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THE COUPLED MODE BETWEEN THE KUROSHIO REGION MARINE HEATING ANOMALY AND THE NORTH PACIFIC ATMOSPHERIC CIRCULATION IN WINTERTIME

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Abstract: Using monthly reanalysis data of the National Center for Environmental Research/National Center for Atmospheric Research (NCEP/NCAR) and Objectively Analyzed Air–Sea Heat Flux (OAFlux) gathered during the winter, singular vector decomposition (SVD) analysis was conducted to reveal the coupled mode between the Kuroshio marine heating anomaly and the geopotential height at 500 hPa (Z500) over the North Pacific. The first SVD mode showed that when the northern Kuroshio marine heating anomaly was positive, the Z500 in the central and western sections of the North Pacific was anomalously low. By composing the meteorological field anomalies in the positive (or negative) years, it has been revealed that while the Aleutian Low deepens (or shallows), the northwesterly wind overlying the Kuroshio strengthens (or weakens) and induces the near-surface air to be cool (or warm). Furthermore, this increases (or decreases) the upward heat flux anomaly and cools (or warms) the sea surface temperature (SST) accordingly. In the vicinity of Kuroshio and its downstream region, the vertical structure of the air temperature along the latitude is baroclinic; however, the geopotential height is equivalently barotropic, which presents a cool trough (or warm ridge) spatial structure. The divergent wind and vertical velocities are introduced to show the anomalous zonal circulation cell. These are characterized by the rising (or descending) air in the central North Pacific, which flows westward and eastward toward the upper troposphere, descends (or rises) in the Kuroshio and in the western section of North America, and then strengthens (or weakens) the mid-latitude zonal cell (MZC).

Key words: Kuroshio; heat flux; atmospheric circulation; coupled mode

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1 INTRODUCTION

The Kuroshio is a strong, warm western boundary current of the subtropical ocean gyre in the North Pacific. In the winter, Kuroshio radiates vast heat flux into the atmosphere, thereby intensifying the transport of atmospheric meridional heat flux. In the mid-latitudinal Kuroshio, instead of the sea surface temperature (SST), the heat flux could substantially represent the ocean heating the atmosphere [1].

There have been many studies on the relationship between the Kuroshio and the atmospheric circulation, as well as its impact on the weather in China. By analyzing the relationship between the air-sea heat exchange in the East China Sea and the entire Kuroshio, Zhao [2] discussed the connection between the precipitation in the midstream and downstream sections of the Yangtze River. Furthermore, Zhao [3] calculated and analyzed the characters of the air-sea exchange in the mid-latitudes of the North Pacific. He likewise detected a strong correlation between the air-sea heat exchange in the mid-latitudinal Kuroshio and the long wave evolution over the North Pacific. Meanwhile, Zhao and McBean [1, 4] demonstrated that the heat flux anomaly in the Kuroshio played an important role in long-term climate variations and that air-sea interaction was a positive feedback in the winter. Moreover, the ocean's heat flux anomaly has important impact on the atmospheric circulation prevailing in the North Pacific which occurs in the latter half of the successive year. Weng et al. [5] identified the reversed long-term trend between the Kuroshio heat transport in the East China Sea in the winter and the precipitation in the Huanghuai Plain during the rainy season. Using the statistical and numerical model methods, Yu et al. [6, 7] analyzed three main regions (including the Kuroshio)

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and studied their impact on the Chinese summer precipitation. Zhang et al. [8] analyzed the relationship of the SST anomaly in the Kuroshio in the spring, along with the occurrence of Chinese summer (June to August) precipitation, Z500, and water vapor transport. Liu et al. [9] compared the output of the FGCM-1.0 and the observations and concluded that on the interannual timescales, strong (weak) Kuroshio transports to the east of Taiwan Island leading to the increasing (decreasing) net heat flux, which is centered over the Kuroshio Extension, by 1–2 months. This is characterized by low (high) pressure anomaly appearing at 500 hPa over the North Pacific (north of 25°N) in the winter. Furthermore, they suggested that the northward heat transport of the Kuroshio is one of the important heat sources to support the warming of the atmosphere by the ocean and the formation of the low pressure anomaly at 500 hPa over the North Pacific in the winter.

Until now, few studies have been made on the coupled patterns between the heat flux anomaly in the Kuroshio and the atmospheric circulation over the North Pacific. In this paper, the singular value decomposition (SVD) method was used to study the anomalous ocean heating of the atmosphere and its coupled relationship with the atmospheric circulation over the North Pacific. Finally, the meteorological field anomalies in the positive and negative years were composed to analyze their respective spatial distributions.

2 DATA AND METHODS

The ocean influences the atmosphere via heat flux, which mainly depends on the latent heat flux (Q_L), sensible heat flux (Q_S), and net upward longwave heat flux (Q_{LW}). The heating of the atmosphere by the ocean can thus be defined as:

$$Q = Q_L + Q_S + Q_{LW}\,. \tag{1}$$

All variables were defined as upward (downward) and positive (negative). The monthly turbulent heat flux of the ocean surface (Q_L and Q_S) used in this study were developed by the OAFlux project [10]. The project's main aim was to develop the global ocean-surface heat flux reanalyzed data, involving many types of data which included satellite observations, sea surface floats, ship, and reanalyzed surface data of the atmospheric numerical model. This project was funded by the NOAA Office of Climate Observations (OCO), and implemented by the WHOI Cooperative Institute for Climate and Ocean Research (CICOR). The horizontal resolution of the monthly-averaged reanalysis was 1°×1°, and the domain of this reanalysis extended from 89.5°S to 89.5°N, covering the period from January 1958 to December 2006. The upward longwave heat flux (Q_{LW}), provided by monthly means reanalysis gathered from the NCEP/NCAR, was approximately 1.904°×1.825° horizontally (T62 Gaussian grid with 192×94 points). In order to match the OAFlux horizontal resolution, the NCEP-NCAR data were bilinearly interpolated into 1°×1°.

Temperature, geopotential height, sea level pressure (hereafter SLP), vertical velocity, stream function, and velocity potential were global monthly-averaged reanalysis [11] from the NCEP/NCAR, ranging from January 1951 to December 2006.

The monthly-averaged SST dataset was the Extended Reconstructed Sea Surface Temperature, version 3 (ERSST.v3) [12]. The data covering the global ocean and its horizontal resolution was identified to be at 2°×2°, ranging from January 1885 to December 2007.

Data from 1958 to 2005, constituting 48 years' equivalent of wintertime data, were used in this study. The annual winter season was defined as beginning from December of the current year being studied until February of the following year.

The SVD method [13] is a useful method to decompose the coupled mode of the two meteorological fields, because it has simple computation and explicit physical significance in coupled signals. Ding and Jiang [14] theoretically proved that the SVD method can be generally applicable in diagnosing the spatiotemporal coupled signals, since it can derive the mutual correlation between two meteorological fields. In this study, the total heat flux in the winter (Defined as formula (1)) and the geopotential height at 500 hPa (hereafter referred to as Z500), were both standardized initially, after which the SVD method was used to calculate the coupled modes. The domain of the Kuroshio spans 15.5°N－32.5°N, 120.5°E－150.5°E [15], while that of the North Pacific spans 10°N－60°N, 100°E－100°W.

3 COUPLED MODES BETWEEN THE KUROSHIO HEAT FLUX ANOMALY AND Z500 OVER THE NORTH PACIFIC IN THE WINTER

The first and second modes of SVD contributed to the total variance by 86.24% and 8.07%, respectively. In contrast, the rest can only explain little variance. Thus only the first two modes were analyzed in this study. Figures 1 and 2 show the spatiotemporal distributions of the first and second modes, respectively.

The first mode (Figs. 1a & 1b) indicates that the Kuroshio heat flux anomaly in the winter and the Z500 anomaly over the North Pacific are closely correlated with each other in the northern Kuroshio and the central and western North Pacific. The physical signal of the coupled mode reflects that when the north Kuroshio (i.e., the southern and southeastern regions of Japan) releases much more heat flux into the atmosphere, the Z500 rises in the central and western North Pacific (i.e., the eastern part of Japan Island). The correlation coefficient of the corresponding two time series (Fig. 1c) is 0.804, which suggests that the leading SVD mode can substantially represent the main coupling features between the Kuroshio marine heating anomaly and the atmospheric circulations.

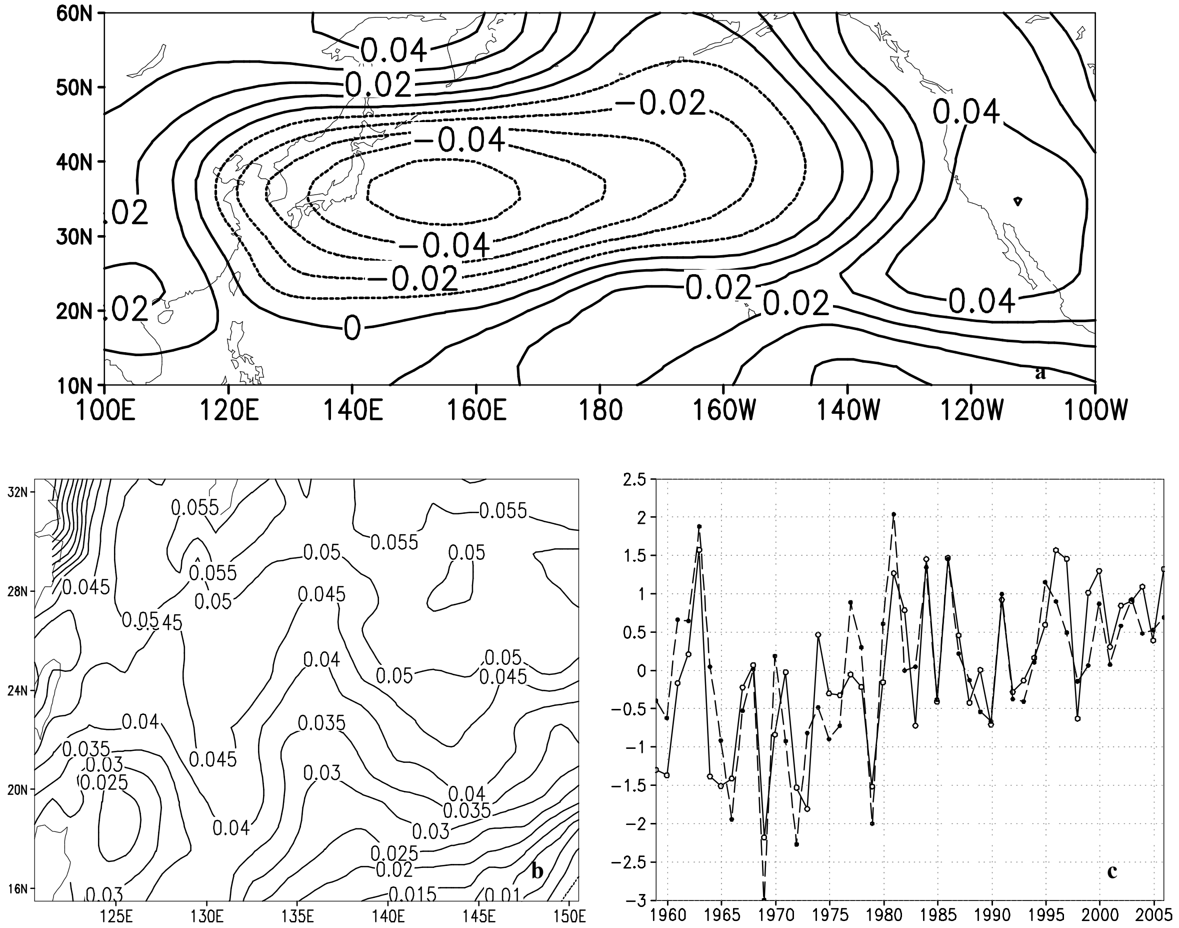


Fig.1 Spatiotemporal distribution of the first SVD mode (a: spatial pattern of the geopotential height at 500 hPa; b: spatial pattern of the heat flux; c: corresponding normalized time series (the solid line and dashed line correspond to the heat flux and Z500, respectively); the correlation coefficient of the two time series is 0.804.

The second mode (Figs. 2a & 2b) indicates the highly correlated regions located in the southern and northeastern Kuroshio and the southern and northern North Pacific. This means that when the southern Kuroshio releases less heat flux into the atmosphere, the geopotential height of the North Pacific would be characterized by taking 35°N as a nodal line to the north (south), which presents the negative (positive) anomaly. The correlation coefficient of the two time series (Fig. 3c) is 0.549.

Given that the leading SVD mode had much more variance than the others, we only analyzed the meteorological field anomalies related with the first mode. The meteorological field anomalies in the positive (negative) years, defined as the corresponding normalized time series larger (smaller) than 0.6 (–0.6), were thus composed to analyze their respective spatial distributions. The positive years were 1962, 1980, 1983, 1985, 1990, 1995, 1999, 2002 and 2005, for a total of nine years. The negative years were 1959, 1964, 1965, 1968, 1971, 1972, 1978 and 1989, for a total of eight years.

4 COMPOSITE METEOROLOGICAL FIELD ANOMALIES IN THE ANOMALY YEARS

The composite meteorological field anomalies in the positive years hold similar spatial distribution to those in the negative years, except for their reversed signs. Therefore, only the composite fields in the positive years are discussed in this paper.

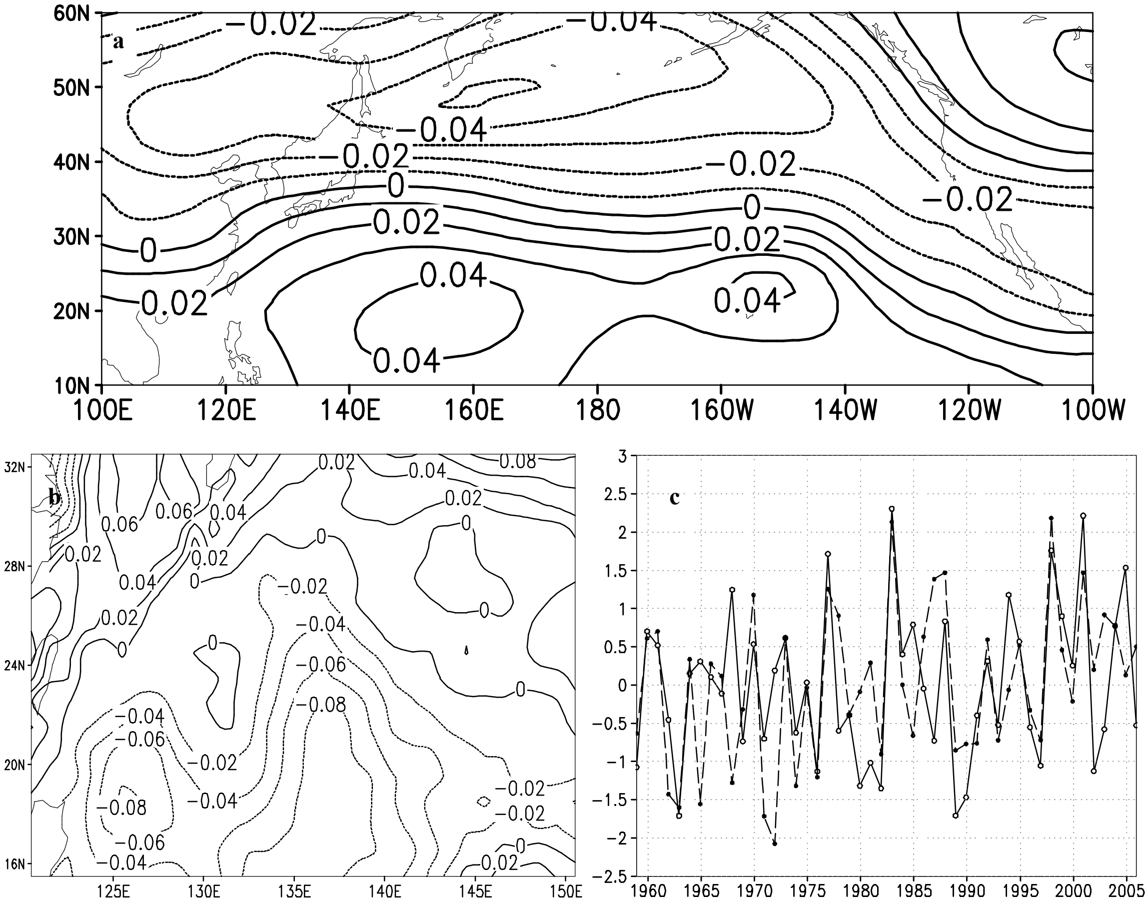


Fig.2 Same as in Fig. 1 but for the second SVD mode. The correlation coefficient of the two time series is 0.549.

4.1 *Composite near-surface field anomalies*

The near-surface field anomalies were first analyzed. For the extra-equatorial regions, the leading physical process is one that the atmosphere forces the ocean [16]. In this study, a significance test was conducted based on the Student's *t*-test. In Fig. 3a, we can see the composite of the SLP anomaly, which shows that, in accordance with the SLP decrease, the Aleutian Low intensifies whereas the SLP in the western Kuroshio and western North America regions increases. Correspondingly, the 10-m winds (Fig. 3b) are cyclonic in the North Pacific, and the central region is located at (40°N, 160°W), northern and southern to this area are the northeasterly and southwesterly flow, respectively. Moreover, there is an intensified northwesterly flow over the Kuroshio. The near-surface air temperature anomaly (Fig. 3c) shows that there is no marked change in the central North Pacific, whereas it becomes warmer over the western North America. From the distribution of the composite SST anomaly (Fig. 3d), it is found that SST rises in the latitudinal region of 30°N, west of 140°W; in contrast, the SST in both the northern and southern regions tends to drop. This pattern resembles a weak North Pacific (NP) mode [17, 18]; furthermore, the second SVD mode manifests the ENSO mode. The NP mode demonstrates the atmospheric intrinsic variance, while the ENSO mode shows the result of the equatorial Pacific's impact on the North Pacific SST through the "atmospheric bridge" process [19, 20]. Nevertheless, the difference in the correlation coefficient of the two modes' Z500 with PNA is marginal at just 0.638 and 0.553, respectively.

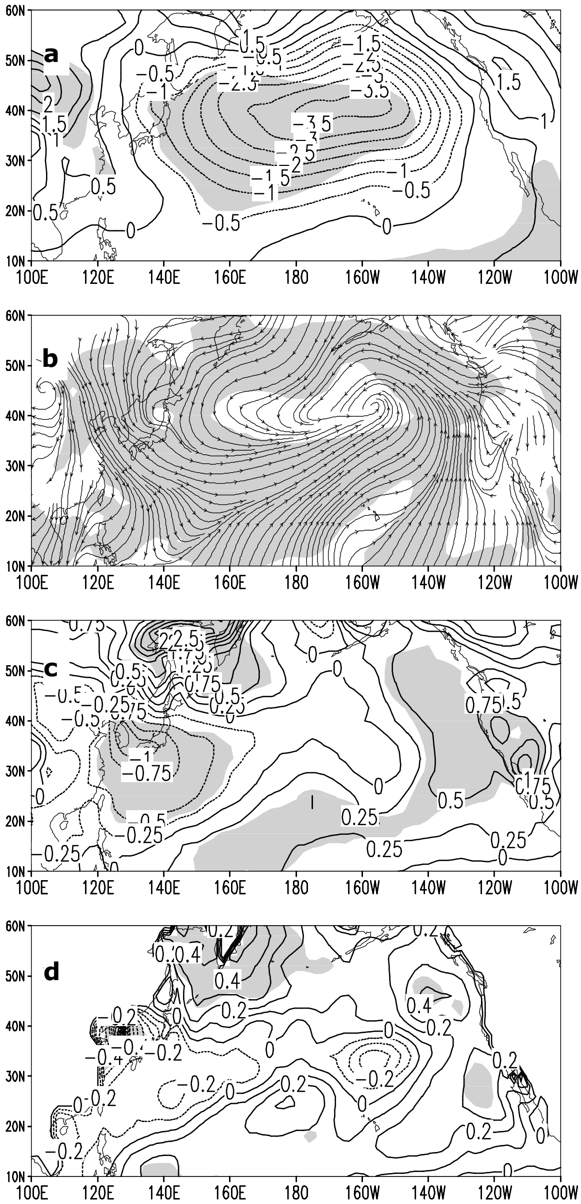


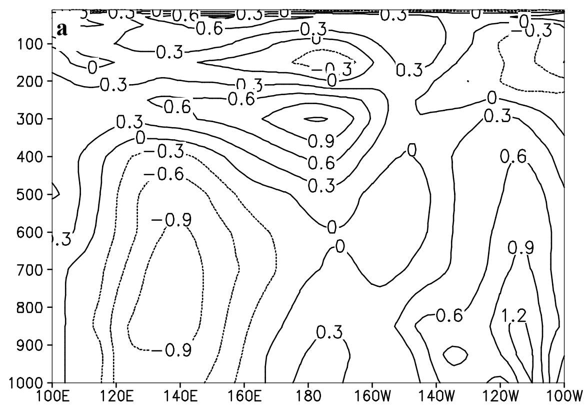
Fig.3 Composite of the meteorological fields anomalies in the positive years. (a: sea level pressure; b: 10-m wind velocity; c: near-surface temperature; d: sea surface temperature. The units are hPa, m/s, K and K, respectively.) Areas exceeding the 95% significance level are shaded.

In fact, we only analyzed the simultaneous interaction of the atmosphere and ocean in this study, instead of the lead-lag regression correlation. It mainly reflects that the atmosphere affects the ocean [21]. In terms of the forcing of atmosphere on the ocean, when the Aleutian Low deepens, that is, when the SLP decreases in the central North Pacific, the wind anomaly exhibits a corresponding cyclonic structure; thus, the northwesterly flow intensifies over the Kuroshio, after which the near-surface temperature becomes cooler owing to the enhanced cold air. Afterwards, more heat flux radiates into the atmosphere before finally resulting in cooler SST. With regard to the heat flux effect on the ocean, the ocean, radiating more intense heat flux to levels upward, causes low pressure in the air, which in turn deepens the Aleutian Low. This enhances the northwesterly flow over the Kuroshio. As the temperature becomes cooler, the heat flux radiates more rapidly, constituting the positive feedback of the atmosphere and heat flux [22]. However, because of the negative feedback between the atmosphere and heat flux [23, 24], the cooler SST causes less radiative heat flux. Consequently the SST becomes warmer, dampening the positive feedback between the atmosphere and ocean to some degree. In the following analysis, the vertical cross-sections along the latitude in the positive years of the temperature and Z500 are compared.

4.2 *Vertical cross-sections along the latitude*

As the height increases, the negative temperature anomaly over the Kuroshio moves northward, resulting in an extended domain. However, in the upper troposphere, the temperature becomes positive anomaly, whereas the potential height exhibits coherent negative anomaly in the whole troposphere over the central and northern sections of the North Pacific (Figures not shown).

Figure 4a shows the vertical section of temperature anomaly along 30°N. From this, we can see that the temperature has a baroclinic structure in the vertical direction. Over the Kuroshio, the temperature is cooler (warmer) below (above) 400 hPa; moreover, the biggest decrease in temperature appears at 850 hPa of the lower troposphere. The temperature is warmer, however, in the lower troposphere in the central and western North Pacific.



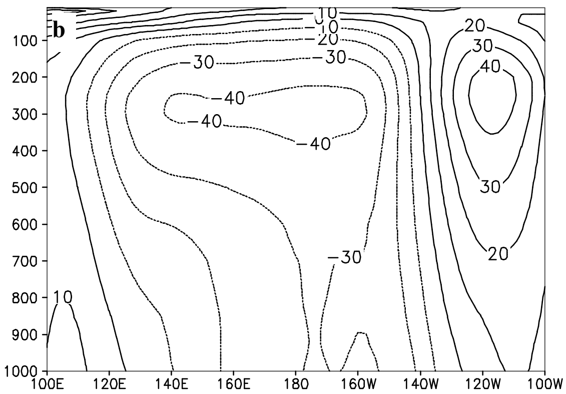


Fig.4 Vertical cross sections along the latitude in the positive years. (a: air temperature along 30°N；b: geopotential height along 40°N. The units are K and m, respectively.)

Meanwhile, the geopotential height anomaly's vertical section along 40°N is seen in Fig. 4b, which reflects an equivalent vertical barotropic structure. The geopotential height decreases consistently over the North Pacific, but increases uniformly in the western North American region where the peak appears at approximately 300 hPa.

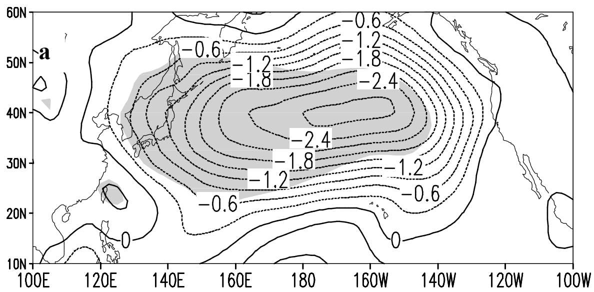
From the figures showing the vertical section of the temperature and geopotential height, we can conclude that a cold low-pressure structure in the positive years lies over the Kuroshio and its downstream. In contrast, there exists a warm high-pressure structure in the negative years, which also reflects the warm-ridge structure [22].

4.3 *Vertical circulation cell*

The NCEP/NCAR monthly-averaged stream function, velocity potential at sigma levels, and vertical velocity at pressure levels were applied to analyze the zonal vertical circulations over the Kuroshio and the North Pacific in the positive years. For stream function and velocity potential, the 0.995 and 0.2582 sigma levels were chosen to represent the lower and higher troposphere, respectively; whereas 850-hPa and 200-hPa pressure levels represent the vertical velocity at the lower and higher troposphere, respectively.

The anomaly of the stream function at the 0.995 sigma level (Fig. 5a) shows that there are negative anomalies in the central and eastern North Pacific, which suggest a cyclonic circulation, whereas the variation in the stream function does not change markedly over the Kuroshio and western North America. At the 0.2582 sigma level, the stream function anomaly (Fig. 5b) is negative in the central North Pacific and its center lies over Japan. Given that stream function is a non-divergent (or rotational) component of the wind velocity, which reflects the geostrophic part of the wind stress, it can be concluded that the anomalous structures agree well with the geopotential height. For instance, the negative geopotential height is in accordance with the cyclonic circulation.

The non-rotational (divergent) component of the wind velocity is a direct index indicating the forcing of the atmosphere on the ocean [25]. Therefore, the non-rotational wind velocity and vertical velocity were used to confirm the atmospheric vertical circulation cell. At the 0.995 sigma level of the lower troposphere (Fig. 5c), there is negative anomaly over the Kuroshio. That its peak center lies on the northern Kuroshio reflects the a corresponding divergent wind to the positive radiative heat flux over the Kuroshio. In addition, the positive velocity potential center is located in the central and eastern Pacific, thereby indicating a convergence. The velocity potential is very small, reflecting that the convergence and divergence are not obvious. In the upper troposphere with a 0.2582 sigma level (Fig. 5d), the trend is opposite to that of the lower layer. This means that the positive velocity function anomaly lies in northern Kuroshio, and that its peak area is located in the area which radiates excessive heat flux. There exists a positive velocity function anomaly in most areas over the North Pacific, except in the central and eastern North Pacific. As we know, the divergence and convergence correspond to descending and ascending air motion, respectively. The vertical velocity anomaly at 850 hPa (Fig. 5e) shows that it descends over the Kuroshio and its peak is located at its northern, western, and northeastern sections as in most places in North America. Reversely, the vertical velocity ascends in most regions of the North Pacific; in fact, at 200 hPa (Fig. 5f), the descending areas over Kuroshio have become broader. The direction of vertical velocity is the same as in the lower troposphere in the central and eastern Pacific and in North America, with either ascending or descending activity, respectively.



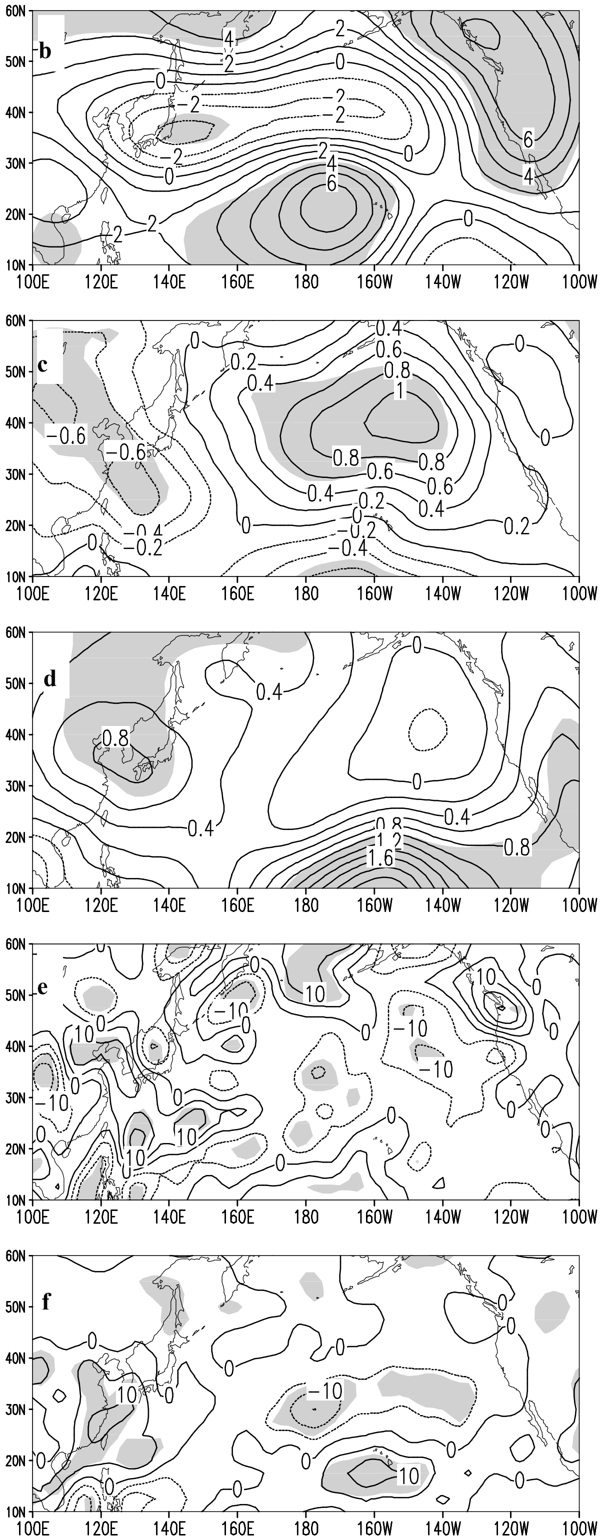


Fig.5 Composite anomalies of meteorological fields in the positive years (a, c: the stream function and velocity potential on the 0.995 sigma level, respectively; b, d: the same as in a, c, but on the 0.2582 sigma level; e, f: the vertical velocity at 850 hPa and 200 hPa, respectively. Stream function and velocity potential are the results with an amplification factor of 10^6. Vertical velocity is the result with an amplification factor of 10^3, with positive and negative values representing the descending and ascending motion, respectively.) Areas exceeding the 95% significance level are shaded.

In light of the non-rotational component of wind velocity and stream function, it could be concluded that a zonal vertical circulation cell exists, characterized by the air ascending (or descending) in the central North Pacific, flowing westward and eastward in the upper troposphere, descending (or ascending) in the Kuroshio and the western section of North America, thus strengthening (or weakening) the mid-latitude zonal cell (MZC) [26].

5 SUMMARIES AND DISCUSSION

Using the SVD method, the coupled modes between the heat flux over the Kuroshio and Z500 in the North Pacific in the winter were studied. Furthermore, the corresponding meteorological anomalous fields in the positive years were analyzed. The summaries are as follows:

(1) The first and second SVD modes dominate the total variances, which represent the main coupled patterns between the Kuroshio heating atmosphere and atmospheric circulation. Particularly, the first SVD mode accounts for most of the total variances, which reflect that, in the northern Kuroshio, much more heat flux radiates into the atmosphere as the geopotential height in the North Pacific decreases. The second SVD mode illustrates that when the southern and northeastern Kuroshio radiate less heat flux, the geopotential height would have a dipole structure, increasing and decreasing in the southern and northern regions of the North Pacific, respectively.

(2) For the first mode, in the positive years, the physical images behave such that the northwesterly wind blows strongly when the Aleutian Low deepens, corresponding to the cyclonic atmospheric circulation. This causes the near-surface temperature to become cooler and much more capable of radiating heat flux; sequentially the SST decreases and vice versa. Given that much more heat flux is radiated, the pressure becomes lower over the ocean, causing the Aleutian Low to intensify and the northwesterly wind to blow strongly. Consequently, the air temperature cools, and the ocean radiates much more heat flux, constituting a positive feedback between the atmosphere and heat flux. However, because of the negative feedback between the heat flux and SST, the positive feedback between the atmosphere and SST is dampened to some degree. Along the zonal vertical section, the temperature is baroclinic over the Kuroshio and its downstream, while the geopotential height is equivalently barotropic, corresponding to cold low pressure.

(3) The composite non-rotational component of wind velocity and vertical velocity anomalies suggest that a zonal circulation cell exists at the mid-latitudes,

characterized by the air ascending (or descending) in the central North Pacific, flowing westward and eastward in the upper troposphere, descending (or ascending) in the Kuroshio and the western regions of North America, thus strengthening (or weakening) the mid-latitude zonal cell (MZC).

In this paper, we studied the coupled patterns between atmospheric circulation and the Kuroshio which radiates much more heat flux into the atmosphere. The anomalous fields related to the first SVD mode were likewise analyzed. At mid-latitudes, because of the strong baroclinic atmosphere and transient eddy perturbation, the extent to which the ocean impacts the atmosphere and whether the atmosphere is able to affect the ocean are some of the issues that need to be addressed in future observational and modeling studies.

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