Dipole anomaly in the Arctic atmosphere and winter Arctic sea ice motion

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Abstract This paper investigates a previously-ignored atmospheric circulation anomaly-dipole structure anomaly in the arctic atmosphere, and its relationship with the winter sea ice motion, based on analyses of the International Arctic Buoy Programme Data (1979—1998) and datasets from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) for the period of 1960—2002. The dipole structure anomaly is the second-leading mode of EOF of monthly mean SLP north of 70°N during the winter season (Oct.—Mar.), which accounts for 13% of the variance. One of its two anomaly centers is over the Canadian Archipelago; the other is situated over northern Eurasia and the Siberian marginal seas. Due to the dipole structure anomaly's strong meridionality, it becomes an important mechanism to drive both anomalous sea ice export out of the Arctic Basin and cold air outbreaks into the Barents Sea, the Nordic Seas and northern Europe.

Keywords: dipole anomaly, winter season, Arctic, sea ice motion, sea ice export.

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Arctic sea ice, an important component of the climate system, has received significant attention recently. Arctic sea ice variation is an important indicator of changes in the climate system, such as global change and polar amplification, and observation and climate modeling suggests that sea ice can itself be an agent of climate change[1—4]. Previous studies[3,5] have shown that sea ice influences the surface and atmospheric boundary layer temperature. Potentially more important is the transport of sea ice out of the Arctic from Fram Strait[6], which influences the stability and variability of thermohaline circulation (THC), oceanic stratification and deep convection.

With respect to atmospheric forcing regimes that are associated with arctic sea ice, many previous studies focused mainly on the North Atlantic Oscillation (NAO)[2,7—14], the Arctic Oscillation (AO)[3,15—17] and anticyclonic/cyclonic circulation over the Arctic Basin[18]. In the Arctic region, besides the NAO, the AO, and atmospheric anticyclonic/cyclonic circulations, there must be other else atmospheric forcing mechanism responsible for sea ice motion anomalies, which is ignored before. The purpose of the present study is to explore this question. In this study, an atmospheric dipole structure anomaly (thereafter, dipole anomaly), which strongly influences arctic sea ice motion (SIM) and sea ice export out of the Arctic Basin, was investigated.

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1 Data and methods

The primary datasets used in this study are monthly mean sea level pressure (SLP), surface wind, and geopotential heights at 500 hPa obtained from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis datasets for the period of 1960—2002, and monthly SIM obtained from International Arctic Buoy Programme (IABP) for the period 1979—1998. For detailed information about the SIM dataset, see Rigor et al.[3].

We applied empirical orthogonal function (EOF) analysis to monthly mean SLP north of 70°N to reveal dominant modes of variations in SLP. In this study, we pay our attention to the winter season (October to March). Following the procedure of Vinje[16], we used monthly mean SLP gridpoint (80°N, 10°W and 72.5°N, 20°E) data to approximately calculate the wind-induced ice volume flux through Fram Strait. Based on the wave-activities flux theory[19], this paper also provides a preliminary discussion of the possible mechanism for maintaining the dipole anomaly.

2 Results

We focus our attention on the Arctic Basin and the Arctic marginal seas, considering only the area north of 70°N. In order to reveal dominant modes of SLP variations, we applied the EOF analysis to monthly mean SLP (October to March) north of 70°N for the period 1960 to 2002 (sample number: 252). The spatial distributions for the first two modes are shown in Fig. 1, and they account for 61% and 13% of the total variance, respectively. We calculated autocorrelations of the principle component of EOF2:

$R(0)=1$, $R(1)=0.15$, $R(2)=0.008$,

$R(3)=0.026$, $R(4)=0.019$, ….

Based on those autocorrelations, the number of degrees of freedom was found to be $N_{\text{effective}}=243$. With $N_{\text{effective}}=240$, we then calculated the sampling error in the first four eigenvalues based on North et al. (1982)[20]:

$\lambda_1=195769.2$, sampling error: $\delta\lambda_1=\lambda_1(2/N_{\text{effective}})^{1/2}=17871.2$,

$\lambda_2=41259.95$, sampling error: $\delta\lambda_2=\lambda_2(2/N_{\text{effective}})^{1/2}=3766.5$,

$\lambda_3=29551.86$, sampling error: $\delta\lambda_3=\lambda_3(2/N_{\text{effective}})^{1/2}=2697.704$,

$\lambda_4=15387.37$, sampling error: $\delta\lambda_4=\lambda_4(2/N_{\text{effective}})^{1/2}=1404.668$,

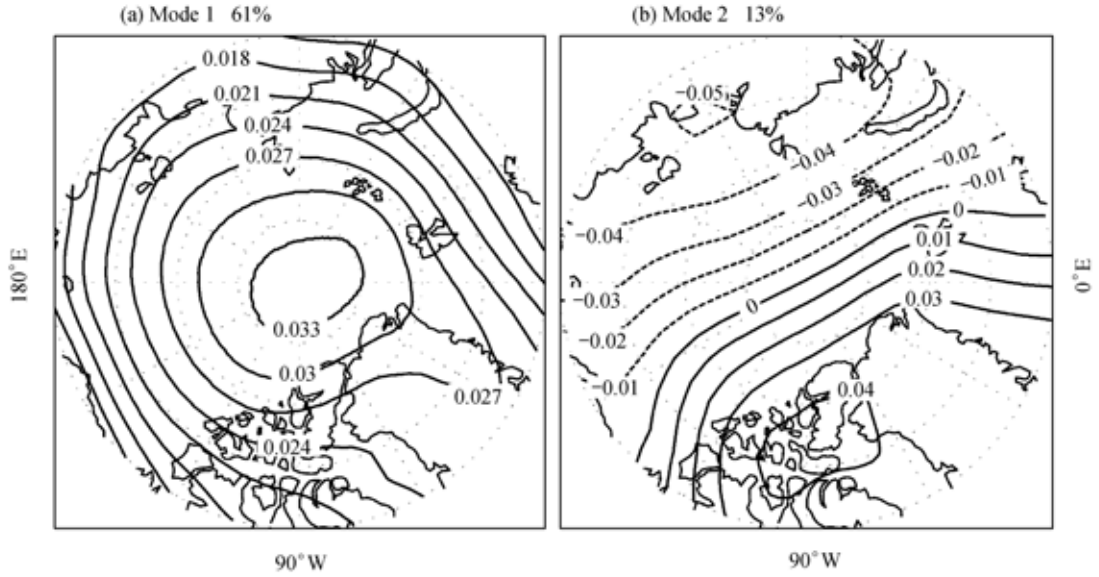


Fig. 1. Spatial distributions of the first two leading EOF modes of winter monthly mean SLP (Oct.—Mar.) (70—90ºN) (a) EOF1 and (b) EOF2.

$\lambda_1 - \lambda_2$=154509.25, $\delta\lambda_1+\delta\lambda_2$=21637.7, $\lambda_1 - \lambda_2 > \delta\lambda_1+\delta\lambda_2$,

$\lambda_2 - \lambda_3$=11708.09, $\delta\lambda_2+\delta\lambda_3$=6464.204, $\lambda_2 - \lambda_3 > \delta\lambda_2+\delta\lambda_3$,

$\lambda_3 - \lambda_4$=14164.49, $\delta\lambda_3+\delta\lambda_4$=4102.37, $\lambda_3 - \lambda_4 > \delta\lambda_3+\delta\lambda_4$.

Consequently, the EOF2 is well separated from the other modes.

The leading mode represents the Arctic Oscillation, with a -0.93 of correlation between the principle component of the leading mode and Thompson and Wallace's (1998) AO index[21]. Fig. 1(b) shows two centers with opposite signs over the eastern and the western Arctic: one center is over northern Eurasia and the arctic marginal seas, and the other is over northern Canada and Greenland, a dipole structure (hereafter the dipole anomaly). The zero isoline cuts through the central Arctic Basin and the Barents Sea. Such distributions of SLP anomalies are favorable for both sea ice export out of the Arctic Basin and cold air outbreaks into the Nordic seas and the Barents Sea.

Due to a strong annular structure, the AO obstructs cold air outbreaks over the Barents Sea and northern Eurasia, and there is a weak connection between the AO and sea ice efflux through Fram Strait[16,22]. Considering sea ice and freshwater export out of the Arctic Basin and its potential effect on the thermohaline circulation in the North Atlantic and further on the global climate system, the dipole mode of atmospheric variations could play an important role in the effect of sea ice export on climate, although it only accounts for 13% of the total variance.

It should be pointed out that although the dipole anomaly is similar to the "Barents Oscillation"[23] in the Arctic (strong meridionality), it differs from the "Barents Oscillation" for the following reasons: (1) The "Barents Oscillation" is not a significant mode because it is not well separated from the third and fourth EOFs as Skeie (2000)[21] suggested; (2) the correlation between the dipole anomaly and the "Barents Oscillation" is only marginal significant (0.26, 42 winters); and (3) the spatial distribution of the dipole anomaly differs from the "Barents Oscillation" over the Siberian marginal seas (not shown). Consequently, the dipole anomaly and "Barents Oscillation" are independent of each other.

Figure 2(a) and (b) show SLP and 500 hPa geopotential height anomalies obtained from a linear regression analysis (regression on EOF2), respectively. Fig. 2(a) shows a −4 hPa isoline covering northern Asia and the eastern Arctic marginal seas, with concurrent more than 2 hPa anomalies over northern America and Greenland (Fig. 2(a)). At 500 hPa, negative geopotential height anomalies occupied the northern Kara Sea and the northeastern Barents Sea, and more than 30 GPM anomalies cover Canadian Arctic Archipelago (Fig. 2(b)). Consequently, the dipole anomaly shows a strong qausi-barotropic structure. Statistic significance test for mean surface wind differences between positive phase of the dipole anomaly ($\sigma \geqslant 1$: 1961/62, 1967/68, 1968/69, 1988/89, 1992/93, 1994/95, 1995/96) and negative phase ($\sigma \leqslant -1$: 1969/70, 1976/77, 1982/83, 1984/85, 1989/90, 1993/94, 1998/99, 1999/2000, 2000/01) clearly demonstrate that over the Arctic Basin, particular over most of the Barents Sea and the vicinity of Fram Strait, surface wind differences are significant (Fig. 2(c), (d)). Consequently, dipole anomaly strongly influences surface wind, and further influences SIM[24]. Fig. 3 shows correlation coefficients of the surface wind with the winter AO and the dipole anomaly (interannual timescale, 42 samples). No significant correlation (in this paper, we only discuss the confidence levels over 99% and 99.9%) can be found over the Barents Sea, the Greenland Sea and the vicinity of Fram Strait (Fig. 3(a), (b)), implying that the winter AO is not a major factor to directly drive sea ice into the Greenland and the Barents Seas. However, the dipole anomaly shows a close relationship with the surface wind over partly the Greenland Sea, most of the Barents Sea and the vicinity of Fram Strait (Fig. 3(c), (d)).

Certainly, there should be different responses of the winter SIM to different atmospheric forcing. Based on a linear regression analysis, the winter SIM responds

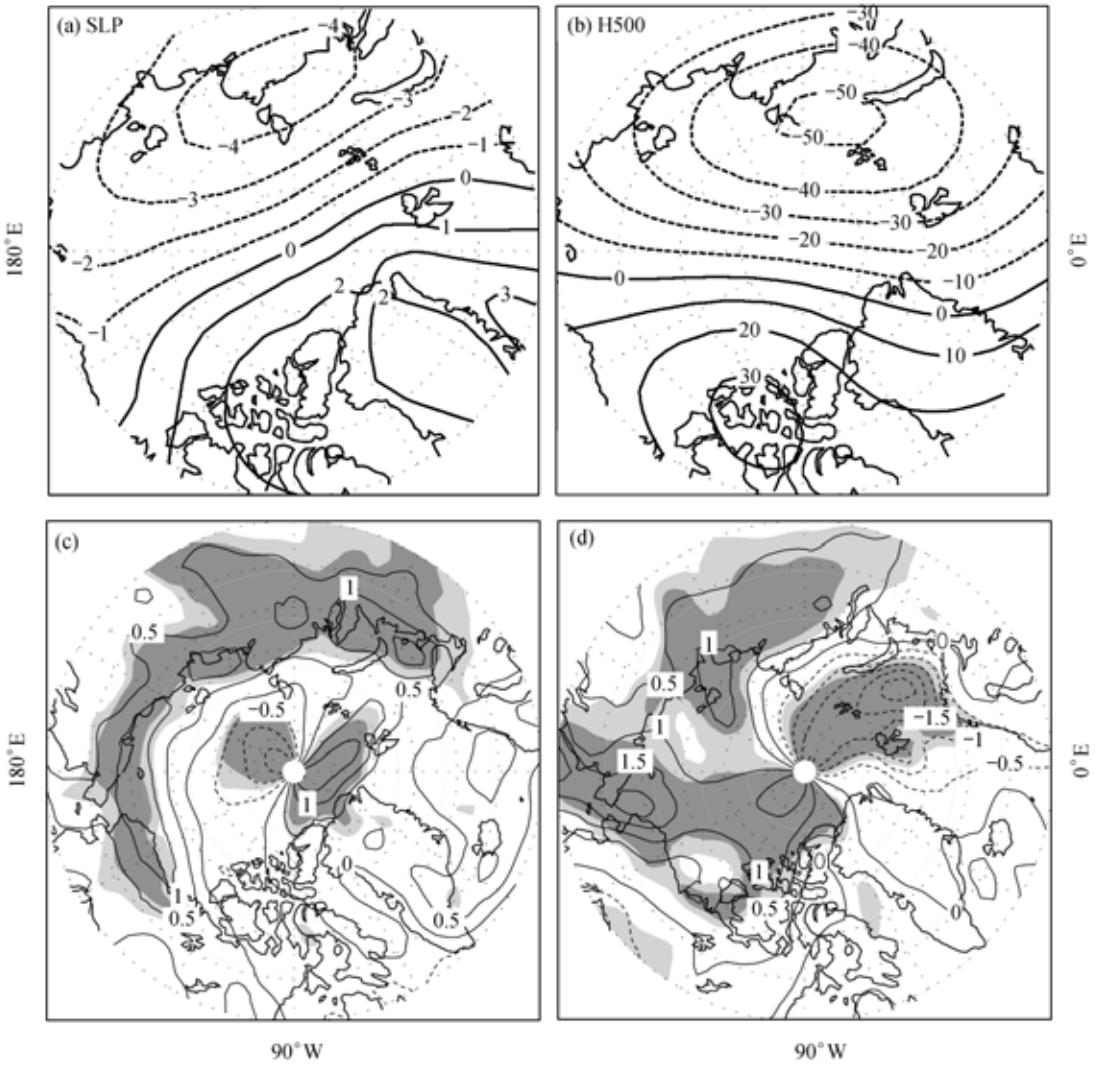


Fig. 2. Regression maps of (a) SLP (hPa) and (b) 500 hPa geopotential height (gpm). Regressions on EOF2. (c) Mean u component differences (surface wind) between positive and negative phases of the dipole anomaly and a Student-t test. The gray and dark gray areas denote that mean u component differences exceed 95% and 99% confidence levels, respectively. (d) Same as (c), except for v component.

to different atmospheric forcing regimes as shown in Fig. 4. In the Arctic Basin, in response to the winter AO, the SIM variation exhibits cyclonic circulation anomalies covering the whole Arctic Ocean (Fig. 4(a)), which is consistent with previous results[3,17]. In contrast, the winter SIM response to the dipole anomaly shows that all the SIM anomalies in the whole Arctic Basin flow towards the Barents and Greenland Seas (Fig. 4(b)). Holland's numerical simulation result[17] also shows that ice export through Fram Strait is closely related to reduced SLP along the Eurasian Coast and increased SLP in northern Canada and Greenland (see her Fig. 14). Consequently, the simulation result by Holland[17] is consistent with the result here (Figs. 2(a) and 4(b)).

Winter SIM composite indicates that compared to winter SIM climatology (1979－1998) (Fig. 5(a)), during positive phase of the dipole anomaly (winter SIM climatology plus the regression analysis shown in Fig. 4(b)) there are coherent large-scale changes in intensity and character of sea ice transport in the Arctic Basin. The significant changes include: (1) a weak-

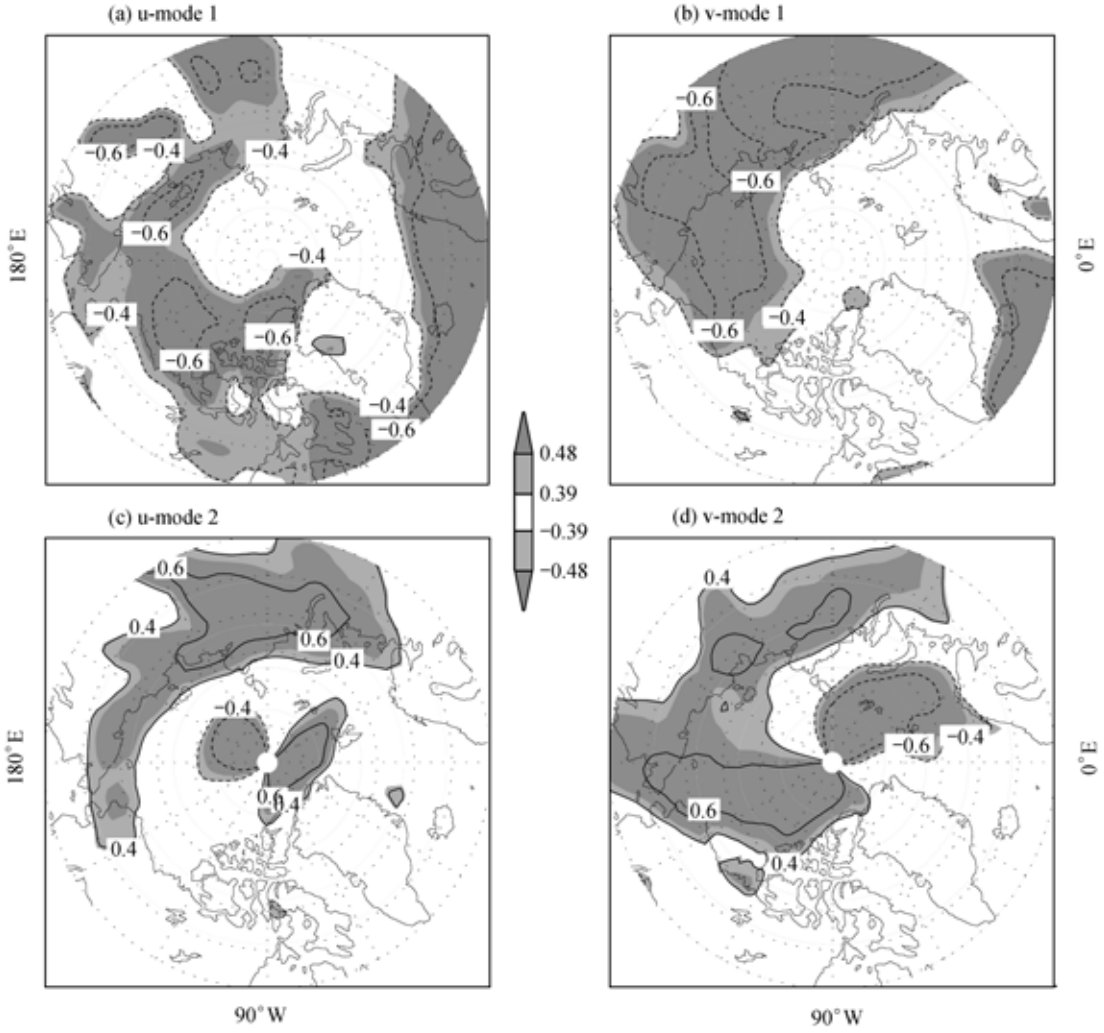


Fig. 3. Correlations of winter surface wind (interannual) (u, v) with the principle component of (a, b) EOF1 and (c, d) EOF2. The gray and dark gray area denote the correlations ≥99% and ≥99.9% confidence levels, respectively.

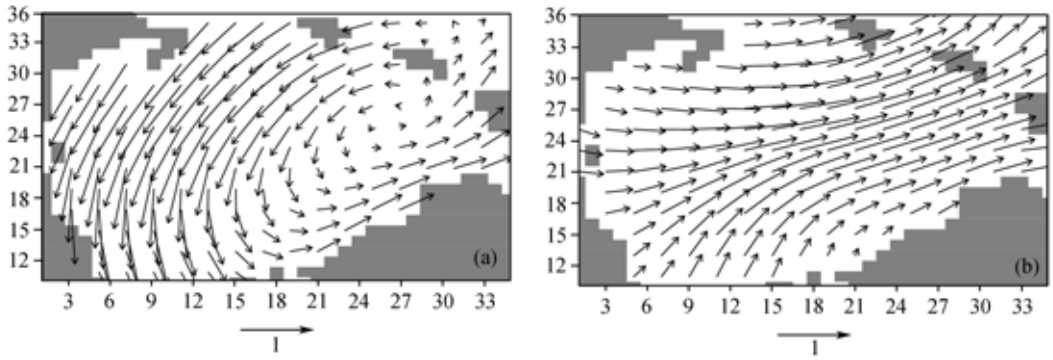


Fig. 4. Regression maps of winter sea ice motion. Regressions on the principle component of (a) EOF1 and (b) EOF2 (cm/s).

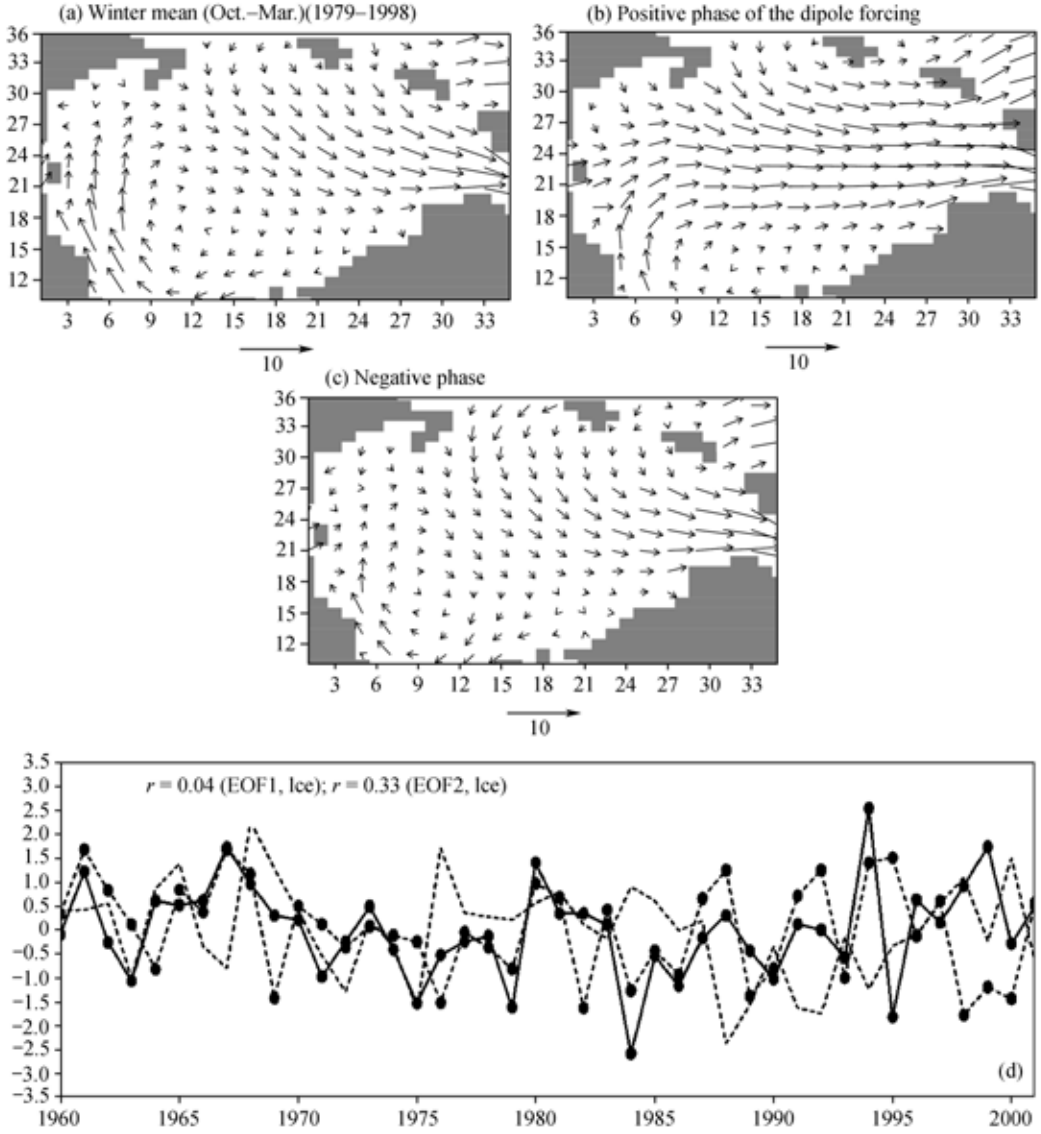


Fig. 5. (a) Winter (Oct.—Mar.) mean sea ice motion averaged for the period 1979-1998; (b) winter sea ice motion composite for positive phase of the dipole anomaly (winter SIM climatology plus the regression analysis shown in Fig. 4(b)); (c) same as (b), except for negative phase composite (winter SIM climatology minus the regression analysis shown in Fig. 4(b)), cm/s; (d) normalized winter sea ice volume flux through Fram Strait (solid line) and the principle components of EOF1 (dashed line) and EOF2 (dashed line with dots). The year refers to winter (Oct.—Mar.) season, taken as the year of Oct.

ening of the Beaufort Gyre and a strengthening of the Transpolar Drift Stream; (2) an increase in sea ice export out of the Arctic Basin through Fram Strait and the northern Barents Sea; and (3) enhanced sea ice import from the Laptev Sea, the East Siberian Sea and the Beaufort Sea into the Arctic Basin (Fig. 5(b)). When the dipole anomaly is in its negative phase (winter SIM climatology minus the regression analysis shown in Fig. 4(b)), winter SIM parallel to the coast is weak compared to the climatology (Fig. 5(c)). Undoubtedly, the negative phase of the dipole anomaly obstructs sea ice export out of the Arctic Basin into the Barents Sea and the Nordic Seas. Furthermore, the circulation patterns in the dipole anomaly extremes are unlike the two regimes of wind-forced ice circulation discussed by Proshutinsky and Johnson[18]. The

correlation coefficient between time series of the dipole anomaly and the sea leve1 gradients in the central Arctic Basin is poor (Proshutinsky and Johnson, 1997, see their Fig. 18). The correlation between the winter AO and winter sea ice volume flux through Fram Strait is only 0.04 (Fig. 5(d)), which is consistent with Vinje's[16] conclusion. However, the dipole anomaly shows a higher correlation coefficient (0.33, at the 95% confidence level) with the winter sea ice export (Fig. 5(d)). It should be pointed out that the relationship of the winter AO with sea ice flux through Fram Strait is complicated, which depends on sea ice flux dataset[9,16] and the specific period[25]. Additionally, Figure 5d shows that during the winters from 1960/1961 to 1968/1969 the positive phase prevailed in the EOF2; during the following winters from 1969/1970 to 1979/1980 the negative phase was predominant. Therefore, the positive phase epoch corresponded to more winter sea ice in the Nordic Seas and the Barents Sea, which is consistent with the result by Deser et al. (2000, see their Fig. 3)[2].

Using the maximum entropy spectrum analysis, we further revealed that the EOF2 involved a predominant 2-year periodicity, with a weak 5—7-year periodic variability (not shown). Therefore, the dipole anomaly displays a strong interannual variability with no apparent interdecadal trend, which differs from the winter AO. What mechanism is responsible for the existence of the dipole anomaly in the arctic atmosphere? By means of composite analysis of SLP and geopotential heights at 700 hPa (not shown) and Fig. 2(a) and (b), it is evident that anomalies related to the dipole anomaly have a qausi-barotropic structure in the atmosphere. Consequently, the Siberian High could not give a reasonable explanation for this anomaly due to its strong baroclinicity[26]. Considering the combination of the dipole anomaly's predominant 2-year periodicity and its quasi-barotropic structure, the internal atmospheric dynamic process should be a major factor to maintain the existence of dipole anomaly. Wave-activities flux, which is conservable quantity, reflects energy propagation associated with the internal atmospheric dynamic process[19]. Considering the dipole anomaly's qausi-barotropic structure, we only analyze wave-activities flux at 500 hPa. Fig. 6 shows that energy propagation from the Nordic Seas, Greenland, northern Canada, and northern Asia into the Arctic plays an important role in maintaining the dipole anomaly in the arctic atmosphere. Note that there are two branches of the energy propagation that originate in the Arctic: one is through the Barents and Kara Seas into northern Eurasia, usually accompanied with southward cold air outbreaks; and the other is from the Arctic to the northern Pacific sector via Alaska. From the two branches of the energy propagation, the arctic atmospheric circulation directly influences climate variability over northern Europe and Alaska.

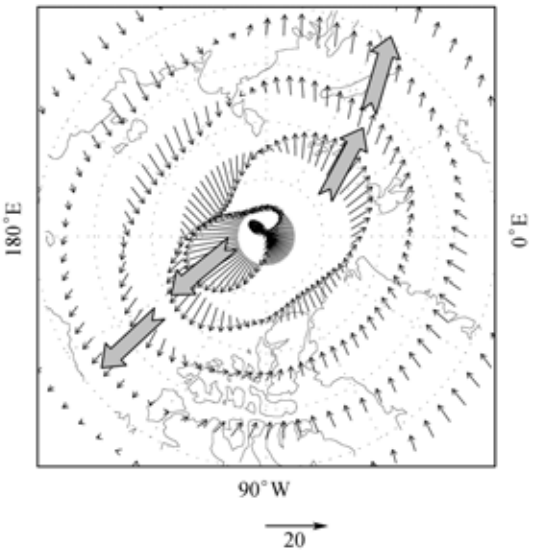


Fig. 6. 500 hPa wave-activities flux (m^2/s) corresponding to geopotential height anomalies shown in Fig. 2 (b). The large arrow represents directions for propagation of wave-activities flux.

3 Conclusion

This study investigated a previously undiscovered atmospheric circulation anomaly-dipole structure anomaly and its relation with the winter SIM in the Arctic Basin, based on the NCEP/NCAR re-analysis dataset and the IABP dataset. The dipole anomaly in the arctic atmosphere is the second dominant mode, accounting for 13% of the variance. The dipole anomaly plays an important role in driving sea ice export out of the Arctic Basin into the Greenland Sea and the Barents Sea. When the dipole anomaly remains in its positive phase, the atmospheric forcing contributes to

coherent large-scale changes in intensity and character of sea ice transport in the Artic Basin. The significant changes include: (1) the weakening of the Beaufort Gyre and the strengthening of the Transpolar Drift Stream; (2) the increase in sea ice export out of the Arctic Basin through Fram Strait and the northern Barents Sea; and (3) enhanced sea ice import from the Laptev Sea and the East Siberian Sea into the Arctic Basin. The negative phase of the dipole anomaly directly causes decrease in sea ice export out of the Arctic Basin. The finding indicates that winter (Oct.—Mar.) sea ice volume flux through Fram Strait shows a higher correlation (0.33, 42 samples) with the dipole anomaly than the winter AO forcing (0.04). The dipole anomaly displays a predominant interannual variability with no apparent interdecadal trend, which differs from the winter AO.

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