THE COUPLING CHARACTERISTICS OF ARCTIC SEA ICE CONCENTRATION AND SEA ICE MOTION IN WINTER

Jie Su[1], Qian Shi[1], Ping Chen[1], Hongjie Liang[1]
Physical Oceanography Laboratory/CIMST, Ocean University of China and Qingdao National Laboratory for Marine Science and Technology, Qingdao, 266100, China

ABSTRACT

The coupled characteristics of winter Arctic sea ice concentration (SIC) and sea ice velocity (SIV) was analysed using EOF and SVD methods. The results show winter Arctic SIC increases to the north of CAA which could be explained by the strengthening of BG+TPD pattern. We related the variation of sea ice drift through Barents Sea with the Pacific-Atlantic seesaw of SIC. Our results also show that the correlation between AO/BBO and Arctic sea ice area flux (AF) through Fram Strait still exist with exception for short periods.

Index Terms— Sea ice concentration, Ice Motion, Coupling characteristics, sea ice area flux

1. INTRODUCTION

Arctic sea ice experienced drastic changes in recent years. Multi-year ice sharply decreases due to the accelerated melting of sea ice [1, 2]. Since the late 1990s, the Arctic ocean has no longer been dominated by multi-year ice [3]. By 2014, 5+ years ice accounted for just 5% of SIE (Sea Ice Extent) in Arctic [1]. This is accompanied by the decreasing of sea ice concentration (SIC) and thinning of sea ice thickness (SIT). And the variation of SIT is determined by the combined effect of thermodynamics and dynamics. In short time scale, divergence of sea ice movement caused the generation of the lead and open water. Convergence of sea ice movement leads to the retreat of ice edge in ice margin zone and ridges [4].

The thinner ice is more conducive to the sea ice velocity (SIV) increase [5, 6]. It has been revealed that the overall increase trend of Arctic ice speed is 0.6 cm/s (10a) during 1979-2007, and the increase of sea ice speed in winter is greater than that in summer [6]. The trend of ice velocity has also been confirmed by [7] and [8]. According to [7], from 2004 to 2009, the increase rate of ice speed is 46%/10a. They indicated that the change in ice speed in the central Arctic Ocean is mainly caused by the strengthening of the wind, while the acceleration of sea ice in the marginal sea of the Arctic Ocean is caused by the thinning of sea ice. Based on satellite and buoy data, [9] found that before 2000, the increase of SIV in basin scale is not obvious, but during 2000-2009, SIV increase significantly in winter. After 2004 the rate reaches 46%±5%/10a [9].

The average Arctic SIV shows two main characteristics: Transpolar Drift (TPD) and Beaufort gyre (BG). Researchers concluded the large-scale Arctic sea ice motion into four types, namely BG+TPD, anti-cyclonic pattern, cyclonic pattern and double vortex pattern, according to the monthly average SIV field from 1979 to 2006 [10]. Their result showed the anti-cyclonic pattern occurs mainly in winter and spring. When AO (Arctic Oscillation) is at strong positive (negative) phase, Arctic sea ice drift presents cyclonic (anti-cyclonic) pattern [10]. During 1982 to 2009, both TPD and BG were strengthened, especially in the last decade. From 2001 to 2009, the Arctic Dipole Anomaly (DA) had a significant effect on summer sea ice drift and enhanced sea ice export through Fram strait. In addition, along with the change of AO, the sea ice velocity also changes greatly [9].

However, many researches (such as [3, 11, 12]) show AO and Arctic sea ice are decoupled in recent years. And DA became the dominated atmospheric circulation pattern effecting Arctic sea ice [11, 13, 14]. Is it a new regime or just a short-term adjustment? To answer this question and to understand the influence of SIV on the rapid change of sea ice, especially SIC distribution, we will use methods of EOF (Empirical Orthogonal Function) and SVD (Singular Value Decomposition) to analyze the distribution and variability characters of SIV and SIC and their coupling characteristics. Furthermore, our study will involve the correlation of sea ice export from Fram Strait and the corresponding atmospheric circulation pattern.

2. DATA AND METHODS

Monthly SIC data with 25 km spatial resolution employed here are obtained from the National Snow and Ice Data Center (NSIDC) based on the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I) [1].

Monthly Sea ice motion used in this paper is the Polar Pathfinder Sea Ice Motion Vectors (Version 3), which also comes from NSIDC. This monthly ice motion data set is distributed on a 25 km Equal Area Scalable Earth grid (EASE) from Oct. 1978 to Feb. 2017 [2].

The sea ice area flux (AF) through Fram Strait we used here is from [3], which was based on high-resolution SAR ice motion during 2002-2014 and expanded to 1949-2014 by sea level pressure gradient across Fram Strait.

According to the characterization of SIV distribution, we roughly generate average monthly SIV from Oct. to May as SIV field of winter half year. For consistence, the same process was done for SICs.

The EOF analysis method could decompose temporal-spatial variables into spatial patterns and corresponding time series. We apply the EOF method to sea level pressure (SLP) data within north of 70°N from ERA-Interim reanalysis dataset [4]. And the first three leading pattern are referred as AO, DA and BBO, respectively. In addition, Central Arctic Index (CAI) is acquired from the ERA-interim SLP gradient across 81°N according to [8].

The singular value decomposition (SVD) method, based on the maximum of covariance of two data matrices, could extract temporal and spatial correlation by decomposing two coupled matrices. In this paper, we use SVD method to identify the locations of high spatial correlation between SIV and SIC fields.

3. RESULTS

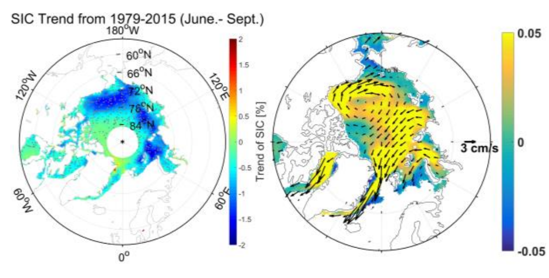
3.1 Variability of SIC and SIV

The trends of Arctic winter SIC and SIV distributions from 1979-2015 are showed in Fig. 1a. It is clear that SIC decreases mainly in marginal ice zone, especially in Atlantic sector. It should be noticed that SIC to the north of Canada Arctic Archipelago (CAA) increased to some extent (exceeding 95% significance level). TPD and BG are strengthened while ice export from Fram Strait and Demark Strait increases significantly (Fig. 1b). The ice drifts climatologically toward north of CAA. Although we cannot directly explain the increase of CAA SIC by the large-scale climatological ice drift field. We can conclude this SIC increase is due to dynamic effect rather than thermodynamic effect.

The method of EOF was used to extract the inter-annual variability of SIV which would help explain the dynamic effect of SIV on SIC. Fig. 2 shows the three leading mode of Arctic SIV in winter. The PC1 shows dominant BG and TPD, which is very similar to the climatological pattern, but with significant positive trend during study period. When PC1 is positive, more sea ice will be exported from Fram Strait. The peak occurred in 2007/08 winter following the dramatic record retreat of SIE in 2007 summer. As more multi-year ice changes to one-year ice [19], the ice will be driven more effectively by wind.

The spatial distribution of PC2 shows a shift of anticyclonic/cyclonic pattern mainly in decadal scale as well as inter-annual scale without long term trend. By numerical model [20] and satellite remote sensing data [21], the 5-7 years periodic oscillation has been found in the large-scale Arctic sea ice movement which alternatively changes between cyclonic and anti-cyclonic pattern under corresponding wind field. Fig. 2 also shows that when PC2 stays at positive phase, the sea ice export from Fram Strait decreases.

SIV pattern of PC3 shows the ice drift along the direction of 45°E and 135°W. Since there is no ocean outflow observed in this place, we need to further explore the physical process of the statistic results. However, no matter the ice drift is driven by wind or it is just a squirt of sea ice caused the movement of ice edge, when this pattern is positive, sea ice export from Arctic through the Barents Sea will increase, which has also been found in [22]. At the same time, ice export through the Fram Strait presents a reverse direction on east and west sides (outflow in the east and inflow in the west). For the long term variation, this pattern weakened during the study period, especially after 2004.



(a) (b)

Fig. 1. Winter SIC trend (a), ice speed trend (colored, unit: cm/s per year) and climatological ice motion (b) during 1979-2015

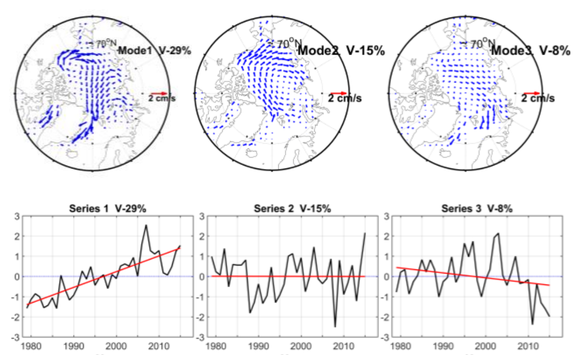


Fig. 2. Spatial distribution and time series of three leading EOF modes of winter SIV during 1979-2015

3.2 Coupling characteristics of Arctic SIC and SIV

In order to further reveal the coupled relationship of SIC and SIV, SVD method was employed. Fig. 3 shows the three leading modes of SVD. Although thermodynamic factor plays a major role of regulating Arctic SIC, the result of PC1 indicates that the dynamic effect does explain the increase of SIC to north of CAA and cannot be omitted. The spatial pattern of SIV matches very well with the EOF PC1 of SIV.

So does the SIV PC2 and PC3, which show seesaws between the east and west and between the Pacific and Atlantic sector, respectively.

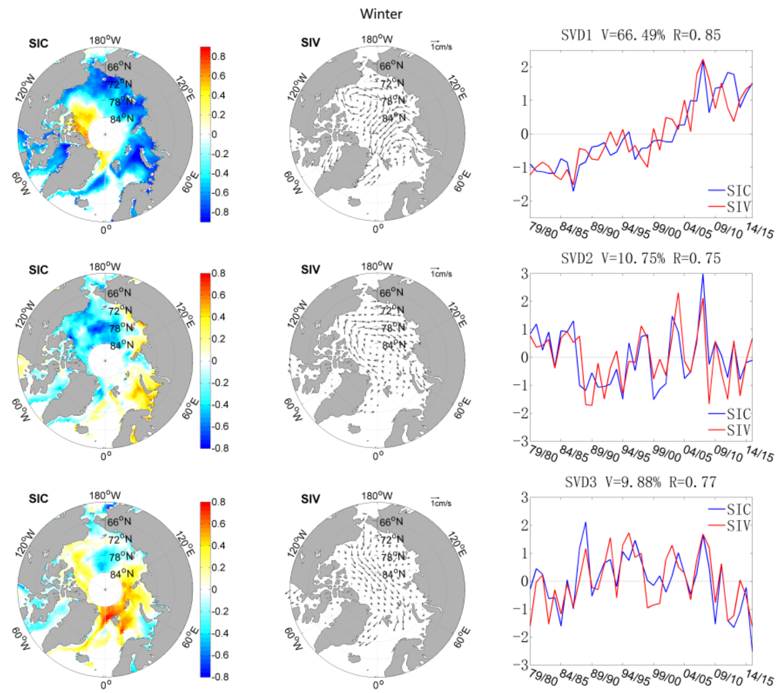


Fig. 3. SVD results of three leading modes in winter

3.3 Connection between sea ice export through Fram Strait and Atmospheric circulation pattern

The SIV and SIC patterns are driven by atmospheric circulation. From the above results of EOF and SVD, we know that the three PC patterns have different effects on the TPD and sea ice export through Fram Strait. Here we use CAI and AF index (see part 2) to depict the strength of TPD and Arctic sea ice export from Arctic Ocean and use AO, DA and BBO index (also see part 2) to depict large-scale atmospheric pattern. The correlation with a 7-year running window is given in Fig. 4. Since CAI and AF are highly correlated, here we just give the results of AF. It shows that AO and BBO has significant correlation with AF before 1989 and during 1992-2005. However, DA's correlated period is different. So, in inter-annual time scale, the three atmospheric circulation pattern all affect AF through Fram Strait except for one or two short term periods.

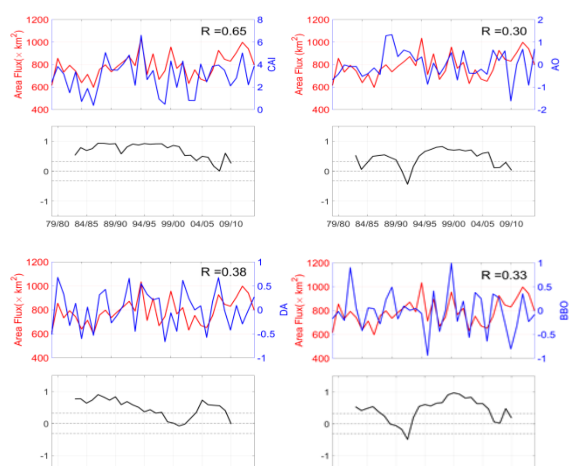


Fig.4. Relationship of Fram Strait sea ice AF and CAI and atmospheric circulation patterns.

4. DISCUSSIONS AND CONCLUSION

While many studies focus on the decadal and inter-annual variability of the cyclonic and anti-cyclonic ice motion driven by wind, we notice the coupled characteristics of Arctic SIC and SIV in this paper. The results show both SIV and the coupled patterns has three main modes respectively. When the climatologic pattern of SIV with TPD and BG (PC1) strengthens, it is beneficial for the convergence of SIC to the north of CAA and Greenland Island. As to the contribution to sea ice export through Fram Strait, this pattern is more important than the shift of cyclonic and anti-cyclonic circulation in basin scale. We also found that the consistent variation in Pacific-Atlantic seesaw SIC and the ice drift which might connected the sea ice squirt through Barents Sea. Although AO and Arctic SIE's correlation is not as good as previous after the mid-1990s [12], our results show the correlation between AO as well BBO and sea ice AF still exist with exception for short periods. The reason of this inconsistence is worth to be further studied.

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