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Impact of polar lows on synoptic scale variability of Atlantic inflow in the Fram Strait

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Abstract

The Atlantic inflow in the Fram Strait (78°50′N) has synoptic scale variability based on an array of moorings over the period of 1998–2010. The synoptic scale variability of Atlantic inflow, whose significant cycle is 3–16 d, occurs mainly in winter and spring (from January to April) and is related with polar lows in the Barents Sea. On the synoptic scale, the enhancement (weakening) of Atlantic inflow in the Fram Strait is accompanied by less (more) polar lows in the Barents Sea. Wind stress curl induced by polar lows in the Barents Sea causes Ekman-transport, leads to decrease of sea surface height in the Barents Sea, due to geostrophic adjustment, further induces a cyclonic circulation anomaly around the Barents Sea, and causes the weakening of the Atlantic inflow in the Fram Strait. Our results highlight the importance of polar lows in forcing the Atlantic inflow in the Fram Strait and can help us to further understand the effect of Atlantic warm water on the change of the Arctic Ocean.

Key words: Fram Strait, Atlantic inflow, synoptic scale variability, polar lows

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1 Introduction

Oceanic exchanges with the lower-latitude ocean play an important role in the Arctic Ocean's volume, heat and freshwater budget (Maslowski et al., 2004; Rudels, 2010; Chafik et al., 2015; Marnela et al., 2016). The warming of the Atlantic water flowing from the Nordic Sea into the Arctic Ocean contributes to the recent dramatic warming of the Arctic Ocean intermediate water and further to the dramatic shrinkage of sea ice coverage by tidal-generated mixing (Steele and Boyd, 1998; Comiso et al., 2008; Polyakov et al., 2010; Spielhagen et al., 2011; Lique, 2015; Rippeth et al., 2015). The sea ice coverage shrinkage contributes to the sea-ice-atmosphere positive feedback and the Arctic amplification, and further affects the weather and climate in the middle and low latitude by atmospheric bridge (Holl et al., 2006; Screen and Simmonds, 2010; Kumar et al., 2010; Overland et al., 2011; Tang et al., 2013; Kug et al., 2015; Zhao et al., 2015). At the same time, the freshwater flowing from the Arctic Ocean into the Nordic Sea can prevent the formation of high density water in the Nordic Sea, and slow down the Atlantic Meridional Overturning Circulation and further affect the global climate (Aagaard and Carmack, 1989; Vellinga and Wood, 2002; Stouffer et al., 2006; Wu et al., 2008; Ionita et al., 2016).

The warm and salty Atlantic water enters into the fresh and cold Arctic Ocean by two-branched inflow (Helland-Hansen and Nansen, 1909; Orvik and Niiler, 2002; Lien et al., 2013). The branch entering the Arctic Ocean through the shallow Barents Sea releases a substantial amount of heat to the atmosphere and barely carries heat into the Arctic Ocean (Schauer et al., 2002; Smedsrud et al., 2010). However, the branch flowing through the deep Fram Strait retains a large part of its heat as it flows along the Arctic continent slope (Polyakov et al., 2005; Dmitrenko et al., 2008). Hence, the Fram Strait branch to a large degree determines the amount of heat entering from the Atlantic Ocean into the Arctic Ocean. Because of the important roles that the Fram Strait branch plays in the heat, salinity and volume exchange between the Nordic Sea and the Arctic Ocean, the volume of the Atlantic inflow in the Fram Strait has attracted the attention of many scientists (Aksenov et al., 2010; Beszczynska-Möller et al., 2012; Lien et al., 2013; Chafik et al., 2015; Kawasaki and Hasumi, 2016). Among these studies, two issues have been especially discussed: (1) multiple time scale variability of the Atlantic inflow in the Fram Strait; (2) the role polar lows play in the variability of the Atlantic inflow. Due to the complicate ocean circulation in the vicinity of the Fram Strait, both the issues are still being studied and openly debated.

Polar lows mainly occur in winter and spring, and are the main synoptic scale force field in the vicinity of the Fram Strait (Rojo et al., 2015). Previous studies showed that polar lows could

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impact the mean oceanic circulation and co-variability of the Atlantic inflow branches to the Arctic Ocean in climate state (Condron and Renfrew, 2013; Lien et al., 2013; Jung et al., 2014). However, the synoptic scale variability of the Atlantic inflow and the role polar lows play in the synoptic scale variability of Atlantic inflow in the Fram Strait remain unclear. In this paper, our study shows that Atlantic inflow in the Fram Strait has obvious synoptic scale variability, and is related with the spatial distribution of polar lows in the Barents Sea. The rest of the paper is organized as follows. Section 2 briefly describes the data and method. Section 3 shows the identification and synoptic scale variability of the Atlantic inflow, and the impact of polar lows on the Atlantic inflow in the Fram Strait. Section 4 is a conclusion and discussion of this paper.

2 Data and method

2.1 *Data*

The mooring array from the physical oceanography group of the Alfred Wegener Institute (AWI) (F1–F10 and F15–F16; Beszczynska-Möller et al., 2012) and the Norwegian Polar Institute (NPI) (F11–F14; Steur et al., 2009) has been located in the Fram Strait since 1997 (Table 1). The mooring data (14 moorings before 2002, and 16 thereafter) contain year-round velocity, temperature, and salinity, and are available from the data publisher PANGAEA (Beszczynska-Möller et al., 2015). The data accuracy and treatment are described in some details by Fahrbach et al. (2001) and Schauer et al. (2004). It deployed along a zonal section along 78°50′N across the whole Fram Strait from western Svalbard Island shelf through the deep part to the shelf east of Greenland Island (Fig. 1), and are instrumented at five standard levels: ~50 m, ~250 m, ~750 m, ~1 500 m where available; ~10 m above the bottom) (Beszczynska-Möller, et al., 2012). The temporal sampling frequency is ranged from 20 min to 2 h. However, the mooring data are discontinuous in some years. F1, F3 and F10 are not available from August 22, 2006 to September 11, 2007, from August 1, 2000 to August 1, 2002, and from August 30, 2005 to September 8, 2006, respectively.

The ERA-Interim product from the European Center for Medium-Range Weather Forecasts (ECMWF) (http://apps.ecmwf.int/datasets/) is a reanalysis set of the global atmosphere with a spatial resolution of 1°×1° on 60 standard levels in the vertical direction from 1979 to the present (Berrisford et al., 2011). It has four rounds of analysis per day at 00, 06, 12, and 18 UTC. The ERA-Interim product has multiple variables, such as sea level pressure (SLP), wind speed, and 2 meters temperature and so on. We use SLP to identify and track polar lows and to composite SLP based on the intensity of the Atlantic inflow in the Fram Strait.

Table 1. Deployment details of the 16 moorings considered in this study

Time	Location							
	78.83°N, 8.65°E	78.84°N, 8.32°E	78.84°N, 7.97°E	78.83°N, 6.96°E	78.82°N, 6.15°E	78.83°N, 5.01°E	78.82°N, 4.02°E	78.83°N, 2.68°E
1997	F1	F2	F3	F4	F5	F6	F7	F8
1998	F1	F2	F3	F4	F5	F6	F7	F8
1999	F1	F2	F3	F4	F5	F6	F7	F8
2000	F1	F2	F3	F4	F5	F6	F7	F8
2001	F1	F2		F4	F5	F6	F7	F8
2002	F1	F2	F3	F4	F5	F6	F7	F8
2003	F1	F2	F3	F4	F5	F6	F7	F8
2004	F1	F2	F3	F4	F5	F6	F7	F8
2005	F1	F2	F3	F4	F5	F6	F7	F8
2006	F1	F2	F3	F4	F5	F6	F7	F8
2007	F1	F2	F3	F4	F5	F6	F7	F8
2008	F1	F2	F3	F4	F5	F6	F7	F8
2009	F1	F2	F3	F4	F5	F6	F7	F8
2010		F2	F3	F4	F5	F6	F7	F8
2011		F2	F3	F4	F5	F6	F7	F8

Time	Location							
	78.91°N, 0.28°W	78.92°N, 2.06°W	79°N, 3.06°W	78.98°N, 4.22°W	78.96°N, 5.34°W	79.01°N, 6.84°W	78.83°N, 1.6°E	78.83°N, 0.46°E
1997	F9	F10		F12	F13	F14		
1998	F9	F10	F11	F12	F13	F14		
1999	F9	F10	F11	F12	F13	F14		
2000	F9	F10	F11	F12		F14		
2001	F9	F10						
2002	F9	F10					F15	F16
2003	F9	F10					F15	F16
2004	F9	F10					F15	F16
2005	F9	F10					F15	F16
2006	F9	F10					F15	F16
2007	F9	F10					F15	F16
2008	F9	F10					F15	F16
2009	F9	F10					F15	F16
2010	F9	F10						F16
2011								

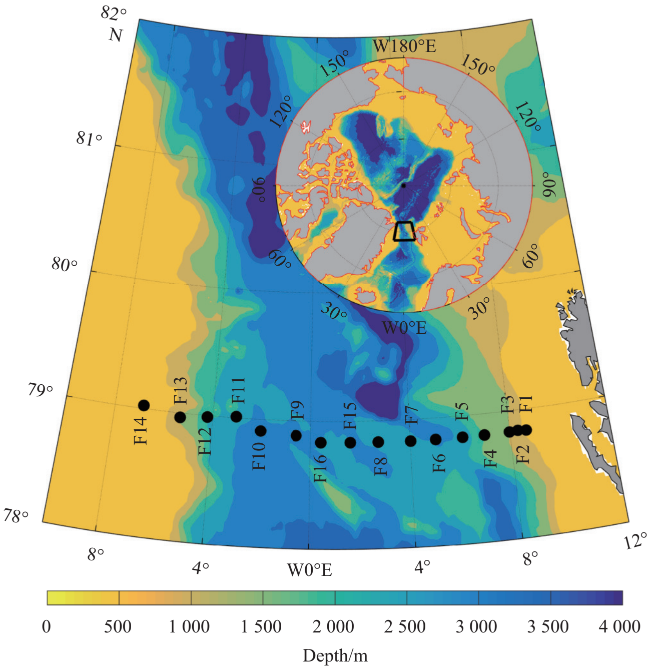

Fig. 1. Map of the bathymetry around the Fram Strait. The median locations of the moorings considered in this study are marked by the black dots. The inset in the top right corner shows the entire Arctic Ocean. The extent of the main map is shown as a black polygon in the inset.

2.2 *Method*

Following Zhang et al. (2004) and Wernli and Schwierz (2006), we used 6-h snapshots of SLP in the ERA-Interim product and developed the following modified procedure to identify and track polar lows: (1) there exist closed SLP contours, and if the SLP difference between its center and its outermost contour is greater than 6 hpa, a polar low candidate is identified; (2) if polar lows candidates appear with a radius less than 1 200 km at the same time, they are considered to be a polar low; (3) if a polar low candidate's location is within a radius of 600 km of a polar low's location during the previous 6-h time, this location is considered to be a new location of the existing polar low; (4) if the lifetime of a polar low candidate is shorter than 12 h, it is removed from the polar lows candidates. The modified procedure is almost the same as the method described by Zhang et al. (2004), except the first threshold for choosing the polar lows we need.

3 Results

3.1 *Identification of the Atlantic inflow in the Fram Strait*

Figure 2a gives that current vectors distribution of F1–F10 at different depths from 50 to 1 500 m. It shows that current vectors of F1–F5 and F8–F10 are almost in the same direction from the upper layer to the bottom, indicating the barotropic feature of the flow field, however, it is almost oppositely directed for the current vectors of F6–F7 due to the baroclinic feature (Schauer et al., 2008). Current vectors of F6–F10 are mainly southward, westward or eastward, while the ones of F1–F5 have an obvious northward component which is also shown in Fig. 2b in the vertical direction. The northward component of F1–F5 can reach 2 500 m deep and the maximum value of the northward component has exceeded 15 cm/s. Because we only consider the meridional component of the current vectors in the study of the Atlantic inflow from the Nordic Sea to the Arctic Ocean, the meridional component of F1–F5 is chosen to represent the Atlantic inflow candidates in the Fram Strait. The Atlantic water is defined as warmer than 2°C (Beszczynska-Möller, et al., 2012). Figure 2c shows that the Atlantic inflow is mainly distributed in the upper 500 m and extends west to about 0.5°E. The maximum temperature of the Atlantic water in the Fram Strait can reach 4°C and the temperature decreases from the coast to the inside, which is consistent with the results of Beszczynska-Möller et al. (2012).

Due to the temporary discontinuity of the mooring observation in some years, we calculate the sampling probabilities distribution of F1–F5 (Fig. 3). Figure 3 shows that sampling probabilities are high at most observation points, except in the 750 m layer. The high value is often in the upper layer, the maximum value can reach 0.91 in the 250 m layer of F4, and the minimum value is 0.35 which is located in the 750 m layer of F5. In order to maintain continuity of the Atlantic inflow observation, we choose the observation points whose sampling probabilities are greater than 70% and mean temperature is greater than 2°C as the Atlantic inflow observation points, which are marked by the blue dots and are located in the 50 m and 250 m layers of F1–F2 and F4–F5, respectively in Fig. 3.

3.2 *Synoptic scale variability of the Atlantic inflow in the Fram Strait*

Figure 4a gives the time series of daily Atlantic inflow anomaly from the year 1998 to 2010, showing that the daily Atlantic inflow anomaly is generally between –20 cm/s and 20 cm/s, with obvious high-frequency variability and seasonal variability. The maximum and minimum values of the seasonal variability are in winter and in summer, respectively. After removal of the seasonal signal, we apply the residual time series to the wavelet analysis. As shown in Fig. 4b, there are multiple time scale periods, for example, synoptic scale periods, one month period, two months period and so on. Among these periods, synoptic scale periods

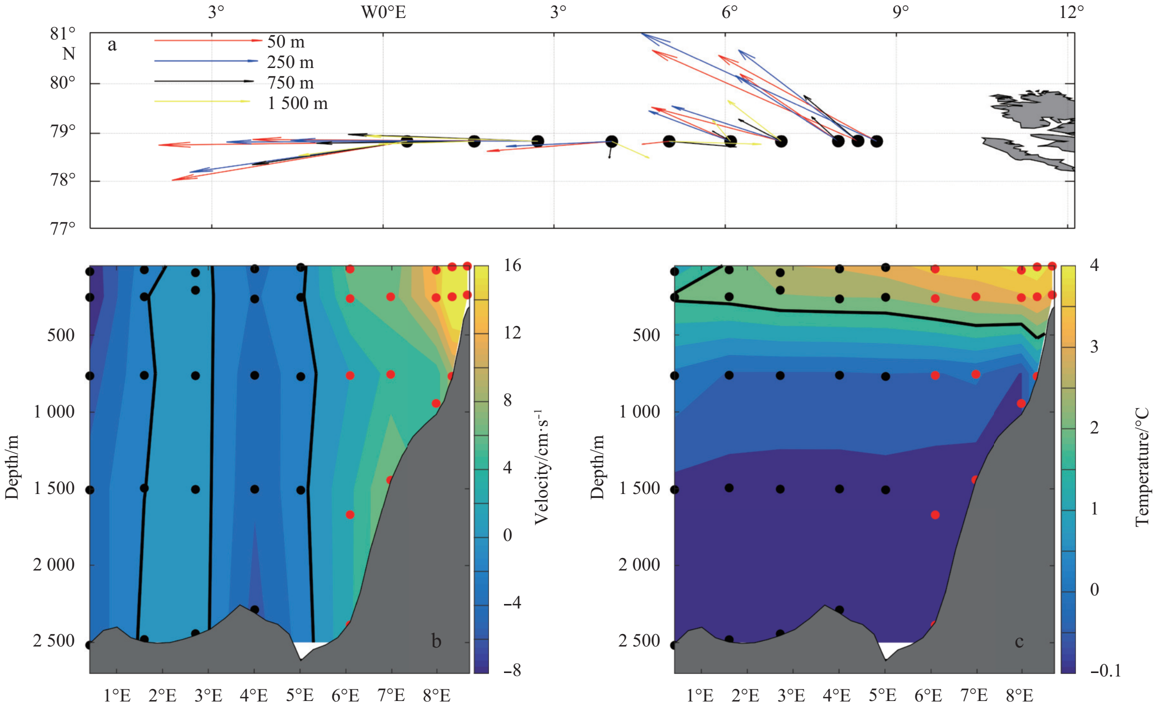

Fig. 2. Identification of the Atlantic inflow. a. Long-term mean (1997–2010) current vectors measured at the moored array at different depths; b. long-term mean (1997–2010) meridional velocity (cm/s) (the current component across the section), and the black full line represents the zero contour; c. long-term mean (1997–2010) temperature (°C) measured by moored instruments, and the black full line represents the 2°C contour. The red dots and the black dots represent the median measure depth of F1–F5 and F6–F10, respectively.

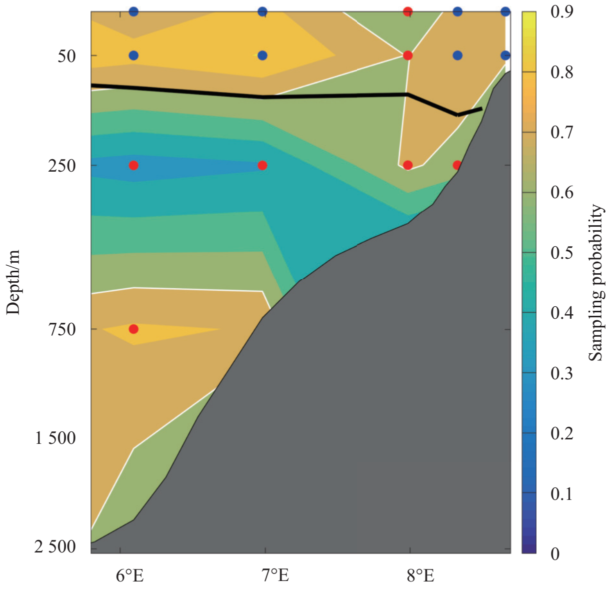

Fig. 3. The sampling probabilities distribution (in color). The sampling probabilities mean that sampling frequency divided by the whole frequency at a certain observation point. The black full line represents the 2°C contour, and the white full line represents 70% contour. The blue dots and the red dots represent the median measure depth of F1–F5, while the blue dots represent the observation points whose sampling probabilities are greater than 70%.

have a remarkable rule and mainly exist in winter and spring (from January to April), which is emphasized by the black straight full lines in Fig. 4b. Figure 5 shows that, on the synoptic scale, the 3–16 days period is subject to the significance test (as shown in Fig. 5a), and the occurrence days number of the 3 days period reaches the maximum (as shown in Fig. 5b).

Polar lows mainly occur in winter and spring, and their periods are based on the synoptic scale (Rojo et al., 2015). The occurrence time and periods of the polar low are almost the same as the synoptic scale variability of Atlantic inflow in the Fram Strait, which indicates that the temporal coherence of polar low and synoptic scale variability of Atlantic inflow in the Fram Strait is significant. And previous studies have demonstrated that polar lows could impact variability of the Atlantic inflow in the Fram Strait in climate state (Lien et al., 2013). So we deduce that synoptic scale variability of the Atlantic inflow in the Fram Strait is related with polar lows. The polar lows are identified and tracked based on the method described in Section 2. Using the time series of daily Atlantic inflow anomaly of each winter and spring as the Atlantic inflow intensity index (AIII) (Fig. 6a), we composite polar lows locations and SLP anomaly (Figs 6b and c) based on the days when the positive and negative intensity index values are more than one standard deviations away from the mean. A seesaw pattern of SLP anomaly and number of polar lows locations between in the Nordic Sea and in the Barents Sea are shown in Figs 6b and c. As there are less (more) polar lows in the Barents Sea, especially west of the Svalbard Island, and more (less) polar lows in the Nordic Sea, the SLP anomaly is positive (negative) in the Barents Sea and negative (positive) in the Nordic Sea, and further the Atlantic inflow in the Fram Strait weakens (strengthens). The dynamic mechanism will be discussed in Section 3.3.

What is the relative importance of polar lows in the Nordic

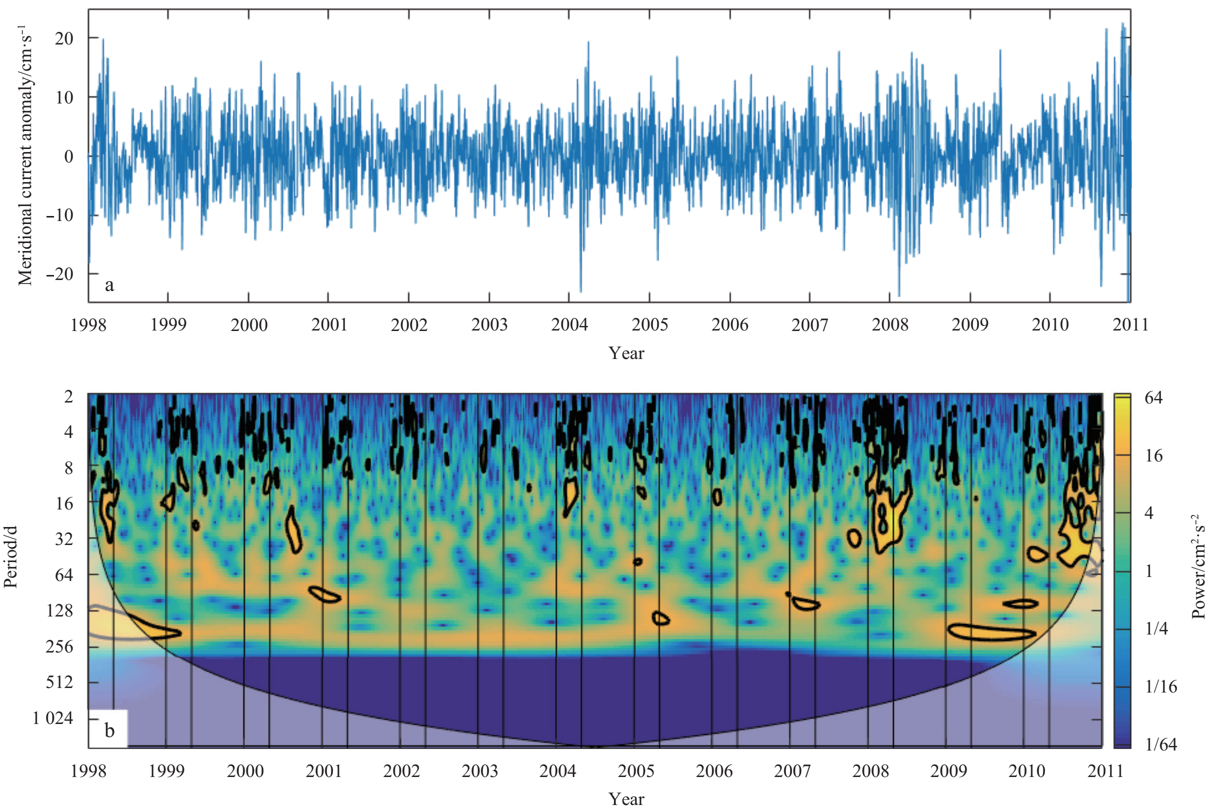

Fig. 4. Time series of the Atlantic inflow anomaly and its wavelet analysis. a. A time series of the daily meridional current component of the Atlantic inflow anomaly in the Fram Strait and b. wavelet analysis of the Atlantic inflow in the Fram Strait. The power spectrum is divided by the variance of the time series, and then the log function is applied to the base two of the power spectrum, which is represented by the color in this figure. The regions surrounded by the black full line is the one which is significant at the 95% level. The fuzzy region in the bottom is the one which should be removed due to the boundary effect. The black straight full lines represent the beginning of January and the end of April from 1998 to 2011.

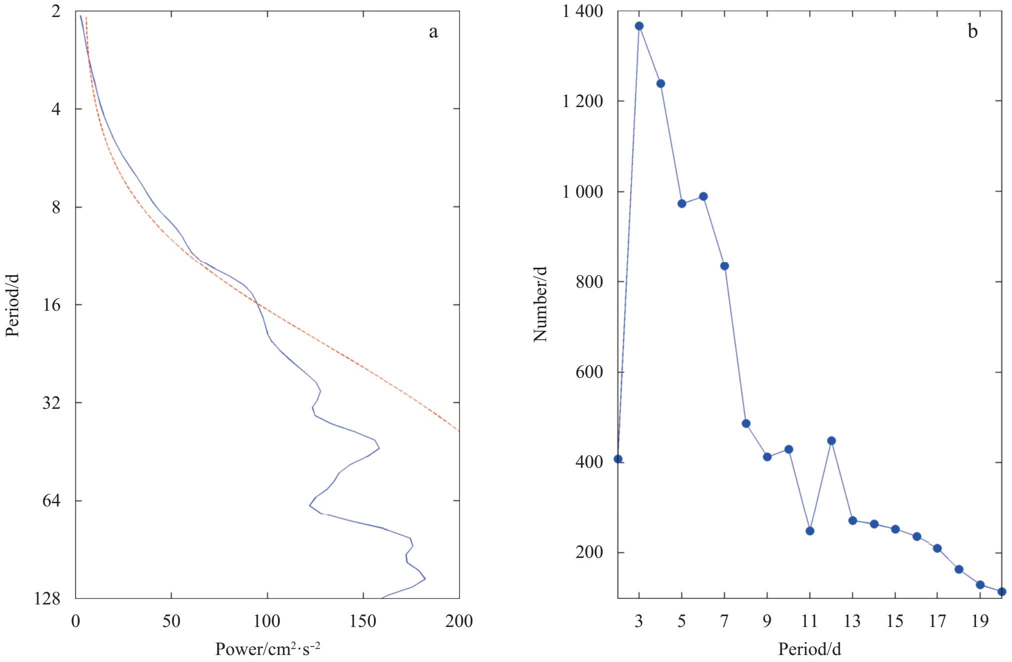

Fig. 5. Significant periods of the Atlantic inflow and their corresponding occurrence days number. a. Global wavelet spectrum of the residual time series of Fig. 4a after removal of the seasonal signal, the blue solid line represents the power spectrum, and the red dotted line represents the 95% significant level; and b. the occurrence days number of different periods in winter and spring (from January to April).

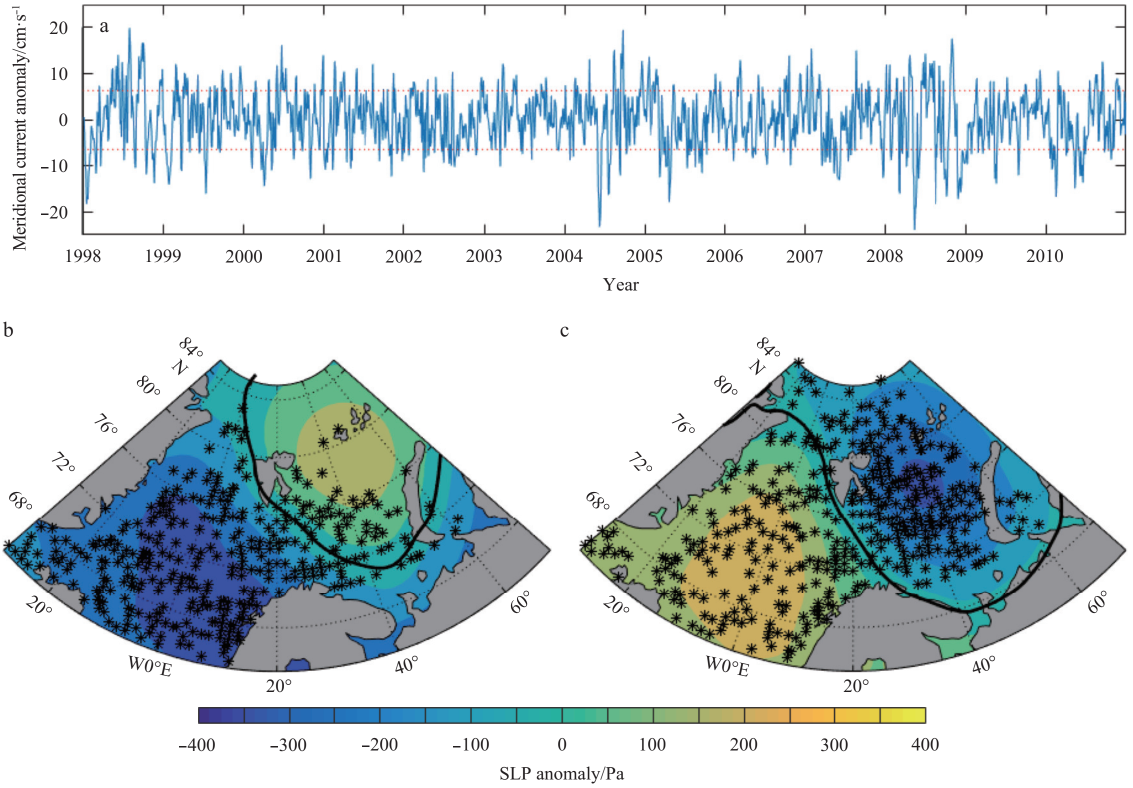

Fig. 6. Time series of the Atlantic inflow anomaly in winter and spring, and composition of SLP anomaly and polar lows location. a. A time series of daily Atlantic inflow anomaly of each winter and spring from 1998 to 2010. The black dotted line above represents the sum of the one times standard deviation and the average value of the time series, and the black dotted line below represents the difference of the one times standard deviation and the average value of the time series. b. Composition of SLP anomaly and polar lows location for negative index time. c. Same as Fig. 6b, except for positive index time.

Sea and in the Barents Sea? To solve this, we need to construct an index to reflect the relationship between occurrence number of polar low and AIII in the Nordic Sea and the Barents Sea. Because the days number of positive and negative AIII is different, it is irrational to use the sum of polar low occurrence number when the AIII is positive or negative to construct the index. It is necessary to construct a relative sense index, so we define an index named polar lows occurrence rate, which means the occurrence number of polar lows divided by occurrence days of polar lows in a spatial region. Figure 7 gives that polar lows occurrence rate anomaly for the days when the positive and negative intensity index values are more than one standard deviations away from the mean in the Nordic Sea and the Barents Sea, respectively. Figure 7 shows that the polar lows occurrence rate anomaly in the Barents Sea is markedly bigger than the one in the Nordic Sea. When the positive and negative AIII values are more than one standard deviations away from the mean, the polar lows occurrence rate anomaly in the Barents Sea can reach –0.56 and 1.1, however, the polar lows occurrence rate anomaly in the Nordic Sea can only reach 0.1 and –0.21. Based on the above conclusion that the synoptic scale variability of the Atlantic inflow in the Fram Strait is related with polar lows, the polar lows occurrence rate anomaly in the Barents Sea is five times more than the one in the Nordic Sea, which means that, under the condition that the strength and distance of polar lows in the Barents Sea are the same as those in the Nordic Sea, the contribution of polar lows in the Barents Sea to AIII variation is five times more than those in the Nordic Sea. So polar lows in the Barents Sea play a more important role in the synoptic scale variability of the Atlantic inflow in the Fram Strait. Note that the conclusions above are not sensitive to the choice of the spatial scope of the Barents Sea and the Nordic Sea. We run a series of tests with different spatial scopes of the Barents Sea and the Nordic Sea, and the conclusions are consistent.

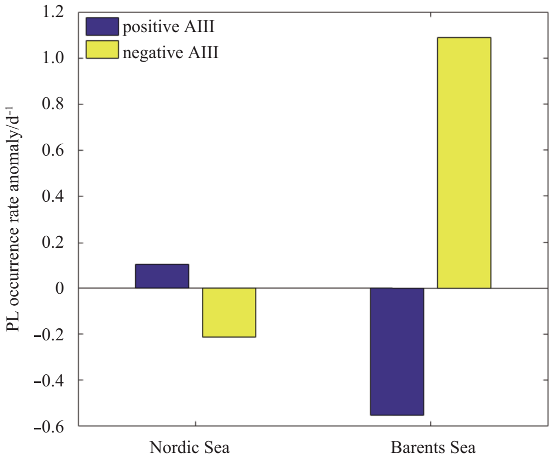

Fig. 7. Polar lows (PL) occurrence rate anomaly for the days of positive and negative AIII in the Nordic Sea and the Barents Sea. The latitude-longitude limits of the Barents Sea and the Nordic Sea are 76°–82°N, 20°–60°E and 65°–82°N, 30°W–20°E, respectively.

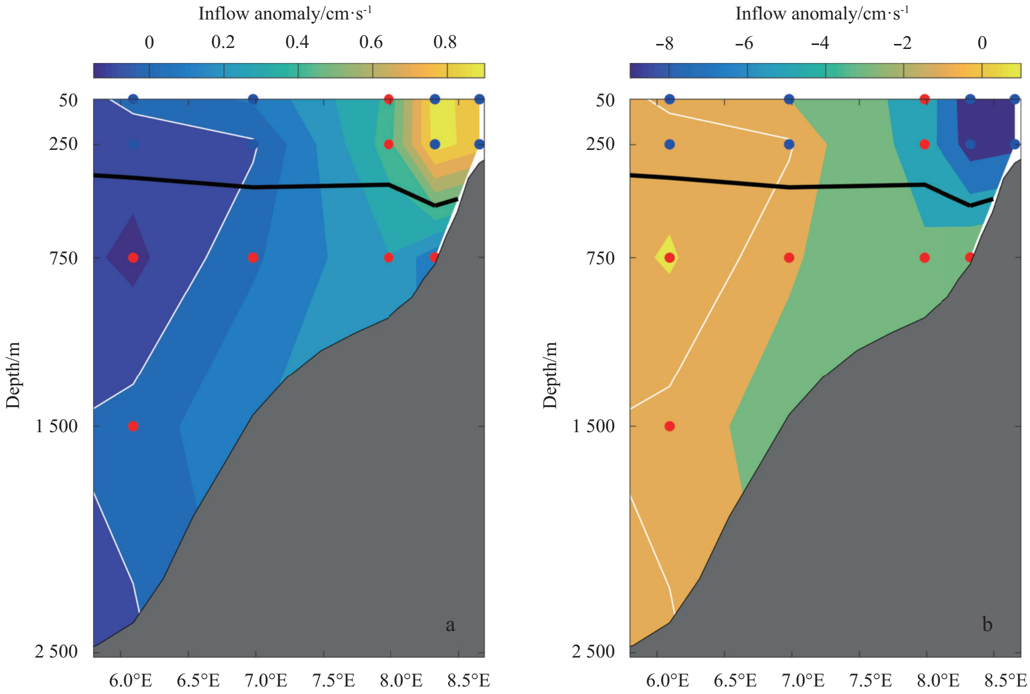

Fig. 8. The correspondence between Atlantic inflow anomaly and polar lows in the Barents Sea. a. Atlantic inflow anomaly for the days when there are no polar lows in the Barents Sea; and b. Same as Fig. 8a, except for the days when there are polar lows in the Barents Sea. The black and white full lines represent the 2°C and 0 cm/s contours, respectively. The blue dots and the red dots represent the median measure depths of F1–F5, while the blue dots represent the observation points whose sampling probabilities are greater than 70%.

3.3 *Impact of polar lows on Atlantic inflow in the Fram Strait*

Based on the conclusion above that the synoptic scale variability of the Atlantic inflow in the Fram Strait is related with polar lows in the Barents Sea, we composite the meridional current anomaly in the Fram Strait based on the days when there aren't or are polar lows in the Barents Sea (Figs. 8a and b). Figure 8 shows that, the meridional current anomaly is positive and negative in the most region of Fig. 8a and Fig. 8b, respectively. As there are no polar lows in the Barents Sea, Atlantic inflow strengthens and the maximum value can reach 0.96 cm/s. However, when polar lows occur in the Barents Sea, Atlantic inflow weakens and southward velocity anomaly can reach 8.3 cm/s. It indicates that polar lows in the Barents Sea can markedly impact the strength of the Atlantic inflow in the Fram Strait. The abnormal values in Figs 8a and b both gradually decrease from east to west, which implies that the impact of polar lows on Atlantic inflow gradually weakens from east to west. Note that the abnormal value in Fig. 8a is obviously smaller than the one in Fig. 8b. This is because that, the number of occurrence days of polar lows in the Barents Sea is 78 in all and only accounts for 10.5% of the total number of days, and the abnormal value in Fig. 8b is more away from the average than the one in Fig. 8a.

Figure 9 shows that the contour of SLP anomaly is dense and closed around the Barents Sea, which indicates that there are strong negative and positive wind stress curls around the Barents Sea in Figs 9a and b, respectively. Lien et al. (2013) have come to the conclusion below by using the numerical model and observation data. Wind-induced Ekman-transport causes sea surface height to reduce off the northern Barents Sea shelf, and the resulting decrease in sea surface height can induce a cyclonic circulation anomaly along the slope encircling the northern Barents Sea shelf area, further inducing the weakening of the Atlantic inflow in the Fram Strait. So according to Lien et al. (2013), the dynamic mechanism by which polar lows in the Barents Sea impact Atlantic inflow in the Fram Strait can be described as follow. Wind stress curl induced by polar lows in the Barents Sea causes Ekman-transport, leads to decrease of sea surface height in the Barents Sea, further induces a cyclonic circulation anomaly around the Barents Sea, and causes the weakening of the Atlantic inflow in the Fram Strait.

At the same time, the direct atmosphere forcing (wind) can affect the upper ocean. The question is: what role does the wind play in the synoptic scale variability of the Atlantic inflow in the Fram Strait. When wind acts on the ocean surface, the upper ocean will produce the Ekman drift, and according to the computational formula of the Ekman depth (Stewart, 2009), the Ekman depth is between 3.7 m and 37.2 m. However, the Atlantic inflow is deeper than 250 m according to Fig. 3, and the Atlantic inflow is barotropic, so we think that wind doesn't play an important role in the synoptic variation of the Atlantic inflow in the Fram strait.

4 Discussion and conclusions

Based on a suite of mooring data and reanalysis data, a feature is revealed: the Atlantic inflow in the Fram Strait has a significant period of 3–16 days in winter and spring, which is related with polar lows occurring in the Barents Sea. In winter and spring on the synoptic scale, when there are no (are) polar lows in the Barents Sea, Atlantic inflow strengthens (weakens). It indicates that polar lows in the Barents Sea can markedly impact the strength of the Atlantic inflow in the Fram Strait on the synoptic scale. According to Lien et al. (2013), the dynamic mechanism

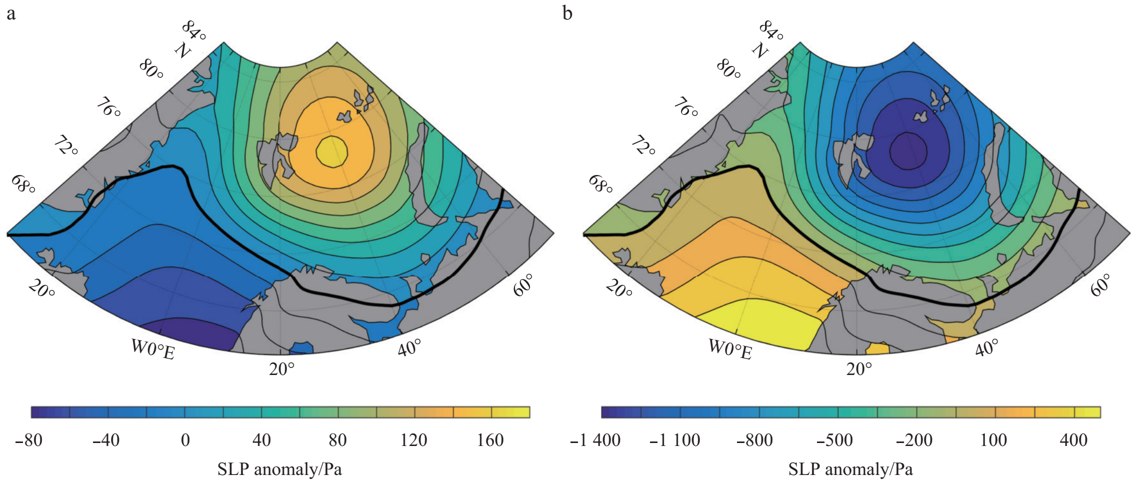

Fig. 9. The correspondence between SLP anomaly and polar lows in the Barents Sea. a. SLP anomaly for the days when there are no polar lows in the Barents Sea, the interval of contour is 20 Pa; b. same as Fig. 9a, except for the days when there are polar lows in the Barents Sea, the interval of contour is 150 Pa. The black thick lines in Figs 9a and b both represent 0 Pa contour. The latitude-longitude limits of the Barents Sea is 76°–82°N, 20°–60°E.

can be described as follows. Wind stress curl induced by polar lows in the Barents Sea causes Ekman-transport, leads to decrease of sea surface height in the Barents Sea, further induces a cyclonic circulation anomaly around the Barents Sea, and causes the weakening of the Atlantic inflow in the Fram Strait.

However, the conclusion is rudimentary in this paper. There are several topics worthy of further study in the future. For example, polar lows in the Barents Sea have interannual variability (Kvammen, 2014; Rojo et al., 2015), so what is the impact of interannual variability of polar lows in the Barents Sea on the Atlantic inflow in the Fram Strait? The impact of polar lows in the Barents Sea on Atlantic inflow gradually weakens from east to west in the Fram Strait. What is the effective distance that polar lows can impact Atlantic inflow in the Fram Strait? What is the impact of polar lows in the Nordic Sea on the Atlantic inflow in the Fram Strait, and so forth?

Our results highlight the importance of polar lows in forcing the Atlantic inflow in the Fram Strait and help us to further understand the effect of Atlantic warm water on the change of the Arctic Ocean.

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