

Variability of the Coupling Between Surface Air Temperature and Northern Annular Mode at Various Levels*

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ABSTRACT

This article focuses on the variability of the coupling between surface air temperature (SAT) and northern annular mode (NAM) at various levels. To measure the coupling intensity between the SAT and the NAM anomaly fields, the coupling index has been defined as the leading principal component of the partial least squares regression model of the SAT and NAM anomalies. Both a composite analysis and the coupling index have been used to reveal level-by-level and month-to-month variability of the coupling between the upper anomalous NAM and the SAT in the Northern Hemisphere. The major results are as follows: the January SAT anomaly is more strongly coupled with the January NAM anomaly at the middle-upper tropospheric levels than that at the other levels, while the same is true for the February SAT anomaly with the January NAM anomaly at the lower stratospheric levels. The January NAM anomaly at the middle-upper tropospheric levels is most strongly coupled with the January SAT anomaly, and the coupling intensity is successively reduced month by month and becomes trivial after April. The January NAM anomaly at the lower stratospheric levels is more strongly coupled with January, February and March SAT anomalies, but the coupling becomes trivial after April.

Key words: northern annular mode, surface air temperature, partial least squares regression

1. Introduction

Thompson and Wallace (1998) found the Arctic Oscillation (AO), which represents such a spatial distribution that the geopotential height variations are opposite in the middle and high latitudes and there is a ring-like belt in the middle latitude circling the active center in Arctic (Fig.1). Thompson and Wallace (1998) and Baldwin and Dunkerton (1999) discussed that such a spatial distribution exists not only in surface but also in all the levels from stratosphere to surface, and it is the dominative mode in extratropical regions of the Northern Hemisphere. The northern annular mode (NAM) has been considered to be a more accurate name to describe such a spatial distribution than the AO.

The influence of the anomalous NAM on weather and climate in the Northern Hemisphere has been concerned by a number of researchers. Thompson and Wallace (1998, 2000) discussed the close coupling between the NAM and surface air temperature (SAT),

and indicated that the positive polarity of the JFM (January-February-March) AO is associated with the positive SAT anomalies throughout high latitudes of Eurasia and North Canada, while negative anomalies over extreme eastern Canada, North Africa, and Middle East.

There is no doubt about the obvious coupling the between anomalous NAM and SAT. Our question is if the coupling between the NAM and the SAT anomalies differs in different levels? Former researches focused on the relationship between the SAT and the NAM in one particular level, for example, in surface level. In this paper, we compare the coupling intensities of the SAT with the anomalous NAM in different levels and focus on the differences of the coupling between the SAT with the stratospheric and that with the tropospheric anomalous NAM. We also try to answer these questions: In which level the NAM anomaly couples the SAT the strongest? In which period the coupling is the most significant and how long such a relationship can last? How to measure the response intensity

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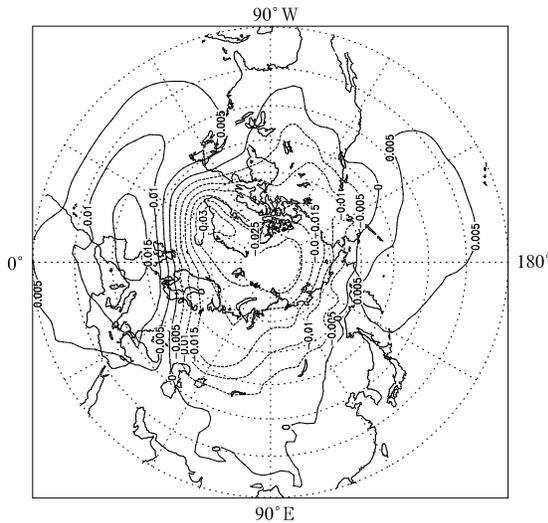


Fig.1. The first EOF mode of the January Northern Hemispheric 1000-hPa monthly mean geopotential height field (20° – 90° N).

of the SAT to the NAM anomaly?

2. Data and analysis techniques

The monthly-mean SAT and geopotential height datasets in the Northern Hemisphere are taken from the National Centers for Environmental Prediction /National Center for Atmospheric Research (NCEP/NCAR) reanalysis datasets. The data resolution is $2.5^{\circ} \times 2.5^{\circ}$. The time period is from 1948 to 2005. The datasets include 17 pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa.

Because strong NAM anomalies often occur in winter, and January is the representative month of winter, we use the January monthly mean geopotential height data to define the NAM index which can indicate the NAM anomaly strength. The NAM index is defined as the first empirical orthogonal time function of the January monthly mean geopotential height field over the domain poleward of 20° N. There are 17 NAM indices calculated corresponding to the 17 pressure levels. And these indices are standardized prior to the following analysis.

When the value of the standardized NAM index is larger than 1, the corresponding year is recorded as a strong positive anomalous NAM year, and when the

value of the standardized NAM index is smaller than -1 , the corresponding year is recorded as a strong negative anomalous NAM year. Corresponding to the NAM index at each pressure level, there are one set of the strong negative anomalous NAM years and one set of the strong positive anomalous NAM years. There are 34 sets of years totally. Because the atmospheric circulations in different levels are often different in the same period, the years selected are not the same for different levels. The monthly-mean SAT anomaly fields are obtained by removing the multi-year average from the original monthly-mean SAT fields. Then the monthly-mean SAT anomalies in the strong negative and positive anomalous NAM years are averaged respectively.

In order to measure the responsive intensity of SAT to upper NAM anomalies, the partial least squares regression (PLSR) method has been used to define a responsive index. The PLSR has more advantages than the normal linear regression as discussed by Stone and Brooks (1990) and Frank and Friedman (1993). The PLSR is suitable for constructing a regression model: 1) when variables are highly correlated, and 2) when the number of samples is less than that of variables. It is useful especially for meteorological research because the meteorological variables nearby are often correlated highly, and in many instances, the number of samples is much less than that of the variables.

The PLSR equations are as below:

$$\begin{aligned} \mathbf{E}_0 &= t_1 \mathbf{p}'_1 + t_2 \mathbf{p}'_2 + \cdots + t_s \mathbf{p}'_s, \\ \mathbf{F}_0 &= t_1 \mathbf{r}'_1 + t_2 \mathbf{r}'_2 + \cdots + t_s \mathbf{r}'_s + \mathbf{F}_s, \end{aligned}$$

where t_i is the principal component (PC), i refers to the step number, \mathbf{p}_i is the loading vector of \mathbf{E}_0 , and \mathbf{r}_i is the projected vector of another field \mathbf{F}_0 onto the PC axis. The symbol “ $'$ ” means transpose.

In our research, the multi-year averages are firstly removed from the monthly mean SAT fields and the NAM indices before the PLSR is performed with these two variable fields. The SAT anomaly field is treated as \mathbf{E}_0 and the NAM index time series is treated as \mathbf{F}_0 . Then we use the PLSR to extract the first PC t_1 from the SAT anomaly field. Here the difference be-

tween the PLSR and the ordinary PC analysis is that the information of the NAM index is also considered in the PLSR, thus the first PC we obtained not only represents the largest variation but also includes the portion that maintains the highest correlation between the NAM anomaly and the SAT. The coupling index is defined as the first PC, which can measure the coupling intensity of the whole SAT field with the NAM anomalies. The coupling mode is defined as the first loading vector of SAT. The mode shows the pattern of the coupling between SAT and NAM.

An example is shown in Fig.2. The latitude range in the mode is from 20° to 90° N in order to emphasize the characters in extratropical regions because the coupling in tropical regions is very weak, although our research covers the whole Northern Hemisphere. The mode shows the spatial distribution of the coupling

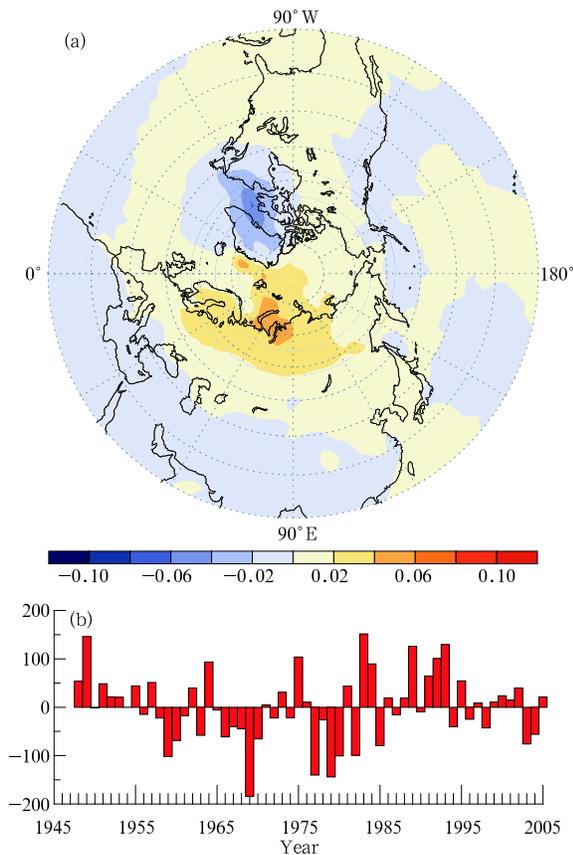


Fig.2. The coupling mode (20° – 90° N) between the January SAT and 1000-hPa NAM anomalies (a) and corresponding coupling index (b).

between the January SAT and the anomalous NAM at 1000-hPa level. There is a negative center at Greenland, and a positive annular belt along middle to high latitudes circles the negative center. The northern Eurasia near the Arctic has a positive response center. Another relatively weak positive response center covers North America. These patterns are consistent with the results in Thompson and Wallace (1998, 2000). This means the mode can demonstrate the patterns of the coupling well. The coupling index is a time series and the value in one particular year stands for the coupling intensity of the whole SAT field with the NAM at 1000 hPa for this year. The product of the mode and the index is the regressed field.

Figure 3 shows the composite analysis results of the regressed fields and the original SAT anomaly fields. The patterns and the coupling amplitude in Fig.3a/3b quite resemble those in Figs.3c/3d. The correlation coefficients between the original fields and the regressed fields are 0.842 in the positive 1000-hPa NAM anomaly years and 0.939 in the negative 1000-hPa NAM anomaly years. These results prove that the regression model using the PLSR is able to capture the coupling/response of SAT to NAM anomaly, both in the coupling/response patterns and in the coupling/response intensity.

3. Results

3.1 The coupling between SAT and NAM in different levels

Previous researches showed that the strongly anomalous NAM is coupled with the SAT. In this section, we emphasize the coupling intensity of SAT with NAM in different levels, especially in the lower stratosphere and the mid-upper troposphere.

The variance curve of the January coupling index is shown in Fig.4. The variance of the coupling index time series represents the averaged coupling intensity. This curve keeps rising from the surface level and arrives at the peak in middle and upper tropospheric levels, then falls in stratosphere levels. That means that the January anomalous NAM in the middle and upper troposphere couples the January SAT more

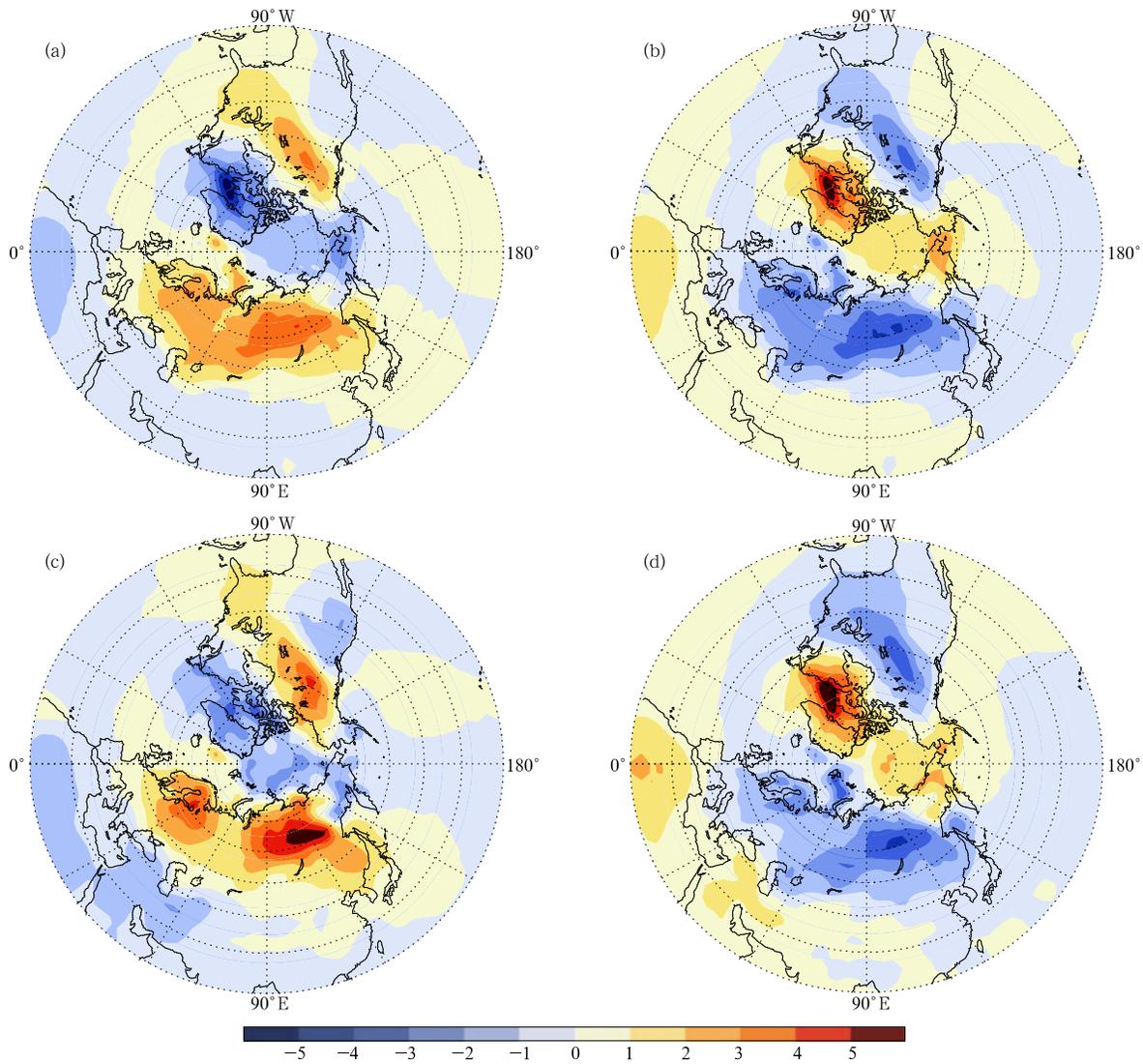


Fig.3. Composite January SAT anomaly distributions (20° – 90° N) for January strong positive/ negative 1000-hPa NAM anomaly years (a,c/b,d) obtained by using the PLSR method (a/b) and the simple average method (c/d).

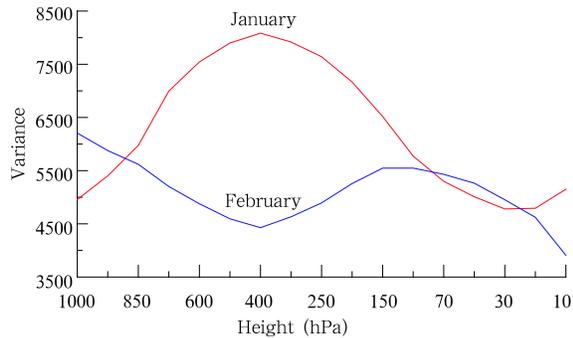


Fig.4. Variance curves of the January (red line) and February (blue line) coupling indices.

strongly than that in the lower troposphere and stratosphere. Specially, we choose the levels of 400 and 30 hPa for a detailed comparison. The averaged January SAT anomaly fields are shown in Figs.5a, b. Figure 5a is for the strong positive anomalous NAM at 30 hPa and Fig.5b is for the strong positive anomalous NAM at 400 hPa. Comparing Figs.5a with 5b, we find that in the Arctic region, the strong decreases of SAT almost cover the whole Arctic in Fig.5b, while only a relative weak and small center covers the north of Greenland in Fig.5a.

But the situation in February is different from

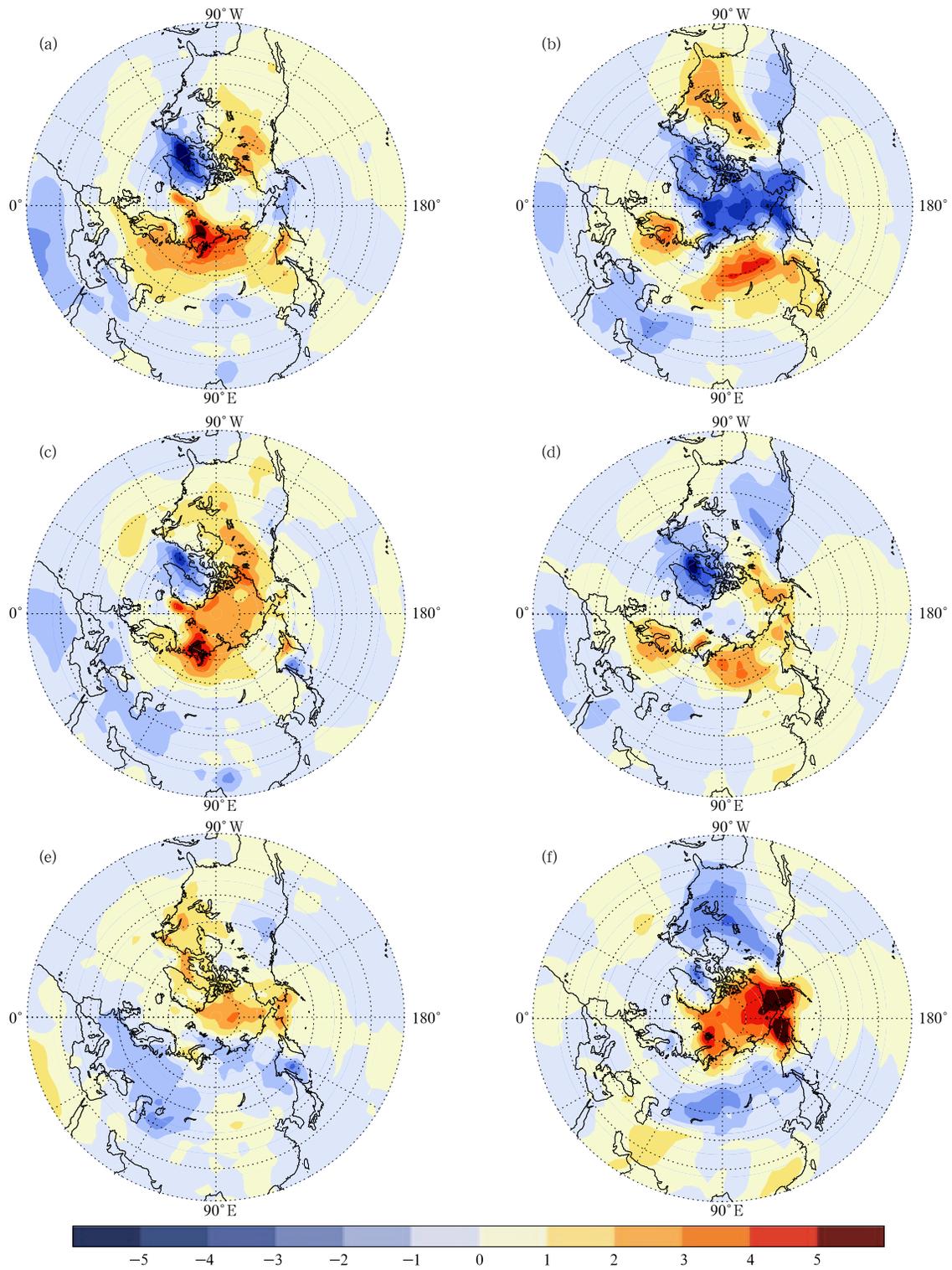


Fig.5. Average January (upper plots; a, b) and February (middle plots; c, d) SAT anomaly fields (20°–90°N) for January strong positive NAM anomaly years for (a, c) 30 hPa/ (b, d) 400 hPa, and (e, f) difference fields of (c) minus (a) or (d) minus (b).

that in January. The curve shows a slow climbing from the middle troposphere to the lower stratosphere, and there is a peak at about 100 hPa. Like Figs.5a, b, Figs.5c, d show also the composite results, but for the February SAT. The SAT changes in the northern Eurasia in Fig.5c are larger than that in Fig.5d. It means that the January anomalous NAM in the lower stratosphere (30 hPa, Fig.5c) couples with the February SAT a little stronger than that in the middle and upper troposphere (400 hPa, Fig.5d).

Comparing the two curves in Fig.4, we can find several interesting features. The variance of the January indices is much larger than that of February in middle and high troposphere. This indicates that the January anomalous NAM in the middle and upper troposphere couples with the January SAT much stronger than the February SAT. The variance for February is a little larger than that for January at some lower stratosphere levels. That means the coupling of the January anomalous NAM in the lower stratosphere with the February SAT is close to or stronger than that with the January SAT.

Baldwin and Dunkerton (1999, 2001) revealed that the strong winter NAM anomalies often appear in the stratosphere and propagate into the troposphere. The propagation needs several weeks in average. That may be the cause of the one-month delay in the influences on the SAT of the stratosphere NAM anomaly.

3.2 Monthly variability of the SAT and NAM coupling

The monthly variability of the SAT anomalies caused by the NAM anomalies in different levels has some common features. As shown in Fig.6, the fluctuations of SAT are large from January to March, reducing sharply in April, keeping very small quantities

during the whole summer and increasing a little from October to the end of the year. This means that the direct and obvious effects of upper large NAM anomalies on SAT can last about two months, and then diminish sharply. The difference between Figs.6a and 6b is that the coupling of SAT with the NAM anomalies in the lower stratosphere levels is a bit bigger in February and March than in January (Fig.6a), while the response to NAM anomalies in the middle and upper troposphere levels is stronger in January than in February and March (Fig.6b).

Not only the coupling intensities but also the patterns exhibit some differences in different months. Because of the monthly variability of the effect from the upper NAM anomalies, some regions may suffer a sharp SAT change, especially from January to February. An example is the Northeast Russia and the adjacent wide ocean region. Unlike some other regions discussed below: the North Eurasia (Thompson and Wallace, 1998, 2000), the Arctic (Rigor et al., 2000), and the North America (Higgins, et al., 2002; Wettstein and Mearns, 2002), this region should be stressed because of the sharply monthly-variability of SAT caused by the upper NAM anomalies. Comparing Figs.5a with 5c and Figs.5b with 5d, we find the upper positive (negative) NAM anomalies can cause the SAT in this region decrease (increase) in January and increase (decrease) in February. Figures 5e, f are the difference fields between January and February. The region emphasized above has larger or at least comparable SAT increases from January to February than the other regions. The SAT responses in this region to the anomalous NAM in other levels are similar from January to February (figure omitted). The January-February displacement of the response location with time causes the rapid SAT change in the region. The

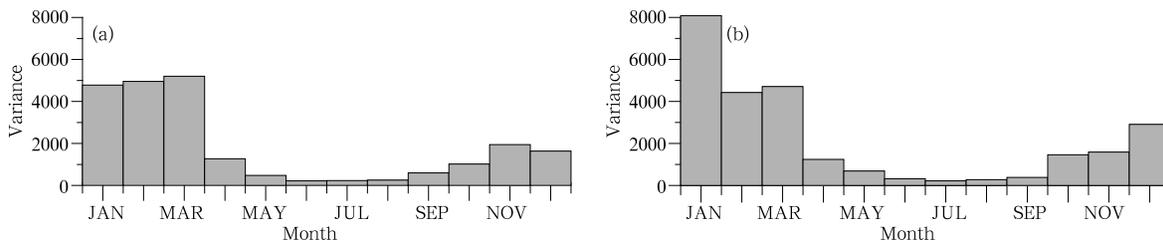


Fig.6. Variances of monthly (a) 30-hPa/ (b) 400-hPa NAM coupling index time series.

positive center in the Eurasia in January extends into the Arctic and covers the Northeast Russia and the Bering Sea till February, and the negative center over the Arctic in January becomes smaller and weaker in February. Though the SAT changes in the Northeast Russia are not so large within each month, the anti-phase with temperature decrease in January and increase in February brings the violent January-to-February variability of SAT. Such a transition also exists in some other regions. Thus, the anomalous NAM can change the variability of short-term climate in certain regions and such changes should draw more attention.

4. Conclusions

An index is used to measure the coupling intensity between SAT and NAM, and it is defined as the first PC of partial least squares regression on SAT anomalies and the NAM index. Using composite analysis and this coupling index, we obtain the following conclusions:

1) The relationship between the SAT and the anomalous NAM differs in different levels. The January anomalous NAM in the middle and upper troposphere couples the January SAT more strongly than that in the lower troposphere and stratosphere, while the January anomalous NAM in lower stratosphere couples February SAT a bit more strongly than that in the middle and upper troposphere.

2) The monthly variability of the coupling between SAT and NAM demonstrates that the middle and upper troposphere NAM couples most strongly with the SAT in January, turns weaker in February and March, then diminishes sharply in April. The coupling between the NAM in the lower stratosphere and the SAT is obvious in January–March and also diminishes sharply in April.

3) Some regions, for example the area near the Bering Sea, suffer a sharp SAT variability because of the displacement of the response region from January to February.

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