LETTER

Interdecadal variation of summer rainfall in the Greater Mekong Subregion and its possible causes

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Abstract
This paper investigates the interdecadal variation in summer rainfall over the Greater Mekong Subregion (GMS) during 1981–2020 and its possible causes, using Climate Hazards Group Infrared Precipitation with Station rainfall datasets, European Centre for Medium-range Weather Forecasts Reanalysis fifth generation data and the atmospheric general circulation model ECHAM6. The dominant mode of summer rainfall in the GMS features a seesaw pattern with an increase in rainfall over the central–southern GMS and a decrease in rainfall in northwestern Myanmar–Yunnan. The dominant mode of the GMS summer rainfall shows a change in regime around 2001/2002. Interdecadal variability in rainfall is largely related to sea surface temperature anomalies (SSTAs) over the Western Pacific Warm Pool (WPWP). Warmer SSTAs in the WPWP lead to interdecadal variation in summer rainfall in the GMS by exciting an anomalous cyclone in the lower troposphere over the southern GMS–South China Sea. This is accompanied by anomalous ascending motions in the central–southern GMS and anomalous descending motions in northern Myanmar–Yunnan. The Matsuno–Gill mechanism, which links SSTAs with interdecadal variations in the GMS summer rainfall, is further confirmed by numerical experiments.

1. Introduction

The Greater Mekong Subregion (GMS) includes Yunnan in China and all of the countries on the Indochina Peninsula. There are four transboundary rivers: Dulong-Irrawaddy River, Nu-Salween River, Lancang-Mekong River, and Yuan-Red River over the GMS. Previous studies indicate that the GMS has a typical monsoon climate with a wet season from May to October (e.g. Matsumoto 1997, Qin et al 1997, Nguyen et al 2014, Darby et al 2016, Fan and Luo 2019, Yang and Wu 2019a, Yang et al 2020). The GMS is located where the East Asian summer monsoon (EASM) and Indian summer monsoon (ISM) meet; therefore, the wet-season rainfall, which contributes >80% of the total annual rainfall in the GMS, is modulated synchronously by the two summer monsoons (Holmes et al 2009, Cao et al 2012, 2016, Tao et al 2016, Yang et al 2019a, 2019b). Socioeconomic development across the GMS is limited by environmental problems caused by floods or droughts (Li et al 2019). For example, severe droughts, which occurred continuously in Yunnan over 2009–2012 and in most parts of the southern GMS from late 2015 to mid-2016, caused severe environmental problems and greatly damaged local socioeconomic development (Cao et al 2014, 2017, Ma et al 2017, Yang and Wu 2019a). It is evident that a better understanding of the spatiotemporal evolution of rainfall over the GMS would provide key insights for the subregion’s socioeconomic development.

Studies have shown that summer rainfall in Thailand is largely related to the Indian Ocean Dipole, El Niño, and La Niña (Singhrattna et al 2005a, 2005b, Gale and Saunders 2013, Rasänen and Kummu 2013). The EASM and the Indochina Monsoon have a greater impact on the flood regime of the southern GMS (Delgado et al 2012,
Tsai et al (2015), Ge et al (2017), Fan and Luo (2019).

Misra and DiNapoli (2013) demonstrated that anomalous summer rainfall over the GMS is closely related to moisture transport from the Bay of Bengal (BOB) or the South China Sea (SCS). Cao et al (2014) revealed that sea surface temperature anomalies (SSTAs) in the subtropical Indian Ocean are among the most important factors in summer rainfall variability over the northern GMS. Cao et al (2017) found that the May rainfall over the northern GMS is closely associated with the thermal contrast between the BOB and the southeastern Tibetan Plateau. Yang et al (2019a) demonstrated that the BOB–East Asia–Pacific teleconnection is closely related to summer rainfall over the GMS. Endo et al (2009) suggested that the rainfall intensity on wet days increased from the 1950s to the 2000s, and some studies have reported a slight increase in summer rainfall over part of the northern GMS in recent decades (Fan and He 2015, Wu et al 2016). Limsakul and Singhruck (2016) identified two decadal transitions in rainfall in the 1970s and 1990s in response to the Pacific Decadal Oscillation. Most recently, Faikrua et al (2020) demonstrated that the Atlantic Multidecadal Oscillation has been a key factor in the decadal increase in summer rainfall in Thailand after the mid-1990s.

The studies outlined above indicate that Yunnan experienced droughts while Thailand experienced floods on interdecadal timescales. Yunnan is in the northern GMS and Thailand is mostly in the southern GMS. This configuration of floods and droughts in the southern and northern GMS, respectively, motivates us to explore whether the two extreme phenomena are connected, and the cause(s) of any such connection.

2. Data, method, and AGCM

We used fifth generation reanalysis data from the European Centre for Medium-range Weather Forecasts Reanalysis fifth generation (ERA5; Hersbach et al 2019, Hoffmann et al 2019) for the period 1981–2020. The resolution of the ERA5 data is $0.25^\circ \times 0.25^\circ$ latitude and longitude. The ERA5 data has 37 pressure levels ranging from 1000 to 1 hPa. The precipitation datasets are from two sources, including the Climate Hazards Group Infrared Precipitation with Station rainfall with 0.05$^\circ$ horizontal resolution for the period 1981–2020 (CHIRPS; Funk et al 2015), and the Asian Precipitation–Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) gridded by 0.25$^\circ$ in latitude and longitude during 1951–2015 (Yatagai et al 2012). We also adopted CHIRPS and the Asian Precipitation–Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) gridded by 0.25$^\circ$ in latitude and longitude during 1951–2015 (Yatagai et al 2012). We also adopted ECHAM6, provided by the Max Planck Institute for Meteorology in Germany, to confirm the key physical processes revealed by observational analysis (Giorgetta et al 2013). The equivalent resolution of the ECHAM6 is 1.8758$^\circ$ on a Gaussian grid. There are 47 hybrid sigma-pressure levels in the vertical layer. Empirical orthogonal function (EOF) analysis was adopted to reveal the main spatiotemporal evolution of summer rainfall over the GMS. We used regression and composite analysis and their corresponding Student’s t-tests to determine which physical processes were critical. The interdecadal component of PC1 is extracted using a nine year binomial smooth function. The effective degree of freedom ($N_{\text{ dof}}$) defined by Bretherton et al (1999) is evaluated following

$$N_{\text{ dof}} = N\left(1 - r_1 r_2\right)/\left(1 + r_1 r_2\right),$$

where $N$ is the sample size and $r_1$ and $r_2$ are the lag-1 autocorrelations of the two time series. In this study, summer was defined as June–September (JJAS).

3. Interdecadal variation in summer rainfall in the GMS

We used EOF analysis to reveal the spatiotemporal characteristics of the GMS summer rainfall. The leading EOF mode (EOF1) accounted for 24.5% of the total variance of the GMS summer rainfall in the CHIRPS dataset. The EOF1 showed a meridional seesaw pattern with the ‘+’ ‘−’ varying from the south to the north (figure 1(a)). Above-normal rainfall generally occurs in the central–southern GMS, whereas below-normal rainfall is observed in northwestern Myanmar–Yunnan. To verify the interdecadal variation of the GMS summer rainfall, the same EOF analysis was performed again on the APHRODITE dataset. The total variance explained by the EOF1 of the APHRODITE dataset (22.7%) is close in CHIRPS dataset, although its time span differs from the CHIRPS dataset. The EOF1 (figure 1(b)) also showed the similar seesaw pattern to figure 1(a) from south to north. The intensity of negative center becomes stronger, and its location shifts mainly from Yunnan to Myanmar (figure 1(a)). The associated principal component time series (PC1, hereafter referred to as the GMS summer rainfall index (GMSSRI)) exhibited a prominent interdecadal variation (figures 1(c) and (d)). In fact, the mean values of the GMSSRI in CHIRPS (APHRODITE) dataset are $−0.53$ ($−0.25$) for 1981–2001 and 0.59 (0.55) for 2002–2020 (2002–2015). Their corresponding significance test above the 99% confidence level. The power spectra of the GMSSRI calculated using the two datasets agree well with each other. There is a significant period band at values greater than eight years. Additionally, another significant peak appears at the quasi-biennial period (figures 1(e) and (f)).
Accordingly, a nine year binomial smooth is applied to extract the interdecadal component of the GMS summer rainfall (GMSSRI-ID). The GMSSRI-ID of APHRODITE and CHIRPS datasets can explain 68.28% and 58.12% of the total variance in the GMSSRI, respectively; therefore, this interdecadal variation is one of the most important components observed in the variability of the GMS summer rainfall. These results indicate that the interdecadal variation of summer rainfall over GMS is robust regardless of the rainfall datasets.

To observe the pattern of the GMS summer rainfall that is associated with its interdecadal component, the GMSSRI-ID was first regressed onto summer rainfall over the GMS. Figure 2(a) shows a meridional seesaw pattern with the ‘+, −’ varying from north to south. Significantly enhanced summer rainfall exceeding 20 mm is located principally in the central–southern GMS. Summer rainfall exceeding 70 mm is distributed mainly in the coastal areas of Myanmar, Thailand, and Vietnam. In contrast, decreases in summer rainfall are observed in the northern GMS and in a few parts of the southern GMS. To verify the summer rainfall pattern associated with the interdecadal shift that occurred around 2001/2002, we further calculated the difference in GMS summer rainfall using the 1981–2001 average subtracted from the 2002–2020 average (figure 2(b)). The difference in GMS summer rainfall (figure 2(b)) resembles that shown in figure 2(a), exhibiting significant interdecadal variation with a meridional seesaw pattern, although the region of positive anomalies is a little wider in the southern GMS than that in figure 2(a). These results from the EOF, regression, and composite difference analyses suggest that the interdecadal variation in summer rainfall over the GMS is robust and has a meridional seesaw pattern. When the GMS summer rainfall is heavier in the central–southern GMS, it will be lighter in northwestern Myanmar–Yunnan, and vice versa, on interdecadal timescales.

4. Possible physical processes for the interdecadal variation in the GMS summer rainfall

To determine the possible physical processes for the interdecadal variation in the GMS summer rainfall, the atmospheric circulation was first regressed onto the GMSSRI-ID. At 850 hPa, the region at 0°–15° N, 90°–135° E is dominated by anomalous westerly winds, whereas the region spanning
20°–30° N, 90°–135° E is controlled by anomalous easterly winds. These winds indicate that cyclonic anomalies dominate in the central–southern GMS–tropical western Pacific (figure 3(a)). Figure 3(b) shows that significant anomalous ascending motions, averaged over 90°–110° E, control the region from 10° to 20° N below 200 hPa, with minimum values of less than −9 × 10^{-3} Pa s^{-1}, and anomalous descending motions dominate the region north of 20° N with maximum values exceeding 6 × 10^{-3} Pa s^{-1}. The column-integrated water vapor flux anomalies (figure 3(c)) show the same pattern as the 850 hPa horizontal winds (figure 3(a)). The anomalous easterly water fluxes over 20°–35° N lead to a reduction in the transport of water vapor from the Indian Ocean by weakening climatological southwesterly winds, but the anomalous westerly water fluxes south of 20° N increase the transport of water vapor from the Indian Ocean by strengthening climatological southwesterly winds (figure 3(c)). Correspondingly, the central–southern GMS is dominated by anomalous convergence in the column-integrated water vapor with values of below −1 × 10^{-3} kg m^{-2} s^{-1} in the center of the region. The regions north of 20° N and south of 10° N are both dominated by anomalous divergence in the column-integrated water vapor flux with values greater than 5 × 10^{-6} kg m^{-2} s^{-1} at the center of the anomalies. This configuration results in enhanced water vapor convergence (divergence) over the central–southern (northern) GMS, providing favorable (unfavorable) water vapor conditions for more (less) rainfall in that region on an interdecadal timescale. These results suggest that the anomalous cyclone with anomalous ascending motions in the central–southern GMS–tropical western Pacific is a key circulation system, causing the interdecadal variation in GMS summer rainfall.

To verify the effectiveness of the anomalous cyclone in reducing the interdecadal variation in GMS summer rainfall, we plotted the composite difference between each variable averaged over 2002–2020 minus the average over 1981–2001. The composite differences of winds at 850 hPa, the vertical velocity averaged at 90°–110° E, the column-integrated water vapor flux and its divergence between the two periods (figures 3(e)–(h)) generally share the same patterns as those same variables when regressed onto the GMSSRI-ID (figures 3(a)–(d)). This key anomalous cyclone in the lower troposphere can be also be observed in the same region from the central–southern GMS to the tropical western Pacific (figure 3(e)), except that the size of the significant area around the northern SCS and tropical western Pacific is smaller than in its regression counterpart (figure 3(a)). A dipole of vertical motions from the lower to the upper troposphere also occurs at 10°–30° N with values below −1.5 × 10^{-2} Pa s^{-1} in the center of the negative region around 12.5° N, and values of 1.2 × 10^{-2} Pa s^{-1} in the center of the positive region around 25° N (figure 3(f)). The intensity of the dipole of the vertical velocity tends to be stronger than that of the results from the regression onto the GMSSRI-ID (figure 3(b)). Although the composite difference of the column-integrated
water vapor flux also shows an anomalous cyclone in the central–southern GMS, it becomes weaker in the tropical western Pacific than in the corresponding results from the regression analysis (figures 3(c) and (g)). The composite difference of the divergence in the column-integrated water vapor flux (figure 3(h)) is much stronger than the divergence from the data regressed onto the GMSSRI-ID (figure 3(d)). The clear similarities between figures 3(a)–(d) and (e)–(h) indicate that the atmospheric circulation in this region also experienced interdecadal variability around 2001/2002, and eventually led to the interdecadal variation in summer rainfall over the GMS.

To reveal the impact SSTAs have on the interdecadal variation in summer rainfall over the GMS, the sea surface temperature was regressed onto the GMSSRI-ID. Figure 4(a) shows that the positive phase of the GMSSRI-ID corresponds to coherent SSTAs from warming over the Western Pacific Warm Pool (WPWP, red shading in figure 4(a)) with a clear horseshoe-like pattern. Figure 4(b) shows that the composite difference in SSTAs between 1979–2001 and 2002–2020 is characterized by significant positive anomalies with a maximum of >0.6 °C in the western Pacific. Its distribution is consistent with the SSTAs that were regressed onto the GMSSRI-ID (figure 4(a)), but the region becomes much larger (figure 4(b)), which may be caused by human influence signals in the composite difference of SSTAs between the two periods (Zhang et al 2021). The correlation coefficients between the SST index averaged over 10° S–10° N, 140°–170° E (blue dashed
rectangle) and the GMSSRI-ID remain significant at the 99% confidence level from previous autumn to concurrent summer, even after considering the effective degree of freedom (not shown). The contemporaneous correlation coefficients between the GMSSRI-ID and the SST index reach 0.58, significantly exceeding the critical value at the 99% confidence level. Meanwhile, the correlation coefficient is 0.67 between the SST index and local rainfall. These results suggest that the SST in the WPWP probably drives the interdecadal variation in the GMS summer rainfall by forcing out an anomalous cyclone on its northwest flank (figure 3; Wu et al 2006).

5. Modeling results

The diagnostic results above have identified a possible mechanism by which the SSTAs in the WPWP can impact the interdecadal variation in the GMS summer rainfall. Here, numerical experiments based on ECHAM6 are employed to further confirm these diagnostic results. Two experiments were performed to
Figure 5. Composite differences in the JJAS mean variables between the SE and CE. (a) 850 hPa horizontal winds (vector, m s$^{-1}$), (b) 90°–110° E vertical velocity (CI = 5 × 10$^{-3}$ Pa s$^{-1}$), and (c) rainfall (CI = 10 mm). Areas shaded from light to dark colors denote differences that are significant at the 99%, 95%, and 99% confidence levels, respectively. In panel (a), the region bounded by the green solid line indicates the GMS.

complement the results obtained in section 4. One experiment is the control run (CE), in which the SST climatology was adopted for each month over all oceans; the other is the sensitive experiment (SE), in which 0.5°C SSTAs are superimposed on the SST climatology of the WPWP in January–December, and the SST climatology was still used over the rest of the oceans. Each experiment was integrated for 30 years. The first year was discarded as spin-up, and the other 2–30 years are analyzed in this section.

We analyzed the simulated differences in 850 hPa horizontal winds, vertical velocity, column-integrated water vapor flux, and its divergence in JJAS, computed using the SE minus the CE. The simulated differences of the 850 hPa horizontal winds have almost the same pattern as the diagnostic results for the whole research domain (figures 3(a) and 5(a)), but the cyclonic anomalies with anomalous easterly winds in 20°–30° N and anomalous westerly winds in 0°–15° N become stronger and much more significant (figure 5(a)). The vertical velocity presents an obvious meridional dipole pattern (figure 5(b)) resembling figure 3(b). The troposphere over the region spanning 10°–20° N is controlled by anomalous ascending motions with a value at the center of the anomaly of less than −6 × 10$^{-2}$ Pa s$^{-1}$ averaged over 90°–110° E, whereas the troposphere over the region north of 20° is controlled by anomalous descending motions with a value in the center of the anomaly of greater than 5 × 10$^{-2}$ Pa s$^{-1}$.

The simulated configuration of anomalous 850 hPa horizontal winds, and anomalous vertical velocity provide optimum conditions for an increase in simulated rainfall in the central–southern GMS, and a decrease in simulated rainfall in the northern GMS. In fact, the simulated rainfall anomalies (figure 5(c)) present a meridional dipole pattern with positive anomalies in the central–southern GMS and negative anomalies in western Myanmar–Yunnan. It is worthy of note that the simulated rainfall anomalies robustly reproduce the anomalous rainfall pattern in the diagnostic results (figures 1(a) and 2). The simulated results obtained above confirm that the key physical process driving the interdecadal variation of SSTAs over the WPWP play a significant role in regulating the interdecadal variation in GMS summer rainfall.

6. Summary

This study investigates the interdecadal variation in the GMS summer rainfall and its possible causes, based on reanalysis datasets for the period 1981–2020 and the ECHAM6 model. The observed leading mode of the GMS summer rainfall variability is extracted using EOF analysis, and the associated atmospheric circulation and potential drivers are analyzed using linear regression analysis. The positive EOF1 phase of the summer rainfall features heavier rainfall over the central–southern GMS, and a reduction in rainfall over northwestern Myanmar–Yunnan. The rainfall
index shows that the GMS summer rainfall experienced a clear interdecadal shift around 2001/2002. The interdecadal component, accounting for 68.27% of the total variance in the GMS summer rainfall, indicates that interdecadal variation in the GMS summer rainfall cannot be ignored. Before 2001, reductions in summer rainfall usually occurred in the central–southern GMS, and heavier rainfall occurred in northwestern Myanmar–Yunnan. The opposite conditions prevail after 2002. The interdecadal variation in the GMS summer rainfall is further verified by the results of composite difference and power spectral analyses.

The cyclone anomalies in the lower troposphere over the central–southern GMS–tropical western Pacific, which are responsible for the interdecadal seesaw variation in the GMS summer rainfall, are excited by the SSTAs in the WPWP via the Matsuno–Gill mechanism (Matsuno 1966, Gill 1980). When the WPWP is warmer on interdecadal timescales, cyclone anomalies will be forced out from its northwest flank, which is located in the central–southern GMS–tropical western Pacific. The strengthened ascending motion and water vapor convergence, responding to the cyclone anomalies, dominate conditions over the central–southern GMS. Meanwhile, in compensation, a strengthened descending motion and water vapor divergence occurs over the northern GMS. Consequently, summer rainfall increases over the central–southern GMS, but decreases over northwestern Myanmar–Yunnan on interdecadal timescales. The simulated results of numerical experiments confirm the role of SSTAs over the WPWP in the interdecadal variation of GMS summer rainfall.

This study focuses on the interdecadal variation in the GMS summer rainfall and one of its most important causes; i.e. SSTAs in the WPWP. The interannual variability in the GMS summer rainfall and the physical processes associated with this variability are also important problems in need of further study. Recent studies have found that interdecadal Pacific Oscillation (IPO) transitioned from a positive phase to a negative phase around early 20th century (Lee et al 2019, Liu et al 2019). So, future studies are needed to investigate how the IPO drives the rainfall anomalies over the GMS.

Data availability statement

The ERA5 reanalysis data used in the study are openly available through https://climate.copernicus.eu/climate-reanalysis. The monthly mean SST data were downloaded from www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html. The APHRODITE rainfall were downloaded from http://aphrodite.st.hirosaki-u.ac.jp/products.html.

The data that support the findings of this study are openly available at the following URL/DOI: https://data.chc.ucsb.edu/products/CHIRPS-2.0/.

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References

Bretherton C S, Widmann M, Dymnikov V P, Wallace J M and Bladé J 1999 The effective number of spatial degrees of freedom of a time-varying field J. Clim. 12 1990–2009
Cao J, Gui S, Su Q and Yang Y L 2016 The variability of the Indian–East Asian summer monsoon interface in relation to the spring seesaw mode between the Indian Ocean and the central-western Pacific J. Clim. 29 5027–40
Cao J, Hu J M and Tao Y 2012 An index for the interface between the Indian summer monsoon and the East Asian summer monsoon J. Geophys. Res. 117 D18108
Cao J, Tao P, Wang L and Liu K 2014 Summer rainfall variability in low-latitude highlands of China and subtropical Indian Ocean dipole J. Clim. 27 880–92
Cao J, Zhang W K and Tao Y 2017 Thermal configuration of the Bay of Bengal–Tibetan Plateau region and the May rainfall anomaly in Yunnan J. Clim. 30 9303–19
Darby S E, Hackney C R, Leyland J, Kummu M, Lauri H, Parsons D R, Best J L, Nicholas A P and Aalto R 2016 Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity Nature 539 276–9
Delgado J M, Merza B and Apel H 2012 A climate–flood link for the lower Mekong river Hydrol. Earth Syst. Sci. Discuss. 16 1533–41
Endo N, Matsumoto J and Iwin T 2009 Trends in precipitation extremes over Southeast Asia SOLA 5 168–71
Faikrua A, Pimonsree S, Wang L, Limskakul A, Singhruck P and Dong Z Z 2020 Decadal increase of the summer precipitation in Thailand after the mid-1990s Clim. Dyn. 55 3253–67
Fan H and He D M 2015 Temperature and precipitation variability and its effects on streamflow in the upstream regions of the Lancang–Mekong and Nu–Salween Rivers J. Hydrometeorol. 16 2248–63
Fan X M and Luo X 2019 Rainfall and flow variations in the Lancang–Mekong River basin and the implications of monsoon fluctuation and regional topography Water 11 2086
Funk C et al 2015 The climate hazards infrared rainfall with stations—a new environmental record for monitoring extremes Sci. Data 2 066
Gale E L and Saunders M A 2013 The 2011 Thailand flood: climate causes and return periods Weather 68 233–7
Ge F, Zhi X F, Babar Z A, Tang W W and Chen P 2017 Interannual variability of summer monsoon precipitation over the Indochnina Peninsula in association with ENSO Theor. Appl. Climatol. 128 523–31
Gill A E 1980 Some simple solutions for heat-induced tropical circulation Quart. J. Roy. Meteorol. Soc. 106 447–62
Giorgetta M A et al 2013 Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase J. Adv. Model. Earth Syst. 5 572–97
Gui S and Yang R W 2020 Quasi-biweekly oscillation of the Bay of Bengal–East Asia–Pacific teleconnection in boreal summer J. Clim. 33 7643–62
Hersbach H et al 2019 Global reanalysis: goodbye ERA-Interim, hello ERA5 ECMWF Newsletter 159 17–24
Hoffmann L et al 2019 From ERA-Interim to ERA5: the considerable impact of ECMWF’s next-generation reanalysis on Lagrangian transport simulations Atmos. Chem. Phys. 19 3097–124
Holmes J A, Cook E R and Yang B 2009 Climate change over the past 2000 years in Western China Quat. Int. 194 91–107
Lee S H, Seo K H and Kwon M 2019 Combined effects of El Niño and the Pacific Decadal Oscillation on summertime circulation over East Asia Asia-Pac. J. Atmos. Sci. 55 91–9
Li H, Zhou Y and Wei Y D 2019 Institutions, extreme weather, and urbanization in the Greater Mekong Region Ann. Am. Assoc. Geogr. 109 1317–40
Limsakul A and Singhruck P 2016 Long-term trends and variability of total and extreme precipitation in Thailand Atmos. Res. 169 361–17
Liu Q, Zhou T J, Mao H T and Fu C B 2019 Decadal variations in the relationship between the western Pacific subtropical high and summer heat waves in East China J. Clim. 32 1627–40
Ma S M, Zhou T J, Angelil O and Shiogama H 2017 Increased chances of drought in southeastern periphery of the Tibetan Plateau induced by anthropogenic warming J. Clim. 30 6543–60
Matsumoto J 1997 Seasonal transition of summer rainy season over Indochina and adjacent monsoon region Adv. Atmos. Sci. 14 231–45
Matsumoto T 1966 Quasi-geostrophic motions in the equatorial area J. Meteorol. Soc. Japan. 44 25–43
Misra V and DiNapoli S 2013 The variability of the Southeast Asian summer monsoon Int. J. Climatol. 34 893–901
Nguyen D Q, Renwick J and McGregor J 2014 Variations of surface temperature and rainfall in Vietnam from 1971 to 2010 Int. J. Climatol. 34 249–64
Qin J, Ju J H and Xie M E 1997 Weather and Climate in Low Latitudes Plateau (Beijing: China Meteorology Press) p 210 (in Chinese)
Räsänen T A and Kummu M 2013 Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin J. Hydrol. 476 154–68
Singhrajnna N, Rajagopalan B, Kumar K K and Clark M 2005a Interannual and interdecadal variability of Thailand summer monsoon season J. Clim. 18 1697–708
Singhrajnna N, Rajagopalan B, Kumar K K and Clark M 2005b Seasonal forecasting of Thailand summer monsoon rainfall Int. J. Climatol. 25 649–64
Tao Y, Cao J, Lan G D and Su Q 2016 The zonal movement of the Indian–East Asian summer monsoon interface in relation to the land–sea thermal contrast anomaly over East Asia Clim. Dyn. 46 2759–71
Tsai C, Behera S K and Waseda T 2015 Indo-China monsoon indices Sci. Rep. 5 8107
Wu F F, Wang X, Cai Y P and Li C H 2016 Spatiotemporal analysis of precipitation trends under climate change in the upper reach of Mekong River basin Quat. Int. 392 137–46
Wu R G, Kirtman B P and Pegion K 2006 Local air–sea relationship in observations and model simulations J. Clim. 19 4914–32
Yang R W, Gui S and Cao J 2019b Bay of Bengal–East Asia–Pacific teleconnection in boreal summer J. Geophys. Res. Atmos. 124 4359–412
Yang Y Y and Wu R G 2019a Seasonal variation of rainfall over the Indochina Peninsula and its impact on the South China Sea spring warming Int. J. Climatol. 39 1618–33
Yang Y Y, Wu W R and Wang C H 2020 Individual and combined impacts of tropical Indo-Pacific SST anomalies on interannual variation of the Indochina Peninsular precipitation J. Clim. 33 1069–88
Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N and Kitoh A 2012 APHRODITE: constructing a long-term daily gridded rainfall dataset for Asia based on a dense network of rain gauges Br. Am. Meteorol. Soc. 93 1401–15
Zhang L X, Chen Z M and Zhou T J 2021 Human influence on the increasing drought risk over Southeast Asian monsoon region Geophys. Res. Lett. 48 e2021GL093777