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LETTER

Aerosol forcing of extreme summer drought over North China

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Abstract

The frequency of extreme summer drought has been increasing in North China during the past sixty years, which has caused serious water shortages. It remains unclear whether anthropogenic forcing has contributed to the increasing extreme droughts. Using the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) re-analysis data and Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations with various combinations of historical forcings, the authors investigated the driving mechanism behind the observed changes. Metrological drought is usually measured by precipitation anomalies, which show lower fidelity in current climate models compared to large-scale circulation patterns. Based on NCEP/NCAR re-analysis, a linear relationship is firstly established between the weakest regional average 850 hPa southerly winds and extreme summer drought. This meridional winds index (MWI) is then used as a proxy for attribution of extreme North China drought using CMIP5 outputs. Examination of the CMIP5 simulations reveals that the probability of the extreme summer droughts with the first percentile of MWI for 1850–2004 under anthropogenic forcing has increased by 100%, on average, relative to a pre-industrial control run. The more frequent occurrence of extremely weak MWIs or drought over North China is ascribed from weakened climate and East Asian summer monsoon (EASM) circulation due to the direct cooling effect from increased aerosol.

1. Introduction

Global warming is expected to substantially alter regional water cycles with direct impact on drought, floods, water resources, and ecosystems (Held and Soden 2006, Wu *et al* 2010, Dai 2013, Wu *et al* 2013). North China, one of the most important social (red box in figure 1(*a*)), economic, and agriculture regions in China, has been facing serious water shortages due to frequent and persistent droughts. Extreme droughts over North China have become increasingly more serious as shown by the drought affected area, intensity, duration, and frequency, and are a result of reduced precipitation and warmer temperatures (Ma and Fu 2006, Yang *et al* 2015, Yu *et al* 2014, Zhang and Zhou 2015). However, the driving mechanisms behind the increasing trend remains unknown; especially, the relative contribution of internal climate variability or anthropogenic climate change is not clear.

Many previous studies showed that reduced summer precipitation over North China is caused by weakened East Asian summer monsoon (EASM) circulation, which is indicated by decreased low-level southwesterly winds (Zhou and Yu 2005, Li *et al* 2010, Song *et al* 2014). There are many factors that might contribute to weakened EASM circulation, including tropical warming related to phase transition of Pacific decadal oscillation (PDO) (Hsu *et al* 2014, Li *et al* 2010, Qian and Zhou 2014), and anthropogenic forcing (Zhou *et al* 2009, Zhu *et al* 2012). The importance of anthropogenic aerosol forcing on this

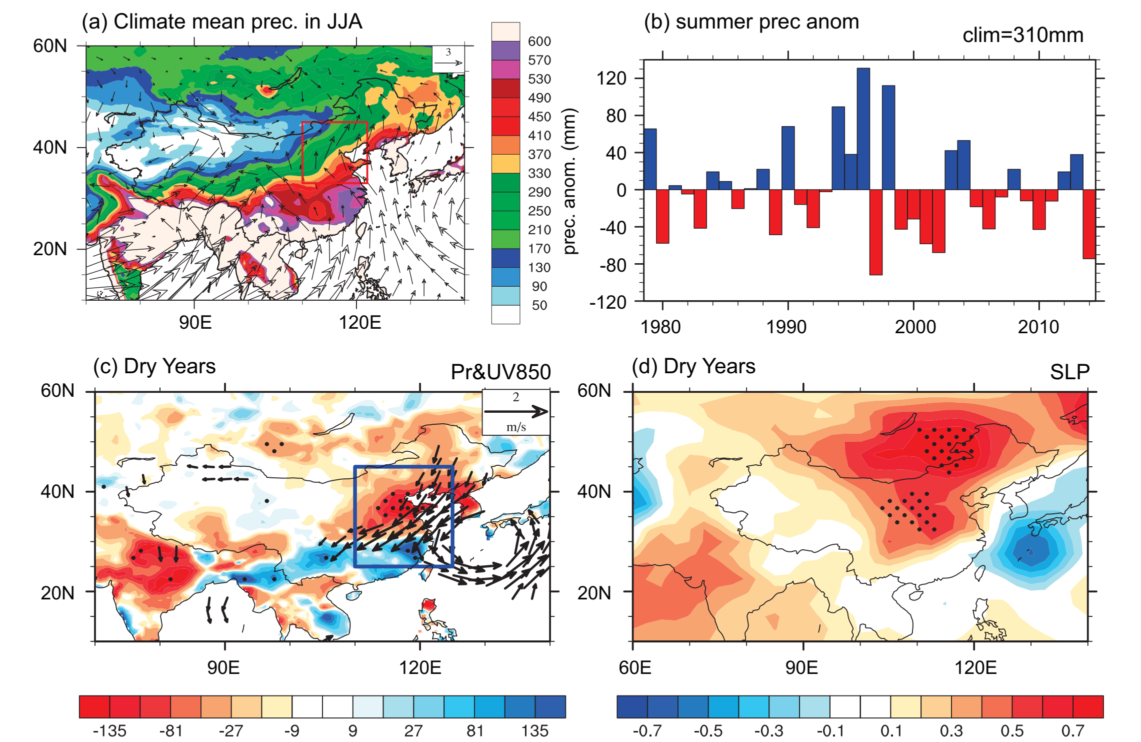

Figure 1. Characteristics of North China summer drought: (*a*) climate mean summer (June–July–August, JJA) precipitation amount (shading, mm) and 850 hPa winds (vector, m s^{-1}) for 1979–2014; (*b*) time series of regional summer precipitation anomalies (mm) averaged over North China (33°N–45°N, 110°E–122°E marked by the red box in (*a*); (*c*) composite precipitation anomalies (shading, mm) and anomalous 850 hPa winds (vector, m s^{-1}) for the six driest summers in North China; (*d*) same as (*c*), but for sea level pressure (hPa). Dotted areas are statistically significant at the 10% level and only statistically significant wind anomalies are shown in (*c*) and (*d*).

weakening EASM has been well demonstrated by using both global general circulation models (Polson *et al* 2014, Jiang *et al* 2013, Menon *et al* 2002, Lau *et al* 2006, Song *et al* 2014) and regional climate models (Giorgi *et al* 2002, Huang *et al* 2007, Wang *et al* 2015). A recent study about the interaction between EASM and aerosol using a coupled regional climate–chemistry model documented that the EASM got weakened due to total aerosols, and the weakened EASM further led to an increase of aerosol in surface and low layers of the atmosphere (Wang *et al* 2015). Nevertheless, these studies mainly focus on summer mean precipitation and circulation trends, and whether these factors could alter the occurrence of extreme drought in North China remains unknown.

Climate models are widely used for attribution studies, but the fidelity of precipitation and regional water cycles simulated by state of the art climate models is generally low (Kusunoki and Arakawa 2015, Sperber *et al* 2013). A recent study on severe drought over Northeast China in the summer of 2014 found that precipitation responses to forcing are small, partly related to climate model bias in simulating precipitation (Wilcox *et al* 2015). An intermediate approach is needed to best utilize currently available climate model information to support climate change impact assessment and adaptation. Climate proxies have been widely used in the mean climate attribution over China, and some extreme event attribution studies occurred in other regions (Swain *et al* 2014, Harrington *et al* 2014). Given the fact that climate models can well capture the large-scale circulation of EASM (Song and Zhou 2014a, Song and Zhou 2014b), this paper attempts to find a large-scale proxy for North China's extreme summer droughts to enable us to conduct attribution studies based on CMIP5 model simulations. Section 2 describes the model and data used, sections 3 and 4 presents the main results and conclusions, respectively.

2. Model and data description

The observational precipitation data used in this study is the monthly precipitation data from CRU TS3.1 datasets (Harris *et al* 2014), and the re-analysis dataset is the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) re-analysis for 1950–2014 (Kalnay *et al* 1996). Considering the data quality problem of re-analysis, we selected the sub-period of 1979–2014 to obtain the relationship between precipitation and a large-scale proxy. To derive all possible changes of observational variation of circulation, the whole period of 1950–2014 is used in model evaluation.

To explore anthropogenic forcing, separate forcing experiments from 13 climate models from CMIP5 archived for 1860–2004 is used, including the all forcing experiment (historical_ALL) forced by both anthropogenic (greenhouse gases, aerosols, land use, and ozone) and natural forcings (volcanic and solar), the greenhouse gases forcing experiment (historical_GHG), and the historical natural experiment (historical_Nat). The external forcings of each experiment can be found in table S1 (stacks.iop.org/ERL/12/034020/mmedia) in the supplementary material. To derive climate responses to all forcing, the pre-industrial simulations (piControl) are also included in this study as a reference of historical simulation (table S2 in the supplementary material). In the analysis, following Taylor *et al* (2009), the response to aerosol forcing is calculated as subtracting the responses to natural and greenhouse gases from historal_ALL.

Extremes are usually based on statistics on the tail of the probability distribution. In this study, the most extreme percentiles of minimum precipitation are used to represent extreme drought. In section 3.1 we selected the top 15% driest summers given the short observational period. In section 3.2, we selected the first to tenth percentiles, using a longer time with 145 yr historical simulations and more than 300 yr piControl simulations.

3. Results

3.1. Large-scale circulation proxy of extreme summer drought over North China

The climatological distribution of summer (June–July–August, JJA) mean precipitation calculated from the CRU monthly means and 850 hPa winds using the NCEP/NAR re-analysis over the period 1979–2014 is shown in figure 1(*a*). The mean summer precipitation over North China gradually decreases from southeast to northwest, with a maximum in the southeast of 500 mm and a minimum in the northwest falling below 100 mm. The southwesterly summer monsoon winds overflow the East Asian coast, transporting warm moist air toward North China, the area marked by the red box in figure 1(*a*). Climatologically the prevailing winds in summer are always southerly. Meteorological droughts, measured by precipitation anomalies, are the main cause for agricultural failures and hydrological water shortages. Figure 1(*b*) shows the time series of regional mean summer precipitation anomalies over North China. With a mean precipitation of 310 mm, interannual variability is robust, often exceeding 25% of the long-term average. Since the region is located around the northern tip of the EASM, it is sensitive to circulation changes. Figure 1(*c*) shows the composite precipitation and 850 hPa wind anomalies, and figure 1(*d*) shows the mean sea level pressure (SLP) anomalies for the top 15% driest years (corresponding to the years 1980, 1986, 1997, 1999, 2002, and 2014). Negative precipitation anomalies over North China come together with anomalous high SLP over land, paired with low SLP anomalies over the sea, and consequently anomalous northeasterly winds. Thus, summer precipitation in North China is closely associated with anomalous low-level winds driven by large-scale dynamics.

Given the coarse model resolution and hence low reliability of precipitation simulation, it is desirable to use a large-scale dynamic proxy for attribution instead of simulating precipitation directly. Based on the above analysis and also previous studies (Zhou *et al* 2009, Li *et al* 2010), a dynamic proxy is defined as a meridional wind index (MWI) using regionally averaged 850 hPa meridional winds over a box bounded by (25°N–45°N, 110°E–125°E, marked by the blue box in figure 1(*c*)). Figure 2(*a*) shows the relationship between regional precipitation anomalies and the MWI for the period 1979–2014. Their correlation coefficient is 0.60, and their regression coefficient is 73.5 mm /(m s^{-1}) at the 1% statistical significance level. The relationship is particularly strong with extreme droughts. All six driest years constituting the top 15% of droughts measured by precipitation anomalies correspond to negative MWI values, and five of the six driest years in precipitation terms remain in the top 15% category in MWI terms. Figure 2(*b*) shows the composite precipitation anomalies based on the top 15% weakest MWIs, which is similar to figure 1(*c*) which directly uses precipitation data. It is thus reasonable to use our large-scale dynamic proxy MWI for extreme summer droughts over North China.

The advantage of MWI over precipitation in the climate modeling perspective can be further seen from figures 2(*c*) and (*d*), where the consistency among CMIP5 models is compared. The simulated precipitation distribution shows much larger spread among different models compared to MWI simulations from the same model. Following Harrington *et al* (2014), the observed range of the first and third quarter (dashed red lines in figures 2(*c*) and (*d*)) during 1950–2004 is regarded as a reasonable range of observed climate mean value, and a reasonable simulation is the simulated climates mean value falling in this range. If the models are selected using the observational threshold (dashed red lines in figures 2(*c*) and (*d*)), all 13 models pass based on MWIs, while only 8 out of the 13 pass using precipitation. In addition, the simulated JJA mean MWI in the piControl simulation is examined. In the observation, climatologically the prevailing winds along the East Asian coast in summer are always southerly. That means the MWI of JJA is always positive (see observed MWI variation in figure 2(*d*)). The models with negative MWIs are excluded, leaving nine models in the attribution study (table A2 in the supplementary material).

3.2. Anthropogenic impact on extreme summer droughts occurrence

An extreme summer drought is defined as a case when the MWI falls in the first ten percentiles. Figure 3(*a*) shows the frequency changes for each percentile from the historical_ALL simulations with MWIs below the

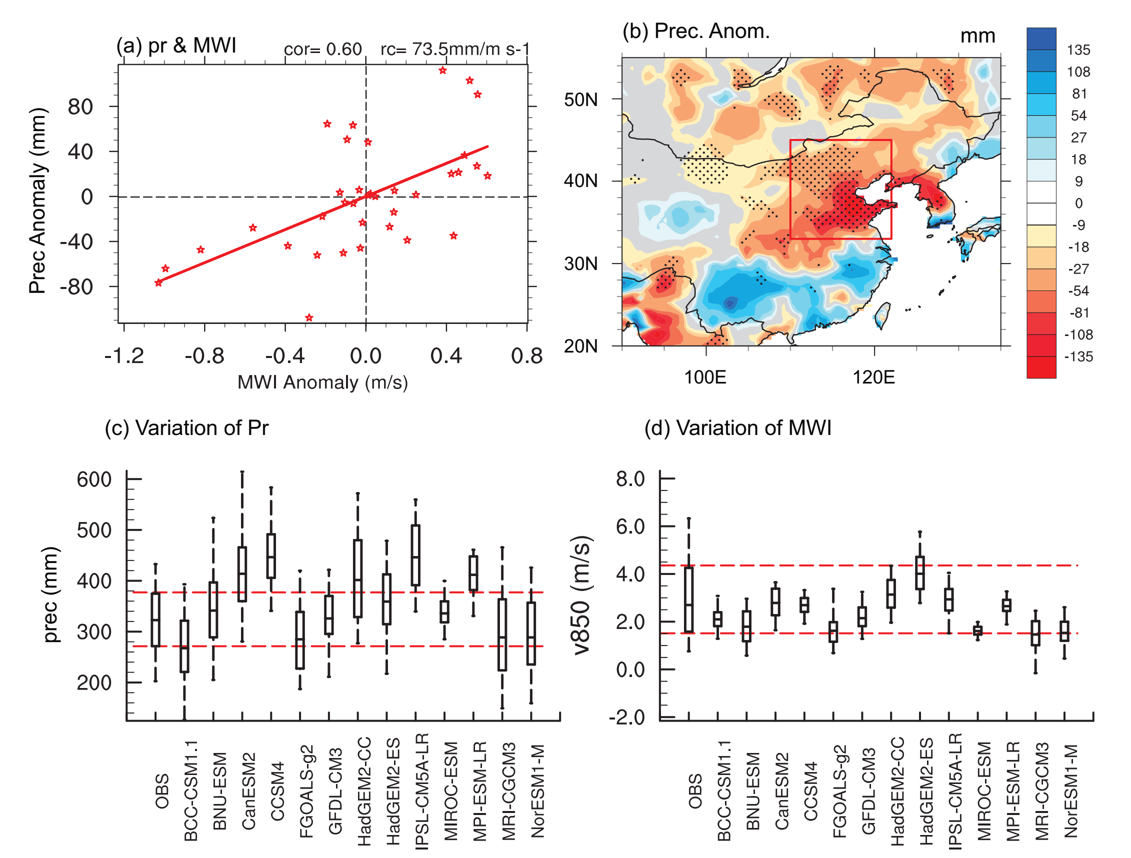

Figure 2. Comparison of a precipitation index with a dynamic proxy: (*a*) scatter plot of summer precipitation anomalies over North China against the MWI anomalies for 1979–2014; (*b*) composite summer precipitation anomalies (mm) based on the top 15% weakest WMIs; (*c*) box plot comparing observed range of average North China summer precipitation (mm) with CMIP5 model simulations for the period 1951–2005, where each box indicates the median, first and third quartiles, and the whiskers extend to maximum and minimum values. The red dashed lines denote the first and third quartiles of the observation. (*d*) Same as in (*c*), but for MWI.

corresponding model's piControl (black), in comparison with greenhouse gases (GHG, red), natural (Nat, green), and aerosol (AA, blue) forcing only simulations. First of all, the frequency range changes of any running 145 yr simulation (4128 in total) in piControl of the nine models is examined (orange). The median frequency change of the first ten percentiles of MWI in piControl is around zero. Event occurrence increases categorically in all of the first ten percentiles in historical_ALL, with decreasing uncertainty toward the most extreme scenario. The median increase under the first percentile is 1.0%, which indicates one time more extreme droughts under the influence of historical external forcing. Both the median mean and maximum frequency change in historical_ALL are beyond those ranges in piControl. However, the systematic increase in extreme summer droughts is seen only from the aerosol forcing simulations, and cannot be explained by either GHG only or Nat only forcing. This is because GHG forcing consistently induces a negative (red) response while Nat forcing induces a small response (green).

There are two factors that may alter the odds of extreme low values of MWI, i.e. shift of the climate mean state and increase standard deviation. Thus, figure 3(*b*) shows the forced response of the MWI distribution in different forcing scenarios, with the horizontal axis being changes in mean, and the vertical axis being changes in standard deviation. Relative to the piControl, eight out of the nine models simulate a weakened climatological mean MWI in historical_ALL, while changes in standard devastation are not robust (black dots in figure 3(*b*)), thus suggesting a shift toward weaker MWIs, which favor more frequent extreme summer droughts over North China. A comparison of responses to different forcings indicates that all forcing responses are dominated by the anthropogenic aerosol (blue dotes in figure 3(*b*)).

In addition, there are three models with prescribed aerosol concentration among the models used in this study. All show reduced MWI under aerosol forcing, with a magnitude of -0.04 m s^{-1} in BCC-CSM1.1, -0.12 m s^{-1} in CCSM, and -0.17 m s^{-1} in FGOALS-g2, respectively. In comparison, the spread of MWI responses among the models with prescribed aerosol emissions is larger, with the largest response of -0.47 m s^{-1} in MIROC-ESM. This indicates the uncertainties caused by aerosol representations in climate models.

To further examine the reliability of our large-scale dynamic proxy in the representation of extreme

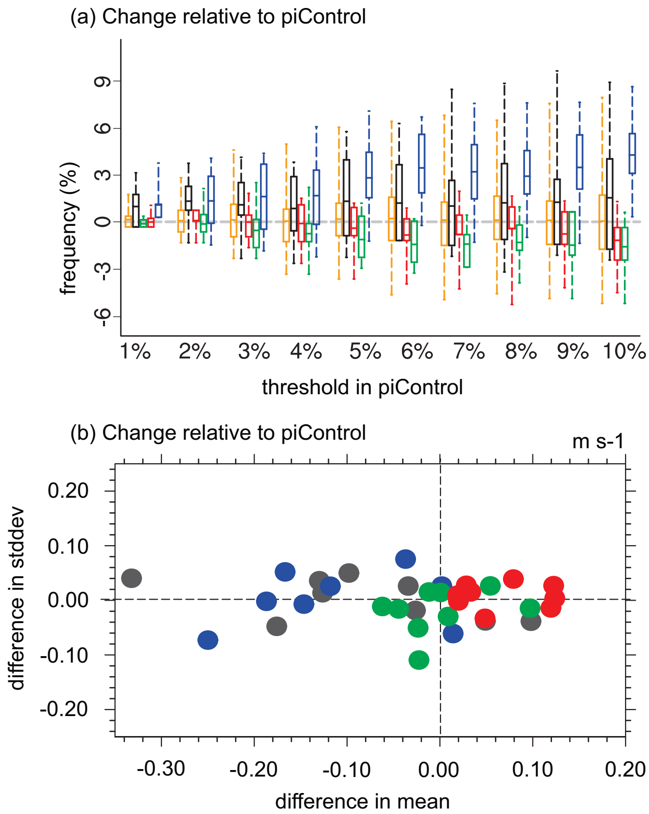

Figure 3. (*a*) Frequency change (unit: %) of historical simulation with MWIs below the first to tenth percentiles in piControl. The orange box shows the range of frequency changes of the first to tenth percentiles of MWIs for any running 145 yr simulations (4128 in total) in piControl. The black, red, and green boxes are the results from historical_ALL, historical_GHG and historical_Nat, respectively. Each box indicates the median and first and third quartiles, while the whiskers extend to maximum and minimum values. (*b*) Change in mean (*x*-axis, unit: m s^{-1}) and standard deviation (*y*-axis, unit: m s^{-1}) of MWI in the historical simulations relative to piControl. Each dot represents an individual model. The black, green, red, dark blue, and light blue dots are the results from historical_ALL, historical_Nat, historical_GHG, historical_AA, and the aerosol forcing experiment, respectively.

summer droughts over North China, figure 4 shows the composite precipitation with 850 hPa wind and SLP anomalies in historical_ALL for the years with MWIs less than the first percentile of piControl based on the multimodel ensemble. An anomalous northeasterly wind over East Asia and negative precipitation anomalies are shown over North China, which are associated with positive SLP anomalies over the Asian continent and negative anomalies over the Northwestern Pacific Ocean. The similarity between figure 4 and figure 1 (*c*) and (*d*) demonstrates the robustness of our dynamic proxy index.

The weakened mean of summer southerly wind was extensively investigated by previous studies using state-of-the-art climate models. Although uncertainty exists on the aerosol forcing of precipitation, a consistent result among these studies is that the anthropogenic aerosol forcing tends to weaken the EASM, as seen by weakened southerly winds along the East Asian coast (Jiang *et al* 2013, Polson *et al* 2014, Song *et al* 2014, Dong *et al* 2016). Aerosol has an overall cooling effect on land because the direct impact of the sulfate burden over Asia reduces solar radiation (figure S1-2). Thus, a positive SLP anomaly and negative SLP anomalies can be found over the northern Asian continent and Northwestern Pacific, respectively (figure S1(*a*)). The weakened land–sea thermal contrast leads to weakening of the EASM and a reduction in summer precipitation over North China.

4. Summary and discussion

There has been an increase of extreme summer droughts over North China during recent decades. Due to the poor representation of precipitation in current climate models, the attribution of anthropogenic forcing of the increased occurrence of extreme drought remains unknown. This paper investigates the driving mechanisms and external factors behind the observed trend using CMIP5 climate model ensembles. Given a reasonable simulation of large-scale circulation, a dynamic proxy MWI is firstly established based on observations and re-analysis. For the targeted region located around the northern edge of the EASM, the MWI is found to be a reasonable indicator of summer precipitation that characterizes meteorological drought. Since the MWI is a large-scale dynamic proxy that climate models can reasonably simulate, it enables us to carry out a detection and attribution study taking advantage of the existing CMIP5 archive.

Analysis of CMIP5 model ensembles using different combinations of estimated historical forcings has shown that anthropogenic aerosols have played a

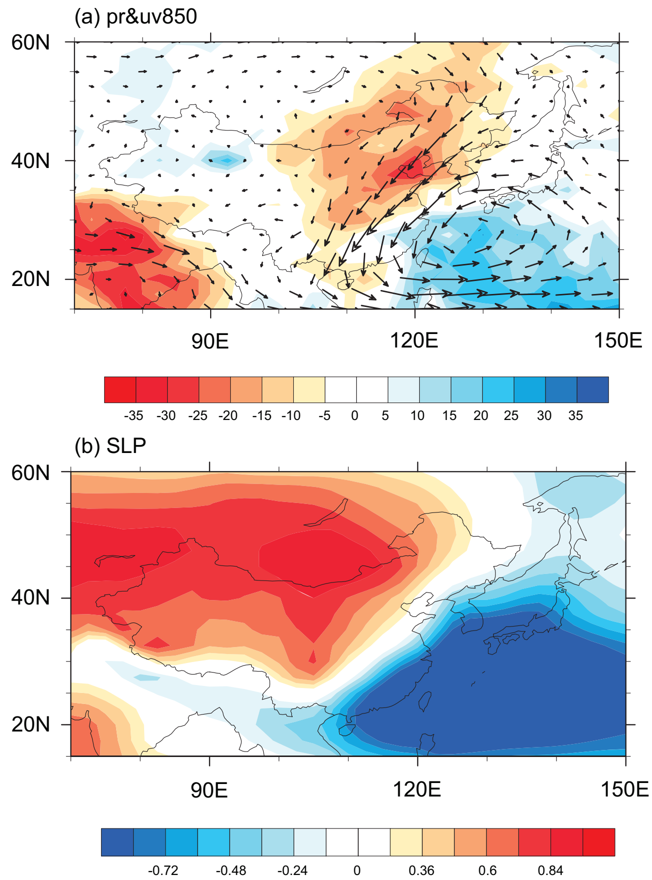

Figure 4. Composite JJA anomaly fields in historical_ALL for the years with MWIs less than the first percentile of piControl derived from the multimodel ensemble mean for (*a*) precipitation anomaly percentage (shading, %) and 850 hPa wind (m s^{-1}), and (*b*) sea level pressure (hPa).

significant role in increasing the occurrence of extreme summer droughts. Extreme summer droughts measured by the first ten percentiles of the MWI show a robust increase in frequency across the CMIP5 ensemble relative to each model's corresponding preindustrial control simulation when all external forcings are included, with the probability of the first percentile of MWI increased by 150% on average. The increase in extreme summer drought occurrence is due to a shift of the MWI toward reduced southerly winds that reflect the weakening of the EASM caused by the direct cooling effect from increased aerosol use.

The impact of aerosol forcing in this study is assessed by subtracting the responses to natural and greenhouse gases from all forcings, following Taylor *et al* (2009). This residual may also include other anthropogenic forcings, such as land use and ozone in some models. Among all models used, four considered land use changes, and two (CanESM2 and CCSM4) have land use only simulations. Our assessment shows that land use changes may only account for up to 25% of the residual forcing (figure S3 in the supplementary material), which confirms that anthropogenic aerosol forcing plays a major role in the residual.

The sensitivity of precipitation to sulfate aerosols has been investigated (e.g. Wu *et al* 2013, Haywood *et al* 2013 and Wilcox *et al* 2015). Detection and attribution in regional water cycles including drought and precipitation remains difficult. Because of the unique position of our targeted area, the large-scale dynamic proxy MWI has been demonstrated to be a useful approach for utilizing current climate model information. Given the large uncertainties associated with simulated precipitation from climate models, this approach may be generally applicable to other areas of research related to regional water cycles. However, for drought in general, evapotranspiration plays an important role and the thermodynamic effect of regional warming should be considered. This is particularly important for future climate projections. A joint large-scale dynamic thermodynamic proxy will be desirable to study drought and regional water cycles. We also note that the MWI proxy defined in this study focuses on North China and should not be applied to the Yangtze River Valley, where the correlation coefficient between the local precipitation and MWI index is −0.13 for the 1979–2014 period, which is not statistically significant at the 5% level. Thus, the increasing trend of extreme summer drought in the Yangtze River Valley is not simulated under anthropogenic forcing, even though the northly wind anomaly is captured. In addition, natural variability related to PDO has been demonstrated to be the main factor that has driven the enhanced rainfall along the Yangtze River valley (Li *et al* 2010), and this process is not included in the ensemble simulation.

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