Recent and future changes in the combination of annual temperature and precipitation throughout China

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ABSTRACT: Climate involves different combinations of temperature and precipitation, and each year’s combination of factors can be assigned a climatic year type (CYT; e.g. Warm-Humid). Describing the changes in the CYT provides more information than describing the temperature or precipitation data alone. In this study, we defined nine CYTs using the probability density function of annual temperature and precipitation. Recent and future spatiotemporal changes in CYT were analysed using 507-station observational data and projected data obtained from the CMIP5 multi-model ensemble under RCP2.6, RCP4.5, and RCP8.5 scenarios. China was divided into six subregions to analyse the spatiotemporal changes. Obvious differences in spatial patterns among the various CYTs reflect the climate regime throughout China. The warmth-associated CYTs (Warm-Humid, Warm-Dry, and Warm-Normal) mainly occur in West China (e.g. Southwest China). The cold-associated CYTs (Cold-Humid, Cold-Dry, and Cold-Normal) dominate at high latitudes and high altitudes (e.g. Northeast China and the Tibetan Plateau). The climate in China changed from cold to warm in the last half-century, accompanying the transformation of Cold-Humid, Cold-Dry, and Cold-Normal before the early 1990s to Warm-Humid, Warm-Dry, and Warm-Normal from the early 1990s onward. In the 21st century, the projected CYTs are mainly Warm-Humid, Warm-Dry, and Warm-Normal in China. Warm-Humid dominates in West China, North China, and Northeast China. Warm-Dry is mainly projected in the Yellow River Valley and South China. High-frequency Warm-Normal is projected in the Yellow River Valley. Warm-Humid is projected to increase whereas Warm-Dry and Warm-Normal are projected to decrease from 2015 to 2099. All three CYTs are projected to exhibit larger changes in trends under stronger versus weaker RCPs (RCP8.5 > RCP4.5 > RCP2.6). Compared with temperature or precipitation data alone, CYTs provide more complete information on climate change and more accurately characterize regional differences in climate throughout China.

KEY WORDS combination of temperature and precipitation; climatic year type; CMIP5; temperature and precipitation; China

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1. Introduction

Changes in temperature and precipitation constitute some of the most important concerns regarding global climate change and are closely tied to natural ecosystems and human society. Changes in temperature and precipitation have altered the distribution of vegetation (Du et al., 2011; Gottfried et al., 2012; Ge et al., 2014; Jarlan et al., 2014), agriculture (Piao et al., 2010; Lobell et al., 2011), the extent of glaciers (Scherler et al., 2011; O’Gorman, 2012; Sorg et al., 2012), and sea level (Yin et al., 2009). These changes have also caused more extreme weather and climate events (Choi et al., 2009; Yabi and Afouda, 2012; Du et al., 2013b). Therefore, many studies have been conducted that examine changes in temperature and precipitation at different spatiotemporal scales (Wu et al., 2006; Thompson et al., 2008; Srivastava et al., 2009; Choi et al., 2011; Du et al., 2013a; Mengistu et al., 2014; Basha et al., 2015; Sun et al., 2015).

The average global temperature increased by approximately 0.85°C between 1880 and 2012, and Northern Hemisphere mid-latitude land areas have exhibited an overall increase in precipitation (IPCC, 2013). In China, the change in annual mean temperature was $0.078 \pm 0.027 ^\circ C$ between 1906 and 2005 (Tang et al., 2010), while annual mean precipitation declined 1–2 mm between 1960 and 2009 (Li et al., 2012). Many studies of regional changes in temperature and precipitation have been conducted in China, e.g. studies of temperature and precipitation changes in Northeast China (Zhao et al., 2007), Southwest China (Fan et al., 2011), North China (Ren et al., 2008), the Loess Plateau of China (Li et al., 2010), the Tibetan Plateau (Dong et al., 2012), South China (Fischer et al., 2011), and the Yangtze River Valley (Hu et al., 2015). Although a single climate variable (temperature or precipitation) can provide significant information, some limitations exist when drawing conclusions based on one variable (Li and Zhu, 2015). The climatic year type (CYT; which combines temperature and precipitation) is an important method for researching regional climate change and provides more complete information than temperature or precipitation data alone.
The study of CYT can supplement the study of single climate variable and can further illuminate the effects of climate change on ecosystems. Moreover, assessing the trends in terms of changes in CYTs can provide an important understanding of overall climate change characteristics.

In China, some studies of regional CYTs have been conducted. For example, Shi et al. (2007) found that the climate has changed from warm and dry to warm and wet in Northwest China. Li et al. (2007) noted that the trend of Cold-Warm and dry climate in recent decades may be the main reason for the decline in the level of Lake Qinghai in China. Li et al. (2004) found that vegetation and soil carbon densities were high in warm and wet regions, such as Southeast China and Southwest China. However, the previous studies lack a clear definition of different CYTs. A comprehensive scientific study of the recent and future changes in CYTs throughout China was needed. Therefore, this study aims to investigate the recent and future changes in CYTs in China using long-term data from 507 meteorological stations plus the output of model simulations developed by the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al., 2011). The purposes of this study are (1) to define CYTs by the probability density function (PDF) of temperature and precipitation, (2) to investigate the recent spatiotemporal changes in CYTs in China, and (3) to explore the future changes in CYTs throughout China.

2. Data and methods

2.1. Data

Recorded data for daily precipitation (rainfall amount) and daily mean temperature (Tmean) during the period between 1961 and 2013 were obtained for 842 weather station locations throughout China from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do). Data quality control, especially for data homogeneity tests, is important for detecting climate changes. Data quality control efforts were comprised of two parts: (1) checking for erroneous data (e.g., negative precipitation, days on which the maximum temperature was less than or equal to the minimum temperature) and (2) searching for potential outliers outside a range based on the 99th percentile during the period from 1961 to 1990 for precipitation, and defined as lying within four standard deviations (std) of the climatological mean of the value for the day, that is, the mean ± 4 × std for temperature (Alexander et al., 2006). These potential outliers were checked manually. The erroneous data and identified outliers were treated as missing values. For the homogeneity test, we used RHtestV4 software (Wang and Feng, 2013). We chose the reference series for the temperature data using the approaches proposed by Xu et al. (2013). For precipitation, homogeneous stations were identified using the corresponding monthly precipitation data. However, due to the spatial heterogeneity of precipitation, making adjustments to inhomogeneous data is a complex and difficult task. Thus, the precipitation datasets were not adjusted. After the quality control and homogeneity tests, stations with less than 1% missing values were retained, which left 507 high-quality stations; this remaining subset of stations was used in this study (Figure 1).

For our projections of future climate change, we used the output databases of seven CMIP5 models under three representative concentration pathway (RCP) scenarios. Further details on these models can be found on the CMIP5 website (http://cmip-pcmdi.llnl.gov/cmip5/availability.html). Table 1 shows an overview of these models, listing the associated institutions and the specific atmospheric model component. The selected models include both 20th-century climate simulations and
21st-century climate projections under low-, medium-, and high-emissions scenarios (the RCP2.6, RCP4.5, and RCP8.5 scenarios). The three scenarios predict radiative forcing to peak at 2.6, 4.5, and 8.5 W m\(^{-2}\) by 2100, respectively (Riahi et al., 2011; Thomson et al., 2011; Van Vuuren et al., 2011). The CMIP5 models have different spatial resolutions. Data from the different general circulation models were bilinearly interpolated into a common 1° × 1° grid before further processing. The projections are relative to a base period between 1986 and 2005.

We analysed the spatial patterns of changes in temperature and precipitation by dividing China into six subregions (Xu et al., 2011). The subregions and the corresponding number of remaining station are: Northeast China (NEC, 82 stations), North China (NC, 108 stations), Northwest China (NWC, 88 stations), Southwest China (SWC, 54 stations), the Yellow River Valley (YRV, 132 stations), and South China (SC, 43 stations; Figure 1). These subregions were determined according to societal and geographic conditions.

### 2.2. Method

#### 2.2.1. Definition of CYT

In the China National Standard of warm winter grade, China Meteorological Administration (2008) classified winter into warm winter, normal winter, and cold winter by evenly dividing the probability density of winter mean temperature into three grades (trichotomy-based probability density method). The prerequisite of the method is that winter mean temperature follows normal distribution. Similar to winter mean temperature, the long-term annual mean temperature and precipitation follow a normal distribution pattern (Zhang et al., 2010). Therefore, the annual cold, warm, dry, humid, and normal types were classified by the trichotomy-based PDF of annual temperature and precipitation. The calculation is based on a certain 30-year climatological period. In the period of 1961—2013, we chose the middle three decades (1971—2000) as the base period in this study. For each station, the PDF of annual mean temperature and precipitation in the base period is as follows:

\[
PDF(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(x - \mu)^2}{2\sigma^2} \right] \quad (1)
\]

where \(x\) is the annual mean temperature or precipitation; \(\mu\) and \(\sigma\) are the mean value and standard deviation of \(x\) in the base climatological period, respectively.

Let

\[
X = \frac{x - \mu}{\sigma} \quad (2)
\]

Then, \(X\) obeys the standard normal distribution:

\[
PDF(X) = \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{X^2}{2} \right) \quad (3)
\]
Figure 2. Graph shows the probability for cold/dry, normal, and warm/humid conditions, based on the PDF using temperature and precipitation as variables for two stations. One station is Tuoli station located in northern China (the first row, 83.6°E, 45.93°N). Another station (Simao station) locates in southern China (the second row, 100.97°E, 22.78°N).

Table 2. Definition of nine CYTs.

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Temperature</th>
<th>Cold</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid</td>
<td>Warm-Humid</td>
<td>Cold-Humid</td>
<td>Normal-Humid</td>
</tr>
<tr>
<td>Dry</td>
<td>Warm-Dry</td>
<td>Cold-Dry</td>
<td>Normal-Dry</td>
</tr>
<tr>
<td>Normal</td>
<td>Warm-Normal</td>
<td>Cold-Normal</td>
<td>Normal-Normal</td>
</tr>
</tbody>
</table>

The probability density of the standard normal distribution is evenly divided into three classes at $X = \pm 0.43$ (that is, the probability of each is 33.3%). Therefore, $x = \mu \pm 0.43\sigma$ are the two critical values evenly dividing the probability density of annual temperature and precipitation into three classes. The corresponding thresholds of different types mentioned above are $\mu - 0.43\sigma$ and $\mu + 0.43\sigma$ (Figure 2).

For temperature, each year was determined to be cold, normal, or warm based on the calculation above. For precipitation, each year was defined as dry, normal, or humid. Therefore, a total of nine CYTs were developed by combining temperature and precipitation conditions (Table 2). We used this method to calculate the CYTs for each station.

2.2.2. Calculation of temperature and precipitation anomalies

The anomaly ($\bar{x}$) was calculated by

$$\bar{x} = x - \mu$$

for annual temperature, and

$$\bar{\mu} = \frac{x - \mu}{\mu}$$

for annual precipitation, where $x$ is the annual temperature and precipitation and $\mu$ is the mean value of $x$ in the based period.

2.2.3. Calculation of the occurrence ratio of CYTs

Each subregion contains different number of station or grid. To eliminate the effects of such different number on the calculation of trends in the frequency of CYTs among subregions, we calculated the occurrence ratio of each CYT for each subregion. The occurrence ratio of each CYT was defined as the percentage of the number of stations (grids) of occurrence CYT in the number of total stations (grids) in each subregion:

$$\lambda_i = \frac{n_i}{N} \times 100\%$$
where $\lambda_i$ is the $i$th-year occurrence ratio of each CYT in each subregion; $n_i$ is the number of the stations (grids) of occurrence CYT in the $i$th-year, and $N$ is the number of total stations (grids) in each subregion.

### 2.2.4. Calculation of trend

We calculated the trends in variables using the linear tendency method, with the ordinary least squares technique (Ma et al., 2015). In this study, the variables contain annual temperature and precipitation, annual temperature and precipitation anomalies, and annual occurrence ratio of CYTs in the six subregions and all of the China. The formula is as follows

$$y_t = a + bt_t$$

where $y_t$ is the time series of variables; $t_t$ is the corresponding time series (1961–2013 for the recent change and 2015–2099 for the projected change); the regression coefficient $b$ represents the linear trend, and $a$ is a constant.

For the trends in annual temperature and precipitation (and both anomalies), we firstly calculated the regional mean values, and then calculated the regional trends. The units were °C 10⁸⁻¹ and mm 10⁻¹ (°C 10⁻¹ and % 10⁻¹) for temperature and precipitation (and both anomalies), respectively. For the CYTs, we firstly calculated the regional occurrence ratio of CYT in each year, and then calculated the trends in occurrence ratio. The unit was % 10⁻¹. The significance level ($p$ value) for trend calculation is 0.05 in this study.

### 2.2.5. Evaluation of the performance of CMIP5 models

To evaluate the performance of CMIP5 models at regional scale, we compared the root-mean-square errors (RMSEs) of CYTs calculated by the observations and by the models. The observation temperature and precipitation data of the 507 stations over China were interpolated into 1°×1° grid. If there is not any observation station in a 2° range around a grid, this grid was set as missing data for both gridded observation data and model data. The RMSE of each CYT between the observation data and each model was calculated as

$$\text{RMSE} = \sqrt{\langle (X - Y)^2 \rangle}$$

where $X$ and $Y$ denote the simulated and observed CYTs, respectively; the angular bracket represents spatial averaging over China on the 1°×1° grid. Then we defined the relative model error (RMSE') for each model as

$$\text{RMSE'} = \frac{\text{RMSE} - \text{RMSE}_{\text{mean}}}{\text{RMSE}_{\text{mean}}}$$

where $\text{RMSE}_{\text{mean}}$ is the mean of RMSEs for all individual models.

The remaining seven-model ensemble-averaged precipitation was expected to increase throughout China between 2015 and 2099 by 0.48% 10⁻¹ for RCP2.6, 0.92% 10⁻¹ for RCP4.5, and 1.66% 10⁻¹ for RCP8.5 (relative to 1986–2005) (Figure 4(a)). The expected warming trends throughout China between 2015 and 2099 were 0.05 °C 10⁻¹ for RCP2.6, 0.24 °C 10⁻¹ for RCP4.5, and 0.62 °C 10⁻¹ for RCP8.5. The simulation and projections by the seven-model ensemble in this study were similar to the results by Xue and Xu (2012) using 11-model ensemble and by Tian et al. (2015) using 22-model ensemble. This indicated that the remaining seven models were enough to project the changes in CYTs for China. We also compared the observed historical annual mean temperature and precipitation data with the simulation by the seven-model ensemble (Figure 4). There were differences between the observation and the model simulation from 1961 to 2005, which were greater for precipitation than temperature. However, the differences in the change trends were small between the observation and simulation. The trends in simulated (purple line) historical temperature and precipitation were 0.24 °C 10⁻¹ ($p < 0.05$) and −0.022% 10⁻¹ ($p > 0.05$) throughout China from 1961 to 2005 (relative to 1986–2005), respectively. In the same period, the trends in observed (black line) historical temperature

![Figure 3. Evaluation of the performance of CMIP5 models. The values represent the RMSE' among individual models. Negative (positive) value indicates that the corresponding model performs better (worse) than the majority (50%) of models. The mean value of the RMSE' of all CYTs was marked as ‘All CYTS’ for each model.](image-url)
Precipitation decreased in all the other three subregions, NC, SWC, and YRV, with the largest amplitude of (−12 mm 10a⁻¹) recorded in SWC. However, only one trend was significant (p < 0.05): 7.1 mm 10a⁻¹ for NWC and −12 mm 10a⁻¹ for SWC. In total, the decreasing amplitudes were larger than the increasing amplitudes. Therefore, the annual mean precipitation throughout China generally showed a non-significant negative trend (−1.5 mm 10a⁻¹) during the period from 1961 to 2013.

In contrast with changes in precipitation, significant positive trends for temperature were observed for all six subregions (Table 3). The coldest region was NEC, which is the most sensitive region to global climate change, and it showed the largest changes (0.3 °C 10a⁻¹) among all of the subregions. SC exhibited the maximum mean annual temperature in China, and it was comparatively the most stable region (with the trend of 0.147 °C 10a⁻¹). In general, colder regions are more sensitive to global climate change, and vice versa. From most sensitive to most stable, the order of the regions was NEC, NWC, NC, SWC, YRV, and SC. In other words, the sensitivity to global climate change varies from a low level in low latitudes (and low altitudes) to a high level in high latitudes (and high altitudes). On average, the trend in temperature anomalies for all of China was an increase of 0.233 °C 10a⁻¹ between 1961 and 2013.

3. Results

3.1. Observed changes in CYTs

3.1.1. Temporal changes in observed temperature and precipitation

The change trends in precipitation anomalies were clearly different among the various subregions (Table 3). Three subregions, NEC, NWC, and SC, showed positive trends with the largest value of 9.7 mm 10a⁻¹ recorded in SC.

Percipitation and precipitation were 0.234 °C 10a⁻¹ (p < 0.05) and −0.107% 10a⁻¹ (p > 0.05) for China, respectively. The differences were 0.085% 10a⁻¹ for precipitation and 0.006 °C 10a⁻¹ for temperature. Such small differences between observed and simulated data indicated, on the other hand, that the multi-model ensemble projections in this study performed relatively well. The projected changes in CYTs based on the ensemble-averaged data performed well and outperformed individual models because some of the systematic errors in individual models were cancelled out in the multi-model mean.

3.1.2. Observed spatial patterns in the frequency of CYTs

The spatial distribution of the occurrence frequency for the nine CYTs throughout China from 1961 to 2013 is shown in Figure 5. Warm-Humid mainly occurs in SWC, especially in the Tibetan Plateau region, which is few in NEC. Warm-Dry dominates in SWC, YRV, SC, and western NEC; this CYT is rare in the Tibetan Plateau region. More Warm-Normal occurs commonly in west China, but is less commonly distributed in east China. Cold-Humid is mostly distributed in the NEC and NC regions, and that CYT occurs least often in west and southwest China. Cold-Dry mainly appears at high latitudes and high altitudes (NEC, NWC, and the Tibetan Plateau). The NC and YRV regions have few occurrences of Cold-Dry. Cold-Normal is distinctly concentrated in the NEC region. Normal-Humid mostly occurs in the NC and SC regions. Few instances of Normal-Dry occur in the SWC region. For Normal-Normal, non-evident spatial assembly patterns were observed.

3.1.3. Observed temporal changes in the frequency of CYTs

Table 4 represents the trends in the average occurrence rate (the total number of occurrences divided by the

Table 3. Trends in annual mean temperature and precipitation for the six subregions in China between 1961 and 2013.

<table>
<thead>
<tr>
<th></th>
<th>NEC</th>
<th>NC</th>
<th>NWC</th>
<th>SWC</th>
<th>YRV</th>
<th>SC</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm/10a)</td>
<td>1.4</td>
<td>−10</td>
<td>7.1*</td>
<td>−12*</td>
<td>−1.5</td>
<td>9.7</td>
<td>−1.5</td>
</tr>
<tr>
<td>Temperature (°C/10a)</td>
<td>0.3*</td>
<td>0.267</td>
<td>0.297*</td>
<td>0.221*</td>
<td>0.154*</td>
<td>0.147*</td>
<td>0.233*</td>
</tr>
</tbody>
</table>

The symbol ‘*’ indicates a significant trend (p < 0.05).
The occurrence ratio is equal to the number of occurrences divided by the number of total stations for each region. The unit is %/10a. The symbol ‘*’ indicates a significant trend ($p < 0.05$).

number of stations for each region) of the nine CYTs throughout China between 1961 and 2013. For all regions, the Warm-Humid, Warm-Dry and Warm-Normal CYTs showed significant positive trends ($p < 0.05$). Instances of Normal-Humid also increased in all subregions, but that trend was not significant ($p > 0.05$) in the YRV subregion. The fastest changes for these four CYTs occurred in the YRV, SC, YRV, and SWC subregions, respectively, which are mainly in southern China. The other five CYTs, Cold-Humid, Cold-Dry, Cold-Normal, Normal-Dry, and Normal-Normal, showed decreasing trends. The negative trends in Cold-Humid, Cold-Dry, and Cold-Normal were significant ($p < 0.05$) in all subregions. The decrease in Normal-Dry was significant ($p < 0.05$) only in the NC, NWC, and YRV subregions. The Normal-Normal CYT showed a non-significant decreasing trend in all subregions. The largest decreases in occurrences of Cold-Humid, Cold-Dry, and Cold-Normal occurred in SWC, NEC and NWC, and SC, respectively.

The annual changes in the occurrence rate of the nine CYTs throughout China between 1961 and 2013 are shown in Figure 6. The changes are different among the various CYTs. The CYTs associated with cold conditions (Cold-Humid, Cold-Dry, and Cold-Normal) mainly dominated in the period before the early 1990s, whereas the CYTs associated with warm conditions (Warm-Humid, Warm-Dry, and Warm-Normal) occurred comparatively less frequently during this period. In contrast, Warm-Humid, Warm-Dry, and Warm-Normal significantly increased from the early 1990s onward. The cold-associated CYTs became rare during this period. Normal-Dry also occurred mainly before the mid-1990s. The frequency of occurrence for the Normal-Humid CYT was less than that of Normal-Dry during the early period, but this trend reversed from the late 1990s onward. The annual variability of Normal-Humid and Normal-Normal was relatively small, showing a non-significant negative trend for Normal-Normal and a very weak decreasing trend for Normal-Humid. In the context of global warming, the climate throughout China changed from cold to warm during the last half-century; this accompanies the transition from higher occurrences of Cold-Humid, Cold-Dry, and Cold-Normal before the early 1990s to higher occurrences of Warm-Humid, Warm-Dry, and Warm-Normal, respectively, from the early 1990s onward. An abrupt detection by the Mann-Kendall test (Mann, 1945; Kendall, 1975) showed that the annual mean temperature experienced a significant abrupt warming at the early 1990s, whereas not any abrupt change was found for the annual mean precipitation between 1961 and 2013 (figure is not shown for brevity). The warm- and cold-associated CYTs experienced an abrupt change at the early 1990s. Therefore, the early 1990s were the transition period for these CYTs. Similar changing characteristics were also observed for the six subregions (which are not shown in this paper).
3.2. Projected changes in CYTs

3.2.1. Projected spatial patterns in the frequency of CYTs

Figure 7 shows the spatial distribution of the projected frequency of occurrence for the Warm-Humid, Warm-Dry, and Warm-Normal CYTs throughout China between 2015 and 2099 for each of the three RCP scenarios. According to the simulated projections, future CYTs are expected to be mainly Warm-Humid, Warm-Dry, and Warm-Normal. Therefore, in this study, we only analysed the changes in these three CYTs. The spatial patterns of the three CYTs are similar among the three RCP scenarios. A high frequency of occurrence of Warm-Humid is mainly projected in West China, NC, and NEC for all three RCP scenarios, whereas a low frequency for Warm-Humid is mostly projected in YRV and SC. In contrast, a high frequency of Warm-Dry is projected to occur in YRV and SC, especially in the southeast coastal areas, but a low frequency of Warm-Dry is mostly projected in West China, NC, and NEC, according to the three RCP scenarios. For Warm-Normal, a high frequency is projected in YRV, while a low frequency is projected in east NWC and SWC. The differences in projected frequency for these three CYTs among the three RCP scenarios were readily apparent in SC and NEC. In these two subregions, the low scenario model (RCP2.6) projects fewer occurrences of Warm-Humid and more occurrences of Warm-Dry and Warm-Normal; but the high scenario model (RCP8.5) projects a higher frequency of Warm-Humid and a lower frequency of Warm-Dry and Warm-Normal.

3.2.2. Projected temporal changes in the frequency of CYTs

Table 5 shows the trends in the projected average occurrence rate (the total number of occurrences divided by number of the grid for each region) of the three CYTs for all subregions between 2015 and 2099, as modelled by the three RCP scenarios. For all subregions under the three RCP scenarios, the frequency of Warm-Humid is projected to increase while Warm-Dry and Warm-Normal decrease. Most of the changes are significant \((p < 0.05)\). The most obvious trends for Warm-Humid, Warm-Dry and Warm-Normal were: 6.6% \(10^{-1}\) in NEC and YRV for RCP8.5, –5.1% \(10^{-1}\) in YRV for RCP8.5 and –4.9% \(10^{-1}\) in NC for RCP8.5. In contrast, the least-obvious trends were: 1.6% \(10^{-1}\) in NWC for RCP4.5; 0.6% \(10^{-1}\) in NWC for RCP8.5; and 0.3% \(10^{-1}\) in SC for RCP2.6.

Figure 8 shows the annual changes in the projected occurrence rates of CYTs throughout China between 2015 and 2099, as modelled by the three RCP scenarios. Warm-Humid is expected to increase significantly \((p < 0.05)\) under all three RCPs. The projected increase under the RCP8.5 scenario was approximately twice that of RCP2.6. All three RCPs projected significant \((p < 0.05)\) decreasing trends in the occurrences of Warm-Dry and Warm-Normal. For Warm-Dry, the negative trends are similar among the different RCPs. However, under the RCP8.5 scenario, occurrences of Warm-Normal are expected to decrease more quickly than for RCP4.5 and RCP2.6. For all three RCP scenarios, the projected change in Warm-Humid is more obvious than that in Warm-Dry and Warm-Normal. In the future, the Warm-Humid CYT may dominate in China, indicating that China may become increasingly warm and humid. A few small differences among the six subregions are projected, but the trends for the six subregions are generally similar to those over all of China (which are also not shown in this paper).

3.3. Comparison of single- and dual-variable CYTs

To demonstrate the difference between single-variable CYTs (temperature or precipitation alone) and the more sophisticated dual-variable CYTs (combined temperature and precipitation), we first compared spatial distribution. Figure 9 depicts temperature and precipitation separately; it shows the spatial distribution of temperature-associated CYTs (a–c: Warm year, Cold year, and Normal temperature year) and precipitation-associated CYTs (d–f: Humid year, Dry year, and Normal precipitation year) between 1961 and 2013 throughout China. We found numerous differences in the spatial distribution of the single-variable CYTs in Figure 9 and the dual-variable CYTs as shown in Figure 5. Warm years most often occurred in the SWC and YRV subregions (Figure 9(a)). In comparison, a high frequency of Warm-Humid mainly occurs in the Tibetan Plateau region, but Warm-Dry is rare in this region.
Changes in the combination of temperature and precipitation over China

Figure 7. Spatial distribution of the projected frequency of the Warm-Humid (first column), Warm-Dry (second column), and Warm-Normal (third column) CYTs throughout China between 2015 and 2099 for the RCP2.6 (first row), RCP4.5 (second row), and RCP8.5 (third row) scenarios.

Table 5. Projected trends in the occurrence ratio for the Warm-Humid, Warm-Dry, and Warm-Normal CYTs for all subregions from 2015 to 2099 under the RCP2.6, RCP4.5, and RCP8.5 scenarios.

<table>
<thead>
<tr>
<th>Subregion</th>
<th>Warm-Humid</th>
<th>Warm-Dry</th>
<th>Warm-Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEC</td>
<td>2.9°</td>
<td>-1.2°</td>
<td>-1.7°</td>
</tr>
<tr>
<td>NC</td>
<td>6.2°</td>
<td>-1.3°</td>
<td>-2.9°</td>
</tr>
<tr>
<td>NWC</td>
<td>7.5°</td>
<td>-3.5°</td>
<td>-3.4°</td>
</tr>
<tr>
<td>SWC</td>
<td>5.9°</td>
<td>-6.6°</td>
<td>-5.1°</td>
</tr>
<tr>
<td>YRV</td>
<td>6.6°</td>
<td>-8.3°</td>
<td>-4.0°</td>
</tr>
<tr>
<td>SC</td>
<td>3.8°</td>
<td>-4.1°</td>
<td>-1.5°</td>
</tr>
</tbody>
</table>

The occurrence ratio is equal to the number of occurrences divided by the number of total grids for each region. The unit is%/10a. The symbol ‘*’ indicates that the change trend is significant (p < 0.05).

(Figure 5). Cold years were mostly observed in NEC (Figure 9(b)), but Cold-Humid occurs mainly in the southeast part of NEC and rarely in northwest regions of NEC (Figure 5). The distribution of Cold-Dry is opposite to that of Cold-Humid. Humid years are distinctly concentrated in the SWC and NC subregions (Figure 9(d)). However, Warm-Humid occurs mainly in the Tibetan Plateau region (SWC) and is relatively rare in NC. Cold-Humid is rare in SWC but mainly occurs in NEC (Figure 5). Dry years occurred more frequently than any other CYT in China between 1961 and 2013, and that CYT was mainly distributed in the NEC, NWS, and YRV subregions, plus a portion of the SWC region (Figure 9(e)). The distribution of Warm-Dry is similar to that of the Dry year CYT, but Cold-Dry is rare in YRV (Figure 5).

These differences between the spatial distribution of the single-variable CYTs and the dual-variable CYTs show that the latter more accurately characterize regional differences in climate throughout China and provide more complete information than temperature or precipitation data alone.

Temporal analysis also demonstrates differences between the single-variable CYTs and the dual-variable CYTs. Single-variable temperature or precipitation CYTs provide only limited information (Figure 10). Throughout

Figure 8. Annual changes in the average occurrence rate of the projected Warm-Humid, Warm-Dry, and Warm-Normal CYTs throughout China between 2015 and 2099 under the three RCP scenarios.

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China between 1961 and 2013, the significant trends ($p < 0.05$) in the average frequency of Warm year, Cold year, and Normal temperature year are $14.8\% 10^{-1}$, $-11.7\% 10^{-1}$, and $-3.1\% 10^{-1}$, respectively. The average frequency for Warm year ($14.8\% 10^{-1}$) actually contains $4.6\% 10^{-1}$ for Warm-Humid, $5.6\% 10^{-1}$ for Warm-Dry, and $4.7\% 10^{-1}$ for Warm-Normal (Figure 6). However, these more comprehensive results could not be derived if temperature data is analysed alone. Similarly, valuable information is lost if precipitation data is used alone. Throughout China, the average frequency of Humid year, Dry year, and Normal precipitation year are $0.5\% 10^{-1}$, $0.1\% 10^{-1}$, and $-0.7\% 10^{-1}$, respectively, none of which are significant trends ($p > 0.05$). When Humid year ($0.5\% 10^{-1}$) is examined using dual-variable CYTs, as shown in Figure 6, significant trends emerge. The average frequency of the Warm-Humid CYT, at $4.6\% 10^{-1}$, is a significant trend, as is the average frequency of the Cold-Humid CYT, at $-3.7\% 10^{-1}$. But the trend for the Normal-Humid CYT, at $-0.3\% 10^{-1}$, is not significant. Looking at humid-associated CYT, if one is using only single-variable CYT, then the Humid-CYT would simply be treated as an insignificant weak trend of $0.5\% 10^{-1}$ between 1961 and 2013 for all of China, which is misleading. The dual-variable CYTs that combine temperature and precipitation (Warm-Humid, Dry-Humid, and Normal-Humid) provide more in-depth and accurate information on climate change in China.

4. Discussion

Climate has changed from cold to warm over the vast majority of regions in the world, and from humid to dry in eastern United States, southeastern South America, northern Europe, and northeastern Australia and dry to humid in southern Europe, western Africa, and eastern Asia (IPCC, 2013). However, separate analysis of temperature or precipitation cannot characterize the coupled relationship of these two climate factors. For the joint analyses of temperature and precipitation, there are many sophisticated indices, such as various moisture indices and drought indices. These climate indices were widely used to quantify climate variability (Grundstein, 2009; Vicente-Serrano et al., 2010), to assess drought severity (Gunda et al., 2016; Zhang and Zhang, 2016; Zhang et al., 2016), to do climatic regionalization (Fraser et al., 2013; Liu and Zhai, 2014), and commonly led to a synthetic result. However, we usually cannot obtain the temperature and precipitation situation from such a result. For example, if the moisture index $MI$ ($MI = P/WI$, where $P$ is the annual precipitation, and $WI$ is the sum of the >$5^\circ$C monthly average temperature, Xu, 1985) increased in a certain period for a certain region, we could not know which of the cases (precipitation increased, or temperature decreased, or both increased, but the increasing rate of precipitation was greater than that of temperature) caused the result. By contrast, we can easily obtain the change situation of temperature and precipitation from the CYT results. Moreover, CYT can directly reflect the allocations of temperature and precipitation, which is important for climate change research (e.g. for simulating/assessing climate change, crop growth, and vegetation distribution).
Several regional CYT studies have been conducted in China. The results, such as an increase in Warm-Humid in NWC (Shi et al., 2007) and a dominating Warm-Humid in SWC and SC (Li et al., 2004), are in agreement with our findings. Shi et al. (2007) found an increasing trend in Warm-Humid based on increasing temperature and precipitation. However, their definitions were not clear as to how to determine when one CYT would change to another and the number of years over which a certain CYT occurs. A Warm-Cold or Humid-Dry climate in a certain station/grid is relative to the time series; thus, a certain CYT must be determined based on a specific standard. For example, both temperature and precipitation increased in NEC during 1961–2013 (Table 3), which does not signify that NEC has only experienced the Warm-Humid CYT during this period. Regarding this point, two aspects should be considered: (1) The increase in temperature indicates that the temperature changed relatively from colder to warmer. Therefore, the CYT should change from a cold-associated to a warmth-associated CYT. The change in CYT in association with precipitation was similar to the change related to temperature. (2) Changes in temperature and precipitation trends fluctuated, especially for precipitation, for which the trends were generally not significant. An increase in the annual precipitation series may lead to many relatively dry years. There is not only the Humid-associated CYT but also Dry-associated CYT in such an annual precipitation series. Therefore, a scientific and clear definition for CYT is needed. The method used to define the CYT in this study references the China National Standard of warm winter grades (China Meteorological Administration, 2008). The trichotomy-based PDF, using variables of annual temperature and precipitation, can clearly divide the annual temperature and precipitation time series into cold/normal/warm and dry/normal/humid years. The definition makes the CYTs comparable among different spatial and temporal scales. Hence, the spatiotemporal changes and comparisons of CYTs over different subregions are reliable in this study.

Uncertainties in the projected results produced by the model should be noted. The standard deviation of the multi-model projected results was a metric to quantify the uncertainties (Tian et al., 2015). The greater standard deviation indicates a greater difference among the multi-model projections. That is, greater standard deviation denotes greater uncertainty, and vice versa. We calculated the standard deviation of the total frequencies of Warm-Humid, Warm-Dry, and Warm-Normal in 2015–2099 among individual models for each grid under the three scenarios (Figure 11). Warm-Humid had greater uncertainties than Warm-Dry and Warm-Normal. Warm-Normal had the smallest uncertainties among the three CYTs. For the subregions, the uncertainties in NEC, NC, and SC were relatively small, especially for NEC. NWC, SWC, and YRV had relatively high uncertainties. The uncertainties in NWC were the largest among different subregions. The uncertainties in the projections were larger under high forcing scenario than those under low forcing scenario (RCP8.5 > RCP4.5 > RCP2.6), which was similar to the results by Tian et al. (2015) and Zhou et al. (2014). We used the inter-model discrepancy to analyse the uncertainty of projections. However, other analysis of the uncertainties of the projections, such as the models’ resolution, physical processes or other processes, was not discussed. Further study should focus on the adoption of a more rational and scientific approach to reduce the uncertainties as well as on using the enhanced projections to analyse changes in CYT.

5. Conclusions

In this study, we examined historical and projected changes in CYT based on the observed daily temperature and precipitation data throughout China between 1961 and
Spatial patterns are distinct among the various CYTs, which clearly reflects China’s climate regime. Between 1961 and 2013, a high number of occurrences of CYTs associated with warm conditions (Warm-Humid, Warm-Dry, and Warm-Normal) mainly occurred in West China (e.g. SWC), whereas a high frequency of the CYTs associated with cold conditions (Cold-Humid, Cold-Dry, and Cold-Normal) dominated at high latitudes and high altitudes (e.g. NEC and the Tibetan Plateau). Warm-Humid, Warm-Dry, and Warm-Normal showed significant positive trends ($p < 0.05$) for all subregions, whereas Normal-Humid showed an insignificant positive trend. The other five CYTs, Cold-Humid, Cold-Dry, Cold-Normal, Normal-Dry, and Normal-Normal, showed decreasing trends. Throughout China, the climate has generally changed from cold to warm in the last half-century, accompanying the transition of predominantly Cold-Humid, Cold-Dry, and Cold-Normal before the early 1990s to Warm-Humid, Warm-Dry, and Warm-Normal, respectively, from the early 1990s onward. Therefore, the early 1990s marked the transition period or period of mutation for these CYTs.

The projected CYTs are mainly Warm-Humid, Warm-Dry, and Warm-Normal throughout China for the years 2015 to 2099 for all three RCPs. Warm-Humid is projected to dominate in West China, NC, and NEC. Warm-Dry is mainly projected to occur in YRV and SC. A high frequency of Warm-Normal is projected in YRV. The difference in the projected frequency of the three CYTs among the three RCP scenarios was most apparent in SC and NEC, where stronger radiative forcing is projected to have higher Warm-Humid frequency and lower Warm-Dry and Warm-Normal frequency, and vice versa. For all subregions and for all of China, Warm-Humid is projected to increase, whereas Warm-Dry and Warm-Normal are projected to decrease. A higher rate of occurrence is expected for all three CYTs under a stronger RCP than under a weaker one (RCP8.5 > RCP4.5 > RCP2.6).

The combination of temperature and precipitation (the dual-variable CYTs) provides more complete information on climate change and more accurately characterizes regional differences in climate throughout China than temperature or precipitation alone. Compared with other sophisticated indices, such as moisture indices, CYT can directly reflect the allocations of temperature and precipitation.

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