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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Changes in regional wet heatwave in Eurasia during summer (1979–2017)

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Abstract

Wet heatwaves can have more impact on human health than hot dry heatwaves. However, changes in these have received little scientific attention. Using the ECMWF Reanalysis v5 reanalysis dataset, wet-bulb temperatures (T_w) were used to investigate the spatial-temporal variation of wet heatwaves in Eurasia for 1979–2017. Wet heatwaves were defined as three day or longer periods when T_w was above the 90th percentile of the summer distribution and characterized by amplitude, duration and frequency. Maximum values of amplitude, close to 31 °C, occur in the Indus–Ganges plain, the lower Yangtze valley, and the coasts of the Persian Gulf and Red Sea. Significant positive trends in the frequency and amplitude of wet heatwaves have occurred over most of Eurasia though with regional variations. Changes in heatwave amplitude (HWA) are largely driven by changes in summer mean T_w. For Eurasia as a whole, increases in temperature contribute more than six times the impact of changes in relative humidity (RH) to changes in T_w HWA. Changes in T_w have a strong dependence on climatological RH with an increase in RH of 1% causing a T_w increase of 0.2 °C in arid regions, and only increasing T_w by 0.1 °C in humid regions. During T_w heatwaves in Europe, parts of Tibet, India, East Asia and parts of the Arabian Peninsula both temperature and humidity contribute to the increase in T_w, with temperature the dominant driver. During wet heatwaves in part of Russia, changes in humidity are weak and the increase in T_w is mainly caused by an increase in temperature. In the Mediterranean and Central Asia, RH has fallen reducing the increase in T_w from general warming.

1. Introduction

There is no universal definition of a heatwave, but extreme events associated with particularly hot sustained temperature have significant impacts on human health, infrastructure and biophysical systems (Easterling *et al* 2000, Welbergen *et al* 2008, McMichael and Lindgren 2011, Xu *et al* 2016, Campbell *et al* 2018). The effects of the most lethal heatwaves are not only due to high temperature, but also to the effects of humidity (Steadman 1979a, 1979b). Hot and humid conditions can be more dangerous than equivalently hot but dry conditions, as the ability of humans to cool themselves by sweating is diminished as relative humidity (RH) increase (Wehner *et al* 2017).

Eurasia is a region with large population densities, which is vulnerable to environmental extreme events such as heatwaves. Recent examples of heatwaves include the European heatwave of 2003 (Christoph and Gerd 2004) and the Russia heatwave of 2010 (Russo *et al* 2014), which caused more than 70 000 heat-related death rolls; the 2013 heatwave in eastern China (Hou *et al* 2014, Xia *et al* 2016) and the 2017 Shanghai heatwave (Chen *et al* 2019), causing widespread drought and cascading economic losses

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(e.g. Xia *et al* 2018). Many studies have found an increase in dry heatwave occurrences during the last few decades over most of the Eurasia (Karl *et al* 1995, Meehl and Tebaldi 2004, Alexander *et al* 2006), whereas others studies point out the regional differences in these trends (Zhai *et al* 2003, Perkins-Kirkpatrick *et al* 2016).

Previous research on heatwaves has mainly emphasized changes in temperature with limited studies of recent changes in hot and wet heatwave events in Eurasia. Most previous studies on wet heatwaves used observations from local ground stations that can provide accurate temperature and humidity datasets. For example, using station observation temperature and RH datasets, Ding (2011) classified the wet and dry heatwave by mean RH and investigated the geographical patterns and temporal variation of heatwave events in China. However, there are some issues when using observations directly, such as missing records, inconsistencies through time, especially the RH datasets, which has serious quality issues (Zhu *et al* 2015, Li *et al* 2020). Using reanalysis and CMIP5 dataset, Russo (2017) explored global humid heat wave hazards at different levels of global warming and found the magnitude and apparent temperature peak of heatwaves have been amplified by humidity, such as Chicago heatwave in 1995 and China heatwave in 2003. Based on a reanalysis dataset, Kang (2018) calculated the wet bulb temperature (T_w) in the North China Plain, which can be used to measure high temperature and humidity climatic events, finding that heatwave risk had increased due to the anthropogenic effects of irrigation in this region. However, this kind of wet heatwave analysis has not been previously studied in Eurasia.

This study focuses on the spatial-temporal variation of hot and wet extreme events in Eurasia, and the reason for its changes since 1979. We use T_w to identify the wet heatwave. This is a suitable index to investigate the impact of climate change on heat stress (Pal *et al* 2016, Tong *et al* 2017). While the core temperature of human body is around 37 °C, the skin temperature is slightly cooler at 35 °C. If the environmental T_w exceeds 35 °C, then human body is unable to dissipate heat by sweating, leading to hyperthermia (Sherwood *et al* 2010, Tong *et al* 2017). In the current climate, T_w rarely exceeds 31 °C at daily timescale (Sherwood and Huber 2010). Other combined empirical temperature and humidity indices have been used to investigate the impacts of climate change on heat stress such as wet bulb globe temperature (WBGT) (e.g. ISO 1989) which is the basis for time limitations of work in different heat exposure standards. The black globe temperature is not observed in many places (Luo and Lau 2019), which makes WBGT more complex and difficult to measure. In contrast, T_w can be measured using standard methods and it also provides a physically based relationship to the human body's core temperature (Stull 2011, Pal 2016). Hence, T_w is feasible for daily use and has been used more often in climate studies (e.g. Pal and Eltahir 2016, Raymond *et al* 2017).

This paper investigates changes in wet heatwave events in Eurasia using T_w, calculated from a reanalysis dataset. In this study, we compare the variation of the temperature and humidity during wet heatwaves in Eurasia, focusing on the large scale pattern of change in wet heatwaves and analyzing the reason for differential regional changes. The data and methods are described in section 2; the results are presented in section 3, and main conclusions and discussion are given in section 4.

2. Data and methods

2.1. Study region and datasets

We defined Eurasia as land points within the following eight (Giorgi and Francisco 2000) regions: Northern Europe (NEU), Mediterranean Basin (MED), Central Asia (CAS), Tibet (TIB), North Asia (NAS), East Asia (EAS), South Asia (SAS) and part of Sahara (SAH), noting that our MED and SAH regions do not include parts of North Africa. The analysis used the ECMWF Reanalysis v5 (ERA5) reanalysis data for the period from 1979 to December 2017 with a spatial resolution of 0.25° × 0.25° (Hersbach *et al* 2020). This study used daily mean temperature (T_{mean}) and RH from 1979 to 2017. The time during the day when maximum RH and maximum temperature are not the same (Maqsood *et al* 2005, Hong and Wang 2009). T_w would be overestimated if maximum temperature and maximum RH were used to calculate it. Thus, in this study, we computed daily T_w from mean temperature and RH. RH in China was homogenized (Freychet *et al* 2020) by comparison with a nudged global atmospheric model simulation, as China is the only large-scale region where RH observation systems were systematically changed around 2003–2004 (Li *et al* 2020).

2.2. Quantification of wet heatwaves

T_w was calculated using equation (1) of Stull (2011) giving T_w (°C) as a function of temperature (T_{mean}) and RH (%)

$$\begin{aligned} T_w = T_{mean}\mathrm{atan}\left[A(\mathrm{RH}+B)^{\frac{1}{2}}\right] \\ + \mathrm{atan}\left(T_{mean}+\mathrm{RH}\right) - \mathrm{atan}\left(\mathrm{RH}-C\right) \\ + D(\mathrm{RH})^{\frac{3}{2}}\mathrm{atan}\left(E\times\mathrm{RH}\right) - F \end{aligned} \quad (1)$$

where A, B, C, D, E, F are constants ($A = 0.152$, $B = 8.314$, $C = 1.676$, $D = 0.004$, $E = 0.023$, $F = 4.686$), obtained by fitting functions (Stull 2011).

Extreme T_w days were defined as days when T_w was above the 90th percentile summer (June–August) days. A wet heatwave event was defined as three or

more consecutive extreme T_w days during the summer period (Russo *et al* 2015, Freychet *et al* 2020).

Several climate indices have been applied in order to quantify the dry heatwave duration (HWD) and intensity based on daily maximum and minimum temperature (Meehl and Tebaldi 2004, Alexander *et al* 2006, Fischer and Schär 2010, Perkins *et al* 2012) and there is no one universal index. Based on the previous research, we defined three new indices to represent the frequency, duration, and intensity of wet heatwaves: heatwave day frequency (HWF) which is the total number of days in heatwave events per summer; HWD which is the duration of the longest heatwave in a summer; heatwave amplitude (HWA) which is the maximum T_w value in all heatwave events in a summer.

2.3. T_{mean} and RH contribution to T_w

Based on equation (1), T_w is affected by T_{mean} and RH. In order to quantify the contributions of changes in T_{mean} and RH to changes in T_w, we calculated $\partial T_w/\partial T_{mean}$ (°C/°C) and $\partial T_w/\partial$RH (°C/%) which are:

$$\frac{\partial T_w}{\partial \mathrm{RH}} = \frac{A \times T_{mean}}{2(\mathrm{RH}+B)^{\frac{1}{2}}\left[1+(A)^2(\mathrm{RH}+B)\right]} - \frac{1}{1+(\mathrm{RH}-C)^2} + D\left[\frac{3}{2}(\mathrm{RH})^{\frac{1}{2}}\mathrm{atan} \times (E\times \mathrm{RH}) + (\mathrm{RH})^{\frac{3}{2}}\frac{E}{1+(E\times \mathrm{RH})^2}\right] \quad (2)$$

$$\frac{\partial T_w}{\partial T_{mean}} = \mathrm{atan}\left[A(\mathrm{RH}+B)^{\frac{1}{2}}\right] + \frac{1}{1+(T_{mean}+\mathrm{RH})^2}. \quad (3)$$

A, B, C, D, E, F are the same as equation (1). For small changes in mean temperature (ΔT_{mean}) and RH (ΔRH) then the change in wet bulb temperature is (Taylor 1717):

$$\Delta T_w = \Delta T_{mean}\frac{\partial T_w}{\partial T_{mean}} + \Delta \mathrm{RH}\frac{\partial T_w}{\partial \mathrm{RH}} + R \quad (4)$$

where R is a residual representing 2nd, and higher, order terms. We use this to partition changes in wet bulb temperature due to changes in mean temperature and RH.

2.4. Statistical methods

For the regional analysis trends were computed at each grid point and the median computed. Uncertainty in the median was computed by bootstrapping (Efron and Tibshirani 1994) by randomly sampling 1000 times from all the grid points in the area calculating the median value. Unless otherwise stated, we use 5%–95% uncertainty ranges. Significance in gridpoint trends was taken from the standard error in the linear regression trend assuming each calendar year is independent.

3. Results

3.1. Climatological characteristics of wet heatwaves in Eurasia

Figures 1(a) and (b) show the annual mean HWF and HWA during the summer (June, July and August) in Eurasia. Wet heatwave frequency is largest (more than five days/summer) in Saudi Arabia, parts of Southern and Eastern Asia (figure 1(a)). For HWA (figure 1(b)), two areas of wet heatwaves are located in SAS and EAS with largest values in the Indus–Ganges plain and in eastern China. Regional mean HWA is 24.4 °C and 22.1 °C for SAS and EAS, respectively. These monsoonal regions have high temperature and humidity, which leads to higher T_w heatwave intensity (figure 1(b)). High values of HWA also occur around the Persian Gulf with HWA values of 30.3 °C. This is the largest value of HWA in Eurasia and is close to the dangerous T_w of 31 °C (Sherwood and Huber 2010), which is rarely exceeded in the current climate. One possible reason for this is the high humidity in coastal areas, which contributes to the high T_w value. Therefore, it is meaningful to investigate the regional differences of the contribution of humidity and temperature on T_w.

SAS (figure 1(c)) is the region with the highest significant ($p < 0.1$) increasing trends in regional mean HWF and HWD, with 87% and 80% of the grids, respectively, showing an increasing trend indicating that heatwaves have become more frequent and last longer here. In most regions, HWA shows significant ($p < 0.1$) positive trends with largest values in NEU and MED, at 0.38 °C and 0.32 °C·decade^{-1}, respectively. However, the CAS region shows little change in wet heatwave indicators.

3.2. Changes of humidity and temperature during heatwave days and summer mean

T_w is affected by both temperature and humidity and so the contributions of temperature and humidity to wet heatwave changes might have strong regional differences in Eurasia. To explore this we first compare the mean value and the linear trend of temperature and humidity during 1979–2017, then the quantitative contributions of T_{mean} and RH to T_w changes are discussed in section 3.3.

When a heatwave occurs, largest T_w values occur in the monsoon regions including SAS and EAS (figure 2(a)). Highest T_{mean} values, during wet heatwaves, occur mostly in part of SAH, especially Saudi Arabia, CAS, SAS and EAS. High RH centers are located in SAS, EAS, and part of NAS. Lower RH in Saudi Arabia, CAS and Mongolia was due to high temperatures and low humidity in these regions. In contrast, in northeast NAS, low values of temperature lead to high RH in this region.

To examine how different heatwave conditions are from summer-mean conditions, we calculated

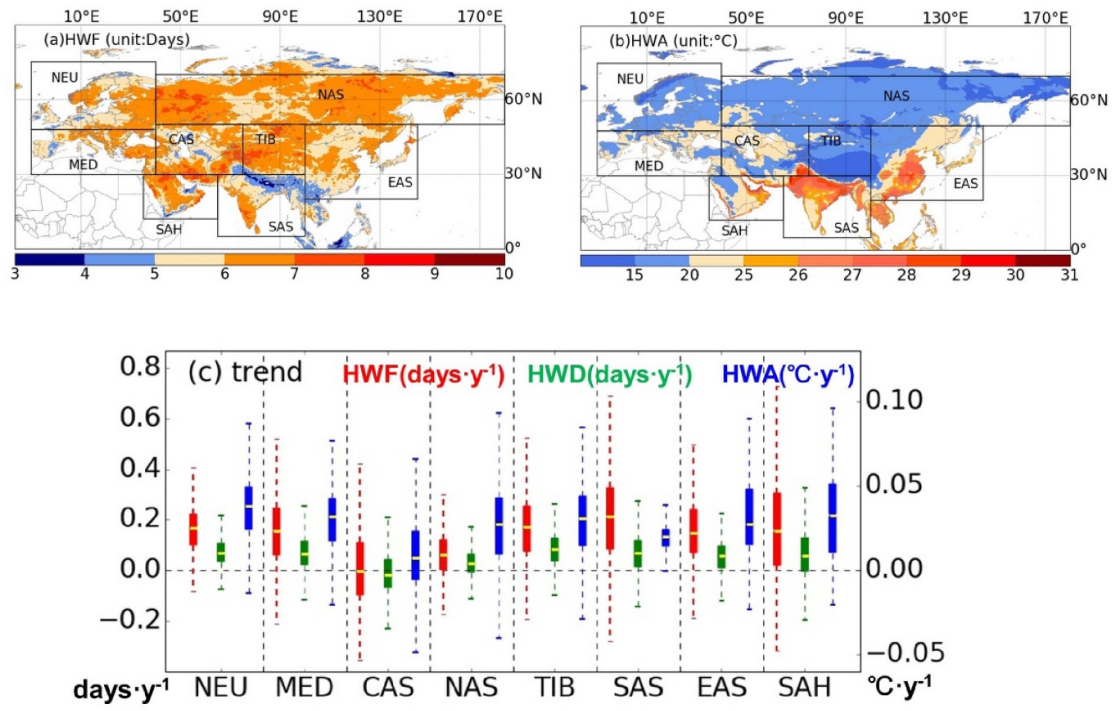

Figure 1. Geographical distribution of the mean value of (a) HWF (unit: days), (b) HWA (unit: °C) for summers during 1979–2017. The color bar in (b) is non-uniform to focus on high values. (c) Box and whisker plot of the liner trend of summer HWF (red boxes), HWD (green boxes), and HWA (blue boxes) in eight Giorgi regions (Giorgi and Francisco 2000) during 1979–2017 from the 0.25 × 0.25 ERA-5 dataset. For each boxplot, the bottom and top of the boxes are the lower and upper quartiles, respectively, the bar near the middle of the box is the median, and the whiskers show the 5% and the 95% values.

the differences of mean T_w, T_{mean}, and RH on heatwave days from the 1979 to 2017 summer mean (figures 2(b), (d), (f)). Where these differences are large, this is where heatwave T_w is larger than the summer mean. T_w differences between wet heatwave and summer days increased smoothly from South to North (figure 2(b)) with largest differences in Arctic Ocean coast. This suggests that wet heatwaves are more extreme in these regions, which might lead to more serious impact. T_{mean} (figure 2(d)) differences are similar to T_w differences and are also smooth, possibly indicating the dominant contribution (see below) of dry-bulb temperature to T_w. This implies that wet heatwaves are different from conventionally defined dry heatwaves, because dry heatwaves often happens under high pressure centers (anticyclone) hence with dry air (Baldi *et al* 2006, Gershunov *et al* 2009). For RH differences (figure 2(f)), high values are found at SAS, TIB and north EAS. In most regions, heatwave RH is about 20% higher than the climatological mean, though with significant regional heterogeneity, suggesting a large, though heterogeneous, increase in RH when wet heatwaves occur.

To understand the regional trends in T_{mean} and RH when wet heatwave happens, we analyze trends in T_w, T_{mean} and RH during heatwaves (figures 3(a), (c), (e)). In NEU, northwest EAS, and parts of Arabia and TIB, increasing T_w is accompanied by an increase in temperature and RH. This implies that increasing T_w in these regions is due to increases in both temperature and humidity. In eastern parts of CAS and SAS, as T_w increases, a significant positive trend in RH is observed, with no significant positive T_{mean} trends in these areas. An extreme case is in parts of SAS, where T_{mean} declined significantly in heatwave days in part of the region. Thus, the increases in T_w in these regions are likely mainly due to the increase in RH. In western Russia, southeastern EAS and the northern Mediterranean, where T_w increased significantly, T_{mean} has significant positive trends and changes in RH are not significant. Thus, T_w increases are likely being driven by T_{mean} increases. Quantitative analysis of the contributions of changes in T_{mean} and RH to changes in T_w is shown in section 3.3.

Over most of Eurasia, differences between the trends of heatwave day and summer mean for T_w, T_{mean} and RH are not significant during 1979–2017 (figures 3(b), (d), (e)). This suggests that significant changes of T_w, T_{mean} and RH in heatwave days are largely due to changes in the summer mean.

3.3. Quantitative contribution from changing T_{mean} and RH to T_w

To measure quantitatively the sensitivity of T_w to T_{mean} and RH, respectively, we calculated $\partial T_w/\partial T_{mean}$ (°C/°C) and $\partial T_w/\partial$RH (°C/%) from mean conditions during wet heatwaves (equations (2) and (3)). For most of Eurasia, an increase of

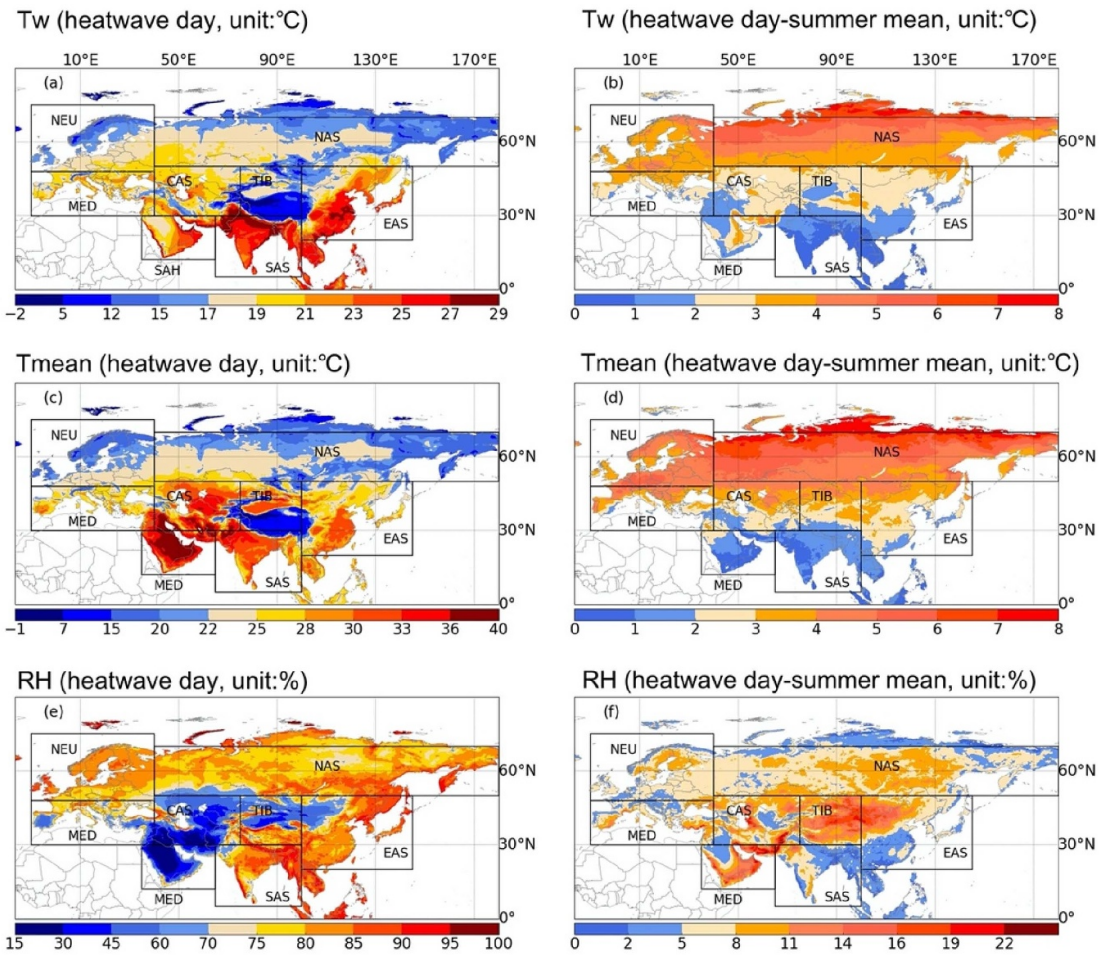

Figure 2. Geographical distribution of the mean value of (a), (b) T_w, (c), (d) T_{mean}, (e), (f) RH during heatwave days (left) and mean value on heatwave days minus summer mean (right) during 1979–2017. To calculate the heatwave day mean minus summer mean, for each grid point and each year, we calculate the mean value of T_w, T_{mean} and RH for all heatwave days and then subtract the mean value of summer T_w, T_{mean} and RH for that year. The color bars in (a) and (c) are non-uniform to focus on high values.

1 °C in T_{mean} during wet heatwaves increases T_w by 0.6 °C–1 °C (figure 4(a)) with lowest sensitivity in arid regions and highest sensitivity in Scotland, Ireland, Southeast Asia, parts of India and the Pacific coast of Russia. A 1% increase in RH causes a T_w increase of 0.05 °C–0.2 °C (figure 4(b)) with higher RH sensitivity in the Arabian Peninsula, eastern China, South EAS and SAS and lower sensitivity in Scandinavia, Siberia and TIB.

To measure quantitatively the contributions of changes in T_{mean} and RH to changes in T_w (see equation (4)), both the sensitivity of T_w and the changes of T_{mean} and RH were considered (figures 4(c)–(e)). T_{mean} is the largest driver of changes in T_w though the quantitative contribution depends on both the sensitivity of T_w to temperature and the change in temperature (figures 4(c)–(e)). Considering Eurasia as a whole, changes in T_w are largely driven by changes in temperature, but the contributions of temperature and humidity to the HWA changes exhibit significant regional differences (figure 4(c)). Over the eight regions, the dominant driver of increasing median T_w on heatwave days is dry-bulb temperature with only small contributions from RH trends. In CAS drying offsets the warming effect leading to only small changes in T_w. The Mediterranean region also shows a drying effect which reduces the temperature driven increase in T_w. In contrast, the TIB region shows a modest increase in T_w over the dominant temperature driven increase from changes in RH.

4. Discussion and conclusion

In summary, this work provides an overview of the changes in summer wet heatwave in Eurasia and investigates the reasons for its changes. Significant increasing trends in the frequency, duration and intensity were observed in most of Eurasia, especially the monsoon regions including SAS and EAS, which show the highest HWA during 1979–2017. In most of Eurasia, T_w shows a significant increasing trend during heatwave days. The main driver of this change is increasing dry-bulb temperatures with reductions in RH partly offsetting this increase in some regions. The decrease trend of RH in these regions suggests that

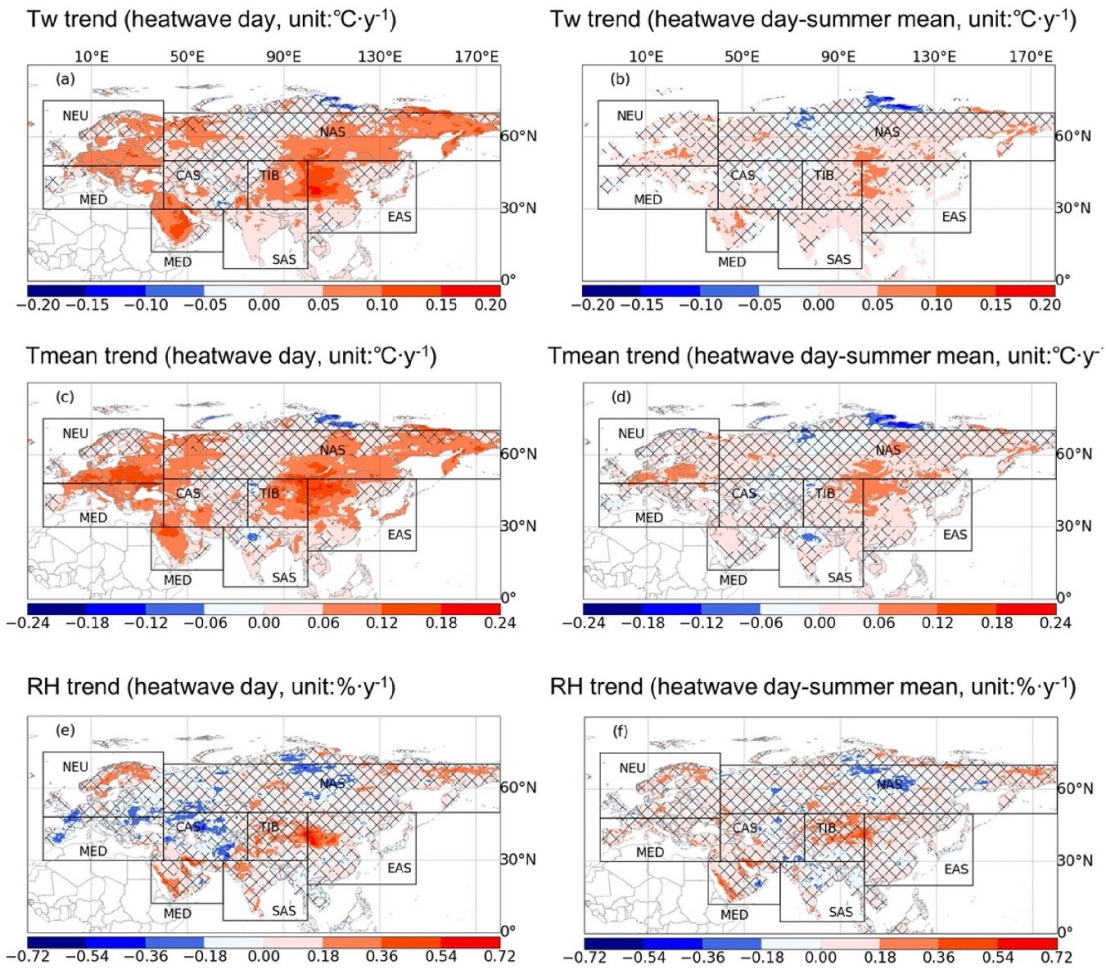

Figure 3. Geographical distribution of the linear trend of (a), (b) T_w, (c), (d) T_{mean}, (e), (f) RH during heatwaves (left) and heatwave mean minus summer mean (right) during 1979–2017. Shading indicates non-significant ($p < 0.1$) trends. To calculate the trend of heatwave mean minus summer mean, for each grid and each year, we calculate the mean value of T_w, T_{mean} and RH for heatwave days and subtract the mean value of summer T_w, T_{mean} and RH, and then calculate trend and significance from the difference time series.

the saturated water vapor pressure increases faster than actual water vapor pressure with rising temperature, consistent with Lou and Lau (2019). They use apparent temperature as a measure of heat stress, and, like us, find heat stress in China is mainly caused by high temperature, rather than high RH. Significant changes in T_w during wet heatwave days are largely due to the T_{mean} changes in summer mean. Compared with humid areas, arid areas are more sensitive to changes in RH and less sensitive to T_{mean} increases. This result is partly consistent with the conclusion of Wang *et al* (2019), who used Chinese observations. Wang *et al* (2019) also show that humidity has higher dominance in the arid and semiarid regions compared with in the Southern and Northeastern China. In our study, Eurasia is divided into eight sub-regions which highlights the regional difference. Over the eight regions, the dominant driver of increasing median T_w on heatwave days is dry-bulb temperature, whereas changes in RH play a relatively minor role. This is different in some sub-regions. In CAS drying offsets the warming effect leading to only small changes in T_w. The Mediterranean region also shows a drying effect which reduces the temperature driven increase in T_w. In contrast, the TIB region shows a modest increase in T_w over the dominant temperature driven increase from changes in RH.

These results are derived from a reanalysis gridded dataset which may introduce errors through interpolation of inhomogeneous station observations. This is especially so for RH observations (Willett *et al* 2008, 2014, Freychet *et al* 2020), which are prone to inhomogeneous biases due to non-climate changes in the local observing system. For example, Song (2012) found that RH in most of China showed a reducing trend. Some researchers have suggested that changes in the Chinese RH observing system from manual to automated is the main reason for the decline of RH in humid areas during the early 2000s (Yu and Mou 2008, Yuan *et al* 2010) likely due to use of Soviet practice and instruments for manual wet-bulb measurements in humid regions (Hu 2004). In this work, we used ERA5 RH data corrected in China as Freychet (2020), which partly reduced the impact

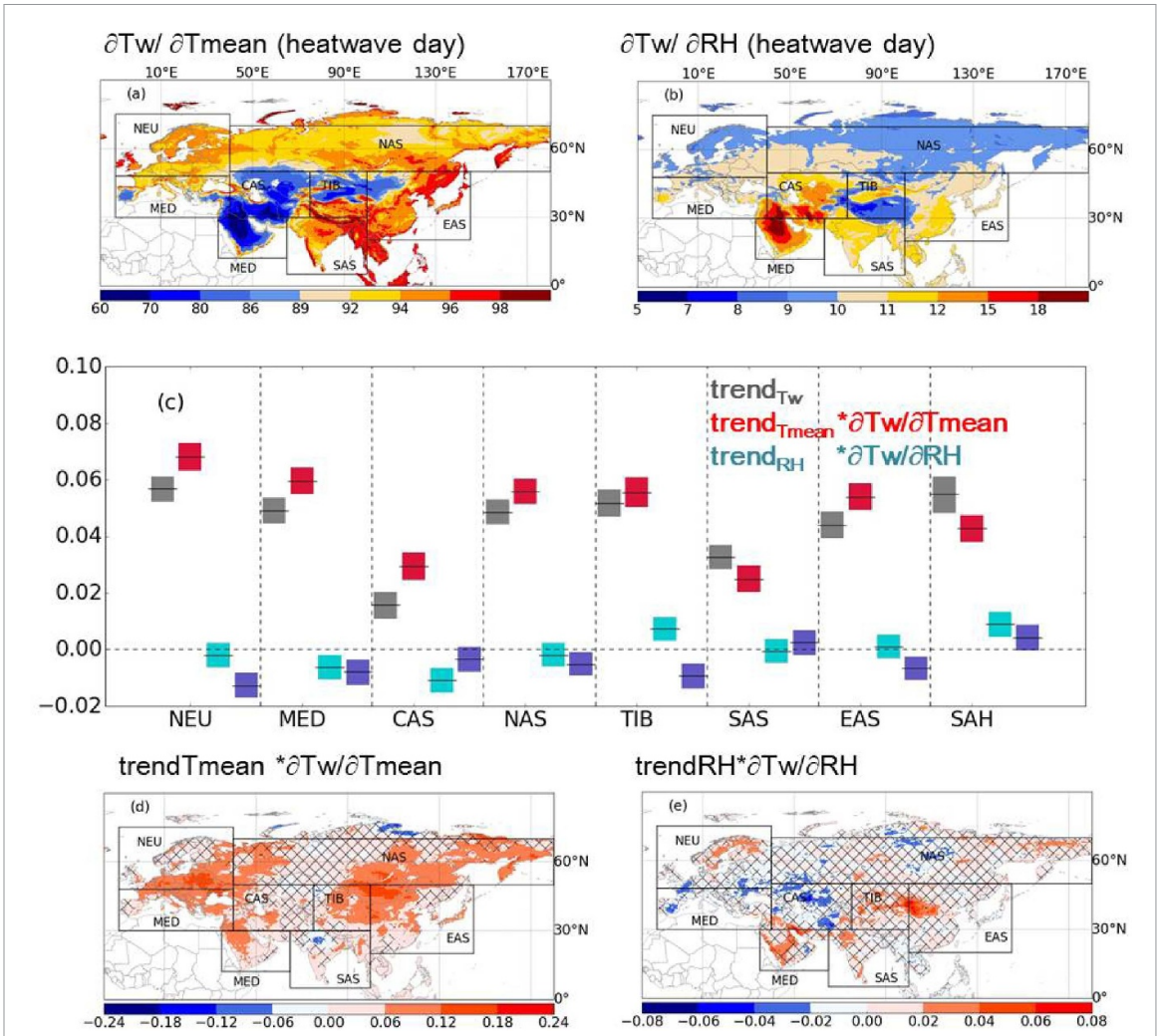

Figure 4. Geographical distribution of the (a) $\partial T_w/\partial T_{mean}$ (100*°C/°C; equation (2)) and (b) $\partial T_w/\partial RH$ (100*°C/%; equation (3)) during heatwave days (right) for 1979–2017, where T_w, RH, T_{mean} are the mean values for all heatwave days during 1979–2017. (c) Plot of median trend$_{Tw}$ (gray boxes), trend$_{Tmean}$*$\partial T_w/\partial T_{mean}$ (red boxes), calculated by equation (2) and the median of the trend$_{RH}$*$\partial T_w/\partial RH$ (blue boxes), calculated by equation (3), residual = trend$_{Tw}$ − (trend$_{Tmean}$*$\partial T_w/\partial T_{mean}$ + trend$_{RH}$*$\partial T_w/\partial RH$) (purple boxes), in eight sub-regions during 1979–2017. For each region, the short black horizontal line shows the median of all the grids in this region; the vertical bar shows the small uncertainty interval of the median. The 5% and 95% of the medians show the uncertainty interval. The color bars in (a) and (b) are non-uniform to make the distribution clear. Geographical distribution of (d) trend T_{mean}*$\partial T_w/\partial T_{mean}$ and the (e) trend RH*$\partial T_w/\partial RH$ during 1979–2017. Shading indicates non-significant ($p < 0.1$) trends. Color bar in (d) is three times than in (e).

of inhomogeneity of RH in this region, leading to an increasing trend of T_w in China. Therefore, it is important to explore the sensitivity of these results to use of other higher quality global reanalysis data. In addition, the main findings of this study are dependent on the definition of heat stress parameter. In this study, wet heatwave is measured by T_w. However, many other heat stress indicators, such as heat index (Rothfusz and Headquarters 1990, Lou and Lau 2019), humidex (Masterson and Richardson 1979), discomfort index (Epstein and Moran 2006), temperature exposure (Jones *et al* 2015), etc, have also been used in the previous research. Although many of them describe the joint effects of high temperature and humidity, a thoroughly and unified assessment is needed to reduce uncertainty in the future.

Overall, it is important to recognize regional differences in setting heatwave adaptation policies to reduce the impacts of wet heatwaves. Our main finding is that summer-mean temperature changes are the main driver for changes in wet HWA in Eurasia. Thus, one can hypothesize, with global warming, such increases in wet heatwave events will continue into future leading to more severe society impacts especially dealing with human health. Based on two greenhouse gas scenarios, Pal *et al* (2016) suggests that by the end of the century (2071–2100), annual T_w in parts of southwest Asia (e.g. Dhabi, Dubai) was projected to exceed 35 °C, the threshold which people cannot exposure in for more than 6 h, several times in the 30 years. However, current projections of T_w were mainly based on the variation in the mean T_w, and the research region was usually small and not suitable for identifying the regional differences across a large scale. More research is needed to understand the impacts of extreme wet heat events now and in

the future, and different mitigation measures should be considered in different regions.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Alexander L V *et al* 2006 Global observed changes in daily climate extremes of temperature and precipitation *J. Geophys. Res. Atmos.* **111** D05109

Baldi M, Dalu G, Maracchi G, Pasqui M and Cesarone F 2006 Heat waves in the Mediterranean: a local feature or a larger-scale effect? *Int. J. Climatol.* **26** 1477–87

Campbell S, Remenyi T A, White C J and Johnston F H 2018 Heatwave and health impact research: a global review *Health Place* **53** 210–8

Chen Y, Chen W, Su Q, Luo F, Sparrow S, Wallom D, Tian F, Dong B, Tett S F B and Lott F C 2019 Anthropogenic warming has substantially increased the likelihood of July 2017—like heat waves over central eastern China *Bull. Am. Meteorol. Soc.* **100** S91–5

Christoph S and Gerd J 2004 Hot news from summer 2003 *Nature* **432** 559–60

Ding T and Qian W 2011 Geographical patterns and temporal variations of regional dry and wet heatwave events in China during 1960–2008 *Adv. Atmos. Sci.* **28** 322–37

Easterling D R, Evans J L, Groisman P Y, Karl T R, Kunkel K E and Ambenje P 2000 Observed variability and trends in extreme climate events: a brief review *Bull. Am. Meteorol. Soc.* **81** 417–26

Efron B and Tibshirani R J 1994 *An Introduction to the Bootstrap* (Boca Raton, FL: CRC Press)

Epstein Y and Moran D S 2006 Thermal comfort and the heat stress indices *Ind. Health* **44** 388–98

Fischer E M and Schär C 2010 Consistent geographical patterns of changes in high-impact European heatwaves *Nat. Geosci.* **3** 398–403

Freychet N, Tett S F B, Yan Z and Li Z 2020 Underestimated change of wet-bulb temperatures over East and South China *Geophys. Res. Lett.* **47** e2019GL086140

Gershunov A, Cayan D R and Iacobellis S F 2009 The great 2006 heat wave over California and Nevada: signal of an increasing trend *J. Clim.* **22** 6181–203

Giorgi F and Francisco R 2000 Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM *Clim. Dyn.* **16** 169–82

Hersbach H *et al* 2020 The ERA5 global reanalysis *Q. J. R. Meteorol. Soc.* **146** 1999–2049

Hong W and Wang Y 2009 Diurnal variations of air temperature and relative humidity in the surface layer on clear day in summer in marsh *Wetland Sci.* **7** 01

Hou W *et al* 2014 Climatic characteristics over China in 2013 *Meteorol. Mon.* **40** 482–93

Hu Y F 2004 Differences between data of automatic and manual observation *J. Appl. Meteor. Sci.* **15** 719–26

International Standards Organisation 1989 Hot environments estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature) ISO Standard

Jones B, O'Neill B C, McDaniel L, McGinnis S, Mearns L O and Tebaldi C 2015 Future population exposure to US heat extremes *Nat. Clim. Change* **5** 652–5

Kang S and Eltahir E A B 2018 North China Plain threatened by deadly heatwaves due to climate change and irrigation *Nat. Commun.* **9** 1–9

Karl T R, Knight R W and Plummer N 1995 Trends in high-frequency climate variability in the twentieth century *Nature* **377** 217–20

Li Z, Yan Z, Zhu Y, Freychet N and Tett S 2020 Homogenized daily relative humidity series in China during 1960–2017 *Adv. Atmos. Sci.* **37** 318–27

Luo M and Lau N C 2019 Characteristics of summer heat stress in China during 1979—2014: climatology and long-term trends *Clim. Dyn.* **53** 5375–88

Maqsood I, Khan M R, Huang G H and Abdalla R 2005 Application of soft computing models to hourly weather analysis in southern Saskatchewan, Canada *Eng. Appl. Artif. Intell.* **18** 115–25

Masterton J M and Richardson F A 1979 *Humidex: A Method of Quantifying Human Discomfort Due to Excessive Heat and Humidity* (Downsview: Environment Canada, Atmospheric Environment)

McMichael A J and Lindgren E 2011 Climate change: present and future risks to health, and necessary responses *J. Intern. Med.* **270** 401–13

Meehl G A and Tebaldi C 2004 More intense, more frequent, and longer lasting heat waves in the 21st century *Science* **305** 994–7

Pal J S and Eltahir E A B 2016 Future temperature in southwest Asia projected to exceed a threshold for human adaptability *Nat. Clim. Change* **6** 197

Perkins S E, Alexander L V and Nairn J R 2012 Increasing frequency, intensity and duration of observed global heatwaves and warm spells *Geophys. Res. Lett.* **39** 20714

Perkins-Kirkpatrick S E *et al* 2016 Natural hazards in Australia: heatwaves *Clim. Change* **139** 101–14

Raymond C, Singh D and Horton R M 2017 Spatiotemporal patterns and synoptics of extreme wet-bulb temperature in the contiguous United States *J. Geophys. Res. Atmos.* **122** 13–108

Rothfusz L P and Headquarters N S R 1990 The heat index equation (or, more than you ever wanted to know about heat index) National Oceanic and Atmospheric Administration, National Weather Service, Office of Meteorology, Fort Worth p 9023

Russo S *et al* 2014 Magnitude of extreme heat waves in present climate and their projection in a warming world *J. Geophys. Res. Atmos.* **119** 12–500

Russo S, Sillmann J and Fischer E M 2015 Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environ. Res. Lett.* **10** 124003

Russo S, Sillmann J and Sterl A 2017 Humid heat waves at different warming levels *Sci. Rep.* **7** 1–7

Sherwood S C and Huber M 2010 An adaptability limit to climate change due to heat stress *Proc. Natl Acad. Sci.* **107** 9552–5

Song Y, Liu Y and Ding Y 2012 A study of surface humidity changes in China during the recent 50 years *Acta Meteorol. Sin.* **26** 541–53

Steadman R G 1979a The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science *J. Appl. Meteorol.* **18** 861–73

Steadman R G 1979b The assessment of sultriness. Part II: effects of wind, extra radiation and barometric pressure on apparent temperature *J. Appl. Meteorol.* **18** 874–85

Stull R 2011 Wet-bulb temperature from relative humidity and air temperature *J. Appl. Meteorol. Climatol.* **50** 2267–9

Taylor B 1717 Methodus incrementorum directa & inversa Inny pp 21–23 Prop. VII, Thm. 3, Cor. 2 Translated into English in Struik D J 1969 *A Source Book in Mathematics 1200–1800* (Cambridge, MA: Harvard University Press) pp 329–32

Tong H, Wong C and Lee S 2017 Projection of wet-bulb temperature for Hong Kong in the 21st century using CMIP5 data *The 31st Guangdong-Hong Kong-Macao Seminar on Meteorological Science and Technology and the 22nd Guangdong-Hong Kong-Macao Meeting on Cooperation in Meteorological Operations* p 27

Wang P *et al* 2019 Extreme wet-bulb temperatures in China: the significant role of moisture *J. Geophys. Res. Atmos.* **124** 11944–60

Wehner M, Castillo F and Stone D 2017 The impact of moisture and temperature on human health in heat waves *Oxford Research Encyclopedia of Natural Hazard Science* 1–38

Welbergen J A, Klose S M, Markus N and Eby P 2008 Climate change and the effects of temperature extremes on Australian flying-foxes *Proc. R. Soc.* B **275** 419–25

Willett K M, Dunn R J H, Thorne P W, Bell S, de Podesta M, Parker D E, Jones P D and Williams Jr C N 2014 HadISDH land surface multi-variable humidity and temperature record for climate monitoring *Clim. Past* **10** 1983–2006

Willett K M, Jones P D, Gillett N P and Thorne P W 2008 Recent changes in surface humidity: development of the HadCRUH dataset *J. Clim.* **21** 5364–83

Xia J, Tu K, Yan Z and Qi Y 2016 The super-heat wave in eastern China during July–August 2013: a perspective of climate change *Int. J. Climatol.* **36** 1291–8

Xia Y, Li Y, Guan D, Tinoco D M, Xia J, Yan Z, Yang J, Liu Q and Huo H 2018 Assessment of the economic impacts of heat waves: a case study of Nanjing, China *J. Clean. Prod.* **171** 811–9

Xu Z, FitzGerald G, Guo Y, Jalaludin B and Tong S 2016 Impact of heatwave on mortality under different heatwave definitions: a systematic review and meta-analysis *Environ. Int.* **89** 193–203

Yu J and Mou R 2008 Research on the cause of difference between AWS-and MAN-relative humidity observations *Meteorol. Mon.* 14

Yuan Y *et al* 2010 The difference of the relative humidity between automatic and manual observations *Meteorol. Monogr.* **36** 102–8

Zhai P and Pan X 2003 Trends in temperature extremes during 1951–1999 in China *Geophys. Res. Lett.* **30** 1913

Zhu Y N *et al* 2015 Homogenization of surface relative humidity over China *Clim. Change Res.* **11** 379–86