

Projected changes in near-surface wind speed in the Arctic by a regional climate model

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ABSTRACT

This study investigates seasonal changes in near-surface wind speeds in the Arctic using the regional climate model (RCM) simulations with RCA4 driven by four global climate models (GCMs) CMIP5 under Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios. In addition, the RCM RCA-GUESS (RCA4 with interactive vegetation dynamics) is used to investigate the role of biogeophysical feedbacks in modulating near-surface wind speeds under different RCP scenarios. Our results show that the reduction in ocean surface roughness induced by sea-ice reduction leads to a projected increase in near-surface wind speeds over the Arctic Ocean, with the most pronounced effects occurring in autumn and winter. Overall, the projected changes in near-surface wind speeds from the RCM are consistent with the changes from the forcing GCMs though the RCM simulations show larger amplitude changes compared to the GCMs. The expansion of vegetation on land increases surface roughness and alters atmospheric circulation by modifying static stability and the land-sea temperature contrast, leading to changes in near-surface wind speeds. Specifically, wind speeds decrease over continental regions but increase over parts of the Arctic Ocean. This study emphasizes that interactive vegetation dynamics significantly influence changes in land surface properties and near-surface wind speeds. These processes should be incorporated into Earth system models to enhance the accuracy of future climate projections.

1. Introduction

The Arctic is undergoing significant change due to a rapid increase in surface temperature, leading to an unprecedented reduction in the extent of sea ice (Mokhov and Parfenova, 2021; Previdi et al., 2021). Such warming in the Arctic is facilitating economic activities, such as shipping, oil and gas extraction, and renewable energy production in the region (Akperov et al., 2022, 2023a; Mokhov, 2022).

Surface winds, an important element of atmospheric circulation in high latitudes, are closely connected with changes in sea-ice, cyclones, vegetation dynamics (Akperov et al., 2023b; DuVivier et al., 2023). A number of recent studies have documented an increase in surface wind speeds and ocean wave heights over the Arctic in current and future

climate conditions (Khon et al., 2014; Kay et al., 2015; Mokhov, 2015; Aksenov et al., 2017; Jakobson et al., 2019; Mokhov and Pogarsky, 2021; Akperov et al., 2024). The strengthened winds are closely linked to decreasing surface roughness and lower tropospheric stability resulting from sea ice loss, surface warming, as well as local changes in storm tracks (Mioduszewski et al., 2018; Akperov et al., 2019; DuVivier et al., 2023). Jakobson et al. (2019) analyzed variations and trends of surface wind speed and sea ice using NCEP CFSR reanalysis for the 1979–2015 and found that both warming and sea ice retreat reduce both atmospheric stratification and surface roughness that favor stronger surface winds. Therefore, future sea ice loss will likely enhance surface winds (Alkama et al., 2020). However, it should be noted that regions covered by sea ice exhibit complex dependencies between surface

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Table 1

Reanalysis, regional and global climate models and their corresponding information.

Type	Institution/ Country	Data/Model name	Original Resolution Vertical levels, horizontal resolution	Boundary conditions	Reference
Reanalysis	ECMWF/UK	ERA5 ERA5-bias corrected	L137, 0.28° (~30 km)		Hersbach et al. (2020) Cucchi et al. (2020)
Regional climate models (RCMs)	SMHI/Sweden	RCA4-MPI RCA4-EC-EARTH RCA4-CanESM2 RCA4-NorESM1	L40, 0.44° (~48 km)	MPI-ESM-LR EC-EARTH2.3 CanESM2 NorESM1-M	(Berg et al., 2013; Koenigk et al., 2015)
	LU/Sweden	RCA-GUESS-EC-EARTH	L40, 0.44° (~48 km)	EC-EARTH2.3	(Smith et al., 2011; Zhang et al., 2014)
Global climate models (GCMs)	MPI/Germany	MPI-ESM-LR	L47, 1.8° (~200 km)		Giorgetta et al. (2013)
	ICHEC/EU	EC-EARTH	L62, 1.1° (~122 km)		Hazeleger et al. (2012)
	CCCma/Canada	CanESM2	L35, 2.8° (~310 km)		Arora et al. (2011)
	NCC/Norway	NorESM1-M	L26, 2.5° (~277 km)		Bentsen et al. (2013)

roughness and sea ice features such as floe edges and pressure ridges. These features significantly affect the atmospheric boundary layer and influence the exchange of momentum, heat and moisture between the ocean and the atmosphere. For example, features such as floe edges and pressure ridges can change surface roughness, which in turn affects wind patterns and turbulence (Lüpkes et al., 2012; Lüpkes and Gryanik, 2015; Chechin et al., 2015; Castellani et al., 2014; Mchedlishvili et al., 2023; Zhang et al., 2024). Additionally, ocean roughness can also influence surface wind speed (Duvier et al., 2023). Understanding these interactions is crucial for accurate modelling of climate processes in polar regions, as variations in sea ice morphology can lead to significant changes in atmospheric dynamics and energy balance.

In the future, surface winds can change not only over the Arctic Ocean but, due to the greening, over the adjacent land areas as well (Tape et al., 2006; Bhatt et al., 2013; Zhang et al., 2018). Changes in vegetation, such as the spread of shrubs and shifts in the latitudinal and altitudinal positions of tree lines, may alter the distribution of various vegetation types (Alkama et al., 2022). This can result in changing surface roughness and a positive feedback loop where lower surface albedo contributes to increased surface temperatures, along with negative feedback involving enhanced evapotranspiration (Pearson et al., 2013; Zhang et al., 2013, 2014, 2018). Notably, these vegetation changes can exert an influence on both regional and large scale atmospheric circulation (e.g. Pielke and Vidale, 1995; Matthes et al., 2012). Consequently, the large-scale atmospheric circulation patterns influenced by vegetation feedback can contribute to the amplification of surface warming, particularly during the summer when warming reduces the temperature contrast across high latitudes (Jeong et al., 2014). Previous research (Day et al., 2018; Screen et al., 2018; Akperov et al., 2021) has pointed out that differential surface heating between land and ocean, along with Arctic amplification, has the potential to impact cyclone activity. Hence, forthcoming changes in Arctic vegetation may lead to shifts in surface heat exchanges, resulting in significant alterations to atmospheric heating and circulation. These changes could, in turn, influence the seasonal characteristics of Arctic cyclones by modifying atmospheric baroclinicity (Akperov et al., 2021), ultimately impacting on the surface winds. However, the relationships between these processes are complex and need further exploration (e.g. Jakobson et al., 2019; Duvivier et al., 2023).

A spatial density of meteorological stations in the Arctic is very heterogeneous, with large areas very poorly covered by observations. This poses a challenge in accurately assessing changes in regional wind speeds. To address this, regional climate models (RCMs) can be employed to evaluate the impact of climate changes on surface winds in the Arctic, even when there is limited climate data available. Compared to global climate models, RCMs for the Arctic region, with their detailed consideration of surface processes, have the potential to better depict alterations in near-surface winds, particularly in the Arctic (Gutjahr and

Heinemann, 2018). As shown by Akperov et al. (2018), RCMs can quite well capture cyclone activity and its variability in the Arctic. Therefore, we may expect that surface wind statistics and their future changes in the Arctic are also well simulated. However, it should be noted that the parameterization of sea ice surface roughness and its dependence on sea ice topography in RCMs still needs improvement due to the complex relationships between surface roughness and sea ice conditions.

To explore the role of vegetation in the changes of surface winds in the Arctic, we employ the regional climate model RCA-GUESS, which incorporates the RCM RCA4 with interactive vegetation-atmosphere coupling (LPJ-GUESS). This model, which has previously been used to study the effects of vegetation-atmosphere interactions on Arctic climate, atmospheric circulation, and cyclone activity (Zhang et al., 2018, 2020; Akperov et al., 2021), allows us to assess the impact of vegetation on Arctic wind patterns. Therefore, the aim of this study is to assess the role of sea ice retreat and vegetation expansion in altering the surface wind characteristics under different future climate scenarios, based on various RCP pathways.

2. Materials and methods

2.1. Data

We use the monthly mean near-surface wind speed (at 10 m) from the regional climate model (RCM) RCA4, driven by four different GCMs (NorESM1, CanESM2, MPI-ESM-LR, EC-EARTH) from CMIP5 and ERA5 reanalysis data (Table 1) for the Arctic region (Fig. 1) for all four seasons – winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

In addition to ERA5, we also use ERA5 bias-corrected near-surface wind speed data (Cucchi et al., 2020). This dataset provides bias-corrected reconstruction of near-surface meteorological variables derived from the ERA5. It is intended for use as a meteorological forcing dataset for land surface and hydrological models. The data have been adjusted using an elevation correction and monthly-scale bias corrections based on data from the Climatic Research Unit (CRU) and the Global Precipitation Climatology Centre (GPCC). Additional corrections are included for varying atmospheric aerosol-loading and separate precipitation gauge observations. Bias-corrected ERA5 only covers land and lakes, see Cucchi (et al., 2020) for full details. For comparison with RCM RCA4, we use modified ERA5 bias-corrected data, where we filled in missing near-surface wind speed data over sea and ice from the ERA5 near-surface wind speed data, i.e. hereafter bias-corrected ERA5.

To compare the RCM RCA4 results with the ERA5 reanalysis for the present (1980–2005), we use monthly mean near-surface wind speed data from the ERA5 reanalysis and historical periods from RCM RCA4. The RCM uses the Arctic CORDEX grid (rotated $0.44^\circ \times 0.44^\circ$ grid, 116×133 grid points), therefore the ERA5 reanalysis and the four forcing GCMs have been bilinearly interpolated onto this grid for better

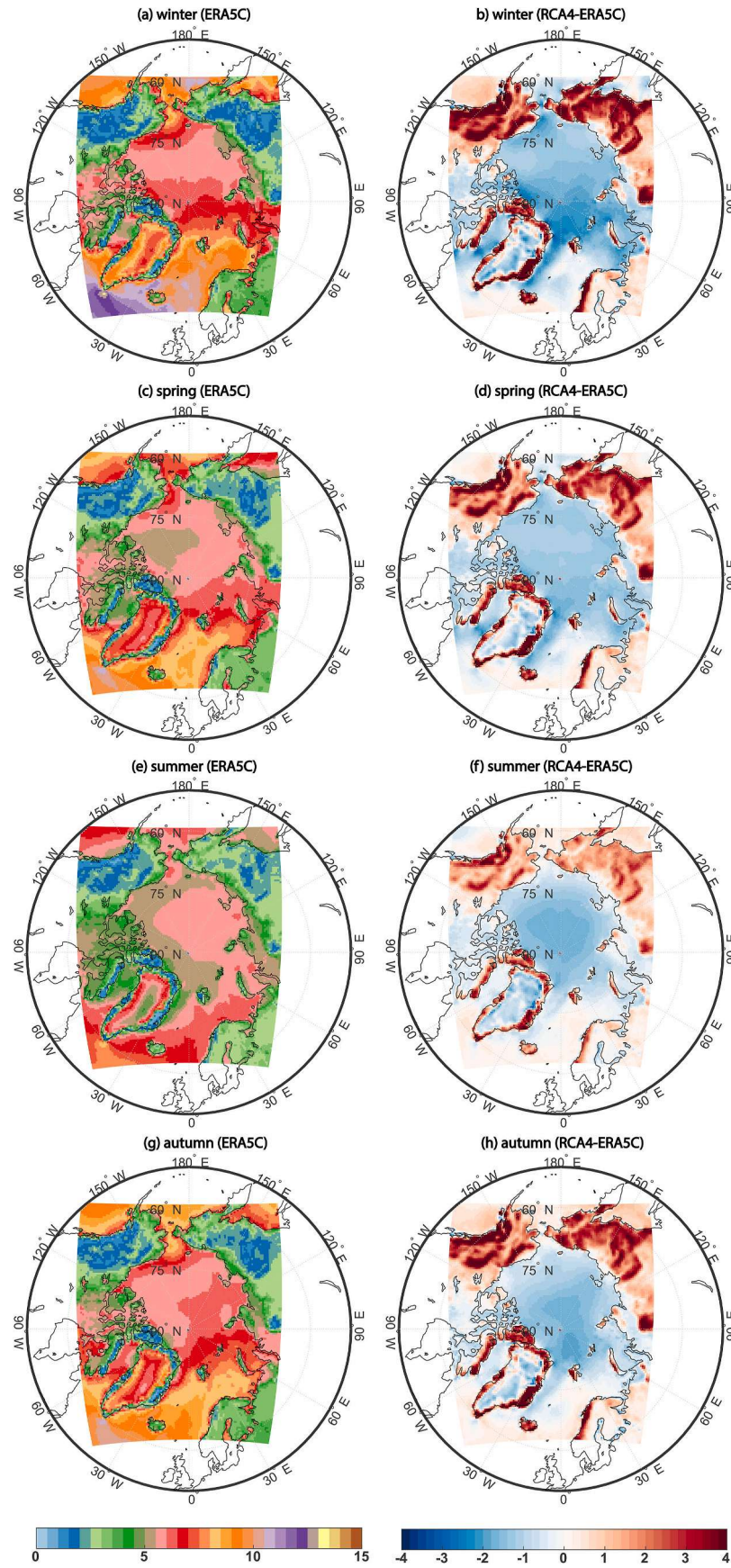


Fig. 1. Climatological mean of near-surface wind speed (m/s) for ERA5C and differences between RCA4 ensemble mean and ERA5C for the 1980–2005 for the different seasons.

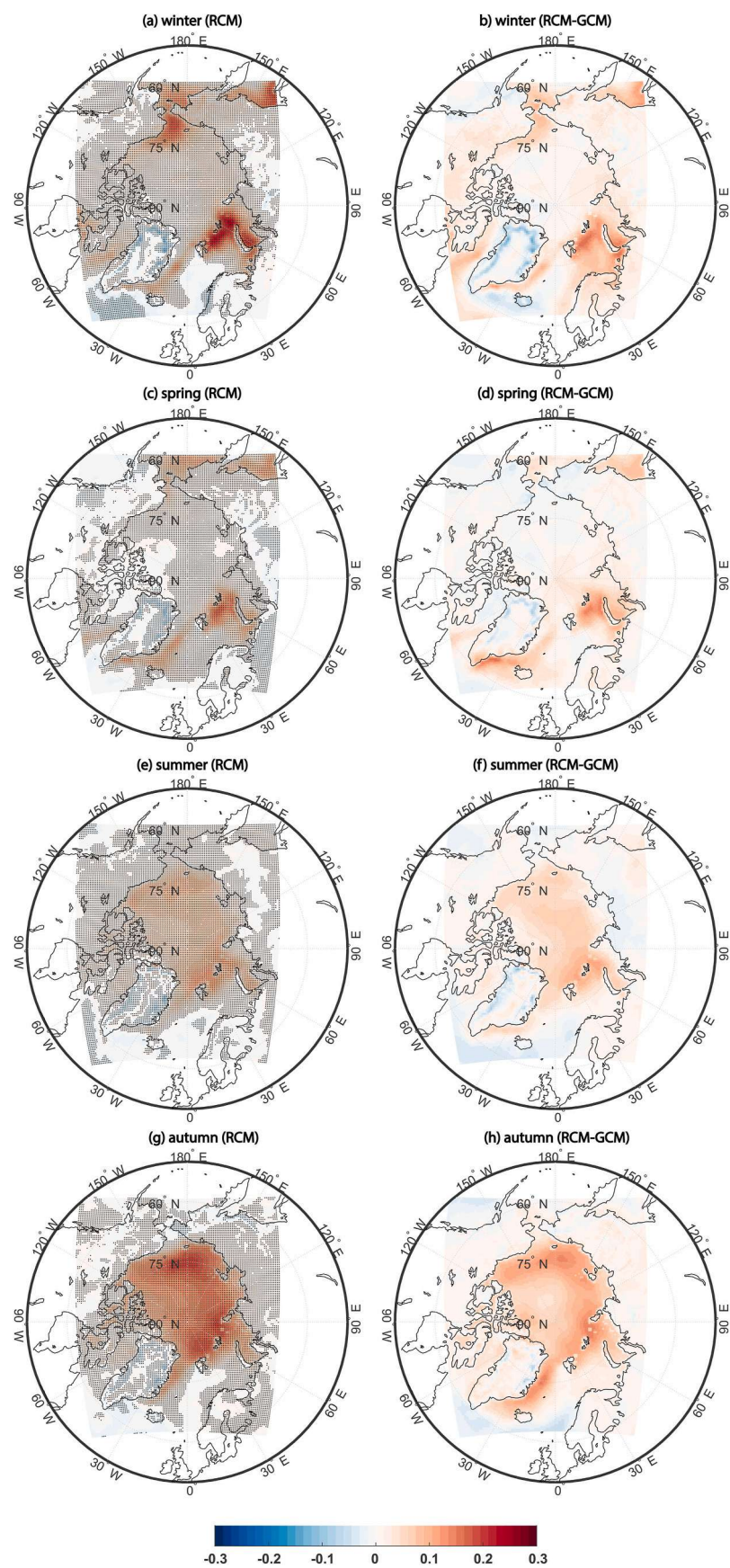


Fig. 2. Near-surface wind speed trends [m/s per decade] for the RCA4 ensemble mean and differences between RCM and GCM ensemble mean of RCP4.5 for the different seasons. Statistically significant trends are indicated by black dots ($p < 0.05$).

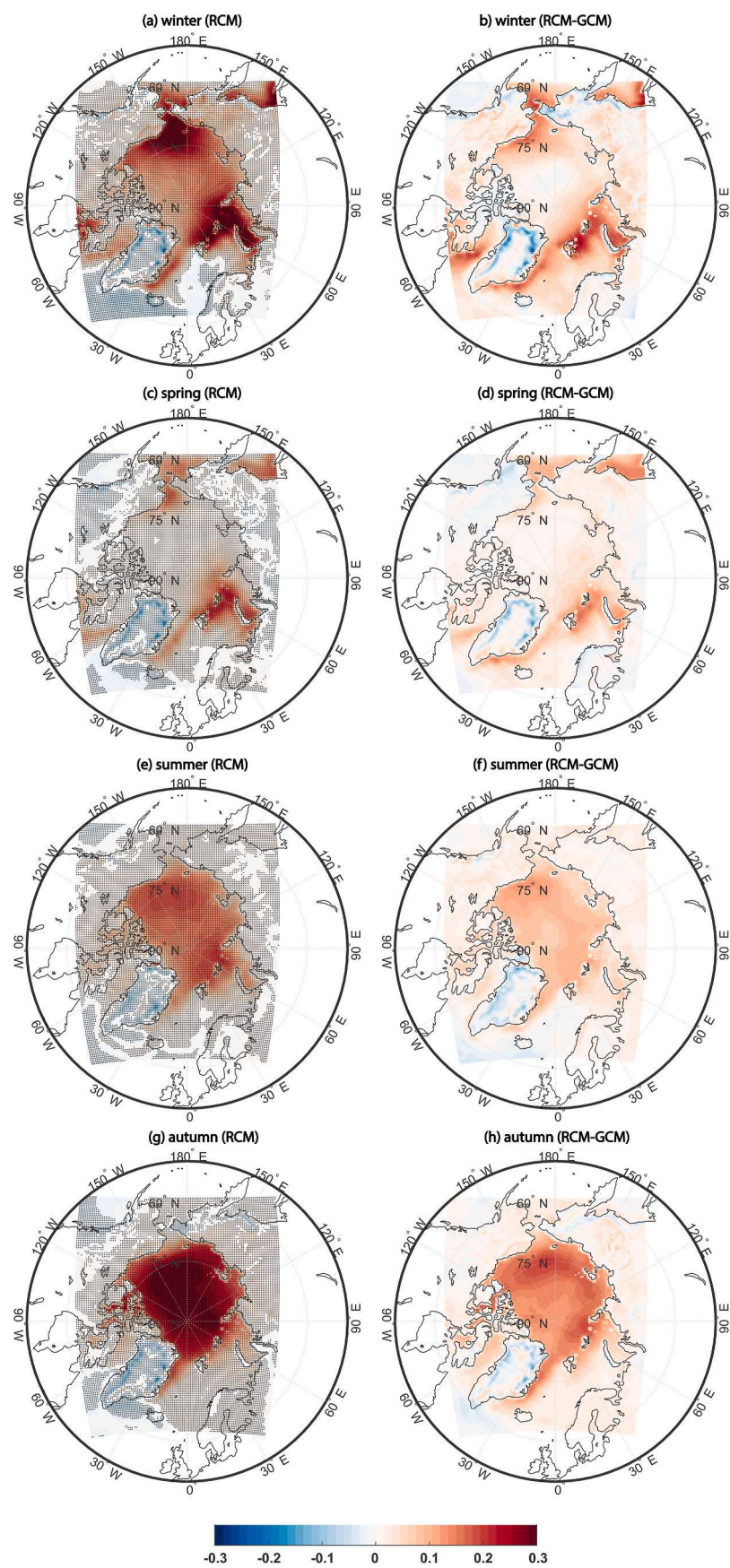


Fig. 3. Near-surface wind speed trends [m/s per decade] for the RCA4 ensemble mean and differences between RCM and GCM ensemble mean of RCP8.5 for the different seasons. Statistically significant trends are indicated by black dots ($p < 0.05$).

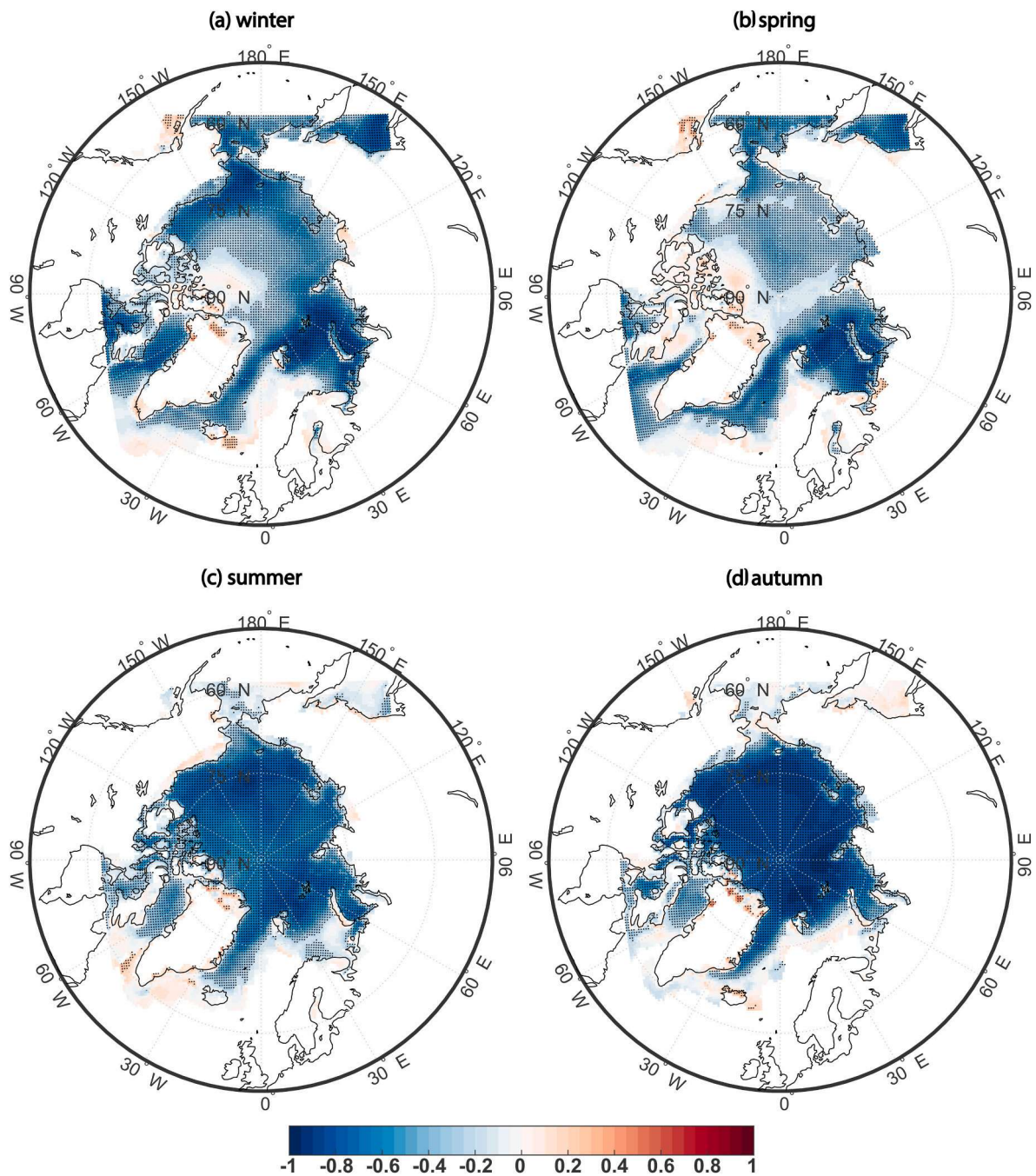


Fig. 4. Correlations between near-surface wind speed and sea-ice concentration for the multi-model mean for RCP4.5 for the different seasons. Statistically significant trends are indicated by black dots ($p < 0.05$).

comparison.

The lateral boundary conditions of RCM are driven by future scenario simulations of the general circulation models (GCM) for 2006–2099 using RCP4.5 (moderate) and RCP8.5 (strong) scenarios. The RCP4.5 scenario represents a moderate pathway where greenhouse gas emissions peak around 2040 and then decline, leading to a stabilization of radiative forcing, while the RCP8.5 scenario is a high-emissions pathway characterized by continuously rising emissions throughout the century, resulting in significantly greater climate impact. For the lower boundary conditions, we use monthly sea-ice concentration (SIC) and sea surface temperature (SST) data from the driving GCMs.

In addition, we take a quantitative and transient modelling approach to focus on the responses of spring and summer near-surface wind speed to biogeophysical feedbacks, as Zhang et al. (2018) have shown that the

most pronounced biogeophysical feedbacks to Arctic climate are found in spring and summer. To quantify these responses, we compare results of two simulations with RCM RCA4 with and without the interactive vegetation module LPJ-GUESS (here, RCA-GUESS) respectively from weak to strong climate change scenario (RCP2.6, RCP4.5 and RCP8.5) (Smith et al., 2011; Zhang et al., 2014). Here we use monthly data for near surface air temperature (t2m), temperature at 850 hPa, mean sea level pressure (MSLP), leaf area index (LAI), near surface wind speed and wind speed at 500 hPa. The difference between the monthly temperature at 850 hPa and the near-surface air temperature is used to calculate static stability.

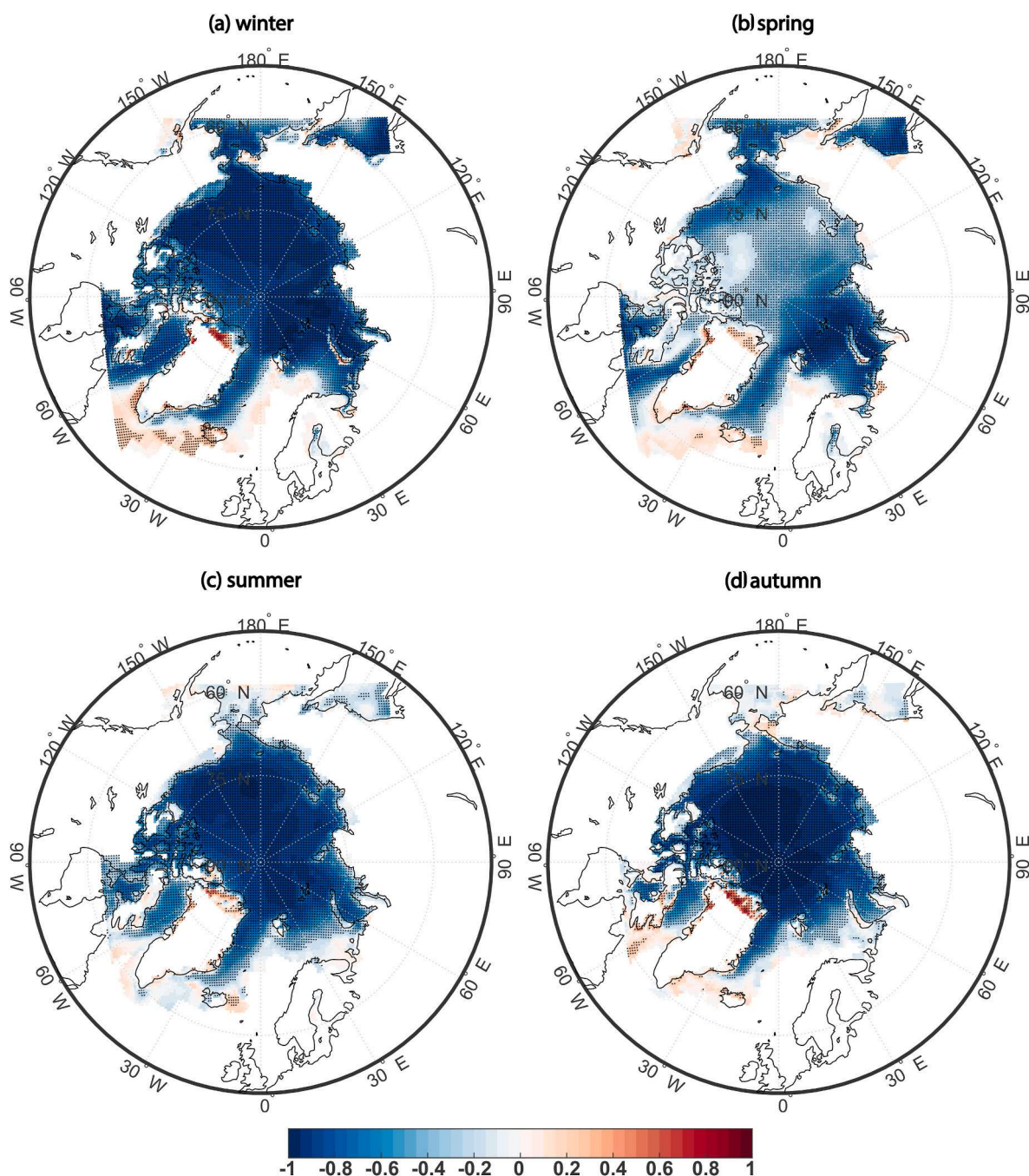


Fig. 5. Correlations between near-surface wind speed and sea-ice concentration for the multi-model mean for RCP8.5 for the different seasons. Statistically significant trends are indicated by black dots ($p < 0.05$).

2.2. Biogeophysical feedback experiments

The lateral boundary conditions used in RCA-GUESS were based on the CMIP5 simulations with the EC-Earth GCM (Hazeleger et al., 2010, 2012) under RCP2.6, RCP4.5 and RCP8.5 scenarios. To disentangle biogeophysical feedback, we conducted simulations with and without interactive vegetation-atmosphere coupling, hereinafter denoted as the feedback run (FB) and non-feedback run (NoFB). The coupled model ran two stages of spin-up to give initial states for vegetation structure and composition, carbon pools and climate conditions consistent with 1961–1990 forcing. In the first spin-up stage, the vegetation model was forced for 300 years with observation-based climatology from the CRU TS3.0 data set (Mitchell and Jones, 2005) to obtain realistic vegetation distributions and C pools. The second spin-up employed the

fully-coupled model based on the initial 30 years of lateral boundary conditions and the starting vegetation and carbon states from the first spin-up stage. Detailed evaluation of RCA-GUESS for the historical period (1961–1990) was performed by Zhang et al. (2014). NoFB was based on the same procedure as FB, which implemented interactive vegetation dynamics in the land surface scheme for the entire simulation period (1961–2100). Land surface properties of NoFB were fixed by using the biophysical variables (e.g., leaf area index and fractional coverage for needle-leave, deciduous forests and grassland) averaged from 1961 to 1990 to run the simulation for 1991–2100.

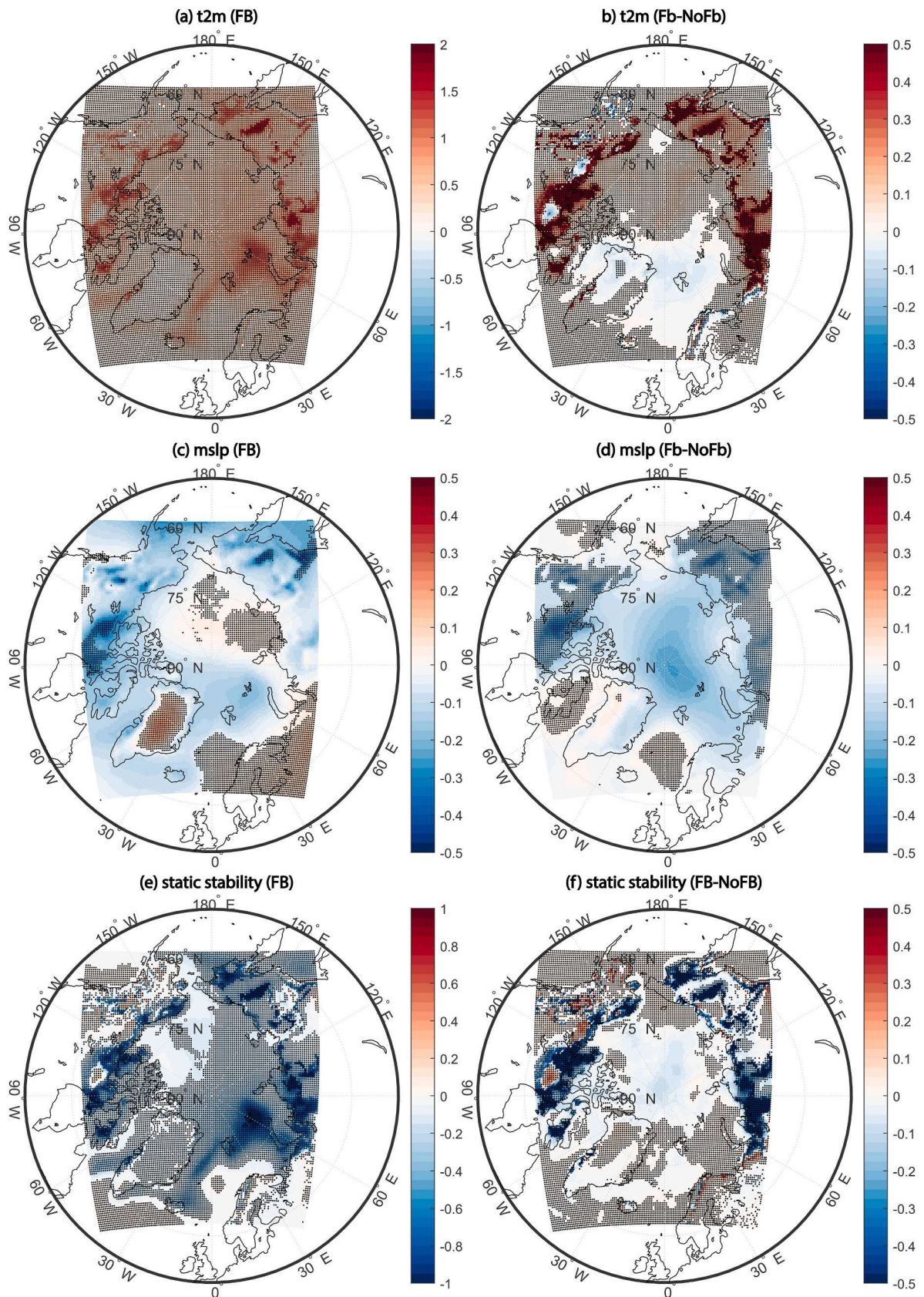


Fig. 6. Near-surface air temperature [K/decade], mean sea level pressure [hPa/decade] and static stability [K/decade] trends from FB simulations and trends for their differences ("FB"-NoFB) for spring for RCP4.5. Statistically significant trends are indicated by black dots ($p < 0.05$).

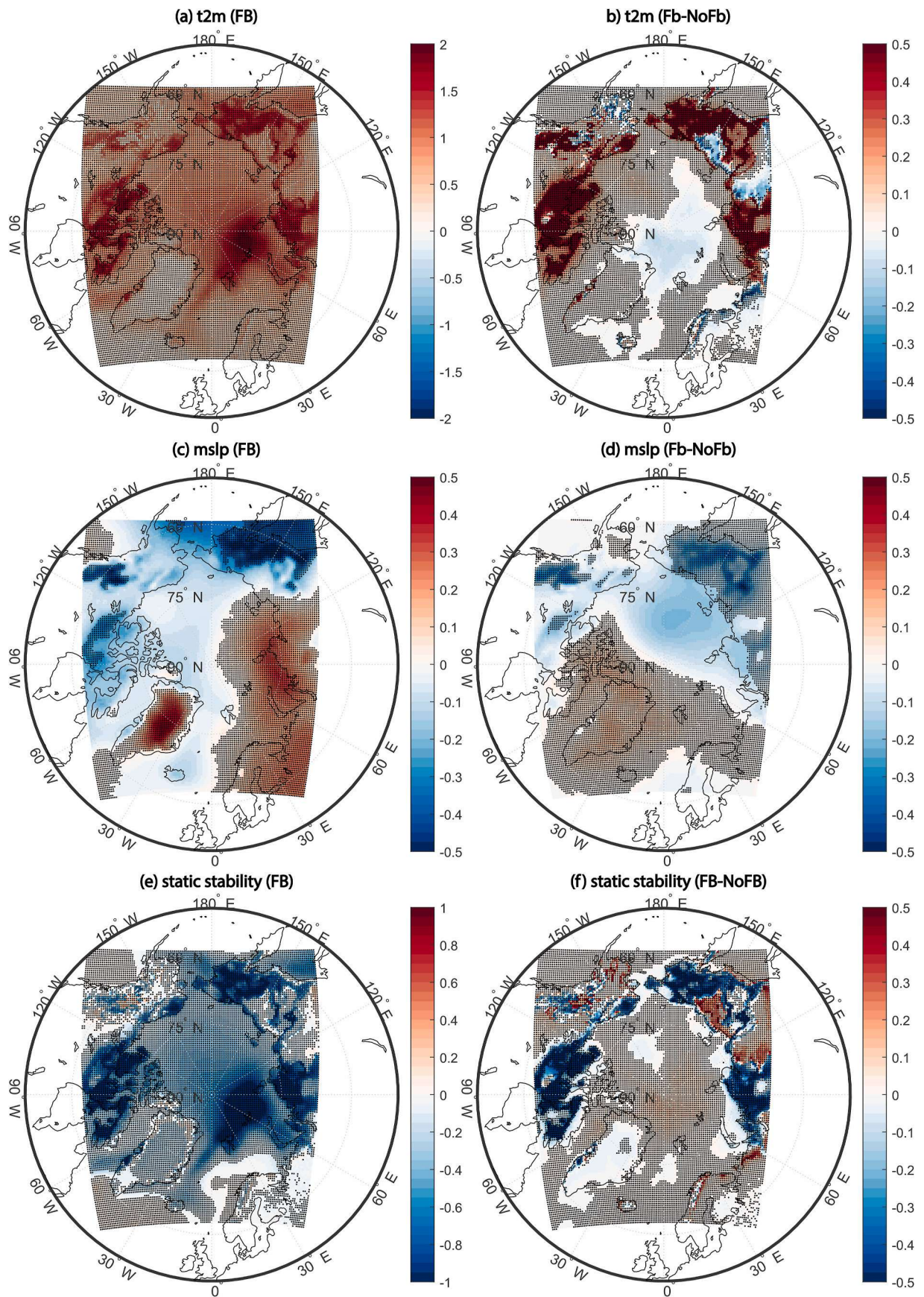


Fig. 7. Near-surface air temperature [K/decade], mean sea level pressure [hPa/decade] and static stability [K/decade] trends from FB simulations and trends for their differences ("FB"-NoFB) for spring for RCP8.5. Statistically significant trends are indicated by black dots ($p < 0.05$).

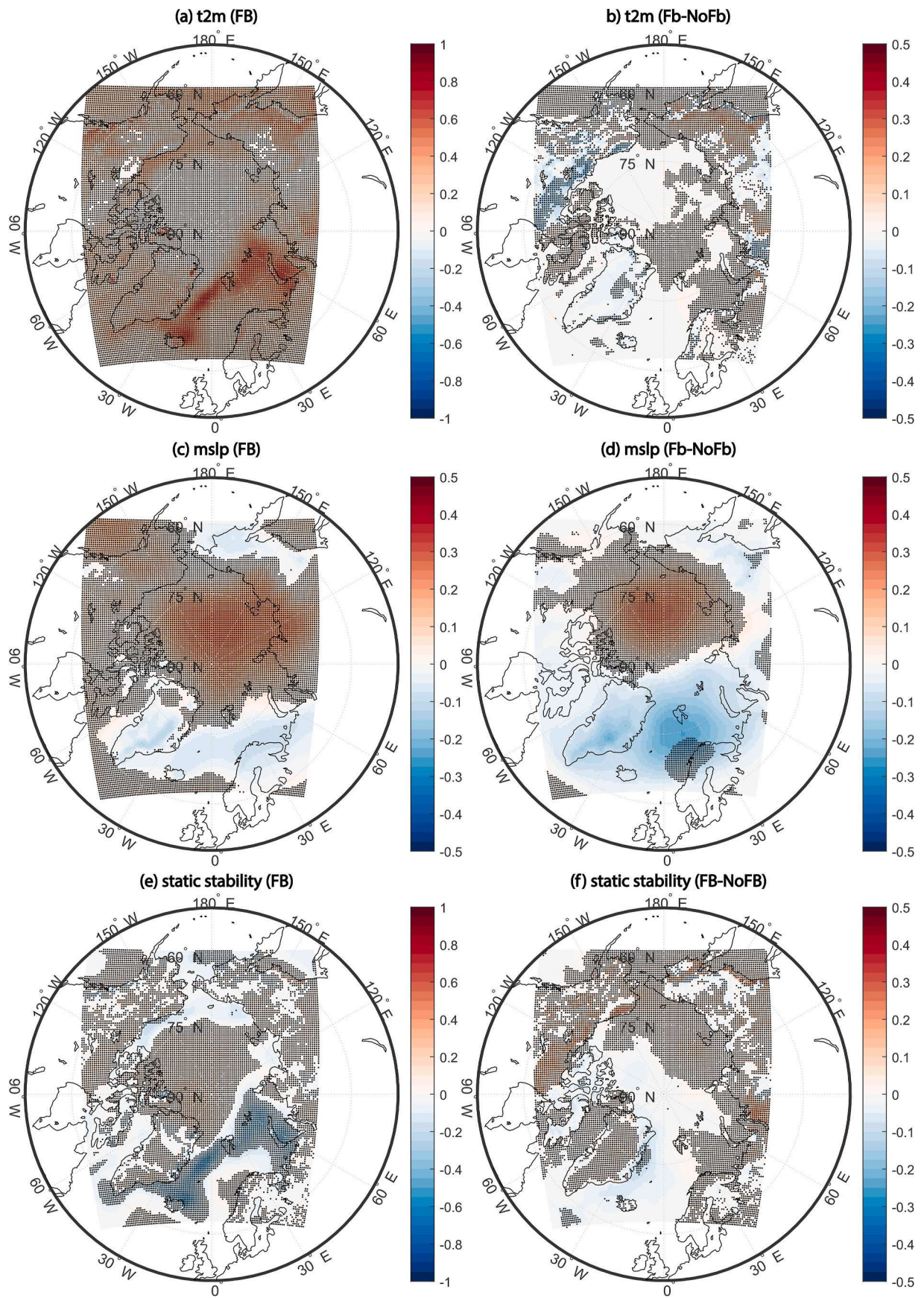


Fig. 8. Near-surface air temperature [K/decade], mean sea level pressure [hPa/decade] and static stability [K/decade] trends from FB simulations and trends for their differences ("FB"-NoFB") for summer for RCP4.5. Statistically significant trends are indicated by black dots ($p < 0.05$).

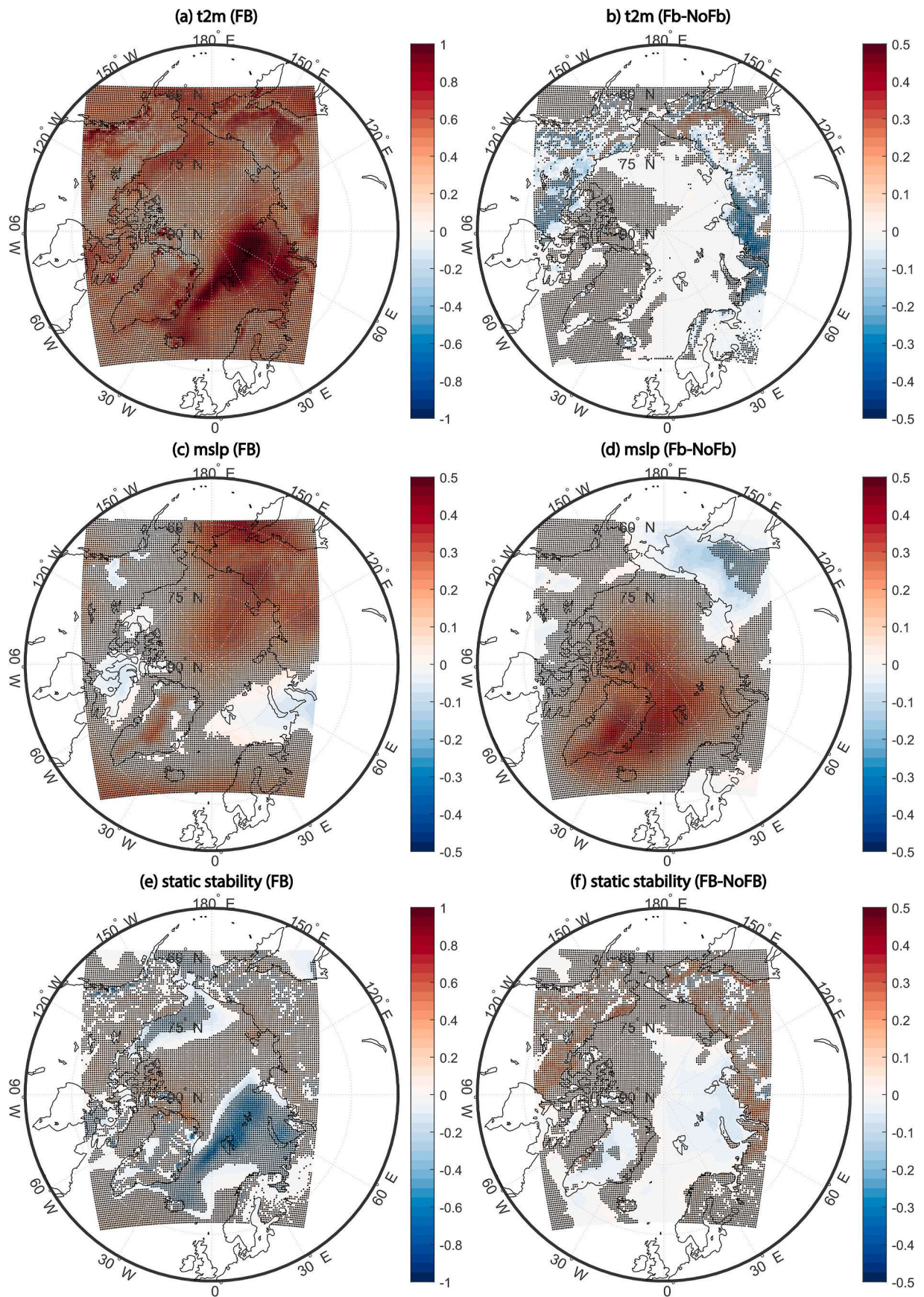


Fig. 9. Near-surface air temperature [K/decade], mean sea level pressure [hPa/decade] and static stability [K/decade] trends from FB simulations and trends for their differences ("FB"-NoFB) for summer for RCP8.5. Statistically significant trends are indicated by black dots ($p < 0.05$).

3. Results

3.1. Climatology of the near-surface wind speed from the RCM in comparison with the reanalysis

One of the challenges in the Arctic is the lack of observational data to compare with model results. However, the near-surface winds from ERA5 show the best agreement among the modern reanalyses with in situ observations in mid-latitudes and some areas in the polar latitudes (Minola et al., 2021; Ramon et al., 2019) and are widely used for assessments of wind energy resource assessments for the different regions (Olauson, 2018; Soares et al., 2020; Lambin et al., 2023; Akperov et al., 2023). In this study, we use near-surface wind speeds from the modified bias-corrected ERA5 (hereafter ERA5C) as the reference data in our analysis which is an improvement of the ERA5 reanalysis (see Section 2). It should be noted that the differences between ERA5 and ERA5C over the continents are quite similar and do not exceed ± 0.3 m/s (SFig. 1). However, despite the accurate representation of surface wind speeds in some high-latitude regions, it is well known that all reanalysis data, including ERA5, have limitations, particularly over the Arctic Ocean (Dörenkämper et al., 2020; Gruber et al., 2022; Pernov et al., 2024).

We compare the near-surface wind speed climatology from the ensemble mean (the mean of four RCA4 simulations with different driving GCMs) of historical runs with the ERA5C reanalysis for the period 1980–2005. Fig. 1 shows the near-surface wind speed climatology from the ERA5C reanalysis, the regional model ensemble mean, and their differences for the four seasons (DJF, MAM, JJA, and SON) in the Arctic. For all four seasons, an overestimation of the ensemble mean near-surface wind speed is observed over the continents and an underestimation over the Arctic Ocean. Therefore, the land-sea difference in near-surface wind speeds in the RCM is substantially smaller than in the ERA5C. In spite of quantitative differences, the RCM ensemble mean reproduces the spatial distribution of the near-surface wind speed over the Arctic, with a maximum speed over the Nordic Seas (the region of highest cyclone activity) and a minimum over the continents for all four seasons.

The driven GCM ensemble mean historical runs also show substantial biases compared to the RCM ensemble mean. The near-surface wind speed in RCM is higher over the ocean and continents (SFig. 2), especially over the areas of complex topography (East Greenland, Norwegian coasts, South Alaska and etc.). These biases may be associated with improvement of local topography and wind systems, such as katabatic winds in the RCM compared to the GCM.

3.2. Projected changes of the near-surface wind speed

The most significant changes in near-surface wind speed over the Arctic, especially over the Arctic Ocean, occur in winter and autumn, while changes in spring and summer are less pronounced under RCP4.5 scenarios for the period 2006–2100 (Fig. 2). In winter, areas of the greatest increases in near-surface wind speeds are found over the northern Barents, Kara, Greenland and Chukchi Seas, while in autumn, they are concentrated over the Arctic Ocean. In spring and summer, the areas of near-surface wind speed increase are also located over the same areas as in winter and autumn. The trend of increasing near-surface wind speed is even stronger under RCP8.5 scenarios (Fig. 3).

The RCA4 ensemble mean shows the largest amplitude of projected changes compared to the ensemble means of the four driving GCMs. The direction of near-surface wind speed changes aligns with those in the GCMs. Overall, these changes occur in the same regions associated with sea ice retreat, and the differences between the RCM and GCM projections can reach ca. 100% (Figs. 2 and 3). In general, the presented near-surface wind speed changes in the Arctic are also in agreement with the results of the CMIP5 large ensemble (Vavrus and Alkama, 2022).

3.3. Impact of sea ice retreat and biogeophysical feedbacks on projected near-surface changes

3.3.1. Impact of sea ice retreat

The seasonal near-surface wind speed trends show a very clear relationship with the projected sea ice retreat in terms of spatial patterns for the period 2006–2100 (Fig. 4). The maximum spatial correlation coefficients of the multi-model mean near-surface wind speed trends with SIC occur over the areas of greatest near-surface wind speed changes (Figs. 2 and 3). The correlations between near-surface wind speed and sea ice becomes stronger under RCP8.5 (Fig. 5). The explanation of near-surface wind speed changes over the sea ice loss regions using reanalysis and model data has already been documented (Mioduszewski et al., 2018; Jakobson et al., 2019; Alkama et al., 2020; DuVivier et al., 2023) and is presumably due to reduced surface roughness and atmospheric stability (Akperov and Mokhov, 2013). The transition from sea ice to open ocean, which lowers surface roughness, is often cited as the primary reason for the intensified surface winds observed in the Arctic Ocean (Stegall and Zhang, 2012; Mioduszewski et al., 2018; Jakobson et al., 2019; Alkama et al., 2020; DuVivier et al., 2023). On the other hand, decreasing sea-ice as result in increase of heat flux from ocean to atmosphere led to reduce stratification which also favor in increasing surface winds. The highest correlation between sea-ice and static stability is found over the areas of reducing sea-ice for all seasons (SFig. 3). However, the negative correlation observed in the narrow region over the Arctic Ocean may be related to the difficulty of the model to reproduce a realistic temperature profile in the layer between SST and 850 hPa over this region in summer (Jakobson et al., 2019). However, it should be noted that changes (increases) in cyclone activity in the future climate may also have a significant impact on near-surface winds (Akperov et al., 2019). Therefore, we note, that the physical mechanism behind the obtained changes needs further study with an employment of regional model output with higher spatial resolution and correct parametrizations.

3.3.2. Impacts of biogeophysical feedbacks

For the land areas in the polar latitudes, vegetation changes such as shrinkage and latitudinal and altitudinal shifts of the tree line may alter the fractional coverage of different vegetation types and thus change the surface roughness induced by vegetation expansion. This may result in a positive surface temperature feedback associated with lower surface albedo and negative feedback associated with higher evapotranspiration and circulations changes (Pielke and Vidale, 1995; Eliseev and Mokhov, 2011; Pearson et al., 2013; Zhang et al., 2014, 2018). This, in turn, may alter the atmospheric circulation as well as near-surface wind changes in the Arctic.

The effects of biogeophysical feedbacks on the temporal variation of the land-sea temperature difference for RCP2.6, RCP4.5 and RCP8.5 scenarios show contrasting spatial patterns in the spring and summer seasons (Figs. 6–9). Biogeophysical feedback induced changes in the land-sea temperature difference in spring show an increasing trend, leading to an increase in the land-sea temperature difference of 1–1.9 °C from 2006 to 2099 (SFig. 4). The slopes of linear fits of the trends under RCP2.6, RCP4.5 and RCP8.5 are 0.106, 0.132 and 0.193 °C decade⁻¹ respectively. On the contrary, decreasing trends in the land-sea temperature difference are found in summer. The slopes of the linear fits of the trends are 0.002, -0.006, -0.025 °C decade⁻¹ respectively.

These temporal variations in the land temperature difference can be attributed to changes in the patterns of near-surface air temperature and surface energy fluxes in spring and summer. The noticeable changes in near-surface air temperature due to biogeophysical feedback in spring and summer are well observed over the land (Zhang et al., 2014, 2018; Akperov et al., 2021). In general, biogeophysical feedback induced warming (e.g. mainly in spring) or cooling effects (e.g. mainly in summer) are enhanced in the warmer RCP8.5, although the fraction of biogeophysical feedback induced warming relative to anthropogenic

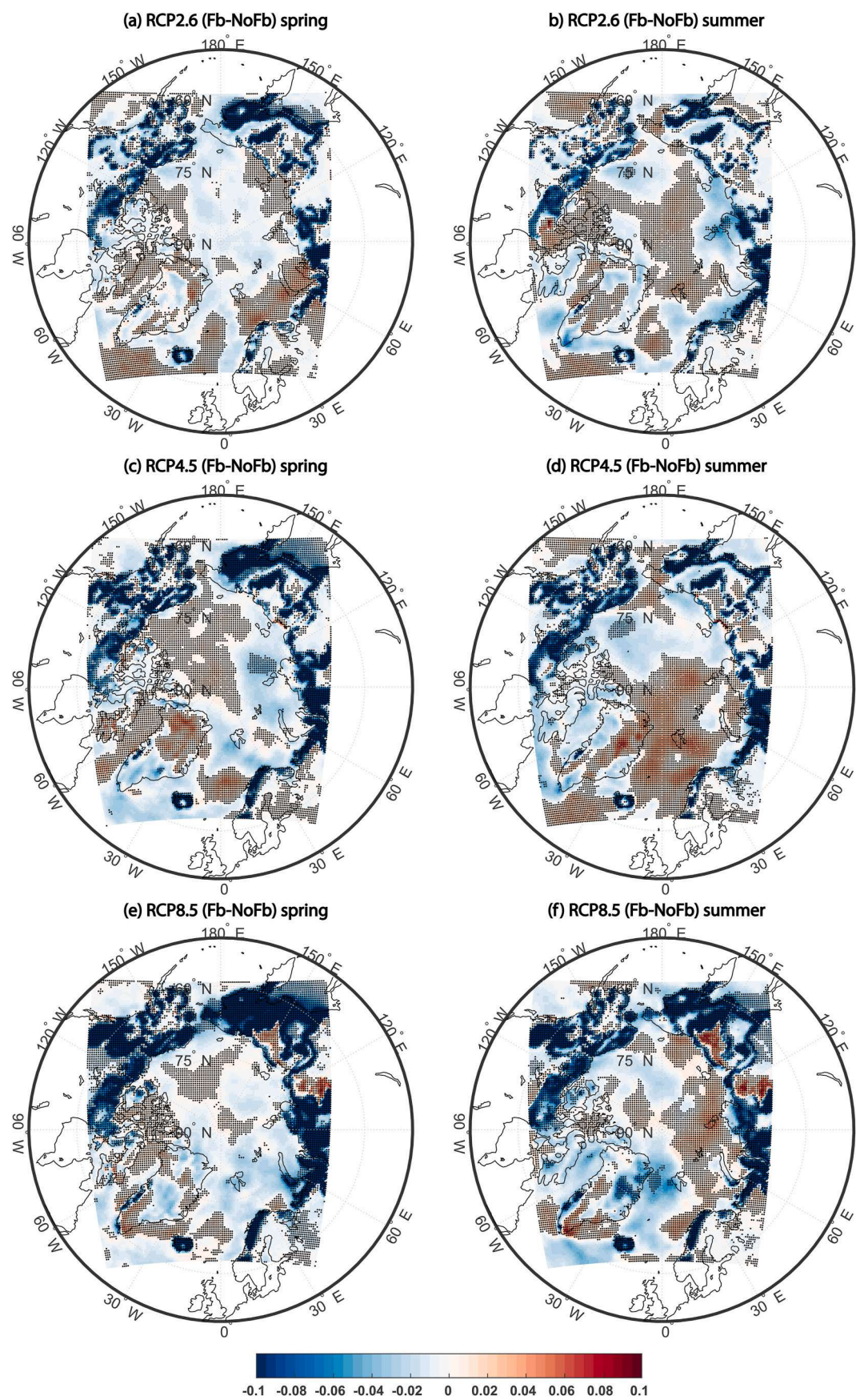


Fig. 10. Differences (“FB”-“NoFB”) in near-surface wind speed [m/s/decade] trends for spring and summer for RCP2.6, RCP4.5 and RCP8.5 scenarios. Statistically significant trends are indicated by black dots ($p < 0.05$).

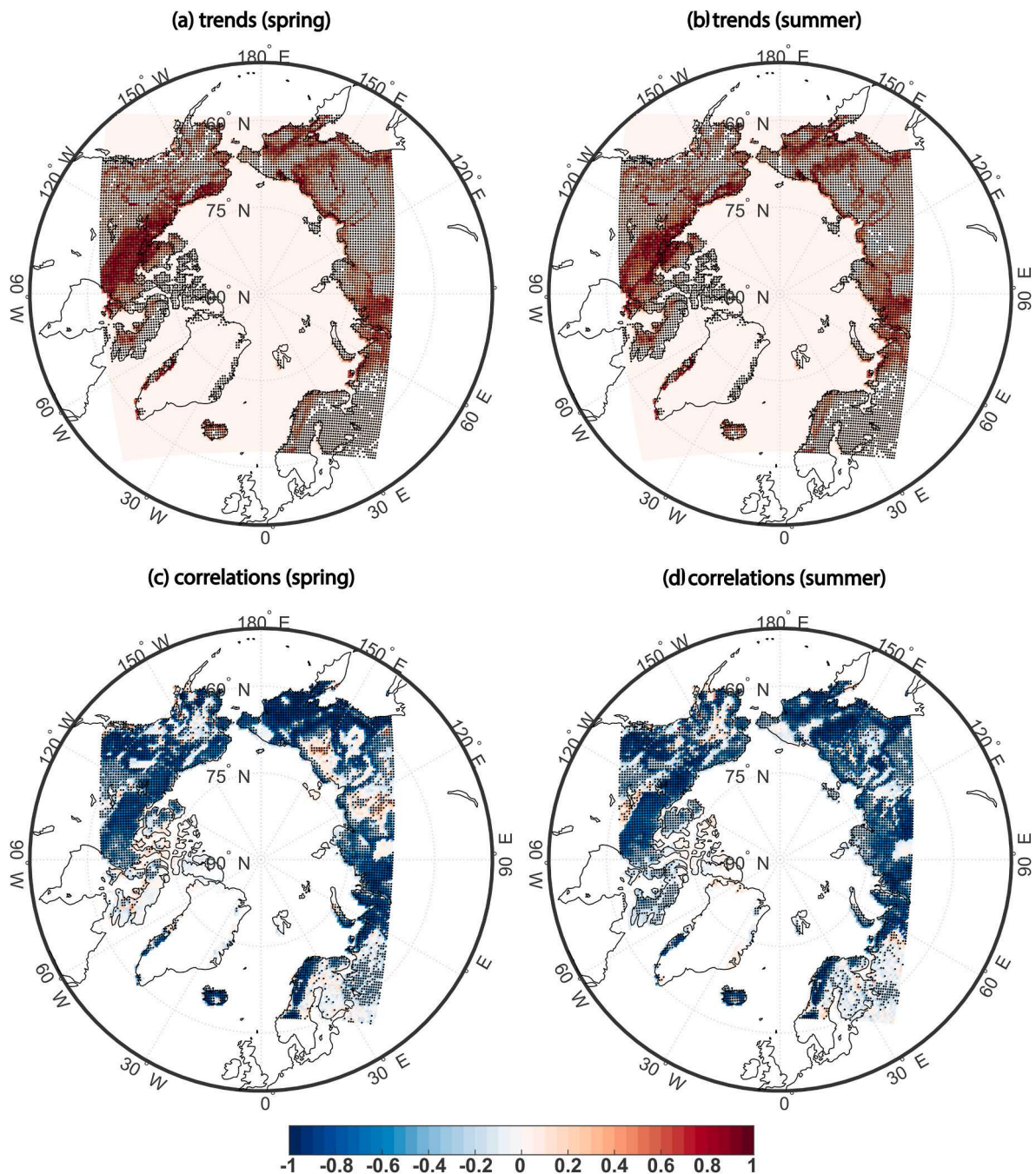


Fig. 11. Trends of LAI (a, b) and correlations between LAI and near-surface wind speed (c,d) for RCP8.5 for the different seasons. Statistically significant trends and correlations are indicated by black dots ($p < 0.05$).

warming becomes smaller.

Figs. 6–9 and SFig. 5 and 6 show the trends in near-surface air temperature, mean sea level pressure and static stability for the FB and the differences between FB and NoFB in spring under different RCP scenarios. In spring, the near-surface air temperature in the FB simulation increases faster over the continents than over the Arctic Ocean (Figs. 6 and 7b). The increase in near-surface air temperature over the continents extends and exceeds $1\text{ }^{\circ}\text{C}/\text{decade}$ in the strong RCP8.5 scenario (Fig. 7b). Therefore, as already shown in SFig. 4, the meridional temperature gradient between the Arctic Ocean and the continents is decreasing. Increased surface energy fluxes also lead to a decrease in static stability over the continents (Figs. 6 and 7f). This, in turn, reduces MSLP over the continents and Arctic Ocean (Figs. 6 and 7d). As a result, the atmospheric circulation over the Arctic becomes more cyclonic/less

anticyclonic, and therefore the near-surface wind speed should increase both on the continents and the Arctic Ocean. Some areas show an increase in atmospheric circulation, particularly the Nordic Seas and the area around Greenland, including Greenland (Fig. 7d). On the other hand, due to the increase in LAI as well as roughness length over the continents (Zhang et al., 2018), the near-surface wind speed should decrease. As shown in Fig. 10a–c,e, the near-surface wind speed decreases over the continents, reaching up to $-0.5\text{ m}\cdot\text{s}^{-1}/\text{decade}$. However, small areas of increase in near-surface wind speed are observed over the Arctic Ocean.

In summer, biogeophysical feedback induced changes in near-surface heating and surface heat fluxes lead to a decrease in the land-sea temperature contrast (Fig. S3) and an increase in static stability over the continents (Figs. 8–9). As a result, the circulation over the

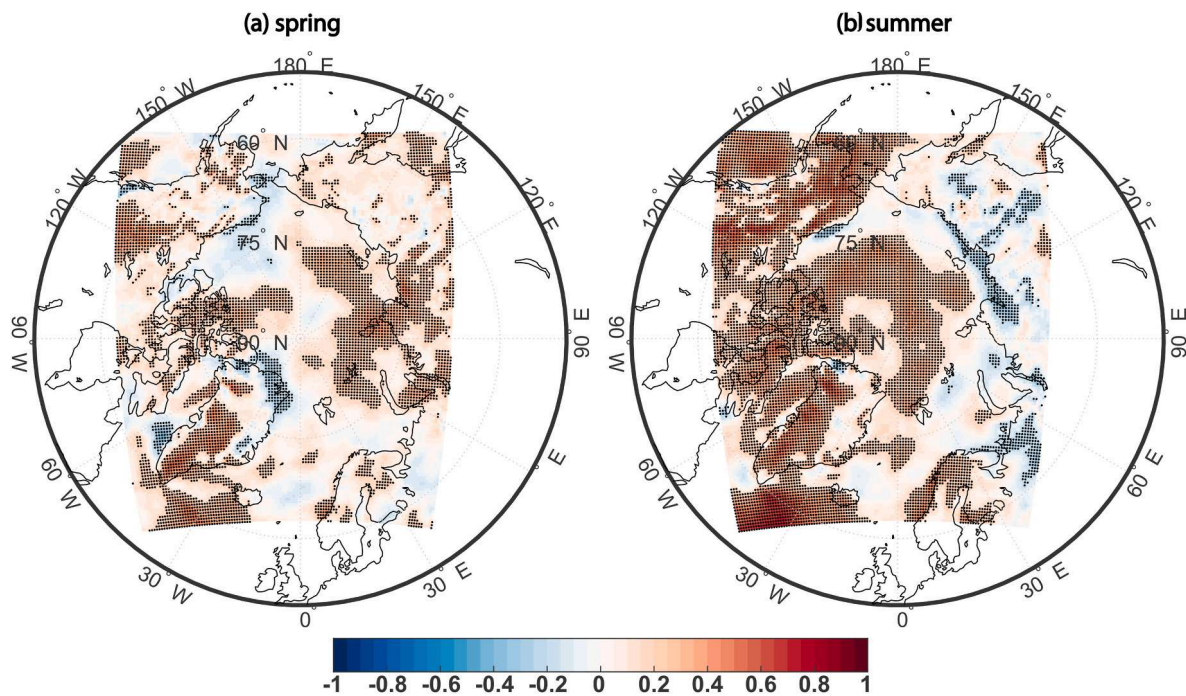


Fig. 12. Correlations between near-surface wind speed and wind speed at 500 hPa for RCP8.5 for the different seasons. Statistically significant correlations are indicated by black dots ($p < 0.05$).

Arctic Ocean and large areas over the continents becomes more anti-cyclonic/less cyclonic in summer compared to spring under the strong RCP8.5 scenario (Fig. 9d), which should lead to a decrease in near-surface wind speed.

However, under RCP4.5 scenario, regions with cyclonic circulation are observed over the Nordic Seas (Fig. 8d), with an increase in near-surface wind speed (Fig. 10d). In the strong RCP8.5 scenario, anti-cyclonic circulation prevails over the large areas over the Arctic, including the continents with cyclonic circulation over eastern Russia (Fig. 9d). The near-surface wind speed decreases over the large areas over the continents where anti-cyclonic circulation prevails and increases along the Russian Arctic seas. The increase/decrease in near-surface wind speed over the Arctic reaches up to $+0.1/-0.5 \text{ m s}^{-1}/\text{decade}$ in summer (Fig. 10b–d,f). Despite the prevailing anti-cyclonic circulation over the Arctic, the increase in near-surface wind speed along the Russian Arctic Seas is seen over the areas of weak decrease in static stability (Fig. 9f).

The RCA simulations, coupled with interactive vegetation dynamics, highlights changes in land surface properties (such as albedo, surface roughness, and the proportions of open land and forests) driven by dynamic vegetation responses (e.g., shifts in the tree line, shrub coverage, and increased LAI) to rising temperatures and elevated CO_2 levels (Zhang et al., 2018). The feedback from vegetation on wind profiles involves two major dynamic phenomena. The first is linked to shifts in the position of the polar front (Pielke and Vidale, 1995), determined by the contrasting land surface heating between boreal forests and tundra. This effect is particularly pronounced in the spring and summer along the northern edge of boreal forests. Our model has reported similar responses in studies examining the biogeophysical impacts on Arctic cyclone activities in our earlier study, in which biogeophysical feedback-induced changes in near-surface warming and surface heat fluxes lead to changes in land-sea temperature contrast and atmospheric stability (Akperov et al., 2022). The second phenomenon involves changes in the local wind profile. Increased LAI leads to greater surface roughness, which causes wind to lose energy near the surface, thereby reducing near-surface wind speeds (Launiainen et al., 2016). Our simulations show negative correlations between changes in LAI and near-surface wind speeds in the areas with the higher increase in LAI

(Fig. 11). However, the impact of LAI on wind speed differs in dependence on levels in the atmosphere and seasons. In spring, when albedo effects dominates as well as land-sea contrast increase, winds decreases also on higher levels, at least till 500 hPa. However, summer is dominated by evapotranspiration effects and higher turbulent-induced increase in the high level winds is only found in summer. This align with this response, showing opposite trends in wind speed changes between higher and lower levels of the atmosphere in different seasons (Fig. 12).

In addition, the changes in wind speeds are also linked to noticeable shifts the atmospheric baroclinicity, which in turn lead to cyclone activity in the Arctic. Specifically, there is an increase of cyclone frequency over the Arctic in spring and decrease in summer (Akperov et al., 2021), however, the cyclone depth (as a measure of cyclone kinetic energy) decreases in both seasons (as shown in their table 2), which may contribute to the decline in near-surface wind speed. Therefore, we may conclude that the decrease in near-surface wind speed is due partly atmospheric circulation, in particular changes in cyclone activity induced by biogeophysical feedback, and partly to the increase of surface roughness (Luu et al., 2023). However, model experiments are needed to further understand and disentangle the effects of circulation and surface roughness in order to assess their contribution in changes to near-surface wind speeds.

4. Summary and conclusions

In general, ensemble mean simulations using the regional climate model RCA4, driven by four different global models, show biases in the near-surface wind speed compared to the bias-corrected ERA5 reanalysis. Across all seasons, there is a consistent pattern of overestimation of near-surface wind speed over the land and underestimation over the Arctic Ocean. Despite these quantitative discrepancies, the RCM reproduces the spatial distribution of near-surface wind speed over the Arctic region reasonably well, with higher wind speeds observed over the Nordic Seas and lower wind speeds over land areas in all seasons. Historical simulations of the RCM RCA4 also show biases relative to the forcing GCMs, in particular higher near-surface wind speeds over the sea and continents, especially in areas with complex topographic features.

These biases are likely to be related to improvements in the representation of local topography and wind dynamics, including katabatic winds, within the RCM framework, compared to the GCMs.

The RCA4 ensemble mean projects an increase in near-surface wind speed over the northern Barents, Kara, Greenland and Chukchi Seas in winter and spring, and over the Arctic Ocean in summer and autumn under the RCP scenarios. The amplitude of the changes increases in the very strong RCP8.5. Seasonal trends in near-surface wind speed show a strong spatial correlation with projected sea ice retreat. The highest spatial correlation coefficients between the multi-model mean near-surface wind speed and sea ice concentration are found where the largest near-surface wind speed increases occur.

The RCA4 ensemble mean also shows the largest projected changes in near-surface wind speed compared to the four forcing GCMs. This is particularly evident over areas where sea ice changes are most pronounced. At the same time, the direction of changes in the near-surface wind speed over the Arctic Ocean is consistent between the RCM and the forced GCM ensemble mean.

The role of sea ice retreat and vegetation expansion in the projected changes in near-surface wind speed in the Arctic is also assessed. The reduction in ocean surface roughness caused by the transition from ice-covered to open water, and the reduced atmospheric stability and increased vertical momentum mixing from the enhanced surface warming lead to a projected increase in near-surface wind speeds over the Arctic, with a strong effect in winter and autumn.

Projected vegetation changes affect near-surface wind speeds through both changes in surface roughness and atmospheric circulation induced by biogeophysical feedbacks. In spring and summer, when surface roughness increases and circulation becomes more cyclonic or anticyclonic, near-surface wind speed decreases due to decrease of cyclone intensity in both seasons. Therefore, both factors contribute to the reduction of near-surface wind speeds over the continents.

CRedit authorship contribution statement

Mirseid Akperov: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Data curation, Conceptualization. **Wenxin Zhang:** Writing – review & editing. **Torben Koenigk:** Writing – review & editing. **Alexey Eliseev:** Writing – review & editing, Methodology. **Vladimir A. Semenov:** Writing – review & editing. **Igor I. Mokhov:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.polar.2024.101162>.

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