Changes in consecutive dry/wet days and their relationships with local and remote climate drivers in the coastal area of China

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ABSTRACT

Being located between Eurasia continent and the western Pacific Ocean, the coastal area of China (hereafter as CAC) is vulnerable to climate change and prone to climate-related disasters. Based on the daily meteorological dataset of 156 stations, variations of consecutive dry days (CDD) and consecutive wet days (CWD) and their relationships with local and remote climate drivers from 1961 to 2017 over CAC were investigated. Results showed that the multi-year averages in CDD and CWD were 22.5–93.7 and 3.4–11.8 days, generally presenting a “high north and low south” and “low north and high south” spatial pattern, respectively. The decadal trend rates in CDD and CWD were -4.5 – -2.7 and -0.7 – -0.6 days per decade, respectively, both showing universal insignificant change trends over CAC. There was a significant negatively correlation between CDD and precipitation at partial of meteorological stations clustered in Guangxi autonomous region, and a predominantly significant positive relationship between CWD and precipitation over CAC. Both CDD and CWD correlated significantly with Multivariate ENSO Index (MEI) and Southern Oscillation Index (SOI) in parts of northern coastal areas close to the sea, while a common insignificant linkage was detected between CDD/CWD and large-scale circulation indices such as North Atlantic Oscillation (NAO), Northern Oscillation Index (NOI), Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) over CAC. Results from this paper are anticipated to provide insights into the drought/flood disaster risk mitigation and prevention as well as water resources management in the coastal area of China.

1. Introduction

One of the most profound effect of global warming is the redistribution in precipitation around the world, including significant changes of precipitation tendency and its spatiotemporal differentiation, as well as shift of precipitation extremes in terms of frequency, intensity and duration (Allan and Soden, 2008; Papalexiou and Montanari, 2019). The fluctuation of precipitation and its extreme events, especially the latter, has a profound impact on the natural ecosystem and human living environment (Mishra et al., 2010). And compared with the occasional individual extreme precipitation event, the impact of consecutive precipitation extremes with the characteristics of long duration and vastly subsequent effect is more intense (Merino et al., 2018).

Consecutive dry days (CDD) and consecutive wet days (CWD),

indicating the longest period of rainless and rainy day, respectively, are both two important climate indicators to assess the duration of precipitation extremes (Huang et al., 2017). Not only directly characterize the dry and wet weather spell, CDD and CWD but also associate closely with the occurrence of drought and flood events (Li et al., 2017; Wu and Chen, 2019). For example, a prolonged dry period with no or rare precipitation is more likely to trigger drought events due to severe lack of rainfall, on the contrary, long-term continuous rainy days are prone to induce flood events attributable to large rainfall totals (Li et al., 2017; Wu and Chen, 2019). What's more, these long-lasting extreme precipitation events are more particularly relevant to meteorological disasters as well as secondary and derivative disasters (Li et al., 2012; Huang et al., 2017), which pose a serious threat facing natural ecosystems and human society (Aguilera et al., 2019; Ding et al., 2019), and thus consequently being attached widespread attentions among

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scientist, stakeholders and decision makers during the last few decades. Therefore, analysis of variation and its causes in consecutive dry/wet days is beneficial to climate disaster risk management as well as climate mitigation and adaptation (Singh et al., 2014).

Previous studies of CDD and CWD mainly focused on the temporal trend and spatial distribution analysis at a variety of scales such as global (Alexander, 2016), continental (Marengo et al., 2010; de Skansi María et al., 2013; Roque-Malo and Kumar, 2017), national (Brown et al., 2010; Keggenhoff et al., 2014; Shi et al., 2018) as well as regional (Nie et al., 2012; Croitoru et al., 2013; Wang et al., 2013b; Song et al., 2015; Zhan et al., 2017), pointing to inconsistent characteristics of temporal trend and diversity spatial pattern in CDD and CWD overall, which all have provided useful information about the spatiotemporal variations of consecutive days of precipitation extremes. However, regarding to trend detecting in CDD and CWD by application of non-parametric method such as Mann-Kendall trend test, few studies considered serial correlation elimination (Huang et al., 2017; Mullick et al., 2019), which would lead to deviations or even inaccuracies in the rate of change.

In addition, the climate forcings in consecutive days of precipitation extremes is another worldwide concern, which is subjected to on-going debate that linking changes in consecutiveness of precipitation extremes with natural climate shift and the impact of human activities. Regarding to natural climate fluctuations, numerous publications documented that local climate drivers such as temperature and precipitation as well as remote climate forcings like large scale atmospheric and oceanic circulations all play roles in the variation of extreme precipitation duration, but no consensus of the relationship had been reached on how relevant and to what extent, especially when facing different space-time scales. On the terms of local climate forcing, for example, Easterling et al. (2007) found both temperature and precipitation took responsibilities for the persistent drought in the continental United States during 1950–2006. And in China, Yang et al. (2020) revealed that precipitation and temperature were strongly correlated with agricultural drought, and precipitation was more sensitivity to drought loss than temperature. Mei et al. (2018) found the trend magnitudes of CDD and CWD both correlated negatively with annual total precipitation in northern China (Jing-Jin-Ji district), of which the former was significantly. In the southwest of China, Liu et al. (2015) demonstrated that the soil water storage capacity in the karst landforms highlighted the increased CDD in the context of global warming, which could thus further exacerbate the drought risk in the local region. What's more, Wu and Chen (2019) found that variabilities of average precipitation and temperature resulted in changes of dryness and wetness duration in the Pearl river basin during 1960–2015.

Furthermore, studies also pointed out that there were some relevancies between extreme precipitation duration and large-scale circulation modes of climate variability around the world. For instance, in the North America, a good correlation between CDD and El Niño–Southern Oscillation (ENSO) was found by Griffiths and Bradley (2007). And in the South America, Cavalcanti (2012) documented that tropical and extratropical large-scale climate variability, such as the Pacific and Atlantic Sea Surface Temperature, the Pacific South America pattern, the Southern Hemisphere annular mode and features of the North Atlantic Oscillation could partly explain the consecutive days of precipitation extremes variations. In China, although there was no significant correlation between remote forcing and precipitation extremes duration at national scale, Multivariate ENSO Index (MEI) and Atlantic Multidecadal Oscillation (AMO) could respectively explain the changes in CWD and CDD partly in the northern China during 1961–2015 (Shi et al., 2018). Moreover, both Liu et al. (2017) and Jiang et al. (2019) confirmed that remote forcing such as ENSO, Pacific Decadal Oscillation (PDO) and Southern Oscillation Index (SOI) all had strong influences on precipitation extremes duration in the Weihe river basin in central China. And in another south watershed, named Pearl river basin, Zhao et al. (2014) indicated that changes in CDD and CWD were

attributed in part to the strengthening anticyclonic circulation, weakening monsoonal flow and vapor transportation over Eurasia.

The coastal area of China is located between Eurasia continent and western Pacific Ocean, presenting a diversity and changeable climate background under the combined effects of land, ocean as well as atmosphere (Yi et al., 2011), thus is highly susceptible to frequent climate disasters (Jiao et al., 2015). Characterized by a spatial pattern with dry north and wet south, CAC is especially prone to suffer drought in the north and flood in the south. Studies in the early stage have conducted on the spatiotemporal variation of consecutive dry/wet days in the areas associated with CAC (Jiang et al., 2011; Wang et al., 2017a; Wang et al., 2017b; Mei et al., 2018), but rare has concerned the influence of climate forcings on consecutive dry/wet days with a continuous space perspective in the coastal area of China as a whole (Ji et al., 2019). Therefore, it is essential to quantify not only the changes in consecutive dry/wet days with the latest observational meteorological data but also the connections between climate forcings and such extremes in the Chinese coast. The objectives of this study are to analyze the characteristics of consecutive dry/wet days during 1961–2017, and to assess the relationships between consecutive dry/wet days with local climate divers (temperature and precipitation) and remote climate forcings (large-scale atmospheric and oceanic circulations), which aim to provide insights into the drought/flood disaster risk mitigation and prevention as well as water resources management in the coastal area of China.

The outline of this article is as follows. Section 2 describes the study area, dataset and methodology employed to evaluate consecutive dry/wet days. In Section 3 the characteristics of consecutive dry/wet days are analyzed. Then the relationships between precipitation extremes duration and climate drivers are presented in Section 4. Finally, discussion and conclusion are given in Section 5 and Section 6, respectively.

2. Data and methodology

2.1. Study area

In eastern China, the region with spatial domain covering coastal provinces, autonomous district and municipalities are identified as the study area (including Beijing for ensuring spatial integrity and consistency of the study area, and excluding Taiwan, the South China Sea islands and waters due to data absence), as shown in Fig. 1. From north to south, the coastal area of China covers temperate, warm temperate, subtropical and tropical zone, with annual mean temperature and annual total precipitation generally increasing from 3.5 °C to 25.4 °C (Fig. 1a) and 291.0 mm to 2741.0 mm (Fig. 1b), respectively, from 1961 to 2017. On the one hand, CAC occupies 14% of the country's total land area that feeds 45.8% of the population, produces 56.3% of GDP and plays an important role in China, on the other hand, suffering from the increasing temperature and non-uniform distribution precipitation, as well as large-scale atmospheric and oceanic circulation oscillations, this coastal region is prone to climate-dependent disasters, which could be aggravated due to the larger population density, better developed economy and denser concentrated wealth over CAC.

2.2. Data

2.2.1. Meteorological data

The observed daily precipitation and temperature records of 244 meteorological stations from 1951 to 2017 were available in the coastal area of China, which were provided by the National Meteorological Information Center, China Meteorological Administration (<http://data.cma.cn/>). RCLimDex software developed by researches from Canadian Meteorological Service (Zhang et al., 2005) was employed to carry out the meteorological data quality control in terms of missing data processing, standard deviation test as well as abnormal data screening. 27

Fig. 1. Location map of the coastal area of China and distribution of the meteorological stations. And the spatial patterns of annual mean temperature (Fig. 1a) and annual total precipitation (Fig. 1b) during 1961–2017 over CAC.

stations were excluded due to the missing data was large than 10% of the total records, and 61 stations which are unable to satisfy the criteria that data records spanning longer than 50 years were also removed. Then the double mass curve method (Su et al., 2006), which was often used to test the homogeneity of precipitation and runoff records in the hydrometeorological field was applied to assess the homogeneity of climate data series for each meteorological station, and no remarkable inconsistency was found for the data series of all the remained stations. It is note that not every minor discontinuity was identified and we acknowledge there may some inhomogeneities remaining, however, the uncovering inhomogeneities would have limited impacts on the change trends of climate variables with long history records over 50 years. Finally, 156 meteorological stations (Fig. 1a) with the historical climate records covering the period from 1961 to 2017 were selected.

2.2.2. Large-scale atmospheric and oceanic circulation patterns

Variation of rainfall extremes at diversity time scales was partly related to the persistence in large scale atmospheric and oceanic circulation (Kenyon and Hegerl, 2010; Willems, 2013), which provide a circulation background field for climate change (Wang et al., 2019). In this study, time series of six monthly large-scale atmospheric and oceanic circulation indices, including Multivariate ENSO Index (MEI), Southern Oscillation Index (SOI), Northern Oscillation Index (NOI), North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) for the period of 1961–2017 were employed to investigate the correlations between continuous dry/wet days and large-scale circulation modes of climate variability. Both MEI and SOI here are utilized to represent the ENSO. And the above six climate indices were obtained from National Oceanic and Atmospheric Administration's NOAA Earth System Research Laboratory's Physical Sciences Division (<https://www.esrl.noaa.gov/psd/data/climateindices/>).

2.3. Methodology

Consecutive dry days and consecutive wet days are used to describe the duration of precipitation extremes according to the daily precipitation. These two climate extreme indicators are recommended by

the World Meteorological Organization CCL/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI). CDD and CWD are defined as the maximum number of consecutive days with daily precipitation less than 1 mm and daily precipitation more than or equal to 1 mm, which respectively measure the length of the driest and the wettest part of the year (Zhang et al., 2005). Here, both CDD and CWD were calculated year by year at each meteorological station using the RCLimDex software (<http://etccdi.pacificclimate.org/software.shtml>).

Mann-Kendall test with Sen's slope estimator, which is a proper and effective trend method for time series (Sen, 1968) was used to calculate the long-term trend magnitudes for the annual time series of CDD and CWD station by station. Considering that the climate records have serial correlation, trend-free pre-whitening procedure (Yue et al., 2002; Hussain and Mahmud, 2019) was employed to remove the autocorrelation of CDD and CWD series before evaluating the change trend. And then the trend magnitudes of CDD and CWD were expressed into slopes per decade at each meteorological station finally. The statistical significance for a trend in CDD and CWD was estimated using the nonparametric Mann-Kendall trend test, and a trend was statistically significant at the 95% confidence level (Kendall, 1975).

The correlation coefficient is an effective indicator to measure relevance between the sets of data. As the most used metric of correlation, Pearson correlation coefficient (Kim et al., 2015) which is based on the covariance matrix of the data was employed to quantify the relationships between the series of consecutive dry/wet days and climate drivers for each meteorological station over CAC during 1961–2017. In the current study, R was denoted as the correlation coefficient, and T statistic (Fisher, 1934) was used to test the significance of correlation degree considering the significant difference at $p \leq .05$.

Inverse Distance Weight interpolation technique (ESRI, 2020) was applied to convert the meteorological station scale data in terms of multi-year averages and decadal trend rates in extreme precipitation duration as well as correlation coefficients between CDD/CWD and climate drivers to spatial layers with a resolution of 1×1 km, for the purpose of quantitatively depicting the variations and causes related to extreme precipitation duration with maps intuitively. Here, calculation of change trend and correlation coefficient, as well as significance test

Fig. 2. Spatial distribution of multi-year averages in CDD and CWD over CAC during 1961–2017.

are implemented with Python program, and spatial interpolation is achieved by ArcGIS.

3. Changes in consecutive dry/wet days

3.1. Multi-year averages in consecutive dry/wet days

The spatial distribution of multi-year averages in CDD and CWD over CAC from 1961 to 2017 is shown in Fig. 2. The multi-year average in CDD was 22.5–93.7 days over CAC, generally presenting a “high north and low south” spatial pattern, with the maximum between 75.0 days to 93.7 days in the west of Liaoning province, the north of Hebei province and Beijing municipality, and the minimum from 22.5 days to 30.0 days being found in Zhejiang province and the north of Fujian province (Fig. 2a). With a characteristic of “low north and high south” in spatial, the multi-year average in CWD was 3.4–11.8 days in the coastal area of China during the considered period, and the regions with the longest wet spells more than 7 days mainly situated in the southern coastal areas while the regions with the shortest duration less than 4 days located in the most parts of Beijing and Tianjin municipalities as well as the south of Hebei province generally (Fig. 2b).

3.2. Decadal trend rates in consecutive dry/wet days

Fig. 3 depicts the spatial signature of decadal trend rates in CDD and CWD over CAC from 1961 to 2017. The decadal trend rate in CDD was -4.5 – 2.7 days per decade in the coastal area of China, with a positive tendency generally found in Shandong and Guangdong provinces as well as Guangxi autonomous district, and a commonly negative tendency in the remaining coastal areas (Fig. 3a). For CWD, -0.7 – 0.6 days per decade trend rate was noticed over CAC, presenting a principally downward trend except sporadic areas placed in south (Fig. 3b). It's should be noted that the changing trends in consecutive days of precipitation extremes were generally insignificant from 1961 to 2017 in the coastal area of China, apart from the regions around the coast of Hangzhou bay located in the northeast of Zhejiang province, where

there presented a centralized significant negative tendency in CDD, and several stations scattered around the northern coastal areas showed remarkable downward trends in CWD.

4. Relationships between consecutive dry/wet days and climate drivers

4.1. Correlations between consecutive dry/wet days and local climate drivers

4.1.1. Correlations between CDD and local climate drivers

The spatial distribution of correlation coefficients between CDD and annual mean temperature and annual total precipitation over CAC during 1961–2017 is presented in Fig. 4. It's found that the correlation coefficient between CDD and temperature was -0.36 – 0.30 in the coastal area of China, presenting a weak positive relationship in the most parts of northern and southwestern coastal areas and a slight negative correlation in the eastern and southeast coast generally (Fig. 4a). Fig. 4b demonstrated that correlation coefficient between CDD and annual total precipitation was -0.41 – 0.19 over CAC, and a common mild negative connection between CDD and precipitation was identified in the coastal region of China. What's more, apart from a portion of stations distributed in the southern coast showing a significant correlation between CDD and precipitation, the relationships between consecutive dry days and temperature as well as precipitation were not statistically significant over CAC in general.

4.1.2. Correlations between CWD and local climate drivers

Fig. 5 shows the spatial patterns of correlation coefficients between CWD and local climate drivers over CAC during 1961–2017. The correlation coefficient between CWD and annual mean temperature was -0.38 – 0.24 over CAC (Fig. 5a). In addition to some areas in the south, a general insignificant and weak negative correlation was identified between CWD and temperature in the Chinese coastal regions. Fig. 5b revealed that a general prominent positive relationship between CWD and annual total precipitation was widespread confirmed with a correlation coefficient between -0.06 to 0.60 in the coastal region of

Fig. 3. Spatial distribution of decadal trend rates in CDD and CWD over CAC during 1961–2017. The red dot represents the station with significant change trend at the 95% confidence level.

China during 1961–2017.

4.2. Correlations between consecutive dry/wet days and remote climate drivers

4.2.1. Correlations between CDD and remote climate drivers

The spatial distribution of correlation coefficients between CDD and

Fig. 4. Spatial distribution of correlation coefficients between CDD and local climate drivers over CAC during 1961–2017.

R_{CDD_Tem} and R_{CDD_Pre} represent the correlation coefficients between CDD and annual mean temperature and annual total precipitation, respectively. The pink dot refers to the station with a statistically significant correlation ($p \leq .05$), the same as below.

Fig. 5. Spatial distribution of correlation coefficients between CWD and local climate drivers over CAC during 1961–2017.

R_{CWD_Tem} and R_{CWD_Pre} represent the correlation coefficients between CWD and annual mean temperature and annual total precipitation, respectively.

remote climate drivers over CAC during 1961–2017 is displayed in Fig. 6. The relationship between CDD and MEI were generally negative in the northern coastal areas but positive in the southern coasts (Fig. 6a), on the contrary, CDD was basically correlated with SOI positively in north but negatively in south (Fig. 6b). Fig. 6c demonstrated that a general weak positive/negative linkage between CDD and NOI was found in the northern/southern coastal regions, which was rather similar to that of SOI. There was a common weak positive relationship between CDD and NAO in the northern and eastern coastal areas, and negative in the remaining coastal regions over CAC (Fig. 6d). For AMO, a dominant mild negative correlation with CDD was found in the coastal area of China (Fig. 6e). And Fig. 6f showed that CDD generally correlated with PDO positively in south and negatively in north.

For ENSO (MEI and SOI), it's revealed that several stations concentrated in the northern coasts close to the sea were found to be significantly correlated with CDD. However, the connections between CDD and the other large-scale modes of climate variabilities such as NOI, NAO, AMO and PDO were not significant generally over CAC, except very limited number of stations which fragmented in the coastal region of China.

4.2.2. Correlations between CWD and remote climate drivers

Fig. 7 revealed the spatial patterns of correlation coefficients between CWD and remote climate drivers over CAC during 1961–2017. It's found that the relationship between CWD and MEI was generally presenting a “negative north and positive south” spatial pattern (Fig. 7a), while correlation between CWD and SOI was found to be positively in north and negatively in south (Fig. 7b). Regarding to NOI, a common feeble positive connection with CWD was discovered in the northern coastal regions while a general slight negative correlation in the southern coasts, which was also like the spatial signature of correlation that between CWD and SOI (Fig. 7c). Fig. 7d showed that CWD mostly correlated with NAO positively in south and negatively in north. And a general negative correlation between CWD and AMO was revealed over CAC except parts of eastern and southwestern coastal areas (Fig. 7e). For PDO, a positive relevance between CWD was presented in

the southeastern and parts of northern coastal areas, and a negative correlation was found in the other coastal regions (Fig. 7f).

It's worth noting that some stations clustered in the northern coasts were found to be showed significant correlations between CWD and ENSO (MEI and SOI), which was similar as that of CDD. What's more, in addition to very small amounts of stations distributed discretely in the coast, the teleconnection correlations between CWD and NOI, NAO, AMO as well as PDO were insignificant basically in the coastal area of China from 1961 to 2017.

5. Discussion

5.1. Spatial patterns in consecutive dry/wet days

The spatial patterns of multi-year averages in CDD and CWD showed a general opposite feature in the coastal area of China, presenting a “high north and low south” spatial pattern for the former while “low north and high south” the latter, which confirmed the previous studies on persistent extreme precipitation events in the region related to Chinese coast (Chen and Zhai, 2013; Shi et al., 2018). The regions in the north of CAC, such as Hebei province, Beijing and Tianjin municipalities as well as the west of Liaoning province located in the semi-humid region with limited rainfall were suffered from the longest continuous dry days much more than 60 days, on the contrary, the southern coastal areas those situated to the south of Zhejiang province with abundant rainfall were susceptible to the longest consecutive wet days extra 7 days. These spatial characteristics of dry and wet spells over CAC further evidence of drying in the north and wetting in the south in China (Li et al., 2017; Yuan et al., 2017).

In the whole coastal area of China, it calculated that CDD showed no change trend while the decadal trend rate in CWD was -0.1 days per decade ($p > .05$) during 1961–2017 after serial correlation elimination. The changing trend of CDD in this study is in accordance with those of You et al. (2011) and Shi et al. (2018), who both documented that the variation tendency of CDD was not statistically significant in China. And for CWD, a same decadal trend rate was found by this study

Fig. 6. Spatial distribution of correlation coefficients between CDD and remote climate drivers over CAC during 1961–2017.

R_{CDD_MEI} , R_{CDD_SOI} , R_{CDD_NOI} , R_{CDD_NAO} , R_{CDD_AMO} and R_{CDD_PDO} represent the correlation coefficients between CDD and MEI, SOI, NOI, NAO, AMO and PDO, respectively.

and Shi et al. (2018), the latter, however, indicated a significant trend in China as a whole. The spatial patterns of decadal trend rates in consecutive days of precipitation extremes visualized the regional differences over CAC. Specifically, this study showed CDD prominently climbed in Shandong and Guangdong provinces as well as Guangxi autonomous region from 1961 to 2017, confirming the results of Wang et al. (2014a) and Liu et al. (2015), which both demonstrated an ascending trend of drought duration in the corresponding region. What's more, the broad negative trend in CWD over CAC further verified the regional studies by Jiang et al. (2011) and Wang et al. (2017a), who concerned the variation of precipitation extremes over Circum-Bohai-Sea region and Yellow Sea western coast, respectively. What needs more attention is that a concentrated significant and negative tendency of CDD and a general insignificant and positive trend of CWD in the areas around the coast of Hangzhou bay were consistent with Wang et al. (2016), who clarified that CDD decreased but CWD increased generally in the Yangtze River Delta during 1960–2012. It is thus reasonable to believe that this coastal region would be facing increasing

possibility of flood-induced disasters when considering both the rise of precipitation and its extremes (Wang et al., 2016; Wang et al., 2017b).

The results mentioned above further illustrated the variation in consecutive days of precipitation extremes exhibiting diverse patterns in spatial. It's worth mentioning that the definition of the consecutive days of precipitation extremes is based on daily precipitation, which is characterized as significant spatial heterogeneity due to the impacts of physical features and anthropogenic activities (Tammets and Jaagus, 2013; Jiao et al., 2015), and thus would lead to differences in the variation of precipitation duration. Therefore, considering the high heterogeneity of precipitation and suddenness in its extremes (Sura, 2011), it's much more necessary to explore the consecutive days of precipitation extremes in the perspective of spatial pattern for highlighting the regional differences of the dryness-wetness duration.

Fig. 7. Spatial distribution of correlation coefficients between CWD and remote climate drivers over CAC during 1961–2017.

R_{CWD_MEI} , R_{CWD_SOI} , R_{CWD_NOI} , R_{CWD_NAO} , R_{CWD_AMO} and R_{CWD_PDO} represent the correlation coefficients between CWD and MEI, SOI, NOI, NAO, AMO and PDO, respectively.

5.2. Climate drivers of changes in consecutive dry/wet days

5.2.1. Local climate drivers of changes in consecutive dry/wet days

In this study, we found CDD/CWD was correlated with temperature positively/negatively in the most parts of northern coastal areas, which have evinced by previous studies already (Zhou et al., 2012; Wang et al., 2018). The coastal areas of northern China located in the semi-humid region, prevailing a dry and rainless climate. On the one hand, the water resource is insufficient but in great demand in the northern coastal regions (Mo et al., 2017), on the other hand, the soil moisture that exhibits robust influence on weather and climate exerted a decreasing trend under the background of evident warming over north of China (Xu et al., 2019), which results in a further decline in water storage capacity. Consequently, the increasing temperature would be prone to take away large amounts of water, leading to persistent drying in the northern coastal area of China finally.

In addition, we found a weak positive relationship between CDD and temperature was dominantly in the southwest coastal areas.

Previous research demonstrated that the thin soil layer and weak soil water storage capacity in the karst landforms of Guangxi autonomous district could have highlighted the increased CDD as temperature increasing (Liu et al., 2015), and the climate conditions in terms of high temperature, strong solar radiation as well as large transpiration and evapotranspiration all had positively impacts on the continuous dry days in the southwest coastal regions in China (Wang et al., 2014b; Wu and Chen, 2019). A slight positive correlation between CWD and temperature was also detected in the southwest coast, especially in Guangdong province, which indicated that the increasing temperature would also result in rising wetting duration in the south coast of China.

What's more, a common slight negative relationship between CDD/CWD and temperature was found in the eastern and southeast coast, which revealed that the continuous dry/wet duration were not synchronized with rising temperature during 1961–2017 in these coastal areas. Yuan et al. (2017) pointed out that local climate forcings such as precipitation, sunshine duration and relative humidity affected the wet-dry condition changes considerably in the southeast coastal regions,

which confirmed that temperature was not the key factor affecting the dryness/wetness condition in the coast of southeast. What need to be pointed out is that the relationships between CDD/CWD and temperature were not statistically significant in the coastal area of China in general, indicating a mild and limited influence of temperature on dry/wet duration overall. Therefore, it needs further work to confirm whether the increasing temperature is bound to make prolonged consecutive dry/wet days in the Chinese coastal regions at higher resolution of time scales, for example, monthly and seasonal scales, and even at scales of synoptic as well as weather event.

Regarding to the correlation between consecutive dry/wet days and precipitation, an exactly opposite relationship was revealed by this study, clarifying that CDD and CWD was respectively correlated with precipitation negatively and positively in the coastal area of China commonly. It's found that a portion of stations scattered in the southern coast (mainly located in southwest coast) showed a significant negative correlation between CDD and precipitation, which indicated a critical resistance effect of precipitation on continuous dry days in these regions. Precipitation in the southern coast, especially in Guangxi autonomous district which situated in the southwest coast, is characterized by a large spatial variability and an uneven temporal distribution (Wang et al., 2014b), would have a certain impact on dryness duration, which had been identified by previous studies already (Liu et al., 2015; Wu and Chen, 2019). While for CWD, a universal significant positive relationship between precipitation was presented over CAC, meaning that precipitation obviously promoted the occurrence of continuous wet days in the Chinese coastal regions. As demonstrated by Yuan et al. (2017) and Yang et al. (2020), precipitation was sensitivity to wet-dry condition with performance for alleviating dryness and boosting wetness in China, and thus had distinctly impacts on the extreme precipitation duration. Therefore, it can be concluded that precipitation is a primary local climate driver of change in continuous wet duration in the Chinese coastal regions.

5.2.2. Remote climate drivers of changes in consecutive dry/wet days

Compared to the local climate drivers, the large-scale atmospheric and oceanic circulation patterns are thought to be the fundamental forcings leading to weather and climate changes (Wang et al., 2019). Some studies have implied that large-scale climate variables, such as ENSO, NOI, NAO, AMO and PDO are the major climate drivers for the variation of precipitation and its extremes in the whole China or regional areas (Tian and Fan, 2012; Gao et al., 2017; Liu et al., 2017; Shi et al., 2018; Cheng et al., 2019; Song et al., 2019).

To be specific, the ENSO is a well-known climate factor to cause global climate variability by the cycle of warm and cold sea surface temperatures in the equatorial Pacific arising from complex interactions between the atmosphere and ocean, and has been commonly recognized to be closely related to the precipitation as well as the occurrences of drought and flood (Sun et al., 2015; Shi et al., 2017; Agilan and Umamahesh, 2018). In this study, although a general weak correlation between CDD/CWD and ENSO (MEI and SOI) was revealed out, with a spatial pattern of “negative north and positive south” between CDD/CWD and MEI while “positive north and negative south” between CDD/CWD and SOI over CAC, some stations clustered in the northern coastal regions close to the sea exhibited significant correlation between consecutive dry/wet days and ENSO. Our results are in line with Shi et al. (2018) who found that CDD/CWD were not significantly correlated with MEI in China as a whole except for North China, but are different from the results of Gao et al. (2017) who documented that ENSO had a pronounced negative effect on CDD over monsoon region in China.

There is a broad recognition that the phase of the ENSO cycle influences the precipitation regimes depending on the areas, which would thus have a further impact on the dryness-wetness duration. For example, Jiang et al. (2006) demonstrated that ENSO episodes, i.e., El Niño (warm episode of ENSO) and La Niña (cold episode of ENSO),

presented different relations with floods/droughts in the different reaches of Yangtze catchment. What's more, Su and Chen (2019) also found that the extreme dry/wet events occurred during El Niño/La Niña years in the south China. The obviously spatial difference in the correlation between CDD/CWD and indices of MEI and SOI in the coastal area of China in this study furtherly confirmed the impacts of ENSO on the dry/wet weather condition at local and regional scales. The researches refer to the physical mechanism of ENSO on precipitation in China have shown that the subtropical high in the western Pacific region and the Eurasian continental high both play important roles in the modulation of ENSO on the Eastern Asian monsoon, which thus influences the water vapor transport and then causes the variation of precipitation and its extremes in the coastal regions of China (Jiang et al., 2006; Zhang et al., 2016; Song et al., 2019).

The NOI is defined as the difference in Sea Level Pressure (SLP) anomalies at the North Pacific High (NPH) in the northeast Pacific (NEP) and near Darwin region, Australia, which represents a wide range of tropical and extratropical climate events impacting the north Pacific on various time scales due to the atmospheric wave trains associated with fluctuations of global atmospheric circulation (Schwing et al., 2002). In the coastal area of China, a general insignificant correlation between CDD/CWD and NOI was detected positively in north and negatively in south by the current study, which is dissimilar to Singh and Qin (2020) who pointed out that NOI significantly correlated with dry days and wet days in southeast Asia. We found that the spatial signatures of correlation coefficients between CDD/CWD and NOI were highly similar to those between CDD/CWD and SOI, which is attributed to the fact that the NOI is roughly the north Pacific equivalent of the SOI and correlates with SOI much closely (Peng et al., 2011). It has been evinced that the NOI is significantly correlated with Sea Surface Temperature (SST) over much of the global ocean, and has a dynamic connection with the regional and remote processes including surface wind stress, ocean waves and upper ocean stability in the NEP, which thus provides a perspective of climate variation, especially in the North American (Schwing et al., 2002). Therefore, more detailed researches at different temporal scales on the relevance between the NOI and the climate variability as well as its physical mechanism are needed furtherly to identify whether the modulation effect of NOI influences the climate change over CAC.

As a climatic phenomenon presenting fluctuations of atmospheric pressure at sea level between the Icelandic Low and the Azores High, the NAO plays an important role in regulating the variabilities of surface temperature and precipitation over the Northern Hemisphere (Hurrell, 1995). Previous studies have revealed that the NAO has a significant impact on the seasonal precipitation and its extremes (Sung et al., 2006; Tian and Fan, 2012; Wu et al., 2019), and the cross-Eurasia wave trains originate from the North Atlantic and then propagate to East Asia was the major bridge between the NAO and the extreme precipitation in China, which would influence the occurrence of dryness-wetness condition along the western pacific coast finally (Zhu et al., 2011). In this study, a negative correlation between CWD and NAO in the eastern coastal regions confirmed the results of Tian and Fan (2012) and Xiao et al. (2015), who both revealed that the NAO was negatively correlated with extreme precipitation events in the lower of Yangtze River Valley. In addition, we found that CDD/CWD correlated with the NAO insignificantly in the Chinese coastal areas overall, demonstrating a common slight effect of NAO on consecutive dry/wet days over CAC on annual scale, which meets with Shi et al. (2019) who discovered that the variations of precipitation indices were not significantly related to the NAO in the vast majority of China.

The AMO is a coherent pattern of natural climate oscillation in the North Atlantic, and is defined as an ongoing series of long-duration changes in the North Atlantic Ocean SST with a cycle of 65–80 years (Kerr, 2000; Enfield et al., 2001). As a pacemaker of climate within the globe, the AMO is considered to connect with the global warming and modulate the ENSO variability (Kerr, 2000; Lu et al., 2006; Zhong et al.,

2017; Wu et al., 2019). Some studies have investigated that the AMO could exert certain influences on the regional precipitation as well as dryness-wetness condition in China. For example, Li and Bates (2007) documented that the warm/cold phase AMO was linked to a wetter/drier winter in China except for the southern coastal areas. Gao et al. (2017) found the warm/cold phase of AMO was generally associated with more/less summer rainfall over the monsoon region of China, however, a relatively limited impact of AMO on annual precipitation in the Ordos Basin of China was disclosed by Zhong et al. (2017). In the coastal area of China, there was a dominant insignificant negative relationship between CDD/CWD and AMO during 1961–2017, except some eastern and southwestern coastal regions where presented a mild positive correlation between CWD and AMO. Our result is different from Gao et al. (2017) who revealed that the AMO had a strong effect on the consecutive wet days over the monsoon region of China, but consists with Shi et al. (2018) who indicated that the AMO had insignificant correlations with CDD/CWD in China generally. Previous researches suggested that the coupled atmosphere-ocean feedbacks over the western Pacific and Indian Oceans as well as the tropospheric temperature variations in Eurasia which were both in response to the AMO-related Atlantic SST anomalies largely influenced the climate variability over East Asia through the mid-latitude westerly anomalies and the propagation of atmospheric Rossby waves (Lu et al., 2006; Sutton and Hodson, 2007; Wang et al., 2013a).

Defined as the primary principal component of monthly SST anomalies in the North Pacific Ocean poleward of 20°N, the PDO is most referred to as a long-lived ENSO-like pattern of the Pacific climate variability (Zhang et al., 1997; Xiao et al., 2015), and has profound impacts on the interdecadal variations of precipitation and its extremes across the Pacific basin and even around the globe (Zhang et al., 2010; Lv et al., 2014; Song et al., 2019). Results in this study indicated that a mild positive/negative correlation between CDD and PDO was found in the northern/southern coasts of China, and a positive linkage between CWD and PDO in the southeastern and parts of northern coastal areas while a negative connection in the other coastal regions was detected. The weak correlations between CDD and PDO over CAC in the current study is rather opposite to Gao et al. (2017) who pointed out that the PDO had a stable positive effect on CDD across the period of 1960–2014 over the monsoon region of China. And for the correlation between CWD and PDO, although a significant relationship with a 3-year signal during the certain period of 1993–1995 was uncovered in the Wei River basin of China, a general insignificant connection in the remaining years during 1960–2014 (Liu et al., 2017) was similar with the result of this study. It suggested that the warm SST anomalies in the tropical Indian-Pacific Ocean (Li et al., 2010), the land-sea thermal contrast over East Asia (Gao et al., 2016) as well as the wave trains of Pacific-Japan interconnection pattern (Lv et al., 2014) all might have important impacts on the precipitation and its extremes such as extreme dry/wet conditions in the whole China or regional areas.

It should be noted that there are complex associations between these large-scale circulation patterns which would play a synergetic role and has coupled effects on the climate variability. For example, the influences of ENSO on the East Asia precipitation are generally modulated by PDO, and the AMO warm phase also can enhance the impacts of ENSO on annual precipitation (Zhang et al., 2010; Xiao et al., 2015; Zhong et al., 2017). Therefore, the complex interactions between the climate indices would cause uncertainties in their relationship with CDD/CWD. Furthermore, the feedbacks between the climate variability and large-scale atmospheric circulation indices are highly depend on spatial and temporal scales (Mallakpour and Villarini, 2016; Wu et al., 2019), thus, more comprehensive and systematic investigations focusing on the relationship between climate extremes and the large-scale climate drivers are required in the following research.

6. Conclusion

Based on the daily meteorological dataset of 156 stations from 1961 to 2017, variation of consecutive dry/wet days in the coastal area of China has been investigated. And main conclusions are as follows,

- (1) The multi-year averages in CDD and CWD were 22.5–93.7 days and 3.4–11.8 days, respectively, generally presenting a spatial pattern of “high north and low south” for the former but “low north and high south” for the latter. Coastal areas in the north such as Hebei province, Beijing and Tianjin municipalities as well as the west of Liaoning province were suffered from the longest continuous dry days much more than 60 days, and the southern coastal areas situated to the south of Zhejiang province were susceptible to the longest consecutive wet days extra 7 days.
- (2) The changing trends in CDD and CWD were -4.5 – 2.7 days per decade and -0.7 – 0.6 days per decade, respectively. Apart from a generally positive tendency in CDD was presented in Shandong and Guangdong provinces as well as Guangxi autonomous district, a universal negative tendency in CDD/CWD was detected over CAC, but only the regions around the coast of Hangzhou bay presented a centralized significant negative tendency in CDD and several stations spread over the northern coastal areas showed remarkable downward trends in CWD.
- (3) CDD was correlated with temperature positively in most parts of Hebei, Shandong and Hainan provinces as well as Guangxi autonomous district, and negatively in the remaining coastal areas. There was a common negative relationship between CDD and precipitation over CAC, and a partial of meteorological stations clustered in Guangxi autonomous district presented a significant correlation. A general insignificant negative linkage between CWD and temperature as well as a predominantly significant positive relationship between CWD and precipitation was detected in the whole coastal area of China, respectively.
- (4) Both CDD and CWD were found to be correlated with ENSO (MEI and SOI) significantly in the partial northern coastal areas close to the sea. And universal insignificant connections with different spatial patterns were detected between CDD/CWD and the other large-scale circulation indices such as NOI, NAO, AMO and PDO over CAC.

There is a popular consensus that climate change not only behaves naturally, but also is affected largely by human activities. However, this study doesn't address the contribution of human activities to the trend of consecutive dry/wet days of precipitation quantitatively, which will be issued in continuous work. Moreover, the limited temporal range of records would influence the conclusions of the climate change trend and relationships between extreme climate events and climate drivers. Uncertainties with observational records are also related to gaps in studies, including data processing and analytical method.

Author statement

Manuscript title: *Changes in consecutive dry/wet days and their relationships with local and remote climate drivers in the coastal area of China.*

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the *Atmospheric Research*.

Authorship contributions

- The general idea and technical framework of this manuscript is proposed by the corresponding author Xiyong Hou.
- The first author Xiaoli Wang is responsible for the data processing, analysis and interpretation, as well as writing and revising the manuscript.
- The third author Yijing Zhao is charge of data collection and curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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