

An inverse relationship between South China Sea summer monsoon intensity and ENSO

By JAE-WON CHOI*, *College of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing, China*

(Manuscript Received 8 May 2019; in final form 23 March 2021)

ABSTRACT

Correlations between the South China Sea summer (June–September) monsoon (SCSSM) and El Niño Southern Oscillation (ENSO) for the past 32 years (1979–2010) were analyzed. As a result, a higher (lower) SST in the Niño-3.4 areas was associated with a weaker (stronger) SCSSM intensity. To examine the cause of this correlation, the differences between the June–September average of 8 El Niño years and the June–September average of 8 La Niña years were analyzed. Differences in the 850 hPa stream flows between the two groups found that anomalous huge cyclones existed in the subtropical Pacific regions of both hemispheres, which reinforced cold and dry anomalous northerlies in the SCS and anomalous westerlies from the Maritime Continent (MC) to the coastal waters of Chile. An analysis of the differences in the 200 hPa stream flows between the two groups found an anomalous pressure system pattern that was opposite to the result of the analysis of the differences in the 850 hPa stream flows between the two groups. Anomalous anticyclones existed in the subtropical Pacific of both hemispheres, which reinforced the anomalous easterlies from the MC to the equatorial central Pacific. When the anomalous atmospheric circulations of the upper and lower layers of the troposphere were also considered, the structure of anomalous atmospheric circulations in which the air current that rose in the equatorial central and eastern Pacific fell down in the MC. This indicates weakening of the Walker Circulation and a typical structure of atmospheric circulations that appears in El Niño years.

Keywords: South China Sea summer monsoon, El Niño Southern Oscillation, Maritime Continent, equatorial central Pacific, Walker Circulation

1. Introduction

South China Sea is located at the center of the Asian–Australian monsoon system and at the joint region between the East Asian monsoon and the western North Pacific monsoon. Therefore, the South China Sea summer monsoon (SCSSM) is a key element of the Asian summer monsoon (Murakami and Matsumoto, 1994; Wang et al., 2009). Even though there is no consensus about the definition and domain of the SCSSM onset, one of the most distinct features of the SCSSM is its abrupt climatological onset in the mid-May throughout the South China Sea (Lau and Yang, 1997; Wang and Xu, 1997; Wang, 2002). It is characterized by reversal of the wind direction from low-level premonsoon easterlies to monsoon westerlies in the South China Sea between 5°N and 15°N and by being accompanied by reinforced convection as rainfall bursts in the northern South China Sea (10°–20°N).

Recently, the interdecadal changes of the western North Pacific monsoon including the SCSSM have been discussed (Kwon et al., 2005, 2007). Kwon et al. (2005) discovered that East Asian summer monsoon (EASM) has a considerable decadal change and this change is also associated with the western North Pacific summer monsoon. Yim et al. (2008) found that the long-term integration of the hybrid coupled model simulation had similar interdecadal changes. Wang et al. (2009) revealed that summer and autumn rainfalls have increased since 1993 in the southern China and northern South China Sea, but decreased in the central South China Sea. They observed interdecadal changes in seasonality based on the season-reliant empirical orthogonal function (SEOF) analysis. Kajikawa and Wang (2012) discovered there was a clear interdecadal variation in 1993/1994 during the SCSSM onset. They confirmed that relatively late onset during the first epoch was determined by northward seasonal movements of the intertropical convergence zone (ITCZ)

*Corresponding author: e-mail: jaewonchoi@nuist.edu.cn

and relatively early onset during the second epoch was affected by the strengthened activities of the northwestward-moving tropical disturbances from the equatorial western Pacific.

However, the details of such decadal changes have not been fully explored and the possible mechanisms have not been fully established. Moreover, the interdecadal changes around 1993/1994 were found to be in the spatio-temporal structure of intraseasonal variability (ISV) in the South China Sea during boreal summer (Kajikawa et al., 2009). They found that relatively late onset during the first epoch was determined by the seasonal movement to the north of the intertropical convergence zone (ITCZ), and the relatively early onset during the second epoch was affected by the reinforced activity of the northwestward-moving tropical disturbances from the equatorial western Pacific. Lin and Zhang (2020) investigated the characteristics of anomalous circulations during spring associated with the climate shift of the South China Sea summer monsoon (SCSSM) onset in 1993/1994 and its physical causes. They found that the interdecadal shift of SCSSM onset happened in 1993/1994 is related closely to the 850 hPa zonal wind anomalies over the area around Kalimantan Island. Consequently, the SCSSM onset greatly contributes to the understanding of Asian monsoon variability, and atmospheric circulations have considerable influence on the SCSSM system in the western and central Pacific. The SCSSM onset is signaled by the start of rainy season in eastern Asia and western North Pacific (Tao and Chen, 1987; Ding, 1992; Wang, 2002).

Many researchers have strived to explain the possible relationship between the El Niño-Southern Oscillation (ENSO) and EASM and the western North Pacific summer monsoon (Ju and Slingo, 1995). Luo and Lin (2017) suggested that El Niño can delay the monsoon onset and advance the SCSSM withdrawal, thus shortening the length of the summer monsoon season. Wang et al. (2000) discovered that the ENSO events influenced the East Asia climate through the Pacific-East Asian (PEA) teleconnection together with the anomalous anticyclone to the east of the Philippines. Zhang et al. (1996) emphasized the effects of El Niño events on EASM through the variations of convective activity in the equatorial western Pacific. Oort and Yienger (1996) found that during La Niña (El Niño), the local Hadley circulation was suppressed (enhanced) in the western tropical Pacific and enhanced (suppressed) in the eastern tropical Pacific. However, it is difficult to find the relationship between ENSO and SCSSM. The SCSSM onset indicates the beginning of the EASM (Wang et al., 2004). An early or late SCSSM onset could affect the precipitation pattern of the EASM to some extent. Although a consensus on the domain and the definition of the SCSSM onset has

yet to be reached (So and Chan, 1997; Wang and Wu, 1997; Li and Mu, 1999; Ding and Liu, 2001), a general conclusion from these studies is that such an onset is associated with a switch of the zonal winds over the SCS from easterly to westerly, and a concomitant increase in convective activity. The onset of the EASM is often signified by an abrupt increase in precipitation (Tao and Chen, 1987). The SCSSM onset has therefore been considered as the beginning of the East Asian subtropical summer monsoon evolution (Tao and Chen, 1987; Lau and Yang, 1997). Zhou and Chan (2007) demonstrated that in a warm (cold) ENSO event year, the SCSSM onset becomes later (faster) and the SCSSM intensity becomes weaker (stronger). Hu et al. (2019) found that SCSSM withdrawal mainly occurred due to the westward intrusion of the western North Pacific (WNP) subtropical high, which is accompanied by the retreat of the weakening low-level intertropical convergence zone (ITCZ) and rain-belt in the SCS-WNP. However, above studies used the short-term data, therefore, in this paper, using longer period data, a close correlation between SCSSM intensity and ENSO will be demonstrated.

In Section 2, the data and analysis method are introduced. In Section 3, the correlation between SCSSM intensity and ENSO is analyzed. In Section 4, the cause of the correlation between the two variables is examined through an analysis of the differences in large-scale environments between El Niño years and La Niña years. Finally in Section 5, a summary of this study is presented.

2. Data and methods

2.1. Data

This study used the variables of geopotential height (unit: gpm), wind components (unit: ms^{-1}), precipitable water (unit: kg m^{-2}), and specific humidity (unit: g kg^{-1}) data from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis for the period 1979 to 2010 (Kalnay et al., 1996; Kistler et al., 2001). This NCEP-NCAR reanalysis data consisted of spatial resolution such as latitude and longitude $2.5^\circ \times 2.5^\circ$ and 17 vertical levels (specific humidity is 16 vertical levels and precipitable water is 1 level). Also, velocity potential consisted of grid box such as latitude and longitude 192×94 and 5 sigma levels.

The National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed monthly Sea Surface Temperature (SST) (Reynolds et al., 2002), available from the same organization, was also used. The data have a horizontal resolution of $2.0^\circ \times$

2.0° latitude-longitude and are available for the period of 1854 to the present day.

Also, the NOAA interpolated outgoing longwave radiation (OLR) data retrieved from the NOAA satellite series, are available starting from June 1974 from NOAA's Climate Diagnosis Center (CDC). However, the data are incomplete, with a missing period from March to December of 1978. Detailed information about this OLR data can be found on the CDC website (<http://www.cdc.noaa.gov>) and in the study by Liebmann and Smith (1996).

In addition, the horizontal spatial resolution of the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) data (Xie and Arkin, 1997) is the same as the NCEP-NCAR reanalysis dataset. This data is based on the monthly average and is available from 1979 to the present day. The CMAP data, which is global precipitation data that covers the ocean, are derived by merging rain gauge observations, five different satellite estimates, and numerical model outputs. On the other hand, the Earth2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI) dataset was compiled to support the bias correction of climate input data for the impact assessments carried out in phase 2b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b; Frieler et al., 2017), which will contribute to the 2018 IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. The EWEMBI data cover the entire globe at 0.5° horizontal and daily temporal resolution from 1979 to 2013. Data sources of EWEMBI are ERA-Interim reanalysis data (ERA-Interim), WATCH forcing data methodology applied to ERA-Interim reanalysis data (WFDEI), earth2Observe forcing data (E2OBS) and NASA/GEWEX Surface Radiation Budget data (SRB). The SRB data were used to bias-correct E2OBS shortwave and longwave radiation. Variables included in the EWEMBI dataset are Near Surface Relative Humidity, Near Surface Specific Humidity, Precipitation, Snowfall Flux, Surface Air Pressure, Surface Downwelling Longwave Radiation, Surface Downwelling Shortwave Radiation, Near Surface Wind Speed, Near-Surface Air Temperature, Daily Maximum Near Surface Air Temperature, Daily Minimum Near Surface Air Temperature, Eastward Near-Surface Wind and Northward Near-Surface Wind. Although EWEMBI data performs better than CPC-CMAP product, we used CPC-CMAP product.

The tropical cyclone (TC) data in this study was obtained from the Best-track of TC provided by Regional Specialized Meteorological Center (RSMC)-Tokyo Typhoon Center. This data consist of TC name, latitude

and longitude location of TC, TC central pressure, and TC Maximum Sustained Wind Speed (MSWS), which were observed in every 6 hours for 35 years from 1978 to 2012. TC is generally classified into four classes by the criteria of MSWS as follows: Tropical Depression (TD, $MSWS < 17 \text{ ms}^{-1}$), Tropical Storm (TS, $17 \text{ ms}^{-1} \leq MSWS \leq 24 \text{ ms}^{-1}$), Severe Tropical Storm (STS, $25 \text{ ms}^{-1} \leq MSWS \leq 32 \text{ ms}^{-1}$), Typhoon (TY, $MSWS \geq 33 \text{ ms}^{-1}$). Along with the four classes of TC above, this study included extratropical cyclone, which was transformed from TC for analysis. This was because such extratropical cyclone also incurred great damage on property and human in the mid-latitude regions in East Asia.

2.2. Methods

This study used the Student's t test to determine significance (Wilks, 1995). In case that two independent time series follow a t distribution and their time averages are denoted as $\bar{x}_1$ and $\bar{x}_2$ respectively, the test statistic is given by

$$t = \frac{\bar{x}_1 - \bar{x}_2}{(s_1^2/n_1 + s_2^2/n_2)^{1/2}} \quad (1)$$

where, S_1 and S_2 are standard deviations, and n_1 and n_2 are numbers of the two time series, respectively. From the above formula, if the absolute value of t is greater than threshold values with a level of significance, the null hypothesis would be rejected at the $\alpha(\times 100)\%$ significance level.

Cold and normal ENSO years in June-September were decided based on the website of NOAA CPC (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyers.shtml). Warm and cold years based on a threshold of $\pm 0.5^\circ\text{C}$ for the Oceanic Niño Index (ONI) [3 month running mean of SST anomalies in the Niño 3.4 region (5°S - 5°N , 170°E - 120°W)], based on centered 30-year base periods updated every 5 years. The percentage of the selected ENSO years that remain as ENSO years until winter is about 40% (1982, 1987-1988, 1991-1992, 1997-2000, 2002, 2004, 2009-2010) of entire analysis period (32 years).

For obtaining the SST anomalies (SSTA), this study used the 32-year average SST from June to September in the Niño-3.4 region.

Summer in this study is defined as the period from June to September.

The normalized 850 hPa and 200 hPa zonal wind indices averaged in the Niño-3.4 region were provided from the website of the NOAA CPC (<http://www.cpc.ncep.noaa.gov/data/indices>).

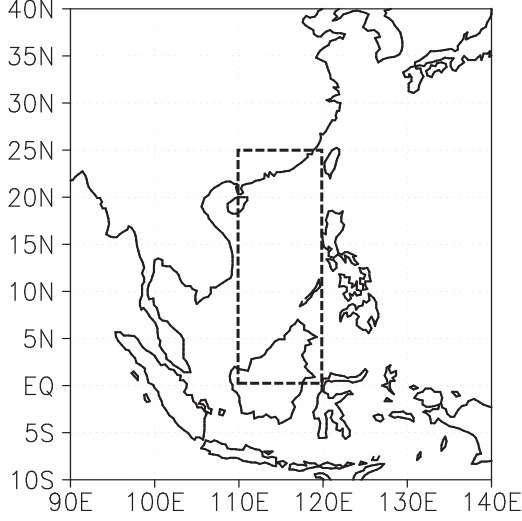


Fig. 1. Definition of South China Sea (SCS) domain (0°–25°N, 110°E–120°E) in this study.

2.3. Definition of South China Sea summer monsoon (SCSSM) index

In this study, the SCSSMI was defined using the Dynamical Normalized Seasonality (DNS) index of Li and Zeng (2002, 2003, 2005). The basic concept of the DNS index is based on the intensity of the normalized seasonality. As monsoons have very strong seasonal variations in wind direction, strong and weak monsoons should be validly defined using the intensity of the normalized seasonality of the wind field. Using this basic concept of monsoon, the DNS index is calculated by the following equation:

$$\delta_{mn} = \frac{||\bar{V}_1 - V_i||}{||\bar{V}||} - 2 \quad (2)$$

Where, $\bar{V}_1$ and V_i denote the January climatological wind vector and monthly wind vectors at a point, respectively, and $\bar{V}$ denotes the mean of January and July climatological wind vectors at the same point. Then, the SCSSM index is defined as the area-averaged seasonally (June–September) DNS at 850 hPa within the South China Sea domain (see Fig. 1, 0°–25°N, 110°E–120°E) (Li and Zeng, 2002). The result of this study showed a clear negative correlation between the SCSSM index calculated through the above equation and the June–September rainfall in the South China Sea, thereby proving the validity of the above definition of SCSSM. In other words, a higher (lower) SCSSM index indicates a weaker (stronger) SCSSM. In addition, during boreal summer, the SCSSM exhibits strongly positive correlations with rainfall over the warm pool of the western Pacific, North Pacific between 10°N and 25°N, South American monsoon regime and southeast South Pacific. Also the SCSSM is

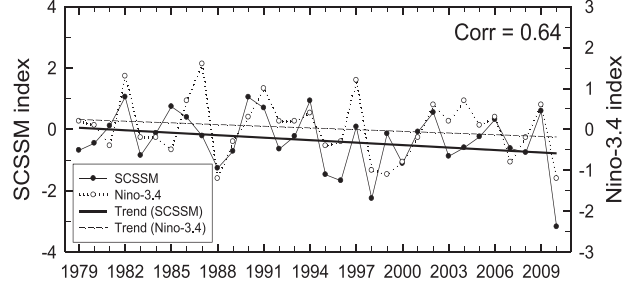


Fig. 2. Time series of South China Sea summer monsoon (SCSSM) index and Niño-3.4 index and their trends for June–September (JJAS). Even though the decreasing trend of the Niño-3.4 index is insignificant, the decreasing trend of the SCSSM index is significant at the 90% confidence level.

well negatively correlated with precipitation over a broad domain extending from the Arabian Sea across the tropical Indian Ocean to Indonesia and Malaysia. In addition, SCSSM is well negatively correlated with precipitation of a region extending from the Central American across the Caribbean Island countries to the North Atlantic Ocean between 10°N and 20°N and the Indian Ocean regions adjacent to the south and west Australia (Luo and Lin, 2017).

3. Relationship between SCSSM and ENSO

Figure 2 shows the time series of the June–September average SCSSM index and Niño-3.4 index. Both variables tended to decrease until 2010. In general, both time series have distinct interannual and interdecadal variations. Furthermore, even though the decreasing trend of the Niño-3.4 index is insignificant, the decreasing trend of the SCSSM index is significant at the 90% confidence level. Meanwhile, the two time series have a clear in-phase relationship. Therefore, an analysis of the correlation between these two variables revealed a high correlation of 0.64, which is significant at the 99% confidence level. This means that a higher (lower) Niño-3.4 index is associated with a weaker (stronger) SCSSM intensity.

Therefore, in the study, differences between the June–September average of the 8 El Niño years (1982, 1986–87, 1991, 1997, 2002, 2004, and 2009) and the June–September average of the 8 La Niña years (1985, 1988, 1995, 1998–2000, 2007, and 2010) are analyzed.

4. Differences between El niño years and La niña years

To investigate the differences in convective activity between El Niño years and La Niña years, differences in OLR between the two groups were analyzed (see Fig. 3a). Strong positive anomalies exist in the Maritime Continent

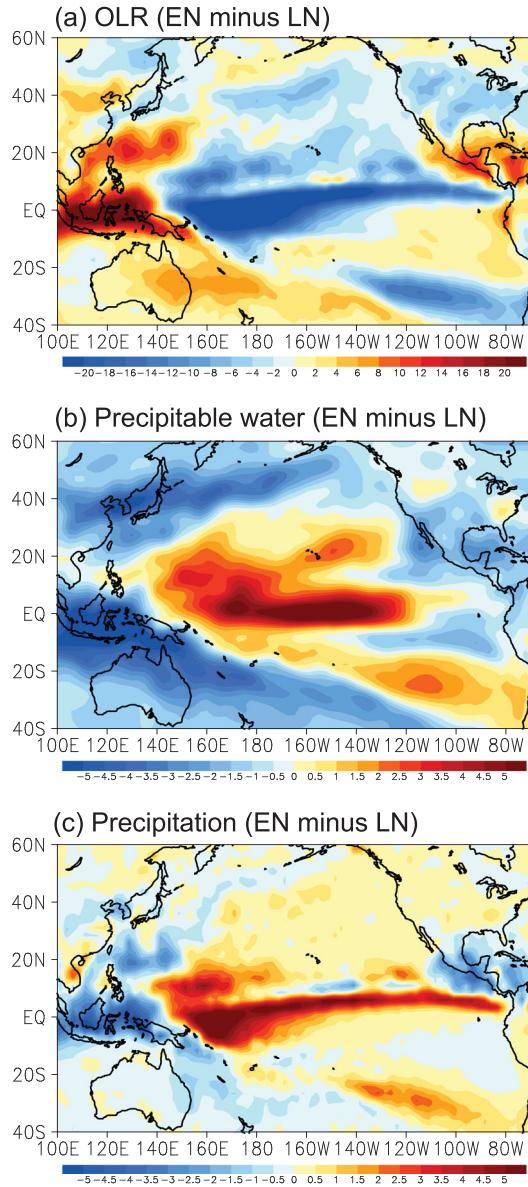


Fig. 3. Differences in (a) OLR, (b) precipitable water, and (c) precipitation between El Niño years and La Niña years.

through the South China Sea from the subtropical and tropical western Pacific. On the other hand, strong negative anomalies exist in the east-west direction along the equatorial Pacific. This is a typical spatial distribution that appears in El Niño years. A smaller OLR indicates more active convection. Therefore, convection is weak in the Maritime Continent through the South China Sea from the subtropical and tropical western Pacific, whereas convection is strong in the equatorial Pacific.

This difference in convective activity between the two groups is reflected in the differences in precipitable water and precipitation between the two groups (see Figs. 3b

and 3c). First, the analysis of precipitable water shows positive anomalies in the tropical and subtropical Pacific of both hemispheres, and their center is located in the equatorial Pacific (see Fig. 3b). In other regions, negative anomalies are formed in most cases. The result of the precipitation analysis reveals a spatial distribution that is opposite to the result of the OLR analysis (see Fig. 3c). Strong negative anomalies are formed in the Maritime Continent through the South China Sea from the subtropical and tropical western Pacific, whereas strong positive anomalies are formed in the east-west direction along the equatorial Pacific. From this result, it follows that a higher Niño-3.4 index (that is, a higher SST in the Niño-3.4) is associated with a weaker SCSSM intensity, as it was analyzed before.

As analyzed above, to examine the reason for the weakening SCSSM intensity in the El Niño years compared to the La Niña years, differences in 850 hPa stream flows between the two groups were analyzed (see Fig. 4a). Anomalous huge cyclonic circulations are reinforced in both hemispheres and from these two anomalous cyclones, the anomalous northerlies have joint in the southern sea of the South China Sea toward the coastal waters of Peru. Therefore, the reinforcement of anomalous westerlies in the equatorial Pacific (weakening of trade winds) and of the cold and dry anomalous northerlies in the South China Sea forms a good environment for weakening the SCSSM intensity.

The analysis result of the differences in 200 hPa stream flows between the two groups indicates a spatial distribution that is direct opposite to the anomalous pressure system pattern shown in 850 hPa (Fig. 4b). Anomalous anticyclonic circulations are reinforced in the subtropical Pacific of both hemispheres. By this anomalous anticyclone in either hemisphere, anomalous easterlies are reinforced in the equatorial western and central Pacific. Linking this result with the atmospheric circulations of the lower layer of troposphere shows that atmospheric circulations have been reinforced in which the rising air current in the equatorial central and eastern Pacific falls down in the South China Sea and the Maritime Continent. This means the weakening of Walker Circulation. Therefore, we can see that the SCSSM intensity was weakened by the Walker Circulation during the El Niño years.

To investigate whether the Walker Circulation is aggravated during the El Niño years, the differences in the vertical zonal circulation that has been averaged for the latitudinal zone of South China Sea (0-25°N) between the two groups were analyzed (see Fig. 5a). The anomalous vertical zonal atmospheric circulations have become reinforced where the air current rises in the equatorial central and eastern Pacific, moves toward the west, falls

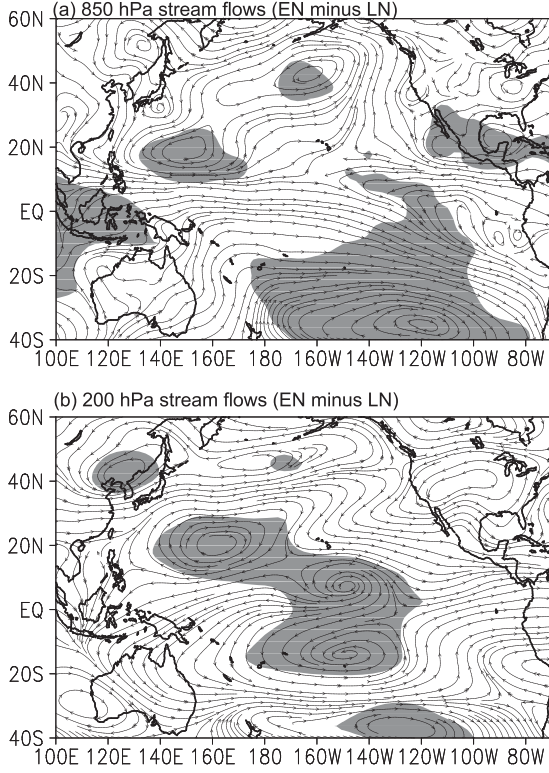


Fig. 4. Same as in Fig. 3, but for (a) 850 hPa stream flows and (b) 200 hPa stream flows. Shaded areas are significant at the 95% confidence level.

down in the South China Sea and the sea near the Philippines and moves toward the east again. These circulations are an opposite pattern of the Walker Circulation and imply that Walker Circulation was deteriorated during the El Niño years. Therefore, as the Walker Circulation was more weakened in the El Niño years than in the La Niña years, the SCSSM intensity has been weakened.

The differences in the vertical specific humidity and vertical air temperature averaged for the latitudinal zone of the South China Sea were examined (see Figs. 5b and 5c). First, in the analysis of specific humidity, the area to the west of 150°E shows negative anomalies in all layers of the troposphere, whereas the east area shows reinforced positive anomalies in all layers of the troposphere (see Fig. 5b).

The analysis of air temperature shows that the west area of 170°E indicated cold anomalies in most layers of the troposphere, whereas the east area indicated warm anomalies in the most layers of the troposphere (see Fig. 5c). The reason for this is that as analyzed in the differences in vertical zonal circulation between the two groups, Walker Circulation was weakened in the El Niño years than in the La Niña years.

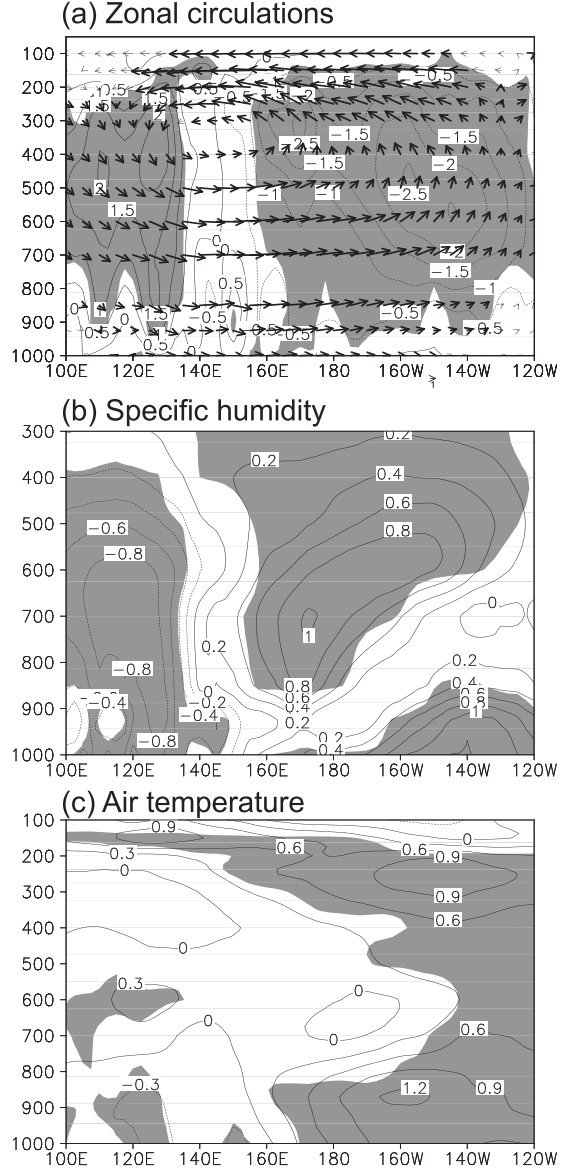


Fig. 5. Composite differences of longitude–pressure cross section of (a) vertical velocity (contours) and zonal circulations (vectors), (b) specific humidity, and (c) air temperature averaged along 0°–20°N between El Niño years and La Niña years for JJAS. The values of vertical velocity are multiplied by -100. Bold arrows and shaded areas are significant at the 90% confidence level. Contour intervals are 0.5 hPa s^{-1} for vertical velocity, 0.2 g kg^{-1} for specific humidity, and 0.3°C for air temperature, respectively.

To examine whether the SST distribution of the El Niño pattern appears in the differences in SST between the two groups, the differences in SST between the two groups were analyzed (see Fig. 6). Warm anomalies are reinforced from the western coast of North America through the equatorial central and eastern Pacific to the

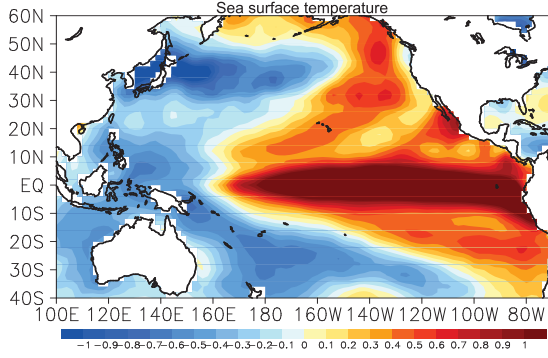


Fig. 6. Same as in Fig. 3, but for sea surface temperature (SST).

west coast of South America, and the center of the warm anomalies is located in the equatorial central and eastern Pacific. In the other areas, which are the tropical and subtropical western Pacific of both hemispheres, cold anomalies are reinforced. This spatial distribution of SST is a typical spatial pattern of SST that appears in El Niño years. The reason for this is that as described above, anomalous equatorial westerlies were reinforced due to the weakening of Walker Circulation during the El Niño years. As a result, the stronger (weaker) the phenomenon of El Niño (La Niña) is, the weaker (stronger) the SCSSM intensity becomes.

To determine whether the weakening of Walker Circulation in El Niño years is associated with the weakening of the SCSSM intensity, the time series of the June–September averaged 850 hPa zonal wind and 200 hPa zonal wind that were area-averaged in the Niño-3.4 region (5°S – 5°N , 170°E – 120°W) were compared with the time series of the SCSSM index (see Fig. 7). First of all, the interannual variation was generally distinct in the time series of the 850 hPa zonal wind (dotted line with an open circle in Fig. 7a). Furthermore, the 850 hPa zonal wind tends to decrease until 2010, which is significant at the 90% confidence level. On the other hand, an in-phase relationship is clear between the two variables, and there is a high positive correlation of 0.79 between the two variables, which is significant at the 99% confidence level. This means that in the lower layer of the troposphere of the equatorial central and eastern Pacific, the SCSSM intensity becomes weaker (stronger) as the westerlies (easterlies) become stronger.

The time series of the 200 hPa zonal wind also showed clear interannual and interdecadal variations in general (dotted line with an open circle in Fig. 7b). Furthermore, the 200 hPa zonal wind tended to increase until 2010, which is significant at the 95% confidence level. Meanwhile, these two variables have a distinct out-of-phase relationship and there is a high negative correlation of -0.73 , which is significant at the 99% confidence level.

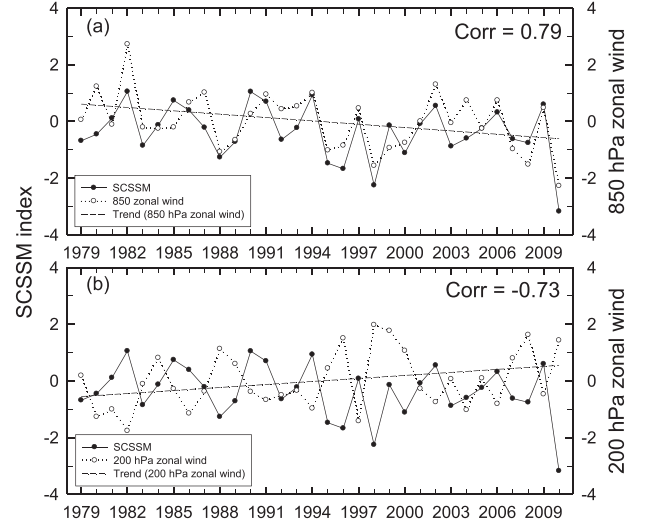


Fig. 7. Time series of SCSSM index and (a) 850 hPa zonal wind and (b) 200 hPa zonal wind averaged for Niño-3.4 region (5°S – 5°N , 170°E – 120°W). The trends of 850 hPa zonal wind and 200 hPa zonal wind are significant at the 90% and 95% confidence levels, respectively.

This means that in the upper layer of the troposphere of the equatorial central and eastern Pacific, the stronger the easterlies (westerlies) are, the weaker (stronger) the SCSSM intensity becomes. Therefore, the result of the above correlation analysis reconfirms that the weakening of Walker Circulation during the El Niño years is associated with the weakening of the SCSSM intensity.

Meanwhile, the effects of TCs cannot be ignored in the variations of summer precipitation in South China Sea. Therefore, the differences in TC passage frequency between the two groups were analyzed for each $5^{\circ} \times 5^{\circ}$ grid (see Fig. 8). During the El Niño years, TCs mainly moved north from the remote east sea of the Philippines to the east sea of Japan and the east sea of the Okhotsk sea. On the other hand, during the La Niña years, TCs tend to move from the Philippines through South China Sea and land in the southern region of China before moving north to the Korean Peninsula. This result agrees with the result of Wang and Chan (2002) which showed that during the El Niño years, TCs moved further in the east region than the TCs during the La Niña years. Therefore, during the El Niño years, even the TC frequency is low in South China Sea, thus influencing the weakening of the SCSSM intensity.

Meanwhile, to investigate the characteristics of the global-scale atmospheric circulation, differences in 850 hPa and 200 hPa velocity potentials between the two groups were examined (see Fig. 9). First, in the 850 hPa velocity potential, negative anomalies are reinforced in the west region of 170°E and positive anomalies are reinforced in

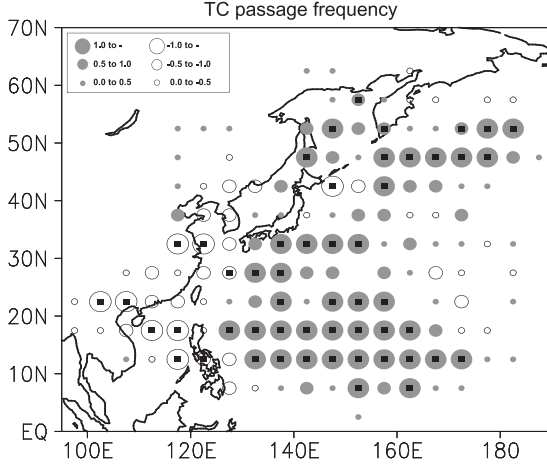


Fig. 8. Differences in the mean TC passage frequencies between El Niño years and La Niña years for JJAS within each $5^\circ \times 5^\circ$ latitude-longitude grid box. Small solid rectangles indicate that the differences are significant at the 95% confidence level.

the east region (see Fig. 9a). The centers of negative anomalies and positive anomalies are located in the Maritime Continent and the equatorial central Pacific, respectively. This implies that in the lower layer of the troposphere, anomalous convergence is developed in the east region of 170°E whereas anomalous divergence is developed in the west region. The spatial distribution of the 200 hPa velocity potential shows a direct opposite pattern of the spatial distribution of the 850 hPa velocity potential (see Fig. 9b). Positive anomalies are located in the west region of 170°E and negative anomalies in the east region. The centers of positive and negative anomalies are located in the west sea of the Maritime Continent and the equatorial central Pacific, respectively. This means that in the upper layer of the troposphere, anomalous convergence is developed in the west region of 170°E whereas anomalous divergence is developed in the east region. Therefore, to summarize the above findings, the global-scale atmospheric circulation where the air rises in the east region of 170°E , moves to the west and falls down in the west region of 170°E was further reinforced during the El Niño years. Therefore, the formation of such global-scale atmospheric circulations during the El Niño years weakened the Walker Circulation, which also weakened the SCSSM intensity.

5. Summary and conclusion

In this study, the correlations between the South China Sea summer (June–September) monsoon (SCSSM) and the ENSO for the past 32 years (1979–2010) were analyzed. There was a correlation in the Niño-3.4 area where

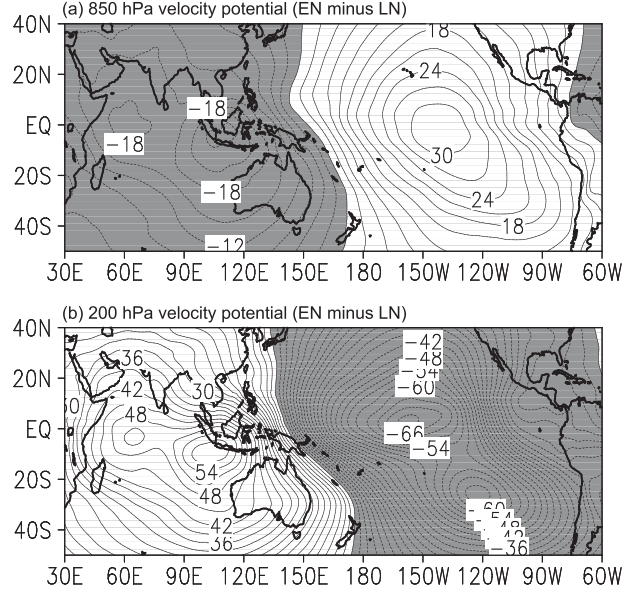


Fig. 9. Same as in Fig. 3, but for (a) 850 hPa velocity potential and (b) 200 hPa velocity potential. Shaded areas denote negative anomalies. Contour interval is $3 \text{ m}^2 \text{ s}^{-1} 10^{-6}$.

a higher (lower) SST was associated with a weaker (stronger) SCSSM intensity. To investigate the cause of this correlation, the differences between the June–September average of the 8 El Niño years and the June–September average of the 8 La Niña years were analyzed.

The analysis of the differences in OLR, precipitable water, and precipitation between the two groups showed that convective activity was weakened from the tropical western Pacific through South China Sea to the Maritime Continent, whereas it was reinforced in the equatorial Pacific.

The analysis of the differences in the 850 hPa stream flows between the two groups found that the existence of anomalous huge cyclones in the subtropical Pacific of both hemispheres reinforced more cold and dry anomalous northerlies in South China Sea, and also reinforced anomalous northerlies from the Maritime Continent to the coastal waters of Chile. The analysis of the differences in the 200 hPa stream flows between the two groups showed an anomalous pressure system pattern that was opposite to the result of the analysis of the differences in the 850 hPa stream flows between the two groups. Anomalous anticyclones existed in the subtropical Pacific of both hemispheres, which reinforced anomalous easterlies from the Maritime Continent to the equatorial central Pacific. A simultaneous consideration of the anomalous atmospheric circulations in the upper and lower layers of the troposphere revealed the structure of anomalous atmospheric circulations where the air current rose in the equatorial central and eastern Pacific and fell down in

the South China Sea and Maritime Continent. This indicates the weakening of Walker Circulation and a typical structure of atmospheric circulations that appear during the El Niño years.

To determine whether Walker Circulation is weakened during the El Niño years, the differences in vertical zonal circulations averaged for the latitudinal zone (0–25°N) of South China Sea between the two groups were analyzed. The anomalous vertical zonal atmospheric circulations where the air current rises in the equatorial central and eastern Pacific, moves to the east, falls down in the South China Sea and the sea near the Philippines, and then moves to the east were reinforced.

In the analysis of the differences in vertical specific humidity and vertical air temperature that were averaged for the latitudinal zone of South China Sea between the two periods, the west region of 150°E including the South China Sea showed cold and dry atmospheric condition throughout the troposphere, whereas the east region showed warm and humid atmospheric condition throughout the troposphere. These atmospheric circulations and atmospheric condition are the opposite pattern of Walker Circulation and means that Walker Circulation worsened during the El Niño years. Therefore, the SCSSM intensity weakened as the Walker Circulation more weakened during the El Niño years compared to the La Niña years.

To determine whether the weakening of Walker Circulation during the El Niño years is actually linked to the weakening of the SCSSM intensity, the time series of the June–September averaged 850 hPa zonal wind and the June–September averaged 200 hPa zonal wind that were area-averaged in the Niño-3.4 region (5°S–5°N, 170°E–120°W) were compared with the time series of the SCSSM index. As a result, the 850 hPa zonal wind and the SCSSM index showed a high positive correlation whereas the 200 hPa zonal wind and the SCSSM index showed a high negative correlation, reconfirming that the Walker Circulation was more weakened during the El Niño years.

To examine the effect of TCs on the SCSSM, the differences in the TC passage frequency between the two groups were analyzed for each 5°×5° grid. TCs during the El Niño years mainly moved north from the remote east sea of the Philippines to the east sea of Japan and moved to the east sea of the Okhotsk sea, whereas during the La Niña years, TCs moved from the Philippines, passed the South China Sea, landed in the southern region of China, and moved north toward the Korean Peninsula. Therefore, even the TC frequency in the South China Sea was lower during the El Niño years, which affected the weakening of the SCSSM intensity.

To investigate the characteristics of the global-scale atmospheric circulation, the differences in 850 hPa and

200 hPa velocity potentials between the two groups were examined. As a result, the global-scale atmospheric circulations where the air rises in the east region of 170°E, moves to the west and falls down in the west region of 170°E were further reinforced during the El Niño years.

This study found that the SCSSM intensity was closely associated with the ENSO. Therefore, the ENSO can be used as a key predictor for seasonal predictions of the SCSSM. For example, if the seasonal forecast model such as GloSea global model produces ENSO prediction data some months in advance, ENSO data can be used as a predictor for SCSSM intensity prediction. In future studies, a statistical model for seasonal predictions of the SCSSM using the ENSO will be developed.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This paper is supported by The Startup Foundation for Introducing Talent of NUIST (Grant/Award number: 2018r059). For this study, NCEP-NCAR reanalysis and NOAA Extended Reconstructed monthly SST and RSMC-Tokyo Typhoon Center's best-track were provided.

References

- Ding, Y. H. 1992. Summer monsoon rainfalls in China. *J. Meteorol. Soc. Jpn.* **70**, 373–396. doi:10.2151/jmsj1965.70.1B_373
- Ding, Y. H. and Liu, Y. J. 2001. Onset and the evolution of the summer monsoon over the South China Sea during SCSMEX field experiment in 1998. *J. Meteorol. Soc. Jpn.* **79**, 255–276.
- Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J. and co-authors. 2017. Assessing the impacts of 1.5°C global warming — Simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model Dev.* **10**, 4321–4345. doi:10.5194/gmd-10-4321-2017
- Hu, P., Chen, W., Ruping, H. and Nath, P. 2019. Climatological characteristics of the synoptic changes accompanying south China sea summer monsoon withdrawal. *Int. J. Climatol.* **39**, 596–517. doi:10.1002/joc.5828
- Ju, J. and Slingo, J. 1995. The Asian summer monsoon and ENSO. *Q. J. R. Meteorol. Soc.* **121**, 1133–1168. doi:10.1002/qj.49712152509
- Kajikawa, Y. and Wang, B. 2012. Interdecadal change of the South China Sea summer monsoon onset. *J. Clim.* **25**, 3207–3218. doi:10.1175/JCLI-D-11-00207.1

- Kajikawa, Y., Yasunari, T. and Wang, B. 2009. Decadal change in intraseasonal variability over the South China Sea. *Geophys. Res. Lett.* **36**, L06810.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D. and co-authors. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77**, 437–471. doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2
- Kistler, R., Collins, W., Saha, S., White, G., Woollen, J. and co-authors. 2001. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bull. Am. Meteorol. Soc.* **82**, 247–267. doi:10.1175/1520-0477(2001)082<0247:TNNYRM>2.3.CO;2
- Kwon, M., Jhun, J. G. and Ha, K. J. 2007. Decadal change in east Asian summer monsoon circulation in the mid-1990s. *Geophys. Res. Lett.* **34**, L21706. doi:10.1029/2007GL031977
- Kwon, M., Jhun, J. G., Wang, B., An, S. I. and Kug, J. S. 2005. Decadal change in relationship between east Asian and WNP summer monsoons. *Geophys. Res. Lett.* **32**, L16709. doi:10.1029/2005GL023026
- Lau, K. M. and Yang, S. 1997. Climatology and interannual variability of the Southeast Asian summer monsoon. *Adv. Atmos. Sci.* **14**, 141–162. doi:10.1007/s00376-997-0016-y
- Li, C. and Mu, M. 1999. El Niño occurrence and sub-surface ocean temperature anomalies in the Pacific warm pool. *Chin. J. Atmos. Sci.* **5**, 513–521.
- Li, J. P. and Zeng, Q. C. 2002. A unified monsoon index. *Geophys. Res. Lett.* **29**, 1274.
- Li, J. P. and Zeng, Q. C. 2003. A new monsoon index and the geographical distribution of the global monsoons. *Adv. Atmos. Sci.* **20**, 299–302.
- Li, J. P. and Zeng, Q. C. 2005. A new monsoon index, its interannual variability and relation with monsoon precipitation. *Clim. Environ. Res.* **10**, 351–365.
- Liebmann, B. and Smith, C. A. 1996. Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteorol. Soc.* **77**, 1275–1277.
- Luo, M. and Lin, L. 2017. Objective determination of the onset and withdrawal of the south China sea summer monsoon. *Atmos. Sci. Lett.* **18**, 276–282. doi:10.1002/asl.753
- Murakami, T. and Matsumoto, J. 1994. Summer monsoon over the Asian continent and western North Pacific. *J. Meteorol. Soc. Jpn.* **72**, 719–745. doi:10.2151/jmsj1965.72.5_719
- Oort, A. H. and Yienger, J. J. 1996. Observed interannual variability in the Hadley circulation and its connection to ENSO. *J. Clim.* **9**, 2751–2767. doi:10.1175/1520-0442(1996)009<2751:OIVITH>2.0.CO;2
- Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C. and Wang, W. 2002. An improved in situ and satellite SST analysis for climate. *J. Clim.* **15**, 1609–1625. doi:10.1175/1520-0442(2002)015<1609:AIISAS>2.0.CO;2
- So, C. H. and Chan, J. C. L. 1997. An observational study on the onset of the summer monsoon over South China around Hong Kong. *J. Meteorol. Soc. Jpn.* **75**, 43–57. doi:10.2151/jmsj1965.75.1_43
- Tao, S. and Chen, L. 1987. A review of recent research on the East Asian summer monsoon in China. In: *Monsoon Meteorology* (eds. C.-P. Chang and T. N. Krishnamurti). Oxford University Press, pp. 60–92.
- Wang, B. and Chan, J. C. L. 2002. How strong ENSO events affect tropical storm activity over the western North Pacific. *J. Clim.* **15**, 1643–1658. doi:10.1175/1520-0442(2002)015<1643:HSEAT>2.0.CO;2
- Wang, B., Huang, F., Wu, Z. W., Yang, J., Fu, X. H. and co-authors. 2009. Multi-scale climate variability of the South China Sea monsoon: A review. *Dyn. Atmos. Oceans* **47**, 15–37. doi:10.1016/j.dynatmoce.2008.09.004
- Wang, B., Wu, R. and Fu, X. 2000. Pacific–East Asian teleconnection: How does ENSO affect East Asian Climate? *J. Clim.* **13**, 1517–1536. doi:10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2
- Wang, B. and Wu, R. 1997. Peculiar temporal structure of the South China Sea summer monsoon. *Adv. Atmos. Sci.* **14**, 177–194. doi:10.1007/s00376-997-0018-9
- Wang, B. and Xu, X. H. 1997. Northern Hemisphere summer monsoon singularities and climatological intraseasonal oscillation. *J. Clim.* **10**, 1071–1085. doi:10.1175/1520-0442(1997)010<1071:NHMSMA>2.0.CO;2
- Wang, B. 2002. Rainy season of the Asian–Pacific summer monsoon. *J. Clim.* **15**, 386–398. doi:10.1175/1520-0442(2002)015<0386:RSOTAP>2.0.CO;2
- Wilks, D. S. 1995. *Statistical Methods in the Atmospheric Sciences*. Academic Press, 467 pp.
- Xie, P. and Arkin, P. A. 1997. Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteorol. Soc.* **78**, 2539–2558. doi:10.1175/1520-0477(1997)078<2539:GPAYMA>2.0.CO;2
- Yim, S. Y., Yeh, S. W., Wu, R. and Jhun, J. G. 2008. The influence of ENSO on decadal variations in the relationship between the East Asian and western North Pacific summer monsoons. *J. Clim.* **21**, 3165–3179. doi:10.1175/2007JCLI1948.1
- Zhang, R., Sumi, A. and Kimoto, M. 1996. Impact of El Niño on the East Asian monsoon: A diagnostic study of the '86/87 and '91/92 events. *J. Meteorol. Soc. Jpn.* **74**, 49–62. doi:10.2151/jmsj1965.74.1_49
- Zhou, W. and Chan, J. C. L. 2007. ENSO and the South China Sea summer monsoon onset. *Int. J. Climatol.* **27**, 157–167. doi:10.1002/joc.1380