Asymmetric response of ~~European~~Northern Hemisphere near-surface wind speed to CO_2 removal

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Abstract

Understanding ~~the~~ changes in near-surface wind speed (NSWS) is crucial for weather extremes prediction and wind energy management. This study examines the response of NSWS to atmospheric carbon dioxide (CO_2) removal using large ensemble simulations ~~and the~~ of the Community Earth System Model version 1.2 (CESM1.2) and the models participating in the Carbon Dioxide Removal Model Intercomparison Project ~~models~~. Our results ~~indicate~~reveal that increasing CO_2 ~~levels~~ concentrations lead to an overall ~~reduction~~weakening in the Northern Hemisphere (NH) extratropical NSWS over land. ~~Subsequent CO_2 reduction during the~~ During the initial stage of CO_2 removal (early ramp-down period), NH NSWS rapidly ~~restores NH NSWS.~~recovers. However, this recovery stalls and ~~enters~~transitions into a declining trend during the late ramp-down period, mainly ~~due to opposite~~driven by pronounced negative NSWS trends in Europe. ~~Notably, the~~We find that a concurrent rapid recovery of ~~simultaneous~~the Atlantic Meridional Overturning Circulation (AMOC) counteracts the global cooling-induced recovery of the North Atlantic ~~air~~ meridional air temperature gradient and ~~the~~associated westerly jet ~~by global cooling, therefore~~, thus prolonging NSWS weakening in NH mid-latitudes ~~NSWS weakening.~~. Our findings underscore the pivotal and phase-dependent role of AMOC in ~~modulating~~regulating NH extratropical NSWS variability under varying CO_2 concentrations ~~and provides~~, offering valuable insights for future climate adaptation strategies.

1 Introduction

The phenomena of terrestrial near-surface wind speed (~10 m above the ground; NSWS) "stilling" and subsequent "reversal" have been recognized for over a decade, yet significant gaps remain in understanding these processestheir underlying mechanisms (Wu et al., 2018; Zeng et al., 2019). FutureAccurate future projections of NSWS have garnered significant attention partlyprimarily due to their implications for wind energy development (Karnauskas et al., 2018; Zeng et al., 2019; Zhang and Li, 2020; Pryor et al., 2021; Shen et al., 2024). Several studies based on climate model simulations have investigated thefuture spatiotemporal variations of NSWS in response to increasing atmospheric carbon dioxide (CO_2) forcing in the coming years until the end of this century based on climate models,), revealing complex global and regional variations drivenresponses influenced by polar amplification and altered land-sea thermal gradients (Bichet et al., 2012; Karnauskas et al., 2018; Shen et al., 2021; Zha et al., 2021; Deng et al., 2022). Future projections using these models, mostly from the Coupled Model Intercomparison Project Phases 5 and 6 (CMIP5 and CMIP6) (Taylor et al., 2012; O'Neill et al., 2016), suggest aconsistently project robust reductionreductions in NSWS across theover mid-latitudeslatitude land areas of the Northern Hemisphere (NH) landand increases in the 21st century, while an increase acrossparts of the Southern Hemisphere by the end of the 21st century (Karnauskas et al., 2018; Zha et al., 2021; Deng et al., 2022; Shen et al., 2022). However, the ideal CO_2these idealized CO_2 experiments in CMIP5 and CMIP6 mainly consider an increased carbon emission scenario by the end oftypically focus on scenarios involving continuously rising CO_2 concentrations through the 21st century, andwhile the further potential CO_2impacts of subsequent CO_2 removal impact on NSWS hashave not been studied. Understandingexamined. Clarifying this response is crucial in light of imperative, given global decarbonization goalsobjectives and the extensiveanticipated widespread

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deployment of wind ~~power~~energy resources (Lei et al., 2023).

The irreversibility and asymmetry of various climate phenomena have been investigated ~~under~~through CO_2 ramp-up and ramp-down experiments using the global climate models. Many studies ~~used~~have employed the standard CMIP “1pctCO_2” experiment as the ramp-up ~~period~~experiment, in which ~~the~~ CO_2 concentration gradually increases at a rate of 1% per year for 140 years until it quadruples relative to pre-industrial levels (Eyring et al., 2016). On this basis, different ramp-down scenarios ~~of ramp-down period are~~have been performed to ~~study~~assess the reversibility of CO_2~~-~~-induced climate change (Wu et al., 2010; Cao et al., 2011; Boucher et al., 2012; MacDougall, 2013; Wu et al., 2014; Ma et al., 2016; Field and Mach, 2017; Ehlert and Zickfeld, 2018). ~~Meanwhile~~To systematically explore such scenarios, the Carbon Dioxide Removal Model Intercomparison Project (CDRMIP) in CMIP6 has been launched to provide 1pctCO_2-carbon dioxide removal experiment as the ramp-down period, in which the climate initiates from the end of the 1pctCO_2 experiment and the evolution of CO_2 concentration mirrors that in the 1pctCO_2 experiment (Keller et al., 2018). ~~And~~These experiments facilitate evaluation of climate responses and the ~~projection~~associated uncertainties ~~related to different~~stemming from model ~~frameworks could also be investigated by these experiments~~differences (Zhang et al., 2023; Jin et al., 2024; Su et al., 2024).

Following the CDRMIP protocol (Keller et al., 2018), An et al. (2021) conducted large-ensemble simulations of CO_2 ramp-up and ramp-down simulations using the Community Earth System Model version 1.2 (CESM1.2). It is found that major ocean circulation systems, particularly the Atlantic Meridional Overturning Circulation (AMOC~~)~~), shows a unique delayed recovery that significantly shapes the responses of other climatic factors (An et al.,

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2021; Oh et al., 2022). ~~On this basis, following~~Subsequent studies ~~extend to~~expanded on these results to examine implications for the hydrological cycle (Yeh et al., 2021; Kim et al., 2022; Kug et al., 2022; Im et al., 2024), El Niño–Southern Oscillation (Liu et al., 2023a, b; Pathirana et al., 2023), Hadley cell (Kim et al., 2023), gross primary productivity (Yang et al., 2024) and mid-latitude storm tracks (Hwang et al., 2024), all ~~showing~~demonstrating varying degrees of irreversibility. ~~For the aspect of~~Regarding wind speed, Hwang et al. (2024) ~~found that~~reported enhanced cyclone-related surface wind extremes ~~become more frequent~~ in southern North America and Europe ~~in~~during the late CO_2 removal period~~, while changes in~~. However, the responses of mean NSWS under these CO_2 scenarios have received little attention.

~~-~~Given ~~that CESM has a reasonable performance~~CESM's demonstrated capability in reproducing global historical NSWS patterns (Shen et al., 2022~~),~~) and considering the importance of wind energy resources in the NH mid-latitudes are expected to be significantly developed ~~in the NH mid-latitudes~~ (Pryor et al., 2020). We are motivated to investigate how NSWS in the NH mid-latitudes would respond to potential future CO_2 removal ~~by using the~~. To ensure robustness, we analyze results from CESM1.2 ~~simulations and~~alongside those from three available CMIP6 models participating in the CDRMIP ~~project~~.

2 Data and Method

2.1 CESM1.2 Simulations

~~The~~ CESM1.2 (Hurrell et al., 2013) includes the atmosphere (Community Atmospheric Model version 5), ocean (Parallel Ocean Program version 2), sea ice (Community Ice Code version 4), and land models (Community Land Model version 4). The atmospheric

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~~model~~component features a horizontal resolution of approximately 1° and 30 vertical levels (Neale et al., 2012). The ocean ~~model comprises~~component includes 60 vertical levels, with a longitudinal resolution of about 1° and a latitudinal resolution of about 0.3° near the equator, increasing gradually to about 0.5° near the poles (Smith et al., 2010). The land ~~model~~component includes the carbon-nitrogen cycle (Lawrence et al., 2011).

The experiment followed idealized CO_2 scenarios in two phases (An et al., 2021). In the first phase, the CO_2 concentration was held constant at 367 ppm, representing present-day levels, and the model is integrated for 900 years. In the second phase, the CO_2 concentration increased from 367 ppm to 1,478 ppm at a rate of 1% per year over 140 years (2001–2140: ramp-up period), then decreased back to 367 ppm at the same rate over the next 140 years (2141–2280: ramp-down period). After the ramp-down period, CO_2 levels were stabilized at 367 ppm for 220 years (2281–2500: stabilization period). This second phase was run with 28 ensemble members, each starting from different initial conditions taken from the present-day period, representing various phases of multi-decadal climate oscillations such as the Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation. Such large ensemble simulations provide a sufficient tool to separate the forced responses from internal variability, making it effective in assessing forced changes in regional NSWS (Li et al., 2019; Deser et al., 2020; Zha et al., 2021).

2.2 CDRMIP Simulations

We further utilized CMIP6 models in the CDRMIP to verify the results of CESM1.2. Notably, CanESM5, MIROC-ES2L, and NorESM2-LM models are the only three available models with variables of "sfcWind" (near-surface wind speed) and "msftmz" (stream function, for calculating AMOC), and each model contains one realization. We compared terrestrial NSWS (60°S–70°N) climatology in their present-day run (CESM1.2) and piControl experiments (CanESM5, MIROC-ES2L, and NorESM2-LM) with the ERA5 (Hersbach et al., 2020), and found that the pattern correlation coefficients are 0.85, 0.81, 0.72, and 0.89 for CESM1.2, CanESM5, MIROC-ES2L, and NorESM2-LM, respectively. ~~Indicating their reasonable ability~~For the 20°N–70°N terrestrial NSWS, the pattern correlation coefficients are 0.71, 0.59, 0.52, and 0.83, respectively (Figure S1). The magnitudes between four models and the ERA5 are comparable, and the area weighted root mean squared difference between models and ERA5 are 1.03, 1.07, 1.37, and 0.71 m s^{-1}, respectively. These indicate an overall reasonable ability of models in reproducing the large-scale characteristics of terrestrial NSWS.

2.3 AMOC Index

The AMOC index was calculated as the maximum stream function value at 26.7°N in the North Atlantic (0°N–70°N, 60°W–30°E), providing a robust measure of AMOC strength and variability across different simulation phases (An et al., 2021).

2.4 Statistical Methods

To facilitate consistent analysis, all data were bi-linearly interpolated to a uniform 1.5° × 1.5° grid~~ for both latitude and longitude.~~. All calculations related to NSWS are focused on the land regions. An 11-year running mean was used for all physical variables, unless otherwise stated. To clarify and quantify the contributions of global-mean surface air temperature and AMOC to NSWS changes, we performed a bi-regression analysis. This analysis allowed us to assess the proportion of NSWS variance explained by each factor during different periods.

3 NSWS Responses to CO_2 Ramp-up and Ramp-down

In the CESM1.2 simulations, the annual global-mean surface air temperature (GMST) increases by about 5ºC from 2000 to 2140 (Figure 1a). This warming trend reverses during the ramp-down period (2141–2280) as CO_2 concentrations decrease, ~~but~~although the cooling trend is less pronounced than the ~~prior~~preceding warming. During the stabilization period (2281–2500), GMST remains approximately 1ºC above the year 2000 levels for ~~about~~roughly 40 years before gradually declining ~~until~~toward 2500. Spatially, the ramp-up period shows pronounced warming over high-latitude land areas~~ and less over the oceans~~, whereas oceanic warming is moderate (Figure ~~S1a~~S2a). The Subpolar North Atlantic (SNA) exhibits minimal warming, known as "warming hole" or "cold blob" (Chemke et al., 2020; Keil et al., 2020; Rahmstorf, 2024), and is likely due to reduced heat transport associated with a weakening AMOC under global warming (Zhang et al., 2019). Conversely, during the ramp-down period (2141–2280), most areas cool, including the SNA (Figure ~~S1b~~S2b). The asymmetric surface air temperature (SAT) ~~trend~~trends over the SNA ~~is mostly related to~~are largely driven by the ~~late~~delayed recovery of~~ the~~ AMOC during the late ramp-down period (2221–2280), which is influenced by increased salt advection feedback due to changes in the subtropic-to-subpolar salinity gradient and ocean stratification (An et al., 2021; Oh et al., 2022).

~~During~~Throughout the CO_2 ramp-up period (2001–2140), the NH-averaged (20°N–70°N) annual-mean NSWS decreased, consistent with projections by CMIP6 models (Zha et al., 2021;

Shen et al., 2022). The ramp-down period is divided into early (2141–2220) and late (2221–2280) ramp-down periods (An et al., 2021). During the early ramp-down period (2141–2220), NSWS in the NH extratropics quickly rebounds rapidly to year-2000 levels at about double the rate of the ramp-up period. The correspondingCorrespondingly, SAT pattern features stronger cooling over the SNA (Figure S1cS2c), similar to the ramp-up period, indicating a strengthened meridional SAT gradient. DuringIn contrast, during the late ramp-down period (2221–2280), NH extratropical NSWS trend moderate across the NH extratropicschanges moderately (Figure 1b), accompanied by a notable warming trend over the SNA and weaker cooling trends over theat high NH latitudes of the NH compared to the early ramp-down period (2141–2220) (Figures S1cS2c–d). Throughout the stabilization period (2281–2500), NH NSWS trends in the NH continueinitially continues to decline, for several decades beforeslowly, then gradually increasingincreases towards the end of the periodsimulation.

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To investigatefurther examine the regional reversibility of NSWS under varying CO_2 forcingconditions, Figures 2a–d show the spatial patterns of NH NSWS trends during the ramp-up, ramp-down, early ramp-down, and late ramp-down periods, respectively. During the ramp-up period (2001–2140) (Figure 2a), significant negative NSWS trends dominate theprevail across mid-latitudes ofin the NH. During the ramp-down period (2141–2280), this spatial pattern reverses (Figure 2b), with a pattern correlation coefficient of -0.9 ($P<0.01$) between the ramp-up and ramp-down periods, highlighting a substantial impactthe pronounced effect of $CO_2$$CO_2$ forcing on global NSWS patternsdistributions. Spatial discrepancies between two ramp-down periods are primarily observed over the Eurasia continent: during the early ramp-down period (2141–2220), NSWS shows marked positive trends (Figure 2c); however, these positive trends turn negative in Europe and diminish in North America and Central Asia in the late ramp-down period (2221–2280) (Figure 2d).

~~We further examined~~Additionally, we validated NSWS responses ~~in~~using three CMIP6 models from CDRMIP ~~to testify the CESM1.2-based results~~ (Figures ~~S2~~S3 and ~~S3~~S4). It is found that the time series of NSWS over the NH extratropics are generally similar across the three models (Figure ~~S2~~S3), as are the spatial patterns of NSWS trends (Figure ~~S3). However, there are also some evident~~S4). Nevertheless, noticeable inter-model ~~differences~~discrepancies exist between the CDRMIP models and the CESM1.2~~ model~~. A fast recovery of NSWS is observed in the NH extratropics in the CESM1.2 during the early ramp-down period (Figure 1b), while it shows overall symmetric changes in three CDRMIP models ~~during the~~ throughout ramp-up and ramp-down ~~period~~periods (Figure ~~S2). The discrepancies are partly related to a different~~S3). These differences likely stem from differing AMOC ~~evolution~~evolutions among the models, a point we elaborate further in the ~~CESM1.2, which will be discussed in the next~~following section.

4 Effect of AMOC on Modulating the NH Extratropical NSWS

Previous studies ~~suggested~~indicate that hemispheric-scale NSWS changes are strongly influenced by~~ the~~ large-scale meridional SAT gradient (Zha et al., 2021; Deng et al., 2022; Shen et al., 2022; Li et al., 2024), with NH mid-latitude NSWS ~~changes being~~ closely linked to variations in the westerly jet ~~through the~~due to vertical downward momentum transport ~~of~~from upper~~-level horizontal momentum~~ tropospheric levels (Shen et al., 2023; Shen et al., 2025). Moreover, the strength of the AMOC critically affects these regional patterns by

Formatted: Font: +Body (等线), 10.5 pt modulating the meridional SAT gradient and the westerly jet through its control of the SNA temperature (Zhang et al., 2019; An et al., 2021; Hwang et al., 2024). Figure 3a shows the evolution of the AMOC index in the The CESM1.2, revealing simulations reveal a clear weakening trend in AMOC (~0.5 Sv decade^{-1}) during the ramp-up period extending until about year 2200, followed by a rapid strengthening trendrecovery (~1.2 Sv decade^{-1}) persisting until around year 2300. Temporal changes of AMOC are similar among (Figure 3a). By comparison, the three CDRMIP models (Figure S4), withexhibit symmetric decreasingdeclining and increasingrecovering trends in AMOC strength during ramp-up and ramp-down periods. , respectively (Figure S5).The different responses of AMOC would influenceacross models significantly affect regional temperatureSAT gradient, further modulatethereby altering regional atmospheric circulation (Hwang et al., 2024).

To disentangleelucidate the combined effects of CO_2 levels and AMOC variability on NSWS variations, we analyzed the temporal evolutionevolutions of meridional SAT gradients and westerly jets acrossfor both the NH and North Atlantic (NA) (Figures 3b–e). The NH meridional SAT gradient was defined as the SAT difference between midtropical (0°N–30°N) and high-latitude (60°N–90°N) and tropical (0°N-30°N) bands. Mid-latitude westerly jets were defined as the average 500 hPa zonal winds for 30°N–60°N. A significant negative correlation (-0.78, *P*<0.01) exists between the NH extratropical NSWS (Figure 1b) and the NH SAT gradient (Figure 3b), whereas a strong positive correlation (0.91, *P*<0.01) is detected with the NH westerly jet (Figure 3c). During the ramp-up period (2001–2140), reductions in the weakened NH SAT gradient contributedcontribute to a reducedweaker westerly jet and a weakeningreduced NSWS trend across extratropics. The NH extratropical NSWS trend

~~reverses~~Conversely, in the early ramp-down period (2141–2220~~) as~~), NSWS quickly rebounds alongside recovery of the ~~NH~~ SAT gradient and westerly jet ~~recovers~~. However, ~~in~~during the late ramp-down period (2221–2280), the NH SAT gradient ~~enhanced a bit~~stabilizes (Figure 3b), ~~while~~resulting in slow changes in both the NH westerly jet (Figure 3c) and extratropical NSWS (Figure 1b~~) change slow, disregarding~~), despite the CO_2-removal-induced global cooling. These ~~observations suggest~~dynamics underscore an effect from the AMOC, which strongly modulates the SAT gradient in the NA, and thus local NSWS trends.

During the ramp-up period (2001–2140), the NA SAT gradient (60°W–30°E, 0°N–30°N minus 60°W–30°E, 60°N–90°N) weaken by approximately 1°C (Figure 3d), a ~~smaller change~~relatively small magnitude compared to the 6.5°C reduction in the NH SAT gradient (Figure 3b). ~~Actually, the~~The NA SAT gradient changes are modulated by two combined effects: CO_2-induced global warming/cooling and the AMOC strength (Zhang et al., 2019). This milder NA SAT gradient change is related to a weakened AMOC's role in transporting warm water to the SNA, which partially offsets the hemisphere-scale SAT gradient weakening induced by global warming (Figure 3d). And the weakened NA SAT gradient favors a weakened NA NSWS (Fig. 1b). In the early ramp-down period (2141–2220), the synergistic effects of global cooling and a further weakened AMOC promote a stronger enhancement of the NA SAT gradient (Figure 3d) and westerly jet (Figure 3e~~).~~), which induce a rapidly enhancement of NA NSWS (Fig. 1b). Conversely, during the late ramp-down period (2221–2280), the ~~fast~~rapid recovery of the AMOC dramatically increases warm water flow to the SNA (Figure S1d), diminishes the NA SAT gradient (Figure 3d) despite the prevailing global cooling effect from CO_2-removal, and leads to a weakened NA westerly jet (Figure 3e) and

NSWS (Fig. 1b).

~~The annual mean~~Spatial patterns of 500 hPa zonal ~~wind patterns~~ winds (Figure ~~4~~S6) reflect similar tendencies to those of NSWS in the NH, particularly across mid-latitudes where enhanced zonal winds correlate with increased NSWS (Figure 2), and vice versa. Throughout the ramp-up period (2001–2140), there is a general weakening trend of westerly jets over the ~~mid-latitude regions of the~~ Asian and North American continents, while regional westerlies intensify over NA and Europe (Figure ~~4a~~S6a). The early ramp-down period (2141–2220) witnesses significant strengthening trend of NH westerly jets (Figure ~~4c~~S6c), propelled by global cooling and a weakened AMOC (Figure ~~S1c~~S2c). During the late ramp-down period (2221–2280), recovery of the AMOC causes significant weakening of westerly jets over NA and Europe by reducing the NA SAT gradient (Zhang et al., 2019; An et al., 2021; Hwang et al., 2024) (Figures 3d–e~~, and S5d~~), which correspondingly weakens NSWS over Europe (Figure 2d).

~~To further demonstrate the effect of the~~ Internally generated AMOC ~~on~~ changes ~~in the NA SAT gradient and westerly jet, Figure 5 displays the inter-ensemble~~ can also support our argument about the potential roles played by CO_2-forced AMOC changes. To quantify how internal AMOC variability contributes to the cross-member spread of key NA climate variables, Figure 4 shows the yearly Pearson correlation coefficients ~~between~~among the 28 CESM ensemble members ~~for~~between AMOC strength and (i) the ~~AMOC,~~ NA meridional SAT gradient, (ii) the NA westerly-jet intensity, and (iii) the European (30°–60 °N~~–60°N~~, 5 °W–60 °E) NSWS. ~~The cross-member~~ Because all members share identical external forcing, these inter-ensemble correlations ~~are not significant during the~~ isolate internal variability.

Significant correlations thus indicate that internal AMOC fluctuations are major drivers of atmospheric variability among ensemble members. During the ramp-up period (2001–2140~~)~~ ~~but become prominent in the~~), the ensemble spread of AMOC remains small, and correlations with the three metrics are weak and statistically insignificant. However, during the late ramp-down period (2221–2280), ~~underscoring~~ the ~~crucial effect~~spread of AMOC ~~recovery on weakening~~ substantially increases, and the correlations become statistically significant. These year-by-year correlations clearly demonstrate that larger (smaller) AMOC anomalies are associated with a weaker (stronger) NA SAT gradient ~~and~~ , a reduced (enhanced) westerly jet, ~~leading to strong reductions in~~and lower (higher) European NSWS. ~~These findings indicate that the fast recovery of the AMOC plays a dominant role in shaping the westerly jet during the late ramp-down period, and consequently, the extratropical NSWS.~~

Moreover, we ~~performed~~conducted a bi-regression analysis using GMST and AMOC ~~to fit the changes of NSWS in~~ as explanatory variables for NH ~~extratropics during~~extratropical NSWS variability across three distinct periods. During the ramp-up period (2001–2140), GMST and AMOC explain the variance of NH extratropical NSWS for 98% and 1.2%, respectively. During the early ramp-down period (2141–2220), GMST and AMOC explain 95.3% and 4.2% of the variance, respectively. ~~While~~However, during the late ramp-down period (2221–2280), ~~GMST and~~ the relative influence of AMOC ~~explain 24.5% and~~sharply increases, accounting for 73.2% of ~~the~~ variance, ~~respectively. The regression results show changes in~~ surpassing GMST (24.5%). Thus, while GMST ~~make the dominant role in regulating~~predominantly governs NH extratropical NSWS changes during ~~the ramp-up and early ramp-down~~ periods~~, when~~ of weaker AMOC ~~shows gradually weakening trend. But the~~

effect ofvariability, AMOC plays a key roleemerges as the dominant factor only when its anomalies become significantly large, such as during its rapid recovery in the late ramp-down period due to the fast recovery of AMOC. The results are consistent with those in Fig. S6c, suggestingphase. Besides, we also performed similar analysis for the three CDRMIP models. Among three models and two periods, the contributions of GMST always dominate (contributions >90%) the NH extratropical NSWS changes, further supporting that the trends of the NSWS are not simply in phase with the evolution of either CO2 or thea substantial AMOC anomaly is required for AMOC to notably influence NSWS changes, as observed in CESM.

5 Summary and Outlook

In this study, we utilizeutilized a CESM1.2 $CO_2$$CO_2$ removal experiment to assessevaluate the response of NH extratropical NSWS to anthropogenic CO_2 CO_2 emission levels. and subsequent removal. Our analyses reveal an asymmetric response of the NH extratropical NSWS during the CO_2 ramp-up (2001–2140) and ramp-down (2141–2280) periods., driven by phase-dependent interactions between GMST changes and AMOC-related heat transport anomalies. Figure 65 summarizes the underlying physical mechanisms about how CO_2 and AMOC heat transport modulate European NSWS changes.: During the ramp-up period, (Figure 5a), the gradually weakening AMOC transports less warm water northward, thereby enhancing the meridional SAT gradient and thus strengthen NH and NA NSWS. However, the counteracting effect of CO_2-driven global warming strongly reduces the NH meridional SAT gradient, ultimately dominating the response and resulting in decreased NSWS shows

~~decreasing trends in the~~across NH extratropics. During the early ramp-down period~~, NSWS~~ (Figure 5b), CO_2 removal-induced global cooling combines with further AMOC weakening to substantially ~~intensifies, facilitated by the combined effects of a weakened AMOC and the global cooling induced by CO_2 removal. These conditions strengthened the meridional SAT gradient and~~ enhance the ~~tropospheric~~ SAT gradient, intensifying the westerly jet~~, enhancing NSWS at these latitudes. In contrast~~ and increasing NH NSWS, with GMST remaining the dominant driver due to its stronger anomalies. Conversely, during the late ramp-down period~~,~~ (Figure 5c), a rapid AMOC recovery ~~of~~substantially increases northward heat transport, significantly weakening the ~~AMOC leads to significant reductions in the North Atlantic~~NA SAT gradient and subsequently diminishing the westerly jet and NSWS. This ~~effect is stronger than the global cooling~~ AMOC-driven weakening outweighs concurrent weaker GMST cooling-induced ~~by CO_2 removal, markedly~~strengthening of the SAT gradient, inducing a weakening NH and NA NSWS~~ over Europe and resulting in an NSWS decrease over the NH.~~ .

The European NSWS ~~changes follow~~exhibits distinct anticlockwise trajectories in relation to CO_2 concentrations (Figure ~~7a), indicating~~6a), signifying stronger NSWS during ~~the~~ CO_2 removal ~~period~~ than during the ~~CO_2 increasing~~ ramp-up period at identical CO_2 ~~concentrations~~levels (Kim et al., 2022). Although there are also asymmetries of NSWS over Aisa and North America (Figures ~~7b~~6b–c), ~~but the amplitudes~~their magnitudes are ~~much~~substantially weaker ~~than that over~~compared to Europe. These phenomena imply the ~~effect~~particular importance of AMOC ~~is crucial to~~ variability for European NSWS. ~~Moreover~~Furthermore, three CDRMIP models ~~from the CDRMIP reasonably~~generally replicate NH extratropical NSWS ~~changes over the extratropics. The reason why CDRMIP~~

~~models can not reproduce~~trends but fail to capture the pronounced asymmetry found in CESM, likely due to their relatively symmetric AMOC evolutions, which yield almost linear NSWS responses. This highlights that the asymmetric NSWS ~~response is due to the symmetric AMOC evolution during the ramp-down period, which means the AMOC's effects are linearly in these models~~responses critically depend on nonlinear AMOC dynamics. We acknowledge several uncertainties inherent in our findings, including potential model-dependency arising from CESM's large ensemble experiment and limited realizations from the CDRMIP simulations. Future studies involving more extensive multi-model ensembles could further validate and enhance the robustness of our conclusions.

Before this study, the impact of the AMOC on terrestrial NSWS changes had been less recognized. Our ~~results~~findings advance the understanding ~~in~~within the wind research community~~, offering valuable insights into~~ by highlighting a crucial role for ocean circulation in modulating long-term NSWS ~~dynamics~~trends. The enhanced NH NSWS during the early CO_2 removal period could significantly increase wind energy production (Pryor et al., 2020) but also heighten the risks of wind-related extremes (Hwang et al., 2024; Yu et al., 2024). ~~Therefore~~Consequently, it is critical for monitoring efforts and climate policy formulations to consider these findings in their long-term climate strategies to optimize benefits and mitigate risks associated with wind energy and climate interventions.

Declaration of competing interests

The authors declare no conflicts of interest.

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Data Availability

All data used in this study are publicly available. The CESM1.2 outputs are available from https://data.mendeley.com/datasets/f5ry6hgxkw/2. CMIP6 outputs are available from the Earth System Grid Federation (https://esgf-data.dkrz.de/projects/esgf-dkrz/). And ERA5 reanalysis data are available from the European Centre for Medium-Range Weather Forecasts (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview).

Supplementary Information

The manuscript contains supplementary materials.

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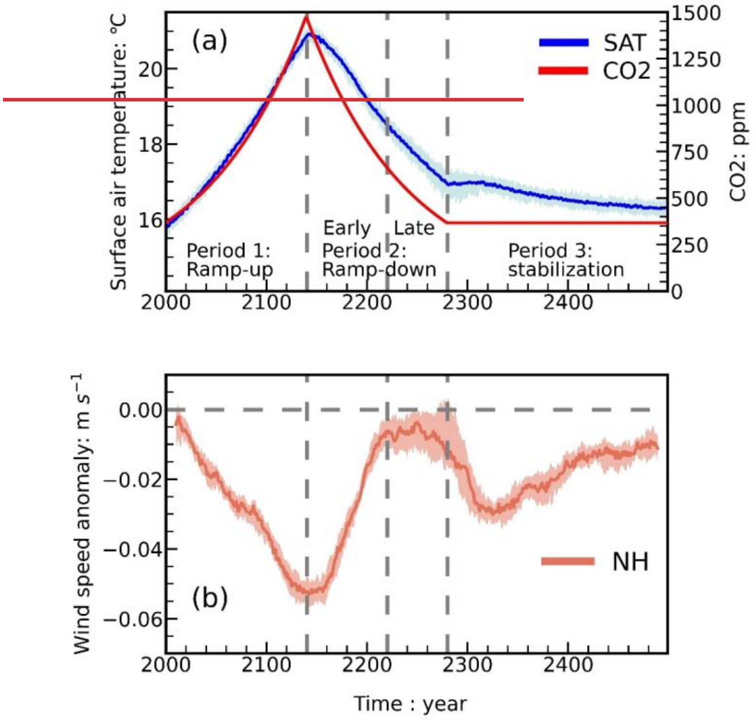


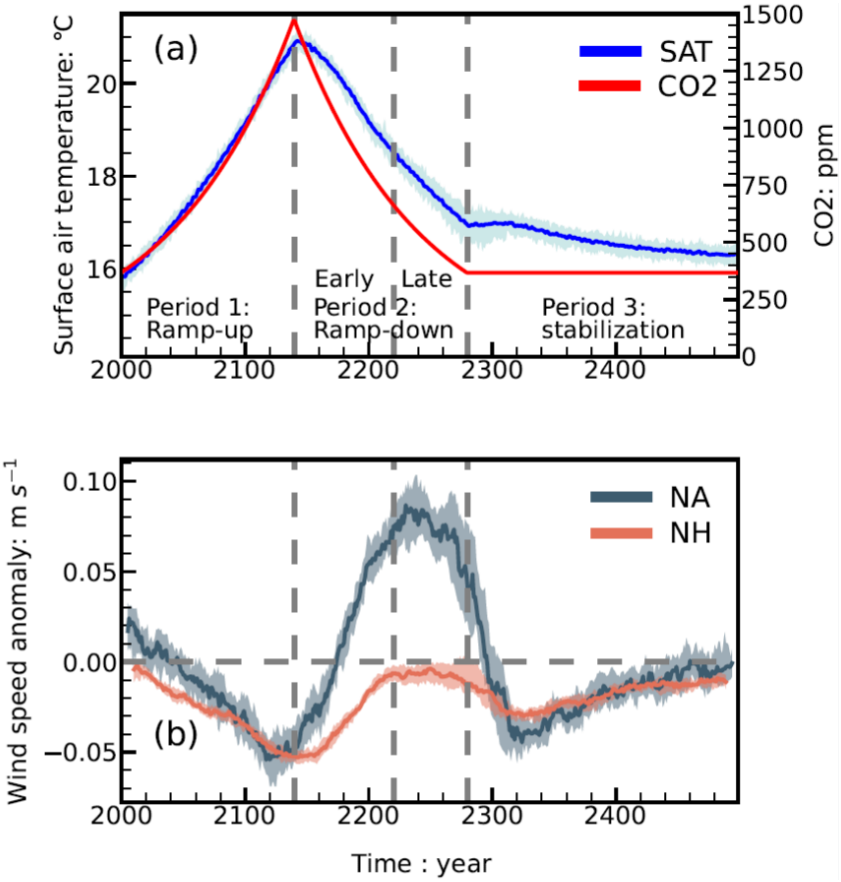


Figure 1. (a) Temporal changes of the annual global mean surface air temperature (SAT; unit: °C) (blue) and CO_2 concentration (unit: ppm) (red). The solid lines represent the ensemble means, while the shaded areas indicate the 25th to 75th percentile range across 28 members. Three dashed gray lines mark the years 2140, 2220, and 2280, highlighting important temporal milestones in the experiment. (b) Temporal changes of annual-mean terrestrial near-surface wind speed (NSWS; unit: m s^{-1}) over Northern Hemisphere (20°N–70°N) (orange~~).~~) and North Atlantic (0°N–70°N, 60°W–30°E) (dark blue). Anomalies are calculated relative to the average NSWS of the constant CO_2 scenario. An 11-year running mean has been applied to smooth out inter-annual variability.

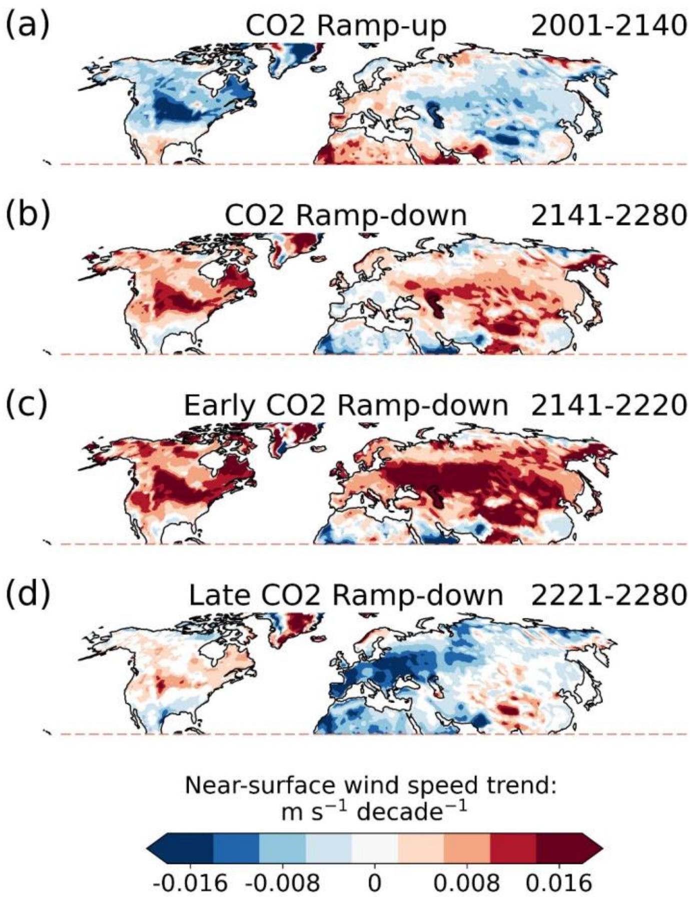
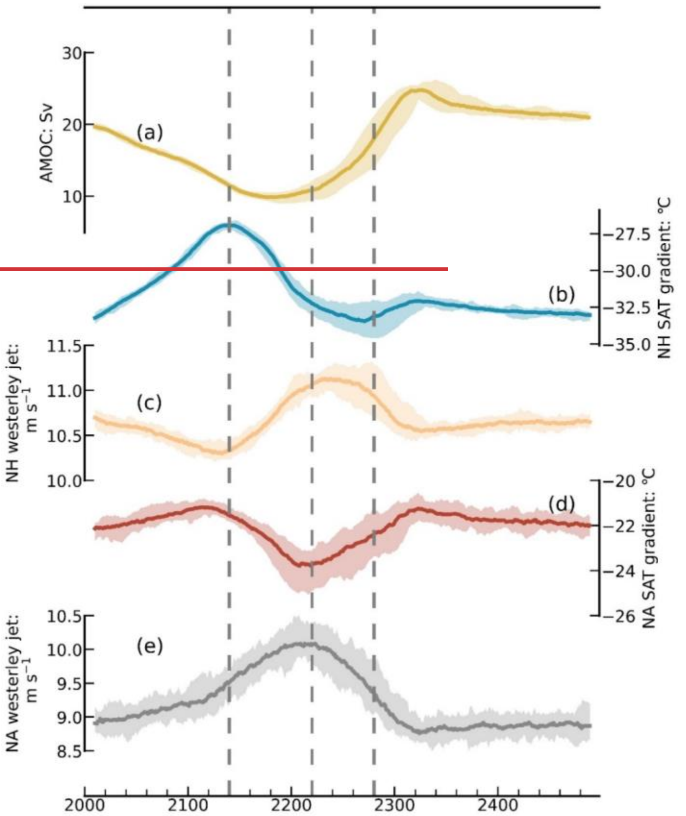


Figure 2. (a) Decadal trend in annual-mean near-surface wind speed (unit: m s^{-1} decade^{-1}) during the CO_2 ramp-up period (2001–2140). Grid points with shadings denote the tendencies are significant at the 0.05 level. (b–d) Same as (a), but for tendencies during the CO_2 ramp-down period (2141–2280), early CO_2 ramp-down period (2141–2220), and late CO_2 ramp-down period (2221–2280), respectively.

608 

AMOC: Sv
(a)
NH SAT gradient: °C
(b)
NH westerley jet: m s⁻¹
(c)
NA SAT gradient: °C
(d)
NA westerley jet: m s⁻¹
(e)
2000
2100
2200
2300
2400

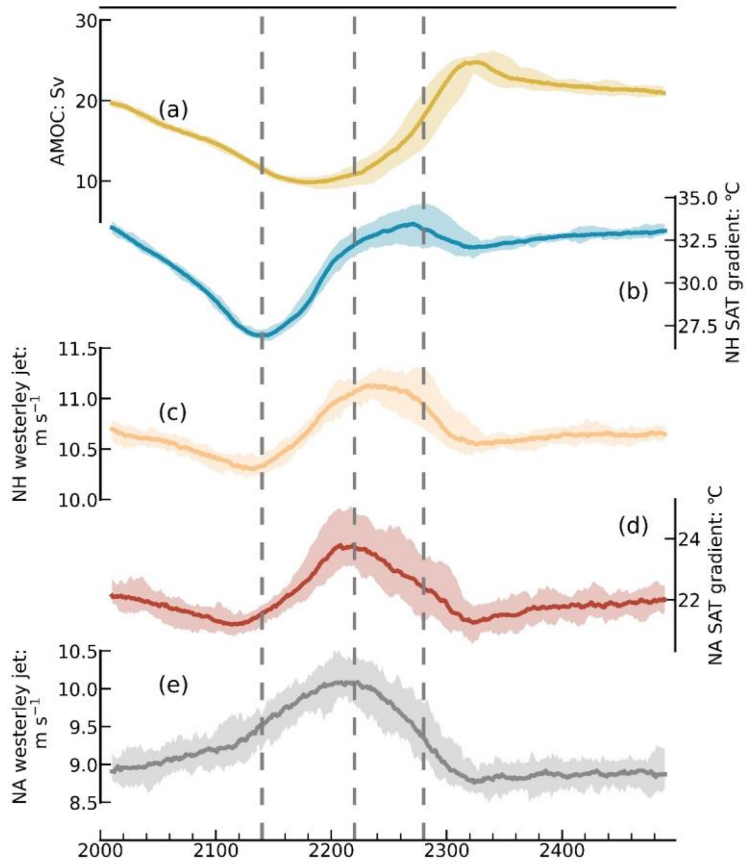


Figure 3. (a) Temporal changes of the Atlantic Meridional Overturning Circulation index (unit: Sv). The solid line represents the ensemble mean, and the shaded area shows the 25th to 75th percentile range of 28 ensemble members. Dashed gray lines at 2140, 2220, and 2280 denote significant temporal markers. (b–e) Same as (a), but for Northern Hemisphere (NH) surface air temperature gradient (600°N–9030°N minus 060°N–3090°N; in °C), NH westerly jet strength (the average for 30°N–60°N; in m s^{-1}) at 500 hPa, North Atlantic (NA, 60°W–30°E) surface air temperature gradient (600°N–9030°N minus 060°N–3090°N; in °C), and NA westerly jet strength (the average for 30°N–60°N, 60°W–30°E; in m s^{-1}) at 500 hPa, respectively. An 11-year running mean has been applied to smooth out inter-annual variability.

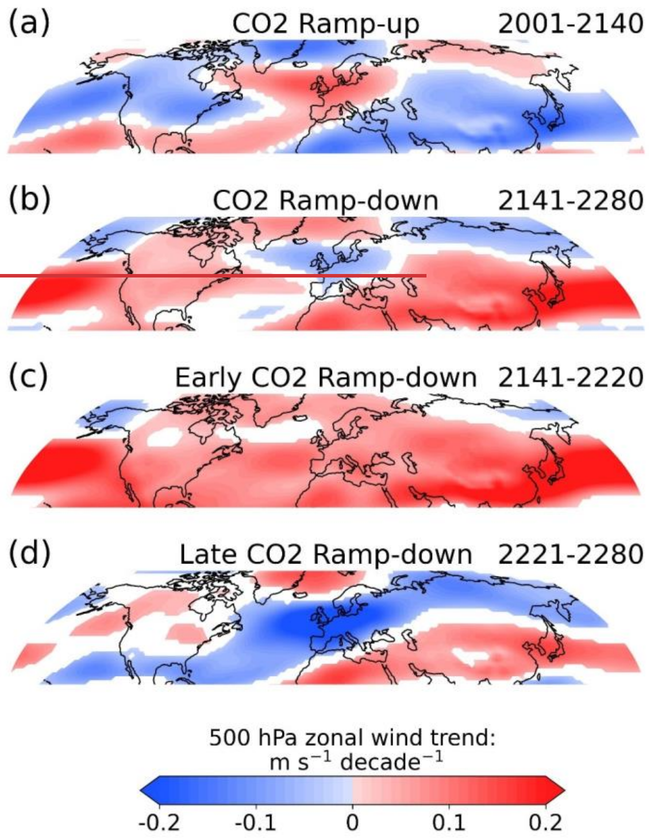


Figure 4. (a) Tendencies of ensemble-mean annual-mean 500 hPa zonal wind (unit: m s^{-1} decade^{-1}) during the CO_2 ramp-up period (2001–2140). Grid points with shadings denote the tendencies are significant at the 0.05 level. (b–d) Same as (a), but for tendencies during the CO_2 ramp-down period (2141–2280), early CO_2 ramp-down period (2141–2220), and late CO_2 ramp-down period (2221–2280), respectively.

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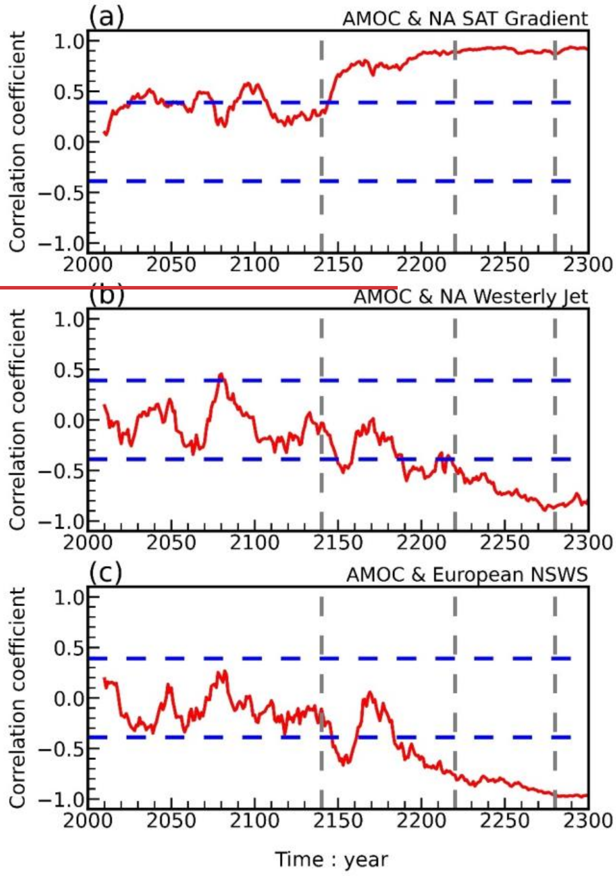
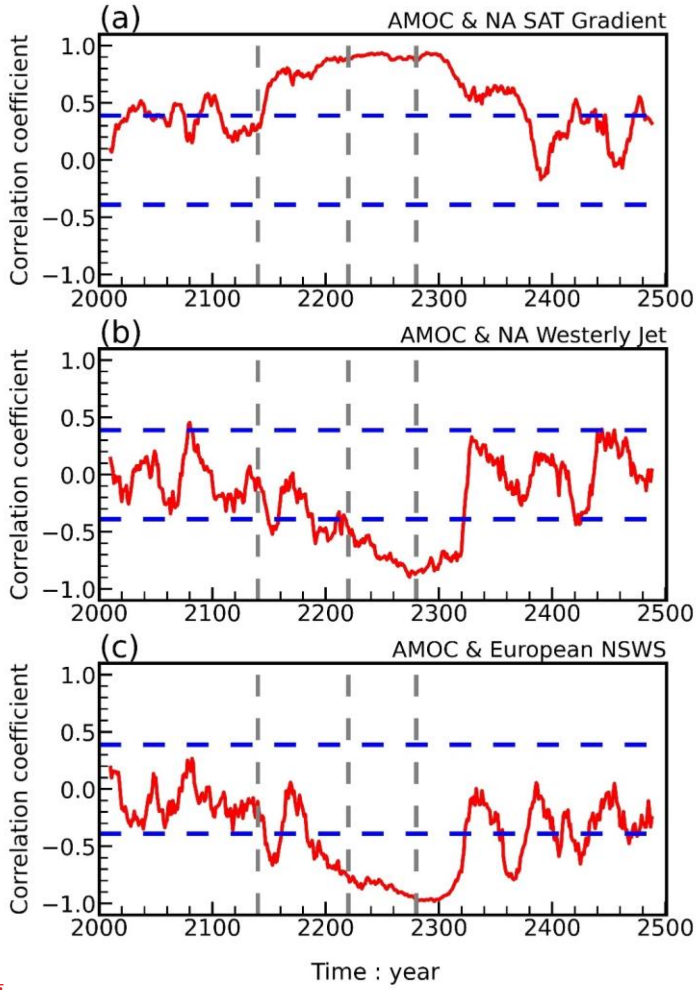

(a)
AMOC & NA SAT Gradient
(b)
AMOC & NA Westerly Jet
(c)
AMOC & European NSWS
Correlation coefficient
1.0
0.5
0.0
−0.5
−1.0
2000
2050
2100
2150
2200
2250
2300
Time : year



~~**Figure 5.**~~

Figure 4. (a) Inter-ensemble correlation coefficients between the 28 ensemble members: the AMOC versus North Atlantic (NA, 60°W–30°E) surface air temperature (SAT) gradient (60°N–90°N minus 0°N–30°N) from 2000 to 2300. Three dashed gray lines denote 2140, 2220 and 2280, respectively. Two dashed blue lines denote the 0.05 significance level. (b) Same as (a), but for correlation coefficients between the AMOC and NA westerly jet strength (30°N–60°N, 60°W–30°E) at 500 hPa. (c) Same as (a), but for correlation coefficients between the AMOC and terrestrial near-surface wind speed (NSWS) over Europe (30°N–60°N, 5°W–60°E). An 11-year running mean has been applied to smooth out inter-annual variability.

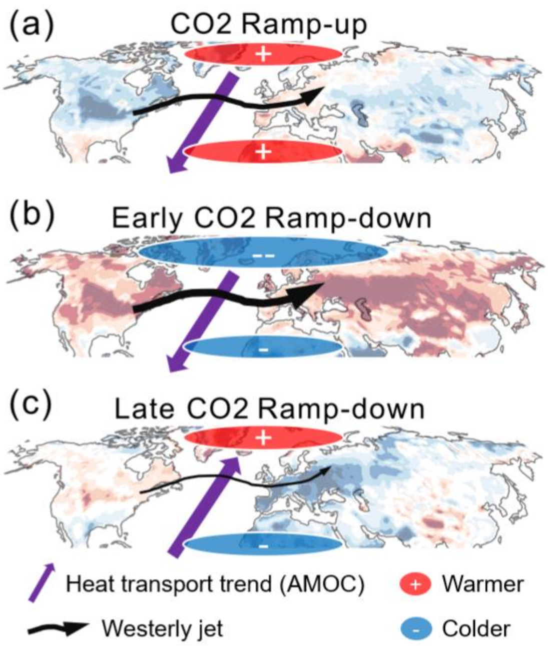


Figure ~~6~~5. The physical mechanisms by which CO_2 and Atlantic Meridional Overturning Circulation modulate extratropical near-surface wind speed during three periods.

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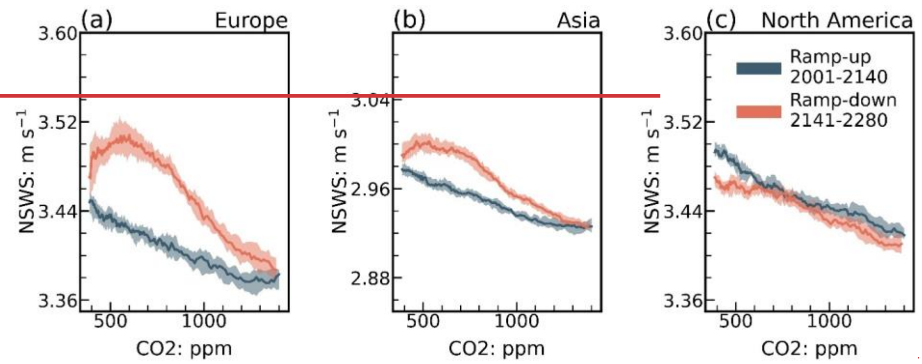

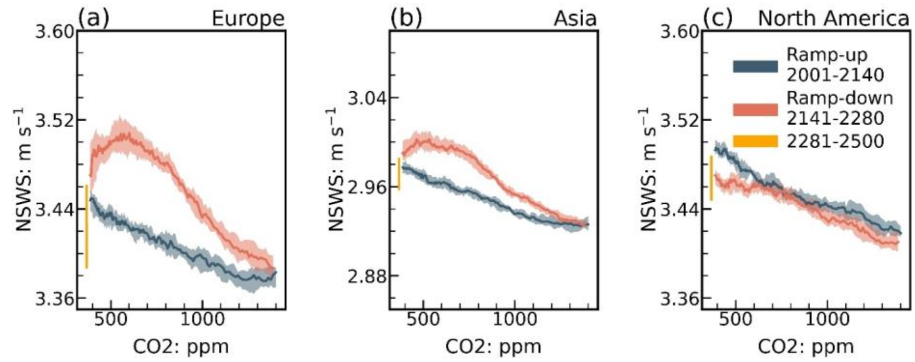

Figure 76. (a) Changes of terrestrial annual-mean near-surface wind speed over Europe (30°N–70°N, 5°W–50°E) as a function of CO_2 concentrations after 11-year running mean. The ramp-up (dark blue) and), ramp-down (orange), and stabilization (yellow) are denoted with different colors. The solid line represents the ensemble mean, and the shaded area shows the 25th to 75th percentile range of 28 ensemble members. (b-c) Same as (a), but for Asia (20°N–70°N, 60°E–180°E) and North America (30°N–70°N, 170°W–50°W). The range of Y-axis is 0.25 m s^{-1} in each subplot.