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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 ERA5 reanalysis dataset, wet-bulb temperatures (Tw) 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 Tw 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 are largely driven by changes in summer mean Tw. For Eurasia as a whole, increases in temperature contribute more than six times the impact of changes in relative humidity (RH) to changes in Tw heatwave amplitude. Changes in Tw have a strong dependence on climatological RH with an increase in RH of 1% causing a Tw increase of 0.2 °C in arid regions, and only increasing Tw by 0.1 °C in humid regions. During Tw heatwaves in Europe, parts of Tibet, India, East Asia and parts of the Arabian Peninsula both temperature and humidity contribute to the increase in Tw, with temperature the dominant driver. During wet heatwaves in part of Russia, changes in humidity are weak and the increase in Tw is mainly caused by an increase in temperature. In the Mediterranean and Central Asia, relative humidity has fallen reducing the increase in Tw from general warming.

Key words: climate extreme, heatwave, wet-bulb temperature, Eurasia, geographical pattern

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 (Campbell et al., 2018; Xu et al., 2016; McMichael et al., 2011; Welbergen et al., 2008; Easterling et al., 2000). The effects of the most lethal heatwaves are not only due to high temperature, but also to the effects of humidity (Steadman, 1979 a, b). 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 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 70000 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 (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 et al., 2017).

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 (Tw) 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 Tw 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 Tw exceeds 35°C, then human body is unable to dissipate heat by sweating, leading to hyperthermia (Tong et al., 2017; Sherwood et al., 2010). In the current climate, Tw rarely exceeds 31°C at daily timescale (Sherwood et al., 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, Tw can be measured using standard methods and it also provides a physically based relationship to the human body’s core temperature (Stull, 2011; Pal et al., 2016). Hence, Tw is feasible for daily use and has been used more often in climate studies (e.g., Pal & Eltahir, 2016; Raymond et al., 2017).

This paper investigates changes in wet heatwave events in Eurasia using Tw, 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 & 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 (Tmean) and relative humidity (RH) from 1979 to 2017. The time during the day when maximum relative humidity and maximum temperature are not the same (Maqsood et al., 2005; Hong and Wang., 2009). Tw would be overestimated if maximum temperature and maximum relative humidity were used to calculate it. Thus, in this study, we computed daily Tw from mean temperature and RH. RH in China was homogenized (Freychet, 2020) by comparison with a nudged GCM 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

Tw was calculated using equation (1) of Stull (2011) giving Tw (°C) as a function of temperature (Tmean) and RH (%).

\[ Tw = \tan^{-1} \left[ \frac{A(RH + B)}{2(RH + B)^2 + 1} \right] + \tan^{-1} \left( Tmean + RH - \frac{(RH - C)^2}{D(RH) \tan(E \times RH) + RH} \right) - F \]

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 et al., 2011).

Extreme Tw days were defined as days when Tw was above the 90th percentile summer (June-August) days. A wet heatwave event was defined as three or more consecutive extreme Tw days during the summer period (Freychet et al., 2017, Russo et al., 2015).

Several climate indices have been applied in order to quantify the dry heatwave duration and intensity based on daily maximum and minimum temperature (Meehl and Tebaldi, 2004; Alexander et al., 2006; Fischer and Schär, 2010; Perkins and Alexander, 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; heatwave duration (HWD) which is the duration of the longest heatwave in a summer; heatwave amplitude (HWA) which is the maximum Tw value in all heatwave events in a summer.

2.3 Tmean and RH contribution to Tw

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

\[ \frac{\partial Tw}{\partial RH} = - \frac{A \times Tmean}{2(RH + B)^2 + (A)^2(RH + B)} - \frac{1}{1 + (RH - C)^2} + D \left( \frac{1}{1 + (E \times RH)} \right) \]

\[ \frac{\partial Tw}{\partial Tmean} = \tan \left[ \frac{A(RH + B)}{2(RH + B)^2 + 1} \right] + \frac{1}{1 + (Tmean + RH)^2} \]
A, B, C, D, E, F are the same as equation (1). For small changes in mean temperature ($\Delta T_{\text{mean}}$) and relative humidity ($\Delta RH$) then the change in wet bulb temperature is (Taylor, 1715):

$$
\Delta T_w = \Delta T_{\text{mean}} \frac{\partial T_w}{\partial T_{\text{mean}}} + \Delta RH \frac{\partial T_w}{\partial RH} + R
$$

(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 relative humidity.

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 grid-point 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

Fig.1a, b show the annual mean HWF and HWA during the summer (June, July & August) in Eurasia. Wet heatwave frequency is largest (more than 5 days/summer) in Saudi Arabia, parts of Southern & Eastern Asia (Fig.1a). For heatwave amplitude (Fig.1b), two areas of wet heatwaves are located in South and East Asia 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 Tw heatwave intensity (Fig.1b). 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 Tw of 31°C (Sherwood & 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 Tw value. Therefore, it is meaningful to investigate the regional differences of the contribution of humidity and temperature on Tw.
Fig. 1 Geographical distribution of the mean value of (a) HWF (unit: Days), (b) HWA (unit: ℃) 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 linear trend of summer HWF (red boxes), HWD (green boxes), and HWA (blue boxes) in eight Giorgi regions (Giorgi & 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.

SAS (Fig. 1c) 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 and 0.32 ℃·decade$^{-1}$, respectively. However, the Central Asian (CAS) region shows little change in wet heatwave indicators.

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

Tw 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 Tmean and RH to Tw changes are discussed in section 3.3.

When a heatwave occurs, largest Tw values occur in the monsoon regions including SAS and
EAS (Fig.2a). Highest Tmean 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, Central Asia 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 the differences of mean Tw, Tmean, and RH on heatwave days from the 1979-2017 summer mean (Fig.2 b, d, f). Where these differences are large, this is where heatwave Tw is larger than the summer mean. Tw differences between wet heatwave and summer days increased smoothly from South to North (Fig.2b) 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. Tmean (Fig.2d) differences are similar to Tw differences and are also smooth, possibly indicating the dominant contribution (see below) of dry-bulb temperature to Tw. 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 (Fig.2f), 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.

Fig.2: Geographical distribution of the mean value of (a, b) Tw, (c, d) Tmean, (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 Tw, Tmean & RH for all heatwave days and then subtract the mean value of summer Tw, Tmean & RH for that year. The color bars in (a) and (c) are non-uniform to focus on high values.

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

Over most of Eurasia, differences between the trends of heatwave day and summer mean for Tw, Tmean & RH are not significant during 1979-2017 (Fig.3b, d, e). This suggests that significant changes of Tw, Tmean & RH in heatwave days are largely due to changes in the summer mean.
Fig.3 Geographical distribution of the linear trend of (a, b) Tw, (c, d) Tmean, (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 Tw, Tmean & RH for heatwave days and subtract the mean value of summer Tw, Tmean & RH, and then calculate trend and significance from the difference time series.

3.3. Quantitative contribution from changing Tmean and RH to Tw

To measure quantitatively the sensitivity of Tw to Tmean and RH, respectively, we calculated $\frac{\partial Tw}{\partial Tmean}$ (°C/°C) and $\frac{\partial Tw}{\partial RH}$ (°C/%) from mean conditions during wet heatwaves (equations (2) and (3)). For most of Eurasia, an increase of 1 °C in Tmean during wet heatwaves increases Tw by 0.6 to 1 °C (Fig.4a) 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 Tw increase of 0.05 to 0.2 °C (Fig.4b) with higher RH sensitivity in the Arabian Peninsula, eastern China, South East Asia and South Asia and lower sensitivity in Scandinavia, Siberia and Tibet.
To measure quantitatively the contributions of changes in $T_{\text{mean}}$ and RH to changes in $T_w$ (See Equation (4)), both the sensitivity of $T_w$ and the changes of $T_{\text{mean}}$ and RH were considered (Fig.4c, d, e). $T_{\text{mean}}$ 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 (Fig.4c, d, 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 (Fig.4c). 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 Central Asia (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 Tibet region (TIB) shows a modest increase in $T_w$ over the dominant temperature driven increase from changes in RH.

![Geographical distribution of the (a) $\partial T_w / \partial T_{\text{mean}}$ (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, $T_{\text{mean}}$ are the mean values for all heatwave days during 1979-2017. (c) Plot of median trend $T_w$ (gray boxes), trend$_{\text{mean}}$*$\partial T_w / \partial T_{\text{mean}}$ (red boxes), calculated by Equation 2 and the median of the trend$R_{\text{H}}$*$\partial T_w / \partial RH$.](image-url)
trend_{RH} \cdot \partial T w/ \partial RH \) (blue boxes), calculated by Equation 3, residual = trend_{Tw} - 
\((\text{trend}_{Tmean} \cdot \partial T w/ \partial Tmean + \text{trend}_{RH} \cdot \partial T w/ \partial RH) \) (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_{Tmean} \cdot \partial T w/ \partial Tmean and the (e) trend_{RH} \cdot \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).

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 South Asia and East Asia, which show the highest heatwave amplitude during 1979-2017. In most of Eurasia, Tw shows a significant increasing trend during heatwave days. The main driver of this change is increasing dry-bulb temperatures with reductions in relative humidity partly offsetting this increase in some regions. The decrease trend of RH in these regions suggests that 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 Tw during wet heatwave days are largely due to the Tmean changes in summer mean. Compared with humid areas, arid areas are more sensitive to changes in RH and less sensitive to Tmean 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 Tw on heatwave days is dry-bulb temperature, whereas changes in RH play a relatively minor role. This is different in some sub-regions. In Central Asia drying offsets the warming effect leading to only small changes in Tw. The Mediterranean region also shows a drying effect which reduces the temperature driven increase in Tw. In contrast, the Tibet region shows a modest increase in Tw 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; Willett et al., 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 of inhomogeneity of RH in this region, leading to an increasing trend of Tw 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 Tw. 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 heatwave amplitude 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 Tw 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 six hours, several times in the 30 years. However, current projections of Tw were mainly based on the variation in the mean Tw, 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.

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