

• Original Paper •

# Influences of the NAO on the North Atlantic CO<sub>2</sub> Fluxes in Winter and Summer on the Interannual Scale

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## ABSTRACT

The differences in the influences of the North Atlantic Oscillation (NAO) on the air–sea CO<sub>2</sub> fluxes (fCO<sub>2</sub>) in the North Atlantic (NA) between different seasons and between different regions are rarely fully investigated. We used observation-based data of fCO<sub>2</sub>, surface-ocean CO<sub>2</sub> partial pressure (pCO<sub>2sea</sub>), wind speed and sea surface temperature (SST) to analyze the relationship between the NAO and fCO<sub>2</sub> of the subtropical and subpolar NA in winter and summer on the interannual time scale. Based on power spectrum estimation, there are significant interannual signs with a 2–6 year cycle in the NAO indexes and area-averaged fCO<sub>2</sub> anomalies in winter and summer from 1980 to 2015. Regression analysis with the 2–6 year filtered data shows that on the interannual scale the response of the fCO<sub>2</sub> anomalies to the NAO has an obvious meridional wave-train-like pattern in winter, but a zonal distribution in summer. This seasonal difference is because in winter the fCO<sub>2</sub> anomalies are mainly controlled by the NAO-driven wind speed anomalies, which have a meridional distribution pattern, while in summer they are dominated by the NAO-driven SST anomalies, which show distinct zonal difference in the subtropical NA. In addition, in the same season, there are different factors controlling the variation of pCO<sub>2sea</sub> in different regions. In summer, SST is important to the interannual variation of pCO<sub>2sea</sub> in the subtropical NA, while some biogeochemical variables probably control the pCO<sub>2sea</sub> variation in the subpolar NA.

**Key words:** air–sea CO<sub>2</sub> flux, North Atlantic Oscillation, interannual time scale, wind speed, surface-ocean CO<sub>2</sub> partial pressure

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## Article Highlights:

- There is a large difference in the fCO<sub>2</sub>–NAO relationship between winter and summer in the subtropical region.
- On the interannual scale, the fCO<sub>2</sub> variation is dominated by NAO-driven wind speed anomalies in winter, but by surface-ocean pCO<sub>2sea</sub> in summer.
- The pCO<sub>2sea</sub> variation is dominated by NAO-driven SSTs in the subtropical region and by other factors in the subpolar region.

## 1. Introduction

Since the industrial revolution, the ocean has played an important role in the absorption of atmospheric CO<sub>2</sub>, and

the North Atlantic (NA) is an important carbon sink. Based on observations, Schuster et al. (2013) estimated that the net CO<sub>2</sub> uptake of the Atlantic Ocean (40°S–79°N) over the years 1990–2009 was  $0.49 \pm 0.05$  PgC yr<sup>−1</sup>, which was equal to the uptake of CO<sub>2</sub> in the NA (north of 14°N) in 2000 reported by Takahashi et al. (2009). The tropical Atlantic is a source of atmospheric CO<sub>2</sub>, and the main sink of CO<sub>2</sub> in the NA is located in the subtropical and subpolar re-

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gions. The subpolar NA is the strongest CO<sub>2</sub> sink (Takahashi et al., 2009; Halloran et al., 2015). The change of physical fields in the NA can affect the uptake of CO<sub>2</sub> in this region. For example, in the subtropical NA, warming sea surface temperature (SST) can lead to an increase in the surface-ocean CO<sub>2</sub> partial pressure (pCO<sub>2sea</sub>), leading to the decrease in CO<sub>2</sub> uptake (Ullman et al., 2009). Thus, the air-sea CO<sub>2</sub> exchange in the NA can be affected by climate change events and can vary significantly (Gruber et al., 2009). For the NA, the most notable climate change event is the North Atlantic Oscillation (NAO) (Scaife et al., 2005).

The strong inverse relationship between Iceland's and the Azores' monthly mean sea level pressure was named by Walker (1925) as the NAO. Because the anomalies in the pressure field must cause the anomalies in the wind field and other atmospheric physical fields, changes of the NAO can result in changes of marine physical fields such as the North Atlantic Meridional Overturning Circulation, SST, and sea-ice cover (Walter and Graf, 2002; Johnston et al., 2012; Woollong et al., 2015; Delworth et al., 2016; Delworth and Zeng, 2016). These changes will further drive changes of CO<sub>2</sub> uptake in the NA, so the NAO has an important impact on the CO<sub>2</sub> uptake in the NA.

The impact of the NAO on the CO<sub>2</sub> uptake in the NA is complex. The responses of the physical fields and carbon cycle in the subtropical and subpolar NA to the NAO are different (Keller et al., 2012), and even the response mechanism of CO<sub>2</sub> fluxes (fCO<sub>2</sub>) in the same NA region to the NAO from different studies is inconsistent. In the subtropical region, based on site observations, Bates (2007) pointed out that during the negative period of the NAO, the CO<sub>2</sub> uptake is reduced because of the reducing wind speed. However, other studies showed that the SST is lower in the subtropical NA, which leads to lower pCO<sub>2sea</sub>, and thus higher rate of CO<sub>2</sub> uptake, offsetting the effects of reduced wind speed (Cayan, 1992; Keller et al., 2012). Therefore, the relationship between the NAO and CO<sub>2</sub> uptake in the subtropical NA is not clear up to now. On the other hand, many studies have reported a decrease in CO<sub>2</sub> uptake in the subpolar NA during the NAO negative phase, especially from the mid-1990s to the mid-2000s (Thomas et al., 2008; Pérez et al., 2013; Schuster et al., 2013), but the reasons for the decrease are inconsistent. Thomas et al. (2008) and Pérez et al. (2013) considered that NAO-driven horizontal advection is an important factor controlling the CO<sub>2</sub> uptake in the subpolar region. During the negative period of the NAO, the northward transport of seawater weakens because of the weakening of the North Atlantic Current, resulting in a higher concentration of dissolved inorganic carbon (DIC) in the subpolar region. As a result, the CO<sub>2</sub> uptake is reduced (Thomas et al., 2008; Pérez et al., 2013). The model results of Keller et al. (2012) suggested that during the NAO negative phase, the CO<sub>2</sub> uptake decreases in the eastern subpolar NA, and the changes of mixed layer depths and upwelling caused by NAO-driven wind anomalies are the main factors affecting the CO<sub>2</sub> uptake. Moreover, Metzl et al. (2010) pointed out that during the shift from a positive NAO index to a

negative index, the CO<sub>2</sub> uptake decreases in the subpolar region due to the change of SST.

Another noteworthy aspect of NA CO<sub>2</sub> uptake is that seasonal variations are different in different regions. The temperature-driven subtropical NA has the strongest seasonal variability of the fCO<sub>2</sub>, and is a sink of CO<sub>2</sub> in winter and a source of CO<sub>2</sub> in summer (Schuster et al., 2009; Landschützer et al., 2013). According to the observations at two time series sites near Bermuda, Bates (2007) pointed out that the influence of the NAO on the CO<sub>2</sub> uptake in the subtropical NA is not significant in winter due to the opposite effects of wind speed and the disequilibrium between the partial pressures of CO<sub>2</sub> in the air and ocean (dpCO<sub>2</sub>); in summer, the NAO impact is important, and during the negative period of the NAO, surface CO<sub>2</sub> release will increase significantly. The subpolar NA is a sink of CO<sub>2</sub> in summer as a result of the biologically driven winter-to-summer drawdown of CO<sub>2</sub> (Landschützer et al., 2013). Because phytoplankton bloom events take place occasionally in the summer of some years, the interannual variability of the fCO<sub>2</sub> in the subpolar NA is significant in summer. In winter, deeper mixing of seawater makes the CO<sub>2</sub> in surface water rich, and the cold seawater temperature makes the biological activity weaker, resulting in high pCO<sub>2sea</sub>, so the region is a stable source of CO<sub>2</sub> in winter (Corbière et al., 2007; Watson et al., 2009). Compared with the subtropical NA, the fCO<sub>2</sub> in the subpolar NA has stronger interannual variability (Friedrich et al., 2006).

Because the seasonal variation of fCO<sub>2</sub> in different regions of the NA is different, and the main controlling factors of fCO<sub>2</sub> are different, to analyze the response of fCO<sub>2</sub> to the NAO in the NA, we need to discuss it in separate regions and seasons. Here, we divided the NA into the subtropical region (25°–45°N) and subpolar region (45°–65°N) to study the response of fCO<sub>2</sub> to the NAO in winter and summer, respectively. The mechanisms for the response are also explored. Due to the limitation of the time range of the observation-based data of fCO<sub>2</sub>, we only analyze the response on the interannual scale. Because there are many ways to define the NAO index (Pokorná and Huth, 2015), we used two different definitions of NAO index for analysis to more accurately determine the relationship between the NAO and the fCO<sub>2</sub> in the NA.

## 2. Data and methods

### 2.1. Data

Monthly observed air-sea fCO<sub>2</sub> data from 1980 to 2015 (positive values indicate CO<sub>2</sub> outgassing from the ocean) based on the Surface Ocean CO<sub>2</sub> Atlas were obtained directly from Rödenbeck et al. (2013) at <http://www.bgc-jena.mpg.de/CarboScope/?ID50c>. The spatial resolution of the data is 1° × 1°, achieved by linear interpolation. Grid-ded pCO<sub>2sea</sub> data from 1983 to 2011 based on a statistical model were obtained directly from Landschützer et al. (2015) at [http://cdiac.ornl.gov/ftp/oceans/SPCO2\\_1982\\_](http://cdiac.ornl.gov/ftp/oceans/SPCO2_1982_)

2011\_ETH\_SOM\_FFN, which have a spatial resolution of  $1^\circ \times 1^\circ$ . The monthly sea level pressure data from 1950 to 2017 were obtained from NCEP–NCAR reanalysis data (<https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html>), with a spatial resolution  $2.5^\circ \times 2.5^\circ$ . The observational sea-ice and SST data from 1870 to 2016 were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (<http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>), which has a spatial resolution of  $1^\circ \times 1^\circ$ . The 10-m wind speed ( $vm_{10}$ ) data used here are based on a synthesis of NCEP–NCAR monthly average meridional and zonal wind from 1948 to 2018, which has a spatial resolution  $1^\circ \times 1^\circ$ , achieved by linear interpolation. When we analyze the relationships between  $fCO_2$  and associated variables (NAO indexes,  $vm_{10}$ ), the time period that matches with the  $fCO_2$  data is selected, whereas when we analyze the relationships between  $pCO_{2sea}$  and associated variables (NAO indexes,  $vm_{10}$ ,  $fCO_2$ , SST), the time period that matches with the  $pCO_{2sea}$  data is selected.

Two definitions of the NAO index are used in this work: (1) site-based NAO index values in summer (June–July–August) and winter (December–January–February) from the Climate Analysis Section of the NCAR (<https://climate-dataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based>), which are directly used and referred to as  $NAO_{NCAR}$  (the time period for  $NAO_{NCAR}$  is from 1949 to 2017); and (2) NAO index values in summer and winter defined by the method proposed by Gong and Wang (2000), referred to here as  $NAO_{Gong}$ :

Summer  $NAO_{Gong}$ :

$$I_{NAO} = P^*(45N, 40-60W) - P^*(65^\circ N, 10-30W). \quad (1)$$

Winter  $NAO_{Gong}$ :

$$I_{NAO} = P^*(35N, 10W-10E) - P^*(65N, 10-30W), \quad (2)$$

where  $P^*$  represents the normalized sea level pressure. A three-point spatially arithmetic average of  $P^*$  differences between the high pressure area and the low pressure area is used to represent the NAO index.

## 2.2. Methods

In order to understand the mechanisms of the impact of the NAO on  $fCO_2$ , we need to know the main factors leading to the change of  $fCO_2$ . The net exchange of  $CO_2$  between the air and the ocean ( $fCO_2$ ) is described by:

$$fCO_2 = K(pCO_{2sea} - pCO_{2air})(1 - \gamma_{ice}); \quad (3)$$

$$K = k\alpha. \quad (4)$$

Here,  $K$  is the air–sea gas transfer coefficient and is the product of  $k$  and  $\alpha$ , where  $k$  is the  $CO_2$  gas transfer velocity at sea water, and  $\alpha$  is  $CO_2$  solubility in seawater, which can be influenced by SST.  $pCO_{2air}$  and  $pCO_{2sea}$  are the partial pressures of  $CO_2$  in air and sea-surface water, respectively.  $\gamma_{ice}$  is the fraction of sea ice. Among them, the  $CO_2$  gas transfer

velocity is mainly related to 10-m wind speed ( $vm_{10}$ ), which is usually calculated by the formula of Wanninkhof (1992):

$$k = 0.31 \times vm_{10}^2 \sqrt{\frac{660}{Sc}}, \quad (5)$$

where  $Sc$  is the Schmidt number and indicates the ratio of sea-water dynamic viscosity to gas diffusion coefficient.

For discussion on the anomalies of physical fields in summer and winter, first, the fields are averaged in winter or summer, and then the trend is removed using the least-squares linear method. The average of the fields in the subtropical NA is an area-weighted average of the region ( $25^\circ-45^\circ N$ ,  $100^\circ W-40^\circ E$ ). Meanwhile, the average of the physical fields in the subpolar NA is also treated, and the selected region is ( $45^\circ-65^\circ N$ ,  $100^\circ W-40^\circ E$ ). The grid point where the sea-ice coverage exceeds 15% is treated as default to avoid the effect of the sea ice on the  $fCO_2$ . For discussion on the influences of the NAO index and associated variables ( $vm_{10}$  and  $pCO_{2sea}$ , SST) on  $fCO_2$ , standardized regression coefficients (RCs) (see sections 3 for more details) are examined.

The specific cycles of the winter (or summer) NAO index and area-average  $fCO_2$  anomalies are obtained by power spectrum estimation. Because the main cycles characterized by the interannual sign of the NAO are within 2–6 years (Jing et al., 2019), the interannual sign is therefore extracted using a 2–6-year Lanczos bandpass filter for the following study, so the anomalies of these variables mean their interannual variabilities. The confidence level of the linear regression is evaluated using the two-tailed Student's  $t$ -test, and the effective degrees of freedom (DOF) is calculated following Bretherton et al. (1999):

$$DOF = N(1 - r_1 r_2)(1 + r_1 r_2), \quad (6)$$

where  $N$  is the sample size, and  $r_1$  and  $r_2$  are the lag-one autocorrelations of the two time series, respectively.

## 3. Results and discussion

### 3.1. Periodicities of the NAO and NA $fCO_2$

The cycles of the NAO indexes over the years 1980 to 2015, which were obtained by power spectrum estimation, are shown in Table 1 and Fig. A1 in Appendix.  $NAO_{Gong}$  and  $NAO_{NCAR}$  in winter both have a significant cycle of 5.8 years characterized by inter-annual signals. Besides,  $NAO_{NCAR}$  in winter also has a significant interannual cycle of 2.7 years. As for the summer NAO indexes,  $NAO_{NCAR}$  has the same periodicity as the winter one, and  $NAO_{Gong}$  has one more cycle of 2.1 years than that in winter. Because the winter and summer NAO indexes mainly reflect the signals of 2–6 years, we use a bandpass filter of 2–6 years in the following analysis.

The cycles of the anomalies of area-averaged net air–sea  $fCO_2$  (positive values indicate  $CO_2$  outgassing from the ocean) in the subtropical and subpolar NA are shown in

**Table 1.** Periodicities of the winter (or summer)  $NAO_{Gong}$ ,  $NAO_{NCAR}$  and area-averaged  $CO_2$  flux ( $fCO_2$ ) anomalies, determined by power spectrum analysis. Specifically, the periodicities are determined by calculating the red noise confidence interval and choosing those at the 90% confidence level. The time period for the data ranges from 1980 to 2015.

	Winter	Summer
$NAO_{Gong}$	5.8	2.1, 5.8
$NAO_{NCAR}$	2.7, 5.8	2.7, 5.8
Subtropical $fCO_2$	3.7–4.3	2.9–3.2, 25
Subpolar $fCO_2$	2.7, 6.7–7.5	2.1–2.2, 14–25

Table 1 and Fig. A2. In both the subtropical and subpolar NA, the anomalies of area-averaged  $fCO_2$  have the interannual signals in winter and summer. In summer, there are decadal signs in the area-averaged  $fCO_2$  in both the subtropical and subpolar NA. Numerous studies have pointed out that the NAO is affected differently by the jet on different time scales, and its effects on the ocean physical field on different time scales are also different (Viles and Goudie, 2003; Woollings et al., 2015). In addition, on the different time scales, the main controlling factors leading to the change of  $fCO_2$  are also different. Couldrey et al. (2016) pointed out that with increasing of time scale the controlling factor of the NA  $fCO_2$  variability changes from the gas transfer velocity to the  $dpCO_2$ . Therefore, discussion on the influences of the NAO on the  $fCO_2$  in the NA on different time scales is of great significance to understand the temporal variation of the  $fCO_2$  and to improve the projection of the carbon cycle in the NA. Unfortunately, because of the lack of long-term  $pCO_{2,sea}$  observation-based data, the impact of the NAO on the  $fCO_2$  at the longer time scale is not included in this study. In order to study the relationship between the  $fCO_2$  and the NAO on the interannual scale, we also used a bandpass filter of 2–6 years on the  $fCO_2$  anomalies.

The correlation coefficients between the NAO indexes and the area-averaged  $fCO_2$  in the subpolar or subtropical NA in different seasons are listed in Table 2. Only the area-averaged  $fCO_2$  in the subtropical region in winter responds

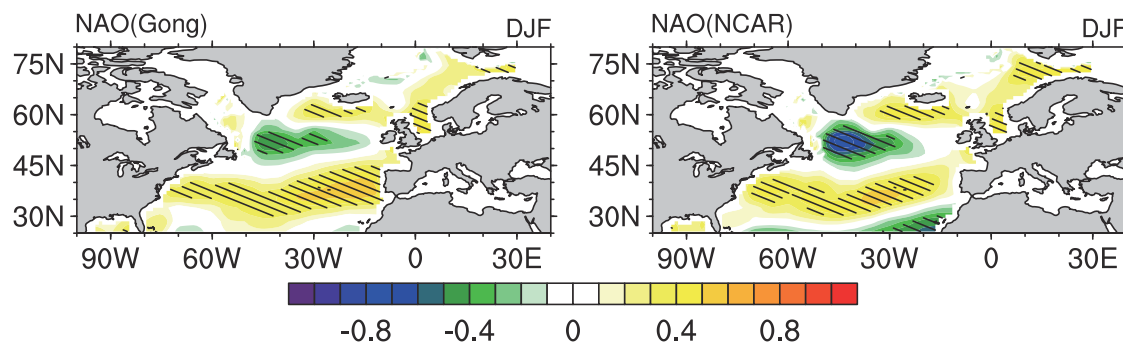
**Table 2.** Correlation coefficients between the NAO indexes and the area-averaged  $fCO_2$  anomalies in the subtropical and subpolar NA on the interannual scale in winter and summer. The time period for data ranges from 1980 to 2015. Numbers in parentheses are the corresponding number of degrees of freedom calculated according to Eq. (6). Bold numbers indicate that the correlation coefficients are significant at the 95% confidence level.

	Summer		Winter	
	Subtropical	Subpolar	Subtropical	Subpolar
$NAO_{Gong}$	0.07 (34)	−0.06 (31)	<b>0.54 (35)</b>	−0.07 (36)
$NAO_{NCAR}$	−0.11 (34)	0.24 (33)	<b>0.34 (36)</b>	−0.12 (36)

very significantly to the NAO, especially to the NAO index defined by the Gong method, for which the correlation coefficient reaches 0.54 with 35 DOFs. It indicates that during the positive phase of the NAO, the  $CO_2$  release from the subtropical NA increases in winter, and the relationship between the NAO and the area-averaged  $fCO_2$  is not significant in summer. This is contrary to the conclusion of Bates (2007), who pointed out that the relationship between the NAO and  $fCO_2$  is not significant in winter, but is significant in summer based on observation-based data from two time series obtained at sites near Bermuda. This also demonstrates that the characteristics of the carbon cycle in Bermuda are not representative of that in the whole subtropical NA. The relationship between the NAO and area-averaged  $fCO_2$  in the subpolar region is not significant in both summer and winter. This is probably due to the inconsistent response of the  $fCO_2$  anomalies to the NAO in different sea areas of the subpolar region.

### 3.2. Relationship between the NAO and $fCO_2$ in winter

Figure 1 shows the RCs of the  $fCO_2$  anomalies against the NAO indexes on the interannual scale in winter. The significant RCs between the NAO indexes and the  $fCO_2$  anomalies are positive–negative–positive along the meridional direction, which shows the relationship of a wave-train-like pattern between the  $fCO_2$  anomalies and the NAO. In the subtropical NA, the positive RCs of the  $fCO_2$  anomalies against the



**Fig. 1.** Regression coefficients (RCs) of the air–sea  $CO_2$  flux anomalies against  $NAO_{Gong}$  and  $NAO_{NCAR}$  in winter (December–January–February) on the interannual scale. Shaded areas indicate that RCs are statistically significant at the 95% confidence level of the Student’s  $t$ -test. The time period for the data ranges from 1980 to 2015.



winter NAO indexes occur in most regions, which is consistent with Table 2. In the subpolar region, the RCs of the  $f\text{CO}_2$  anomalies against the winter NAO indexes (especially  $\text{NAO}_{\text{NCAR}}$ ) are negative within 45°–60°N. Because the positive  $f\text{CO}_2$  indicates the CO<sub>2</sub> release from the sea surface, the CO<sub>2</sub> uptake is in decline during the period of negative NAO phase in the subpolar region in winter, which is consistent with previous studies (Thomas et al., 2008; Pérez et al., 2013). The RCs are positive north of 60°N, as opposed to south of 60°N, which results in a phenomenon whereby the relationships between winter NAO indexes and the area-averaged  $f\text{CO}_2$  in the subpolar region are not significant, as reflected in Table 2.

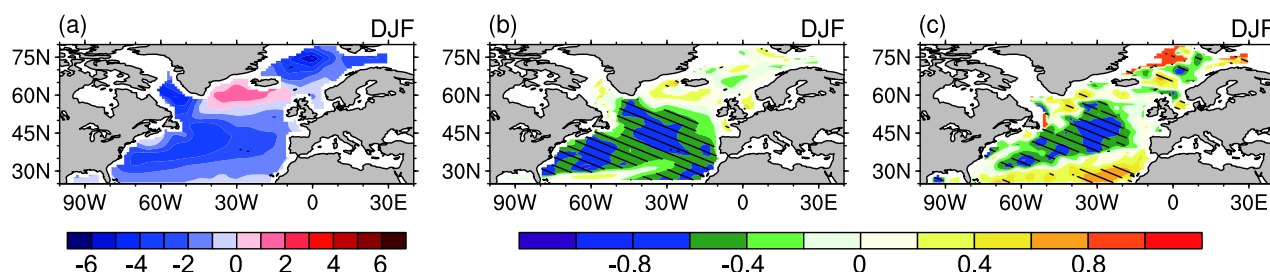
According to Eq. (3), there are two main factors controlling the change of  $f\text{CO}_2$ —namely, the CO<sub>2</sub> gas transfer velocity associated with wind speed, and the difference in  $\text{dpCO}_2$ . Compared with the  $\text{pCO}_{2\text{sea}}$ , the interannual variability of  $\text{pCO}_{2\text{air}}$  is negligible, so only the influence of  $\text{pCO}_{2\text{sea}}$  on the  $f\text{CO}_2$  is investigated. The CO<sub>2</sub> gas transfer velocity can only affect the intensity of the  $f\text{CO}_2$  and the direction of  $f\text{CO}_2$  is determined by the  $\text{dpCO}_2$ . As a result, the impact of the wind speed ( $\text{vm}_{10}$ ) and  $\text{pCO}_{2\text{sea}}$  on the  $f\text{CO}_2$  needs to take the direction of  $f\text{CO}_2$  into consideration. The signs of the value of  $\text{pCO}_{2\text{sea}}$  anomalies and  $f\text{CO}_2$  anomalies (positive values indicate CO<sub>2</sub> outgassing from the ocean) are the same, and the increase of  $\text{pCO}_{2\text{sea}}$  will lead to the increase of CO<sub>2</sub> release. Therefore, the non-significant or negative

RCs of the  $f\text{CO}_2$  anomalies against the  $\text{pCO}_{2\text{sea}}$  anomalies mean that the  $\text{pCO}_{2\text{sea}}$  anomalies are not the dominant factor affecting the  $f\text{CO}_2$  anomalies.

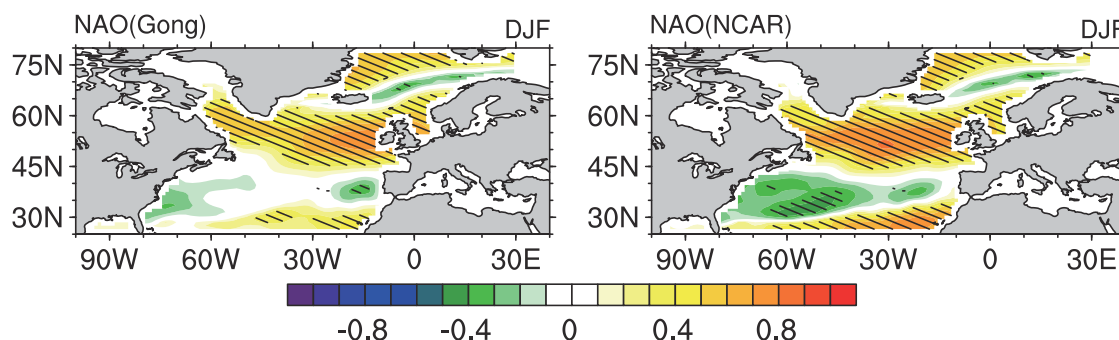
Figure 2 shows the time-averaged  $f\text{CO}_2$  and the RCs of the  $f\text{CO}_2$  against the  $\text{vm}_{10}$  from 1980 to 2015 and against the  $\text{pCO}_{2\text{sea}}$  from 1983 to 2011 in winter. Most of the regions south of 55°N and north of 65°N are a sink of atmospheric CO<sub>2</sub>, with the maximum absolute value of  $f\text{CO}_2$  being at around 40°N. The region south of Iceland (60°–65°N) is the source of atmospheric CO<sub>2</sub> affected by the winter convection mixing.

On the interannual scale, the winter  $\text{vm}_{10}$  can significantly affect the  $f\text{CO}_2$  in the subtropical NA and most of the subpolar NA (Fig. 2b). In the region of the sink of CO<sub>2</sub> (negative  $f\text{CO}_2$ ), the RCs of the  $f\text{CO}_2$  anomalies against the  $\text{vm}_{10}$  anomalies are negative, which indicates that in winter, the phase of  $\text{vm}_{10}$  is consistent with the phase of  $f\text{CO}_2$  in this region. The  $f\text{CO}_2$  anomalies in most regions of the NA are less affected by the  $\text{pCO}_{2\text{sea}}$  anomalies, especially in the region between 30° and 60°N, and only in the small region south of Greenland and south of 30°N is there a significant relationship between the  $f\text{CO}_2$  and  $\text{pCO}_{2\text{sea}}$  (Fig. 2c).

Whether the  $\text{vm}_{10}$  driven by the NAO has an impact on the  $f\text{CO}_2$  anomalies in winter is explored here. In terms of the relationships between winter NAO indexes and  $\text{vm}_{10}$  anomalies (Fig. 3), the RCs of the  $\text{vm}_{10}$  anomalies against the NAO indexes are significantly positive in the region north



**Fig. 2.** Multi-year mean CO<sub>2</sub> fluxes in winter (a), and RCs of the  $f\text{CO}_2$  anomalies against the 10-m wind speed anomalies (b) and against the partial pressures of CO<sub>2</sub> in the sea surface anomalies (c) in winter, respectively. Shaded areas indicate that RCs are significant at the 95% confidence level of the Student's *t*-test. The time period for (a) and (b) ranges from 1980 to 2015, and for (c) ranges from 1983 to 2011.



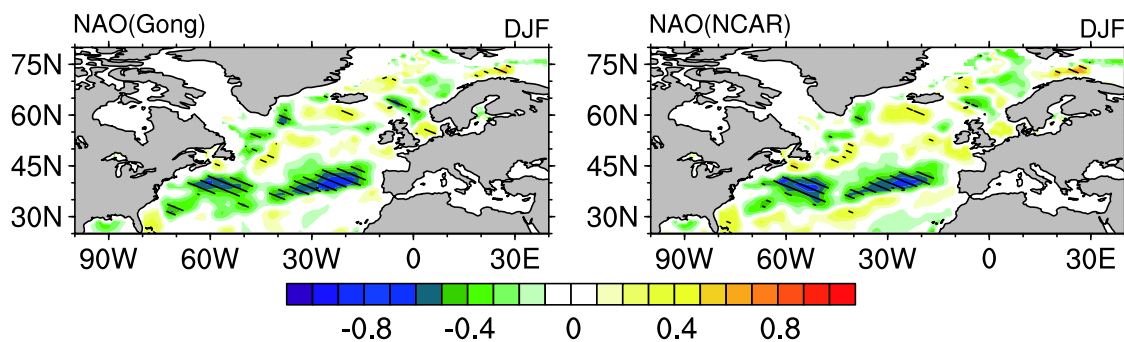
**Fig. 3.** Regression coefficients (RCs) of the  $\text{vm}_{10}$  anomalies against  $\text{NAO}_{\text{Gong}}$  and  $\text{NAO}_{\text{NCAR}}$  in winter on the interannual scale. Shaded areas indicate that RCs are statistically significant at the 95% confidence level. The time period for the data ranges from 1980 to 2015.

of 45°N and significantly negative in the region at around 35°N. The negative RCs of the  $vm_{10}$  anomalies against  $NAO_{NCAR}$  are more significant, compared with the RCs against  $NAO_{Gong}$ . The relationships between the NAO indexes and  $vm_{10}$  anomalies are consistent with the model results of Keller et al. (2012). In addition, in winter, the meridional distribution pattern of significant RCs of the  $fCO_2$  anomalies against the NAO indexes is opposite to that of the  $vm_{10}$  anomalies against the NAO indexes in the region of 30°–60°N in the NA. This is consistent with the fact that in these regions the RCs of the  $fCO_2$  anomalies against the  $vm_{10}$  anomalies are mostly negative. Specifically, during the positive period of the NAO, in the region of  $CO_2$  release south of Iceland and the region of 45°–55°N for  $CO_2$  uptake, enhancement of  $vm_{10}$  leads to the increase in the release and uptake of atmospheric  $CO_2$ , respectively. In the region of the sink of  $CO_2$  south of 45°N, the  $CO_2$  uptake is weakened due to the weakening of  $vm_{10}$ . It demonstrates that, in winter, the response of  $fCO_2$  to the NAO is mainly dominated by wind speed in the NA.

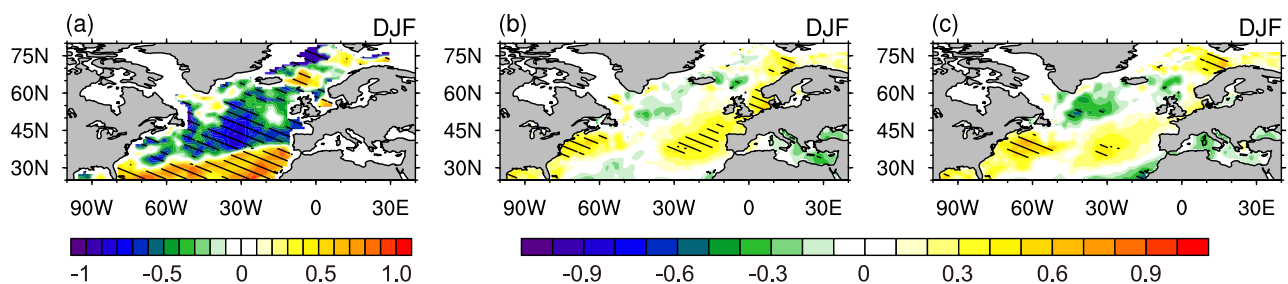
The reason for the weak impact of  $pCO_{2sea}$  on the interannual variation of the  $fCO_2$  is also investigated. There is a significant correlation between the  $fCO_2$  anomalies and NAO indexes in the NA, while the relationship between the  $pCO_{2sea}$  anomalies and the NAO indexes is not significant for most regions with exception of some sporadic small regions, but in the relatively large region of 35°–40°N the  $pCO_{2sea}$  anom-

alies have a strong negative response to the NAO (Fig. 4) as well as the response of  $vm_{10}$  to the NAO (Fig. 3). Both negative responses to the NAO generate different results in the  $fCO_2$  anomalies. In other words, if the  $pCO_{2sea}$  response increases the  $fCO_2$ , the  $vm_{10}$  response decreases the  $fCO_2$ , since the region of 35°–40°N is a sink of atmospheric  $CO_2$  in winter, so that the influences of the NAO-driven  $pCO_{2sea}$  and wind speed on the  $fCO_2$  are opposite to each other. The positive response of the  $fCO_2$  on the NAO indicates that, in this region, the impact of the NAO-driven  $vm_{10}$  on  $CO_2$  uptake is larger than that of NAO-driven  $pCO_{2sea}$ .

The  $pCO_{2sea}$  anomalies in the surface seawater are mainly induced by the change of SST and DIC, and the increase of SST or DIC can enlarge the  $pCO_{2sea}$  (Schuster et al., 2009; Dong et al., 2017). As shown in Fig. 5a, in winter, the SST only dominates the change of the  $pCO_{2sea}$  south of 35°N, which is very similar to the relationship of the  $fCO_2$  anomalies and the  $pCO_{2sea}$  anomalies (Fig. 2c). It indicates that there are other factors controlling the interannual variation of  $pCO_{2sea}$  north of 35°N. As a result, there is no obvious relationship between the interannual variations of  $pCO_{2sea}$  and  $fCO_2$ , which is consistent with the previous finding that the  $pCO_{2sea}$  anomalies in the subpolar NA may be affected by the DIC supply induced by the vertical mixing (Ullman et al., 2009), just like the equatorial Pacific, which has strong upwelling (Dong et al., 2017). In addition, the interannual variation of SST south of 35°N is not induced by the



**Fig. 4.** Regression coefficients (RCs) of the  $pCO_{2sea}$  anomalies against  $NAO_{Gong}$  and  $NAO_{NCAR}$  in winter on the interannual scale. Shaded areas indicate that RCs are statistically significant at the 95% confidence level. The time period for the data ranges from 1983 to 2011.



**Fig. 5.** Regression coefficients (RCs) of the  $pCO_{2sea}$  anomalies against the SST anomalies in winter (a), and RCs of the SST anomalies against  $NAO_{Gong}$  (b) and  $NAO_{NCAR}$  (c) in winter. Shaded areas indicate that RCs are significant at the 95% confidence level of the Student's  $t$ -test. The time period for the data ranges from 1983 to 2011.

NAO (Fig. 5b and c), so there is no response of the  $p\text{CO}_{2\text{sea}}$  to the NAO in this region on the interannual scale (Fig. 4).

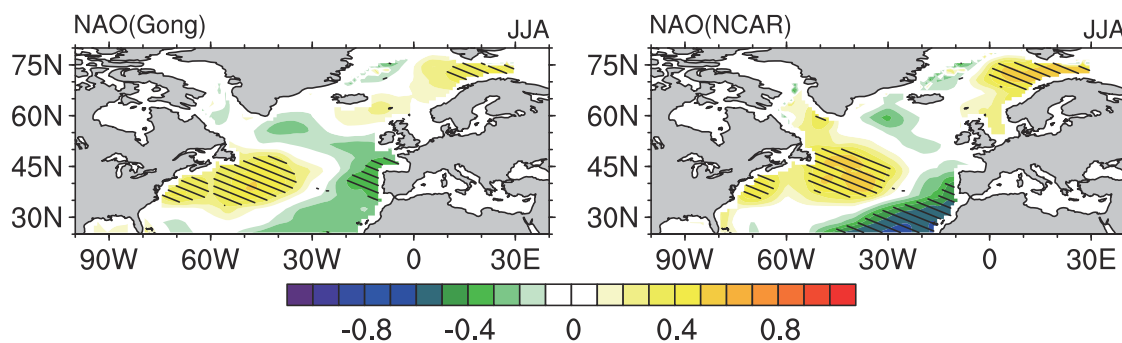
### 3.3. Relationship between the NAO and $f\text{CO}_2$ in summer

The correlation coefficients between the NAO indexes and the area-averaged  $f\text{CO}_2$  in the subpolar or subtropical NA in summer are less than 0.24 and do not reach the 95% confidence level (Table 2). The RCs of the  $f\text{CO}_2$  anomalies against the NAO indexes in summer are shown in Fig. 6. In summer, the response of the  $f\text{CO}_2$  anomalies to the NAO has spatial differences in both the meridional and zonal directions. Along the meridional direction, the latitudes of the regions with positive and negative RCs are generally consistent with those in winter, but absolute values of the RCs in the subpolar region are reduced, for which the RCs do not reach the 95% significance test north of 50°N. Along the zonal direction, compared with winter, the largest difference of RCs in summer occurs in the subtropical region, in which the RCs change from significant positive regions in winter to a positive-west and negative-east distribution pattern in summer. Bates (2007) mentioned that the  $f\text{CO}_2$  in the Bermuda Sea has a significant response to the NAO in summer, which is close to our result, but for the whole subtropical NA, the effect of the NAO on the  $f\text{CO}_2$  anomalies in the region with negative RCs in the eastern region offsets the effect in the region with positive RCs in the central and western region. As a result, in summer the NAO has no significant effect on the area-averaged  $f\text{CO}_2$  in the subtropical re-

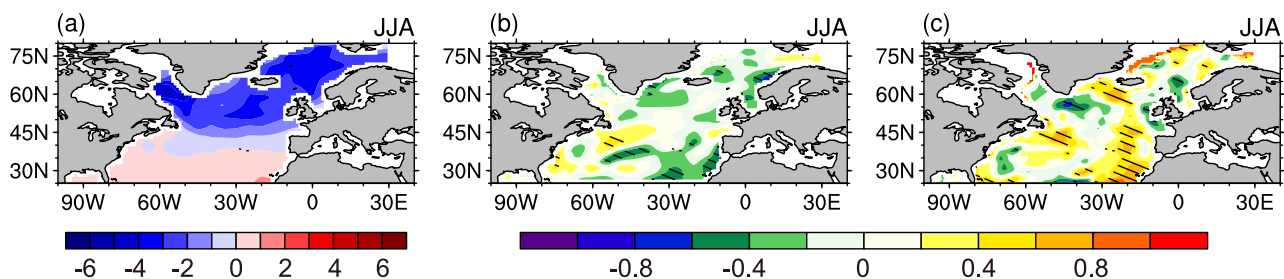
gion (Table 2). From the above analysis, the relationship between the NAO and the  $f\text{CO}_2$  anomalies has a stronger seasonality in the subtropical region than that in the subpolar region.

The significant difference between the response of the  $f\text{CO}_2$  in the NA to the NAO in summer and winter indicates that the main factors controlling the interannual variation of the  $f\text{CO}_2$  have changed from winter to summer. The summertime-averaged  $f\text{CO}_2$  in the NA is shown in Fig. 7a. Affected by the productivity and SST, the region north of 40°N is a sink of CO<sub>2</sub>, while the region south of 40°N is a weak source of CO<sub>2</sub>. As a result, the absorption of atmospheric CO<sub>2</sub> in the NA is significantly weaker in summer than in winter.

Figure 7b shows that  $f\text{CO}_2$  anomalies are less affected by  $\text{vm}_{10}$  in almost all of the NA in summer. In the CO<sub>2</sub> sink region, only in a small part of the sea area in the western subtropical region does the  $f\text{CO}_2$  have a significant relationship with  $\text{vm}_{10}$ . The relationship between the summer  $f\text{CO}_2$  anomalies and the  $p\text{CO}_{2\text{sea}}$  anomalies shows that, in summer, the NA  $f\text{CO}_2$  anomalies are significantly affected by the  $p\text{CO}_{2\text{sea}}$  anomalies in most regions (Fig. 7c). The regions characterized by significant positive RCs at the 95% confidence level are increased relative to those in winter (Fig. 2c), especially in the subtropical NA. The major response regions of the  $f\text{CO}_2$  to  $p\text{CO}_{2\text{sea}}$  are concentrated in the west and east of the subtropical NA, and in the sea area south of Iceland.



**Fig. 6.** Regression coefficients (RCs) of the  $f\text{CO}_2$  anomalies against  $\text{NAO}_{\text{Gong}}$  and  $\text{NAO}_{\text{NCAR}}$  in summer (June–July–August) on the interannual scale. Shaded areas indicate that RCs are statistically significant at the 95% confidence level of the Student's  $t$ -test. The time period for the data ranges from 1980 to 2015.



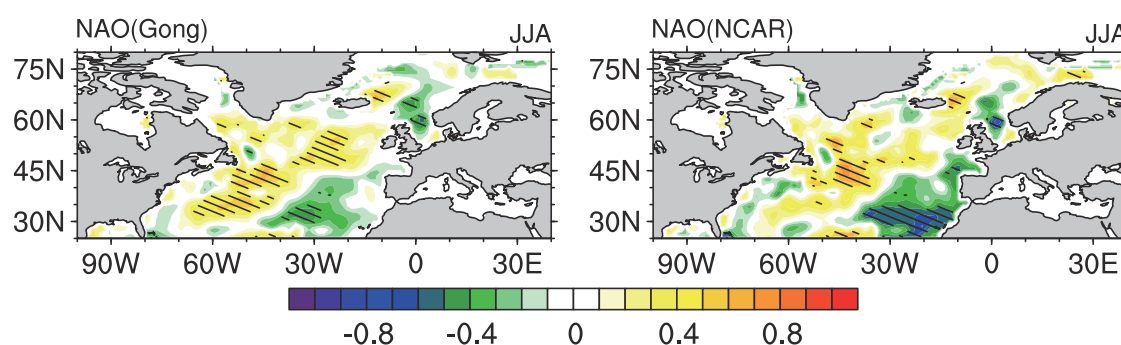
**Fig. 7.** Multi-year mean CO<sub>2</sub> fluxes in summer (a), and regression coefficients (RCs) of the  $f\text{CO}_2$  anomalies against the  $\text{vm}_{10}$  anomalies (b) and the  $p\text{CO}_{2\text{sea}}$  anomalies (c) in summer. Shaded areas indicate that RCs are significant at the 95% confidence level of the Student's  $t$ -test. The time period for (a) and (b) ranges from 1980 to 2015, and for (c) ranges from 1983 to 2011.

The RCs of the summer  $p\text{CO}_{2\text{sea}}$  anomalies against the NAO indexes (Fig. 8) illustrates that, in summer, the response of  $p\text{CO}_{2\text{sea}}$  to the NAO in the subtropical region reveals a converse change for the east and the west, which is consistent with the response of the  $f\text{CO}_2$  anomalies to the NAO in this region (Fig. 6); that is, during the positive period of NAO, the  $\text{CO}_2$  release from the sea surface is increased due to the increase of  $p\text{CO}_{2\text{sea}}$  in the western and central regions, whereas it is weakened in the eastern region. In the subpolar region, the RCs of the  $f\text{CO}_2$  anomalies against the  $p\text{CO}_{2\text{sea}}$  anomalies are significantly positive in the region south of Iceland (Fig. 7c); that is, in this region there is a significant influence of the  $p\text{CO}_{2\text{sea}}$  anomalies on  $f\text{CO}_2$  anomalies. However, the responses of the  $p\text{CO}_{2\text{sea}}$  anomalies to the NAO are very weak, which indicates that the  $f\text{CO}_2$  anomalies in the subpolar region will be affected by the non-NAO driven  $p\text{CO}_{2\text{sea}}$  anomalies in summer.

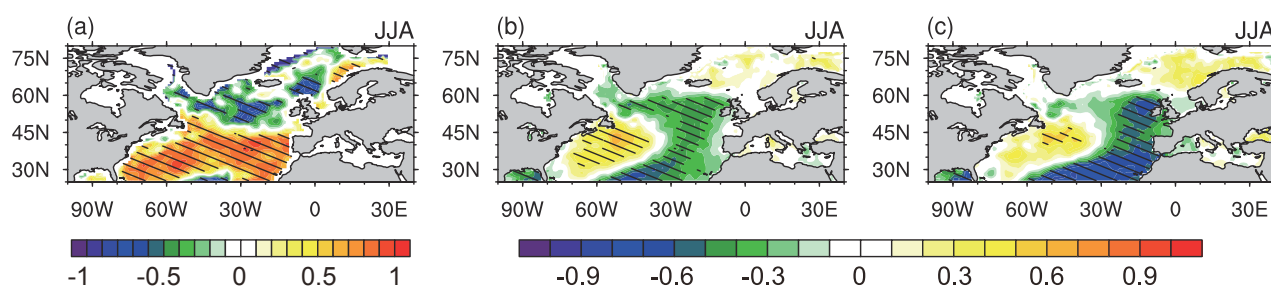
The RCs of the  $p\text{CO}_{2\text{sea}}$  anomalies against the SST anomalies are shown in Fig. 9a. In summer, the SST dominates the change of the  $p\text{CO}_{2\text{sea}}$  in most regions of the NA south of  $50^\circ\text{N}$ . Because there is no strong vertical movement, the change of  $p\text{CO}_{2\text{sea}}$  is largely influenced by the change of SST through the chemical thermodynamic process, like the subtropical Pacific (Li and Xu, 2012). In Figs. 9b and c, the response of SST to the NAO in the subtropical NA reveals a converse change for the east and the west, which is similar to the response of the  $p\text{CO}_{2\text{sea}}$  anomalies to the NAO in this

region (Fig. 8). It can be concluded that in the subtropical NA the change of SST is important for the NAO-driven  $p\text{CO}_{2\text{sea}}$  anomalies in summer. It should be noted, however, that in the subtropical NA, SST is also related to biology through the vertical supply of nutrients to drive the change of  $p\text{CO}_{2\text{sea}}$ : when SST is cold, the vertical supply of nutrients is increased, so the biological production is enhanced, which can decrease  $p\text{CO}_{2\text{sea}}$  (Bennington et al., 2009). The biochemical process may also be important for the subpolar NA because of the strong transport of nutrients by the vertical movement. In the subpolar NA north of  $50^\circ\text{N}$ , the relationship between  $p\text{CO}_{2\text{sea}}$  and SST shows a negative correlation, indicating that  $p\text{CO}_{2\text{sea}}$  in this region may be mainly controlled by other factors, which is similar to that in winter. Because of the lack of long-term observations of biogeochemical variables such as DIC and total alkalinity, analysis of the mechanisms of the response of the  $f\text{CO}_2$  in the NA to the NAO is insufficient.

Another aspect that should be noted is that, because of atmospheric teleconnection, the physical and biogeochemical processes are not only influenced by the local climate change, but also affected by other climate events (e.g., El Niño–Southern Oscillation and Pacific Decadal Oscillation), with a significant lagged correlation, besides the NAO (Patra et al., 2005), which should also be investigated in detail in future work.



**Fig. 8.** Regression coefficients (RCs) of the  $p\text{CO}_{2\text{sea}}$  anomalies against  $\text{NAO}_{\text{Gong}}$  and  $\text{NAO}_{\text{NCAR}}$  in summer on the interannual scale. Shaded areas indicate that RCs are statistically significant at the 95% confidence level of the Student's  $t$ -test. The time period for the data ranges from 1983 to 2011.



**Fig. 9.** Regression coefficients (RCs) of the  $p\text{CO}_{2\text{sea}}$  anomalies against the SST anomalies in summer (a), and RCs of the SST anomalies against  $\text{NAO}_{\text{Gong}}$  (b) and  $\text{NAO}_{\text{NCAR}}$  (c) in summer. Shaded areas indicate that RCs are significant at the 95% confidence level of the Student's  $t$ -test. The time period for the data ranges from 1983 to 2011.



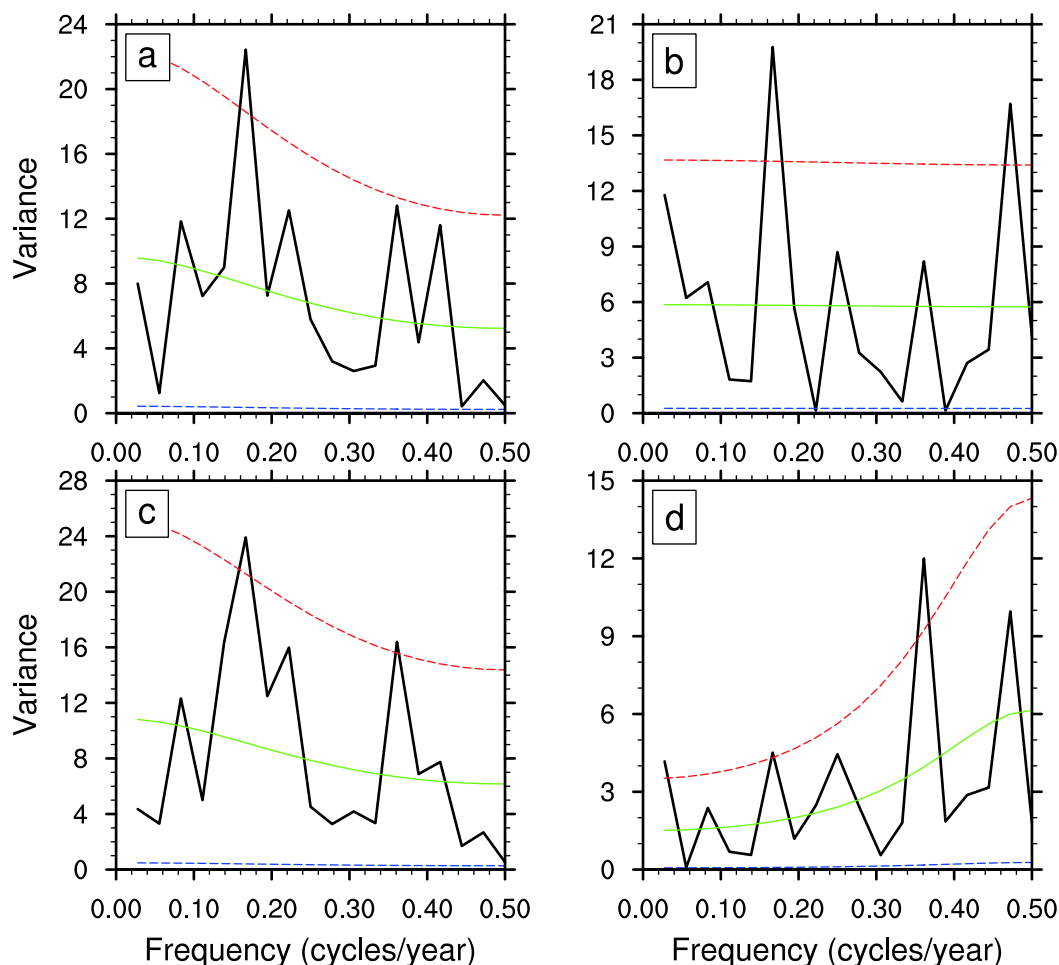
#### 4. Conclusion

The response of the air–sea CO<sub>2</sub> exchange flux of the NA in different seasons to the NAO was studied in terms sub-tropical (25°–45°N) and subpolar (45°–65°N) regions. Power spectrum analysis showed that both the winter and summer NAO indexes and area-averaged fCO<sub>2</sub> in the subtropical and subpolar NA have a significant cycle of 2–6 years characterized by an interannual signal during 1980–2015.

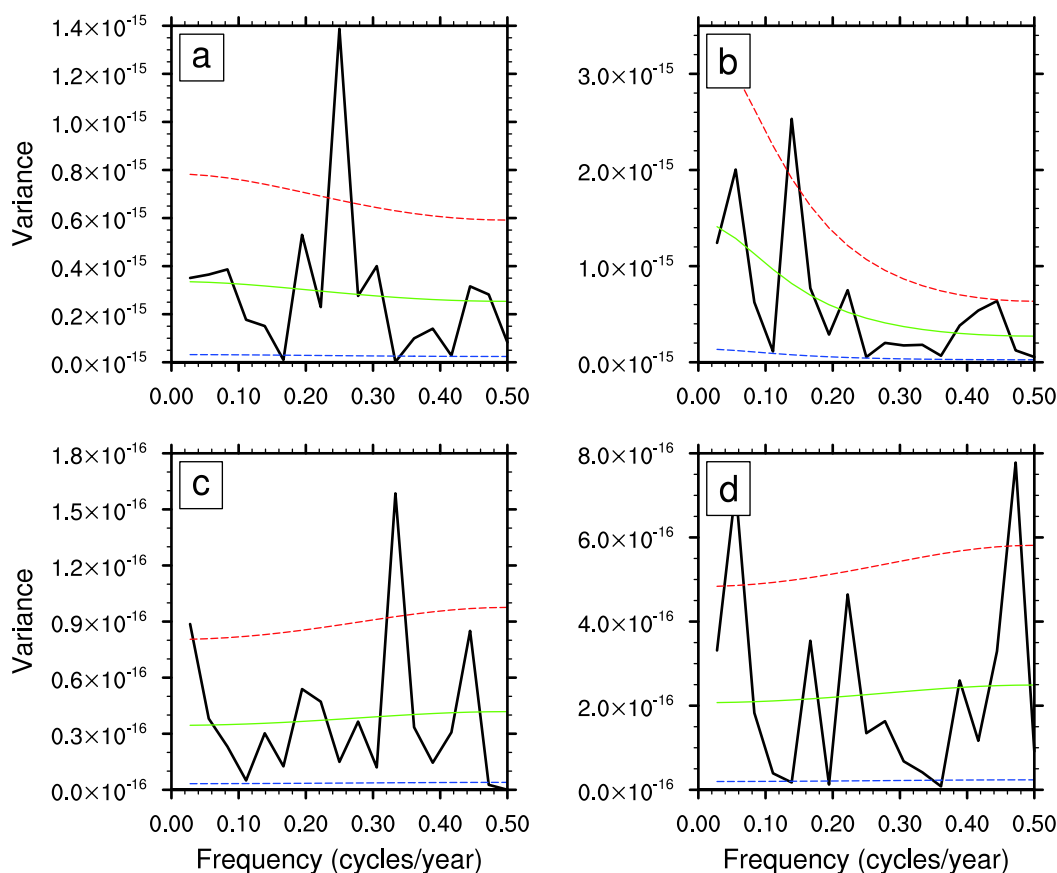
On the interannual scale, there are some differences in the character of the response of the NA fCO<sub>2</sub> to the NAO between winter and summer, which is especially reflected in the subtropical NA. In winter, the fCO<sub>2</sub> anomalies in the NA are affected by the NAO-driven vm<sub>10</sub> anomalies, which induce a wave-train-like distribution of the RCs of fCO<sub>2</sub> anomalies against the NAO along the meridional direction,

with pCO<sub>2sea</sub> having no significant influence on fCO<sub>2</sub> except for in the region south of 30°N where the non-NAO-driven SST is the factor controlling the pCO<sub>2sea</sub> anomalies. There are significant negative RCs between the NAO and pCO<sub>2sea</sub> in the region of 35°–40°N, and the vm<sub>10</sub> effect on fCO<sub>2</sub> is larger than the pCO<sub>2sea</sub> effect. In summer, the fCO<sub>2</sub> anomalies are barely affected by the vm<sub>10</sub> anomalies, and in the subtropical NA, the NAO-driven SST anomalies dominate the change of the pCO<sub>2sea</sub>, which further controls the response of fCO<sub>2</sub> on the NAO in this season and induces the significant difference between the west and east subtropical NA. In the subpolar NA, the response of fCO<sub>2</sub> to the NAO in winter, which is induced by the vm<sub>10</sub>, is more significant than that in summer, with the variability of fCO<sub>2</sub> mainly affected by the non-NAO driven pCO<sub>2sea</sub> anomalies.

### APPENDIX



**Fig. A1.** Power spectrum of NAO<sub>Gong</sub> (a, b) and NAO<sub>NCAR</sub> (c, d) in winter (December–January–February) (a, c) and summer (June–July–August) (b, d). Red and green lines indicate 5% and 90% “red noise” confidence bounds. The time period for NAO<sub>Gong</sub> and NAO<sub>NCAR</sub> is 1980–2015.



**Fig. A2.** Power spectrum of the area-averaged air–sea CO<sub>2</sub> flux in winter (December–January–February) (a, b) and summer (June–July–August) (c, d) in the subtropical (a, c) and subpolar (b, d) regions. Red and green lines indicate 5% and 90% “red noise” confidence bounds. All data are from 1980 to 2015.

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