Seasonal Variation of the Meridional Wind in the Temperate Jet Stream and Its Relationship to the Asian Monsoon*

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ABSTRACT

The features of the temperate jet stream including its location, intensity, structure, seasonal evolution and the relationship with the Asian monsoon are examined by using NCEP/NCAR reanalysis data. It is indicated that the temperate jet stream is prominent and active at 300 hPa in winter over the region from 45°–60°N and west of 120°E. The temperate jet stream is represented by a ridge area of high wind speed and dense stream lines in the monthly or seasonal mean wind field, but it corresponds to an area frequented by a large number of jet cores in the daily wind field and exhibits a distinct boundary that separates itself with the subtropical jet. A comparison of the meridional wind component of the temperate jet stream with that of the subtropical jet shows that the northerly wind in the temperate jet stream is stronger than the southerly component of the subtropical jet, which plays an important role in the temperate jet stream formation and seasonal evolution, and thus the intensity change of the meridional wind component can be used to represent the temperate jet stream's seasonal variation. Analysis of the temperature gradient in the upper troposphere indicates that the temperate jet stream is accompanied by a maximum zonal temperature gradient and a large meridional temperature gradient, leading to a unique jet stream structure and particular seasonal evolution features, which are different from the subtropical jet. The zonal temperature gradient related to the land-sea thermal contrast along the East China coastal lines is responsible for the seasonal evolution of the temperate jet. In addition, there exists a coordinated synchronous change between the movement of the temperate jet and that of the subtropical jet. The seasonal evolution of the meridional wind intensity is closely related to the seasonal shift of the atmospheric circulation in East Asia, the onset of the Asian summer monsoon and the start of Meiyu in the Yangtze and Huaihe River Valleys, and it correlates well with summer and winter rainfall variations in East China. The temperate jet intensity change is earlier than that of the Asian summer monsoon onset and Meiyu, and thus it may be used as a precursor for the prediction of the Asian summer monsoon onset and the beginning of Meiyu.

Key words: temperate jet stream, subtropical jet, Asian summer monsoon, seasonal evolution

1. Introduction

In the upper troposphere and lower stratosphere, there exist two branches of narrow and strong jet streams with large horizontal and vertical wind shears over East Asia, which are referred to as the East Asian subtropical jet and temperate jet (or polar front jet). In winter the southern jet stream extends northeasterly from the southern side of the Tibetan Plateau to the western Pacific, and the northern jet prolongs eastwards from the northern side of the Tibetan Plateau and converges with the southern jet over the western Pacific, then a strongest jet stream is formed there (Cressman, 1981; Sheng et al., 1986; Zou et al., 1990). In company with the seasonal evolution of the upper level jet stream, the atmospheric general circulation over East Asia experiences two abrupt changes in June and October, respectively. Previous studies noticed that the seasonal evolution of the jet stream is closely linked to the monsoon climate in East Asia (Ye and Zhu, 1958; Gao et al., 1962; Ye et al., 1958; Tao et al., 1958). Moreover, the jet stream occupies coincidently the frontal areas in the upper and lower atmosphere, where a lot of disturbances and storms develop, leading to severe weather and climate events, such as heavy rainfall, cold surges (Hoskins and Valdes, 1990; Gao and Tao, 1991; Chang et al., 2002; Hoskins and Hodges, 2002; Ding, 2005; Bengtsson and Hodges, 2006; Ren and Zhang, 2007), and so on. Thus, the upper level jet stream is an important system

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affecting the weather and climate in East Asian monsoon region. It is significant to investigate the seasonal evolution of the upper level jet stream for the weather forecast and climate predication in East Asia.

As the westerly wind prevails along the subtropical jet and the temperate jet, it is difficult to clearly differentiate between the two branches of jet streams geographically by using the monthly or seasonal mean data (Yang et al., 2002; Mao et al., 2007; Ren et al., 2008). Meanwhile, due to the significant transient feature of the temperate jet, there exist apparent changes in the jet intensity and location, leading to an ambiguous mean location of the temperate jet. The temperate jet structure and seasonal evolution as well as its impact on the East Asian weather and climate are still unclear. Previous studies mostly focused on the East Asian subtropical westerly jet. Less attention has been paid to the temperate jet stream so far. The objective of this study is to examine the seasonal evolution features in the intensity and location of the temperate jet stream and its climatic significance, mainly focusing the seasonal variation of the meridional wind in the temperate jet region and its relation to the Asian monsoon.

2. Data

The NCEP/NCAR reanalyzed zonal and meridional wind and temperature data are used in this study (Kalnay et al., 1996). The time period covers 1961–2000. The horizontal resolution of the data is 2.5° (Lat.)×2.5° (Lon.) with 17 levels in the vertical direction. The daily data are converted to monthly (seasonal) mean or pentad mean. The observational precipitation data at 714 stations provided by the National Meteorological Information Center are also used in this study.

3. The structure of the temperate jet stream over East Asia

3.1 Horizontal structure

The NCEP/NCAR reanalyzed stream line and wind speed at 300 hPa in winter (December, January, and February) and summer (June, July, and August) are shown in Fig.1. There exists a region with dense stream lines near 20°–40°N in winter, with wind speed larger than 30 m s^{-1}, which is the location of the East Asian subtropical westerly jet. The belt of strong wind larger than 30 m s^{-1} is narrow to the west of 110°E and broad to the east of 110°E. The strongest wind center is located over the ocean to the southeast of Japan. There is another area with dense stream lines near 45°–60°N, though there is no strong wind center, the stream lines are dense and a ridge of high wind speed extends to this region, which corresponds to the location of the temperate jet. The stream lines in this region are northwest-southeast oriented, indicating that the meridional wind component plays an important role in the formation of the temperate jet. In summer the dense stream lines are mainly located near 30°–45°N, and the strongest wind is situated over the northern side of the Tibetan Plateau near 40°N, corresponding to the subtropical westerly jet. The zonally oriented stream lines demonstrate that the zonal wind is dominant in this region. However, dense stream

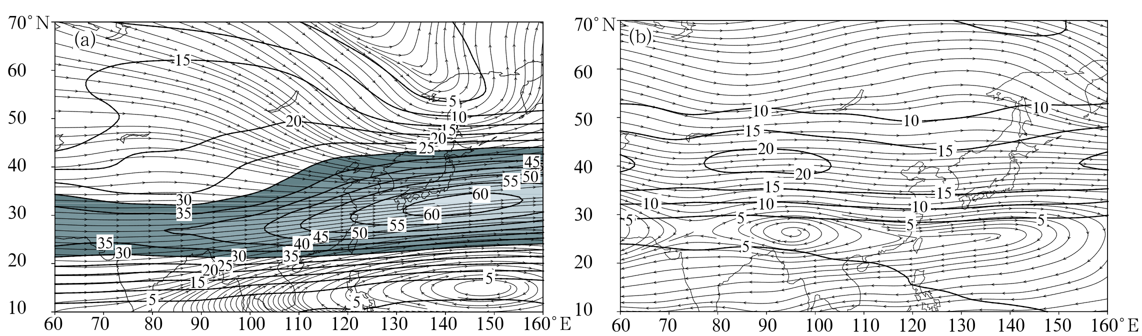

Fig.1. Horizontal wind speed and streamlines at 300 hPa in winter (a) and summer (b). The areas with wind speed larger than 30 m s^{-1} are shaded.

lines and high wind speed do not show up to the north of the subtropical westerly jet this time, suggesting that the temperate jet is weak in summer, and it is difficult to identify in summer the temperate jet from the climatic mean.

To analyze the horizontal structure of the upper level temperate jet stream, the occurrence numbers of the jet stream at 300 hPa in winter and summer are calculated. The methodology used in this study is the same as Ren et al. (2008). The statistic calculation is performed to identify the maximum wind speed centers over the region of 20°–70°N, 60°–160°E. If the identified center satisfies: (1) The central wind speed is larger than 30 m s^{-1}; (2) the wind speed at 8 grid points around the central point is less than that at the central point, then this central point location is defined as a jet center. This calculation is performed using the daily wind data in winter and summer, respectively, and the occurrence numbers of the jet stream at 300 hPa are obtained. Figure 2 shows the jet occurrence numbers at 300 hPa in winter and summer. It is seen that there exist two regions with large jet occurrence numbers over East Asia in winter, one extends from the southern side of the Tibetan Plateau to the ocean over Japan, corresponding to the climatic mean location of the subtropical westerly jet, and the other is located over the region of 45°–60°N, 80°–110°E, the climatic mean location of the temperate jet. In addition, the subtropical westerly jet occurs more frequently than the temperate jet. The northern side of the Tibetan Plateau is frequented the least by the jet stream, thus, this region serves as a dividing zone that separates the temperate jet from the subtropical jet. In summer, the jet stream occurs most frequently along 40°N, corresponding to the summer mean subtropical jet location, whereas the jet stream occurs less frequently in the region of 45°–60°N, only sporadically along 60°N.

3.2 Vertical structure

The above analysis shows that the temperate jet stream prevails over the region of 45°–60°N in winter and the meridional wind component might play an important role in the formation of the temperate jet stream. A cross section of zonal wind along the longitudes of the temperate jet region indicates that the maximum zonal wind speed is located at the same longitude as that of the subtropical westerly jet (figure omitted), and thus only zonal wind cannot represent the temperate jet stream well. In this study, the longitude-height cross section of the meridional wind averaged between 45° and 60°N is used to examine the vertical structure of the temperate jet in winter, as shown in Fig.3a. The northerly wind prevails in the troposphere and lower stratosphere in winter over East Asia, the maximum northerly wind with a value of 11 m s^{-1} occurs at 300 hPa near 110°E, whereas the southerly wind only occurs in the lower troposphere. To analyze the meridional vertical structure of the temperate jet, Fig.3b shows the latitude-height cross section of the meridional wind averaged along 95°–115°E. It is seen that there exist two maximum meridional wind centers over East Asia: one is located to the south of 25°N, where the southerly wind prevails with a maximum southerly wind speed occurring at 200 hPa; the other is situated near 50°N, where the northerly wind prevails with a maximum northerly wind speed occurring at 300 hPa. The transition of

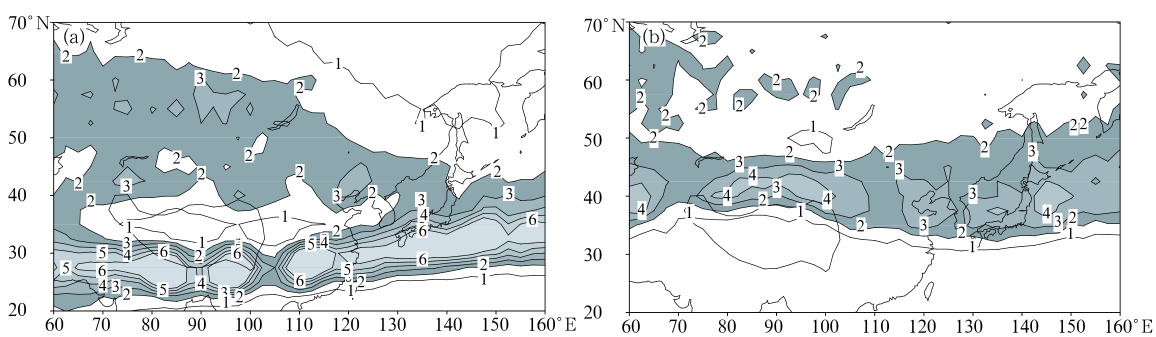

Fig.2. Jet occurrence numbers at 300 hPa in winter (a) and summer (b).

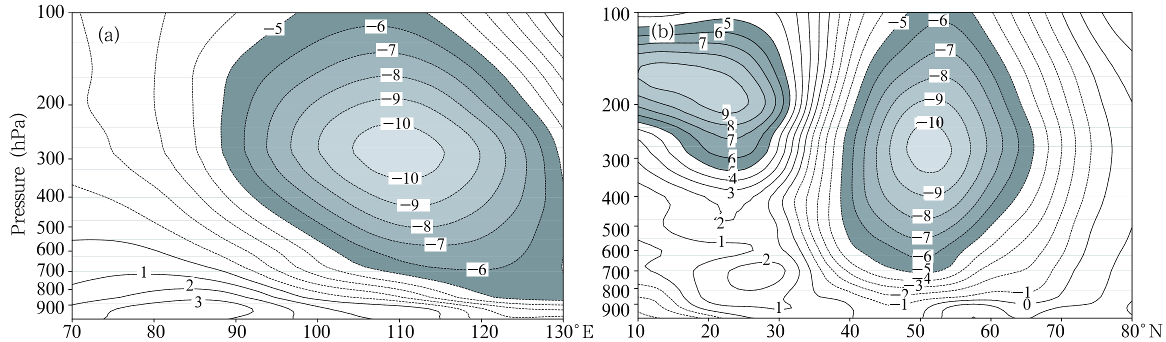

Fig.3. Height-longitude cross section of the meridional wind averaged between 45° and 60°N (a) and height-latitude cross section of the meridional wind averaged along 95°–115°E (b) in winter. The areas with wind speed larger than 5 m s^{-1} are shaded.

wind direction from southerly in low latitudes to northerly in high latitudes occurs near 35°N, where the least jet occurrence is seen previously, corresponding to the dividing line of the two branches of jet streams. Along the southern side of the subtropical jet stream, there exists a southerly wind belt, although the zonal wind is dominant in the subtropical jet, this southerly wind also has a contribution to the strong wind formation to the southern side of the subtropical jet stream. Moreover, the strong northerly wind near 50°N at 300 hPa is located at the temperate jet region, the height of the temperate jet is lower than that of the subtropical jet, and the northerly wind in the temperate jet is stronger than the southerly wind in the subtropical jet. Therefore, the meridional wind component is important for the formation and seasonal evolution of the temperate jet stream, and the meridional wind is useful for analyzing the structure and its seasonal variation. As for the structure of the upper level jet in summer, only the stronger subtropical jet along 40°N can be seen from the latitude- and longitude-height cross sections of the wind field, the temperate jet structure is not evident in the wind field (figure omitted).

4. Seasonal variation of the meridional wind in the temperate jet and its relation to the zonal temperature gradient

4.1 Seasonal evolution of the meridional wind in the temperate jet

Analyses of the horizontal and vertical structures of the meridional wind indicate that the seasonal variation of the location and intensity of the meridional wind in the region of 45°–60°N, 95°–115°E at 300 hPa in winter is associated with the temperate jet. This study focuses on the seasonal evolution of the meridional wind in this region. The latitude-time evolution of the meridional wind averaged from 95° to 115°E at 300 hPa is shown in Fig.4a. The northerly wind prevails along 32°–75°N before the 36th pentad, and the northerly wind larger than 5 m s^{-1} is steady before the 26th pentad, then weakens rapidly after the 26th pentad, and changes to weak southerly wind till the 36th pentad. After the 50th pentad, the northerly wind prevails again and intensifies gradually, until the strongest northerly wind occurs at the 70th pentad. The longitude-time evolution of the meridional wind averaged from 45° to 60°N at 300 hPa (Fig.4b) shows that the northerly wind prevails in the region of 80°–130°E before the 36th pentad, and the northerly wind with a value of 5 m s^{-1} in the region of 110°–130°E weakens first from the 20th pentad, whereas the northerly wind in the region of 100°–110°E maintains a speed of 5 m s^{-1}, then weakens rapidly after the 26th pentad till changes to weak southerly wind around the 36th pentad. After the 50th pentad, the northerly wind prevails again and strengthens gradually. Thus it can be seen that the seasonal evolution of the meridional wind in the region of 45°–60°N, 95°–115°E at 300 hPa represents the seasonal variation of the temperate jet, and the seasonal transition of the meridional wind is closely related to the seasonal transition of the general circulation over East Asia.

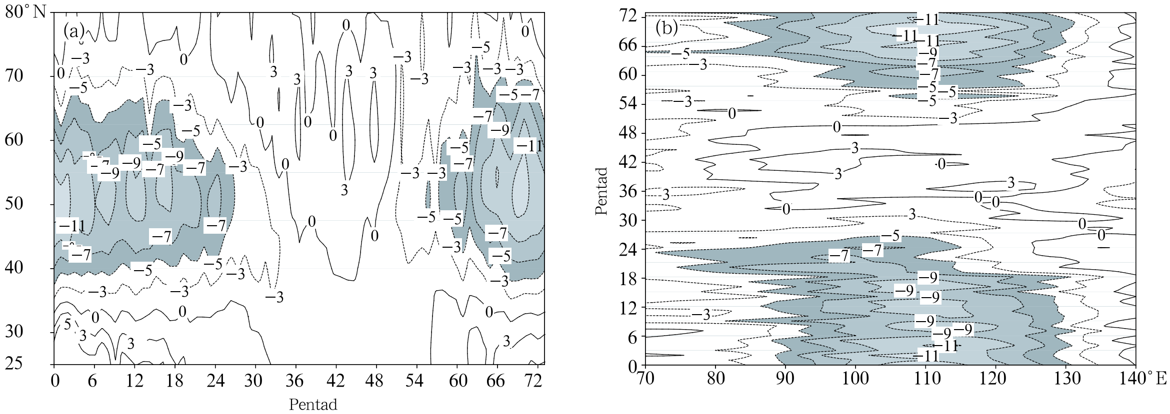

Fig.4. Latitude-time section of the meridional wind averaged along 95°–115°E (a) and longitude-time section of the meridional wind averaged between 45° and 60°N (b). The areas with wind speed larger than 5 m s^{-1} are shaded.

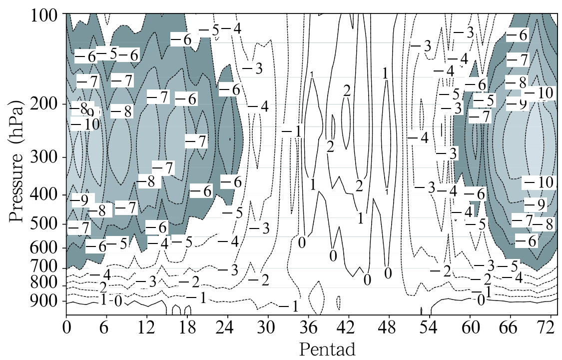

Fig.5. Height-time section of the meridional wind averaged over 45°–60°N, 95°–115°E. The areas with wind speed larger than 5 m s^{-1} are shaded.

To analyze the seasonal evolution of the meridional wind at different heights in the temperate jet region, the height-time variation of the meridional wind in the region of 45°–60°N, 95°–115°E is shown in Fig.5. It is seen that the northerly wind prevails from 900 to 100 hPa before the 36th pentad, and the strongest northerly wind occurs near 300 hPa. After the 36th pentad, the northerly wind changes to the southerly wind, then changes to northerly wind again after the 50th pentad and intensifies gradually, reaching a value of larger than 5 m s^{-1}. Therefore, the seasonal evolution features of the meridional wind in the temperate jet region are consistent at different levels.

4.2 Relationship between the meridional wind and the zonal temperature gradient

Based on the thermal wind principle, the change of the meridional wind with height is related to the zonal temperature gradient. Figure 6 shows meridional wind at 300 hPa and the zonal temperature gradient distribution averaged from 300 to 850 hPa in winter, in which the zonal temperature gradient is calculated by using the air temperature in the east minus that in the west with 2.5° latitude interval, and thus the positive zonal temperature gradient means the atmosphere is relatively warmer in the east and colder in the west. It is noted from Fig.6 that the maximum meridional wind at 300 hPa is located in the region of 40°–60°N, 90°–130°E, corresponding to the temperate jet, whereas the southerly wind occurs from Southwest China to the ocean over South Japan. This pattern of the meridional wind distribution at 300 hPa over East Asia represents the East Asian trough, where the northerly wind and southerly wind occur behind and in front of the trough, respectively. Thus the intensity

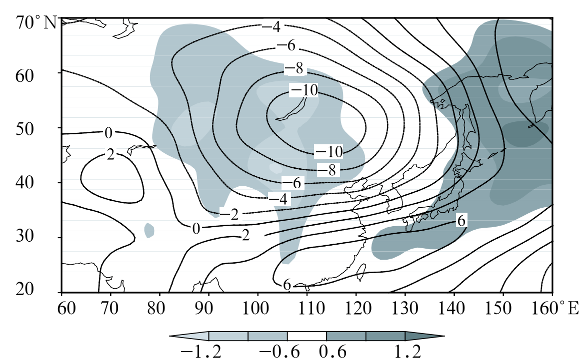

Fig.6. Meridional wind (isoline) at 300 hPa and zonal temperature gradient averaged from 300 to 850 hPa in winter (shaded).

change of the meridional wind in the temperate jet region is probably related to the East Asian trough and winter monsoon. The temperature gradient distribution in Fig.6 shows that the maximum zonal temperature gradient is located over the lake of Baikal, where is relatively warmer in the west and colder in the east, and the maximum temperature gradient matches well with the maximum meridional wind. Over the ocean, a positive temperature gradient occurs, which means warmer air in the east and colder air in the west, leading to a wind direction change from northerly to southerly. The temperature gradient changes along the coastal lines. Therefore, the zonal temperature gradient distribution pattern averaged from 300 to 850 hPa in winter represents the longitudinal land-sea thermal contrast, and the meridional wind and the temperate jet over East Asia are associated with the zonal temperature gradient resulted from the longitudinal land-sea thermal contrast. In addition, the temperature advection near the East Asian trough is also related to this temperature gradient distribution.

To analyze the seasonal variation of the zonal temperature gradient, the latitude-time evolution of the zonal temperature gradient averaged along 95°–115°E is shown in Fig.7. The seasonal variation of the zonal temperature gradient in the region of 45°–60°N is evident. The temperature gradient is negative before the 30th pentad, and then changes to positive, after the 50th pentad changes to negative again. Strong temperature gradient maintains during winter half year. The seasonal variation of the temperature gradient in the latitudinal belt of 45°–60°N matches with the seasonal variation of the meridional wind in the temperate jet region, and the seasonal transition of the temperature gradient and the meridional wind is consistent in time. Moreover, large zonal temperature gradient occurs in the latitudinal belt of 30°–40°N during the period of 30th–56th pentad, which corresponds to the subtropical jet. Analysis of the East Asian subtropical jet and the meridional temperature gradient near the upper level jet indicates that the subtropical jet axis accompanies the maximum meridional temperature gradient, and the south-north displacement of the jet axis matches well with the movement of the meridional temperature gradient (Kuang and Zhang, 2005, 2006; Zhang et al., 2006, 2008). A comparison of the zonal temperature gradient and its seasonal evolution in the temperate jet region with the meridional temperature gradient shows that the maximum zonal and large meridional temperature gradients occur in the temperate jet region. Thus the temperate jet is located in a specific region with maximum zonal and considerable meridional temperature gradients; as a result, the structure and the seasonal variation of the temperate jet are different from that of the subtropical jet.

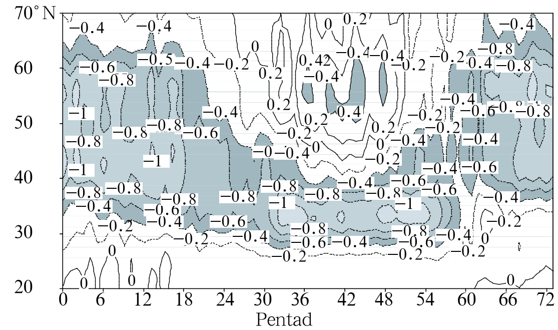

Fig.7. Latitude-time section of zonal temperature gradient along 95°–115°E averaged from 300 to 850 hPa. The areas with temperature gradient larger than 0.4°C are shaded.

5. Possible relationship between the meridional wind in the temperate jet and the Asian monsoon

5.1 Correlation between the meridional wind and precipitation in China

Previous studies about the relationship between the upper level jet and the East Asian monsoon mainly focused on the East Asian subtropical westerly jet, and less attention has been paid to the relationship between the meridional wind in the temperate jet region and the East Asian monsoon. The above analyses show that there exist obvious seasonal variations of the meridional wind and the temperate jet stream. To examine the relationship between the meridional wind in the temperate jet region and the East Asian monsoon, the correlation between the meridional wind intensity in the temperate jet region and the precipitation in winter and summer over China are analyzed below. The 300-hPa meridional wind averaged over the region of 45°–60°N, 95°–115°E is used to calculate the correlation coefficient with the precipitation in winter and summer over China. The correlation coefficient distribution is shown in Fig.8. It is seen that there exists a region with significant positive correlation between the meridional wind in the temperate jet and the winter precipitation to the east of 105°E from the southern part of North China to the south of the Yangtze River Valley. This positive correlation suggests that more precipitation occurs in eastern China when the meridional wind in the temperate jet region is strong. The correlation between the meridional wind in the temperate jet region and the summer precipitation indicates that there exists a region with significant positive correlation in the Great Bend of the Yellow River and North China, and to the west of 105°E there exist a few scattered negative correlation centers. Since the intensity of the meridional wind in the temperate jet region is associated with the cold air activity in the high latitudes and the East Asian trough, these correlations between the meridional wind in the temperate jet region and the winter and summer precipitation represent the relationship between the precipitation and the cold air activity in the high latitudes and the East Asian trough.

5.2 Coordinated variation of the meridional wind with the subtropical jet and its relation to the Asian monsoon onset

It is well known that the location change of the subtropical westerly jet is closely related to the seasonal transition of the East Asian atmospheric circulation, the Asian monsoon onset, and the beginning and end of Meiyu (Ye et al., 1958; Tao et al., 1958; Li et al., 2004; Lu, 2004). Being a part of the entire upper level jet system in East Asia, the temperate jet inevitably changes in coordination with the subtropical jet, and its seasonal evolution is also associated with the Asian monsoon onset and Meiyu. We identified that it is near the 30th (59.1th) pentad when the meridional wind at 300 hPa is below (above) 5 m s^{-1} in the region of 45°–60°N, 95°–115°E, and it is near the 30.6th and 31.5th (58.9th and 59.4th) pentad respectively when the subtropical westerly jet at 200 hPa jumps northward (southward) to the north (south) of 35°N with its axis along 90°E over the Tibetan Plateau and 100°–120°E over the eastern China. This shows that the weakening (intensifying) of the meridional wind in the temperate jet region is consistent with the northward jump (southward retreat) of the subtropical westerly jet. The jump (retreat) of the westerly jet axis over the Tibetan Plateau is one pentad earlier than that over the eastern China. Therefore, the meridional

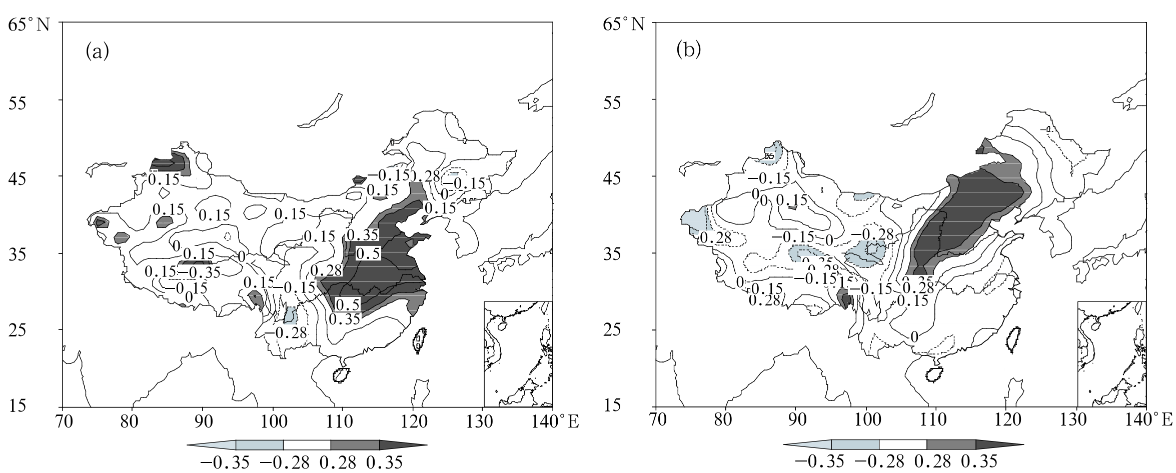

Fig.8. Correlation coefficient distribution between the meridional wind averaged over 45°–60°N, 95°–115°E, and China precipitation in winter (a) and summer (b). Significance exceeding 95% is shaded.

wind intensity in the temperate jet region changes seasonally in coordination with the subtropical jet movement, signifying the establishment of the summer (or winter) general circulation. To analyze the connection between the Asian monsoon onset and the coordinated variation of the meridional wind in the temperate jet and the subtropical jet, we compare the dates during 1980–2000 for the monsoon onset (taken from Li et al. (2004)), the start and end of Meiyu (observed in Nanjing Meteorological Station), and the time when the meridional wind at 300 hPa becomes less than 5 m s^{-1} in the region of 45°–60°N, 95°–115°E. The climatic mean date for the meridional wind weakening to less than 5 m s^{-1} is about the 30.3th pentad, which is one pentad earlier than that of the South Asian monsoon onset, 4 pentads earlier than that of the Meiyu beginning. Thus the change of the meridional wind intensity in the temperate jet is associated with the Asian monsoon onset and Meiyu beginning in the Yangtze-Huaihe River Valley. The meridional wind intensity change in the temperate jet is earlier than the Asian monsoon onset and Meiyu beginning; as a result, it can be used as a precursor for predicting the Asian monsoon onset and Meiyu beginning.

6. Conclusions

The features of the temperate jet stream including its location, intensity, structure, seasonal evolution and its relationship to the Asian monsoon are examined by using NCEP/NCAR reanalysis data in this study. Main conclusions are as follows:

(1) Evident and active at 300 hPa in winter over the region from 45°–60°N and west of 120°E, the temperate jet stream is represented by a ridge area of high wind speed and dense stream lines in the monthly or seasonal mean wind field, but corresponds to an area frequented by a large number of jet cores in the daily wind field. It exhibits a distinct boundary over the northern Tibetan Plateau that separates itself from the subtropical jet. The northerly wind component in the temperate jet is stronger than the southerly component in the subtropical jet region. The meridional wind plays an important role in the formation and seasonal evolution of the temperate jet. The intensity change of the meridional wind component can be used to represent the seasonal variation of the temperate jet.

(2) The temperate jet stream is accompanied by a maximum zonal temperature gradient in the upper troposphere; meanwhile, there also exists a large meridional temperature gradient in the temperate jet region, leading to a unique structure and particular seasonal variation features. The zonal temperature gradient related to the land-sea thermal contrast along the East China coastal lines is responsible for the seasonal evolution of the temperate jet.

(3) There exists a region with a significant positive correlation between the meridional wind in the temperate jet region and the winter precipitation to the east of 105°E from the southern part of North China to the south of the Yangtze River Valley. This positive correlation suggests that more precipitation occurs in the eastern China when the meridional wind in the temperate jet is strong. The correlation between the meridional wind in the temperate jet and the summer precipitation is significantly positive in the Great Bend of the Yellow River and North China. In addition, there exists a coordinated synchronous relation between the movement of the temperate jet and that of the subtropical jet. The seasonal evolution of the meridional wind intensity is closely related to the Asian summer monsoon onset and Meiyu in the Yangtze and Huaihe River Valleys. The time of the temperate jet intensity change is earlier than that of the Asian summer monsoon onset and Meiyu initiation, and therefore it can be considered as a precursor for the prediction of the Asian summer monsoon onset and Meiyu beginning.

This study examines the features of the temperate jet stream including its location, intensity, structure, seasonal evolution and its relationship to the Asian monsoon. The results obtained are preliminary. The mechanisms of the coordinated changes between the temperate jet and the subtropical jet, and the possible reason of its association with the Asian monsoon onset and the Meiyu beginning are worthy of a further study. Further work on the relationship between the temperate jet and the East Asian trough, as well as the East Asian winter monsoon is also needed. Importantly, the role of the temperate jet in the weather and climate change in East Asia remains to be examined by future investigations.

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