Variations of the East Asian Jet Stream and Asian–Pacific–American Winter Climate Anomalies

SONG YANG
NOAA/NWS/NCEP Climate Prediction Center, Camp Springs, Maryland

K.-M. LAU
Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland

K.-M. KIM
Science Systems and Applications, Inc., Lanham, Maryland

(Manuscript received 16 October 2000, in final form 3 August 2001)

ABSTRACT

In this study, the authors apply the NCEP–NCAR reanalysis and other observations to depict the association of the Asian–Pacific–American climate with the East Asian jet stream (EAJS). With an emphasis on boreal winter seasons and on interannual timescales, they analyze the variations of the EAJS and their relationships with El Niño–Southern Oscillation (ENSO) and extratropical North Pacific sea surface temperature (SST), and assess the relative connections of the EAJS and ENSO to the anomalies of atmospheric circulation, surface temperature, and precipitation in the Asian–Pacific–American region.

It is found that the EAJS is coupled to a teleconnection pattern spanning the entire Asian–Paciﬁc–American region with the strongest signals over east Asia and the western Paciﬁc. This pattern differs signiﬁcantly from that associated with ENSO, which inﬂuences the earth’s climate extensively with a strongest impact on the climate over the central Paciﬁc and east. A strong EAJS is associated with an intensiﬁcation of the weather and climate systems in Asia and over the Paciﬁc such as deepening of the east Asian trough and the Aleutian low and strengthening of the east Asian winter monsoon. It is linked to colder and drier conditions in east Asia and stronger convection over the tropical Asia–Australia sector. Compared with ENSO, the EAJS seems to link to the climate signals of Asia and the Paciﬁc more strongly. An intensiﬁed EAJS is also associated with anomalies of temperature and precipitation in North America due to the related changes in stationary wave patterns.

While the EAJS does not strongly link to the tropical central-eastern Paciﬁc SST, it is signiﬁcantly associated with the extratropical North Paciﬁc SST, more speciﬁcally the second most dominant mode of the empirical orthogonal function analysis of the SST. In addition, a strong (weak) EAJS seems to follow a large (small) meridional gradient of the western Paciﬁc SST associated with warming (cooling) in the Tropics–subtropics and cooling (warming) in the extratropics.

1. Introduction

The wintertime upper-tropospheric westerly jet stream over subtropical east Asia and the western Paciﬁc, often referred to as east Asian jet stream (EAJS), is an important atmospheric circulation system in the Asian–Paciﬁc (AP) region. It varies on a wide range of timescales and is closely associated with many features of the AP weather and climate. Substantial efforts have been devoted during the past several decades into investigating the structure, maintenance, and variability of the EAJS as well as its connection to the weather and climate in the AP region [e.g., Hsieh 1951; Ramage 1952; Academia Sinica (Staff Members) 1958; Mohri 1959; Krishnamurti 1961; Reiter 1963; Palmén and Newton 1969; Blackmon et al. 1977; Murakami and Unninayar 1977; Cressman 1984; Kang 1990]. Previous studies have shown that the EAJS is associated closely with many synoptic-scale phenomena such as cyclogenesis, frontogenesis, monsoon, blocking, and storm track activity (e.g., Palmén and Newton 1969; Zeng 1979; Kung and Chan 1981; Dole and Black 1990; Gao and Tao 1991; Bell et al. 2000). Therefore, understanding the variability of the EAJS has also been an important subject of the operational weather analysis and forecast in many Asian countries.

On the seasonal and longer timescales, previous studies have focused on the seasonal cycle and interannual
and longer timescale variability of the EAJS and its association with the AP climate. It has long been known that the seasonal shift of the EAJS marks an abrupt seasonal transition of the atmospheric circulation regimes in Asia (e.g., Yeh et al. 1959). The changes in EAJS are accompanied by many climate signals including monsoon anomalies especially in the east Asian countries (Tao and Chen 1987; Lau et al. 1988; Ding 1992; Webster and Yang 1992; Yang et al. 1996; Liang and Wang 1998; Lau et al. 2000). Much effort has also been devoted to investigating the relationship between the EAJS and the earth’s surface boundary forcing and understanding the EAJS’s teleconnection with other climate systems. Orography and land–sea thermal contrast have been considered important basic forcing for the EAJS (Bolin 1950; Smagorinsky 1953; Huang and Gambo 1982; Wallace 1983). Evidence also indicates that the variability of the EAJS is associated with the Hadley circulation (Palmén 1951; Bjerknes 1966; Hou 1998) and with diabatic heating in the Tropics especially over the Maritime Continent and the western Pacific (Chang and Lau 1980; Hoskins and Karoly 1981; Webster 1981; Chang and Lum 1985; Kang and Held 1986; Lau and Boyle 1987; Yang and Webster 1990; Dong et al. 1999). Numerous studies have reported that the jet stream intensifies and shifts eastward during El Niño winters (e.g., Rasmusson and Wallace 1983; Mo et al. 1998; Chen and van den Dool 1999).

Although the variability of EAJS and its impact on weather and climate have been studied extensively, a number of questions remain unanswered. Firstly, the relationship of the EAJS with climate anomalies on interannual timescales, especially its connection to the anomalies relative to the impact of El Niño–Southern Oscillation (ENSO) has not been well understood. Indeed, our understanding of the EAJS and its climate linkage is largely limited to the knowledge provided by early studies, which are always restricted by the lack of long-recorded observations. Since the mid-1980s after the importance of the 1982/83 El Niño event was realized, interest in the research on AP climate has been shifted overwhelmingly to the understanding of ENSO’s impact (e.g., Rasmusson and Carpenter 1983; Webster and Yang 1992; Nicholls 1995; Shen and Lau 1995; Zhang et al. 1996; Hoerling et al. 1997; Soman and Slingo 1997; Webster et al. 1998; Yang and Lau 1998; Miyakoda et al. 1999; Wang and Fan 1999; Wang and Wu 2000). As a consequence, less and less effort has been devoted to understanding the importance of EAJS in variations of the climate.

Secondly, the physical mechanisms that are responsible for the year-to-year variability of the EAJS are unclear. Ensemble experiments with general circulation models have shown that the predictability of extratropical climate is generally low compared with its tropical
counterpart especially during non-ENSO years (e.g., Harzallah and Sadourny 1995; Sugi et al. 1997; Brankovic and Palmer 2000). In particular, the change in the EAJS is characterized by a strong natural variability. However, is the variability of the EAJS linked to the earth’s surface forcings at all? If yes, how strong is this linkage? The forcings, which can be local or remote, reside in the variations of sea surface temperature (SST) and land surface processes and may not be necessarily linked to the nature of ENSO. Numerous studies have investigated the relationship between the extratropical North Pacific SST (NPSST) and the overlying atmospheric circulation though not particularly the EAJS (Lau and Nath 1990, 1996; Kawamura 1994; Deser and Blackmon 1995; Zhang et al. 1998; Enfield and Mestas-Nuñez 1999). Many studies have delivered diverse results and no conclusive relationship has been recognized between the extratropical SST and atmospheric circulation (e.g., Lau and Nath 1990, 1996; Deser and Blackmon 1995; Peng et al. 1997; Ting and Wang 1997). While some studies claim that the variability of extratropical NPSST is a response to the overlying atmosphere, others indicate that the SST can force, at least provide feedback to, the atmospheric circulation. The recent review by Robinson (2000) shows that the atmospheric response to extratropical SST anomalies is weak but not negligible.

In this study, we will address several issues that are related to the variability of the EAJS and its association with the Asian-Pacific–American (APA) climate with a focus on interannual timescales. First, we will examine the relationships between ENSO and the variability of EAJS, which have often been overshadowed by the connection between ENSO and the upper-tropospheric winds over the northern extratropics of the central Pacific. Second, we will depict the atmospheric and oceanic features that are related to the EAJS and ENSO. Third, we will assess the importance of the EAJS and ENSO in linking both broadscale and regional climate signals of the APA region. In addition, we will examine the relationship of the EAJS with the NPSST in the subtropics and extratropics, without addressing the de-
tailed processes of ocean–atmosphere interaction. This study differs from previous studies in several aspects. We examine the interannual variability of the EAJS and its association with climate signals using updated long-recorded data, which is difficult to do before the availability of reanalysis data. Also, our effort is devoted to understanding the relative connections of the EAJS and ENSO to the climate anomalies of APA region. Furthermore, with a focus on the role of the EAJS, we attempt to provide information that is useful for understanding the linkage between Asian and North American climate anomalies.

After a data description in section 2, we will document the general characteristics of the EAJS and provide a comparison of the features of atmospheric circulation patterns that are related to the EAJS and ENSO in section 3. The association of the APA climate with the EAJS and ENSO will be discussed in section 4, where we analyze both the broadscale signals of the troposphere and the regional climate features in the fields such as winter monsoon flow, temperature, and precipitation. The linkage between the EAJS and NPSST is discussed in section 5. Conclusions and further discussions of the results are presented finally in section 6.

2. Datasets

The primary data used in this study are the winds, temperature, geopotential height, and sea level pressure (SLP) from the reanalysis product of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) for 1968–2000 (Kalnay et al. 1996). The NCEP–NCAR reanalysis data is currently available for a period starting January 1948. However, because the quality of the analysis over Asia may be low prior to 1968 (see the appendix), only the information since 1968 is analyzed in this study.

Another dataset used is the surface air temperature (Ts) from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS). The GISS analysis provides a measure of the monthly global Ts (Hansen et al. 1999). While it uses measurements made at rural and small-town stations, information from urban stations is adjusted such that its long-term trend matches that of the rural counterpart. The direct data source of this analysis is the Global Historical Climatology Network of Peterson and Vose (1997). In our study, the data from 1968 to 1999 is analyzed to be consisted with the NCEP–NCAR reanalysis, in spite of its availability since 1950. For this period, the analysis includes results for a global temperature index (Hansen et al. 1996), which is constructed by combining the meteorological station measurements over land with SST obtained primarily from satellite measurements (Smith et al. 1996). (More information about the GISS analysis can be found online at http://www.giss.nasa.gov/data/update/gistemp.)

The precipitation data analyzed here include the Cli-
mate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997). For the land areas, we also use the precipitation and surface temperature data from a product that has been recently developed by the Climatic Research Unit (CRU) of the United Kingdom (New et al. 2000). In addition, the NCEP reconstructed SST (Smith et al. 1996) and Southern Oscillation index (SOI) are employed in this study. Except for the CMAP data, which is available only since January 1979, we analyze the SOI and the land-area surface temperature and precipitation data since 1968 to match the NCEP–NCAR reanalysis although they are available before that time.

3. EAJS and ENSO associated teleconnection patterns

Figure 1 shows the 1968–2000 December–February (DJF) climatology of the zonal wind component at 200-mb (U200), interannual standard deviation of the wind, and correlation between SOI and the U200 at each grid point. Both the standard deviation and correlation are computed from the yearly DJF-averaged values. Figure 1a indicates that, during wintertime, the largest values of global U200 appear over east Asia, with a maximum wind speed greater than 70 m s$^{-1}$ over the ocean immediately to the south of Japan (around 32.5$^\circ$N, 140$^\circ$E). Two other westerly wind maxima are over Saudi Arabia–Egypt (>50 m s$^{-1}$) and the east coast of the United States (>40 m s$^{-1}$), respectively. Easterly wind maxima are located over Zaire–Tanzania, the Indonesian region, and Peru–Brazil. These easterly centers are major circulation components of the Southern Hemisphere summer monsoon subsystems.

Figure 1b shows that the largest interannual standard deviations of U200 do not appear within the maximum centers of the zonal wind (compared with Fig. 1a), but are concentrated in the tropics and subtropics of the central-eastern Pacific. The variability of U200 is actually small over all of Asia. Ramage (1952) attributed the small variability of the Asian jet stream to the effect of the Tibetan Plateau. Also, the variations of the U200 maximum shown in Fig. 1a are not strongly related to ENSO measured by SOI (Fig. 1c), at least in a linear sense. (The weak ENSO–EAJS relationship will be demonstrated supportively by a composite analysis as shown later in Fig. 4.) Indeed, the correlation between SOI and the wind near the EAJS core area is close to zero. Furthermore, the U200 over broad subtropical Asia and Pacific west of the date line is only weakly correlated with ENSO. Clearly evident in Figs. 1b and 1c is that the maximum U200 variances over the tropical–subtropical central Pacific are associated strongly with ENSO. In addition, the easterlies over the Asian–Australian monsoon regions bear a significant signal related to ENSO, although the magnitude of the winds’ variations is relatively small (Fig. 1b). It should be pointed out that the features shown in Fig. 1c remain largely similar when SOI is replaced by Niño-3 SST in the computation.

To depict the detailed features of variations of the EAJS core, we display in Fig. 2 the statistics including the locations, frequencies, and averaged values of the EAJS maximum. The figure shows that, out of the total 33 winters from 1968 to 2000, the EAJS maximum appears over 32.5$^\circ$N, 140$^\circ$E in 12 seasons, with an averaged intensity of 74 m s$^{-1}$. It only shifts northward to 35$^\circ$N in four winters. Longitudinally, the maximum appears in only one grid (2.5$^\circ$ of lon) to the east of this location in six seasons and to the west of it in three seasons. The EAJS core is always confined within the longitudes of 130$^\circ$–160$^\circ$E, and only in three winters it moves away from its climatological location (32.5$^\circ$N, 140$^\circ$E) by 10$^\circ$ of longitude. These largest shifts occur in the winters of 1976/77 (80 m s$^{-1}$), 1980/81 (82 m s$^{-1}$), and 1986/87 (76 m s$^{-1}$) when the EAJS core moves eastward to 150$^\circ$E and beyond. Note that, among these three events, only 1986/87 is an El Niño case.

The small migration of the EAJS maximum, espe-
Fig. 6. (a) 1968–2000 climatology of DJF geopotential height at 500 mb (H500; in m), (b) difference in H500 between strong and weak EAJS, and (c) difference in H500 between El Niño and La Niña years. (See Fig. 4 for the detail of chosen years).
Fig. 7. Quasi-stationary wave activity flux for (a) strong EAJS, (b) weak EAJS, and (c) the difference between the strong and weak EAJS groups. (See Fig. 4 for the detail of chosen years). The vectors are for the 300-mb horizontal components (in m$^2$s$^{-2}$) and the contours and shadings for the vertical component at 850 mb ($\times 10^4$ m$^2$s$^{-2}$). Values $\geq 4$ m$^2$s$^{-2}$ are shaded in (a) and (b), and positive values are shaded in (c).

Spatially latitudinally, facilitates the construction of an index to measure the variability of the jet stream. We define this index as the yearly DJF U200 averaged within 30$^\circ$–35$^\circ$N and 130$^\circ$–160$^\circ$E. The box covers the area within which all the EAJS maxima appear (see Fig. 2a). Figure 3a shows the time series of the normalized EAJS index, together with that of SOI. Out of the 33 yr, the EAJS strays from its climatological value by one standard deviation or more in 9 yr. (These years are chosen to construct composite patterns that will be analyzed later.) The figure shows no apparent relationship between the EAJS and ENSO. The linear correlation between the two time series is insignificant, with a coefficient of 0.05.
After depicting the ENSO-associated teleconnection (Fig. 1c) and the insignificant ENSO–EAJS relationship, it is interesting to show the teleconnection pattern associated with the EAJS. Figure 3b, in which the correlation between the EAJS index and global gridpoint U200 is displayed, shows that the intensification of the EAJS is accompanied by a reduction of westerly component over the northern extratropics from southeastern Russia to the Bering Sea and over the tropical western Pacific. The strengthening EAJS core increases the U200 upstream and downstream, and the downstream intensification is more evident. Importantly, the EAJS-associated pattern shown in Fig. 3b is substantially different from the ENSO-related pattern shown in Fig. 1c. Except for the Asian–Australian tropical monsoon region, the major ENSO-related features are limited to the east of the date line, oriented in a north–south direction over the central-eastern Pacific. On the contrary, the

**Fig. 8.** (a) Regressions (in m s⁻¹) of the DJF 850-mb winds against the EAJS. Thick vectors represent the values that either EAJS–U850 correlation or EAJS–V850 correlation is significant at 95% confidence level, where U850 and V850 are the zonal and meridional components of the winds. (b) Same as in (a) but for the regressions of the winds against SOI.
features that are related to the EAJS appear mainly over east Asia and the western-central Pacific, oriented from northwest to southeast. At the locations where SOI–U200 correlations are strongest, the EAJS–U200 correlations are among the weakest, and vice versa. These features imply that the EAJS and ENSO are associated with two different modes of the atmospheric circulation over the APA region, which will be confirmed later. It should be pointed out that the pattern of Fig. 3b is nearly identical to the correlation pattern in which the EAJS index is replaced by the one-point U200 time series of the climatological jet core (not shown). Thus, the index shown in Fig. 3a measures appropriately the variability of EAJS maximum.

To confirm the results from correlation computations (Figs. 1c and 3b), we construct composite patterns for strong and weak EAJS years (when the magnitude of EAJS departs from its climatology by one standard deviation or more), and for El Niño and La Niña years (|SOI| ≥ 1). It can be seen from Fig. 4 that the composite features for strong and weak EAJS (Figs. 4a,b) are consistent with those of Fig. 3b and that the composite features for ENSO (Figs. 4c,d) are similar to those of Fig. 1c. Unlike Figs. 1 and 3, Fig. 4 shows the magnitude of the changes in U200 and indicates that the features presented above are not limited to a linear analysis. The main features of the composite patterns remain similar when more data samples are employed by including the years of moderate EAJS and SOI variations (less than one standard deviation). Thus, the features displayed in these figures are very robust and do not depend apparently on analysis methods and data samples.

It is interesting to know whether the ENSO- and EAJS-related teleconnection patterns discussed above are represented by the leading modes of the atmospheric circulation. We compute the empirical orthogonal function (EOF) of DJF U200. We chose the domain of 0°–60°N and 60°E–120°W to focus on the EAJS and the U200 over Asia and the Pacific. Shown in Fig. 5 are the patterns of the eigenvectors and corresponding principal components of the first two gravest EOF modes. Clearly, these two orthogonal leading modes capture the features that are associated with ENSO and EAJS, shown in Figs. 1c, 3b, and 4. The first mode mimics the ENSO-related feature: the subtropical central Pacific U200, centered over 30°N/150°W, increases during El Niño winters and decreases during La Niña winters. On the other hand, the second mode captures the strong signals over Asia and the western Pacific, where the zonal wind bands are oriented in a northwest–southeast direction.

4. EAJS and Asian–Pacific–American climate

a. Broadscale circulation patterns

Figure 6 shows the DJF climatology of 500-mb geopotential height (H500; Fig. 6a) and composite patterns of the difference in H500 between strong and weak EAJS (Fig. 6b) and between El Niño and La Niña years (Fig. 6c). For Fig. 6a, we shall focus on the east Asian trough, the trough over the eastern United States, and the ridges over extratropical central Asia and the west coast of North America. Climatologically, the east Asian trough is anchored along the east coast of east Asia, extending from the Sea of Okhotsk through Japan to the East China Sea. When the EAJS strengthens, the trough deepens remarkably with H500 decreased to the east and increased to the west. It is not difficult to see from the figure that a strong EAJS is associated with an increase in H500 in the ridge locations and a decrease in the troughs over the entire extratropics. Thus, an intensified EAJS is accompanied by an adjustment of the large-scale circulation systems that favors a stronger wave train pattern across Asia, Pacific, and North America.

One of the important features of Fig. 6 is that the changes associated with the EAJS are clearly larger than those with ENSO (compare the middle and lower panels). This feature also emerges from the linear regression patterns of H500 against the EAJS and SOI. El Niño tends to decrease H500 in most of the extratropical APA region except the northern part of North America and southern Asia. The largest changes are the decrease over the eastern Pacific and northern Russia and the increase over Canada. Obviously, the change in H500 associated with ENSO is different from that with the EAJS. Although both the EAJS and ENSO cause changes in the Pacific–North American (PNA) domain (see also Schubert et al. 1993), the centers of H500 difference in both Figs. 6a and 6b are different from those of the PNA teleconnection pattern (Wallace and Gutzler 1981). How these changes in H500 are related to signals in tem-
Fig. 10. DJF correlation between the EAJS and GISS surface air temperature (a) for the period 1968–99 and that between the EAJS and CMAP precipitation (b) for the period 1979–99. Contour intervals are 0.2 in (a) and 0.3 in (b), with the zero contours omitted for clearness. Negative values are plotted in dashed lines and values ≥ 95% confidence level are shaded.

To delineate the source and propagation of wave activity that are associated with the change in EAJS, we compute the stationary wave activity flux (SWAF; Plumb 1985). According to Plumb, the SWAF is more revealing and less misleading than energetic arguments for analyzing wave behaviors. Following Yang and Gutowski (1994), we analyze the horizontal propagation at 300 mb and the source of wave activity at 850 mb. Figure 7 indicates that the stationary wave activity usually propagates eastward and upward, which is consistent with the characteristics of wave train described by Hoskins and Karoly (1981) and the conventional understanding of the stationary wave field (Plumb 1985). The largest flux emanates from east Asia where it propagates both southward and northward. A profound feature of Fig. 7a is that, in the category of strong EAJS, the SWAF is larger with distinctly stronger source over east Asia and the eastern Pacific including western North America. Associated with the enhancement of SWAF over the south of Gulf of Alaska is an intensifying latent heating rate over the region (figure not shown). It can be seen from Figs. 7b and 7c that, for weak EAJS, the northeastward propagation of SWAF over east Asia north of 40°N weakens. This weakening is accompanied
Fig. 11. Patterns of difference in (a) and (c) surface air temperature (°C), and (b) and (d) the percentage change of precipitation, between the strong and weak EAJS for east Asia and the United States. (See Fig. 4 for detail of the years.) The data is from the CRU of the United Kingdom. Negative values are shaded.

by an intensification of the upward propagation over the Sea of Okhotsk and nearby regions. In brief, consistent with Fig. 6, Fig. 7 shows a strong teleconnection between east Asia and North America, associated with the variations of EAJS. It should also be pointed out that the features shown in Fig. 7 are remarkably different from those related to ENSO. The latter is characterized mainly by the changes in meridional propagation of SWAF over the tropical Pacific but weaker signals in the extratropics (figure not shown; see also Karoly et al. 1989).

b. Regional-scale features

In this section, we investigate the association of the EAJS with APA climate anomalies on more regional scales. We will study the fields of low-level circulation, surface temperature, and precipitation by applying both linear and composite analyses.

1) Low-level circulation systems

Presented in Fig. 8 is the pattern of regressions of 850-mb wind vectors against the EAJS. (For comparison, we also show the corresponding pattern associated with ENSO.) Figure 8a shows that an intensifying EAJS is accompanied by a cyclonic pattern over the entire North Pacific (north of 15°N). This pattern, which is statistically significant (see thick vectors), links Asia at one end and North America at the other end. The cyclonic pattern is also related to the change in the trade winds over the tropical central Pacific, which become moderately more vigorous when the EAJS is strong. Other features of Fig. 8a include the intensification of the Asian continent high and the appearance of a cyclonic pattern over the eastern United States and western Atlantic associated with a strong EAJS.

The changes in the low-level circulation pattern associated with ENSO exhibit different features (Fig. 8b). The largest differences between Figs. 8a and 8b exist in the changes in the tropical Pacific trade winds and the Indian Ocean equatorial westerlies, with much stronger signals associated with ENSO. Although ENSO-related cyclonic patterns also appear over the North Pacific and eastern United States, their locations and shapes are inconsistent with those of Fig. 8a. Furthermore, the intensity of the Asian continent high is different between the strong and weak EAJS years but does not respond to ENSO. This feature can be seen more clearly from the field of SLP (figure not presented). An
examination of SLP field also indicates that the EAJS links larger signals in the Aleutian low but ENSO causes stronger changes over the Gulf of Alaska. In addition, Fig. 8 shows that the EAJS is significantly associated with the changes in the east Asian winter monsoon and that the ENSO-related changes in the monsoon are mainly confined over the northern South China Sea, south China, and the East China Sea.

The east Asian winter monsoon is one of the most important systems that determine the characteristics of wintertime AP climate. Although it has been known to link closely to many weather and climate phenomena in east Asia (e.g., Zhang et al. 1997a; Compo et al. 1999), a commonly accepted index that can be employed to measure the monsoon has not been seen. One of the major features of the east Asian winter monsoon is that it is a relatively shallow system, compared with its summer counterpart. Hence, to derive a dynamic index to measure the monsoon, information of low-level circulation especially the meridional wind component at 850 mb (V850) is mostly appropriate (Prof. C. Li 1999, personal communication). In this study, we measure the monsoon’s variability by constructing a time series from the DJF V850 that is averaged over the domain of 20°–40°N, 100°–140°E, the core region of the monsoon.

Figure 9 shows the variability of the east Asian winter monsoon and its relations to the EAJS and ENSO. It can be seen that the winter monsoon is significantly correlated with the EAJS (R=0.67 for the period 1968–2000). It intensifies when the EAJS is strong, and vice versa. The figure indicates that almost every peak of the EAJS index is accompanied by a consistent change in the winter monsoon index. On the other hand, the relationship between ENSO and the east Asian winter monsoon is relatively weaker. Although the monsoon is weak (positive V850) during El Niño years (6 out of 9 yr), no apparent relationship can be found for the La Niña years. Overall, the significance of the correlation between the monsoon and SOI is under the 95% confidence level, with a coefficient of –0.32.

2) SURFACE TEMPERATURE AND PRECIPITATION

We now analyze the signals in the two most basic fields of climate: surface temperature and precipitation. Figure 10 shows the patterns of correlation of the GISS Ts and CMAP precipitation with EAJS. For the EAJS–Ts correlation (Fig. 10a), the key feature is the shaded, significantly negative values in the extratropics and positive values in the subtropics and high latitudes in the Asian–Pacific region. A strong EAJS is associated with colder winter over east Asia and most of the extratropical Pacific but warmer over the tropical western Pacific. A strong EAJS is also associated with warming in Alaska and western North America and cooling in the eastern United States. Over the tropical central-eastern Pacific, no noticeable feature exists. This is consistent with the results of Kang and Lau (1986) whose corresponding atmospheric mode is similar to the EAJS-related mode shown in this study. Clearly, the features described above are different from the relatively more familiar ENSO-related changes in surface temperature that appear dominantly in the Tropics–subtropics of the Pacific and Indian Oceans but show a much weaker signal over the Asian continent.

Figure 10b shows that a strong EAJS is associated with enhanced convective activities over the tropical western Pacific and Maritime Continent, in agreement with the previous results by Chang and Lau (1980) and Lau and Boyle (1987). It is also associated with an increase in latent heating over the ocean south of the Gulf of Alaska. On the other hand, a strong EAJS is connected to a decrease in precipitation over the northern continents especially east Asia, southeast of the Ural Mountains, and the southeastern United States. Al-
Fig. 13. (a) Correlation between the North Pacific SST PC-1 (see Fig. 12) and the DJF U200 at each grid point. (b) Same as in (a), but PC-1 is replaced by PC-2. Values $\geq 95\%$ confidence level are shaded.

though the statistical significance of the precipitation correlation cannot be determined accurately because of the limit in data samples, one of the important features shown in Fig. 10 is that the signals over the extratropics are stronger than those related to ENSO.

We further depict the relationship between the EAJS and surface temperature and precipitation fields by examining composite patterns. In particular, we analyze the information from an independent dataset, the CRU product from the United Kingdom. This product does not contain any information over oceans; however, its data over the land areas has represented an advance over other products (New et al. 2000). For precipitation, it has much longer records than the CMAP product so that we can analyze the information from 1968. Figure 11 shows the patterns of difference in surface temperature and precipitation (percentage change), between the strong and weak EAJS, for east Asia and the United States. It displays features that are generally similar to those shown by Fig. 10. In east Asia, especially in Japan and Korea and over the Sea of Japan and the East China Sea, temperature decreases apparently during the strong EAJS years. At the same time, the precipitation over Japan, Korea, and eastern China is reduced remarkably. In the United States, associated with a strong EAJS are the warm–dry condition in the west and cold–dry condition in the east. Clearly, the features shown in Figs. 11c,d are different from those of the ENSO-related changes in surface temperature and precipitation (see Wang and Fu 2000). It should be pointed out that the features shown in Fig. 11 are not strongly dependent on data samples and the major signals remain similar when more samples are used in the computations by including the years of moderately varied EAJS.
In spite of the difference in record length of the data used, a dynamical consistency can be seen from Figs. 8 and 10–11. The cold and dry conditions over the Asian continent and western Pacific during the strong EAJS are consistent with the strong Asian continent high and east Asian winter monsoon. The intensifying monsoon circulation is associated with stronger Hadley overturning and thus convection over the tropical western Pacific and Maritime Continent. When the EAJS is strong, the anomalous southerly flow over the eastern Pacific may bring warm air and thus increase the temperature in western North America. This anomalous flow may also block storms intruding from the west and reduce the precipitation in this western region. At the same time, the cold/dry condition in the eastern United States and the relatively warm–wet condition in southeastern Canada are dynamically consistent with the anomalous cyclonic pattern over eastern and western North Atlantic. The EAJS-related changes in the atmospheric circulation, temperature, and precipitation in the APA region are also consistent with the explanation of Trenberth and Hurrell (1994) in which a deeper and eastward-shifted Aleutian low (see Figs. 6 and 8) is associated with a warming along the west coast of North America and Alaska, a cooling in the extratropical western-central North Pacific, and a southward shift of the Pacific storm track.

The results discussed in this and the above sections can be confirmed by several approaches. First, the relevant calculations in which SOI is replaced by either Niño-3 or Niño-3.4 SST yield largely similar results to those presented in this study. Second, an analysis of the change in the satellite-derived outgoing longwave radiation (OLR) produces some features consistent with those shown in Figs. 10–11. For example, when the EAJS is strong, the OLR decreases substantially over the tropical Asian–Australian region, indicating strong convection. It also decreases over extratropical Asia and Pacific region, consistent with the cold surface conditions. In addition, the main features presented above are robust and remain consistent from one event to another within the same (strong or weak EAJS) category. This is especially so for the fields of wind and geopotential height. For surface temperature and precipitation, the event-to-event consistency can be seen over east Asia, through the Pacific, to North America in most cases. The most consistent features are the cooling (warming) in extratropical east Asia and the western Pacific and the increase (decrease) of convective activities over the tropical Asian–Australian region when the EAJS is strong (weak).

5. Linkage between EAJS and North Pacific SST

Although only surface air temperature is analyzed in Fig. 10a, the pattern suggests that the variability of EAJS is associated with the SST of subtropical–extratropical North Pacific, where Ts–EAJS correlation is among the strongest. In this section, we will explore more features about the connection of the EAJS to North Pacific SST. We will focus on the statistical relationship between the EAJS and NPSST but not on the detailed features of the interactive processes of SST and overlying low-level atmosphere. Figure 12 shows the patterns of eigenvectors and principal components (PC-1 and PC-2) of the first two gravest modes from the EOF analysis of DJF NPSST. The first mode (Fig. 12a) features SST changes of different sign between the equatorial central-eastern Pacific and subtropical–extratropical Pacific. It is significantly correlated to SOI with a coefficient of 0.85 for the period 1968–99 (suggesting that the first mode is an ENSO mode), but has an insignificant relationship with the EAJS ($r = -0.12$). The dominant feature of the second SST mode (Fig. 12b) is

![Fig. 14: Difference in DJF SST (°C) between strong and weak EAJS. (See Fig. 4 for the detail of chosen years.)](image-url)
the major band in the extratropical western-central Pacific, between 30° and 50°N. This mode is similar to the pattern of correlation between the EAJS and grid-point SST, suggesting that the second SST mode is characterized by the features of both extratropical ocean and atmosphere. Indeed, a significant correlation coefficient of 0.60 has been found between the SST PC-2 and the EAJS. However, the coefficient of correlation between the PC-2 and SOI is only 0.11.

Figure 13 shows the correlation of the PC-1 and PC-2 of NPSST with the gridpoint DJF U200. The PC-1 is significantly correlated to the atmospheric circulation over the central-eastern Pacific and the Americas of both hemispheres, a feature similar to that of SOI–U200 correlation (Fig. 1c). On the other hand, the PC-2 is strongly associated with the changes in the atmospheric circulation over Asia and the western Pacific including the EAJS, resembling the feature of EAJS–U200 correlation (Fig. 3b). While these characteristics have become evident from the analyses discussed above, Fig. 13b does indicate and confirm a very important feature: the connection between the EAJS and NPSST reflects a relationship between the second modes of the atmosphere and ocean in the Asian–Pacific region. It should also be pointed out that the result shown here bears a similarity to the features of intraseasonal timescale described by Nakamura (1996).

To support the above results from linear analyses and to obtain the magnitude of SST changes associated with the EAJS, we examine the composite pattern of SST difference between the strong and weak EAJS. Figure 14 shows that a strong EAJS is accompanied by a broad-scale decrease in the SST of the extratropical North Pacific within 22°–50°N. The maximum SST reduction occurs near 37°N. A decrease in SST can also be seen in the ocean domains adjacent to south and Southeast Asia and in the equatorial central-eastern Pacific. Another feature of the figure is the increase in SST, associated with a strong EAJS, in the subtropical Pacific (8°–22°N) and the equatorial western Pacific Ocean. Overall, the pattern shown in Fig. 14 is similar to that of Fig. 12b, the second mode of NPSST.

We now examine the lag relationship between the EAJS and NPSST. Figure 15 shows the pattern of SST difference for the September–November (SON) seasons before the strong and weak EAJS (strong minus weak). The figure indicates an important feature in the Eastern Hemisphere: before a strong EAJS, the SST increases to the south and decreases to the north of the jet stream with a small change under it. It can be seen from comparing Figs. 14 and 15 that although the northern boundary of cooling lies in a similar latitude, a warming appears from Fig. 15 in a large portion of the tropical–subtropical western Pacific. This indicates a larger meridional gradient of the SST in the western Pacific before a strong EAJS. In the Indian Ocean and the South China Sea, the SST also tends to be higher before a strong EAJS.

The variability of the EAJS and the NPSST seems to be dynamically consistent. A strong DJF EAJS is associated with strong surface westerlies over 25°–42°N as seen from the changes in DJF 1000-mb zonal wind (figures not shown; refer to Fig. 8a), a general equivalent-barotropic feature of extratropical signals. The intensifying surface wind should cause strong mixing and evaporation and decrease the SST. For the same reason, the strong EAJS-related warming in the subtropical Pacific within 8°–22°N is consistently associated with the weakening of the northeasterly trade winds over the ocean domain, which can also be inferred from Fig. 8a. This discussion of the active role of the atmosphere as shown by many previous studies (see review of Robinson 2000) seems to be supported by the changes in the following spring SST (not shown), which bear a
Fig. 16. Difference in the SON 1000-mb winds before the strong and weak DJF EAJS. (See Fig. 4 for the detail of chosen years.)

large similarity to the features shown in Fig. 14 for DJF, although the similarity between the DJF and spring SST patterns may be attributed by the persistence of the anomalies of DJF SST.

A dynamical consistency can also be found between the SST and atmospheric circulation during SON by comparing Fig. 15 to Fig. 16, which shows the pattern of SON 1000-mb winds corresponding to the SST difference presented in Fig. 15. The figures indicate a cyclonic atmospheric circulation pattern over the cooling region in the extratropical North Pacific and an anticyclonic pattern over the warming in the western Pacific. The consistency in the wind and SST distributions can be explained by the Ekman drift and the advection due to wind stress. How these atmospheric features appear is beyond the investigation of this study. Perhaps the more interesting question is whether or not the SST pattern shown in Fig. 15 will exert an impact on the jet stream during the following winter, at least the early winter. Although the above discussion tends to emphasize the forcing of the atmospheric circulation, a feedback of the SST signals to the atmosphere is also possible, as shown by many previous studies (e.g., Lau and Nath 1990; Peng et al. 1995; Ting and Peng 1995; Bladé 1997; Peng et al. 1997; Rodwell et al. 1999; Watanabe and Kimoto 2000) that have been conducted to investigate the complex interactive processes of the extratropical atmosphere and SST. General circulation model experiments with a forcing superimposed by the SST signals shown in Figs. 14 and 15 should provide a better understanding of the relationship of the EAJS to the meridional SST gradient and SST anomaly in the western Pacific, whose importance in midlatitude atmosphere–ocean interaction and in extratropical climate variability has been noticed by previous studies (e.g., Higgins and Schubert 1996; Ting and Wang 1997; Peng and Whitaker 1999).

6. Summary and discussions

In this study, we have investigated the association of the wintertime east Asian jet stream with the climate in the Asian–Pacific–American region. We have studied the interannual variability of the EAJS and its relationship with ENSO and the extratropical North Pacific SST, and addressed the relative connections of the EAJS and ENSO to APA climate signals.

We have defined an index based on the area-averaged U200 over 30°–35°N and 130°–160°E to measure the EAJS whose location does not change significantly from one year to another. The EAJS measured by the index does not strongly link to ENSO and is coupled to a teleconnection pattern that is distinguished clearly from the ENSO-related pattern. Although the major features of the EAJS-related pattern appear mainly over east Asia and the western Pacific, in a northwest–southeast ori-
entation, the EAJS may play an important role in connecting the climate signals over Asia and North America. A strong EAJS is clearly associated with an intensification of many atmospheric circulation systems including the Asian continent high, east Asian trough, Aleutian low, and the ridge over western North America and related to a strong east-southeastward propagation of stationary wave activity. When the EAJS is strong, the east Asian winter monsoon strengthens, colder and drier conditions prevail in east Asia, and enhanced convection appears over the equatorial Asian–Australian region. At the same time, warmer and drier condition appears in the western United States but a colder and drier feature is seen in the eastern part of the country. In addition, compared with ENSO, the EAJS is associated with stronger climate signals over east Asia and the extratropical North Pacific. For example, the east Asian winter monsoon circulation is more significantly correlated with the EAJS ($R = 0.67$) than with SOI ($R = -0.32$).

This study has clearly shown that ENSO and the EAJS are associated, respectively, with the first and second modes of the atmosphere and ocean in the APA region. A strong EAJS is significantly associated with a decrease in the extratropical North Pacific SST. The study has also identified an antecedent signal of the DJF EAJS in SON SST. Before a strong (weak) EAJS, a large (small) meridional gradient of SST has existed in the subtropical–extratropical western North Pacific. Although it is hard to determine the cause-and-effect relationship, there is a dynamic consistency between the SST and surface atmospheric circulation during the SON seasons before strong and weak EAJS events.

Clearly, the variability of the atmosphere and SST in the extratropical APA region is characterized by not only interannual but also other timescales. The teleconnection patterns related to these different timescales can possess similar features (e.g., Zhang et al. 1997b) and phenomena with different dominant timescales such as ENSO and the Arctic oscillation can have a mutual impact on the climate (Higgins et al. 2000). In this study, we only focus on the anomalies of APA climate and their connections to ENSO and the EAJS on interannual timescales. In addition, a brief analysis has indicated that the variations of the EAJS and its related features are also connected to the changes in the Eurasian snow cover (figures not presented). This result is consistent with the findings by Walland and Simmonds (1997) and Clark and Serreze (2000).

Acknowledgments. This study was funded by the Global Modeling and Analysis Program of the Earth Science Enterprise, NASA Headquarters. Song Yang was partially supported by NOAA’s CLIVAR-Pacific Program. We thank Drs. Gil Compo, In-Sik Kang, Kingtse Mo, Siegfried Schubert, and Julian Wang for helpful discussions. The comments from Editor Neville Nicholls and the three anonymous reviewers are appreciated for improving the quality of the paper.
APPENDIX

Possible Problem of the Early NCEP–NCAR Reanalysis Data over Asia

A potential problem of the NCEP–NCAR reanalysis for investigations of the Asian climate is that the quality of the data over Asia may be low prior to 1968. It has been realized that very few SLP data is used in the reanalysis system for the region before 1968 (refer to http://lnx21.wwb.noaa.gov/images/psfc/psfc.html). Although it is difficult to address how seriously this lack of input will affect the quality of the reanalysis data, we display here the possible discontinuity in the property of the data. We compare the time–latitude cross sections of monthly SLP information from the NCEP–NCAR reanalysis and Trenberth’s Northern Hemisphere data (Trenberth and Paolino 1980). The alternative Trenberth SLP was provided by the Data Support Section, Scientific Computing Division at NCAR, which is supported by the National Science Foundation (available online at http://dss.ucar.edu/datasets/ds010.1). Figure A1 shows the SLP anomalies (along 110°E) in which the mean annual cycle of the period 1968–2000 has been removed. It can be seen from Fig. A1a that, in spite of the removal of annual cycle, the reanalysis over Asia (e.g., 25°–60°N) displays consecutively an increase in winter and a decrease in summer, meaning a stronger annual cycle, for all the years before 1968. However, this feature disappears from Fig. A1b. It should be pointed out that because of the availability of the Trenberth data, only the information within 15°–85°N is compared in the figure. Although the reanalysis data varies substantially from year to year over the Antarctic where the quality of the data is always questionable, different from those over Asia, these variations do not show a specific pattern.

Figure A2 shows the patterns of difference in DJF SLP between the periods 1949–67 and 1968–2000, for both the NCEP–NCAR reanalysis and the Trenberth data. Substantial differences exist between the two panels of the figure. Specifically, a large center appears from the reanalysis (Fig. A2a) in eastern Russia, Mongolia, and northern China where the SLP is much higher during 1949–67. Obviously, the Trenberth data exhibits much smaller differences in these regions (Fig. A2b). From the comparison shown in Fig. A1, the feature shown in Fig. A2a does not seem to be a result of multidecadal variability. In addition, for June–August (figure not shown because this study focuses on winter season only), the SLP difference in NCEP–NCAR reanalysis gives a stronger (than the DJF counterpart) center over 30°–60°N, 65°–130°E. (This feature is consistent with that shown in Fig. A1a: the SLP before 1968 is high in winter and low in summer.) On the other hand, in the Trenberth SLP data, only a much weaker and less extensive center of the difference between 1949–67 and 1968–2000 appears over the Himalaya.

We also examined the changes in U200 and found some differences between the two periods before and after 1968. However, these differences are generally small and appear near the equator. Over Asia, the differences are mainly compatible to those over many other places. These features imply that if the lack of SLP in the NCEP–NCAR analysis causes flaws in data quality over Asia, the problem may be more serious at the lower troposphere than at the upper troposphere.

REFERENCES

Academia Sinica (Staff Members), 1958: On the general circulation over eastern Asia. Part II. Tellus, 10, 58–75.


Nicholls, N., 1995: All-India summer monsoon rainfall and sea surface temperatures around northern Australia and Indonesia. J. Climate, 8, 1463–1467.


Ramage, C. S., 1952: Relationship of general circulation to normal weather over southern Asia and the western Pacific during the cool season. *J. Meteor.*, 9, 403–408.


