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Relationship of Arctic sea ice and Northern Hemispheric 500 hPa Polar vortices

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Abstract Using the NCEP/NCAR reanalysis monthly 500 hPa height data on a 2.5 latitude-longitude grid and 1°×1° sea ice data, the polar vortex area, intensity index and arctic sea ice area index are calculated respectively, and the meridional distribution, period variation and the abrupts in the long range trend are analyzed to study their relationship. The results show that the meridional distribution of sea ice and polar vortex h– ave distinctive difference, the relative positions of them are different in the eastern and western hemispheres, and exept they have periods of 4 months, quasi half year, quasi year, 4-5 years and 10 years commonly, and each of them has its own respective variation as well. The sea ice area is decreasing apparently since 1980's, so is the polar vortex area, but their abrupt changge time are different totally. The area of sea ice and polar vortex has prominent positive correlation, but the relationship of sea ice intensity, polar vortex intensity, polar vortex area is complicated.
Key words Arctic sea ice, polar vortex, period, abrupt, correlation

1 Introduction

The ice snow circle, as an important part of climatic system, has interested by many researchers and has been studied a lot recently. Arctic ice is one of the cold sources in the atmospheric heat engine, sensitive to the global climatic changes in the meantime, and its redistribution influences the atmospheric motion by changing the absorption of the solar radiation at the underlying surface and by changing the heat balance and finally arouse the climatic changes. As a result, the influence of the distinctive changes of the arctic sea ice on the atmosphere have great drawn attentions to many meteorologists.

Zhang (1981)[1] studied the relationship of sea ice and seasonal wind. Fang (1986)[2] researched the reaction of the subtropical high and polar sea ice in the northern hemisphere. Zhao *et al.* (2001)[3] demonstrated that the annual variation of sea ice in every season in the southern Ocean and the Arctic Ocean had sudden change and the atmospheric circulation has notable difference before and after the abrupt. Walsh (1979), Overland (1982), Fang (1994), Slonosky and Prisenberg (1997)[4-8] mentioned that variability on timescales of weeks and longer tends is to be organized into large-scale geographical patterns, which are closely associated with the dominat structures of atmospheric circulation variability, particularily during winter. Wang (1991)[9] suggested the temporal and spatial distribution characteristics of the arctic sea ice area are related to many physical factors. The studies of Rigor (2002)[10] showed that the long changing trend of the arctic sea ice is mainly influenced by the changes of the wind field in the surface layer.

The polar vortex is the biggest atmospheric motion system over the north pole and the surrounding sea ice area. Since 1980's, there has been a lot of studies on it in China and prominent success attained[11-16]. It showed that the polar vortex and its underlying surface (sea ice) acted and influenced on each other. The primary analysis of Zhu and zhang considered that the influence of the polar vortex on the polar sea ice is stronger than the influence of the polar sea ice on the polar vortex. In this study, the further statistic analysis is done to study their correlation factually, finding that the relation of arctic sea ice and polar vortex on 500 hPa is more complex rather than merely simple saying of one is stronger than the other. We hope that the further study can provide more detailed statistic proof to diagnose the arctic sea ice and climatic changes.

2 Data and method

2.1 *Data*

The data in this study is derived from the NCEP/NCAR monthly reanalysis data on a 2.5 latitude-longitude grid on 500 hPa in the northern hemisphere from January 1953 to December 2002 supplied by Nanjing Atmospheric Data Service Center of Earth Science. The sea ice data is the monthly sea ice coverage data on a 1 latitude-longitude grid from January 1953 to December 2002 supplied by Hadley Center, of which the coverage range is 0 to 10, 0 means ice free in the grid, 10 means 100% ice coverage, 1 means 10% ice coverage, and the rest may be deduced by analogy.

2.2 *Computing methods*

The polar vortex area and intensity are computed by use of the method deduced in the literature 17. On 500 hPa isobaric surface, the characteristic contour line nearest to the westerly jet axis is used as the borderline of the polar vortex, and the area surrounded by the line is defined as the polar vortex area.

The mass between the 500 hPa isobaric surface and the geopotential surface, where is the southern bound of polar vortex, is defined as the polar vortex intensity. The polar vortex area (PVA) and the polar vortex intensity (PVI) are computed as follows:

$$PVA(i) = R^2 (1 - \sin\varphi(i)) \Delta\lambda \quad (1)$$

$$PVI(i) = \rho R^2 \Delta\varphi \Delta\lambda \sum_i \sum_j (H_0 - H_{ij}) \cos\varphi(i) \quad (2)$$

In which, R is the radius of the earth and its value is 6378 km, $\varphi(i)$ is the latitude of the characteristic contour line of the polar vortex boundary in the i grid, with the precision of 0.1, using the average grid data on 500 hPa, acquired by linear interpolation. $\Delta\lambda$ is the longitude range, ρ is the air density, $\Delta\varphi$ is the latitude difference of the neighbour grid, H_0 is the value of the characteristic contour line (with the unit of geopotential meter), H_{ij} is the geopotential value of the grid in the north of the characteristic contour line. ρR^2 is a constant 0.1 when competing.

The sea ice area index in this paper is that in the north of 45°N, acquired by adding up the ice coverage area index of all grids; the bigger the index, the bigger the coverage area, and vise versa. The power spectrum analysis, wavelet analysis, univariate linear regression and Mann-Kendall test are applied to analyze the sea ice and polar vortex index. Of which, the wavelet analysis is Morlet wavelet analysis, and the expression of its mother wavelet is as follows:

$$\Psi(t) = e^{i2\pi t} e^{-\frac{t^2}{2}} = e^{-\frac{t^2}{2}} \cos 2\pi t + i e^{-\frac{t^2}{2}} \sin 2\pi t$$

Morlet wavelet is complex number wavelet, and is comprised of real and imaginary part, the mode and real part are two important variables. The value of the mode shows the intensity of the signal in the characteristic temporal range. The real part expresses the distribution in different time scales and the phrase of the signals in the different characteristic time scales. The expression of the Morlet wavelet in this paper is that:

$$\Psi(t) = e^{-\frac{t^2}{2}\cdot\frac{\pi^2}{25}} \cos 2\pi t + i e^{-\frac{t^2}{2}\cdot\frac{\pi^2}{25}} \sin 2\pi t$$

of which, $\frac{\pi^2}{25}$ is parameter, used to control the wavelet coefficient. The real part coefficient is used, the expression of which is that:

$$\Psi_Y(t) = e^{-\frac{t^2\pi^2}{50}} \cos 2\pi t$$

3 Longitudinal changes of the arctic sea ice and the index variance of the polar vortex

Figure 1 is the longitudinal distribution of the variance of the 36 sea ice and polar vortex index at an interval of 10 longitudes, which shows that the sea ice varies with longitude. The areas with big variance are 50-100°W, 30-90°E, 170°W-180° and 130-160°E, which means the ice area variation is big in these areas and these are sensitive areas, which is consistent with the results of many literatures. Similarly, the polar vortex index varies largely with longitude, the bigger index variance means more active cold air motion, and the large areas of the polar vortex area and that of intensity are not totally superposed but basically consistent. What interests us is that the longitudinal distribution of polar vortex index and sea ice is not only un-superposed but also obviously different in the eastern and western hemisphere. Fig. 1 shows that the cold air active area in the western hemisphere is 20 longitudes in the east of the sea ice sensitive area, while in the eastern hemisphere, the active area is in the west of the sensitive area. The reason for this distribution is probably the difference of the underlying surface in the both hemispheres, also the sea land distribution, which is the difference of the underlying surface give rise to the difference of the thermal structure and energy exchange in the ground layer, and further leads to the difference in the high and low layer.

4 Seasonal changes of the arctic sea ice and the index variance of the polar vortex

Figure 2 is the average annual variation series of the arctic sea ice and the polar vortex area and intensity over the ice for 50a, which shows that the sea ice area has prominent annual cycle; from October in the former year to March in the next year is the growing period,

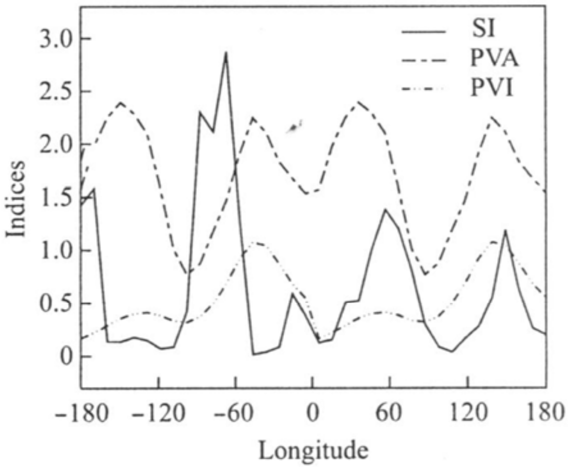


Fig 1 Longitudinal distributions of Arctic sea ice extent (SI) and indices of polar vortex area (PVA) and intensity (PVI).

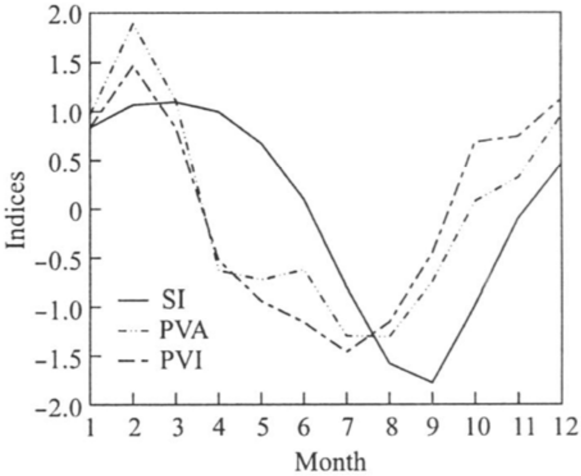


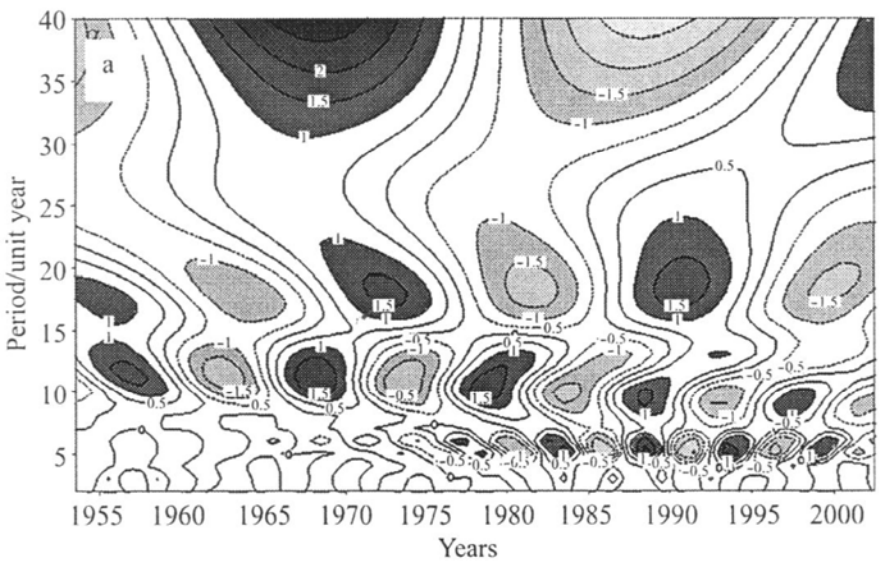
Fig 2 Seasonal cycle of the Arctic sea ice extent (SI) and the indices of polar vortex area (PVA) and intensity (PVI) on the whole Arctic

April to September is melting period, and in March the area is the biggest, in September the smallest The polar vortex area and intensity have obvious seasonal variation the same as sea ice, which means they are both influenced by thermal effect, which is the seasonal variation of the solar radiation The variation of the polar vortex intensity is the smallest in July, the biggest in February, from August in the former year to January in next year is the enhancing period, and from February to July is the weakening period The annual variation of the polar vortex area is more complex than that of the intensity, in July to August it is the smallest, and what is more interesting that the polar vortex area in the northern hemisphere does not decrease all the time just like the sea ice area and the polar vortex intensity, but increases a little in May to June and then decreases to the smallest This undulation of the polar vortex area in late spring and early summer reflects the instability of the atmospheric cell in the adjusting period to some extent The polar vortex area has a gentle decline in April to May and July to August, a slow ascending trend from May to June, and an obvious decline from June to July, indicating that the withdraw of the westerly jet axis in summer is smooth from April to June and from July to August, quick from June to July, and after August the axis is keep southward swift and reaches the southest in February next year The polar vortex intensity reaches the smallest one month earlier than the polar vortex area in summer, but reaches the biggest in February at the same time, indicating that the polar vortex intensity weakens fast from winter to summer but enhances slowly from summer to winter. From the analysis above, it is known that the variation of the polar vortex index is not corresponding, the area and intensity reflect the variation of the polar vortex arising from different aspects, but the total trend is consistent, that is to say the polar vortex enhances in winter and weakens in summer.

Fig. 2 also indicates that the polar vortex intensity in summer is the smallest in July, the polar vortex area is the smallest in August, the sea ice area is the smallest in September, the polar vortex index in winter is the biggest in February, the sea ice index is the biggest in March. By comparison, it is known that the biggest value of the sea ice occurs one to two months later than the polar vortex, indicating that the climatic feature of the sea ice is influenced largely by the atmospheric seasonal variation. In winter, the polar vortex extends the cooling region from north to south in the Arctic area, where the low temperature and small wind speed are sustained, which is of benefit to the growth of sea ice. On the contrary, the polar vortex in summer contracts from south to north, the polar vortex area and intensity both decrease, the sea ice outside the polar vortex melts due to unsustained low temperature, and the sea ice area decreases along with the change.

5 Oscillation periods of the arctic sea ice and the polar vortex

Using the power spectrum analysis and wavelet analysis, the oscillation periods of the sea ice area over the arctic area and the polar vortex index in the northern hemisphere are studied. Firstly, the annual average of the sea ice area and the polar vortex index was calculated, then Morlet wavelet analysis was done to study their annual and decadal oscillation characteristics. Fig. 3 is their real part of the Morlet wavelet coefficient. It shows that the sea ice has the periods of 10-12a and 18a, and 5a since 1970's, the polar vortex area has the periods of 9-10a, 14-15a, 3-4a before 1980's, and 6a after 1990's, and the polar vortex intensity has the periods of 9-10a, 14a and 23-24a, and 3-5a after 1960's.



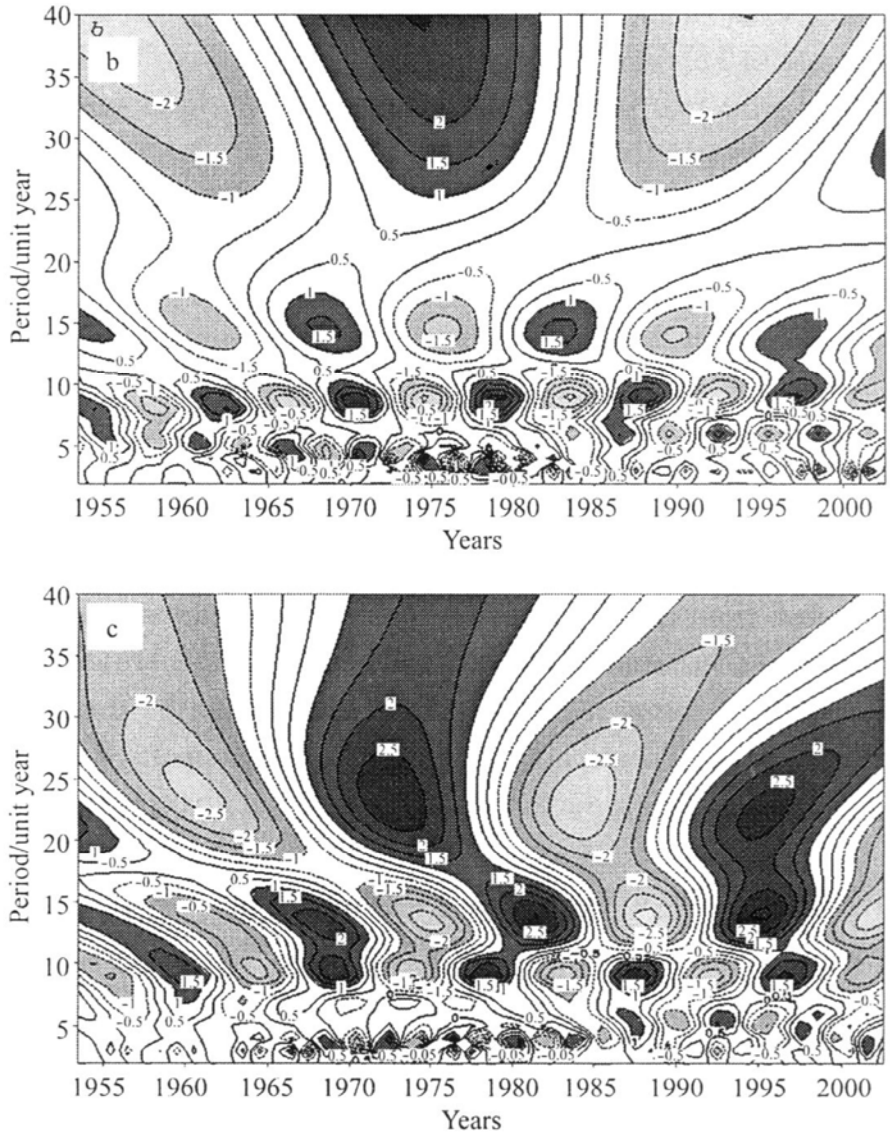


Fig. 3 Real part coefficients of the Morlet Wavelet of the Arctic sea ice extent (a) and the indices of polar vortex area (b) and intensity (c) in the Northern Hemisphere from 1953 to 2002

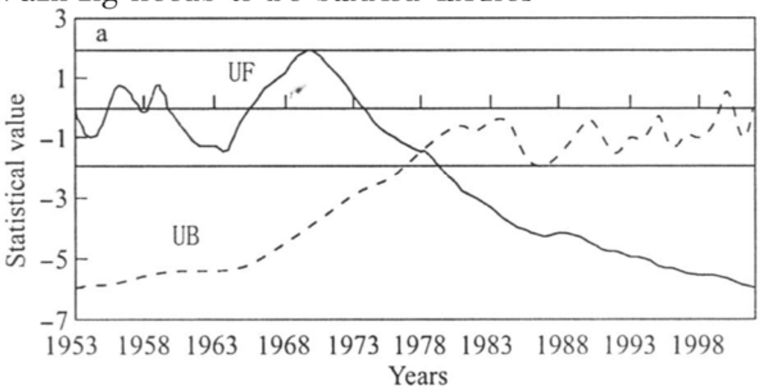
Since the power spectrum is sensitive to the high frequency wave and the inter-annual period variation of the sea ice and the polar vortex were key to problems. When the power spectrum analysis being done on them, 1/3 of the series being taken as the biggest time lag and test with reliability of 5% being done, the marked periods of every series were acquired. It is indicated that the SI for the power spectrum of the arctic sea ice and the polar vortex in 500 hPa in northern hemisphere are 4.2, 6.6 and 12.65 months, the periods of PVA are 4.4, 6.6 and 12.65 months, and the periods of PVI are 4.0, 6.2 and 12.65 months. It is obvious that the sea ice and the polar vortex both have notable oscillation periods of 4 month, half year and 1 year.

Following the analyses above, it is known that sea ice and polar vortex have respective periods but also have the same oscillation periods of month, half year and 1 year. Wang (1991)[9] thought the quasi-half year and quasi-yearly period of Arctic sea ice is related to the half year period of the variation of earth rotation velocity and the 12 month period of the solar radiation intensity. The 3-4 year oscillation period of the arctic sea ice and the polar vortex in the northern hemisphere is corresponding to the period of SOI, which means that the arctic sea ice is basically in answer to the atmospheric oscillation. Of course, besides that the arctic sea ice and the polar vortex are restricted by the same geophysical factors, the interreaction between them also cannot be neglected. In the short run, the modification of the upper polar vortex cell and the change of wind field in surface layer have an important effect on the redistribution of the sea ice, even in the long run, the change of long average status of wind field in surface layer also has an important effect on the distribution of the sea ice. The long term variation of the sea ice will impose effect on the atmospheric cell via the variation of the energy exchange near the ground, and contributes to the long term modification of the atmospheric cell.

6 Short period climatic changes and abrupt of the arctic sea ice and the polar vortex

Recently, many studies indicate that the area of the Arctic sea ice is decreasing in whole. In this article, the univariate linear regression and Mann-Kendall test are applied to the time series of the standard anomaly of the Arctic sea ice and the polar vortex in the northern hemisphere. The figure for the univariate linear regression shows that the sea ice and the polar vortex area both have obvious decrease. Their univariate regression equations are ICE: $x = 1.4215 - 0.0557t$, PVA: $x = 2.2792 - 0.0894t$. The changing trend of the anomaly of the sea ice area and the polar vortex area is tested with the reliability of 0.01, and results show that the decrease trend is marked.

Fig. 4 is the Mann-Kendall sudden change test of the Arctic sea ice area and the polar vortex area and the univariate linear regression of the polar vortex intensity. $\alpha = 0.05$ is the significant level in the Mann-Kendall sudden change test meanwhile its critical value is ± 1.96. The sudden change test of the polar vortex intensity (fig omitted) denotes that is not obviously abrupt in the long run time. In fig 4a, the sudden test of the Arctic sea ice anomaly indicates that the area extended a little in the late of 1950's, early of 1960's, late of 1960's and early of 1970's, its long term trend changed abruptly in late of 1970's, and after 1980's, its contractive trend is marked. This prominent decrease has caused highly attention of scientists. Many people related this decrease trend to the global warming and intended to demonstrate that the decrease of sea ice area is deduced by global warming. But Rigor (2002) considered that it is the effect of wind field that changes the distribution of the sea ice, that is to say, the decrease of sea ice area changes the thermal structure in the ground layer of the Arctic region and further causes the increase of the temperature. From the discussion above, it can be inferred that the relationship between the decrease of the sea ice area and the global warming needs to be studied further.



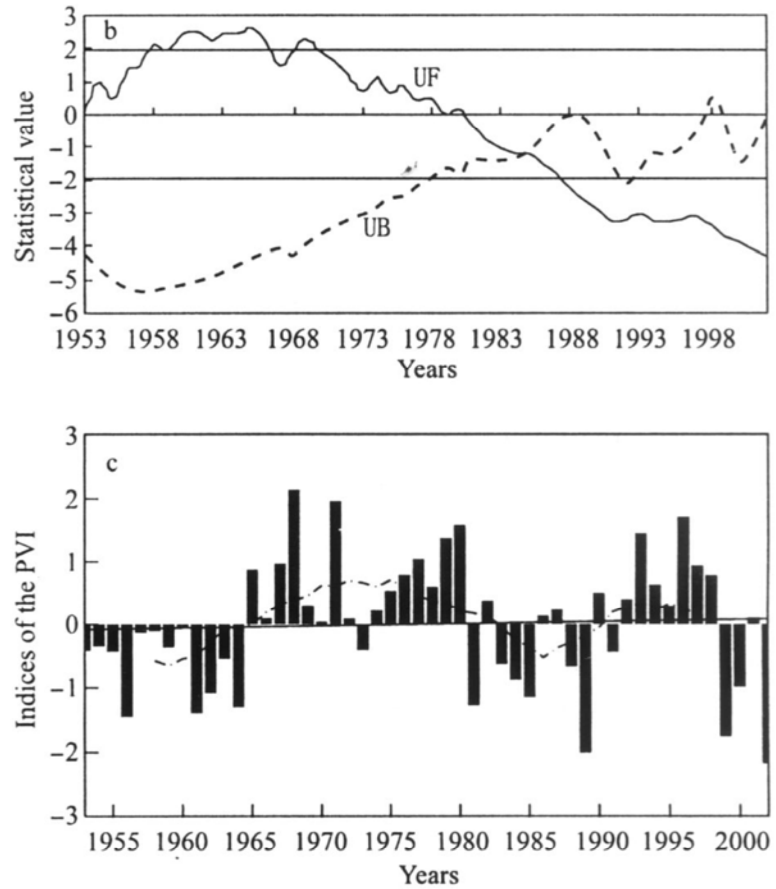


Fig 4 The Mann-Kendall test of sudden change of the Arctic sea ice extent (a) and the index of the polar vortex area (b) and 11-year running mean (dash and dot line) of the polar vortex intensity index (vertical bar) (c).

The sudden change test of the polar vortex area (fig4b) indicates that the area extended before 1980's, especially in 1960's, its abrupt time is in the middle of 1980's, in the late of 1980's the abstract is notable, and this contract trend obviously lags behind the decrease of the Arctic sea ice area for 6-8a, which shows that the influence of the Arctic sea ice area variation on the atmospheric circulation is mainly in long term, and not obvious in short term. From analyses perviously, it is known that the reaction of the Arctic sea ice area and the polar vortex in the northern hemisphere is the notable effect of the modification of the atmospheric circulation on the redistribution of the sea ice in the short run, while in the long run, it is adverse, that also demonstrates that the influence of the sea ice on atmosphere is a slow process.

The univariate linear regression of the polar vortex intensity in fig 4c shows that the variation of the intensity is ascending and reaches 0.1 significant level in the correlation test, which explains that unlike the polar vortex area, the polar vortex intensity changes a little with time, and the ascending trend is not obvious. This means that the polar vortex intensity reflects the short term changes of the cold air intensity in the northern hemisphere. Because the influence of sea ice on the atmosphere is long term, the influence is not obvious in long term. In short term, the variation of sea ice imposes effects on the atmosphere by changing the energy exchange on the ground, and further influences the cold air intensity, also the polar vortex intensity in the Arctic region.

7 Correlation of the Arctic sea ice and the polar vortex

In order to study the relationship between the arctic sea ice and the polar vortex, the relative test is done for the sea ice area and the polar vortex indices, for which a 3-month running is done to filter the seasonal disturbance, with the sample of 598, the critical correlation coefficient r at the significant level of 0.05 is 0.080. The sea ice area and the polar vortex area are positively correlated, with the correlation coefficient of 0.658, which indicates that the southing and northing of the westerly jet is distinctly related to the extending and contracting of the sea ice.

The time series of the polar vortex and the 11a running average are shown in Fig.5, which indicates that the relationship between the polar vortex area and the polar vortex intensity is not simply positive phase or opposite phase, that is, their relationship no with simply positive or opposite correlation. In long run, the polar vortex area and the polar vortex intensity are positively correlated, that is, the polar vortex area extends when the polar vortex intensity enhances and the cold air extends outside. In short run, when the warm air in the south of the northern hemisphere enhances, it will force the polar vortex contract to the polar area, this is the phenomenon which is similar to that with the relationship between the area and the intensity of the subtropical high, that is, the intensity increases while the area decreases.

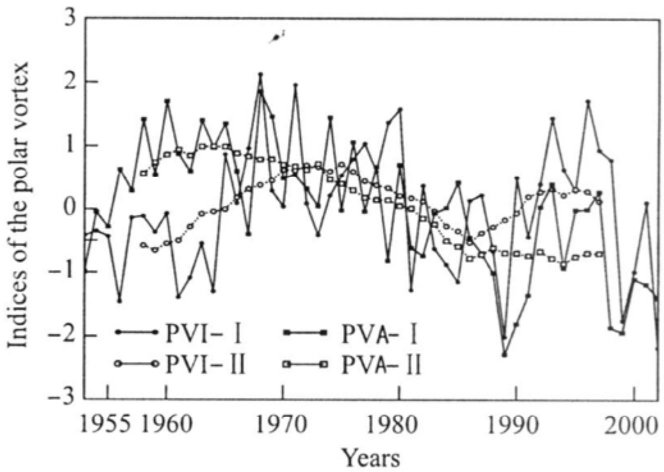


Fig.5 Time sequences and their 11-year running means of the polar vortex area (PVA) and intensity (PVI) on the whole Arctic

The relationship between the sea ice and the polar vortex intensity is also complex. In whole, the increase and decrease of the sea ice cause the enhancement and decline of the polar vortex intensity, but in some cases, the enhancement of polar vortex intensity cannot reflect the increase of the sea ice area. Just as the relationship between the polar vortex intensity and the polar vortex area, the relationship between the polar vortex intensity and the sea ice area is not simply positive correlation, which is restricted by other physical factors, and urgently needs to be studied further.

8 Conclusion and discussion

(1) By analyzing the longitudinal variance, it is known that there are four active re-

gions of the sea ice; but the regions with bigger polar vortex indices changes do not match these four regions; and the surface and high collocations in the western and eastern hemisphere are not the same; why it happens is the difference in surface layers.

(2) The Arctic sea ice area and the northern polar vortex have significant annual variation, and the change of the sea ice area apparently lags behind the polar vortex for 1-2 month, that is to say, the influence of the atmospheric circulation on the Arctic ice is greater than the influence of the Arctic ice on the atmospheric circulation, in short run.

(3) The Arctic sea ice and the northern polar vortex have oscillation periods of 4 month, quasi-half year, quasi-year, 4-5a and 10a. Besides it, different regions have different periods, which shows that the sea ice and the atmosphere not only have the coupled changing periods but also have respective oscillation periods, which are influenced by many factors.

(4) The short term climatic changing trend of the Arctic sea ice and the northern polar vortex area is significant decline, but the sudden change and prominent decline of the polar vortex area lags behind that of the sea ice area, which shows that the effects of the sea ice on the atmospheric circulation are long term. The short term climatic changing trend of the northern polar vortex intensity is light ascending.

(5) The relationship between the Arctic sea ice and the northern polar vortex is very complex. The area of the sea ice and the polar vortex is positive correlation, that is, the extending and contracting of the sea ice area have important meaning to the southing and northing of the westerly jet. However, the relationship between the sea ice area and the polar vortex intensity and that between the polar vortex area and intensity are not simply positive and negative correlation. That is to say, the decrease of the polar vortex area will cause the decrease of the polar vortex intensity in certain range, but while the polar vortex area contracts to certain area, the polar vortex intensity will enhance because the cold air near the pole is piled up.

The physical mechanism of the reaction between the Arctic sea ice and the atmospheric circulation is one of the focuses discussed in the long term climatic model, especially in recent years, the apparent decrease of the Arctic sea ice and the global warming have caused attentions of many scientists. In this paper, it is tried to find some regulation by statistic analyses of the Arctic sea ice and the atmospheric circulation over it, and it is found that the relationship between the sea ice area and the polar vortex intensity and that between the polar vortex area and intensity is very complex. This article merely discussed their correlation qualitatively, and in what areas their relationship transforms and what the physical mechanism needed to be studied further.

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