RESEARCH ARTICLE

Correlation between meridional migration of the East Asian jet stream and tropical convection over Indonesia in winter

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Abstract: The relationship between tropical convective activities and meridional (north-south) migration of the East Asian jet stream (EAJS) in winter (December-February) is investigated for improving our knowledge of processes affecting the meridional migration of the EAJS. The monthly mean fields of outgoing longwave radiation (OLR) produced by NCAR and monthly atmospheric circulations produced by the NCEP/NCAR are used in this study. For 31 winter seasons between 1980 and 2011, the meridional migration of the winter EAJS is found to be strongly correlated with the present and preceding conditions of tropical convection over Indonesia. The anomalies in the tropical convection over the region in the preceding autumn and even preceding summer are a very useful indicator for the abnormal meridional migration of the wintertime EAJS. When the tropical convection over Indonesia weakens (strengthens), the EAJS has an abnormal southward (northward) migration. The atmospheric circulation associated with the abnormal meridional migration of the EAJS features abnormal air temperatures over the EAJS and its south side. The center of abnormal air temperatures occurs over the region south of the Yangtze River. Abnormal air pressures generated by abnormal air temperatures lead to abnormal winds. In the case of weakened tropical convection (positive OLR anomaly) over Indonesia, ascending motion of air mass over Indonesia is reduced, and the strength of Hadley circulation is weakened over the meridional range of the western Pacific Ocean. Consequently, the high-level air mass to the south of the core of the EAJS abnormally ascends and cools and the nearly southerly divergent winds at high-altitudes weaken, leading to significant reduction of heat transport from tropics to the southern China, with negative anomalies of air temperatures in the EAJS and its south side. The above processes increase thermal winds to the south of the Yangtze River and enhance the high-level westerly winds. To the north of the Yangtze River, both thermal winds and the high-level westerly winds are reduced. As a result, the EAJS has an abnormal south migration. In the case of enhanced tropical convection (negative OLR anomaly) over Indonesia, the opposite happens, in which Hadley circulation strengthens, the air mass to the south of the core of the EAJS abnormally descends and warms, heat transport increases from tropics to the southern China with positive air temperatures anomalies over the EAJS and its south side, and the EAJS has an abnormal northward migration.

Keywords: East Asian jet stream, meridional migration, tropical convection, Indonesia, Hadley circulation, temperature anomaly

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Received: January 25, 2017; Accepted: March 31, 2017; Published Online: April 20, 2017

Citation: Hui Yang, Yuanfa Gong and Gui-Ying Yang, (2017). Correlation between meridional migration of the East Asian jet stream and tropical convection over Indonesia in winter. *Satellite Oceanography and Meteorology*, vol.2(1): 60–74. http://dx.doi.org/10.18063/SOM.2017.01.006.

1. Introduction

Jet streams are referred to as narrow but intense westerly currents located nearly at altitudes of the upper troposphere and the lower stratosphere. The intense westerly currents wander from west to east around the entire globe with the horizontal width of a few hundred kilometers and vertical thickness of a few kilometers. Jet streams may merge into one stream or split into two parts. When the maximum wind speeds are less than 30 m/s, however, the westerly currents are no longer called the jet stream. At the cores of jet streams, the westerly winds are highly variable in time and space, with one or more centers of maximum wind speeds.

The East Asian jet stream (EAJS) is the strongest jet stream with its center to the south of Japan. The maximum speed of the EAJS in winter can reach 150–180 m/s and up to 200 m/s. The EAJS impacts significantly on weather and climate in many countries in East Asia, including China. The seasonal transition of the atmospheric circulation in East Asia and the beginning and end of rainy seasons over most parts of China were found to be strongly correlated with meridional (north–south) migrations and changes in strengths of the EAJS. Ye *et al.* (1958) demonstrated that the season changes in Asia are strongly correlated with abrupt changes in the atmospheric circulation in June and October. One of abrupt changes in the atmospheric circulation is dynamic processes associated with the meridional migration of the EAJS. Tao *et al.* (1958) pointed out that the beginning and end of rainy seasons (known as Meiyu) in East Asia are closely related to processes associated with the two northward migrations of the EAJS. Previous studies also demonstrated that changes in strengths and positions of the EAJS in summer lead to significant anomalies of monsoon winds and rainfalls in China (Sun, 1994; Liao *et al*, 2004; Lin and Lu, 2005; Zi *et al*, 2015). The concurrent variations between the East Asian polar front and subtropical jets at high-altitudes were found to play a very important role to processes responsible for the rainy season in the southern China (Li and Zhang, 2014) and frequencies of continuous precipitations in spring (Huang *et al*, 2015). The winter EAJS was suggested to be a more useful index than the El Niño-Southern Oscillation (ENSO) for predicting climate variability in Asia and the Pacific Ocean on interannual time scales. Yang *et al.* (2002) demonstrated that a strong EAJS is a very useful indicator for an intensification of the weather and climate systems in Asia and over the Pacific Ocean such as deepening of the East Asian trough and the Aleutian low and strengthening of the East Asian winter monsoon. An abnormally intensified EAJS is also a very useful indicator for colder and drier conditions in East Asia and stronger convection over the tropical Asia-Australia, and larger anomalies of temperature and precipitation in North America due to related changes in stationary wave patterns (Yang *et al*, 2002). The concurrent variations between the East Asian polar front and subtropical jets were found to correlate strongly with winter cold air activity in China (Ye and Zhang, 2014), and also reflect the atmospheric anomalous signals linked to extreme weather events over East Asia, such as the persistent snowstorm period in 2007/2008 winter over the southern China (Liao and Zhang, 2013; Nie *et al*, 2016). Liang *et al.* (1998) suggested that a southward migration of the EAJS can cause precipitation to increase in areas south of the Yangzi River (the southern China) during June–August (January–March). Conversely, a northward migration of the EAJS in summer (winter) can bring heavier precipitation over the northern China (the Yangzi-Huaihe River Basin). Mao *et al.* (2007) demonstrated that the intensity and meridional migration of the EAJS in winter is strongly correlated with the air temperature and precipitation in China. They found that, in particular, the precipitation in the northern China is affected by the EAJS intensity, and the precipitation in the southern China is affected by the meridional migration of the EAJS. Previous studies also demonstrated that the East Asian winter monsoon is strongly correlated with the intensity of the EAJS, but not with the meridional migration of the Stream. This suggests, therefore, that the intensity and meridional migration of the EAJS do not have the same effects on the climate over eastern China.

Physically, a subtropical jet stream is a response of the atmosphere to the Earth's orography and the land-sea thermal difference (Bolin, 1950; Smagorinsky, 1953; Huang and Gamo, 1982). The formation and variation of the subtropical jet stream were found to have a close relation with convective heating in the tropics. Krishnamurti (1961) found that centers of tropical heating are strongly correlated with centers of winter westerly jet streams on the North Hemisphere. Yang *et al.* (1990) demonstrated that summer convective heating in tropics on a hemisphere can cross the

Equator to affect the position and intensity of winter jet streams on another hemisphere. Based on the outgoing longwave radiation (OLR) data and gridded high-altitude reanalysis, Dong *et al*. (1999) showed that the annual cycle of the jet stream and associated intensity of subtropical westerly winds are correlated to the tropical convective heating. Hu and Huang (1997) demonstrated that, when convective activities over the Philippines are strong (weak), a forced anomaly wave train occurs from East Asia to North America via the North Pacific, with a positive (negative) anomaly over the west coast of the United States and a negative (positive) anomaly to its north, which increases (decreases) pressure gradients in the regions, and strengthens (weakens) the jet streams and intensity of storm activities at the core of storm tracks in the North Pacific. Thus, convective activities in the tropical region play a very important role in the position and intensity of the subtropical EAJS. It is important particularly to have good understanding how convective heating and associated thermal characteristics over the tropical region of the western Pacific Ocean affect the position and intensity of the EAJS and associated interannual variability, in order to improve the skill of the weather and climate simulations over East Asia, particularly in China. Many important scientific issues, however, remain to be addressed regarding the important role of tropical convection in the formation and change of the EAJS. Most of previous studies focused mainly on mechanism affecting the intensity and seasonal variation of the EAJS, without much efforts on the main factors controlling the meridional migration of the wintertime EAJS. The main objective of this study is to examine the correlation between meridional migrations of EAJS and tropical convection over Indonesia in winter.

The structure of this paper is as follows. Section 2 describes the data used in this study. Section 3 presents important findings of atmospheric circulation characteristics associated with significant meridional migrations of the EAJS and the effect of tropical convection over Indonesia on meridional migration. Section 4 is a summary and conclusion.

2. Data

The gridded monthly mean fields of Outgoing Longwave Radiation (OLR) with a horizontal resolution of 2.5°×2.5° during the period 1980–2011 are used in this study. The OLR is a measure of the amount of energy emitted to space by the Earth's surface, oceans and atmosphere, which is a critical component of the Earth's radiation budget. The OLR values are often used as a proxy for convection in tropical and subtropical regions since cloud top temperatures (colder is higher) are a good indicator of cloud height. The OLR fields used in this study were produced by the National Center for Atmospheric Research (NCAR) and interpolated from the polar-orbiting satellite remote sensing data provided by the National Oceanic and Atmospheric Administration (NOAA) of the United States.

In addition, this study also uses the monthly circulation fields extracted from the atmospheric reanalysis dataset with a spatial resolution of 2.5°×2.5° produced by the National Centers for Environment Prediction/National Center for Atmospheric Research (NCEP/NCAR). The NCEP/NCAR reanalysis data were produced by a state-of-the-art atmospheric circulation model with assimilation of various atmospheric observations of synoptic and asynoptic data sources, including observations made by such as radiosondes, drop-sondes, surface stations and ships, satellite and radar remote sensing data, and those made by aircrafts and drifting buoys.

3. Relations Between Meridional Migration of EAJS and Tropical Convection

The maximum westerly wind speeds, on the yearly base, are located at about 200 hPa (Kuang and Zhang, 2006). We follow Mao *et al*. (2007) and set the meridional position index (I_{MM}) for the EAJS as the difference in zonal winds at 200 hPa between the area of (100°E–115°E, 15°N–25°N,) and the area of (100°E–115°E, 30°N–40°N) in winter months (December–February). During the study period 1980-2011, the years with significant abnormal northward displacements of the EAJS consist of 1983/1984, 1998/1999, 2000/2001, 2005/2006, 2007/2008, 2008/2009, and 2010/2011. Among them, 1983/1984, 1998/1999, 2000/2001, 2007/2008, and 2010/2011 are La Niña years (http://ncc.cma.gov.cn). The years with significant abnormal southward displacements consist of 1982/1983, 1989/1990, 1991/1992, 1992/1993, 1997/1998, 2002/2003, and 2006/2007. Among these years, 1982/1983, 1991/1992, 1997/1998, 2002/2003, and 2006/2007 are El Niño years (http://ncc.cma.gov.cn). A La Niña year is referred to as the year when the sea surface temperature across the equatorial eastern-central Pacific Ocean is lower than the normal years by 0.5°C (Trenberth, 1997). By comparison, an El Niño year is referred to as the year when a band of warmer-than-usual surface waters is developed in the central and east-central equatorial Pacific Ocean, including ocean waters off the Pacific coast of South America. Both El Niño and La Niña are opposite phases of the ENSO cycle. The latter is referred to fluctuations in temperature between the ocean and atmosphere in the Equatorial Pacific (Rasmusson and Wallace, 1983). This suggests, therefore, that the abnormal meridional displacements of the EAJS are statistically linked to the ENSO index, which is consistent with previous finding by Yang *et al.* (1990). They found that interannual variability in the position and intensity of the westerly jet streams are closely related to the ENSO phenomenon. The research work about the effect of the ENSO on the meridional migrations of the EAJS, however, is beyond the cope of the current study. It is important to note that the ocean affects the air temperature and circulation in the overlying atmosphere through the sensible and latent heat not only at the local scale but also at the large scale through the zonal Walker circulation, meridional Hadley circulation, and planetary wave propagations. In addition, the oceanographic processes also affect the heating field in the atmosphere to modify the atmospheric circulation (Li and Chen, 1996; Schaack and Johnson, 1994). The Walker circulation is referred to as a zonal (east–west) atmospheric circulation cells along the equatorial belt (Gill, 1982). In the Pacific Ocean, the Walker circulation features trade winds across the tropical Pacific flowing from east to west, air rising above the warm waters of the western Pacific, flowing eastward at high altitudes, and descending over the eastern Pacific (Julian and Chervin, 1978). The Hadley cell (or circulation) is referred to as a meridional (north–south) atmospheric circulation that features air rising near the Equator, flowing poleward at 10–15 kilometers above the Earth's surface, descending in the subtropics, and then returning equatorward near the surface (Gill, 1982). In the next section, we focus mainly on the relationship between the meridional positions of the EAJS and tropical convection.

3.1 Abnormal Tropical Convection and Meridional Migration of EAJS

Since the descending branch of the Hadley cell is located over the south side of the EAJS core, a large meridional displacement is linked to abnormal activities of tropical convection. Figure 1 presents distributions of climatological wintertime OLR and also composite OLR and associated anomalies in years with large southward and northward migrations respectively. The climatological winter-mean OLR distribution (Figure 1A) averaged over the study period features relatively high values at subtropical latitudes and a gradual decrease from latitude of about 27° to the polar region on each Hemisphere of the Earth. The winter-time OLR values are persistently low in the northern and southern polar regions since these two regions are cold. The winter OLR values are the second lowest over Siberia due to the cold climate. At mid-latitudes, the winter OLR values are low over the Tibetan plateau since this region has high altitudes and long durations of snow cover. Over the intertropical convergence zone (ITCZ) at low-latitudes, the OLR values are low due to the strong deep convection, stretching high of the cloud tops and low cloud temperature in the region. Especially over Indonesia, there is a center of low OLR values in winter to be about 200 W/m^2 or less, which indicates strong convective heating in the region. By comparison, the OLR values are relatively high in subtropical regions, especially over deserts of eastern and western sub-Saharan Africa and the cooler parts of the ocean, due to the fact that these regions are relatively dry and cloud-free (Figure 1A).

Two composites of winter OLR fields are calculated using monthly mean OLR fields in winter months in above-defined years with large abnormal southward (D_South, Figure 1B) and northward (D_North, Figure 1C) displacements of the EAJS respectively. The anomalous OLR fields in the two cases are calculated from these two composites of OLR fields with the climatological winter-mean OLR field removed. Figure 1B demonstrates that, when the EAJS has a large abnormal southward displacement in case D_ South, the OLR values over equatorial central Pacific are significantly reduced and the convection of the ITCZ moves eastward. The OLR anomalies in this case are positive over Indonesia, Malaysia, and the Philippines, indicating the weakening of convective activities in the regions. When the EAJS has a large abnormal northward displacement (D_North), in contrast, the OLR values over equatorial central Pacific are significantly strengthened and the convection of the ITCZ moves westward (Figure 1C). Over the Equatorial region between 120°E and 160°E, the winter OLR anomalies in case D_North are significantly negative, indicating strong convective activities over these regions. Therefore, the OLR fields and associated anomalies have significantly different distributions and the tropical convection has very different characteristics, in response to different meridional migrations of the EAJS in winter months. This indicates that that convective activities in tropics have a very important impact on the meridional migration of the EAJS.

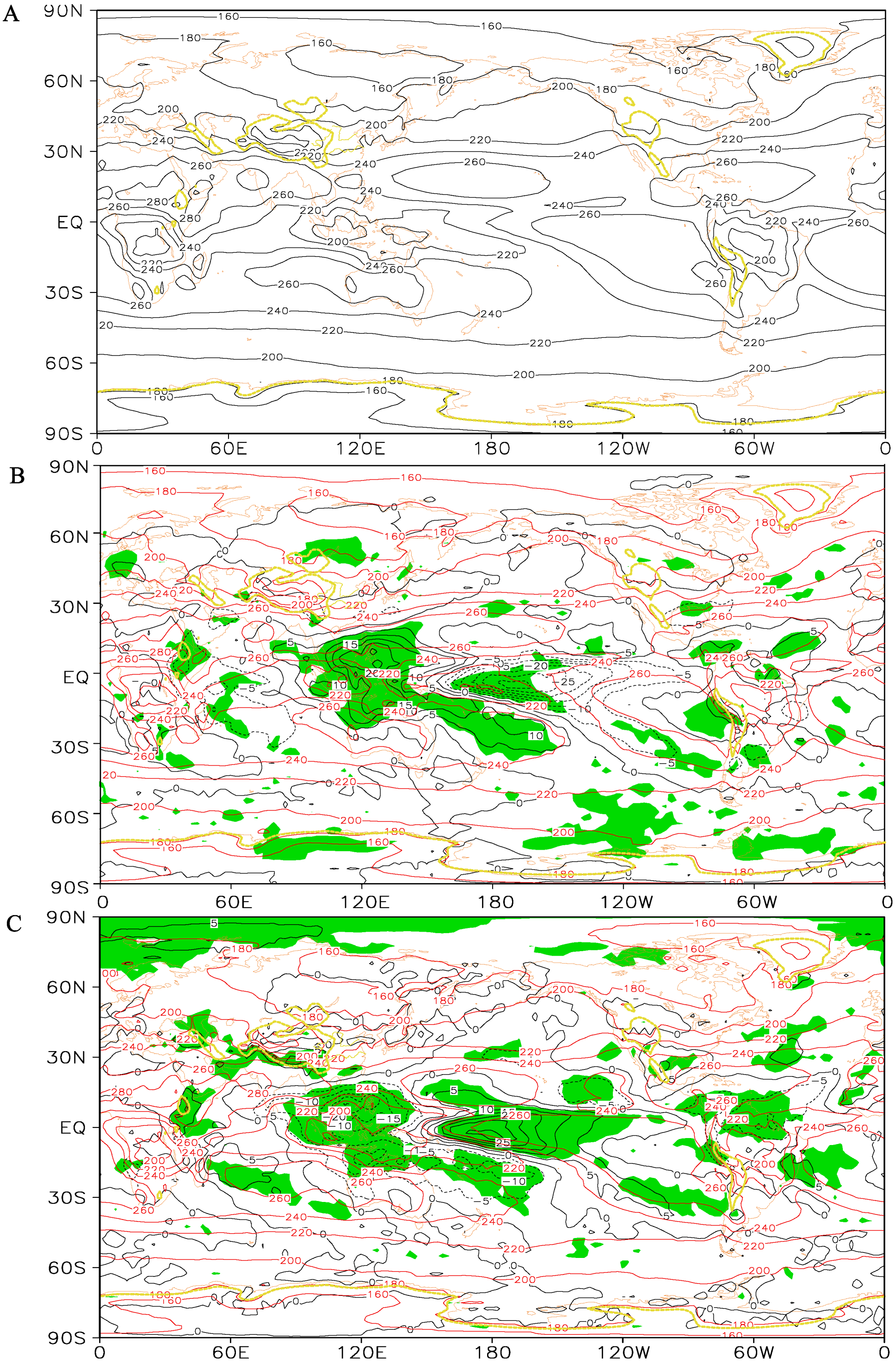

Figure 1. Climatological mean OLR (A), composite OLR (red line) and anomaly (black line) for the southward (B) and northward (C) migration of the EASJ in winter (units: W/m^2). The green shading shows the *t*-test significance at the 5% level. The dashed yellow lines mark the 1500 m above the sea level.

3.2 Lagged Response of Meridional Migration to Tropical Convection

To further determine the relationship between the meridional migration of the EAJS and tropical convection, we examine the response of the wintertime meridional migration of the EAJS to the preceding OLR distributions in previous seasons. The time-lagged (or time-advanced) correlation coefficients are calculated for winter-time meridional migration indices (I_{MM}) with anomalous OLR fields in preceding October and July respectively. The latter are used to represent the anomalous OLR fields in the preceding autumn and summer with respect to the winter-time meridional migration. Figure 2A demonstrates significantly large magnitudes of time-lagged correlation coefficients (either positive or negative) between I_{MM} and the anomalous OLR fields in preceding October. Over the tropical regions, the time-lagged correlation coefficients are significantly negative over the central Pacific and western Indian Oceans, and significantly positive from the eastern Indian to western Pacific Ocean. This suggests that the preceding OLR values are abnormally lower in the central Pacific and western Indian Oceans and abnormally higher from the eastern Indian to western Pacific Oceans when the winter EAJS has significant meridional displacements. This close relationship between the OLR anomalies in preceding seasons and the winter meridional displacements lasts until the winter season. Distributions of correlation coefficients with the zero lag (not shown) have similar spatial distributions to Figure 2A, except for larger magnitudes of the coefficients.

It is important to note that the above-mentioned time-lagged response of the meridional displacements

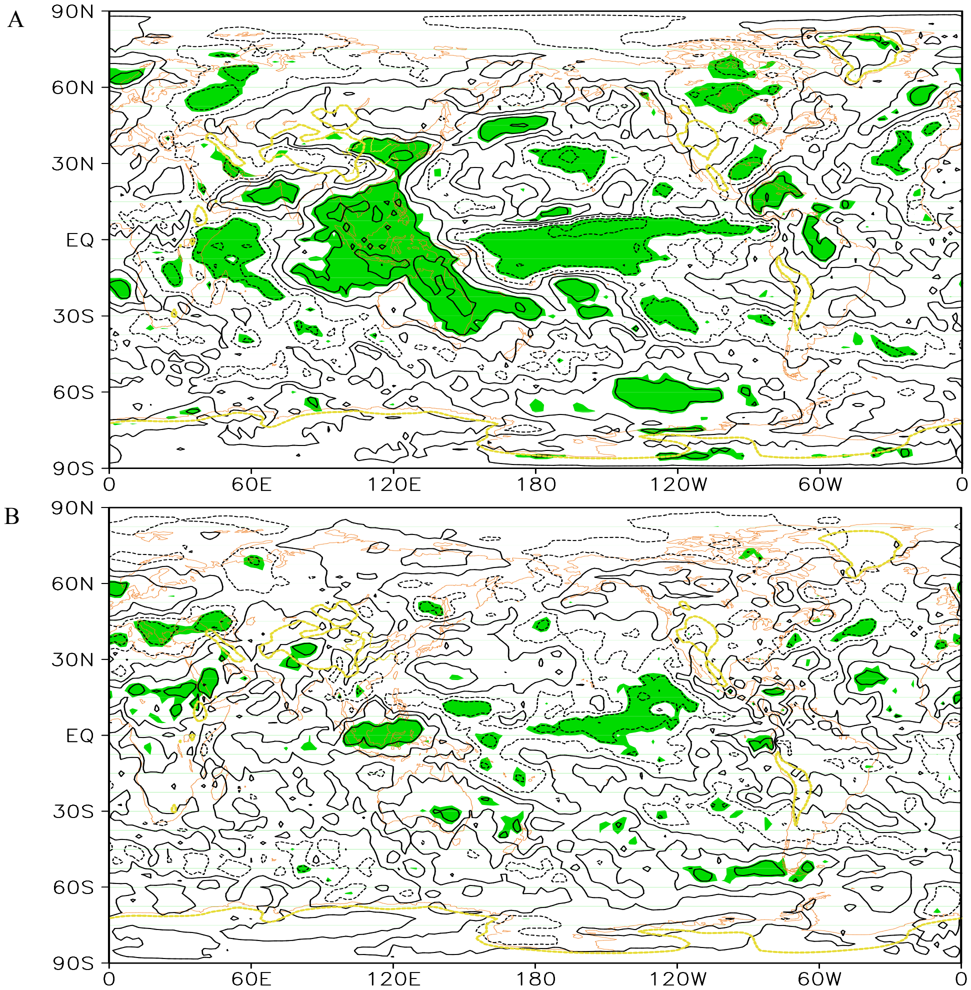

Figure 2. Correlation coefficients between the meridional migration index of the EASJ in winter and OLR in preceding October (A) and July (B) (contour interval is 0.2). The green shading shows the *t*-test significance at the 5% level. The dashed yellow lines mark the 1500 m above the sea level.

of the EAJS relationship to the OLR anomalies in preceding summer occurs. Figure 2B shows the distribution of time-lagged correlation coefficients between the winter EAJS indices (I_{MM}) and the OLR anomalies in preceding July. In comparison with Figure 2A, both the areas with large magnitudes of time-lagged correlation coefficients and areas with significant levels of 5% or higher in Figure 2B are smaller for the OLR anomalies in preceding July. Nevertheless, positive correlation between I_{MM} and the anomalous OLR fields in preceding July still exists over Indonesia, except that correlation values and ranges are smaller in comparison with the anomalous OLR fields in preceding October. For the case of the anomalous OLR fields in preceding July, negative correlation over the central Pacific Ocean moves eastward, and negative correlation disappears over the western Indian Ocean. Therefore, the summer-time OLR anomalies over Indonesia are also a very useful indicator for the winter-time meridional migration of the EAJS.

4. Processes Analysis of the Impact of Tropical Convection Activities

4.1 Circulation Characteristics Associated with Meridional Migration of the EAJS

The analysis and discussion presented in the previous section indicate a certain relationship between the tropical convection over Indonesia and the winter meridional migration of the EAJS. In this section, we examine the atmospheric circulation associated with the winter meridional migration of the EAJS (I_{MM}) to improve our knowledge on the important mechanisms and dynamic connection between the tropical convection and the meridional migration of the winter EAJS. Figure 3 presents the distribution of correlation coefficients between I_{MM} and zonal winds at 200 hPa in winter. The correlation coefficients are positive over the south side and negative over the north side of the climatological winter-mean subtropical westerly jet streams. This indicates that the meridional displacements of the EAJS are strongly linked to meridional displacements of the whole subtropical westerly winds. It should be noted that the correlation coefficients are positive over large areas from the south side of the EAJS to the tropical region on the South Hemisphere. This suggests that, when the winter EAJS has an abnormal southward displacement, large westerly anomalies occur over the same region, with strengthened westerly winds over the subtropical westerlies and weakened equatorial easterly winds. Over the eastern part of the equatorial Pacific Ocean the correlations are negative, which indicates the westerly winds are weakened over this region for the southward migration of the EASJ. Therefore, the meridional migration of the winter EAJS is strongly linked to the changes in the atmospheric circulation over the Pacific and Indian Oceans.

Previous studies indicated that changes in the intensity and meridional migration of the EAJS are linked reasonably to meridional gradients of air temperatures in the middle and upper troposphere (Kuang and Zhang, 2006). During the heating period from the

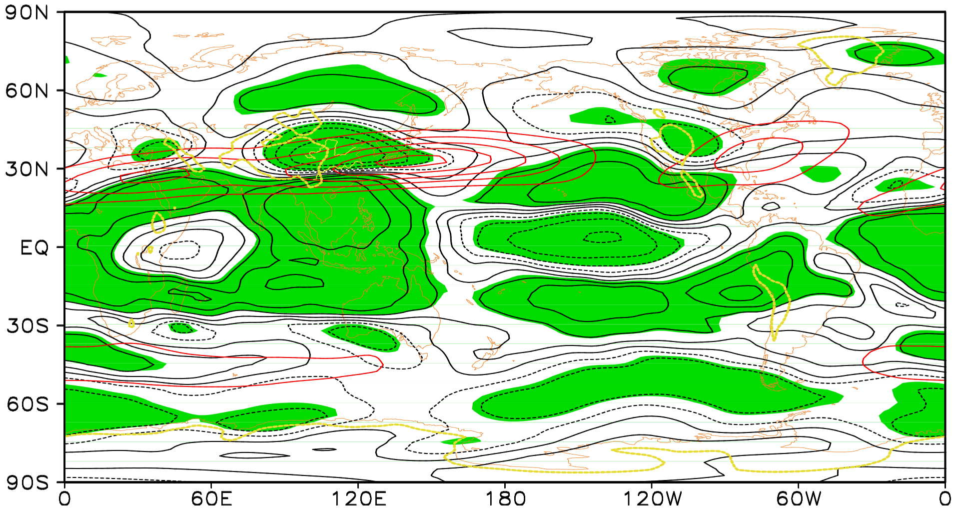

Figure 3. Correlation coefficients between the meridional migration index of the EASJ and 200 hPa zonal wind in winter (contour interval is 0.2). The green shading shows the *t*-test significance at the 5% level. The dashed yellow lines mark the 1500 m above the sea level. The red line is the climatological mean 200 hPa zonal wind greater or equal 30 m/s (contour interval is 10).

winter half-year months (October–March) to the summer half-year months (April–September), meridional temperature gradients in the core of the EAJS are significantly reduced, and the intensity of the EAJS is reduced with large northward migration. During the cooling period from the summer half-year months (April–September) to the winter half-year months (October–March), by comparison, meridional temperature gradients in the core of the EAJS are significantly increased, and the intensity of the EAJS is enhanced with large southward migration (Kuang and Zhang, 2006). Here we examine the influence of air temperature changes in the middle and upper troposphere on the EAJS. Figure 4 presents distributions of temperature anomaly composites in 500–200 hPa for two cases of different meridional displacements of the winter EAJS. In the case of large southward migration of the winter EAJS (D_South), temperature anomalies are negative over the core of the EAJS and its south side (Figure 4A). The center of negative temperature anomalies is located in the area south of the Yangtze River. This indicates that as the core of the winter EAJS moves southward, the air temperature over this region is reduced and the center of large temperature gradients moves southward. Physically, large temperature changes lead to large changes in the air pressure, which causes large changes in the atmospheric circulation over the region. On the south side of the largest negative temperature anomaly, both the thermal winds and westerly winds are increased. Over the north side, both the thermal winds and westerly winds are decreased. As a result, the winter EAJS has a significant southward migration. In the case of large northward migration of the winter EAJS (D_North), in contrast, air temperature anomalies are positive over the core of the EAJS and its south side (Figure 4B).

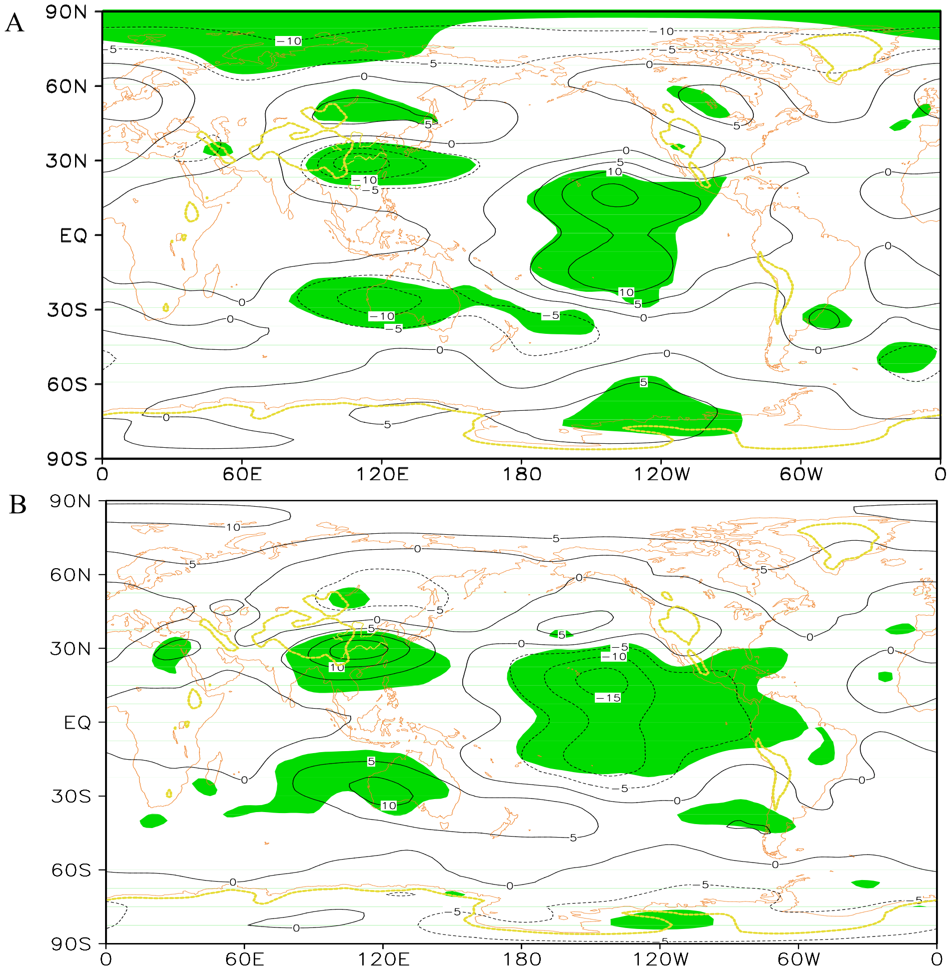

Figure 4. Composite of temperature anomalies in 500-200 hPa for the southward (A) and northward (B) migration of the EASJ in winter (units: °C). The green shading shows the *t*-test significance at the 5% level. The dashed yellow lines mark the 1500 m above the sea level.

The center of positive temperature anomalies is located to the south of the Yangtze River. On the south side of the largest positive temperature anomaly, both the thermal winds and westerly winds are decreased. Over the north side, both the thermal winds and westerly winds are increased. As a result, the winter EAJS has a significant northward migration. It can be concluded, therefore, that the air temperature anomalies over the south side of the EAJS are important factors affecting the meridional migration of the winter EAJS.

The above analysis indicates that the meridional migration of the winter EAJS is affected significantly by tropical convection. The tropical convection plays an important role to the Hadley circulation. Hadley circulation is an important large-scale meridional atmospheric circulation that exchanges the momentum, heat, moisture and air mass between the tropical and extra-tropical regions of the North and South Hemispheres (Ye and Yang, 1955; Ye and Zhu, 1958; Wu, 1988; Trenberth and Stepaniak, 2003). The heat absorbed by the tropical oceans accounts for the majority of the total amount of solar energy absorbed by the Earth surface and atmosphere. Part of this total heat and solar energy is transported by the Hadley circulation from tropical ocean to other regions.

Changes in the upper troposphere have global-scale characteristics much more than the changes in the middle and lower troposphere. Dynamically, the thermal imbalance in the tropical atmosphere can lead to the divergent circulation, and this divergent circulation is linked to the planetary-scale Walker circulation and Hadley circulation. It is expected, therefore, that the horizontal divergence field should have different characteristics for two cases of large southward (D_South) northward (D_North) displacements of the winter EAJS. Figure 5 presents composites of divergent wind velocity and horizontal divergence at 200 hPa in two these cases. In case D_South (Figure 5A), large abnormal high-level divergence occurs over the whole region of East Asia except for central Tibet. The center of the abnormal high-level divergence is located in the area south of the Yangtze River over the south side of the EAJS. This indicates that over that regions the ascending movement of air mass is strengthened. As the air mass rises, its temperature decreases, resulting in large negative temperature anomalies. Abnormal high-level convergence occurs over the tropical western Pacific Ocean, with its center located near Indonesia and the Philippines. In this case, the Hadley circulation is weakened, and the abnormal divergent winds are nearly northerly over a large region from Indonesia to the area south of the Yangtze

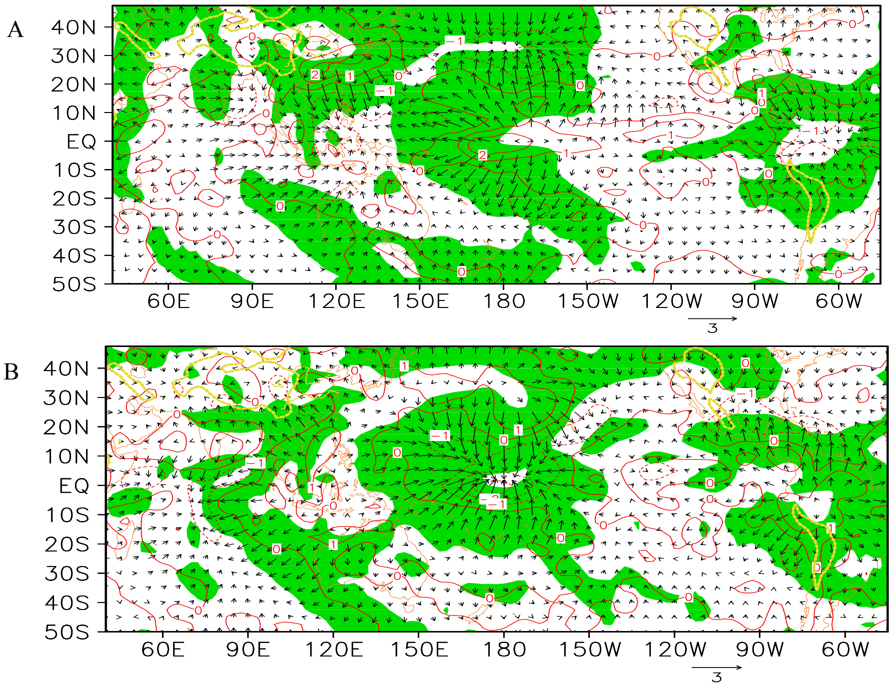

Figure 5. Composite of divergent wind (units: m/s) and divergence (units: 10^{-6}/s) anomalies at 200 hPa for the southward (A) and northward (B) migration of the EASJ in winter. The green shading shows the *t*-test significance at the 5% level. The dashed yellow lines mark the 1500 m above the sea level.

River. This results in weakened southerly winds, decreased heat transport to the southern China, and reduced air temperature in the region.

In case D_North (Figure 5B), large abnormal high-level convergence occurs over the regions south of the Yangtze River, north of the Yellow River, and eastern part of Qinghai-Tibet Plateau, with its centers located over the eastern Tibetan Plateau and the region south of the Yangtze River. The air mass descends and gains the heat. Due to the strengthened convection over Indonesia in this case, high-level divergence occurs over the tropical western Pacific, with its center located over the region close to Malaysia and the South China Sea. This suggests that the Hadley circulation is enhanced, and the abnormal divergent winds are nearly southerly over the region from the Yangtze River to the South China Sea. Over this region, there are positive temperature anomalies due to large transport of warm air mass from the tropics to this region by the abnormal nearly southerly divergent winds.

4.2 Effect of Tropical Convection on Meridional Migration of EAJS

As discussed above, significant correlation between the tropical convection and the meridional migration of the winter EAJS is due to the fact that convective activities over Indonesia affect significantly the atmospheric circulation in the region to the south of the EAJS. In this section we examine the response of the atmospheric circulation to the tropical convection using the following three indices: (a) the intensity index for the tropical convection over Indonesia (I_{TCI}), (b) meridional migration index for the EAJS (I_{MM}); and (c) intensity index for the EAJS (I_{JSI}). The intensity index (I_{TCI}) for the tropical convection over Indonesia is defined as the mean OLR value averaged over the area of (110°E–130°E, 5°S–10°N). The meridional migration index (I_{MM}) for the EAJS has the same definition as given in section 3, which is defined as the difference in zonal winds at 200 hPa between the area of (100°E–115°E,15°N–25°N,) and the area of (100°E–115°E, 30°N-40°N) in winter months. The intensity index (I_{JSI}) for the EAJS is defined as the winter-time zonal winds at 200 hPa averaged over the area of (127.5°E–155°E, 30°N–35°N). It should be noted that the correlation coefficients between the I_{TC} and the monthly mean OLR fields have the same spatial distributions as shown in Figure 1. This indicates that abnormal changes in the tropical convection over Indonesia should result in abnormal changes in the tropical convection in the Pacific-Indian Ocean.

A correction analysis is conducted between time series of these three indices (Figure 6). The analysis shows that the meridional migration index of the winter EAJS (I_{MM}) is strongly correlated to the tropical convection index (I_{TC}), with the correlation coefficient of about 0.87 at the confidence level of 99%. The winter EAJS has a large northward (southward) migration when the westerly winds of the EAJS are strong (weak) (Mao *et al*, 2007). The migration index of the EAJS (I_{MM}) is negatively correlated to the intensity index of the EAJS (I_{JSI}), with the correlation

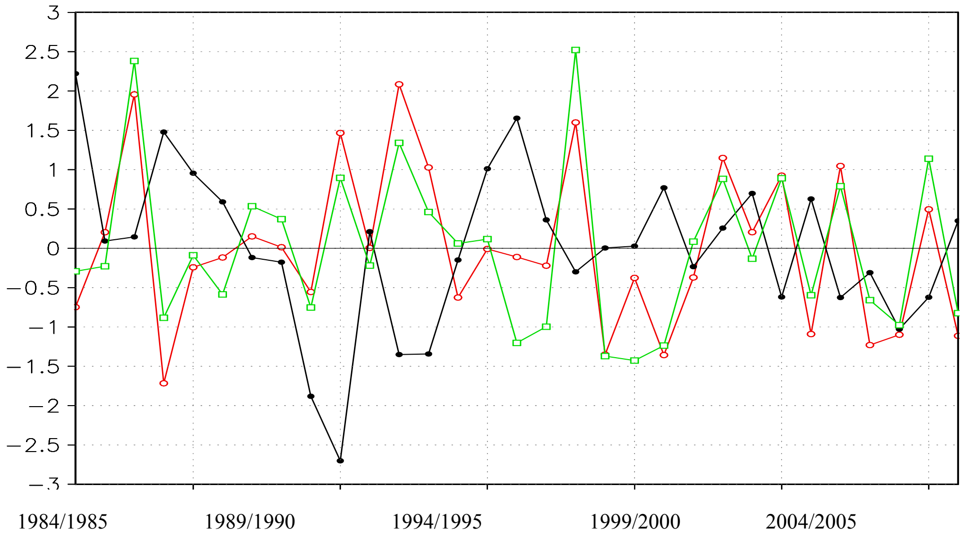

Figure 6. Normalized deviation of the meridional migration index (I_{MM}, red), intensity index for the EAJS (I_{JSI}, black) and the intensity index for the tropical convection over Indonesia (I_{TCI}, green line) from winter of 1980/1981–2010/2011.

coefficient of about –0.44 at the confidence level of 95%. It should be noted that the effect of tropical convection on the meridional migration of the winter EAJS is part of the effect of the tropical convection on the intensity of the EAJS. The intensity index of the EAJS (I_{JSI}) is also negatively correlated to the intensity index of the tropical convection (I_{TCI}), with the correlation coefficient of about –0.38 at the confidence level of 95%. By comparison, the partial correlation coefficient between the intensity index of the EAJS (I_{JSI}) and intensity index of the tropical convection (I_{TCI}) is about –0.003, indicating that statistically the tropical convection around Indonesia is not linked to the intensity of the EAJS. The migration index of the EAJS (I_{MM}), however, is strongly correlated to the intensity index of the tropical convection (I_{TCI}), with the partial correlation coefficient of about 0.85 at the confidence level of 99%. The above correlation analyses suggest that the tropical convection around Indonesia affects mainly the meridional migration of the EAJS.

Physically, abnormal activities of tropical convection can result in the abnormal vertical circulation over the tropical region. Since the divergent winds dynamically represent the vertical circulation, the effect of tropical convections can also be examined using a correlation analysis between the tropical convection intensity index (I_{TRI}) and the divergent winds and the horizontal divergence field at 200 hPa (Figure 7A). The distribution of the horizontal divergence field at 200 hPa is found to have the same features as the OLR field. Positive correlation occurs over the region close to the equatorial International Date Line and over the western Indian Ocean. Negative correlation occurs over Indonesia and the tropical Americas. This shows that, as the tropical convection over Indonesia weakens (strengthens), divergence (convergence) occurs in the upper troposphere over the region close to equatorial International Date Line, indicating the enhanced (weakened) ascending motion over that region. Over the western Pacific Ocean, by comparison, convergence (divergence) occurs, with abnormal descending (ascending) motion over that region. By including the climatologically mean vertical motion, the ascending motion of air mass over that region weakens (strengthens). In the case of weakened tropical convection over Indonesia, ascending motion anomaly prevails over the equatorial western Indian Ocean, and descending motion anomaly occurs over Indonesia, which makes the abnormal zonal-vertical circulation lead to abnormal westerly winds at high-altitudes. Meanwhile, the ascending motion anomaly prevails over the equatorial central Pacific Ocean. One branch of the air mass moves westward to Indonesia to join the descending motion anomaly with abnormal easterly winds at high-altitudes in that region which forms an anomalous zonal-vertical circulation. The other branch moves eastward to the eastern Pacific Ocean and descends with abnormal westerly winds at high-altitudes in that region, which also forms an anomalous zonal-vertical circulation. In the Equatorial region, the abnormal zonal-vertical circulation is strongly linked to the anomalous OLR field, with strong correlation between the abnormal ascending motion and the negative OLR anomalies. The descending motion is strongly linked to the positive OLR anomalies. The opposite happens, however, in the case that the tropical convection over Indonesia strengthens. The major differences between the above two different cases indicate the impact of the tropic convection to the zonal-vertical (Walker) circulation.

The other important feature to be mentioned is differences over East Asia between the two cases. The tropical convection over Indonesia is positively correlated with the horizontal divergence at 200 hPa over the eastern part of the Qinghai-Tibet Plateau. Large correlation also occurs over the region south of the Yangtze River and the upstream region of the Yellow River. This suggests that, as the tropical convection over Indonesia weakens (i.e., positive OLR anomalies), the divergence has positive anomalies, and the vertical ascending motion has positive anomalies over those regions. The circulation flowing out from the center of positive anomalies in the divergence field at 200 hPa and entering the convergence zone over Indonesia is known as the high-altitude air flow of the anomalous Hadley circulation. By including the climatologically mean vertical motion, the meridional circulation of the Hadley cell is weakened. This is consistent with the general features of the divergence fields at 200 hPa shown in Figure 5. In contrast, when the tropical convection over Indonesia strengthens, the Hadley circulation is strengthened. The above-mentioned differences between these two cases indicate the tropical convection is linked to the EAJS through the Hadley circulation. The abnormal activities in the tropical convection lead to anomalous Hadley circulation, which in turn lead to the anomalous heat transport from the tropics to the outside region, resulting in air temperature anomalies over the regions.

Figure 7B presents the horizontal distribution of correlation coefficients ($R_{TCI-TEMP}$) between the index for the tropical convection over Indonesia and the air temperature averaged vertically between 500 hPa and 200 hPa. The correlation is significantly negative over the EAJS and its south side. The center of the negative correlation is located over the region south of the Yangtze River. This indicates that, when the tropical convection is strong (negative OLR anomalies), due to stronger Hadley circulation, abnormal nearly southerly air stream flows out from the tropics (Figure 7A), with increased heat transport to the region south of the Yellow River. Over that region, the air mass converges at high altitudes and then descends with increased air temperature. As a result, the air temperature is increased over the EAJS and its south side. This explains why negative correlation occurs over the EAJS and the large area to the south of the EAJS (Figure 7C), and its center matches with the center of positive correlation between the convection index and convergence field shown in Figure 7A. Since the air temperature significantly rises along the core of the EAJS and its south side, over the north side of the EAJS, however, the air temperature decreases slightly.

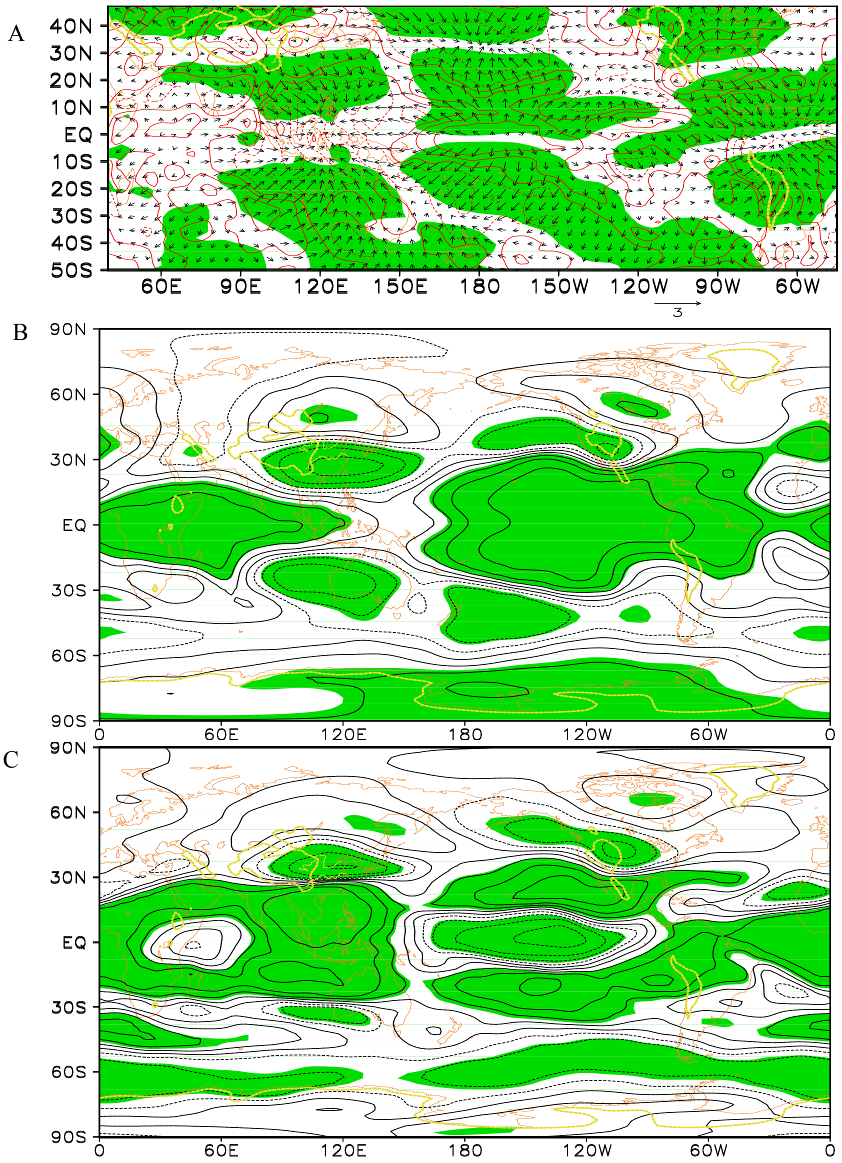

Figure 7. Correlation coefficients between the meridional migration index of the EASJ and divergent wind and divergence (arrow showing correlation coefficient with divergent wind, contour spacing 0.3) at 200 hPa (A), temperature in 500–200 hPa (B), and 200 hPa zonal wind in winter (contour interval is 0.2). The green shading shows the *t*-test significance at the 5% level. The dashed yellow lines mark the 1500 m above the sea level.

Consequently, the large temperature gradients move northward (not shown). Since the position of the EAJS core is also the position of largest temperature gradients, the EAJS have northward migration for negative OLR anomalies. The opposite happens for positive OLR anomalies. These results are consistent with the general distribution of the air temperatures shown in Figure 4.

Large temperature anomalies inevitably lead to large wind anomalies. Figure 7C presents the distribution of correlation coefficients ($R_{TCI\text{-}WND}$) between the tropical convection index (I_{TCI}) and 200 hPa zonal winds. Consistent with correlation coefficients shown in Figure 3, the values of $R_{TCI\text{-}WND}$ are positive over regions from the tropical part of the eastern Indian Ocean to New Guinea, and negative over the central-eastern Pacific Ocean. This indicates that, in the case of enhanced tropical convection over Indonesia, anomalous easterly winds prevail from the eastern Indian Ocean to New Guinea, and anomalous westerly winds prevails over the central-eastern Pacific Ocean. By including the climatological mean condition, the Walker circulation is enhanced. In the case of reduced tropical convection over Indonesia, the Walker circulation is weakened. It should be noted that the values of $R_{TCI\text{-}WND}$ are positive over the south side of the EAJS up to the tropics of the South Hemisphere, with its center located in the tropics. Over the north side of the EAJS, the values of $R_{TCI\text{-}WND}$ are negative. Based on the thermal wind theory, in the case of reduced tropical convection over Indonesia, anomalous westerly winds occur over the region south of the Yangtze River, and anomalous easterly winds over the north side. This leads to the southward migration of the EAJS. In the case of enhanced tropical convection over Indonesia, the opposite happens. This suggests that the anomalous tropical convection over Indonesia affects the vertical air movement above the Equator, not only through the Walker circulation, but also through the Hadley circulation. The latter directly modifies the EAJS and are temperature over the south side of the EAJS, which in turn affects the meridional position of the EAJS.

5. Summary and Conclusion

This study examined the atmospheric circulation associated with large meridional migration of the East Asia jet stream (EAJS) in winter and physical connections between abnormal activities of tropical convection over Indonesia and the abnormal meridional migration of the winter EAJS. The gridded monthly mean fields of Outgoing Longwave Radiation (OLR) and the monthly circulation fields extracted from the NCEP/NCAR atmospheric reanalysis dataset were examined and analyzed. The results presented in this paper demonstrated that, in the case of weakened activities of tropical convection (i.e., positive OLR anomalies) over Indonesia, the winter EAJS has a large southward displacement. In the case of enhanced activities of tropical convection (i.e., negative OLR anomalies) over Indonesia, by comparison, the EAJS has a large northward displacement. It was also found that the preceding autumn-time (even preceding summer-time) OLR anomalies over Indonesia provide a good indicator for the winter-time meridional migration of the EAJS.

The atmospheric circulation associated with the large meridional migration of the winter EAJS features air temperature anomalies over the EAJS and its south side, with the center of large temperature anomalies located over the region south of the Yangtze River. Air temperature anomalies result in air pressure anomalies. For the case of weakened tropical convection around Indonesia, ascending of the air mass at high altitudes over this region is reduced, and the Hadley circulation is weakened over the meridional region of the western Pacific Ocean. The air mass over the south side of the EAJS core rises abnormally and cools down. The nearly southerly divergent winds at high altitudes over the region are weakened, and heat transport is reduced from tropics to the regions south of the Yellow River in this case, resulting in reduced air temperature over the EAJS and its south side. The center of anomalous air temperatures matches to the center of the horizontal divergence at high altitudes in the region south of the Yangtze River. Over the north side of the EAJS, the air temperature rises only slightly in this case. It leads to enhanced thermal winds over the region south of the Yangtze River and increased westerly winds at high altitudes. Over the north side, the thermal winds are reduced, and westerly winds at high altitudes are reduced. As a result, the EAJS has a large southward displacement. The opposite happens for the case of enhanced tropical convection around Indonesia.

Conflict of Interest

No conflict of interest was reported by all authors.

Acknowledgements and Funding

This work was supported by Open Research Fund Program of Plateau Atmosphere and Environment Key Laboratory of Sichuan Province (PAEKL-2016-C8) andby the Special Fund for Pub-lic Welfare Industry (meteorology) (GYHY201306026). The authors thank Professor Jinyu Sheng for his valuable comments on the early version of this manuscript.

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