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South Asian High and Asian-Pacific-American Climate Teleconnection

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ABSTRACT

Growing evidence indicates that the Asian monsoon plays an important role in affecting the weather and climate outside of Asia. However, this active role of the monsoon has not been demonstrated as thoroughly as has the variability of the monsoon caused by various impacting factors such as sea surface temperature and land surface. This study investigates the relationship between the Asian monsoon and the climate anomalies in the Asian-Pacific-American (APA) sector. A hypothesis is tested that the variability of the upper-tropospheric South Asian high (SAH), which is closely associated with the overall heating of the large-scale Asian monsoon, is linked to changes in the subtropical western Pacific high (SWPH), the mid-Pacific trough, and the Mexican high. The changes in these circulation systems cause variability in surface temperature and precipitation in the APA region. A stronger SAH is accompanied by a stronger and more extensive SWPH. The enlargement of the SWPH weakens the mid-Pacific trough. As a result, the southern portion of the Mexican high becomes stronger. These changes are associated with changes in atmospheric teleconnections, precipitation, and surface temperature throughout the APA region. When the SAH is stronger, precipitation increases in southern Asia, decreases over the Pacific Ocean, and increases over the Central America. Precipitation also increases over Australia and central Africa and decreases in the Mediterranean region. While the signals in surface temperature are weak over the tropical land portion, they are apparent in the mid latitudes and over the eastern Pacific Ocean.

Key words: South Asian high, subtropical western Pacific high, mid-Pacific trough, Mexican high, Asian-Pacific-American climate

1. Introduction

It has long been postulated that the Asian monsoon plays an active role in the variability of the world's weather and climate. Perhaps this postulation finds its roots in the observation that the Indian summer monsoon is more strongly related to the conditions of the Southern Oscillation after the monsoon than to those before the monsoon (Walker, 1923, 1924; Normand, 1953). Indeed, for the period of 1950-2000, the correlation coefficient is -0.45 (0.19) between the All-India summer monsoon rainfall and the wintertime Southern Oscillation index after (before) the monsoon. A similar feature has also been demonstrated between the monsoon and the surface pressure in Darwin, Australia (Shukla and Paolino, 1983). Growing evidence has demonstrated the importance of monsoon signals for explaining subsequent changes in the El Niño/Southern Oscillation (ENSO) and the coupled tropical atmosphere-ocean system, especially on the biennial timescales (e.g., Yasunari, 1990; Lau and Yang, 1996; Meehl, 1997; Chang and Li, 2000).

The influence of the Asian monsoon on ENSO has been attributed to the interaction between the westerlies and the easterly trade winds over the tropical Indo-Pacific oceans (Barnett 1984; Webster and Yang, 1992). Numerical models have shown that monsoon-related variability in wind stress and heat flux leads to changes in the intensity and phase of ENSO (Wainer and Webster, 1996; Chung and Nigam, 1999; Kirtman and Shukla, 2000; Kim and Lau, 2001; Wu and Kirtman, 2003). Limited evidence even suggests that monsoon activity triggers the onset of ENSO (Barnett et al., 1989; Li, 1990; Yasunari and Seki, 1992; Xu and Chan, 2001).

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The heating associated with the Asian summer monsoon has been linked to the variability of westerly jet streams in the Southern Hemisphere (Yang and Webster, 1990). Several studies (Yang et al., 1992; Webster et al., 1992, 1998, and Chen, 2003) have also emphasized the importance of this heating on the African monsoon and the climate over the Sahara desert through the lateral monsoon component. According to Rodwell and Hoskins (1996, 2001), while the change in the equatorward portion of the subtropical western Pacific high (SWPH) can be viewed as a Kelvin wave response, the Mediterranean climate is a Rossby wave response to the heating associated with the Asian monsoon.

Although it is known that the anomalies in the tropical western Pacific sea surface temperature (SST) are often linked to atmospheric wavetrains that affect the climate in East Asia, the North Pacific, and North America (e.g., Huang, 1984, 1985; Nitta, 1987; Lau and Peng, 1992), it is only recently that the relationship between the East Asian and North American climate has been studied explicitly (Lau and Weng, 2002; Lau et al., 2004; Ding and Wang, 2005; Lau et al., 2005; Li et al., 2005). The teleconnection pattern of the Asian-Pacific-American (APA) summer climate, which is apparently part of a circum-global pattern, is closely related to the second most dominant mode, as in the case of the winter season (Yang et al., 2002).

In spite of the evidence reviewed above, the impact of the Asian monsoon on the global climate has not been demonstrated as thoroughly as has the monsoon variability associated with factors such as SST and land surface processes. As pointed out by Yang and Lau (2005), the reasons for this problem include the substantial regional features of the monsoon and the difficulties in representing and integrating these regional features in numerical models as forcing functions. While one regional monsoon may be more influential in affecting the large-scale climate during a specific period of time, other regional monsoons may become more dominant at different times. The state-of-the-art general circulation models are still incapable of representing this relative dominance. For example, they cannot specify the meteorological elements that measure the atmospheric and land surface conditions over the Eurasian continent as a forcing for the coupled atmosphere-ocean-land climate system.

The upper-tropospheric South Asian high (SAH) is a major atmospheric component of the Asian monsoon. It plays an important role in affecting the climate in Asia, such as the summer rainfall pattern in central and northern China (e.g., Zhang and Wu, 2001; Huang and Qian, 2004). The SAH is a combined measure of the overall heating in the atmosphere and the land surface conditions (see Yang et al., 2004) and references therein). One of the advantages of representing the variability of the Asian monsoon by the change in the SAH is that the SAH assesses the gross features of the monsoon over a large portion of tropical Asia. Indeed, there exists a close relationship between the SAH and the Webster-Yang monsoon index (Webster and Yang, 1992), which measures the features of the broad-scale Asian monsoon circulation.

In this study, we depict the variability of summertime SAH and the associated variations of Asian, North Pacific, and North American climate. We focus on the interannual signals in the Asian monsoon system, the SWPH, the mid-Pacific trough, and the surface temperature and precipitation in the APA sector. In the next section, we provide a brief description of the datasets used. The results obtained will be analyzed in section 3 and summarized in section 4.

2. Data

The data used in this study include the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al., 1996). From the NCEP-NCAR reanalysis data, which are available from January 1948 to the present, with a horizontal resolution of $2.5° \times 2.5°$, we mainly analyze the geopotential height and winds.

A newly developed precipitation dataset (PREC) at NOAA's Climate Prediction Center (Chen et al., 2004) is used in our analysis of precipitation. The PREC data are available globally between 60°S and 75°N, covering the period from 1948 to the present. The precipitation analysis over land is determined by optimal interpolation of gauge observations for more than 17000 stations. Over the oceans, the analysis is determined by empirical orthogonal function reconstruction using historical gauge observations over islands and satellite-derived estimates.

We also analyze the surface air temperature from the Climate Anomaly Monitoring Systems (CAMS) product (Ropelewski et al., 1985). The CAMS temperature dataset is available for the period starting in 1950, with a resolution of $2° \times 2°$. It was constructed based on station observations over land and SST information over the oceans.

3. Results

3.1 *Variability of the South Asian high*

The South Asian high is one of the major circulation features of the upper troposphere over Asia. AS shown in Fig. 1, the other major summertime circula-

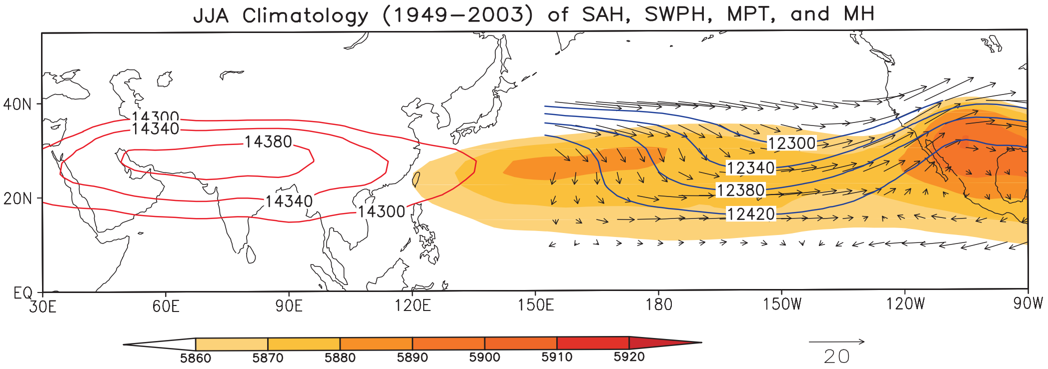


Fig. 1. JJA climatological (1949–2003) locations of the South Asian high measured by contours of 150-hPa geopotential height (in m), the subtropical western Pacific high and the Mexican high by shadings of 500-hPa geopotential height (m), and the mid-Pacific trough by 200-hPa wind vectors (m s^{-1}) and geopotential height (m) contours.

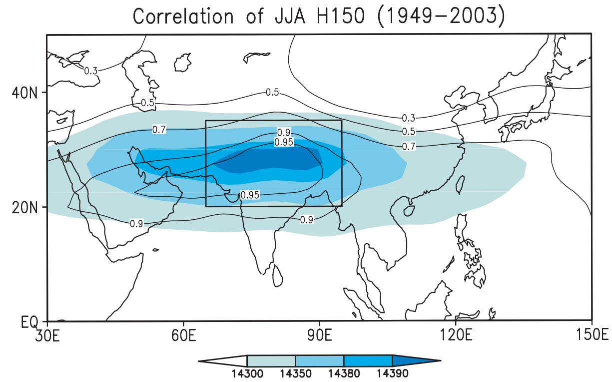


Fig. 2. JJA correlation between grid-point 150-hPa geopotential height and an index, which is the average of the height over 20°–35°N, 65°–95°E (see the box). Shown in the shadings is the pattern of the 150-hPa geopotential height.

tion features over the tropical-extratropical APA region include the subtropical western Pacific high, the mid-Pacific trough, and the Mexican high, besides the Walker circulation over the equator and the East Asian jet stream farther north (not shown in the figure). It is hypothesized that the variability of SAH is linked to the variability of the teleconnection pattern including changes in SWPH, the mid-oceanic trough, and the Mexican high. It is also hypothesized that the teleconnection pattern associated with these changes is accompanied by signals in surface temperature and precipitation in the APA region. These assumptions are based on the representation of the Asian monsoon by SAH (see discussion above), the strong monsoon-SWPH relationship (Rodwell and Hoskins, 1996), and the apparent link of the mid-Pacific trough with SWPH to the west and the Mexican high to the east.

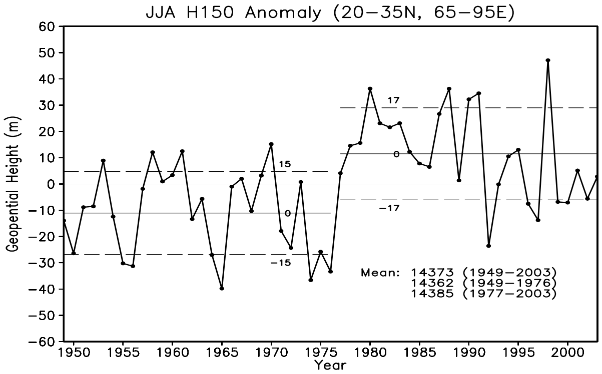
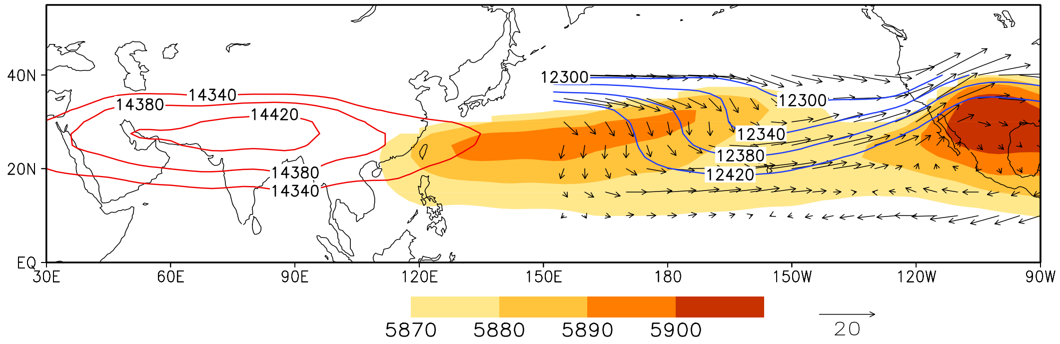


Fig. 3. Anomalies of the JJA SAH index used in Fig. 2 (see the box). Dashed lines indicate the values of standard deviation, which are 15 m for 1949–76 and 17 m for 1977–2003. Also given in the figure are the mean values (m) of the SAH index for different periods.

To measure the variability of SAH, we derive an index using the geopotential height of the 150-hPa level, at which SAH appears most strongly. We construct the index by averaging the June-July-August (JJA) mean height within 20°–35°N, 65°–95°E (see the box in Fig. 2). Figure 2 shows the pattern of correlation between this index (see Fig. 3 later) and the grid-point geopotential height at the same level. The correlation pattern and its resemblance to the SAH indicate the appropriateness of the index in measuring the variability of SAH.

Figure 3 shows the anomalies of the SAH index from 1949 to 2003. The index changes clearly from one year to the next, with a standard deviation of about 16 m. Note that an abrupt change appears in the index in the year of 1977, characterizing different states of SAH before and after that time. The mean value of the index is 14362 m for 1949–76, with a standard deviation of 15 m, and 14385 m for 1977–2003, with a

(a) JJA SAH, SWPH, MPT, and MH for HI



(b) Diff in SAH, SWPH, MPT, and MH for Strong(Solid) and Weak(Dashed lines)

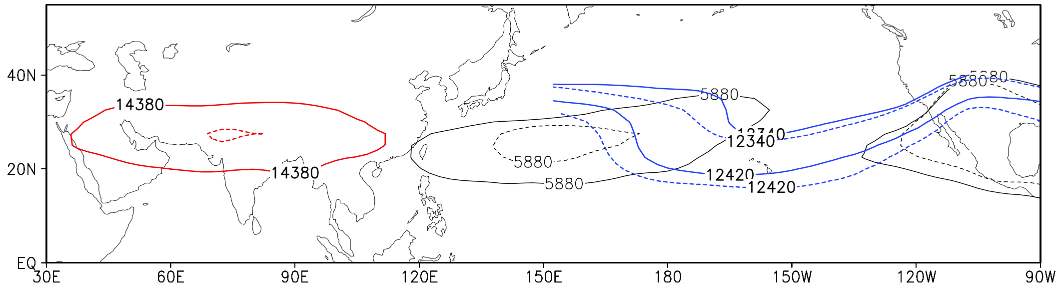


Fig. 4. (a) Same as in Fig. 1 but for the mean of strong SAH years. (b) The mean SAH measured by the contour of 14380 m, SWPH and the Mexican high by the contour of 5880 m, and the mid-Pacific trough by the contours of 12340 and 12420 m for strong SAH years (1980, 1988, 1990, 1991, and 1998; solid lines) and weak SAH years (1992, 1996, 1997, 1999, and 2000; dashed lines).

standard deviation of 17 m. According to Qian et al. (2002), the strengthening and weakening of SAH are linked, respectively, to the diabatic heating (latent, sensible, and shortwave radiative heating) and the cooling effect of infrared radiation.

3.2 *South Asian high and Asian-Pacific-American climate*

It can be seen from Fig. 3 that, besides the large year-to-year variability, an apparent change occurred to the SAH in the 1970s. This change may be related to the so-called climate shift in the mid 1970s (Nitta and Yamada, 1989). However, a number of studies (Yang et al., 2002; Inoue and Matsumoto, 2004; Wu et al., 2005) have demonstrated a potential problem in the NCEP-NCAR reanalysis of the early years in the Asian monsoon region. Without a thorough assessment of data quality, any result about the monsoon variability prior to the 1970s revealed merely by the NCEP-NCAR reanalysis may be misleading. Because of this and because of our focus on the interannual timescales, we limit our analysis to the later period depicted in Fig. 3.

We now conduct a composite analysis of the APA teleconnection patterns and climate variations associated with a strong and a weak South Asian High. We pick the years of strong (weak) SAH as the years when it is stronger (weaker) than normal by one standard deviation. Figure 4a displays the summertime major circulation features for the years of strong SAH. It clearly shows the positions of SAH, SWPH, the mid-Pacific trough, and the Mexican high. Between the strong and weak categories of SAH, the high measured by the contour of 14380 m changes substantially (Fig. 4b). When SAH intensifies, the SWPH (measured by the contour of 5880 m) becomes stronger correspondingly. This feature implies that an increase in the intensity of SAH strengthens the atmospheric sinking motion over the subtropical Pacific, as a response to the overall monsoon heating. This also suggests a stronger zonal-vertical cell between Asia and the North Pacific.

The intensification of the SWPH is also accompanied by a spatial expansion of the system. In particular, the eastward expansion of the high weakens the mid-Pacific trough and pushes the trough eastward. Note that westerlies prevail over this subtropical trough. That is, the trough is closely linked to the so-called "westerly duct" of the atmosphere (Webster and Holton, 1982). These westerlies provide an impor-

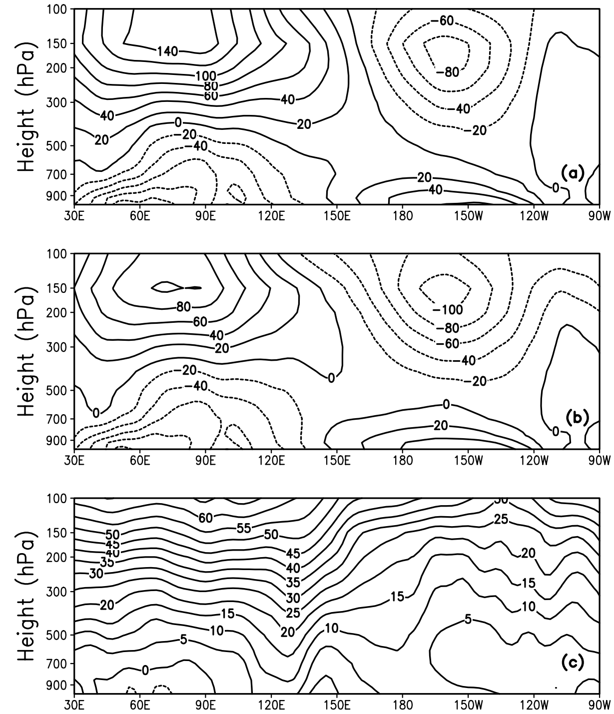


Fig. 5 Longitude-height cross-sections of geopotential height (in m) along 20°–30°N. Values in which zonal means have been removed are shown for (a) strong SAH years, (b) weak SAH years, and (c) their differences.

tant channel for the tropical-extratropical atmospheric interaction, which is manifested by a strong southeastward Rossby wave propagation near the trough. When the mid-Pacific trough weakens and shifts eastward, the southeastward propagation of atmospheric energy, represented by perturbational kinetic energy and potential vorticity, becomes weaker (Arkin and Webster, 1985; Webster and Yang, 1989; Yang, 1990). Figure 4b also illustrates that the weakening in the mid-Pacific trough is accompanied by intensification of the Mexican high in the southern portion.

Figure 5 shows the longitude-height cross sections of the difference in geopotential height between the strong and weak SAH groups, along the latitude band of 20°–30°N. The zonal averages have been removed from the values shown. SAH is clearly an upper-tropospheric phenomenon, which is accompanied by a relative low underneath. On the contrary, SWPH and the Mexican high appear in the middle and lower troposphere. The mid-Pacific trough extends deeply from the upper troposphere, where it is the strongest, to the surface. The westward-tilted (with height) system overlies the subtropical high over the western-central Pacific and extends to the surface over the eastern Pacific.

A stronger SAH is characterized by an increase in height in a deep atmosphere but a decrease in height in the lower atmosphere (Fig. 5c). The largest intensification of SWPH associated with a stronger SAH occurs near 130°E, at the middle troposphere, and the strongest weakening of the mid-Pacific trough appears over 170°–150°W. The strengthening of the Mexican height is most outstanding near 100°W, in the middle troposphere.

Figure 6 shows the climatological pattern of JJA precipitation and the difference in precipitation between the strong and weak SAH categories. The difference in percentage change of precipitation is also shown in the figure to measure the degree of significance of the precipitation changes (see Fig. 6c). When SAH is strong, the summer monsoon rainfall increases over southern and eastern Asia and the tropical eastern Indian Ocean. Over the subtropical Pacific Ocean, a large-scale decrease in precipitation occurs because of the intensification of SWPH. A strong decrease in precipitation also emerges over the equatorial central-eastern Pacific. Over North America, precipitation increases between 10°N and 30°N, associated with a stronger monsoon high, and decreases northward. Figure 6 also shows that precipitation decreases in North Africa, the Mediterranean region, and southern Europe, and increases over the equatorial Atlantic and in central Africa when SAH is strong. In particular, the monsoon rainfall over the Sahel increases.

As seen from Fig. 7, which shows the climatological pattern of JJA surface temperature and the difference in temperature between the strong and weak SAH, the changes in SAH are associated with apparent temperature signals over the mid latitudes of the Northern Hemisphere. Generally, the temperature increases (decreases) in correspondence to the decrease (increase) in precipitation because of the changes in solar radiation due to changes in cloud cover. Over the eastern Pacific Ocean, cooling appears when there is less freshwater input because of the decrease in precipitation (Yang et al., 1999). Nevertheless, cooling in the ocean in turn restrains the development of atmospheric convection. Thus, the local patterns of temperature and precipitation reflect a strong interaction between the atmosphere and the underlying ocean. In addition, the summertime signals over the tropical land portion are relatively weak, as expected.

It is noted from Fig. 7b that negative values of temperature difference appear over the tropical central-eastern Pacific, meaning that the temperature is colder in the strong SAH category than in the weak one. The decrease in the temperature is accompanied by a decrease in precipitation (see Fig. 6). This feature may lead to a speculation of the impact of ENSO on the precipitation and temperature signals. Indeed, in the

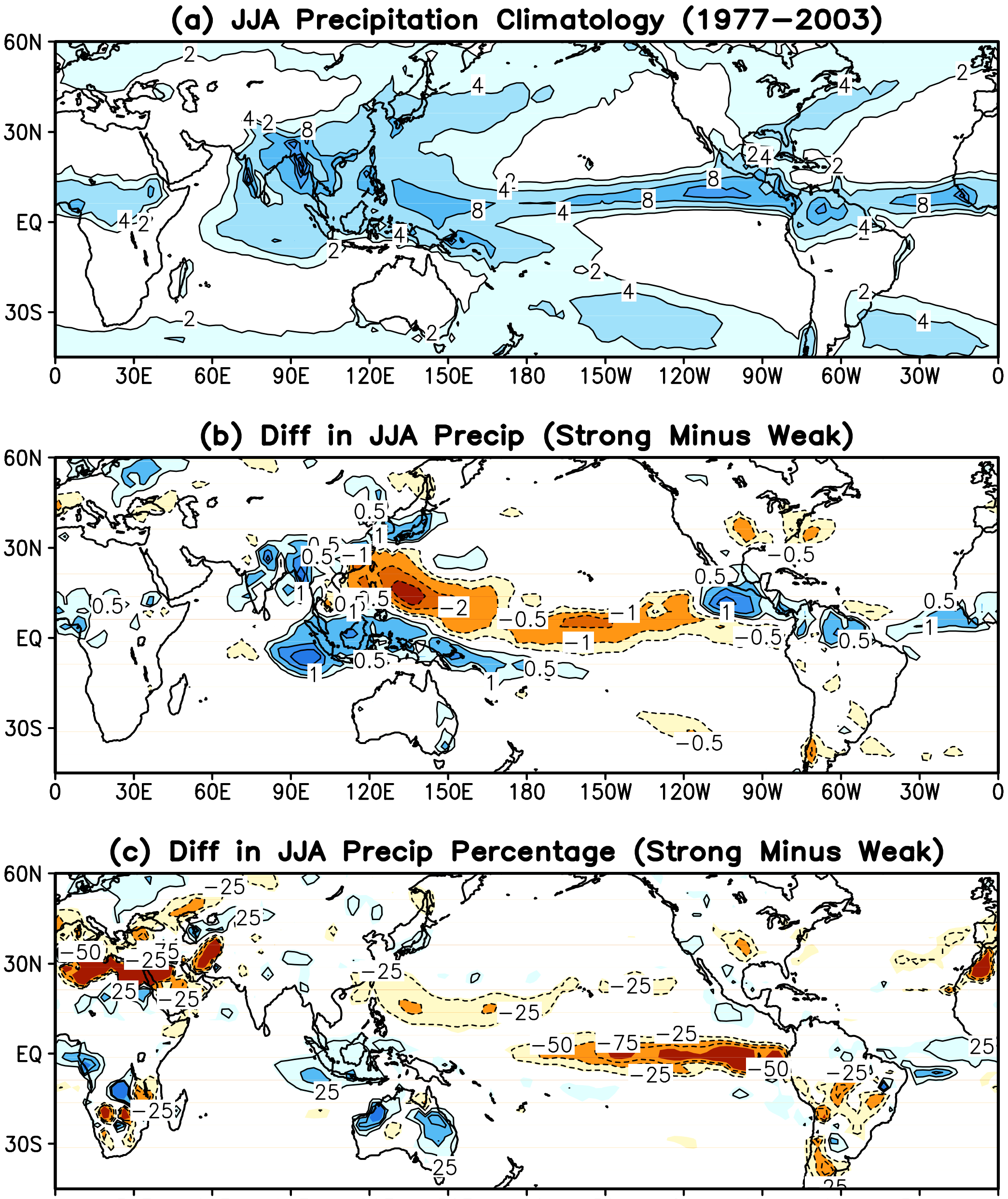


Fig. 6 (a) Climatology of JJA precipitation (1977–2003, unit: mm d^{-1}). (b) Difference in JJA precipitation between strong and weak SAH years (contours: −2, −1, −0.5, 0.5, 1, and 2, unit: mm d^{-1}). (c) Percentage of precipitation change (%) between strong and weak SAH years (contours: −100%, −75%, −50%, −25%, 25%, 50%, and 75%), which is defined as the ratio of the difference in precipitation between strong and weak SAHs to the climatological (1977–2003) precipitation.

five strong SAH summers, the anomalies of Niño-3.4 SST were −1.45 and −1.05 in 1988 and 1998, respectively. Also, in the five weak SAH summers, the Niño-3.4 anomaly was 1.81 in 1997. Thus, the features shown in Figs. 6 and 7, especially those over the tropical Pacific, may have reflected the precipitation and temperature features associated with La Niña events. However, the mean Niño-3.4 SST anomalies are only −0.24 and 0.15 for the strong and weak SAH groups. In fact, the changes in precipitation and temperature shown in the figures are clearly different from the ENSO-related features [e.g., Ropelewski and Halpert (1986); also see http://www.cdc.noaa.gov/ENSO/Compare]. More specifically, the changes in precipitation outside

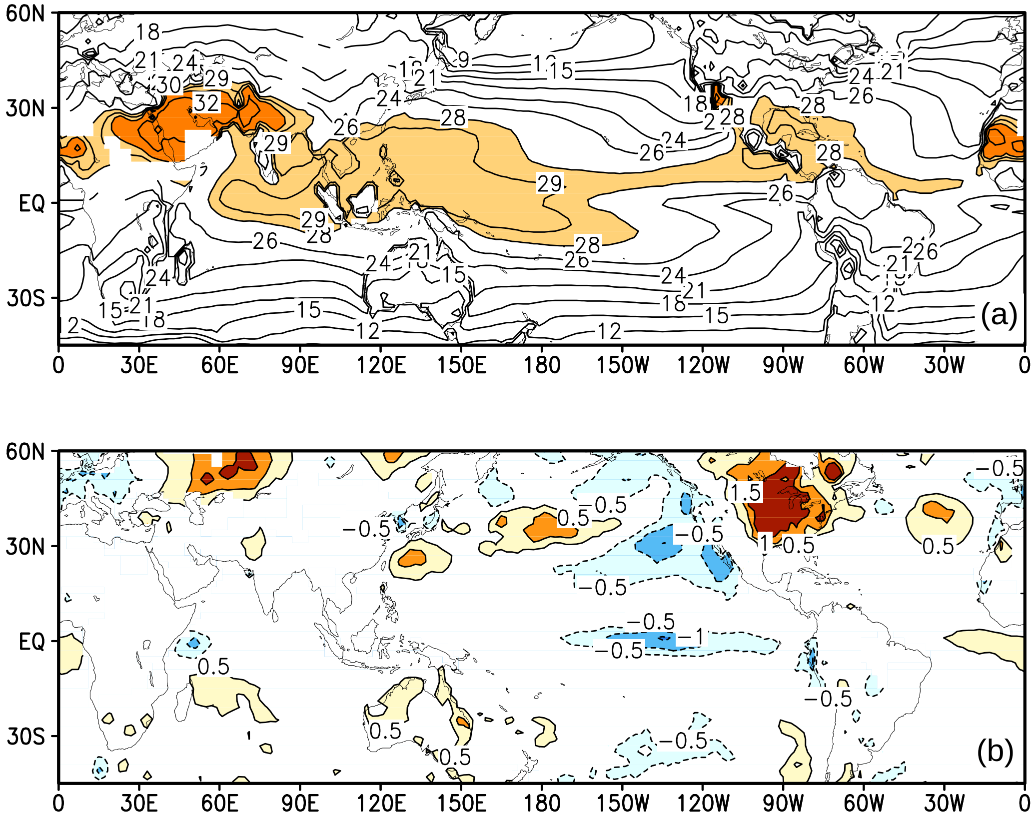


Fig. 7 (a) Climatology of JJA surface air temperature (°C; 1977–2003). (b) Difference in JJA temperature between strong and weak SAH years (contours: −1.5, −1, −0.5, 0.5, 1, and 1.5°C).

the tropical Pacific (Fig. 6) and the changes in surface temperature over the North Pacific, North America, and Europe (Fig. 7) are substantially different from those appearing in the composite patterns for ENSO events.

4. Summary

It is generally believed that the Asian monsoon plays an active role in the variability of the world's weather and climate. However, the impact of the monsoon has not been demonstrated thoroughly due to different reasons such as the large spatial features of the monsoon and difficulties in representing the monsoon's influence in general circulation models. In this study, we assume that the large-scale Asian monsoon can be measured by the South Asian high and test a hypothesis that the variability of SAH is linked to changes in the subtropical western Pacific high, the mid-Pacific trough, and the Mexican high—major circulation systems in the APA region.

A stronger SAH is accompanied by a stronger and expanded SWPH, a weaker mid-Pacific trough, and a stronger Mexican high. Associated with these signals in the atmospheric teleconnection pattern, precipitation and surface temperature change throughout the APA region. When the SAH is stronger, precipitation increases in southern Asia, decreases over the Pacific Ocean, and increases over Central America. Precipitation also increases over Australia and central Africa but decreases in the Mediterranean region. The general decrease in precipitation over the tropical-subtropical Pacific is associated with cooling in the ocean domain.

This is only a preliminary analysis, in which the changes in APA climate associated with the Asian monsoon are revealed. Although a novel hypothesis has been tested in this study with reasonable evidence, more studies are needed to demonstrate the robustness of the results obtained. It is felt that limitations in the availability of reliable, long-recorded data also hamper a thorough observational study in that these data are necessary for us to investigate the interdecadal variability and isolate the influence of ENSO effectively.

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