

A new mean-extreme vector for the trends of temperature and precipitation over China during 1960–2013

Juan Li^{1,2} · Zhiwei Zhu^{1,2} · Wenjie Dong³

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Abstract A mean–extreme (M-E) vector is defined to combine the changes of climate means and extremes. The direction of the vertical axis represents changes in means, whereas the direction of the horizontal axis represents changes in extremes. Therefore, the M-E vector can clearly reflect both the amplitude and direction of changes in climate means and extremes. Nine types of M-E vectors are defined. They are named as MuEu, MuEd, MuEz, MdEu, MdEd, MdEz, MzEu, MzEd, and MzEz. Here M and E stand for climate means and extremes, respectively, whereas u, d, and z indicate an upward, downward trend and no trend, respectively. Both temperature mean and extremely high temperature days are consistently increased (MuEu) in nearly whole China throughout four seasons. However, the MuEd-type vector dominates in some regions. The MuEd-type vector appears over the Huang Huai river basin in spring, summer and winter. For the M-E vector of temperature mean and extremely low temperature days, the MuEd-type spreads the entire China for all

seasons. The M-E vector for precipitation mean and the extreme precipitation days possesses identical trends (MuEu or MdEd) despite of seasons. The MuEu-type dominates in northeastern China and west of 105°E in spring, northwestern and central/southern China in summer, west of 100°E and northeastern China in autumn, and nearly whole China in winter. Precipitation mean and extreme precipitation days are all decreased (MdEd) in the rest of China for all reasons. The trends relationship in means and extremes over China presented herein could provide a scientific foundation to predict change of extremes using change of mean as the predictor.

1 Introduction

The changes in temperature and precipitation are important indicators reflecting climate change. In the last five decades (1960–2013), the surface air temperature in China has increased by 0.27 °C per 10 years, which is higher than the global and northern hemisphere warming rate during the same period (Ding et al. 2004; Wang et al. 2014; Sun et al. 2016). Besides, the annual mean precipitation throughout the country also shows an upward tendency. Global climate changes embodied in not only the climate means but also the climate extremes. Under the context of global warming, it has been indicated that extremes relating to low temperatures, such as cold surges, cold nights and days, frost days, and cool summers are generally decreased in frequency and intensity, whereas extremes that associated with high temperatures, such as heat waves, warm nights and days, frost-free days and warm winters are mostly increased in frequency and intensity (Bonsal et al. 2001; Qian and Lin 2004, 2005; Alexander et al. 2006; Met

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✉ Zhiwei Zhu
zhiweizh@hawaii.edu

¹ Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing, China

² Department of Atmospheric Sciences, International Pacific Research Center, University of Hawaii at Manoa, 1680 East West Road, POST Bldg. 401, Honolulu 96822, HI, USA

³ School of Atmospheric Science, Sun Yat-Sen University, Guangzhou, China

Office 2011; Zhang and Zhou 2013; Cai et al. 2014; Moore et al. 2015). Extreme weather/climate events cause property damage, injury and loss of life, and threaten the existence of some species (Kunkel et al. 1999; Easterling et al. 2000a, b; Meehl et al. 2000; Huynen et al. 2001; Dai 2013; Moore et al. 2015; Lesk et al. 2016), harming the human and natural systems much more than the average climate conditions (Parmesan et al. 2000; Pendleton et al. 2013). Therefore, projecting climate extremes is important for developing mitigation and adaptation measures.

In recent years, global and regional climate models are employed in projecting future changes in climate extreme events (Durman et al. 2001; Boo et al. 2006; Gao et al. 2006; Michel 2007; Thibeault et al. 2010; Engelbrecht et al. 2013; Patricola et al. 2013). However, climate models still have difficulties in simulating historical observed climate extremes (Kharin and Zwiers 2000; Hegerl and Zwiers 2004; Kostopoulou and Jones 2005; Alexander and Arblaster 2009; Jiang et al. 2011; Sillmann et al. 2013; Zwiers et al. 2013; Chan et al. 2014). This leads to an additional uncertainty in projecting future changes in climate extremes. On the contrary, global or regional climate models are more reliable in simulating the climate means (Jiang et al. 2005; Luo et al. 2005; Wild 2009; Brands et al. 2013; Neale et al. 2013).

Because climate means and extremes are closely connected (Mearns and Katz 1984; Griffiths et al. 2005; Peterson et al. 2013), it will be beneficial to projecting future changes of climate extremes using climate means if their relationship are clarified. The change in climate extremes over China in recent decades has been discussed in many studies (Pan et al. 2004; Wang and Zhou 2005; Zhai et al. 2005; Hu et al. 2009; You et al. 2011; Wang et al. 2012; Yin et al. 2015), but its relationship with climate means is seldom documented. Given that the changes in climate extremes over China could be opposite to the changes in climate means and may possess different regional characteristics, investigations of the linkage between climate means and extremes in different regions are important and meaningful for further understanding and projection the changes in climate extremes.

In the present study, we attempt to combine the climate means and extremes to investigate the connection between them. Based on their individual trends, two different variables in climate means and extremes are combined in one vector. The main purpose of this paper is to examine spatial and temporal changes in temperature and precipitation means and extremes over China, and more importantly, to use a new vector to systematically analyze the relationship between the trends of temperature/precipitation extremes and their means during the period 1960–2013. The rest of this paper is organized as follows. Section 2 describes the data, method utilized. Section 3 introduces the definition of

the climate extreme indices and the M-E vector. In Section 4, spatial patterns of the M-E vector for all seasons are investigated, and the temporal evolution for climate means and extremes during summer is further examined. Section 5 provides the conclusion and discussion.

2 Data and methods

2.1 Data

A homogenized daily temperature dataset that derived from the 753 stations in mainland China (Li et al. 2016) are employed. Daily precipitation records of 821 stations obtained from the National Meteorological Information Center of China Meteorological Administration are also utilized. All the records span from 1960 to 2013. Stations with missing records for more than 10 days in each season in any given year are excluded. In the present study, the four seasons stand for the northern spring (March, April and May), summer (June, July and August), autumn (September, October and November) and winter (December, January and February).

3 Methods

The linear regression analysis is adopted to estimate linear trends. The Mann–Kendall test (Mann 1945; Kendall 1975) is used to check the significance of the trend. To display the intrinsic temporal changes of the variables, we use ensemble empirical mode decomposition (EEMD) method to extract the interannual and interdecadal variability (Wu et al. 2007; Qian et al. 2010). Application of the spectral analysis technique EEMD to time series produces an orthogonal set of Intrinsic Mode Functions (IMFs) and a residual (or adaptive trend). The added white noise in each EEMD ensemble member has a standard deviation of 0.2, and a total size of 1000 ensemble is used. Four IMFs are obtained. The adaptive trend is obtained as the residual of EEMD. As the EEMD algorithm is locally adaptive, it is suitable for decomposing time series that appear non-stationary in terms of mean and variance (Wu and Huang 2009). EEMD also achieves a better denoising performance than the conventional filters (Zhang and Zhou 2013).

4 Definitions

4.1 Extreme indices

Three percentile-based extreme indices, i.e., the extremely high, low temperature days and extreme precipitation days,

are defined using the similar definition of previous works (Jones et al. 1999; Yan et al. 2002; Li et al. 2012). For a given station, a daily maximum temperature is defined as an extremely high temperature day if it exceeds the 95th percentile threshold of a set of daily records, including those observed on the same calendar day and 10 neighboring days (five before and five after that day) for the period 1960–2013. Similarly, an extreme of daily precipitation for a given calendar day at a station is defined as exceeding the 90th percentile of a set of daily precipitation records, including those on the same calendar day and 80 neighboring days (40 before and 40 after that day) from 1960 to 2013. Note that the choice of a relatively smaller percentile and longer window for precipitation is simply because that the time series of daily precipitation is not temporally continuous.

4.2 Mean–extreme vector

We defined a new mean–extreme (M-E) vector to investigate the relationship between trends of climate means and extremes. The direction of the vertical axis of vector represents trends in means, whereas the direction of the horizontal axis of vector represents trends in extremes. Therefore, the M-E vector can clearly reflect both the amplitude and direction of changes in climate means and extremes. In this manner, the changes in means and extremes are combined into one vector. Nine types of M-E vectors are defined. They are named as MuEu, MuEd, MuEz, MdEu, MdEd, MdEz, MzEu, MzEd, and MzEz. In each type, M and E represent the climate means and extremes, respectively, and u indicates an upward trend, d indicates a downward trend, z represents no change. For example, MuEd indicates that the climate means have an upward trend whereas the climate extremes owns a decreasing trend (vector shown as ↘), and the vector MuEu that stands for an in phase increasing trends between means and extremes is in the first quadrant (vector shown as ↗). The other seven vectors are expressed in the similar manner. The nine types of M-E vectors are corresponding to four quadrants, four axes and one origin, respectively. An M-E vector that trends in means and extremes are both significant at 95 % confidence level is defined as a significance vector. More detailed information of M-E vector is listed in Table 1.

5 Results

5.1 Spatial pattern of the M-E vector

First, the M-E vectors are applied for describing trends in temperature mean and extremely high temperature days throughout China (Fig. 1). In spring (Fig. 1a), the MuEu-

Table 1 Nine types of mean and extreme (M-E) vectors

Types of M-E vector	Trends in temperature and precipitation	Trends in days of extremely high (low) temperature and extreme precipitation
MuEu ↗	Upward	Upward
MuEd ↘	Upward	Downward
MuEz →	Upward	No change
MdEu ↖	Downward	Upward
MdEd ↙	Downward	Downward
MdEz ←	Downward	No change
MzEu ↑	No change	Upward
MzEd ↓	No change	Downward
MzEz (the origin)	No change	No change

type appears over most of China except for small area along the lower reach of Yellow River basin. The trends over middle and lower reach of Yangtze River basin show relatively larger amplitude than elsewhere. In summer (Fig. 1b), the MuEd-type vector appears over Huang Huai River basin. Over parts of Qinling Mountains, both temperature mean and extremely high temperature days shows decreasing trends (MdEd). In addition, the MdEu-type with decreasing trend of temperature mean and increasing trend of extremely high temperature days occurs around Chongqing Municipality. The rest parts of China are all dominated by the MuEu-type vector, with the larger amplitude and most significant regions over western and southeastern China. In autumn (Fig. 1c), the MuEu-type vectors control the entire China. The amplitude of MuEu over western and central China has relatively large amplitude comparing with elsewhere. In winter (Fig. 1d), the MuEd-type dominates in Huang Huai River basin. The rest of China has increasing trends in both temperature mean and extremely high temperature days. Significant trends mainly locate over western China.

Figure 2 shows the M-E vector for the trends of temperature mean and extremely low temperature days. Note that M-E vectors in the fourth quadrant are dominant almost the entire China in all seasons except for summer. In spring, the MuEd-type vectors are nearly significant over the entire China except parts of central China. In summer, a region of MdEd-type vector appears in parts of Shanxi and Sichuan provinces. In autumn, areas of MdEd-type vector are significant over whole China. In winter, except for Yunnan-Guizhou Plateau and parts of northeastern China, significant MdEd-type vector spreads over the entire China.

Figure 3 shows that the M-E vector for the trends of precipitation means and extreme precipitation days. Generally, trends of precipitation mean and extreme precipitation days have two types of M-E vectors with either

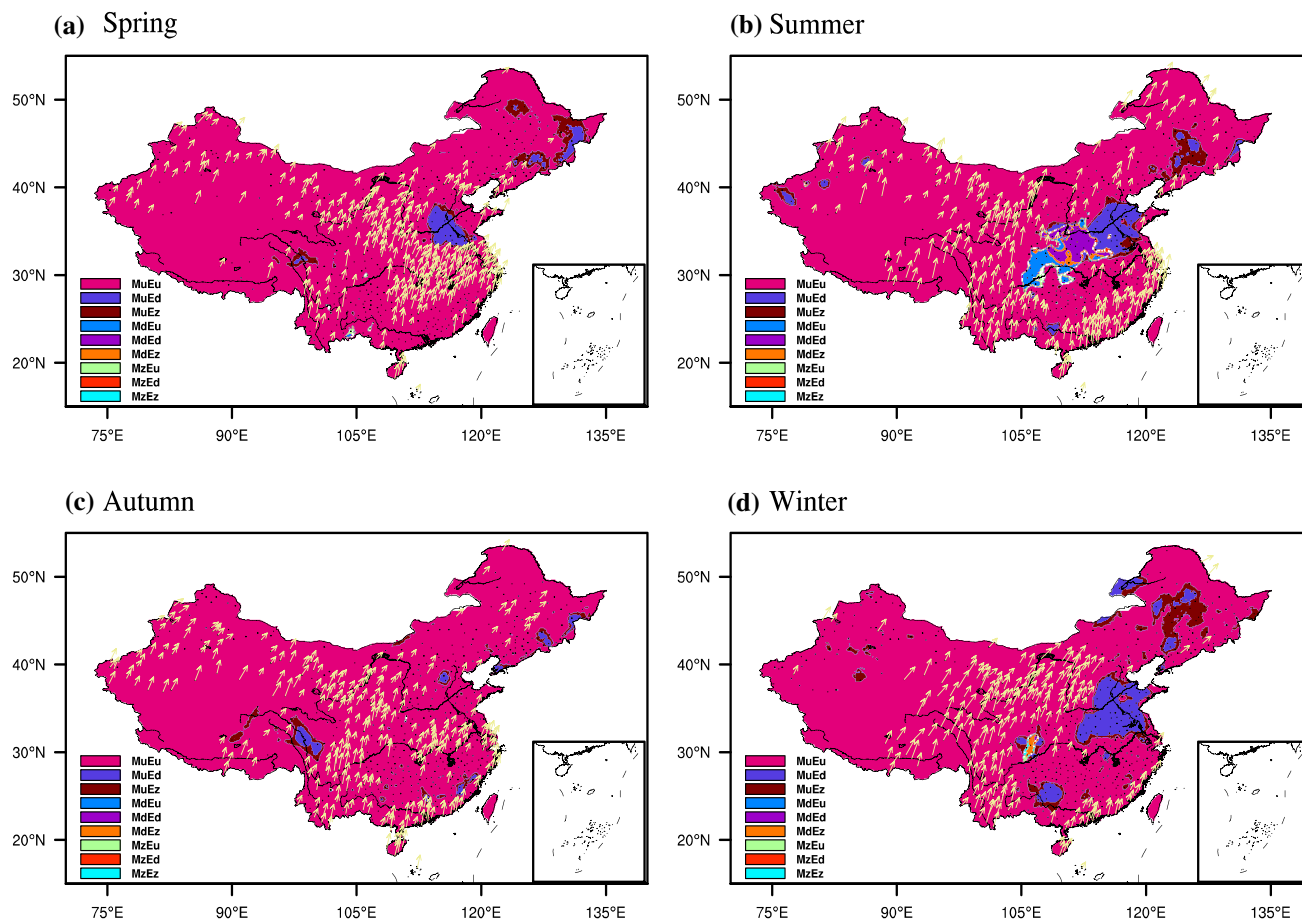


Fig. 1 The distribution of M-E vector for trends of temperature mean and extremely high temperature days in boreal **a** spring, **b** summer, **c** autumn, and **d** winter in China for 1960–2013 (only vectors that significant at the 95 % confidence level are shown)

increasing or decreasing trends in both means and extremes (MuEu or MdEd) throughout all seasons. In spring (Fig. 3a), the MuEu-type vector is distributed over northeastern China and west of 105°E, whereas decreasing trends in both precipitation mean and extreme precipitation days (MdEd-type) are observed in central and southern China. For summer time (Fig. 3b), the precipitation and extreme precipitation days both increase (MuEu) in northwestern, central and southeastern China, and both decrease (MdEd) in southwestern China and northern China. A few stations over eastern Inner Mongolia even display a MuEd-type vector. Note that, the M-E vector over southern China experienced an out of phase relationship between spring and summer. While both precipitation means and extremes over southern China suppressed in spring, they tend to increase during summer. The result is consistent with the previous study of Zhu et al. (2014) in which a season-dependent tropical sea surface temperature anomalies control mechanism is proposed to explain the out of phase rainfall changes during spring and summer over southern China. In autumn, the MdEd-type vector is

distributed to east of 100°E and south of 40°N, whereas the significant MuEu-type vector is distributed to west of 100°E of China. Note that MdEu-type vector appears over northeastern China Plain, suggesting that precipitation mean and extremes have opposite trends. This out of phase relationship between climate means and extremes may be attributable to the increasing influence from the synoptic system, such as Northeast China Cold Vortex (He et al. 2007, 2010). In winter, nearly all the regions display significant increasing trends for both precipitation mean and extreme precipitation days (MuEu). The MdEu and MdEd types are confined to southwestern China.

Climate variations are governed by internal variability, natural external forcing (such as changes in solar radiation and volcanism), and anthropogenic forcing (such as aerosol, greenhouse gas emissions, land use and land cover changes). All of these factors could influence climate means and extremes. Since climate means may provide a background for the occurrence of climate extremes, the physical mechanisms driving changes in mean may also drive changes in extremes (Seneviratne et al. 2012). Thus,

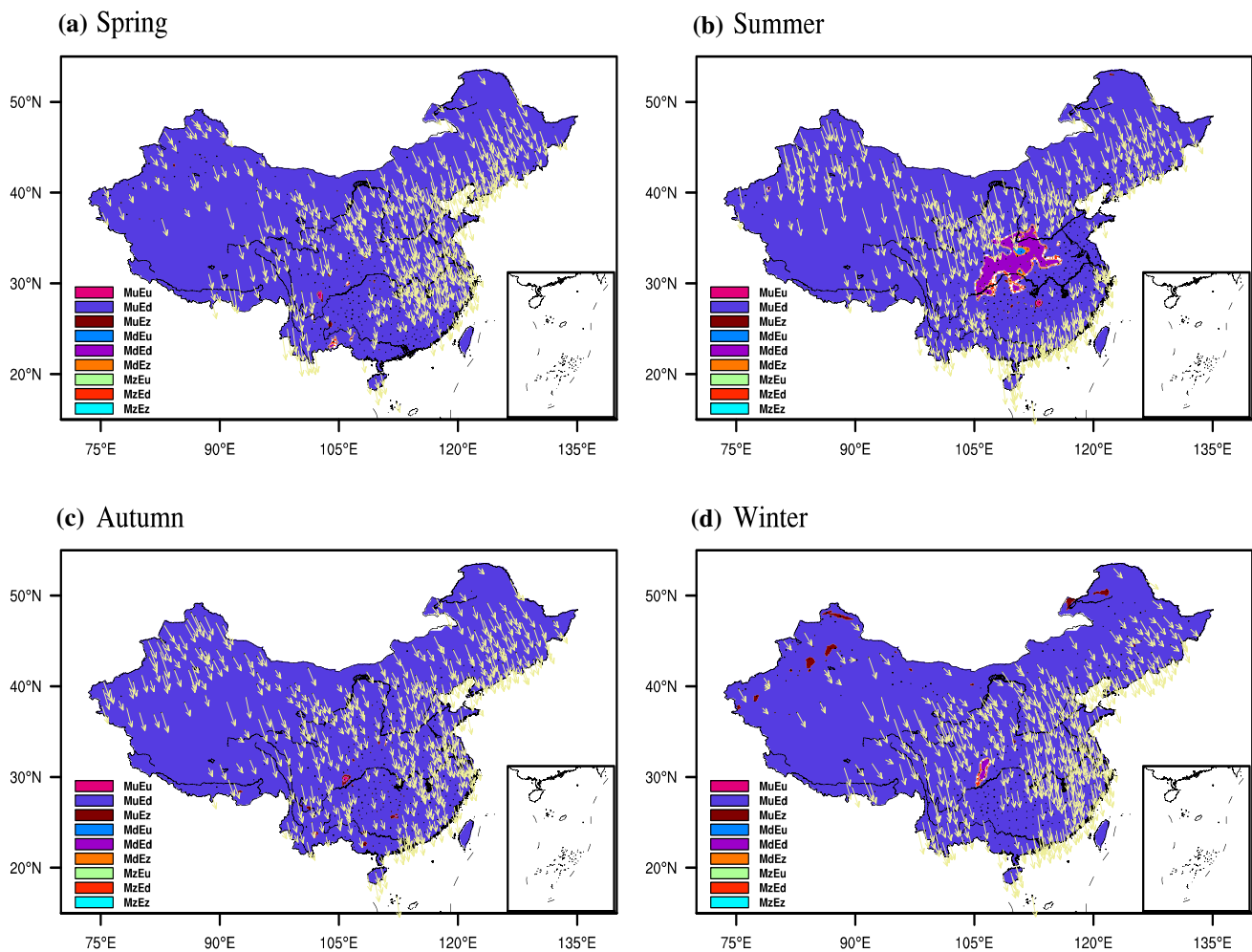


Fig. 2 Same as Fig. 1 but for M-E vector trends for temperature mean and extremely low temperature days

it is not surprising that trends in means and extremes display coherent changes in most parts of China. However, at regional scales, additional processes can still modulate the overall changes in extremes through regional feedbacks such as the land–atmosphere interactions (Seneviratne et al. 2012), leading to the inconsistent between changes in climate means and extremes.

5.2 Temporal changes over the domain of each M-E vector in summer

China is greatly affected by East Asian summer monsoon (Ding et al. 2008; Wang et al. 2008; Ha et al. 2012). Summer temperature and rainfall and the corresponding extremes has critical climatic impacts, thus more attention should be paid to their temporal changes during summer season. In this section, we mainly focus on the temporal evolution of temperature/precipitation means and extremes during summer. The time series averaged over domain of different M-E vector are analyzed to obtain the

temporal features of temperature and precipitation means and extremes.

The trends of summer temperature mean and extremely high temperature days over most parts of China are MuEu type. Figure 4 shows the averaged time series of temperature mean and extremely high temperature days over the region of MuEu-type. As shown in Fig. 4a, b, both mean temperature and extremely high temperature days display significant positive linear trends in summer. The temporal correlation coefficient (TCC) between the extremely high temperature days and the temperature mean is 0.89, exceeding the 95 % confidence level. This indicates that on the year-to-year timescale, more extremely high temperature days will occur if the temperature mean is higher. Figure 4c shows that the adaptive trends of temperature means and extremely high temperature days evolve in phase during the entire period. The temperature mean and extremely high temperature days synchronously declined before mid-1970s and increased dramatically after mid-1970s.

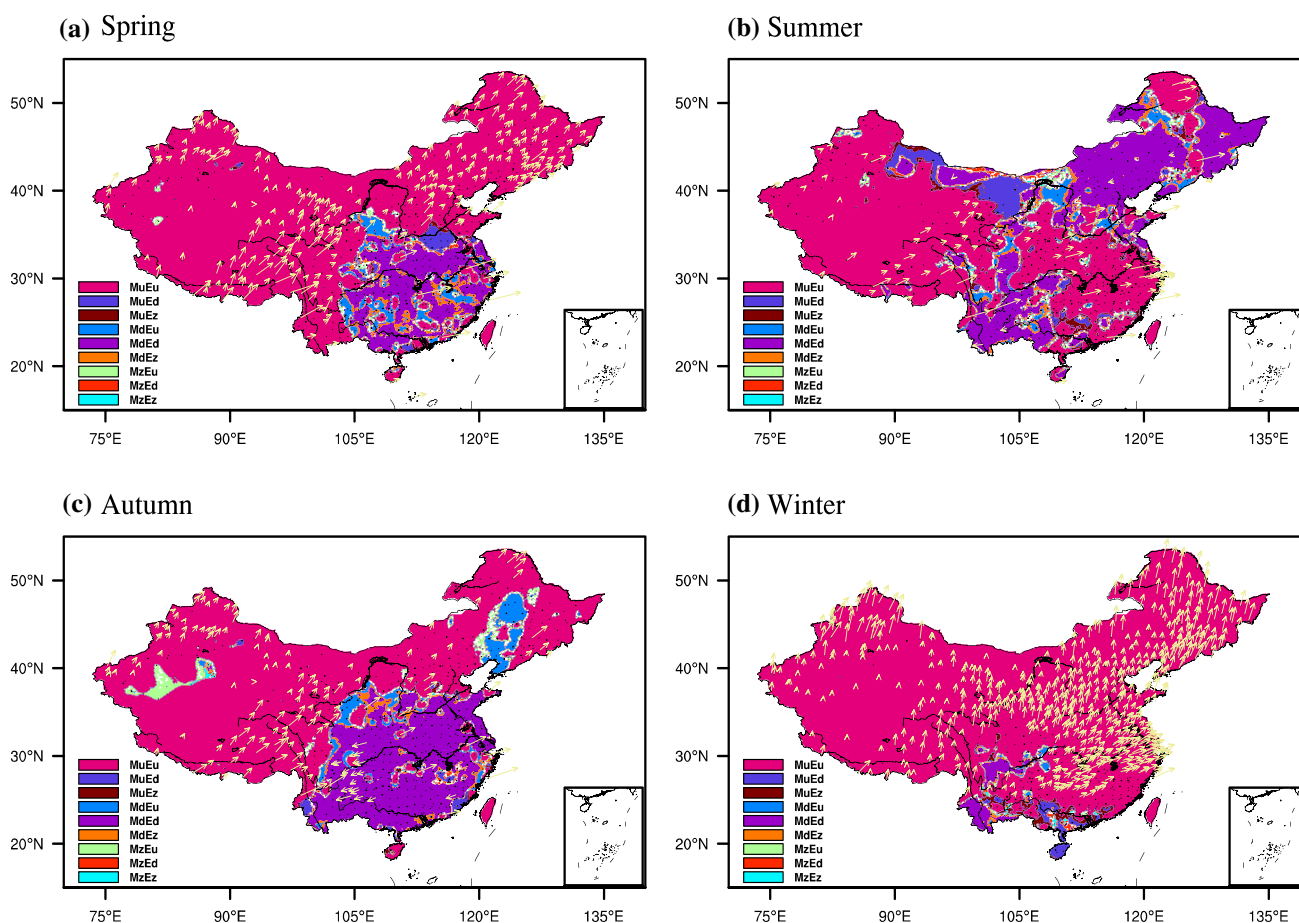


Fig. 3 Same as Fig. 1 but for M-E vector trends for precipitation mean and extreme precipitation days

The trends of summer temperature mean and extremely low temperature days over most parts of China are MuEd-type. Figure 5 shows the time series of temperature mean and extremely low temperature days over the domain of MuEd-type vector. On year-to-year timescale, the TCC between the temperature mean and the extremely low temperature days is -0.85 , exceeding the 95 % confidence level. It means on interannual timescale, with the mean temperature increasing, fewer extremely low temperature days will occur. Over the domain of this MuEd-type vector, same as the highly correlated negative year-to-year relationship, the adaptive trends also have a synchronous negative relationship. The mean temperature decreases before 1970 and increases quite after that, whereas the changes in extremely low temperature days evolve in an opposite way.

Summer precipitation mean and extreme precipitation days display a quite consistent evolution, despite of the year-to-year timescale or the adaptive trends. MuEu and MdEd are the two basic M-E vector types for summer precipitation mean and extremes over southern China and northern China, respectively. Figure 6a, b shows the regional averaged time series of summer precipitation

mean and extreme precipitation days over the domain of the MuEu-type vector. Positive trends are observed in both summer mean and extreme precipitation days. As indicated by the adaptive trend (Fig. 6c), the summer mean precipitation and extreme precipitation days synchronously increased in the whole period. Note that the increasing rate of both precipitation mean and extreme precipitation days is slower after 1990s than the former period. Figure 6d–f shows the temporal evolution over the domain of MdEd-type vector, in which both the summer precipitation mean and extreme precipitation days present negative linear trends. The adaptive trends indicate that the precipitation mean and extremely precipitation days evolve in a quite similar manner. Concurrent with the decrease in precipitation mean from 1960 to 2013, the extreme precipitation days decline during the entire period. Note that, different from summer temperature, summer precipitation and extreme precipitation days either increased or decreased throughout the whole period (1960–2013). The TCC between precipitation means and extremes over the domain of MuEu-type and MdEd-type vector are 0.94 and 0.96, respectively, exceeding the 95 % confidence level. Based

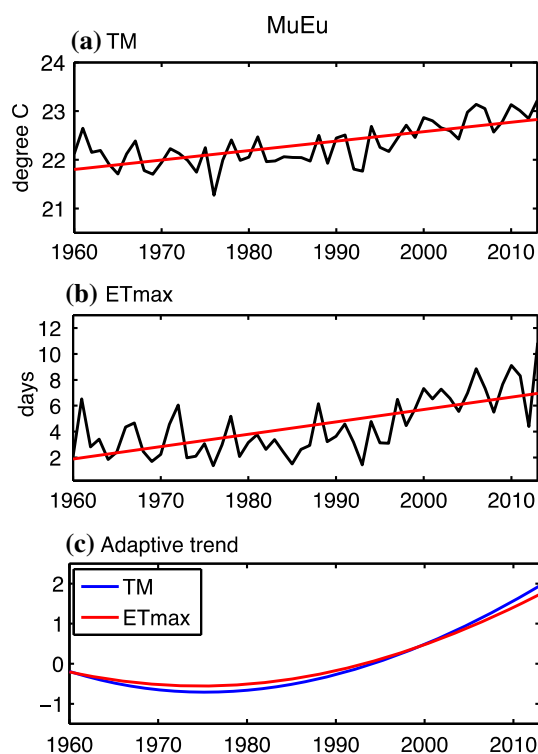


Fig. 4 The averaged time series of **a** temperature mean (TM, dark line, and red line for linear trend), **b** extremely high temperature days (ETmax, dark line, and red line for linear trend), and **c** the adaptive trend of normalized temperature mean (blue line) and extremely high temperature days (red line) over the region of the MuEu-type vector in summer

on TCC, it seems that the summer precipitation means and extremes have a closer relationship comparing with the summer temperature means and extremes.

The changes in temperature/precipitation mean and extremes not only highly correlated on year-to-year time-scale, but also maintain a quite stable relationship in terms of long-term adaptive trend. This close relationship is anticipated to provide a clue to predict climate extremes by taken climate means as predictor.

6 Conclusion and discussion

The present study investigates the relationship of the means and extremes for the temperature and precipitation over China via a newly defined mean–extreme (M-E) vector. For the first time, we combine the trends of climate means and extremes as one single vector. It can better and concisely demonstrate the change of extremes in different regions under the scenario of the changing climate means.

Spatially, both temperature mean and extremely high temperature days consistently increase (MuEu) in nearly

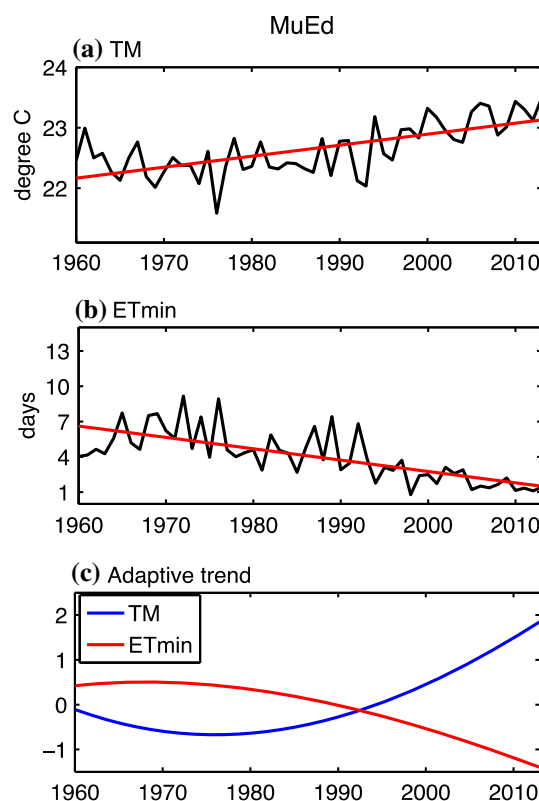
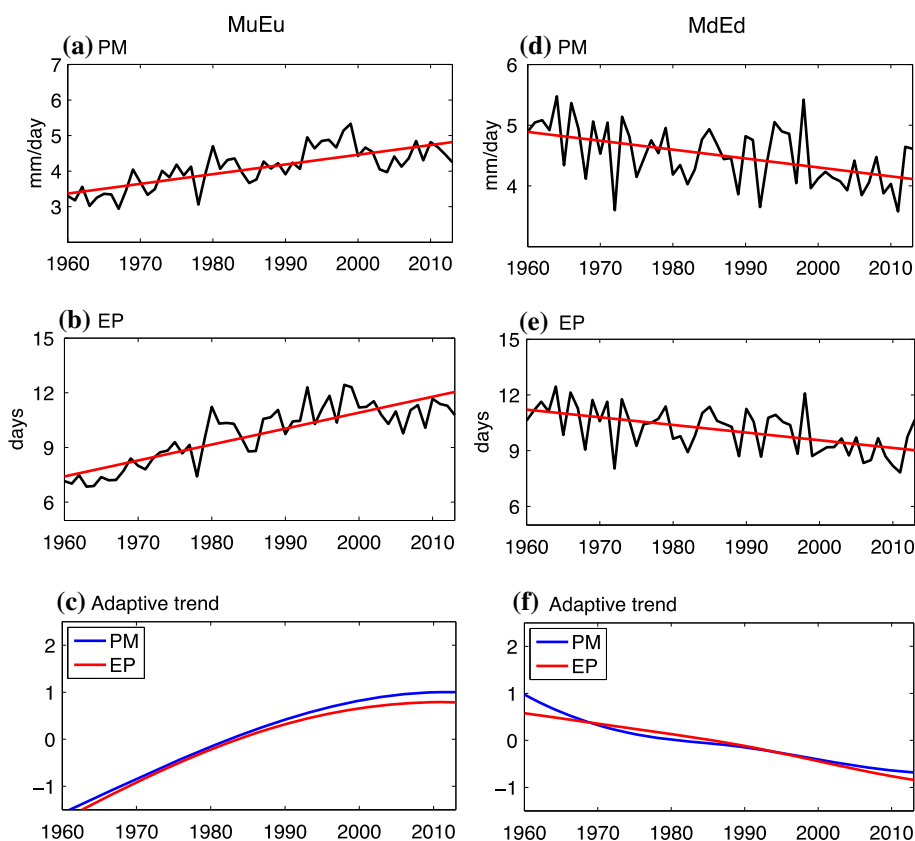


Fig. 5 The averaged time series of **a** temperature mean (TM, dark line, and red line for linear trend), **b** extremely low temperature days (ETmin, dark line, and red line for linear trend), and **c** the adaptive trend of normalized temperature mean (blue line) and extremely low temperature days (red line) over the domain of the MuEd-type vector in summer

whole China for all four seasons. However, the MuEd-type and MdEu-type of M-E vector still exists in some regions. The MuEd-type vector mainly appears over Huang Huai River basin in spring, summer and winter. The MdEu-type appears in small area of Chongqing Municipality in summer. The MdEd-type is found over Qinling Mountains. For the M-E vector of temperature mean and extremely low temperature days, the MuEd-type spreads almost the entire China in all four seasons. However, trends in the temperature mean and the extremely low temperature days are all decreasing (MdEd) in parts of Shanxi and Sichuan provinces in summer.

The trends for precipitation mean and extreme precipitation days are generally identical (either MuEu or MdEd) regardless of seasons. The MuEu-type is distributed in northeastern China and western China in spring, northwestern and central/southern China in summer, western China in autumn, and nearly all China except parts of Sichuan-Yunnan region in winter. Precipitation mean and extreme precipitation days are mostly decreased (MdEd) in the rest of China for all reasons.

Fig. 6 The averaged time series of **a** precipitation mean (PM, *dark line*, and *red line* for linear trend), **b** extreme precipitation days (EP, *dark line*, and *red line* for linear trend), and **c** the adaptive trend of normalized precipitation mean (*blue line*) and extreme precipitation days (*red line*) over the domain of MuEu-type vector in summer. **d–f** are same as (**a–c**), respectively, but over the region of MdEd-type vector



The temporal changes of temperature and precipitation mean and extreme over the domain of each M-E vectors during summer are further studied. On the year-to-year timescale, when the temperature mean increases, the extremely high/low temperature days increases/decreases. As for the adaptive trends, the changes of means and extremes are synchronous over most parts of China. The mean temperature and extremely high temperature days are synchronously declined before mid-1970s and increased dramatically after mid-1970s, whilst extremely low temperature days evolves in an opposite way with increase trend before 1970 but decrease trend after that. No matters for year-to-year variability or adaptive trend, evolutions in precipitation mean and extreme precipitation days are consistent. The precipitation means and extremes both increase (MuEu-type) over southern China with a larger rate before 1990s but slower rate after that, whereas the precipitation means and extremes both decrease (MdEd-type) over northern China with a steady rate throughout the entire period.

Because the predictive skill of dynamic model for climate means is much higher than that for climate extremes (Zhou and Yu 2006; Jiang et al. 2011; Tao et al. 2012), prediction of the frequency of temperature or precipitation extremes over China can be made according to the predicted changes of temperature or precipitation means. The

result of the present study shows that the linear trend of temperature and precipitation means can be used to predict the trend extreme temperature or precipitation days in most parts of China except some small regions that show inconsistent changes. In most parts of China, because both controlled by the large-scale circulation change, the changes in means and extremes are not surprisingly consistent. However, at regional and local scales, additional processes can still modulate the overall changes in extremes (Seneviratne et al. 2012), leading to the inconsistent between changes in means and extremes. Note that, one may ask whether the relationship between extremes and means in the present study are stable across the huge country and in different epochs. To check this issue, we conduct a spatial stratified heterogeneity q-statistic (Wang et al. 2010) to test the significance of classification. Results show the spatial-temporal relationship for means and extremes over China are significant at a 95 % confidence level (figure not shown). So far, the physical mechanism for the trends of climate means and extremes remains unclear. A further understanding on the relationship between climate means and extremes is anticipated to facilitate the future assessment of climate changes.

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