms and implications of a stronger mid-Pliocene Atlantic Meridional Overturning Circulation (AMOC) in PlioMIP2, Climate of the Past, 19, 61–85, https://doi.org/10.5194/cp-19-61-2023, 2023.

White, R. H., Hilgenbrink, C., and Sheshadri, A.: The Importance of Greenland in Setting the Northern Preferred Position of the North Atlantic Eddy-Driven Jet, Geophysical Research Letters, 46, 14 126–14 134, https://doi.org/10.1029/2019GL084780, 2019.

Williams, C. J. R., Sellar, A. A., Ren, X., Haywood, A. M., Hopcroft, P., Hunter, S. J., Roberts, W. H. G., Smith, R. S., Stone, E. J., Tindall, J. C., and Lunt, D. J.: Simulation of the mid-Pliocene Warm Period using HadGEM3: experimental design and results from model–model and model–data comparison, Climate of the Past, 17, 2139–2163, https://doi.org/10.5194/cp-17-2139-2021, 2021.

Woollings, T., Hannachi, A., and Hoskins, B.: Variability of the North Atlantic eddy-driven jet stream, Quarterly Journal of the Royal Meteorological Society, 136, 856–868, https://doi.org/10.1002/qj.625, 2010.

Zanardo, S., Nicotina, L., Hilberts, A. G. J., and Jewson, S. P.: Modulation of Economic Losses From European Floods by the North Atlantic Oscillation, Geophysical Research Letters, 46, 2563–2572, https://doi.org/10.1029/2019GL081956, 2019.

Zappa, G., Hoskins, B. J., and Shepherd, T. G.: The dependence of wintertime Mediterranean precipitation on the atmospheric circulation response to climate change, Environmental Research Letters, 10, 104 012, https://doi.org/10.1088/1748-9326/10/10/104012, 2015.

Zhang, Z., Li, X., Guo, C., Otterå, O. H., Nisancioglu, K. H., Tan, N., Contoux, C., Ramstein, G., Feng, R., Otto-Bliesner, B. L., Brady, E., Chandan, D., Peltier, W. R., Baatsen, M. L. J., von der Heydt, A. S., Weiffenbach, J. E., Stepanek, C., Lohmann, G., Zhang, Q., Li, Q., Chandler, M. A., Sohl, L. E., Haywood, A. M., Hunter, S. J., Tindall, J. C., Williams, C., Lunt, D. J., Chan, W.-L., and Abe-Ouchi, A.: Mid-Pliocene Atlantic Meridional Overturning Circulation simulated in PlioMIP2, Climate of the Past, 17, 529–543, https://doi.org/10.5194/cp-17-529-2021, 2021.

https://doi.org/10.5194/egusphere-2026-4616
Preprint. Discussion started: 12 August 2026

Zhao, A., Brierley, C., Arra-Kastrati, V., Shi, X., and Hu, Y.: North Atlantic Oscillation (NAO) in the Paleoclimate Modelling Intercomparison Project (PMIP), Climate of the Past, 22, 689–708, https://doi.org/10.5194/cp-22-689-2026, 2026.

Zheng, J., Zhang, Q., Li, Q., Zhang, Q., and Cai, M.: Contribution of sea ice albedo and insulation effects to Arctic amplification in the EC-Earth Pliocene simulation, Climate of the Past, 15, 291–305, https://doi.org/10.5194/cp-15-291-2019, 2019.