The profound influence of the North Atlantic Ocean on Northeast Asia: a comprehensive multi-model study

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RESEARCH ARTICLE

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The profound influence of the North Atlantic Ocean on Northeast Asia: A comprehensive multi-model study

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Abstract

We assess the effects of the North Atlantic Sea surface temperature multidecadal variability on Northeast Asia using a set of sensitivity experiments (with a total of 530 ensemble members). We show that a warming of the North Atlantic Ocean leads to a strong and robust increase in temperature over Northeast Asia, which is replicated by a large majority of ensemble members. We show that the effect of the North Atlantic on Northeast Asia is model and season-dependent. We focus on two seasons, for which response to the North Atlantic Ocean is the most robust (autumn) and the less robust (spring) as indicated by the number of models that simulate a statistically significant change in surface air temperature. We use a clustering method to identify the sources of differences between models in simulating the effects of warming in the North Atlantic. We find that the primary mechanism linking the North Atlantic to Northeast Asia is a perturbation of the circumglobal teleconnection pattern (i.e., of the upper tropospheric atmospheric circulation), which allows modulation of the near-surface atmospheric circulation and an increase in temperature over East Asia. A second mechanism is related to the influence of the North Atlantic on the Pacific Ocean and the resulting effects on atmospheric circulation over Northeast Asia.

KEYWORDS

CMIP6 models, East Asian climate, North Atlantic Ocean, telectionnection

1 | INTRODUCTION

East Asia, a densely populated area, is particularly vulnerable to climate variability. In the mid-1990s, Northeast Asia experienced significant warming, surpassing that of its surrounding regions (Chen and Dong, 2019; Chen and Lu, 2014; Dong, Sutton, Chen, et al., 2016). This warming led to a surge in heat extremes (Chen and Dong, 2019; Dong, Sutton, Chen, et al., 2016), a factor directly linked to a rise in the mortality rate.

Previous studies have linked, using observations and simulations, the warming of Northeast Asia to changes in sea surface temperatures (SSTs), sea ice concentration changes and anthropogenic aerosol emissions over the Northern Hemisphere (Dong et al., 2016). The anthropogenic forcing has led to a warming of Northeast Asia since the 1950s, with the warming induced by the Greenhouse gas forcing largely offsetting the cooling that is associated with an increase in anthropogenic aerosol emissions locally (Hu & Sun, 2022; Su et al., 2024). The climate of Northeast Asia is influenced by global variations in SST, with the potential for the decadal modes of variability (e.g., Pacific Decadal Variability; Interdecadal Pacific Oscillation; Atlantic Multidecadal Variability—AMV) to influence the decadal variability of surface air temperature in Northeast Asia (e.g., Cai et al., 2024; Sun et al., 2019). In particular, the North Atlantic Ocean significantly warmed in the mid-1990s (Robson et al., 2012), and a warming of the North Atlantic Ocean has been associated with a warming of Northeast Asia (Gebremeskel Haile et al., 2019; Hodson et al., 2022; Li et al., 2015; Monerie et al., 2020; Qian et al., 2014; Wei et al., 2023).

Two main mechanisms have been described to explain how a warming of the North Atlantic Ocean can affect the surface air temperature over Northeast Asia. On the one hand, the warming of the North Atlantic Ocean is associated with a perturbation of the upper troposphere through the release of sensible and latent heat over the tropical Atlantic Ocean (Monerie et al., 2019, 2020; Ruprich-Robert et al., 2021). The perturbation of the upper atmospheric circulation is then associated with the propagation of a Rossby wave (Hong et al., 2018; Lin et al., 2016; Wu et al., 2016), also known as a perturbation of the circumglobal teleconnection pattern at a decadal timescale (CGT; Ding & Wang, 2005). The perturbation of the CGT affects the climate over Europe and Asia, leading to an increase in temperature over Northeast Asia by modulating temperature advection (Monerie et al., 2020; Sun et al., 2019) and shortwave radiation through changes in cloud cover (Sun et al., 2019). On the other hand, the warming of the North Atlantic Ocean is associated with a strengthening of the Walker circulation and a cooling of the eastern tropical Pacific Ocean (Dong et al., 2006; Lu et al., 2006; Monerie et al., 2020; Ruprich-Robert et al., 2021) and a warming of the western tropical Pacific Ocean. The warming of the western Pacific Ocean allows an increase in precipitation and the propagation of a Rossby wave over the western Pacific Ocean (e.g., Sun et al., 2022) from Southern Japan to Alaska, hence modulating the atmospheric circulation and surface air temperature over northeast Asia (Monerie et al., 2020).

Besides the effects on surface air temperature, previous studies have shown that the warming of the North Atlantic Ocean has multiple impacts on Asia. The decadal variations of the North Atlantic SSTs affect the northeast Asian summer precipitation (Si et al., 2021; Zhao et al., 2019, 2020), decadal variation of Meiyu (Ding et al., 2020), the Indian Monsoon (Monerie et al., 2019), and the temperature over Siberia (Sun et al., 2015), for example.

Mechanisms linking the North Atlantic to the climate of Northeast Asia remain unclear because (i) of the short duration of the observations, which does not allow sampling of many events of the AMV, (ii) that previous studies were based on only one climate model (e.g., Monerie et al., 2020), while the effect of the AMV may be model-dependent. We fill this gap with many ensemble simulations using multi-models from different research projects. These simulations have been designed to specifically assess the question of the observed effect of AMV on climate. We focus the study on the climate of Northeast Asia and assess, for the first time, the relevance of the proposed mechanisms with many specific climate simulations.

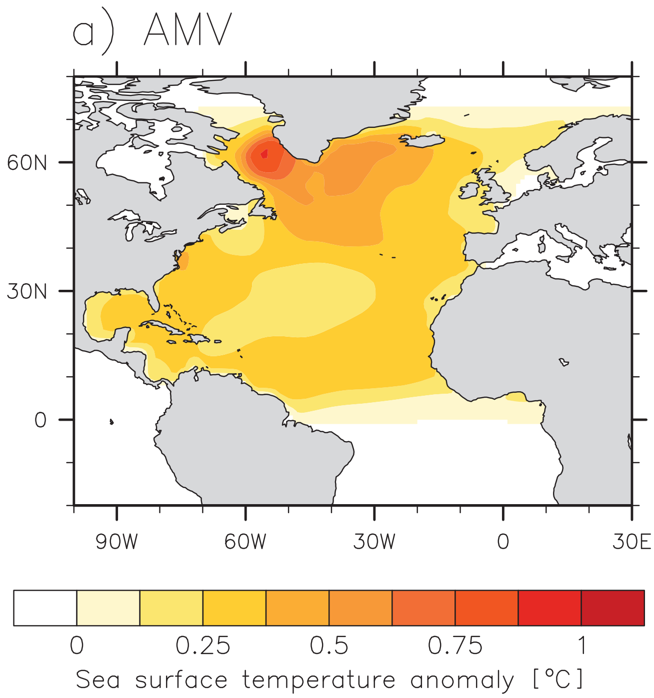

FIGURE 1 Idealised Atlantic SST target anomalies (°C) used in model experiments. The AMV patterns in derived from observed SSTs, following the CMIP6 DCPP-C protocol (Boer et al., 2016; https://www.wcrp-climate.org/wgsip/documents/Tech-Note-1.pdf).

2 | METHOD

2.1 | Simulations

We assess the effects of the AMV on climate using simulations where the North Atlantic SST were restored in the North Atlantic basin, increased, and decreased to mimic the effect of a positive and a negative phase of the AMV, respectively (see the pattern of the anomaly within Figure 1). Patterns are extracted using observations (e.g., Boer et al., 2016), as the regression of the SSTs onto the standardized AMV index over the 1900–2013 period

TABLE 1 List of models and references.

Model	Number of ensemble members	Resolution (latitude × longitude)	Project	References
CNRM-CM6-1	15	1.4° × 1.4°	PRIMAVERA	Voldoire et al. (2019)
CNRM-CM6-1	26	1.4° × 1.4°	DCPP-C	Voldoire et al. (2019)
ECMWF-IFS-LR	30	1° × 1°	PRIMAVERA	Roberts et al. (2018)
ECMWF-IFS-HR	15	0.5° × 0.5°	PRIMAVERA	Roberts et al. (2018)
EC-EARTH3	32	0.7° × 0.7°	DCPP-C	Haarsma et al. (2020)
EC-EARTH3P	25	0.7° × 0.7°	PRIMAVERA	Haarsma et al. (2020)
EC-EARTH3P-HR	17	0.35° × 0.35°	PRIMAVERA	Haarsma et al. (2020)
HadGEM3-GC31-MM	25	0.55° × 0.83°	DCPP-C	Williams et al. (2018)
IPSL-CM6A-LR	50	2.5° × 1.3°	DCPP-C	Boucher et al. (2020)
MetUM-GOML2-LR	15	1.25° × 1.875	PRIMAVERA	Hirons et al. (2015)
MetUM-GOML2-HR	15	0.55° × 0.83°	PRIMAVERA	Hirons et al. (2015)

(see Technical Note; https://www.wcrp-climate.org/dcp-overview for more detailed information).

We use the data from two research projects, the EU Horizon 2020 PRIMAVERA and the Decadal Climate Prediction Project component C (DCPP-C; Boer et al., 2016). PRIMAVERA uses a protocol similar to DCPP-C, with a difference in the background radiative forcing and the imposed SST anomaly, which is twice stronger in PRIMAERVA than in DCPP-C (Hodson et al., 2022). The effect of the AMV has hence been halved in the PRIMAVERA simulations to allow for a comparison between simulations of the two projects, following (Ruprich-Robert et al., 2021) and (Mohino et al., 2024). This assumes a linearity in the effect of the AMV, but which could not be verified here. We use many ensemble members (Table 1; 265 ensemble members for simulations where a warming is imposed and 265 ensemble members where a cooling is imposed). The climate models are ocean–atmosphere general circulation models, except for the MetUM models where the ocean is represented by a mixed-layer model. All simulations run for 10 years (with fixed external forcing), for a total of 5300 years of simulation (265 ensemble members × 2 experiments × 10 years). Outputs have been interpolated to a common 1° × 1° grid using a bilinear interpolation.

2.2 | Method

2.2.1 | The effect of the North Atlantic SSTs

The effects of the AMV are obtained by subtracting the simulations in which the SST was cooled (negative phase of the AMV) from the simulation in which the SST was increased (positive phase of the AMV). We use all years of all simulations to compute the ensemble means. Statistical significance is assessed using a Student's t test. We assess the reproducibility of the result, that is, we define the multi-model mean to be robust when at least 80% of the models produce a change that is statistically significant and has the same sign as the multi-model mean.

2.2.2 | The clustering method

We expect that the changes in the atmospheric circulation are key to understanding the effect of the AMV on Northeast Asian temperature, as shown in Wang et al. (2017), Sun et al. (2019), Monerie et al. (2020). We also expect that the simulations will produce a wide variety of changes in atmospheric circulation. We highlight the diversity in atmospheric circulation anomalies using an agglomerative hierarchical clustering (AHC) algorithm (Jain et al., 1999). The AHC reveals the dissimilarity between clusters according to an Euclidean distance, using Ward's method, which minimises the sum of the squared differences within all clusters (Ward, 1963). The AHC is applied to the changes in 200 hPa geopotential height (Z200), over Eurasia (25°N–70°N; 10°E–150°E), following the above literature. The analysis is performed on the spatial correlation matrix in Z200 computed from 265 simulations, that is, a 265 × 265 spatial correlation matrix. We define four clusters to account for the diversity of responses that can be obtained. The AHC is applied using the Python function SciPy linkage. The AHC has been previously used to classify precipitation anomalies and models (e.g., Monerie et al., 2016; Ullmann et al., 2014).

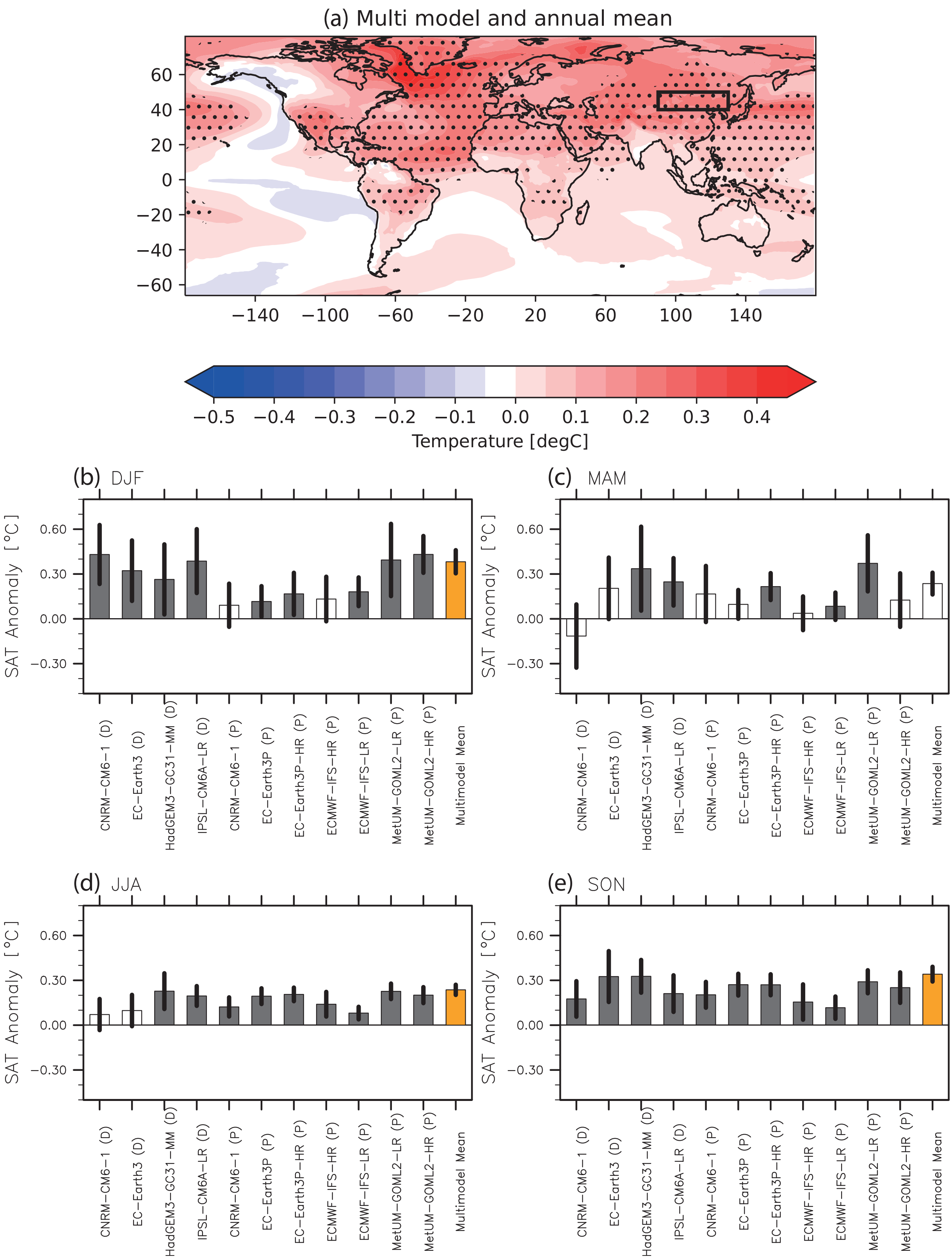

FIGURE 2 Legend on next page.

3 | RESULTS

3.1 | Changes in northeast Asian surface air temperature

The multi-model mean shows a robust effect of the AMV on the Northeast Asian temperature (Figure 2a). A warming of the North Atlantic Ocean is also associated with strong and statistically significant warming over the Northern Hemisphere, with warming over the northern Pacific Ocean, the United States (Ruprich-Robert et al., 2018), North Africa (Mohino et al., 2024), Central Asia and East Asia (Hodson et al., 2022; Monerie et al., 2020) (Figure 2a). The warming of the North Atlantic Ocean is also associated with warm temperatures over the Amazon basin and southern Africa (Figure 2a).

We show the diversity of responses by assessing the changes in surface air temperature for each model and for each season (Figure 2b–e). The models generally produce an increase in temperature over Northeast Asia. However, the change in Northeast Asian surface air temperature is model and season-dependent (Figure 2b–e). For example, all models show a statistically significant increase in temperature over Northeast Asia in autumn (SON) (Figure 2e), while the change in Northeast Asian surface air temperature in spring (MAM) is not robust for the multi-model mean and for about half of the models (Figure 2c). We focus the analysis on these two seasons (SON and MAM), for which we have contrasting responses in the effects of the AMV on Northeast Asian temperature (robust in SON and uncertain in MAM). Besides, those are transition seasons, for which the effects of climate variability are less documented than for the summer and winter.

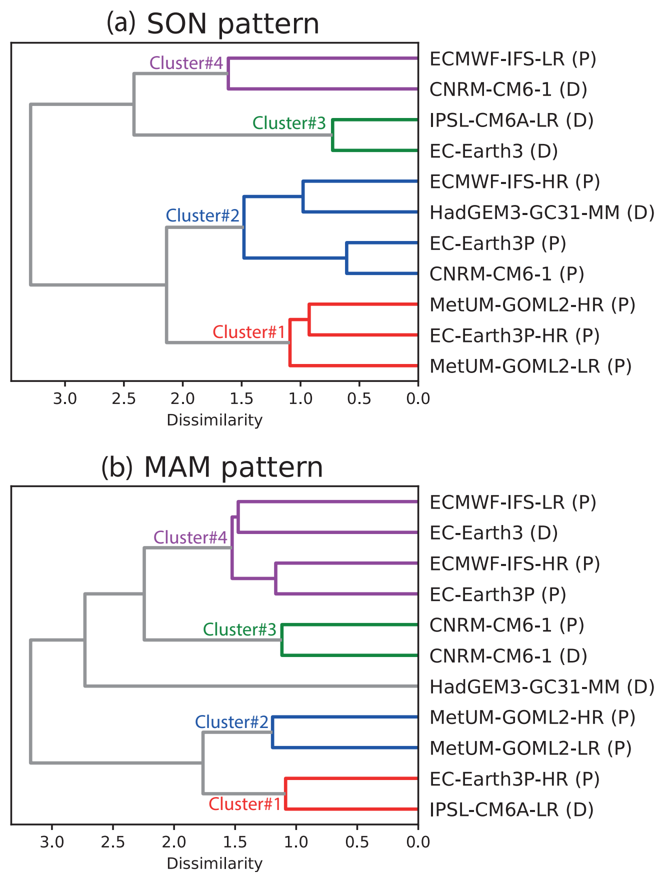

FIGURE 3 Model dendrogram from the DCPP-C and PRIMAERVA simulations on the effect of the AMV on the Z200 (25°N–70°N; 10°E–150°E), for (a) SON and (b) MAM. The dendrogram is computed from a hierarchical clustering of the pairwise distance matrix for Z200; see Section 2.2.2). Simulations on the same branch simulate similar patterns in Z200 anomalies. Each colour denotes a cluster. HadGEMS3-GC31-MM is considered as an outlier in MAM and is not included in the analysis. A "P" ("D") indicates models that are from the PRIMAVERA (DCPP-C) project.

3.2 | A diversity of responses

Figure 3 shows the results of the AHC applied to the effect of the AMV on the atmospheric circulation (Z200). Short distances between models indicate a high degree of similarity between anomalies in Z200. Models that are in the same cluster thus produce similar patterns in Z200 anomaly. There are similarities between the models of the same institution. For example, the two versions of the MetUM-GOML model are in the same cluster for both SON (cluster #1; Figure 3a) and MAM (cluster #2; Figure 3b). The two CNRM-CM6 models are in cluster #3 in MAM (Figure 3b), see also the EC-Earth and ECMWF

FIGURE 2 (a) Effect of the AMV on surface air temperature [°C] for the multi-model mean and the annual mean. Stippling indicates that at least 80% of the models produce a statistically significant (according to a Student's t test at the 1% confidence level) change in surface air temperature with the same sign as the multi-model model. Change in surface air temperature averaged over Northeast Asia (black box on panel a) for each model and for (b) DJF, (c) MAM, (d) JJA, and (e) SON. A grey (white) bar indicates that the change in surface air temperature is (is not) statistically significant according to a Student's t test at the 1% confidence level). The rightmost bar indicates the change in surface air temperature of the multi-model mean, with an orange (white) bar indicating that at least 80% of the models show a change in surface air temperature that is statistically significant. The vertical bars are defined as two times the standard error. A "P" ("D") indicates models that are from the PRIMAVERA (DCPP-C) project.

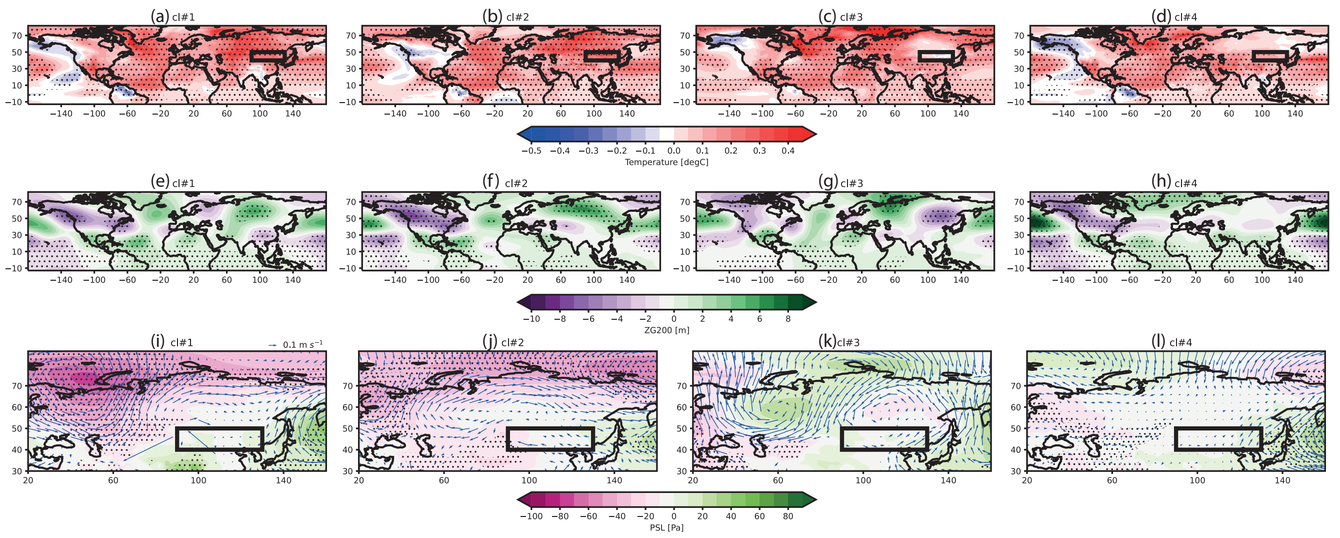

FIGURE 4 Effects of the AMV on (a–d) surface air temperature [°C], (e–h) Z200, and (i–l) sea level pressure and 850 hPa wind speed in MAM, for the ensemble mean of the (a–e–i) cluster #1, (b–f–j) cluster #2, (c–g–k) cluster #3, and (d–h–l) cluster #4. Stippling indicates that the anomaly is statistically significant according to a Student's *t* test at the 5% confidence level.

models in MAM. There are also differences in the responses of models from the same institution. For example, cluster #2 is composed of four different models, and the low-resolution version of EC-EARTH3 is closer to the IPSL model than to its high-resolution version in SON (Figure 3b). This last result could indicate an effect of the resolution on the simulation of the AMV on the atmospheric circulation, but we have too few models to properly assess this scientific question.

3.3 | Mechanisms at play

3.3.1 | In March–April–May

The AMV has a strong and widespread effect on the East Asian surface air temperature only in the first two clusters, while there is no temperature change in cluster #3 and a moderate increase in cluster #4 (Figure 4a,b). The clusters #1, #2, and #3 are associated with a wave train over the Northern Hemisphere, as indicated by the alternation of positive and negative anomalies in Z200. This is a perturbation of the CGT pattern, as shown in previous published studies (e.g., Lin et al., 2016; Monerie et al., 2020; Sun et al., 2019).

The difference between the clusters is, by construction, the pattern of the Z200 anomaly. In clusters #1 and #2 there is an increase in Z200 over central Russia and East Asia (Figure 4e,f), which is associated with an increase in surface air temperature over Northeast Asia (Figure 4a,b). In clusters #3 and #4, there is a decrease in Z200 over East Asia (Figure 4g,h) and no change in temperature over Northeast Asia (Figure 4c,d). There is, therefore, a strong correspondence between changes in surface–air temperature and changes in Z200.

In both clusters #1 and #2, the anomalous southerlies and south easterlies at the west edge of the anomalous anticyclonic circulation over the western North Pacific in the lower troposphere are associated with anomalous heat advection from the tropical Pacific Ocean to East Asia (Figure 4i,j), contributing to the warming of Northeast Asia. In clusters #3 and #4, there is an export of anomalous heat from Northeast Asia to the northwest and western Pacific Ocean, contributing to the absence of an increase in temperature over Northeast Asia (Figure 4k,l). The anomaly in Z200 of cluster #3 also resembles the North Atlantic-East-Asia pattern identified by Chen, Wu, Chen, Hu, and Yu (2020), showing multiple responses of the North Atlantic warming on the atmospheric circulation in the upper troposphere. In cluster #4, temperature increases over the western part of Northeast Asia due to an advecting of heat from the South and the East, where temperature increases significantly (Figure 4l). We thus show that the differences between models in simulating the surface air temperature anomaly are related to the patterns of the Z200 anomaly, but that the mechanism (i.e., the CGT) is the same across models.

3.3.2 | In September–October–November

The warming of the North Atlantic is associated with a warming of Northeast Asia in all clusters (Figure 5a–d).

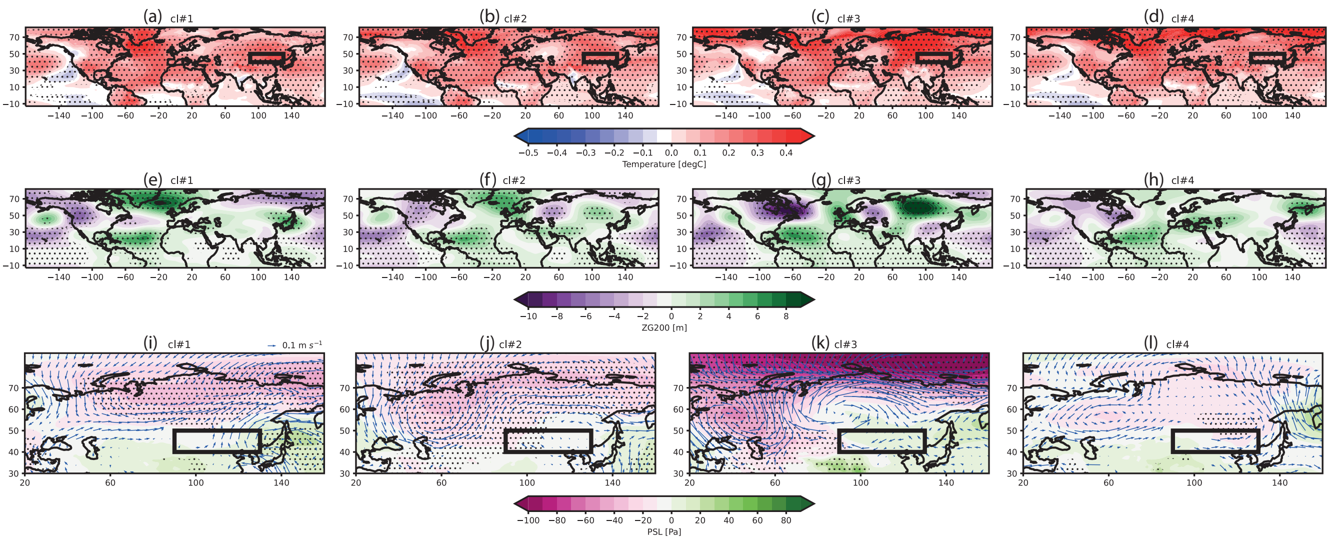

FIGURE 5 Same as Figure 3 but for SON.

However, and like for MAM, the pattern of surface air temperature change is cluster-dependent. We link the pattern of the surface air temperature anomaly to the pattern of the Z200 anomaly. The strong land warming (weak warming) (Figure 5a–d) is associated with an increase (decrease) in Z200 (Figure 5e–h), showing an influence of atmospheric circulation on the effect of AMV on Northeast Asian climate. For example, the strong warming of Northeast Asia is associated with an increase in Z200, while the insignificant warming of Eastern Europe is associated with no change or a decrease in Z200 (Figure 5a–d, e–h). The increase in Z200 over Northeast Asia is associated with an anomalous anticyclonic circulation that can allow the advection of warm air from the tropical Pacific and from the south into Northeast Asia (Figure 5i–l), as seen in Monerie et al. (2020). A comparison of the anomalies of Z200 and Z850 indicates that the anomalies in atmospheric circulation are equivalent barotropic (Figure S1), and that the change in atmospheric circulation is a response to the warming of the North Atlantic Ocean.

In cluster #1, the anomaly in Z200 is not clearly related to a change in CGT. Instead, there is a tripolar anomaly over the Pacific Ocean (decrease in Z200 over the equator and north of 50°N; increase in Z200 over Northeast Asia) that is associated with the Pacific-Japan like pattern (Nitta, 1987). The result of cluster #1 is consistent with (Monerie et al., 2020) who show, using MetUM-GOML2-LR, that the increase in temperature (Figure 4a) and precipitation (Figure S2) of the tropical West Pacific Ocean allows the development of a Rossby wave that affects the climate of Northeast Asia. Cluster #1 is dominated by the MetUM-GOML models, and thus cluster #1 mainly features the effect of the AMV on the Walker circulation and its effect on Northeast Asian climate (Monerie et al., 2020).

Clusters #2 and #3 show an alternation of positive and negative anomalies in Z200 across the Northern Hemisphere, which is a fingerprint of a perturbation of the CGT pattern (e.g., Lin et al., 2016). The perturbation of the CGT pattern is associated with a modulation of the sea level pressure and the wind at 850 hPa, which transports a relatively warm air northwards and increases the temperature (Figure 5j,k).

The third cluster is associated with an increase in Z200 over the Mediterranean Sea and western central Asia (Figure 5h), and a decrease in Z200 over the western subtropical Pacific Ocean (Figure 5h), which allows heat to be transported from the southwest to East Asia (Figure 5l). Z200 decreases over the Pacific Ocean (10°S-30°N) and increases over Siberia, allowing the advection of heat from the tropical Pacific to eastern Asia (e.g., Monerie et al., 2021).

Unlike Sun et al. (2019) we show no strong and robust changes in downwelling shortwave radiation over East Asia (Figure S3). Changes in net longwave radiation allow decreases in temperature, damping a part of the surface warming (not shown). As shown for MAM, we note that other atmospheric circulation can play a role in explaining the effect of the North Atlantic Ocean on Northeast Asia, such as the East Atlantic/West Russian pattern of Chen et al. (2019).

4 | CONCLUSION

Previous studies have shown that the Atlantic Multidecadal Variability (AMV) can affect the climate of Northeast

Asia (Chen et al., 2016, 2021; Chen & Wu, 2017; Chen, Wu, Chen, & Li, 2020; Lin et al., 2016; Monerie et al., 2020; Sun et al., 2019). These results are of societal importance because they suggest that changes in North Atlantic Sea Surface Temperature (SST) can affect extreme events over East Asia, including heat extremes and heat waves. Furthermore, it has been shown that a good prediction of the North Atlantic SST could allow the prediction of surface air temperature over Northeast Asia up to 5 years in advance due to the existing link between the AMV and the climate of Northeast Asia (Monerie et al., 2017).

We, for the first time, describe how the AMV can affect the surface air temperature over Northeast Asia using a large ensemble of climate models and simulations (a total of 11 climate models and 530 ensemble members). We use simulations where the North Atlantic Ocean is warmed and cooled to mimic the SST anomalies associated with the observed AMV. We show that the warming of the North Atlantic Ocean is associated with an increase in temperature over Northeast Asia and that this result is broadly reproduced by all climate models. The warming of Northeast Asia occurs throughout the year. However, the link between the AMV and Northeast Asia is not as robust in March–April–May (MAM) as in the other seasons, with only about half of the models showing a statistically significant effect of the AMV on Northeast Asian temperature in MAM. The response of the North Atlantic warming is particularly robust in autumn when all models show statistically significant warming of Northeast Asia. The strongest response is obtained in winter (DJF).

The main mechanism linking the North Atlantic to Northeast Asia is a perturbation of the circumglobal teleconnection (CGT) pattern, which allows modulation of the atmospheric circulation and an increase in temperature over East Asia. This mechanism was found in most climate models (and clusters) in both spring and autumn. Differences between models in simulating the pattern of the surface air temperature anomaly then depend on the simulated changes in the atmospheric circulation at 200 hPa, with differences in the location of the crossings and ridges. The pattern of the upper atmospheric circulation is thus important in simulating the effect of the AMV on the climate of Northeast Asia. A second mechanism at play, although only included in a limited number of models (and clusters), is related to a change in the atmospheric circulation over East Asia and the western Pacific, which allows the advection of warm air from the western tropical Pacific to Northeast Asia (e.g., Monerie et al., 2021). This aforementioned particular response is associated with a Pacific-Japan pattern and with the propagation of a Rossby wave caused by warming and increased precipitation south of Japan, as shown in (Monerie et al., 2020). The change in the atmospheric circulation can also be the manifestation of different anomaly patterns, such as the North Atlantic-East Asian pattern (Chen, Wu, Chen, Hu, & Yu, 2020) or the East Atlantic/West Russian pattern (Chen et al., 2019), which we expect to be model-dependent. Moreover, we assume that a more in-depth analysis is required to understand better the mechanisms at play for each climate model, such as analysing the thermodynamic and dynamic effects of North Atlantic warming (Wang et al., 2024) or assessing temperature statistics (e.g., extremes). This could be the focus of a future study, with results presented here allowing the efficient selection of climate models for more in-depth analysis with higher-frequency datasets. Similarly, a better understanding of differences between climate models in simulating the CGT pattern is required to improve our understanding of the effects of the North Atlantic Ocean on Northeast Asian climate.

A further study would use these results to assess how Northeast Asian climate could be predicted up to a decade ahead, based on a good prediction of the North Atlantic SST (García-Serrano et al., 2015) and to the robust link between the North Atlantic SST and Northeast Asian climate that we show in this study, building on (Monerie et al., 2017). Predicting Northeast Asian temperature up to a decade in advance is an important societal and scientific issue.

AUTHOR CONTRIBUTIONS

Paul-Arthur Monerie: Conceptualization; methodology; writing – review and editing; writing – original draft; formal analysis. **Buwen Dong:** Writing – review and editing; software; data curation. **Weiwen Sun:** Conceptualization; visualization; methodology. **Lixia Zhang:** Validation; project administration; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ESGF servers at https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/.

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SUPPORTING INFORMATION

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