Ablupt Northward Jump of the East Asian Upper-Tropospheric Jet Stream in Mid-Summer

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Abstract

In this study we document the abrupt seasonal migration of the East Asian upper-tropospheric jet stream (EAJS) in boreal mid-summer over the East Asian coast, based on the NCEP/NCAR reanalysis data from 1958 to 2002. In climatology, an abrupt northward jump of the EAJS is identified in late July. By examining each of the total 45 years there are 27 years in which the EAJS exhibits an abrupt northward jump in mid-summer, and about half of the jump cases occur in late July, suggesting the characteristic of phase locking with the calendar year. A cluster analysis on the meridional variation of the upper-tropospheric zonal wind anomalies along the eastern Asian coast associated with the northward jump of the EAJS reveals that the northward jump of the EAJS is dominated by two categories, in which the intensity of the EAJS is enhanced and weakened, respectively. For both categories, there is a pair of westerly and easterly anomalies which are located to the north and south of the EAJS’s axis. However, these westerly and easterly anomalies exhibit distinct temporal variations between the two categories: The pair of westerly and easterly anomalies shifts southward from the high latitudes to the EAJS region for the first category, but appears as a quasi-stationary meridional dipole pattern for the second category.

1. Introduction

The East Asian upper-tropospheric jet stream (EAJS) is one of the most important components of the East Asian summer monsoon (Tao and Wei 2006), and plays a crucial role in the weather and climate over East Asia (Tao and Chen 1987; Lau et al. 1988; Ding 1992; Liang and Wang 1998; Tao and Wei 2006). On the seasonal timescale, the meridional movement of the EAJS is coherent with the march of the East Asian summer monsoon. Specifically, the northward jump of the EAJS over the Asian continent in June and the sudden southward retreat in October are precursors of the onsets of the East Asian summer and winter monsoons, respectively (Yeh et al. 1959). These indicate that a comprehensive understanding on the seasonal variation of the EAJS is essential for better depicting the East Asian summer monsoon.

The EAJS exists throughout the year, but exhibits a clear annual cycle. The EAJS’s center is located over the western North Pacific (WNP) with the maximum speed of about 60 m s\(^{-1}\) in winter, and it moves northward to north of the Tibet Plateau with a remarkably decreased maximum speed in summer. Kuang et al. (2005, 2007) investigated the structure and seasonal variations of the climatological EAJS, and suggested that the ocean-land distribution and thermal contrast, as well as dynamic and thermodynamic effects of Tibetan Plateau, contribute to the climatological annual cycle of the intensity and location of the EAJS. In the zonal direction, the westward retreat of the climatological EAJS’s core from the WNP at about 140°E to the Asia continent at about 90°E happens during mid-June to mid-July corresponding to the
Mei-yu season over East Asia (Zhang et al. 2006).

The EAJS experiences a northward shift during the transition season (May–June) from winter to summer, concurring with the onset of East Asian summer monsoon. Some case studies suggested that the EAJS jumps northward from the south side of the Himalaya Mountains to the north side in June, which corresponds to the burst of the southwest summer monsoon in India and the onset of Mei-yu over East Asia (Yin et al. 1949; Yeh et al. 1959). Li et al. (2004) further studied the relationship between the EAJS’s jumps and the onset of East Asia summer monsoon in more detail. They argued that the EAJS experiences two distinct times of northward jumps over the East Asian continent in early summer, leading to the onset of the summer monsoon over the South China Sea and Mei-yu over South China, respectively. The first jump happens in early May when the EAJS jumps from between 25°–28°N to north of 30°N, and the second is in early June when the EAJS jumps from about 32°N to north of 35°N.

These previous studies emphasized either zonal or meridional shift of the EAJS’s core in early summer over the East Asian continent. In this study, we identify a northward jump of the EAJS over the East Asian coast in mid-summer (July–August), which is clearly distinct from the aforementioned northward shifts in early summer. This northward jump in mid-summer has not been documented in previous literatures. Therefore, in the current study, we investigate the temporal and spatial variation in circulation associated with this northward jump. The content of this paper is arranged as follows. In Section 2, the climatological feature of the northward jump of the EAJS is shown. In Section 3, we further examine the characteristics of the abrupt northward jump by identifying jump events and performing a cluster analysis in an attempt to sharpen the changes associated with the jump and to illustrate year-to-year variations of the jump. A summary is given in Section 4.

We use pentad data of zonal and meridional winds from 1958 to 2002, which come from the daily NCEP/NCAR reanalysis (Kalney et al. 1996). The pentad data are calculated as non-overlapped five-day mean, with 73 pentads in each year. We also utilize the pentad precipitation data from 1979 to 2002, which are based on gauge observations and satellite estimates (Xie and Arkin 1997).

**2. Climatological northward jump of the EAJS in late July**

Figure 1 shows the northward march of the climatological monthly EAJS’s axis in summer. The location of the EAJS’s axis is defined as the latitude of maximum zonal wind at 200 hPa in each longitude. The EAJS’s axis shifts northward to north of 30°N over the continent from April to May, and such a shift is prominent around 100°E. The axis continues to shift northward from May to June, but during this period the most remarkable shift appears over the Tibetan Plateau, related to the onset of Mei-yu over East Asia (Yeh et al. 1959; Li et al. 2004). These northward shifts in early summer are concentrated over the continent, and are inconspicuous over the East Asian coast.

During mid-summer (July–August), the EAJS’s axis keeps shifting northward, but the prominent movement appears over the East Asian coast. It situates at about 35°N over the East Asian coast in June, moves to north of 40°N in July and reaches the northernmost position (about 45°N) in August. Over the continent, the northward movement of the EAJS’s axis is relatively inconspicuous during mid-summer. Thus, the EAJS exhibits a rather distinct feature of northward movement between early and mid summer, and between the continent

Fig. 1. Climatological northward shift of the monthly EAJS’s axis from April to August.
and the East Asian coast.

Figure 2 shows the climatological seasonal evolution of the EAJS's axis in July pentad by pentad, which exhibits a significant northward jump around pentad 41 (July 20–24). Before mid-July, the EAJS's axis exhibits a slight seasonal northward movement. An accelerated northward shift happens after pentad 40 (July 15–19). At pentad 41, the EAJS jumps northward abruptly, and the axis east of 130°E lies at about 45°N. At pentad 42 (July 25–29), the EAJS east of 120°E moves further northward. After that the EAJS reaches the northernmost point, about 47.5°N at pentad 43 (July 30–August 3), with a conspicuous northward shift over the central North Pacific. However, it should be noted that the EAJS is weak over the central North Pacific, and thus such a shift over the central North Pacific might be artificial. During the northward movement of the EAJS's axis, therefore, the most remarkable shift occurs between 120°–150°E, especially at 135°E along which the EAJS jumps northward about 4 degrees at pentad 41 and 2 degrees at pentad 42.

The seasonal evolution of the EAJS along the longitude of 135°E is shown in Fig. 3a, in which the northward jump is clearly revealed. Within the early summer the intensity of the EAJS decreases steadily, with the maximum velocity from nearly 35 m s⁻¹ in June to about 20 m s⁻¹ in mid-July (pentad 40). In the meridional direction the EAJS's axis situates between 35°N and 40°N, shifting northward less than 5 degrees in the ten pentads (pentads 31–40). Around pentad 41 the EAJS exhibits a clear northward jump and the axis jumps from 40°N at pentad 40 to north of 45°N at pentad 42, more than 5 degrees in the two pentads. After the jump, the EAJS gradually shifts equatorward in August (pentads 43–49), along with increasing intensity.

Related to the northward jump in late July, the most striking feature is characterized by a meridional triplet structure of zonal wind tendency in the upper troposphere over East Asia-WNP (Fig. 3b). The strongest signals are located between 120°–150°E consisting of the zonally-oriented westerly tendency over Northeast Asia and the subtropical WNP, and the easterly tendency in between.

![Fig. 2. Climatological seasonal northward march of the EAJS's axis in July. The dashed lines are for pentads 37 to 40 and the solid lines for pentads 41 to 43.](image-url)

![Fig. 3. (a) Climatological seasonal evolution of zonal winds at 200 hPa (U200) along the longitude of 135°E. (b) Difference of U200 averaged over pentads 41–42 and that over pentads 39–40 in East Asia-North Pacific. Zonal winds exceeding 25 m s⁻¹ are shaded in (a), contour intervals are 5 m s⁻¹ in (a) and 2 m s⁻¹ in (b), and zero contours are omitted in (b).](image-url)
is, after the northward jump (pentads 41 and 42),
the westerly accelerates over Northeast Asia while
decelerates over East Asia, and the easterly decel-
erates over the subtropical WNP. Therefore, the
climatological northward jump of the EAJS in mid-
summer is associated with the remarkable upper-
tropospheric circulation change in a broad region
including East Asia and the WNP. Furthermore,
the tendency of zonal winds tends to extend north-
eastward into the eastern North Pacific, but with
decreased intensity.

3. Events of the abrupt northward jump
of the EAJS

3.1 Definition of the abrupt northward jump

Since the most significant seasonal variation of
zonal winds at 200 hPa (U200) associated with the
climatological northward jump of the EAJS in late
July situates between 120°−150°E (Figs. 2 and 3b),
we refer to the EAJS’s axis (AXIS) as the latitude
of the largest speed of U200 averaged over these
longitudes. An event of the abrupt northward jump
(JUMP) is identified when the AXIS satisfies the
following two criteria for the first time during June–July–August (JJA) in each year:

1. AXIS(i) > 45°N;
2. AXIS(i) − AXIS(i − 1) ≥ 5°,

where i denotes pentad number. Before identifying
the cases, zonal winds have been smoothed by
a 3-pentad running mean with the 1−2−1 weight.
There are 27 events identified in 45 years from
1958 to 2002 (Table 1). All the 27 JUMPs happen
during July–August (Table 1 and Fig. 4). The aver-
age JUMP pentad is 41.9 and the standard devia-
tion is 2.4 pentads. There are 14 in 27 JUMP cases
that occur at pentads 41 and 42 (late July). These
numbers suggest a strong tendency of phase lock-
ing of JUMP with the calendar year.

Figure 5 shows the composite U200 and pre-
cipitation averaged over 120°−150°E based on the
JUMPs. An abrupt northward jump at pentad 0 is
clearly observed (Fig. 5a). Compared with that in
climatology (Fig. 3a), the jump in the composite
result is swifter and more northward, indicated
by the fact that the EAJS's axis jumps northward
almost 10 degrees in one pentad and reaches about
50°N at pentad 0. Before the jump, the EAJS's axis
stabilizes at 40°N with the maximum velocity be-
ing about 25 m s
−1
, while after the jump the EAJS
gradually retreats southward and intensifies con-
tinuously.

Corresponding to the northward jump of the
EAJS, the East Asian rain belt also shows a clear
northward jump (Fig. 5b). Before the northward
jump of the EAJS, the heavy rain belt over East

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<th>Year</th>
<th>Pentad (Date)</th>
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<td>P38 (Jul 5−9)</td>
<td>1974</td>
<td>P41 (Jul 20−24)</td>
<td>1989</td>
<td>P41 (Jul 20−24)</td>
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Asia, depicted by the contour of 4 mm dy$^{-1}$, situates between 30°–40°N, corresponding to the Baiu season in southern Japan. After pentad 0, the heavy rain belt almost diminishes and moves northward with the center of precipitation north of 45°N. This suggests that the northward jump of the EAJS in mid-summer is related to the withdrawal of the Baiu season in Japan.

We also composite U200 anomaly averaged over 120°–150°E based on the 27 JUMPs (not shown). Associated with the northward jump the composite U200 anomalies are composed of a meridional dipole in mid-latitudes, with the westerly center at 55°N and the easterly center at 40°N.

3.2 Cluster analysis
There are case-to-case differences among the 27 JUMP cases (See also Fig. 6). Therefore, it is necessary to examine whether these jump cases can be grouped into some distinct categories.

To classify the northward jump events, we per-
form a cluster analysis based on the similarity among the latitudinal profiles of the U200 anomalies averaged over 120°−150°E between 20°N and 80°N at the jump pentads for the individual summers. The similarity is measured by the spatial correlation coefficient between each pair of the profiles. A positive correlation of +1.0 would represent the most similar coupling, compared to −1.0 for the least similar possible pairing. At the beginning of the cluster analysis, each profile is a cluster in itself. The 27 initial clusters are then merged together into fewer clusters following joining hierarchical clustering algorithm (Johnson and Wichern 1982).

In this study, the cluster analysis classifies 18 of the 27 jump events into two categories, and the remaining events are left unclassified (Table 2). In the first category, the northward jump of the EAJS exhibits the strongest tendency of phase locking with the calendar year. All the jump events except one occur at pentads 41 and 42. This phase-locking tendency is weakest in the unclassified events.

Figure 6 shows the result of the clustering. The first category is characterized by a strong westerly anomaly with the maximum amplitude of about 15 m s$^{-1}$ north of the EAJS’s axis and a weak easterly anomaly to the south at about 40°N. Therefore, this kind of northward jump is related to the enhancement of the EAJS (See also Fig. 7a). For the second category, in contrast, there is a strong easterly anomaly with the maximum amplitude of about 15 m s$^{-1}$ centered at 40°N, along which the axis of the EAJS situates prior to the northward jump, as well as the weak westerly anomalies at about 55°N and 25°N, respectively. Thus, the second kind of northward jump is associated with the weakening of the EAJS (See also Fig. 7b). For the residual cases, no significantly coherent characteristics are observed among them, and the composite anomalies are much weaker in comparison with those for the first and second categories. The amplitude of the northward jump is greatest for the first category and smallest for the residual cases (Fig. 7). These results indicate that the aforementioned composite meridional dipole anomaly in Section 3.1 related to the northward jump is mainly contributed to by the two categories.

Figure 8 shows the composite horizontal wind anomalies at 200 hPa at pentad 0 for the first (enhancing) and second (weakening) categories, respectively. The northward jump is mainly related to the circulation anomalies in middle and high latitudes along the eastern Asian coast for the enhancing category (Fig. 8a), but is related to the anomalies in the low and middle latitudes for the weakening category (Fig. 8b). Corresponding to the jump of the enhancing category, the circulation anomalies are characterized by a strong cyclonic anomaly over eastern Russia and a weak anticyclonic anomaly over Northeast Asia, which are associated with a strong westerly anomaly from Siberia to the Okhotsk Sea, a strong easterly anomaly north of Siberia, and a weak easterly anomaly in East Asia. The jump of the weakening category is mainly related to the anticyclonic and cyclonic anomalies over Northeast Asia and the subtropi-

<table>
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<tr>
<th>Category I (8 years)</th>
<th>Category II (10 years)</th>
<th>The residual (9 years)</th>
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<tr>
<td>Year</td>
<td>Pentad (Date)</td>
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cal WNP with the centers tilting from northwest to southeast. The easterly anomaly in East Asia is stronger than the westerly anomalies in Northeast Asia and the subtropical WNP.

Figure 9 shows the evolution of U200 anomalies averaged over 120°–150°E separately for the enhancing and weakening categories. For the enhancing category, the high-latitude westerly anomaly and the mid-latitude easterly anomaly both exhibit a clear southward phase shift. The maximum westerly anomaly (12 m s\(^{-1}\)) appears at about 55° N north of the EAJS’s axis at pentad 0. Prior to the jump pentad, the significant anomalies appear in the middle and high latitudes, while they exhibit a four-cell anomaly pattern from the subtropical WNP to the high latitudes after the jump pentad. The significant zonal wind anomalies last about 4 pentads from pentad –1 to pentad 3. Further study is required to understand the mechanism for the persistence of the zonal wind anomalies in the

Fig. 7. Same as Fig. 5a, but for the first (a), second (b) categories, and the residue (c) of northward jumps of the EAJS. The thick solid line denotes the composite EAJS’s axis.

Fig. 8. Composite horizontal wind anomalies at 200 hPa at pentad 0 for the first (a) and second (b) categories of northward jumps of the EAJS. Shading indicates significance for U200 anomalies at the 95% confidence level.
middle and high latitudes.

The composite zonal wind anomalies for the weakening category exhibit a rather different feature, in comparison with those for the enhancing category. For the weakening category, the significant anomalies are basically concentrated at pentads 0 and 1. These anomalies do not exhibit a tendency of southward shift, and they are less persistent. Actually, the EAJS's axis also does not show a clear meridional shift during pentads 0 and 1 for the weakening category, while it shifts southward unambiguously for the enhancing category (Fig. 7). For the weakening category, furthermore, the anomalies are in a triple teleconnection pattern from the subtropics to the mid-high latitudes, without the significant easterly in the high latitudes. These differences in anomalous patterns between the enhancing and weakening categories suggest that the mechanisms for these two categories of northward jumps might be different.

Wakabayashi and Kawamura (2004) identified two teleconnection patterns over northern Eurasia associated with the anomalous summer climate in Japan and they called the two patterns as Europe-Japan (EJ) 1 and EJ2. The two EJ patterns in their negative phases both form a cyclone anomaly over the Okhotsk Sea, similar to the composite result for the first category (Fig. 8a). Therefore, the first category of northward jump is likely related to the two EJ patterns over northern Eurasia. For the second category of northward jump, the associated anomalies consist of an anticyclone in mid latitudes and a cyclone in the subtropical of the eastern Asian coast (Fig. 8b), similar to the counterpart of the West Asia-Japan (WJ) pattern over the mid-latitude Eurasia (Wakabayashi and Kawamura 2004). This implies that the mechanisms for the two categories of northward jumps may be different. However, it should be mentioned that the different temporal scales are involved in the abrupt change of the EAJS and the teleconnection patterns, i.e., the abrupt change of the EAJS in the current work is resolved by pentad data, while the teleconnection patterns are defined based on monthly data. Therefore, it is likely that the abrupt change of EAJS reflects the transient features of the wave trains originated from remote source regions, while the teleconnection patterns show the ensemble monthly mean features of the wave train. An in-depth analysis on the possible connections between the two analyses is required for the future research.

4. Summary

In this study using the NCEP/NCAR reanalysis daily data of zonal wind from 1958 to 2002, we doc-
umented the seasonal northward jump of the East Asian upper-tropospheric jet stream (EAJS) in mid-summer over the East Asian coast. In climatology, the northward jump of the EAJS is identified in late July as the EAJS jumps to north of 45°N.

The northward jump of the EAJS in mid-summer shows a strong tendency of phase locking with the calendar year in late July. Based on the objective definition of abrupt northward jump made in this study, 27 northward jump cases are identified in the total 45 years by yearly examination, 14 of which happen in pentads 41 and 42 (July 20−29). The mean number for the jump pentads is 41.9 and the standard deviation is 2.4 pentads. Corresponding to the northward jump, precipitation is greatly suppressed in East Asia consistent with the withdrawal of the Baiu season.

A cluster analysis on the meridional variation of U200 anomalies along the eastern Asian coast associated with the northward jump of the EAJS indicates that two thirds of the northward jump events can fall into two categories: enhancing category and weakening category. In these two categories, the intensity of the EAJS is enhanced and weakened, respectively, corresponding to the northward jump. For the enhancing category, the high-latitude westerly anomaly and mid-latitude easterly anomaly, which are located north and south of the EAJS's axis, respectively, appear prior to the northward jump and present a clear southward phase shift. For the weakening category, in contrast, the significant anomalies are basically concentrated at the jump pentad and the following pentad and do not exhibit a tendency of meridional shift. In addition, after the jump pentad, the significant 200-hPa zonal wind anomalies exhibit a four-cell teleconnection pattern from the subtropical WNP to eastern Russia for the enhancing category, while they are in a triple teleconnection pattern from the subtropics to Northeast Asia for the weakening category. These differences suggest that the mechanisms for the northward jump might be different between these two categories.

The present results showed that the northward jump of the EAJS is related to the significant circulation change, such as the meridional teleconnection pattern in the upper troposphere along the eastern Asia coast. Clearly, much remains to be understood about the dynamical processes and physical mechanisms for this northward jump of the EAJS. On the other hand, what is the effect of this jump on the regional weather and climate in East Asian countries? Such questions are worth further study.

The current evaluation of model simulation on the seasonal evolution of the East Asian monsoon is concentrated on the low-level circulation and precipitation (Kang et al. 2002; Wang et al. 2004; Sumi et al. 2004). Not much attention has been paid to the circulation evolution in the upper troposphere, though the northward shift of the EAJS is found to be related to the seasonal evolution of the East Asian summer rain belt (Yeh et al. 1959; Li et al. 2004, and this paper). The present results may be used to evaluate the seasonal variation of the summer EAJS in climate models.

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