Near-surface warming reduces dew frequency in China

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Abstract

Long-term (1961-2010) observations of dew data collected at 597 stations over China show that dew frequency decreased by 5.2 days per decade due primarily to near-surface warming and associated decreases in relative humidity (RH). Moreover, the percentage decreasing rate of dew frequency in arid regions (precipitation PR<400 mm yr^{-1}) are larger than that in humid regions (PR≥800 mm yr^{-1}). Compared with the 1960s, the mean dew frequency in the 2000s decreased by 28%, 40%, 50% in humid, semi-humid (400≤PR<800 mm yr^{-1}), and arid regions, respectively. Surface warming is larger in arid regions in northwestern China than its humid and semi-humid regions during recent global warming, which leads to larger decreases in surface RH and makes dew events less likely. Since dew contributes significantly to surface water balance in arid regions, the large decreases in dew frequency may contribute to "the drier getting drier" response to global warming over arid regions.

Plain Language Summary

Here we show, by analyzing 50 years (1961-2010) of data collected at 597 stations in China, that dew occurrence in China exhibits a clear decreasing trend, and the decreasing rate of dew frequency in arid regions is higher than that in semi-humid and humid regions. Compared with the 1960s, the mean dew frequency in the 2000s decreased by 28%, 40%, 50% in the humid, semi-humid, and arid regions of China, respectively. Further analysis reveals that the decreased dew frequency is caused primarily by near-surface warming and drying. Large decreases in surface relative humidity in arid regions associated with large warming makes dew events less likely. This could make the region drier as dew is a significant water source in arid regions.

1. Introduction

As one of the most damaging natural disasters, drought exerts devastating impacts on ecosystems, water resources, agriculture, and human welfare, affecting millions of people in the world each year [van Dijk et al., 2013; Sternberg, 2011; Wilhite, 2000; Kallis, 2008]. Historical records of precipitation, stream flow and drought indices all show a trend of increasing drought since 1950 over many land areas [Dai, 2011a; 2013]. Besides natural climate variations, global warming is thought to be an important culprit for much of the drying trend over many land areas [Dai, 2011a; 2013; Feng and Fu, 2013; Diffenbaugh et al., 2015; Dai et al., 2018]. Global warming increases local atmospheric demand for moisture and cause precipitation decreases over many subtropical regions, both contributing to the drought [Dai, 2011a; Dai et al., 2018]. Although most climate models are capable of simulating the general behavior of surface water deficit defined as evaporation minus precipitation [Taylor et al., 2012; Sheffield and Wood, 2008a; Greve et al., 2014], there are large uncertainties in simulating land hydrology and soil moisture [Sheffield and Wood, 2008a, b; Greve et al., 2014; Wang, 2005; Meehl et al., 2007; Dai et al., 2018]. Furthermore, large regional differences exist among different drought indices [Burke and Brown, 2008; Dai, 2011b; Sheffield et al., 2012], possibly due to natural variability, as local drying over a few decades can be caused by both long-term global warming and multi-decadal natural variability [Dai et al., 2018].

Dew, as a resource of fresh water, partly compensates the deficit between potential evaporation and precipitation, and hence contributes to surface water balance, especially in arid regions [Jacobs et al., 1999; Malek et al., 1999; Uclés, et al. 2014; Steinberger et al., 1989]. Although it may not contribute much to the total water balance in humid regions, its contribution in arid regions is considerable [Jacobs et al., 1999]. The annual dewfall ranges between 9%-23% of rainfall in arid ecosystems [Malek et al., 1999; Uclés, et al. 2014]. Furthermore, acting as one of the important water resources, dew is beneficial to the survival, growth and development of the plants in arid regions. For desert ecosystem, dew actually is the main or the only water resource in the dry season on which plants and arthropods rely for survival [Steinberger et al., 1989].

Based on the Clausius-Clapeyron relation, the saturation specific humidity increases by 7% for a 1 K increase in temperature [Sun and Held, 1996]. Relative humidity (RH) will decrease with increasing temperature if specific humidity could not increase as fast as the saturation rate. Near-surface RH is projected to decrease over most land areas under greenhouse gas (GHG)-induced global warming (Chen et al., 2020); concurrent increasing temperature and decreasing surface RH over many land areas has been observed during recent decades [Simmons et al., 2010; Willett et al., 2010; Byrne and O'Gorman, 2018]. Given the decreases in the surface RH over land under GHG-induced global warming, one may expect dew occurrence to decrease over land. However, to the best of our knowledge, no studies have examined historical dew frequency changes. To fill this gap, here we examine the dew frequency changes from 1961-2020 over China and explore the key underlying factors by analyzing the long-term observations collected at 597 meteorological stations over China.

2. Data and method

Dew events were routinely recorded by trained human observers everyday based on the guidelines of China Meteorological Administration (CMA) [CMA, 2003] at Chinese weather stations. Based on the CMA criteria [CMA, 2003], a dew event is identified when moisture condensed from the atmosphere and deposited in the form of small drops upon any surface. The observing practices for dew had not changed during the study period from 1961-2010. Mao et al (2016) evaluated the human observed dew events by comparing with the simultaneous observations of ground grass temperature and near-ground dew-point temperature. Their analyses confirmed the reliability of the human observed dew data. In addition, other meteorological variables, including daily near-surface air temperature, RH and precipitation from the weather stations, are also analyzed. All these meteorological data were obtained from the National Meteorological Information Center of the CMA (http://www.nmic.cn).

In this work, the long-term (1961-2010) daily observations collected at 597 national meteorological stations over China were analyzed. Annual dew frequency was calculated as the total number of days with dew events recorded in a year. To examine regional differences, the whole China is divided into arid, semi-humid, and humid regions according to annual precipitation (PR), with the arid, semi-humid, and humid regions defined respectively as areas with annual PR<400 mm, 400≤PR<800 mm, and PR≥800 mm (Fig.S1).

3. Results and Discussion

Figure 1 shows the trends and decadal variations of annual dew frequency over the period from 1961 to 2010 over China. Dew frequency exhibited a clear decreasing trend, especially after the 1990s. A comparison of dew frequency between the 2000s and 1960s shows that dew frequency decreased at most of the stations (539 out of 597). Averaged over the 597 stations, annual dew frequency decreased by 5.2 days per decade from 1961-2010. Moreover, the decreasing rate of dew frequency in arid regions over northwestern China was much larger than that in humid regions over southeastern China. Compared with the 1960s, the mean dew frequency in the 2000s decreased, respectively, from 82.8 to 59.6, 49.9 to 29.7, and 31.6 to 15.7 days yr^{-1}, or by 28%, 40%, 50% over the humid, semi-humid, and arid regions of China.

To elucidate the key factors that affect dew frequency, the 1961-2010 trend in annual near-surface air temperature (T), relative humidity (RH), and precipitation (PR), together with dew frequency were analyzed (Fig.2). Consistent with recent global warming, there was a clear increasing trend in near-surface air temperature over China, especially after the late 1980s (Fig.2b), and the warming trend was larger in the arid region than over the other areas (Fig.3, Fig.S2c). Mean near-surface air temperature increased by 0. 17, 0. 29, 0. 40°C per decade during 1961-2010 in the humid, semi-humid, and arid regions, respectively. An increase in near-surface air temperature would lead to a decrease in RH when specific humidity (q) could not increase as fast as the increase rate of saturation vapor pressure, which is often the case in arid and semi-humid regions where moisture supply is limited by the dry surface. Thus, the large warming in the arid region may result in a large decrease in RH. Mean RH decreased by 0. 64, 0. 46, 0. 53% (absolute value) per decade during 1961-2010 over the humid, semi-humid, and arid regions, respectively (Fig.S3c). Compared with the 1960s, the mean RH in the 2000s decreased, respectively, from 86.6% to 83.8%, 73.8% to 71.9%, and 61.7% to 59.4%, or by 2.8%, 1.9%, 2.3% (absolute value), over the humid, semi-humid, and arid regions.

It is noteworthy that the absolute decrease of RH over humid regions was higher than arid regions (Fig.S2b), which is contrary to above analysis that the large warming in the arid region may result in a large decrease in RH. Further analysis indicated that RH during 2000-2010 over humid region decreased suddenly with large rate (Fig.3g, Fig.S3c), which contributed to the higher RH decrease rate during 1961-2010 over the humid regions. This sudden change happens to coincide with the change of the observational instrument for RH from psychrometer to humicap in China after 2000 (Hu, 2014), and the later is in good consistent with the former when RH<80%, but lower than the former when RH>80% (Hu, 2014). Thus, this instrumental change might be a dominant factor contributing to the large RH decreases over humid regions in the 2000s (Fig.3g, Fig.S3c). To confirm the influence of instrument change, RH trends during 1961-2000 over the three regions are analyzed (Fig.S4). The results show that RH decreased during 1961-2000 over humid (0.18% per decade) was lower than semi-humid (0.23% per decade) and arid regions (0.48 % per decade). These analyses collectively substantiate the viewpoint that the large warming in the arid region resulted in a large decrease in RH. Byrne and O'Gorman (2015; 2016; 2018) also explained the opposite trends of temperature and humidity over land and proposed an analytical theory based on atmospheric dynamics and moisture transport.

Precipitation is another factor that may affect or be associated with dew frequency; an increase in precipitation may be associated with more moisture and higher RH, thus favoring dew formation. The higher mean dew frequency in higher precipitation regions seems to support this view (Fig.1). On the other hand, the trend in precipitation does not match that of dew frequency (Fig.2), suggesting that the dew and precipitation are also affected by different factors. For example, precipitation may increase with specific humidity, but dew formation depends more on RH.

Correlation analyses between dew frequency and near-surface air temperature, RH, and precipitation suggest that dew frequency is more sensitive to RH (R=0.69) and T (R=-0.68) than to precipitation (R=-0.09) (Tables S1). The drier the region, the stronger the relationship between dew frequency and near-surface air temperature; and the moister the region, the stronger the relationship between dew frequency and RH (Fig.S5). It is noted that these variables are interrelated (Tables S1). For example, RH is related to both surface air temperature and precipitation. To control the effects of the interplay of the variables, partial correlation analysis is conducted. The results further confirm that RH (R=0.58) and near-surface air temperature (R=-0.56) have dominant effects on dew frequency (Table S2), while precipitation (R=0.03) is a weak factor. Partial correlation analysis also confirm that RH is affected by both temperature (R=-0.54) and precipitation (R=0.43) (Table S3). A multivariable regression over 1961-2010 provides an empirical relationship between annual dew frequency (Y, days yr^{-1}) and annual near-surface air temperature (T, °C), RH (%), and precipitation (PR, mm yr^{-1}) over entire China.

$$Y = -129.6 - 8.86T + 3.36RH + 0.0044PR \qquad (1)$$

The adjusted R^2 is 0.65 with a significance level of $p<0.001$ for the regression. Assuming the relationship for the interannual-decadal variation represented by eq. (1) is valid for long-term trend, dew frequency would decrease by 4.2 days per decade over China, broadly consistent with the observation (5.2 days per decade, Fig.3a). Local warming and drying (i.e., decreasing RH) would decrease the dew frequency by 4.3 days per decade over China, much higher than the effect from the concurrent precipitation change (an increase of 0.1 days per decade). To test whether the trends are consistent with expectations based on unforced variability, multivariable regression on detrended data is also conducted (shown in SI). Using eq.(S1) and the trend of T, RH, and precipitation (Fig.2), dew frequency would decrease by 6.8 days per decade over China, which is also broadly consistent with observation (5.2 days per decade). Note that post-2000 RH data may contain a dry bias due to the change of the observational instrument. To exclude this artificial bias affects, correlation analyses and multivariable regression based on data during 1961-2000 are conducted (shown in SI). The results are broadly consistent with that of 1961-2010, just that the contribution of RH decreases slightly. These analyses suggest that local warming and associated RH decreases had reduced dew frequency over China. Near-surface warming is generally strong over the arid climate regions due to coupling of changes in temperatures, water vapor and downward longwave radiation (Zhou, 2017; Wei et al., 2017). Large warming over arid regions, together with large decreases in surface relative humidity, makes dew events less likely.

4. Summary and Concluding Remarks

Long-term observations of dew occurrence and key meteorological variables (near-surface air temperature, RH and precipitation) from 1961-2010 collected at 597 stations over China are analyzed. The results show that dew frequency decreased by 5.2, 6.2, 5.3, and 5.1 days per decade over whole China, its arid, semi-humid, and humid regions, respectively, due to near-surface warming and associated RH decreases. Moreover, the percentage decreasing rate of the dew frequency in arid regions is much larger than that in humid regions. Compared with the 1960s, the mean dew frequency in the 2000s decreased by 28%, 40%, 50% in humid, semi-humid, and arid regions, respectively. Arid regions in northwestern China warmed up faster (by

0.4 ℃ per decade) than its semi-humid (0.29 ℃ per decade) and humid (0.17 ℃ per decade) regions under global warming, leading to larger decreases in RH, which makes dew events less likely.

As dew represents a significant source of water for arid regions, a decrease in dew frequency caused by surface warming may damage the ecosystem in arid regions, further worsening drought. Our results suggest that under global warming the decreased dew frequency will combine with the increased evaporative demand for moisture to worsen the deficit in surface water balance, making arid regions more sensitive to GHG-induced global warming (Huang et al., 2017) and getting even drier.

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Acknowledgments This research is supported by Chinese Key Projects in the National Science and Technology (2018YFF0300101, 2017YFC0209604), Y.L. is supported by the US Department Energy's Atmospheric System Research (ASR) Program.

Additional information

The authors declare no competing financial interests.

Data Availability Statement

The data were obtained from National Meteorological Information Center of China Meteorological Administration (http://www.nmic.cn), which is open to the scientific community, or available at https://zenodo.org/record/4549870.

Figures

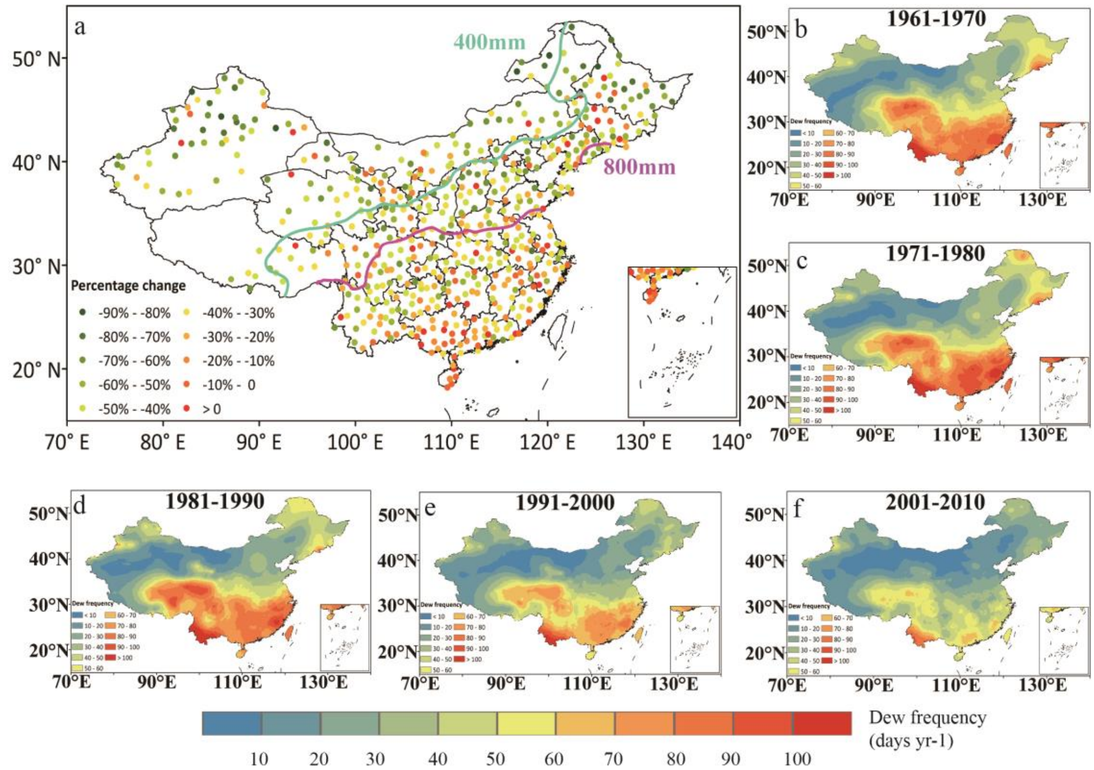

Figure 1. (a) Percentage change of the dew frequency from the 2000s to the 1960s at 597 weather stations over China, and (b-f) the spatial distributions of the decadal-mean dew frequency (days per year) over the period from 1961 to 2010. The cyan and magenta lines in (a) represent annual precipitation contours of 400 mm and 800 mm, respectively, which divide the arid (Ⅰ), semi-humid (Ⅱ), and humid regions (Ⅲ). The regional distribution of annual mean precipitation is shown in Fig.S1.

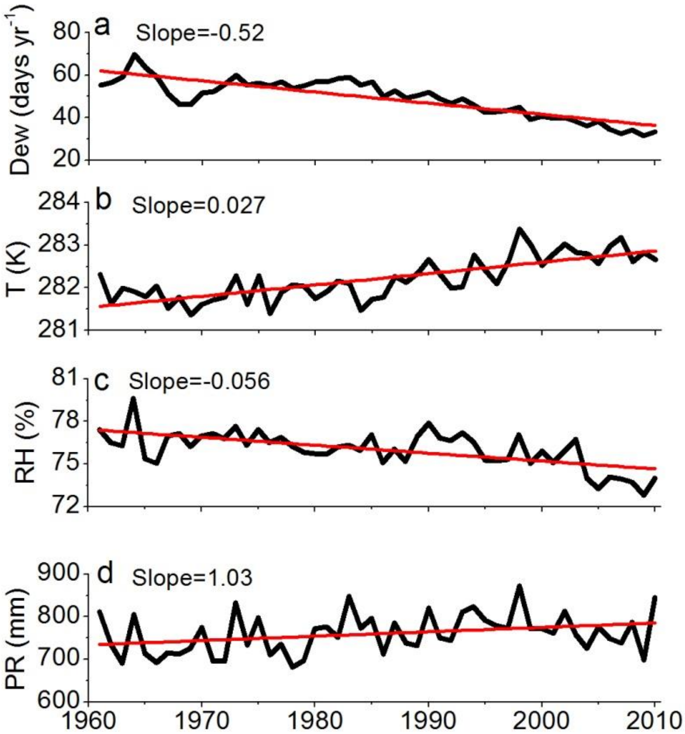

Figure 2. Time series of unweighted annual-mean dew frequency, near-surface air temperature, relative humidity, and precipitation over 597 stations in China. The red lines represent the corresponding linear regressions. The temperature, relative humidity, and wind data were data at 02:00 Beijing Standard Time.

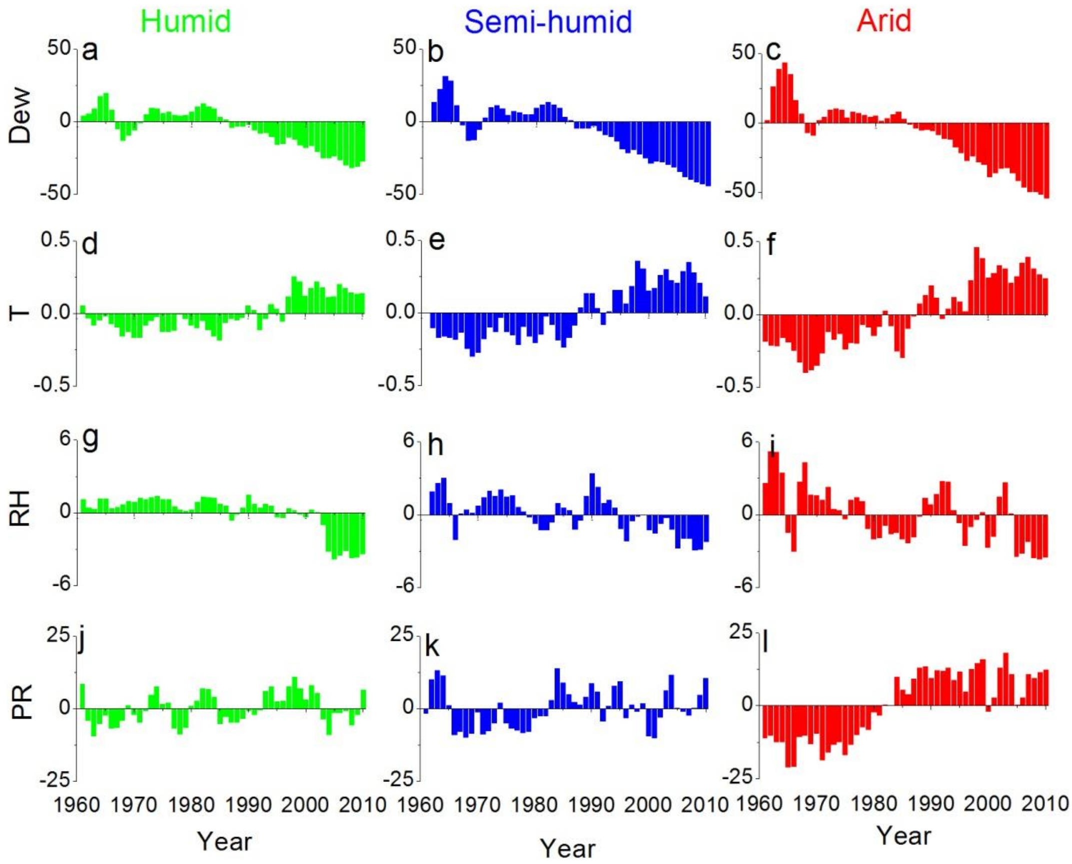

Figure 3. Five-year smoothed percentage anomalies (relative to the 1961-2010 mean) of annual (a, b, c) dew frequency, (d, e, f) near-surface air temperature, (g, h, i) relative humidity, and (j, k, l) precipitation over the humid (left column), semi-humid (mid column), and arid (right column) regions. The three regions are outlined in Fig.1a.