Interdecadal change in autumn rainfall over Southeast China and its association with tropical Pacific SST

Kui Liu1,2 · Jilong Chen2 · Lian-Tong Zhou2 · Zhibiao Wang2 · Yong Liu2

Received: 5 April 2022 / Accepted: 12 October 2022 / Published online: 22 October 2022 © The Author(s), under exclusive licence to Springer-Verlag GmbH Austria, part of Springer Nature 2022

Abstract
In this paper, Japan Meteorological Agency (JRA-55) reanalysis and observational rainfall datasets from the National Climate Center (NCC) of China, as well as satellite datasets from the Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Climatology Project (GPCP), and International Satellite Cloud Climatology Project (ISCCP), are used. The correlation coefficient and fast Fourier transform (FFT) low-pass filter are also used, in order to reveal the interdecadal decrease in autumn rainfall in Southeast China (SEC) after 1990. The close and robust relationship between the interdecadal variation in autumn rainfall in SEC and sea surface temperature (SST) in the tropical Pacific is investigated. The most significant and stable region of correlation is located in 10° S–10° N, 160° E–160° W, in which there also exists interdecadal warming after 1990. Furthermore, the interdecadal warming of SST can induce Gill responses of the atmosphere: a cyclone anomaly is produced on each side of the equator in the lower troposphere, with a westerly anomaly to the west of the dateline, and an anticyclone anomaly is produced in the upper troposphere. In particular, the cyclone anomaly on the northern side of the equator is located in the Northwest Pacific (NWP), and its ambient northerly airflow weakens meridional water vapor transport, as well as the local descending motion and low-troposphere divergence, in favor of the interdecadal decrease in SEC rainfall after 1990. In addition, the sensitive experiments with ECHAM-5.4 model also confirm that the interdecadal warming in the region (10° S–10° N, 160° E–160° W) would motivate the atmospheric Gill response and thereby cause the sinking motion in SEC and support the interdecadal decrease in autumn rainfall in SEC.

1 Introduction
The main meteorological disasters in China include droughts, floods, typhoons, high temperatures, cold waves, low-temperature freezing, sandstorms, hail, and tornadoes. Among them, drought and flood are the primary agricultural meteorological disasters (Zhang et al. 2008). Especially in the context of global warming, extreme weather and climate events and associated meteorological drought and flood disasters have resulted in some new changes. With the continuous development of agricultural resources in China, the ecosystem is relatively fragile, and drought affects the vegetation in the corresponding areas (Zhang et al. 2012), thus affecting the stability of the ecosystem. Analysis of drought and flood changes is conducive to the ecological construction of China. Second, China is a large agricultural country with a large population. To ensure food security and reduce economic losses, the study of the variability of regional precipitation and associated drought and flood causes has become an important topic in China’s climate research.

Southeast China (SEC) includes Fujian, Guangdong, East Guangxi, Jiangxi, Hunan, South Hubei, and South Zhejiang, which is economically booming and a crucial tropical and subtropical agricultural production base in China (Liu et al. 2019). Therefore, the climatology and variation features of rainfall in SEC, as well as associated droughts and floods, have received much attention (Xin et al. 2006; Qiu et al. 2009; Wan et al. 2009; Li et al. 2016a, 2016b; Jin et al. 2017; Liu et al. 2019).

Previous studies have provided some explanation for the interdecadal shift of rainfall in all seasons in SEC, but among them, studies linked to autumn is relatively less (Xin et al., 2006; Wu et al. 2010; Feng and Li 2011; Huang et al. 2013). In the past 50 years, the spring in South China has shown a marked
drought trend (Zuo et al. 2012), which is attributed to the interdecadal variation in the North Atlantic Oscillation (NAO) in the preceding winter (Xin et al. 2006), increase in long-lasting El Niño events, reduction in La Niña episodes (Qiu et al. 2009), increase in anthropogenic aerosol emissions (Hu and Liu 2013), interdecadal shift of Eurasian spring snow after the 1980s (Zuo et al. 2012), and Pacific Decadal Oscillation (PDO) (Wu and Mao 2016). The summer precipitation in South China shows a remarkable interdecadal variation accompanied by increasing flood events (Nitta and Hu 1996; Weng et al. 1999; Ding et al. 2008; Xing et al. 2016), which has been attributed to the increased heating in the tropical Pacific and the tropical Indian Ocean (Chang et al. 2000; Gong and Ho 2002; Yang and Lau 2004), internal dynamics of the atmosphere (Si et al. 2016), weakening of the Asian monsoon (Ding et al. 2008), interdecadal reduction in Eurasian snow water equivalent and increase in tropical cyclones in the South China Sea (SCS) in approximately 1993 (Wu et al. 2010; Chen et al. 2012), and rising emissions of black carbon aerosols (Menon et al. 2002). For winter, the rainfall over South China has also increased significantly in recent decades, with increased moisture over SEC and decreasing snowfall totals (Zhai et al. 2005; Gill 1980; Zhang et al. 2014), which is attributed to the interdecadal shift of the El Niño-Southern Oscillation (ENSO), East Asian winter monsoon (EAWM), Arctic Oscillation (AO), West Pacific sea surface temperature (SST), and SCS SST (Zhou and Wu 2010; Zhou et al. 2010; Zhou, 2011a, b; Yang and Huang, 2021). For example, a weak EAWM is accompanied by anomalous southwesterly winds over the SCS, anomalous moisture convergence, and upward motion, which enhances precipitation in South China (Zhou and Wu 2010; Zhou et al. 2010; Zhou 2011a, b; Yang and Huang 2021; Zhou 2011a, b).

Autumn is the transition period of the atmospheric circulation pattern from summer to winter, and the atmospheric circulation in SEC changes significantly, such as the withdrawal of the subtropical high from land to ocean and the gradual development of the winter monsoon. During these changes in atmospheric circulation, the autumn precipitation in SEC shows salient uniqueness. As shown in Fig. 1, the shading regions, mainly concentrating in SEC, were obtained through a significant $t$ test at the 95% confidence level. It indicates that the autumn precipitation in SEC is weakly related to precipitation in the rest of China. Therefore, this study focuses on the rainfall in SEC to highlight its uniqueness.

In this region, autumn droughts occur more frequently than in other seasons (Jian et al. 2008), and in particular, severe droughts are most likely to occur in southeastern SEC (Chen et al. 2014a, b). The autumn rainfall in South China is a positive anomaly, accompanied by the ridge of the Western Pacific subtropical high located in southern South China, a relatively strong subtropical high, a relatively warm SST in the Western Pacific and North Pacific, and a relatively cold SST in the South Indian Ocean (Niu and Li 2008). In recent decades, the increase in aerosols has benefited the interdecadal decrease in autumn rainfall in SEC by raising atmospheric stability, lessening convective available potential energy, and reducing cloud effective particle size (Chen et al. 2012). Chen et al. (2014a, b) analyzed the variation in autumn drought in South China after the late 1980s. Autumn droughts occurred frequently, and the most strikingly sudden change was after 2002, with an aggravation of drought in this region (Chen et al. 2014b). Lin et al. (2012) reported that the years with autumn droughts are linked with slow adjustment of sea level pressure and inactive cold air, and

Fig. 1 Correlation map showing the average of rainfall at 74 stations in SEC and 553 stations. The thick line represents the zero line, and the contour interval is 0.1. The shaded areas were obtained from a significance $t$ test at the 95% confidence level, the rectangle denotes SEC (22.5° N–30° N, 110° E–120° E), and the dots represent the meteorological stations.
the acceleration of flash droughts in SEC is closely related to anthropogenic climate change (Wang and Yuan 2021). Jia et al. (2015) pointed out that the reduction in typhoon activity in SEC during autumn was an important factor for the decrease in autumn precipitation in SEC. Autumn precipitation anomalies in SEC has a stronger linkage with SST over the southeastern tropical Indian Ocean after 2005 (Huo et al. 2022), and especially, the late autumn rainfall also connects with the process of South China Sea summer monsoon withdrawal (Hu et al. 2020). Moreover, India-Burma Trough, eastern trough of the plateau, and Tibetan Plateau ground heat source could also exert an influence on the autumn rainfall over SEC (Niu and Li 2008; Gu et al. 2012).

Therefore, the factors affecting autumn precipitation over SEC are complex and diverse, but SST in the tropical Pacific could be an important factor. Some previous studies have revealed that the SST in the tropical Pacific has a significant impact on the precipitation in SEC by affecting the atmospheric circulation (Zhang et al. 2011; Wang et al. 2000; Jiang et al., 2014). Zhang et al. (2011) found that CP/EP El Niño events have a significant remote impact on autumn rainfall in SEC through anomalous cyclones and anomalous anticyclones in the NWP (Zhang et al. 2011). Jiang et al. (2014) considered that to the east of the Tibetan Plateau, September rainfall had an interdecadal reduction after the mid-1980s, which may have been related to the variation in SST in the equatorial Central Pacific (Jiang et al. 2014). According to former studies, we note that the relationship between SST in the tropical Pacific and autumn precipitation in SEC is focused on interannual scales. Does the variation in SST in the tropical Pacific cause the interdecadal change in autumn rainfall in SEC? If so, what is the physical linkage? This work explores this issue.

In this paper, the interdecadal change in rainfall in boreal autumn over SEC and its potential cause are investigated in depth. The data and methods used in this study are shown in Section 2. Section 3 confirms the interdecadal shift of autumn precipitation in SEC and associated circulation features. Section 4 investigates the association of the interdecadal warming in the tropical Central Pacific with interdecadal reduction of autumn rainfall in SEC, and Section 5 further explores the physical process of interdecadal warming of the tropical Central Pacific influencing the interdecadal reduction of autumn rainfall in SEC. The summary and conclusions are given in Section 6.

2 Data and method

SEC is selected as the research region marked by a rectangle in Fig. 1, which spans from 22.5° N–30° N to 110° E–120° E. All stations (74 meteorological stations) in the SEC region labeled by dots in Fig. 1 are chosen from 553-station rainfall dataset provided by the National Climate Center (NCC) of China Meteorological Administration (CMA). The monthly reanalysis data JRA-55 are used (Kobayashi et al. 2015), with a horizontal resolution of 1.25° × 1.25°. The monthly average SST is from HadISST version 1.1 from the Hadley Center, with a horizontal resolution of 1° × 1° (Rayner et al. 2003). Simple Ocean Data Assimilation (SODA) sea temperature is also used in this study. Version 3B43 of the Tropical Rainfall Measuring Mission (TRMM) datasets is provided by the National Space Development Agency of Japan (NASA) and the National Aeronautics and Space Administration (NASA), and version 2.1 of the Global Precipitation Climatology Project (GPCP) datasets is provided by the Global Precipitation Climatology Center. Monthly total cloud amount and shortwave and longwave radiation datasets are provided by the International Satellite Cloud Climatology Project (ISCCP), referred to as the ISCCP-D2 dataset, with a horizontal resolution of 2.5° × 2.5° (Klein and Hartmann 1993; Marchand et al. 2010). Autumn refers to the mean of September, October, and November. The study focuses on the period from 1971 to 2018.

Correlation, fast Fourier transform (FFT) low-pass filter (remaining 9-year-and-above signals), Le Page mutation analysis (Yonetani 1992), and numerical simulation are all applied in this paper. It is worth noting that the degrees of freedom of the sequence after the FFT low-pass filter decrease significantly. Using the theoretical proof and Monte Carlo method, Yan et al. (2004) designed a scheme for determining the degrees of freedom of a time series after a FFT low-pass filter: DOF = \( \frac{2 \times \Delta T}{T_c} \times (N - 2) \), where DOF represents the degrees of freedom, \( \Delta T \) is the sampling interval, equal to 1 here; \( T_c \) is the cutoff period for low-pass filtering, equal to 8; and \( N \) that is equal to 38 is the data sample number (Yan et al. 2004). By using this formula, the degree of freedom of the filtered sequence is approximately 10 during the research period.

This work makes use of the ECHAM-5.4 model, with T63L19 resolution (with a horizontal resolution of T63 and vertical resolution of 19 layers), to conduct simulation experiments. The corresponding grid datasets have a 1.875° latitudinal step and meridional Gauss lattice, totaling up to 192 (in the meridional direction) × 96 (in the latitudinal direction) grid points.

3 Interdecadal shift of autumn precipitation in SEC

The standardized rainfall averaged over SEC from 1971 to 2018 is shown in Fig. 2a, and the most notable characteristic of autumn precipitation in SEC is a decreasing trend after 1990 and an increasing trend after 2009. It is clear that the precipitation during 1991–2009 is significantly
lower than that during the 1971–1990 period, as seen from the 9-year running average curve. As shown in Fig. 2b, the standardized rainfall sequence is calculated using the TRMM during 1998–2018 and GPCP datasets during 1979–2018, and their correlations with the sequence in Fig. 2a during the same period are 0.95 and 0.96, respectively. Therefore, the interdecadal change of rainfall in SEC also can be discerned in other datasets. The Le Page mutation analysis of this sequence in Fig. 2a further confirms that the interdecadal change years of autumn precipitation in SEC are approximately 1990 and 2009, respectively (Fig. 2c), and the same conclusion can also be obtained by using another mutation analysis method, such as the sliding t test. Since the data spanning 2010–2018 are too short, the present study mainly focuses on the first interdecadal change at approximately 1990. This change can also be confirmed by the difference in autumn rainfall in SEC between 1991–2009 and 1971–1990. As shown in Fig. 2d, the rainfall decreases uniformly over SEC, and the most obvious decrease is up to 30 mm per month in Guangdong and Fujian Provinces, mainly located in the dotted regions.

As shown in Fig. 3a, flow fields at 850 hPa differ obviously during 1991–2009 compared to those in the 1971–1990 periods, with a significant cyclonic anomaly and positive vorticity anomaly appearing in the Bay of Bengal (BOB). In addition, a cyclonic anomaly appears obviously in the NWP, and the middle-high latitude circulation over the Western Pacific also changes strikingly. An easterly anomaly appears in the middle-latitude westerly belt, and it is transported from the ocean to the land and being opposite to the East Asian trough (EAT) climatological circulation pattern, which would cause the weakening of the EAT and the appearance of a negative vorticity anomaly. In general, the most significant circulation changes are in the BOB, NWP, and EAT regions, along with the interdecadal decrease in rainfall in SEC after 1990.

At 200 hPa, there is an anticyclonic anomaly located in 10° N–20° N, 120° E–140° E; a significantly cyclonic anomaly in 20° N–40° N, 100° E–120° E; and a significant weakening EAT, which can affect SEC (Fig. 3b). Because of the weakening EAT, the temperature increases significantly, mainly north of 30° N, and the geopotential height anomaly is positive (Fig. 3c). The divergent wind diverges at low troposphere values, especially in SEC (Fig. 3d). The water vapor flux and its divergence show that the enhanced BOB cyclonic circulation can only transport anomalous water vapor to Northwest China and southwestern Southwest China after 1990, and it cannot transport water vapor into SEC (Fig. 3e). The NWP cyclonic anomaly transports water vapor southward from the ocean into SEC, but water vapor in this region does not have obvious convergence (Fig. 3e), which

Fig. 2 Standardized rainfall averaged over SEC (a) during the 1971–2018 period using station rainfall. The black curve denotes the 9-year running average (b) during the 1998–2018 period (bar) using the TRMM dataset and during the 1979–2018 period using the GPCP dataset (curve line). c Le Page mutation analysis is used for the sequence in a, and the black straight line with a value of 5.99 (4.61) represents significance from a chi-square distribution test at a 95% (90%) confidence level. d The difference of 74-station rainfall in SEC between 1991–2009 and 1971–1990 (unit: mm month\(^{-1}\)), the dotted regions are the 95% confidence level of Student’s t test)
is consistent with Gu et al. (2012). Anomalous sinking motion prevails in SEC, in which cloud liquid water content decreases significantly at and below 400 hPa (Fig. 3f), which is unfavorable to water vapor condensation and supports the decrease in rainfall. All of these atmospheric changes support the reduction in rainfall over SEC after 1990.

4 Tropical Central Pacific warming associated with the interdecadal change in autumn rainfall in SEC

The SST anomaly in the tropical Pacific is closely related to autumn rainfall in SEC (Liu et al. 2019; Jia et al. 2015; Gu
et al. 2012); therefore, we also calculate the difference in SST and mixed layer sea temperature between 1991–2009 and 1971–1990 (Fig. 4). The results show that the tropical Indian Ocean and the western and Central Pacific undergo salient interdecadal warming, which occurs at the 95% confidence level but with uneven amplitudes, along with the interdecadal decrease in autumn rainfall in SEC. In particular, the most significant warming area is located in the tropical Pacific, with more than 0.3 °C warming during 1991–2009, compared to the 1971–1990 period, which is marked by a rectangle. Figure 4b also shows that the tropical Central Pacific warming extent in the mixing layer is also the largest, which is at the 95% confidence level. Therefore, the interdecadal warming in the tropical Central Pacific appears not only in the sea surface but also in the sea mixing layer.

To ensure whether the key SST region is located in the tropical Central Pacific, we also calculate the correlation between rainfall over SEC and SST, as displayed in Fig. 5. As shown in Fig. 5a, the correlation between the interdecadal sequence of autumn rainfall in SEC and SST is negative, which indicates that when rainfall in SEC is deficient, significant SST warms up in the tropical and subtropical Pacific (20° S–20° N, 140° E–140° W), SCS, and tropical eastern Indian Ocean. The warm SST anomalies, located in the Indian Ocean and SCS, gradually disappear from the preceding summer to simultaneous fall (Fig. 5a-d). However, the anomaly in the tropical Pacific is still maintained, but the central area shrinks to the region 10° S–10° N, 160° E–160° W (Fig. 5d), the same as the region marked in Fig. 4.

Consequently, we believe that the SST anomaly in the tropical Central Pacific (10° S–10° N, 160° E–160° W) is closely related to the interdecadal decrease in autumn precipitation in SEC. Therefore, a tropical Central Pacific SST index (referred to STI) is defined (Fig. 6a). The STI is calculated as the normalized sequence of SST averaged over 10° S–10° N, 160° E–160° W, which is filtered by a FFT low-pass filter. As displayed in Fig. 6b, the STI also experiences an interdecadal change at approximately 1990, consistent with the autumn rainfall in SEC, as displayed in Fig. 2b. Its correlation with the interdecadal sequence of autumn precipitation in SEC is −0.60, which is significant at the 95% confidence level. We further confirm that the interdecadal reduction in autumn rainfall in SEC has a significant connection with the interdecadal enhancement of tropical Pacific SST (mainly at 10° S–10° N, 160° E–160° W).

5 Physical linkage between tropical Pacific warming and the interdecadal decrease in precipitation in SEC

To explore how the STI affects the interdecadal decline of precipitation in SEC, Fig. 7 is shown. As shown in Fig. 7a, with the interdecadal warming in the tropical Central Pacific, an anomalous cyclone is generated on the southern and northern sides of the equator in the low troposphere at 850 hPa, in step with the appearance of a westerly anomaly west of the dateline. However, the anomalous cyclonic circulation at both sides to the equator at 850 hPa is transformed into an anomalous anticyclonic circulation at 200 hPa (Fig. 7b). The configurations of the anomalous circulation in lower and higher layers show that the interdecadal warming of the key sea region in the tropical Central Pacific induces a Gill-type response in the atmosphere (Gillies et al. 2012; Zhang and Krishnamurti 1996; Wu et al. 2000).

Previous studies have emphasized that the anomalous cyclone or anticyclone of the NWP in the lower troposphere is an important atmospheric bridge, conveying the direct and indirect influence of tropical sea temperature on the atmospheric circulation of East Asia. As shown in Fig. 7, the

Fig. 4 a The difference in SST between 1991–2009 and 1971–1990; b same as a, but for the weighted-mean mixed layer sea temperature (including 5 m, 15 m, 25 m, 35 m, and 46 m) (unit: °C); the dotted areas denote the 95% confidence level. Datasets are processed by a FFT low-pass filter before calculating the difference
cyclone anomaly in the NWP in the lower layer at 850 hPa can provide an ambient current to influence SEC. To demonstrate the physical process clearly and how the interdecadal warming in the tropical Pacific influences the interdecadal reduction in rainfall in SEC, Fig. 8 is shown.

The anomalous pattern in Fig. 8a is consistent with that in Fig. 3c, only with more significance in the temperature field at 850 hPa. The positive geopotential height anomaly associated with the STI helps to reduce rainfall in SEC (Fig. 8a). The anomaly of divergent wind diverges in the low troposphere, especially in SEC (Fig. 8b), consistent with that displayed in Fig. 3d. The NWP anomalous cyclone transports southward water vapor from the ocean into SEC, but water vapor in this region is divergent (Fig. 8c), which is consistent with Gu et al. (2012) and Fig. 3e. Anomalous sinking motion prevails in SEC (Fig. 8d), which is unfavorable to water vapor condensation and supports the decrease in rainfall. All of these atmospheric changes associated with the STI support the reduction in rainfall over SEC after 1990. As displayed in Fig. 9, the tropical Central Pacific (10° S–10° N, 160° E–160° W) experiences an interdecadal warming after 1990. In the meantime, an anomalous cyclone is induced in the NWP, accompanied by a local meridional circulation with a subsiding branch in SEC, and these anomalous circulations help to lead to the interdecadal reduction in rainfall in SEC.

To confirm that the interdecadal warming in the tropical Pacific exerts an impact on autumn rainfall in SEC from the atmospheric Gill response, the numerical simulation experiments are designed as follows: the SST anomaly (−1 °C for experiment 1, referred to as EXP1, and 1 °C for EXP2) is...
added over the tropical Central Pacific (10° S–10° N, 160° E–160° W) based on the climatological mean states of SST, and then atmosphere mode ECHAM-5.4.00 is integrated for 22 years.

When the tropical Central Pacific region, 10° S–10° N, 160° E–160° W, has a warming anomaly, an anomalous cyclone is generated at both sides of the equator at 850 hPa in the low troposphere, as shown in Fig. 10a. To the west of the heat source is a westerly anomaly, and to the east is an easterly anomaly. In Fig. 10b, in the upper troposphere at 200 hPa, there exists an anomalous anticyclone on both sides of the equator. These results from simulations are consistent with those from the statistical diagnoses in Fig. 7; therefore, it is confirmed that the warming anomaly in the tropical Central Pacific induces a Gill response in the atmosphere and further impacts autumn rainfall in SEC.

As shown in Fig. 10c, anomalous descending motion in SEC (at latitudes of 17.5° N–40° N) prevails when a warming anomaly appears in the tropical Central Pacific, and the descending motion in the statistical diagnoses is mainly located at 15° N–30° N (Fig. 3f), both of which have little difference, but both support the rainfall decrease in SEC. As shown in Fig. 10d, the decrease of rainfall in the northwestern part in SEC can reappear well, only with some deviation about the location of decreasing rainfall, but the southern part of the simulated rainfall in SEC has some inconsistencies with the observations shown in Fig. 2d. Generally, the wind anomalies in the sensitivity experiments verify the results from statistical diagnoses: warming anomalies in the tropical Central Pacific could exert an influence on autumn rainfall in SEC by exciting the atmospheric Gill response, as well as an anomalous local descending motion. However, the simulated precipitation has some differences from the observations, which indicates that the autumn rainfall in SEC may also be affected by some other factors, requiring further investigation in future work.

6 Conclusions and discussion

The interdecadal decrease in autumn precipitation in SEC occurred in approximately 1990, accompanied by interdecadal warming in tropical Pacific SST, and the correlation
coefficient of the two interdecadal sequences is $-0.6$, exceeding the 95% significance confidence level. The main conclusions are as follows.

The interdecadal warming of the tropical Pacific has caused an atmospheric Gill response, triggering an anomalous cyclone in the lower troposphere of the NWP. The ambient air current of the abnormal cyclone weakens the northward water vapor transport, which supports deficit precipitation in SEC. In addition, weak cold advection, higher tropospheric temperature, and increased geopotential...
Fig. 10 The difference in wind in the sensitivity experiments at a 850 hPa and b 200 hPa (vector, m s\(^{-1}\); red vectors represent exceeding the 99% confidence level). c The difference in meridional wind and vertical motion cross section along 110° E–120° E (omega is multiplied by −100, and the shading indicates exceeding the 99% confidence level). d The difference in rainfall over SEC (unit: 10\(^{-6}\) kg m\(^{-2}\) s\(^{-1}\)). The difference indicates EXP2-EXP1.

Fig. 11 The difference in a total cloud amount in autumn (unit: %), b shortwave radiation obtained by the sea surface (positive value indicating downward transmission), and c the net longwave radiation released (positive value indicating upward transmission; unit: 0.1 W m\(^{-2}\)) between 1991–1998 and 1983–1990. Dotted parts are obtained through a reliability test at the 90% confidence level, and the box area represents the key area of interdecadal warming in the tropical Pacific, as shown in Fig. 4.
height associated with the weakened EAT, as well as the local abnormal downdraft, decreased significant cloud liquid water content in the middle and lower troposphere, as well as a significant divergence wind anomaly at 850 hPa, which is conducive to the interdecadal decrease in autumn rainfall in SEC.

Numerical simulations testify to the results of statistical diagnosis that the anomalous warming of sea temperature in the tropical Pacific exerts an influence on autumn precipitation in SEC by stimulating the atmospheric Gill response.

It is emphasized that the interdecadal warming in the tropical Central Pacific is an important reason for the interdecadal decrease in autumn precipitation in SEC in the above analyses; therefore, we conduct further discussion about the reason for interdecadal warming. As shown in Fig. 11a, the total cloud amount in the region is beneficial to the increase in shortwave radiation (Fig. 11b), which is beneficial to the interdecadal warming of SST in the tropical Pacific. In addition, the interdecadal variation in the longwave radiation in this region is also beneficial to the interdecadal warming of SST in the region (Fig. 11c), but this paper does not analyze the reasons for this in depth. In view of the fact that the data of ISCCP began in 1983, and 1990 is referred to as the dividing year of the difference, we only choose the data spanning from 1983 to 1998 to keep the same time span between 1983–1990 and 1991 to the end. In addition to the effects of atmospheric cloud radiation, the impact of marine dynamic processes and other factors on tropical Central Pacific SST will be further explored in future work.

However, other relevant studies about SEC rainfall have some different focuses. Zhang et al. (2014) considered that the interdecadal variation of winter rainfall in SEC is not only connected with tropical Western Pacific SST, but also linked to AO. Xin et al. (2006) deemed that the interdecadal variation of North Atlantic Oscillation in the preceding winter causes the interdecadal reduction of spring rainfall in SEC. Hu et al. (2020) emphasized that the process of South China Sea summer monsoon withdrawal is significantly linked to the late autumn rainfall in SEC. Hu et al. (2022) considered that the interdecadal enhancement of the relationship between autumn precipitation anomalies in Eastern China and SSTA over the southeastern tropical Indian Ocean has occurred in the recent decades, which implies tropical Indian Ocean plays a bigger role in the variation of autumn rainfall there. In the present paper, we mainly focus on the influence from the tropical Central Pacific. So, about the interdecadal rainfall of SEC, other key sea areas and atmospheric circulation should be paid more attention in the future investigation.

**Author contribution** All the authors contributed to the conceptualization and design of the study. Data were gathered by Kui Liu. An initial draft of the paper was prepared by Kui Liu. The article was repeatedly revised to generate the final version by Lian-Tong Zhou, Jilong Chen, Zhibiao Wang, and Yong Liu.

**Funding** This study was funded by the National Natural Science Foundation of China (grant no. 42105063).

**Data availability** The TRMM dataset is available at http://mirador.gsfc.nasa.gov/cgi-bin/mirador/, the GPCP dataset is available at http://www.esrl.noaa.gov/psd/gridded/data.gpcp.html, the JRA-55 dataset is available at http://jra.kishou.go.jp/JRA-55/, the SODA dataset is available at http://soda.tamu.edu/assim/SODA_2.24, and ISCCP-D2 is available at https://asdc.larc.nasa.gov/PRODOCS/isccp/table_isccp.html.

**Code availability** The codes used for the processing of data can be provided on request to the corresponding author.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** All the authors consented to publish the paper.

**Competing interests** The authors declare no competing interests.

**References**

Chang CP, Zhang Y, Li T (2000) Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part I: roles of the subtropical ridge. J Clim 13(24):4310–4325.

Chen J, Wu R, Wen Z (2012) Contribution of South China Sea tropical cyclones to an increase in Southern China summer rainfall around 1993. Adv Atmos Sci 29(3):585–598

Chen S, Huang J, Qian Y, Ge J, Su J (2014a) Effects of aerosols on autumn precipitation over mid-eastern China. J Trop Meteorol 20(3):242–250

Chen S, Wei G, Guo J, Xing X, Li C (2014b) Variation characteristics of the autumn drought in Southwestern and Southern China. J Arid Meteorol (in Chinese) 32(6):894–901

Ding Y, Wang Z, Sun Y (2008) Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon Part I: observed evidences. Int J Climatol 28(9):1139–1161

Feng J, Li J (2011) Influence of El Niño Modoki on spring rainfall over South China. J Geophys Res Atmos 116(D13).

Gill AE (1980) Some simple solutions for heat-induced tropical circulation. Q J R Meteorol Soc 106(449):447–462

Gillies R, Wang S, Huang W (2012) Observational and supportive modelling analyses of winter precipitation change in China over the last half century. Int J Climatol 32(5):747–758

Gong D, Ho CH (2002) Shift in the summer rainfall over the Yangtze River valley in the late 1970s. Geophys Res Lett 29(10).

Gu W, Li W, Chen L, Jia X (2012) Interannual variations of autumn precipitation in China and their relations to the distribution of tropical Pacific sea surface temperature. Clim Environ Res (in Chinese) 17(4):467–480

Hu N, Lui X (2013) Modeling study of the effect of anthropogenic aerosols on late spring drought in South China. Acta Meteor Sin 27(5):701–715
Hu P, Chen W, Chen SF, Liu YY, Huang RP, Dong SR (2020) Relationship between the South China Sea summer monsoon withdrawal and September-October rainfall over Southern China. Clim Dyn 54(1):713–726

Huang W, Chan JC, Au-Young AY (2013) Regional climate simulations of summer diurnal rainfall variations over East Asia and Southeast China. Clim Dyn 40(7–8):1625–1642

Huo L, Guan Z, Jin D, Liu X, Wang X D, Xia Y (2022) The interdecadal variations and causes of the relationship between autumn precipitation anomalies in Eastern China and SSTA over the southeastern tropical Indian Ocean. Clim Dyn https://doi.org/10.1007/s00382-022-06348-4

Jia Z, Wu L, Wang T, Wen Z (2015) Relationship between autumn rainfall anomalies in South China and typhoons activity, and the anomalous sea surface temperature characteristics. Acta Oceanologica Sinica (in Chinese) 37(1):53–62

Jian M, Qiao Y, Wen Z (2008) Analysis on characteristics of seasonal and inter-seasonal drought events in South China. Acta Scientiarum Naturalium Universitatis Sunyatseni (in Chinese) 47(4):118–121

Jiang X, Li Y, Yang S, He G (2014) Variations of early autumn rainfall in the lee side of the Tibetan Plateau. Theor Appl Climatol 117(3):565–577

Jin D, Guan Z, Huo L., Wang X (2017) Possible impacts of spring sea surface temperature anomalies over South Indian Ocean on summer rainfall in Guangdong-Guangxi region of China. Clim Dyn 49(9):3075–3090

Klein SA, Hartmann D (1993) Spurious changes in the ISCCP dataset. Geophys Res Lett 20(6):455–458

Kobayashi S, Ota Y, Harada Y, Ebita A, Moriya M, Onoda H, Takahashi K (2015) The JRA-55 reanalysis: general specifications and performance. Meteorol Soc Japan 89(5):563–582

Li W, Zhang R, Sun C, Ren H, Liu J, Zuo J, Li X (2016) Recent research advances on the interannual-interdecadal variations of drought/flood in South China and associated causes. J Appl Meteorol Sci (in Chinese) 27:577–591

Li X, Zhou W, Chen Y (2016) Detecting the origins of moisture over Southeast China: seasonal variation and heavy rainfall. Adv Atmos Sci 33(3):319–329

Lin AL, Li C, Gu D, Zheng B (2012) Variation and causes of persistent drought events in Guangdong Province. J Tro Meteorol 18(1):54–64

Liu K, Chen J, Yang R (2019) Connection between two leading modes of autumn rainfall interannual variability in Southeast China and two types of ENSO-like SSTA. Advances Meteorol 1762505

Marchand R, Ackerman T, Smyth M, Rossov WB (2010) A review of cloud top height and optical depth histograms from MISR, ISCCP, and MODIS. J Geophys Res Atmos 115(D16).

Menon S, Hansen J, Nazarenko L, Luo Y (2002) Climate effects of black carbon aerosols in China and India. Science 297(5590):2250–2253

Nitta T, Hu ZZ (1996) Summer climate variability in China and its association with 500 hPa height and tropical convection. J Meteorol Soc Japan 74(4):425–445

Niu N, Li J (2008) Interannual variability of autumn precipitation over South China and its relation to atmospheric circulation and SST anomalies. Adv Atmos Sci 25(1):117–125

Qiu Y, Cai W, Guo X, Pan A (2009) Dynamics of late spring rainfall reduction in recent decades over southeastern China. J Clim 22(8):2240–2247

Rayner N, Parker D, Horton E, Folland C, Alexander L, Rowell D, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res Atmos 108(D14)

Si D, Hu ZZ, Kumar A, Jha B, Peng P, Wang W, Han R (2016) Is the interdecadal variation of the summer rainfall over eastern China associated with SST? Clim Dyn 46(1–2):135–146

Wan R, Zhao B, Wu G (2009) New evidences on the climatic causes of the formation of the spring persistent rains over southeastern China. Adv Atmos Sci 26(6):1081–1087

Wang B, Wu R, Fu X (2000) Pacific-East Asian teleconnection: how does ENSO affect East Asian climate? J Clim 13(9):1517–1536

Wang Y, Yuan X (2021) Anthropogenic speeding up of South China flash droughts as exemplified by the 2019 summer-autumn transition season. Geophy Res Lett 48(9):e2020GL091901

Weng H, Lau K, Xue Y (1999) Multi-scale summer rainfall variability over China and its long-term link to global sea surface temperature variability. J Meteorol Soc Japan 77(4):845–857

Wu R, Wu Z, Yang S, Li Y (2010) An interdecadal change in Southern China summer rainfall around 1992/93. J Clim 23(9):2389–2403

Wu X, Mao J (2016) Interdecadal modulation of ENSO-related spring rainfall over South China by the Pacific Decadal Oscillation. Clim Dyn 47(9):3203–3220

Wu Z, Sarachik E, Battisti D (2000) Vertical structure of convective heating and the three-dimensional structure of the forced circulation on an equatorial beta plane. J Atmospheric Sci 57(13):2169–2187

Yang X, Yu R, Zhou T, Wang B (2006) Drought in late spring of South China in recent decades. J Clim 19(13):3197–3206

Yang W, Wang B, Yim SY (2016) Peak–summer East Asian rainfall predictability and prediction part I: Southeast Asia. Clim Dyn 47(1–13)

Yan H, Zhong M, Zhu Y (2004) Determination of the degree of freedom of digital filtered time series with an application to the correlation analysis between the length of day and the Southern Oscillation Index. Chin Astron Astrophy 28(1):120–126

Yang F, Lau KM (2004) Trend and variability of China precipitation in spring and summer: linkage to sea-surface temperatures. Int J Climatol 24(13):1625–1644

Yang X, Huang P (2021) Restored relationship between ENSO and Indian summer monsoon rainfall around 1999/2000. Innovation 2:100102

Yonetani T (1992) Discontinuous changes of precipitation in Japan after 1900 detected by the Lepage test. J Meteorol Soc Japan 70(1):95–104

Zhai P, Zhang X, Fraedrich K, Sielmann F, Zhi X (2014) Interdecadal variability of winter precipitation in Southeast China. Climate Dyn 43(7–8):2239–2248

Zhang Q, Tao S, Peng J (2008) The studies of meteorological disasters over China. Chinese J Atmospheric Sci (in Chinese) 32(4):815–825

Zhang W, Jin FF, Li J, Ren HL (2011) Contrasting impacts of two-type El Niño over the western North Pacific during boreal autumn. J Meteorol Soc Japan 89(5):563–569

Zhang Z, Krishnamurti TA (1996) Generalization of Gill’s heat-induced precipitation index. J Atmos Sci 53(7):1045–1052

Zhou LT (2011) Impact of East Asian winter monsoon on rainfall over southeastern China and its dynamical process. Int J Climatol 31(5):677–686

Zhou LT (2011b) Interdecadal change in sea surface temperature anomalies associated with winter rainfall over South China. J Geophys Res Atmos 116(D11)
Zhou LT, Tam CY, Zhou W, Chan JC (2010) Influence of South China Sea SST and the ENSO on winter rainfall over South China. Adv Atmos Sci 27(4):832–844
Zhou LT, Wu R (2010) Respective impacts of the East Asian winter monsoon and ENSO on winter rainfall in China. J Geophys Res Atmos 115(D2)
Zuo Z, Zhang R, Wu B (2012) Inter-decadal variations of springtime rainfall over Southern China mainland for 1979–2004 and its relationship with Eurasian snow. Sci China Earth Sci 55(2):271–278

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.