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Anthropogenic heat release due to energy consumption exacerbates European summer extreme high temperature

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Abstract

Anthropogenic heat release (AHR) is the release of heat generated by anthropogenic energy consumption. The global mean flux of AHR is 0.03 W m^{-2}, while AHR is geographically concentrated and fundamentally correlates with economic activity; furthermore, AHR can reach a level sufficient for impacting regional even large-scale climate. In this study, the impacts of AHR on the summer European heatwaves (EHWs) are examined by using the Community Earth System Model version 1 (CESM1). The results show that in Europe, AHR increases the summer mean 2-m temperature by 0.26 °C and the surface minimum and maximum temperatures by 0.14 °C and 0.41 °C, respectively. AHR exacerbates the extreme high temperatures in the summer in Europe, increasing EHW days by 1–2 days in central and eastern Europe in the summer annually from 1992 to 2013. AHR strengthens the surface wind that flows from the ocean to the land in Europe by increasing the land surface temperatures. AHR decreases the lower-troposphere stability (LTS) and reduces the low-cloud amounts in Europe, which leads to more solar shortwave radiation reaching the surface. AHR affects water vapor and the surface energy balance in Europe, which impacts on European summer heatwaves further. AHR acts as a non-negligible factor for summer extreme high temperature in Europe and a potential factor impacting EHW days.

Keywords Anthropogenic heat release · European heatwaves · Climatic effect · Climate feedback

1 Introduction

European heatwaves (EHWs) exert disastrous impacts on human lives, agriculture, and economies and have attracted extensive attention (Schär et al. 2004; Gerald et al. 2004; Barriopedro et al. 2011; Schiermeier 2018; Larcom et al. 2019). Heatwaves are influenced by both natural factors, such as soil moisture, sea surface temperature (SST) and atmospheric flow anomalies, and anthropogenic factors, such as greenhouse gases (GHGs), aerosols, and urbanization (Black et al. 2004; Fischer et al. 2007; Sun et al. 2014; Sebastian et al. 2016; Zhao et al. 2018). The climatic factors contributing to enhanced morbidity and mortality mainly relate to a combination of extremely high day- and night-time temperatures, high relative humidity and often an extended heatwave duration (Fischer and Schär, 2010). Human activities, such as greenhouse gases and aerosols emissions, land use and coverage changes, are considered to increase the risk of EHW occurrence (Stott et al. 2004; Sebastian et al. 2016). Previous research has shown that urban heat islands (UHIs) exacerbate the heat stress produced by heatwaves (Tan et al. 2010; Zhao

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et al. 2018). Anthropogenic heat release (AHR) is the heat generated by anthropogenic energy consumption. It is an important factor influencing UHIs (Forster et al. 2007) and represents one of the most significant human-induced changes to the Earth's surface climate (Zhao et al. 2014). The current global mean flux of AHR is approximately 0.03 W m^{-2} (Chen et al. 2014). Compared to the total radiative forcing (RF) by human activities of approximately 2.72 W m^{-2} (Masson-Delmotte 2021), AHR is a tiny climatic factor (Chen et al. 2019). The geographical distribution of AHR flux is heterogeneous and correlates with economic activities (Chen et al. 2012; Dong et al. 2017; Varquez et al. 2021); in populated urban regions (such as Tokyo) the flux of AHR can exceed 1000 W m^{-2} (Ichinose et al. 1999), whereas in deserted regions, the flux is close to 0. According to the energy consumption statistics, the annual mean flux of AHR in Europe was 0.26 W m^{-2} in 2019, whereas the annual mean flux of AHR in London was greater than 10 W m^{-2} (Iamarino et al. 2012). Moreover, the annual downward surface shortwave radiation at the surface over Europe is 125 W m^{-2} (Sanchez-Lorenzo et al. 2015).

Recent studies show that AHR can affect not only regional and urban climates (Ichinose et al. 1999; Forster et al. 2007; Feng et al. 2012; Zhong et al. 2017), but also the global climate (Flanner 2009; Zhang et al. 2013; Chen et al. 2014, 2019). AHR impacts urban rainfall and extreme climate (Nie et al. 2017; Zhong et al. 2017), and it contributes to global warming due to its uneven heating effect. Previous research found that the anthropogenic heating can produce up to 0.5 K winter warming over western Europe (Block et al. 2004), and significantly increases the annual-mean temperature and planetary boundary layer (PBL) height occur over the regions where the flux of AHR exceeds 3.0 W m^{-2} (Flanner 2009). Furthermore, AHR has obvious impacts on the surface temperatures in the mid- and high latitudes of Eurasia and North America (Zhang et al. 2013; Chen et al. 2016, 2019), while the impacts of AHR on the extreme high temperatures and heat waves across Europe have not yet received much attention. In this study, we examine the possible climatic effects and feedbacks of AHR on EHWs using National Center for Atmospheric Research (NCAR) CESM version 1 (CESM 1). A physical mechanism underlying the effect of AHR on EHWs is elucidated. The data and method used in this study are described in Sect. 2. The results are given in Sect. 3. Section 4 presents a discussion of the results and Sect. 5 draws the conclusion of this study.

2 Data and method

2.1 AHR flux data

The energy consumption statistical data in Europe from 1965 to 2019 provided by British Petroleum (BP) (http://www.bp.com/statisticalreview) and the National Oceanic and Atmospheric Administration (NOAA) Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) data (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html) from 1992 to 2013 are applied in this study to derive the distribution of AHR flux as described in Chen et al. (2014). We assume that all energy consumed by human activities is converted into anthropogenic heat and eventually released into the atmosphere. In previous research, the flux of AHR has been computed in detail at the single-urban-region scale (Iamarino et al. 2012), and the regional climate effects of AHR has been explored by employing regional climate models (Ichinose et al. 1999; Wang et al. 2015). However, the resolution at the single-urban-region scale seems too large for climate models, and this method seems unsuitable for analysis at the global scale. If we use the single-urban-region scale, we find that the DMSP/OLS data are strongly correlated with local economy development level and energy consumption (Chen et al. 2012, 2014). The flux of AHR was estimated from the correlation between the DMSP/OLS data and energy consumption (Chen et al. 2012), and the error in the results obtained using the DMSP/OLS data is generally within 12% (Chen et al. 2015); this approach has been proven to be very useful for estimating the global distribution of AHR.

2.2 Detailed modeling setups for CESM 1 in this study

Previous studies have confirmed that the climatic effects of AHR should not be restricted to regional scales: AHR can impact the thermodynamic structure of the atmosphere and the stability of the lower troposphere, and even change the large-scale atmospheric circulation (Zhang et al. 2013; Chen et al. 2016, 2019). Because of the boundary limitations of regional models for the research of AHR, we use a global climate model CESM in this study. The model we use is CESM1.0.6 (http://www.cesm.ucar.edu/models/cesm1.0/). The CESM1 model has been thoroughly evaluated against observations (Qian et al. 2015; Hurrell et al. 2013). The results show that CESM1 has a good performance in reproducing the surface temperature (Hurrell et al. 2013), heat wave frequency (Perkins and Fischer 2013) and general circulation (Hurrell et al. 2013). We run CESM using the component set F_AMIP_CAM5, which means that CESM is run in coupled atmosphere-land mode and that the ocean and sea ice component only provides the prescribed low boundary conditions for the atmosphere model (http://www.cesm.ucar.edu/models/cesm1.0/cesm/cesm_doc_1_0_4/x42.html#ccsm_component_sets). Community Atmosphere Model version 5 (CAM5), the atmosphere component of CESM1, is run in the coupled land–atmosphere mode with prescribed monthly SST and sea ice coverage (Hurrell et al. 2008) following the Atmospheric Model Intercomparison Project (AMIP) protocols (Gates 1992). The Community Land Model version 4 (CLM4) is coupled with CAM5 to represent the evolutions of land surface boundary conditions. The horizontal resolution of CAM5 used in our model experiments is $0.9° \times 1.25°$ with 30 vertical levels. The land model CLM4 is set with the same resolution ($0.9° \times 1.25°$) as CAM5.

AHR is incorporated into CAM5 as net anthropogenic heat flux in this research. In the model, we consider AHR as an additional source from the surface and treat it as the sensible heat flux at the surface. AHR is distributed equally within each grid cell, without sub-grid variations, whereas the sub-grid distribution of AHR can be considered in the Weather Research and Forecasting Urban Canopy Model (WRF-UCM). We do consider all the AHR from the land cover types, including urban land cover, within each grid cell. Urban areas are supposed to release more heat than the surrounding regions; however, the difference in AHR between urban and rural areas within a grid cell is not considered in our study.

Two sets of experiments are performed: one set of experiments (including 5 ensemble members) considers the AHR in the surface energy balance within the model, while the other set of experiment does not consider the AHR (as the control experiment). Five experiments are performed (3×10^{-14} K, 6×10^{-14} K, 9×10^{-14} K, 12×10^{-14} K, and 15×10^{-14} K) with round-off differences in the initial air temperatures as in Kay et al. (2015). The total number of years of modeling results analyzed in this study is 132 years (22 years × 6 groups including 5 groups with AHR and 1 group for the control simulation without AHR). T-test is used to derive the significance, by comparing daily mean values between the control simulation and the 5 AHR simulations. In this study, we turn off the anthropogenic heat module in CLM. Note that the initial conditions for the sensitive experiments are derived by a 5-year spin-up simulation with all forcings (including AHR) set in 1992. As NCAR, who maintains the CESM model, has suggested, the AMIP simulation is run from 1979 with the initial atmospheric and land conditions derived from the historical results of the fully coupled CESM1, which is at a reasonably balanced state. The reference simulation is run from 1979 to 2013. To run the AHR simulations, we start CESM from UTC 0000 January 1, 1992, of the reference simulation and run the model for 5 years with the forcings (GHG and anthropogenic aerosol and precursor emission) fixed at the year 1992. After the 5-year spin-up, we start CESM from UTC 0000 January 1, 1992, again and run the model from 1992 to 2013.

3 Results

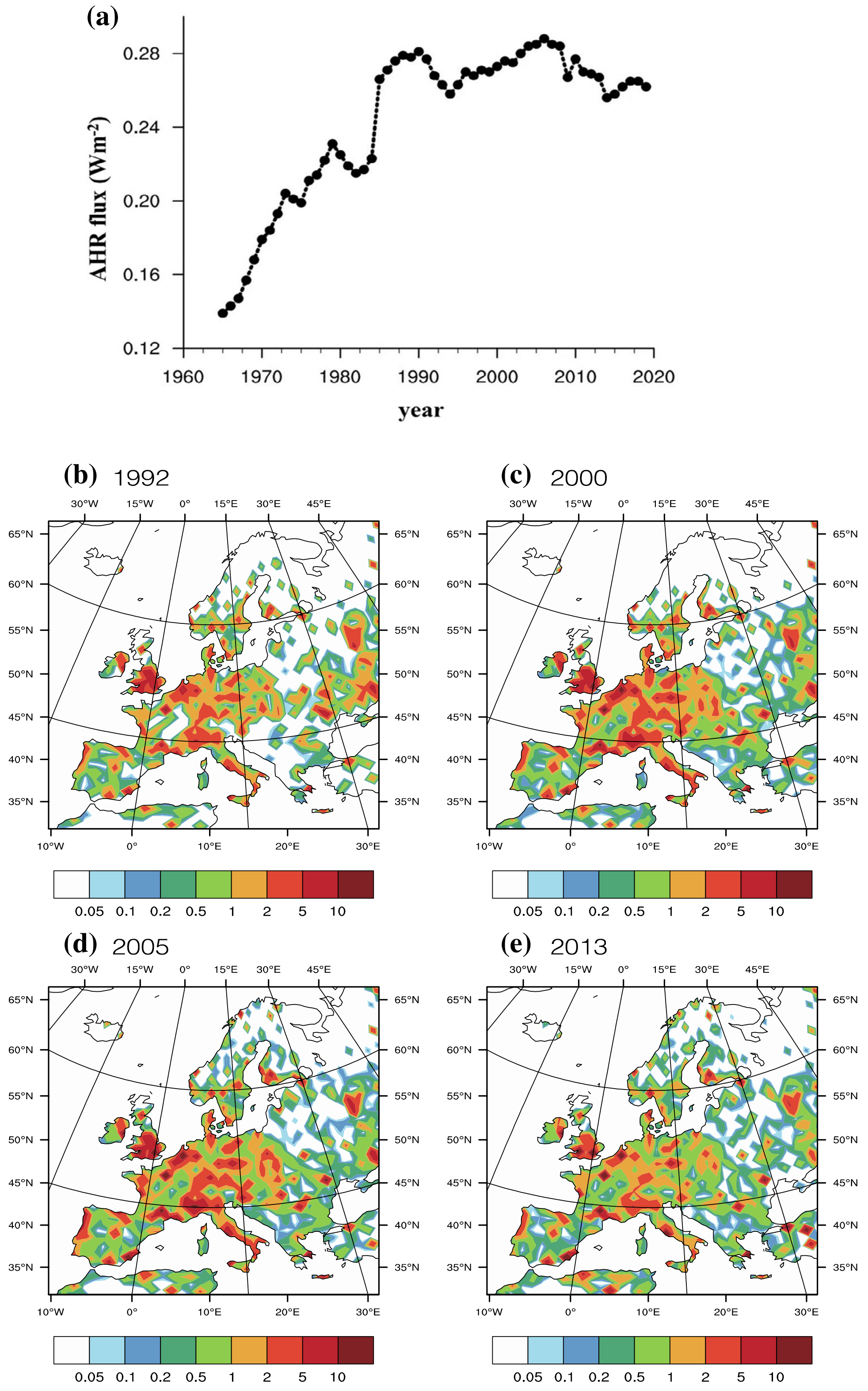
3.1 AHR in Europe

According to the energy consumption statistics by BP, the regional mean AHR flux in Europe from 1965 to 2019 and the annual-mean distributions of AHR flux in Europe (34°N-72°N, 11°W-32°E) from 1992 to 2013 were calculated and are shown in Fig. 1. As shown in Fig. 1a, the regional mean AHR flux in Europe grows quickly from 0.14 W m^{-2} in 1965 until peaking at 0.29 W m^{-2} in 2006; it falls thereafter. The distribution of AHR is closely related to the regional development level. The regions with high AHR fluxes are located in central Europe, the UK and other regions with large cities, where the fluxes of AHR reaches more than 10 W m^{-2}; these results are consistent with results for London reported by Iamarino et al. (2012). The changes in AHR from 1992 to 2013 shown in Fig. 1 demonstrate that the climate effects of AHR are strongly correlated with the development of the economy and urbanization in Europe.

3.2 The impacts of AHR on European temperatures

The modeling results for the summer 2-m air temperature (T_{2m}), average maximum surface temperature (T_{smax}) and average minimum surface temperature (T_{smin}) prove reliable based on their comparison with Climatic Research Unit (CRU) data (as shown in Fig. 5). The impacts of AHR on surface temperature in the European boreal summer are shown in Fig. 2. AHR increases the average T_{2m} in Europe by 0.26 °C. Furthermore, AHR has the strongest effects on the eastern and central parts of Europe between 45°N and 55°N, generally increasing T_{2m} by more than 0.6 °C. Due to the heating effect of AHR, the probability of high temperature increases generally, and the probability that the mean T_{2m} exceeds 25 °C increases by more than 30% (from 4.0% to 5.3%), as shown in Fig. 2d. Figure 2b shows that AHR increases T_{smax} in Europe by 0.41 °C in the summer. It has the most notable effects in the eastern and central parts of Europe between 45°N and 60°N and in the UK and Ireland, with T_{smax} increasing by more than 0.8 °C. The probability of a high T_{smax} increases as a result of AHR, and the probability that T_{smax} exceeds 30 °C is increased by more than 20% (from 6.1% to 7.4%) due to AHR, as shown in Fig. 2e. Figure 2c shows that in the summer, AHR increases T_{smin} in Europe by 0.14 °C, and it has the most obvious effects in central Europe, with T_{smin} generally increasing by more than 0.6 °C. The probability of a high T_{smin} generally increases as a result of AHR, and the probability that T_{smin} exceeds 20 °C is increased by more than 30% (from 2.3% to 3.1%) due to AHR, as shown in Fig. 2f.

Fig. 1 Mean flux of AHR in Europe from 1965 to 2019 in (**a**) (unit: W m^{-2}) and the spatial distribution of AHR flux in Europe in: **b** 1992; **c** 2000; **d** 2005; and **e** 2013 (resolution: $0.9° \times 1.25°$; unit: W m^{-2})



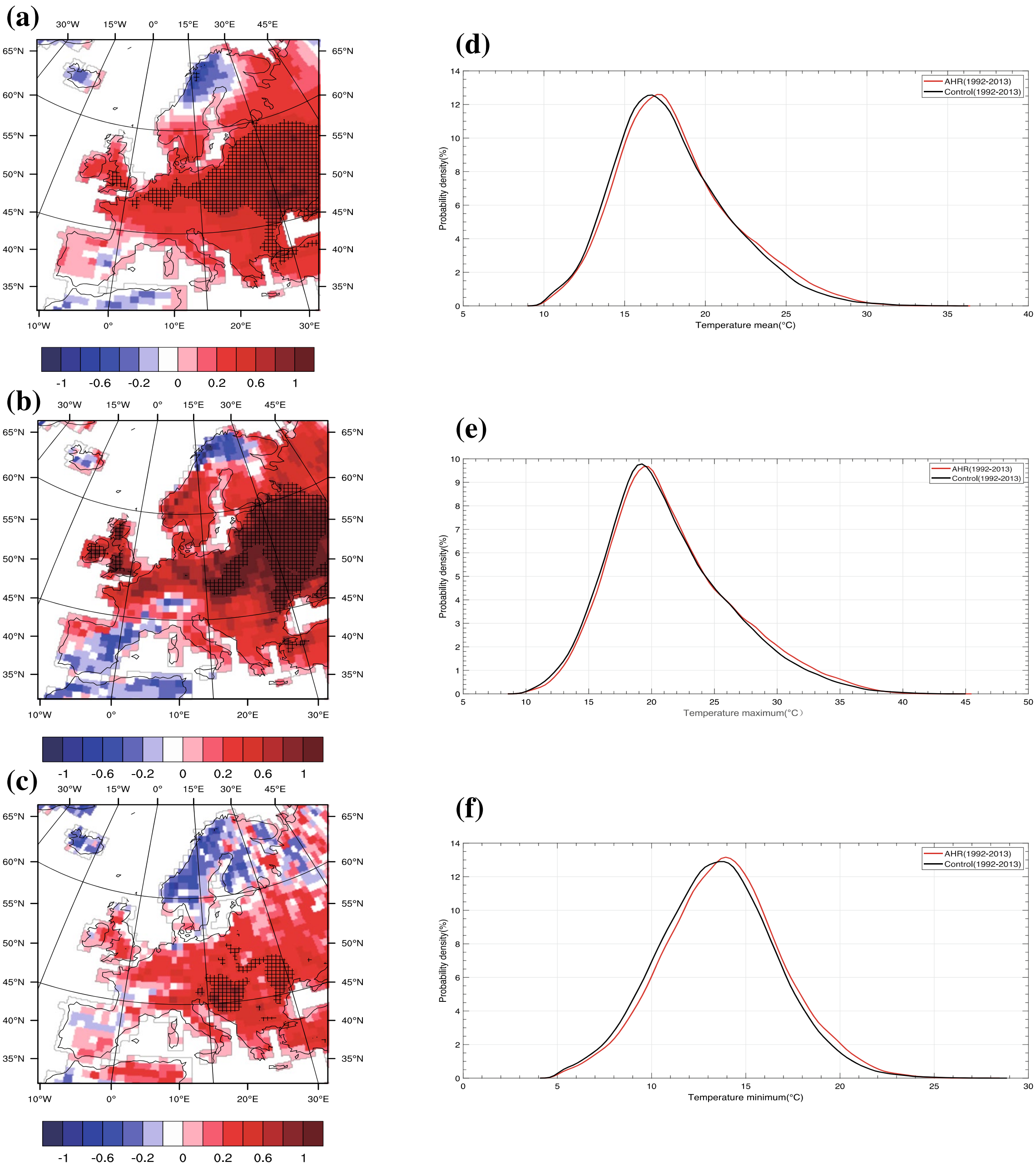


Fig. 2 Effects of AHR on European boreal summer (June-July-August (JJA)) from 1992 to 2013: **a** 2-m air temperature (T_{2m}, unit: °C); **b** maximum surface temperature (T_{smax}, unit: °C); **c** minimum surface temperature (T_{smin}, unit: °C); **d** probability density distributions of mean T_{2m} when considering the AHR (in red) and in the control condition (in black) in the statistically significant regions using daily and spatial variability over 1992 to 2013; **e** probability density distributions of mean T_{smax} when considering the AHR (in red) and in the control condition (in black) in the statistically significant regions using daily and spatial variability over 1992–2013; and **f** probability density distributions of mean T_{smin} when considering the AHR (in red) and in the control condition (in black) in the statistically significant regions using daily and spatial variability over 1992–2013. The cross-hatching in (**a**), (**b**) and (**c**) indicates regions with changes that are statistically significant at the 0.05 level

3.3 The impacts of AHR on European heatwaves

As shown in Fig. 2, AHR has a significant effect on the surface temperature, which is very important for the occurrence of EHW days. A heatwave event in this study is defined as daily mean temperature ≥ 95th percentile of the summertime temperature probability distribution from 1992 to 2013 and a duration of more than 2 days following Anderson and Michelle (2011). The impacts of the heating effect of AHR on the summer EHW days from 1992 to 2013, which are

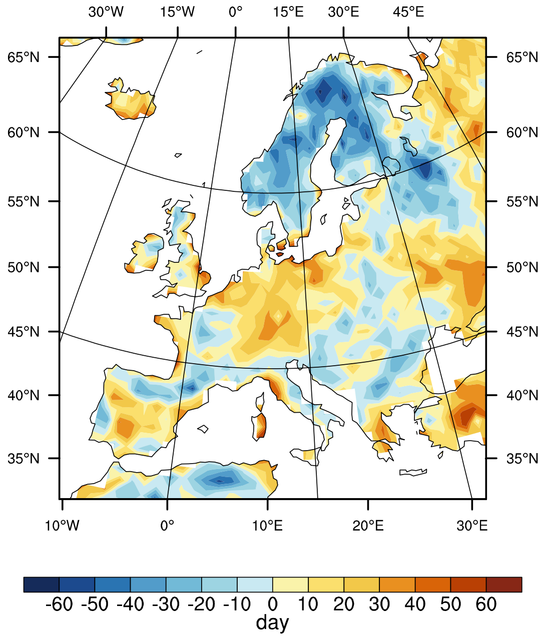


Fig. 3 Effects of AHR on the total of EHW days due to AHR in the summer from 1992 to 2013 (unit: day)

the results of these five experiments are averaged and compared with those of the default experiments without AHR, as shown in Fig. 3. AHR shows no significant effects on EHWs generally. The heating effect of AHR on heatwaves is relatively obvious in eastern and central Europe, especially in eastern and southern UK, Spain, and Germany, with the increase by 1–2 EHW days annually for the summer during 1992–2013.

The possible mechanism underlying the climate impact of AHR in Europe, as shown in Fig. 4, is explored in this study. The lower-troposphere stability (LTS) is defined as the difference between the potential temperature of the free troposphere (700 hPa) and the surface ($LTS = \theta_{700} - \theta_0$), which is correlated strongly with the low cloud fraction (Wood and Bretherton 2006) and affects the energy balance at the surface (Boucher et al. 2013). Figure 4a shows the impact of AHR on the European summer LTS. According to the modeling results, LTS is reduced significantly in eastern and central Europe, which is consistent with the warming centers caused by AHR shown in Fig. 2a.

As determined based on the relationship between LTS and low clouds (Wood and Bretherton 2006), the effect of AHR on the low cloud fraction is shown in Fig. 4b. The low cloud fraction clearly decreases in eastern and central Europe, which is consistent with the results shown in Fig. 2a and 4a. Low clouds are very important in determining the energy balance in the Earth-atmosphere system (Boucher et al. 2013). The impacts of AHR on the European summer surface energy balance are analyzed. We find that the net surface shortwave flux in the European summer changes obviously due to the heating effect of AHR, as shown in Fig. 4c. The regions where the net shortwave fluxes at the surface clearly increase are consistent with the regions where the low cloud fraction decreases, as shown in Fig. 4b. The impact of AHR on surface horizontal winds is shown in Fig. 4d. AHR has a significant impact on westerly winds in the high latitudes of Europe. The surface wind that flows from the ocean to the land is generally strengthened by the heating effect of AHR. A possible reason for this pattern is that AHR increases the land surface temperature in Europe, which affects temperature gradients and wind advection between the ocean and land, thereby strengthening the wind that blows from the ocean. Previous research has shown that AHR enhances mixing and turbulent energy transport, increases dry static energy, and destabilizes the atmosphere through thermal perturbation and strong upward motion, resulting in enhanced convergence in urban areas (Nie et al. 2017), which is important for the turbulent transport of water vapor and heat. The results of the present study show that AHR can impact the large-scale regional atmospheric circulation, which is important in determining regional climate and weather. The results in Fig. 4 show that the net shortwave flux at the surface in eastern and central Europe clearly increases due to the heating effect of AHR, which is strongly correlated with low clouds. These results suggest that AHR exerts dynamic thermal impacts on the lower troposphere and affects the surface energy balance. The results suggest a possible positive feedback mechanism contributing to the exacerbation of summer EHWs induced by AHR: AHR increases the air temperature at the surface due to its heating effect, which decreases the LTS. Since the LTS strongly influences low clouds (Wood and Bretherton 2006), a decreased LTS causes a decrease in the low cloud fraction, leading to more solar shortwave radiation reaching the Earth's surface. The increased surface shortwave radiation will further increase the surface air temperature. This feedback will increase the surface temperature in European boreal summer and the EHWs. Figure 5 shows the effects of AHR on the surface water flux in the summer in Europe: the surface water flux significantly increases in northern and central Europe. As previously discovered, the surface water flux is correlated with soil moisture and air humidity. While moisture and air humidity are important factors for EHWs, the results in Fig. 4 and 5 suggest that AHR acts as a non-negligible factor for the extreme high temperatures in the summer in Europe, even for the EHWs.

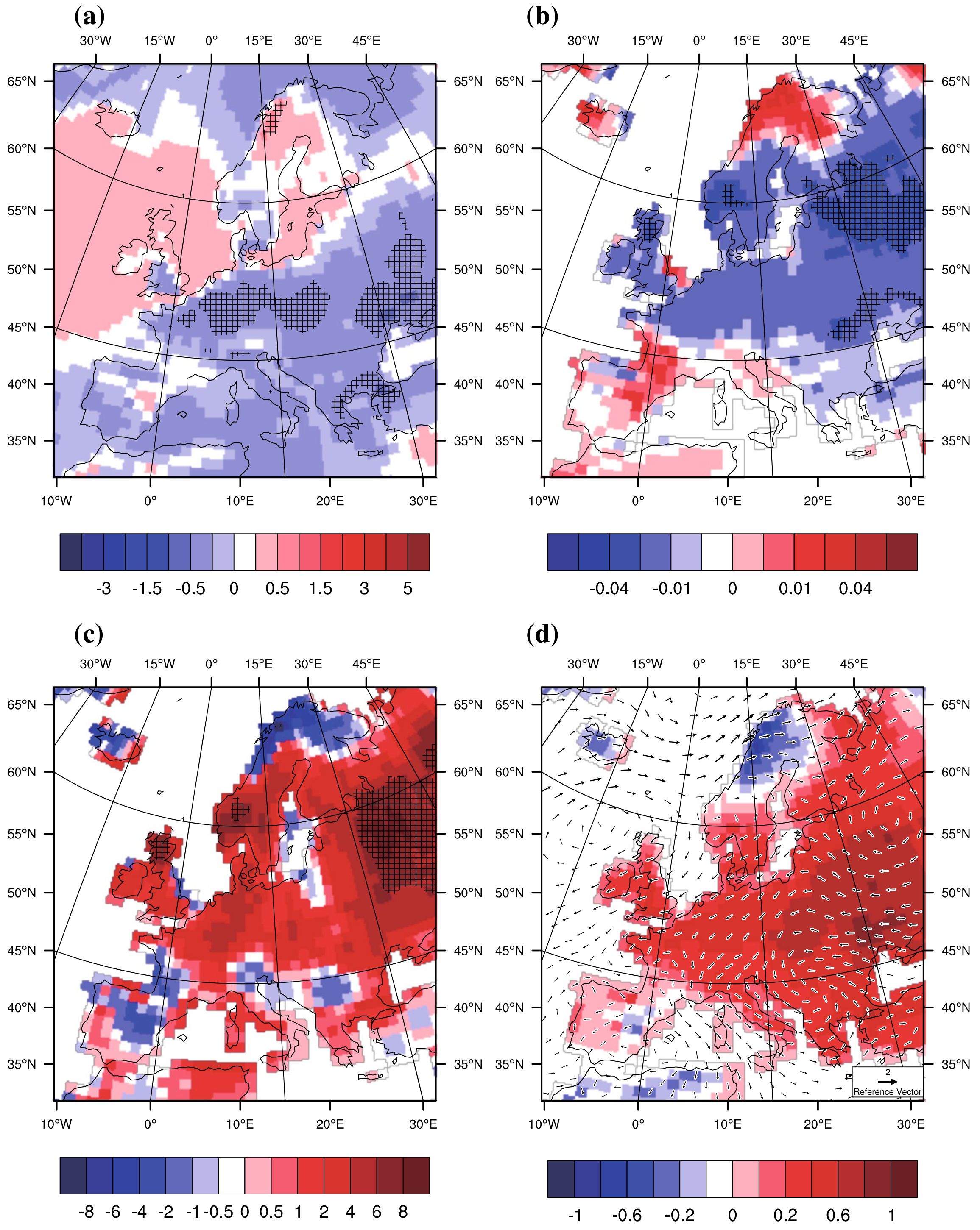


Fig. 4 Effects of AHR on European boreal summer (JJA) from 1992 to 2013: **a** LTS (unit: K); **b** low cloud fraction; **c** net shortwave flux at the surface (unit: W m^{-2}); and **d** surface temperature (shaded in K) and horizontal wind (U, V) at the surface (unit: m s^{-1}). The cross-hatching in the figure indicates that the change is statistically significant at the 0.05 level

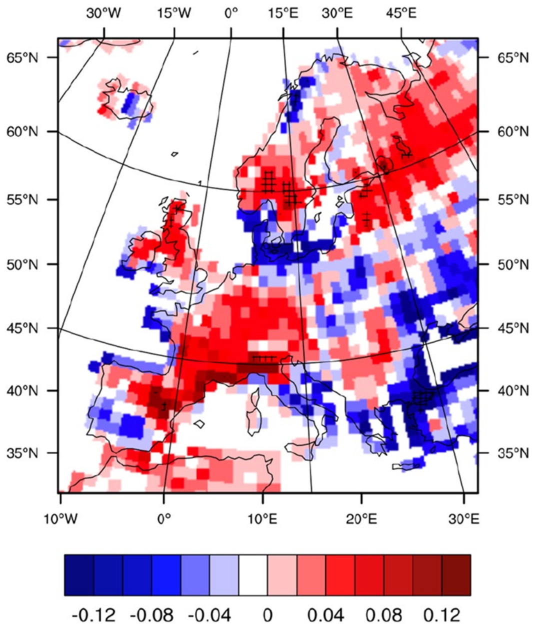


Fig. 5 Effect of AHR on the surface water flux in the boreal summer of Europe from 1992 to 2013 (unit: kg m^{-2} s^{-1}). The cross-hatching in the figure indicates that the change is statistically significant at the 0.05 level

4 Discussion

Previous studies on summer EHWs have focused mostly on the influences of natural factors, including soil moisture, SST and atmospheric flow anomalies, and anthropogenic factors, such as GHGs, aerosols and UHIs. Urbanization impacts on EHWs using regional models (such as WRF) have also been investigated (Black et al. 2004; Stott et al. 2004; Fischer et al. 2007; Sun et al. 2014; Sebastian et al. 2016; Zhao et al. 2018). Compared with the regional climatic effects of AHR on urban climate, the climate effect and physical feedback of AHR due to energy consumption on the summer EHWs, as addressed in this study, have not received enough attention. Previous studies have confirmed that the climatic effects of AHR should not be restricted to regional scale (Zhang et al. 2013; Chen et al. 2019), so we use CESM in this study. We run 6 groups of experiments with CESM1 in order to account for the internal variability. However, limitations exist in this research. The anthropogenic heat could be in the form of ground heat flux, sensible heat flux, or long-wave radiation, and the proper proportion among them for the parameterization of AHR in climate models is still uncertain. In this research, we consider AHR as sensible heat in climate model, which is consistent with Zhang et al. (2013) and Chen et al. (2019). The AHR data used in this study are yearly data, due to lacking the necessary seasonal, monthly and diurnal energy consumption data. We do not consider the difference in AHR between urban and rural areas within a grid cell in this research. Only the grid averaging is considered in this study, which may weaken the effects of AHR. Additionally, only one climate model is used in this study. Likewise, the experimental design and the significance of the results could be improved with the same search for robustness in mind and it would be important for future studies to include other models to assess the robustness of our conclusions.

Comparisons of the modeling results and the results of CRU data, Climate Prediction Center (CPC) data and ERA5 data are presented in Figs. 6, 7, 8, 9 and 10. Regarding the temperature variables (including T_{2m}, T_{smax}, T_{smin}), the spatial distributions and correlation coefficients improve when AHR is considered, as shown in Fig. 6. For T_{2m} over Europe, the spatial correlation coefficient (SCC) increases from 0.58 to 0.60; for T_{smax}, the SCC increases from 0.67 to 0.69; and for T_{smin}, it increases from 0.44 to 0.47. For the heatwave days in Europe, as shown in Fig. 7, the modeled values in the control experiment are slightly higher than the ERA5 data. In northern Europe, where the heatwave days have been reduced due to AHR, the SCC between the modeling results when considering AHR and the ERA5 data is increased by more than 50%. For the low clouds, as shown in Fig. 8, the SCC between the modeling results and ERA5 data increases from 0.95 to 0.98. For the shortwave radiation at the surface, as shown in Fig. 9, the control modeling values are higher than the ERA5 values, and when AHR is considered, the SCC between the modeling results and the ERA5 data improves, although model errors still exist. For the mean horizontal wind (U, V) at 850 hPa, as shown in Fig. 10, the modeling results are quite similar with NCEP/NCAR Reanalysis 1 data results, which suggests that CESM 1 has a good performance in modeling atmospheric circulation.

5 Conclusion

The energy balance in the Earth-atmosphere system is considered the predominant factor affecting climate change (Hansen et al. 2005). AHR is a direct and external energy source to the Earth-atmosphere system, impacting the energy balance of the Earth's surface due to energy consumption and representing an important factor influencing urban climate (Forster et al. 2007). In this study, the impacts of AHR on the summer European heatwaves (EHWs) are examined by using the CESM1. The results show that in Europe, AHR increases the summer mean 2-m temperature by 0.26 °C and the surface minimum and maximum temperatures by 0.14 °C and 0.41 °C, respectively. Our results demonstrate that AHR changes the thermodynamic structure and the stability of the lower troposphere, which has significant effects on the LTS and low clouds and thus is expected to affect the energy balance at the surface. AHR exacerbates

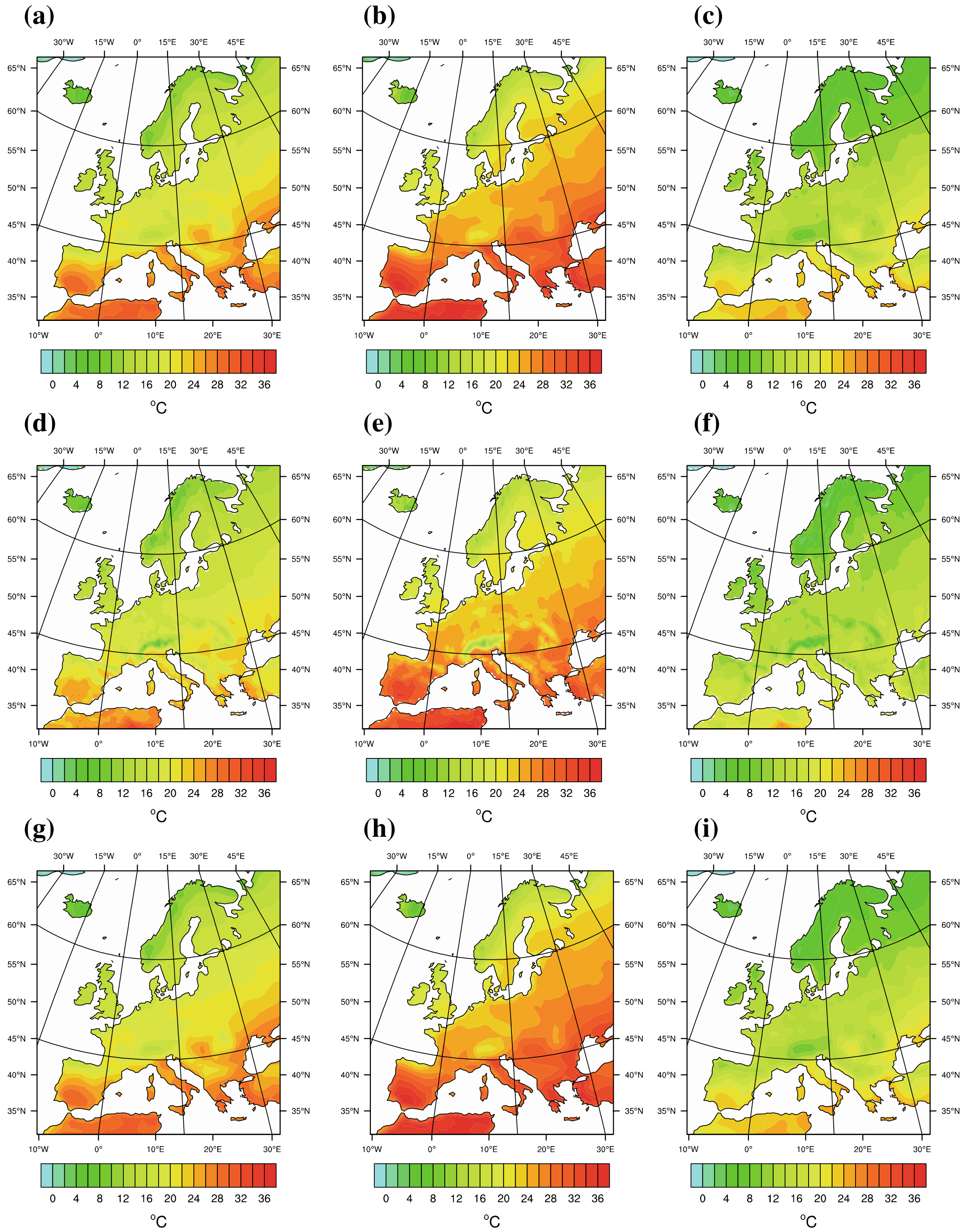


Fig. 6 The CESM1 control modeling results for Europe from 1992 to 2013 in the boreal summer (JJA) without AHR: **a** mean T_{2m}, **b** mean T_{smax}, and **c** mean T_{smin}; CRU data results for Europe from 1992 to 2013 in the boreal summer (JJA): **d** mean T_{2m}, **e** mean T_{smax}, and **f** mean T_{smin}; and CESM1 modeling results for Europe from 1992 to 2013 in the boreal summer (JJA) with AHR: **g** mean T_{2m}, **h** mean T_{smax}, and **i** mean T_{smin}

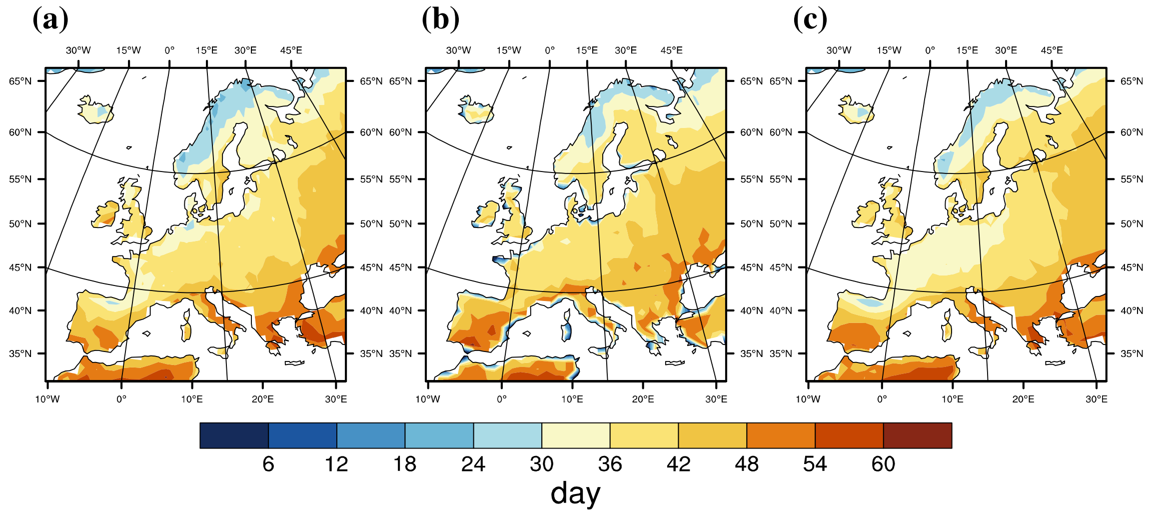


Fig. 7 The mean heat wave days in Europe from 1992 to 2013 in the boreal summer (JJA): **a** CESM1 control modeling results without AHR; **b** ERA 5 data results; **c** CESM1 modeling results with AHR

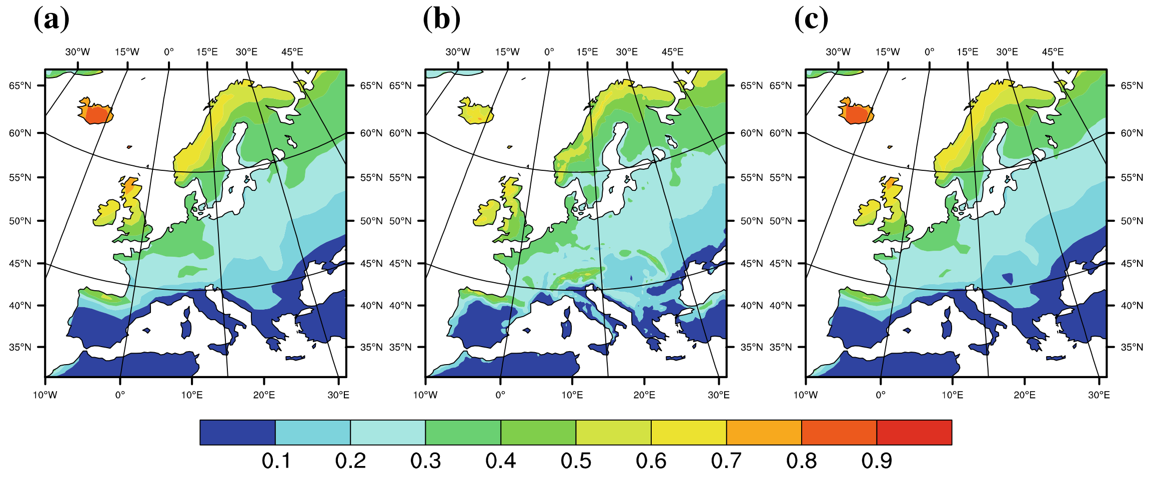


Fig. 8 The mean low cloud fraction in Europe from 1992 to 2013 in the boreal summer (JJA): **a** CESM1 control modeling results without AHR; **b** ERA 5 data results; **c** CESM1 modeling results with AHR

the extreme high temperatures in the summer in Europe, increasing EHW days by 1–2 in central and eastern Europe in the summer annually from 1992 to 2013. AHR increases the surface water flux and the occurrence frequency of summer extreme high temperatures in Europe.

Additionally, AHR impacts regional atmospheric circulation and increases the surface water flux, which increases water vapor in the air and further affects humidity. According to previous research, humidity is considered as an important factor for heatwaves (Li 2020). AHR acts as a non-negligible factor for summer extreme high temperatures in Europe and a potential factor impacting EHW days as well. In a comparison used by Chen et al. (2016), GHGs emissions can be regarded as a blanket that covers the Earth. Increasing the concentration of GHGs causes this blanket to become thicker, leading to a warmer climate. In this analogy, AHR resembles an electric blanket that unevenly heats the lower atmosphere (Chen et al. 2016). The uneven heating effects due to AHR will become more pronounced in the future with the increases in GHG emissions and urbanization in future socioeconomic scenarios (Gridden et al. 2019). Thus, the heating effect of AHR on EHWs should not be ignored. This study improves our understanding of the possible physical mechanisms by which human activities influence regional extreme weather and climate, which should receive more attention in future research.

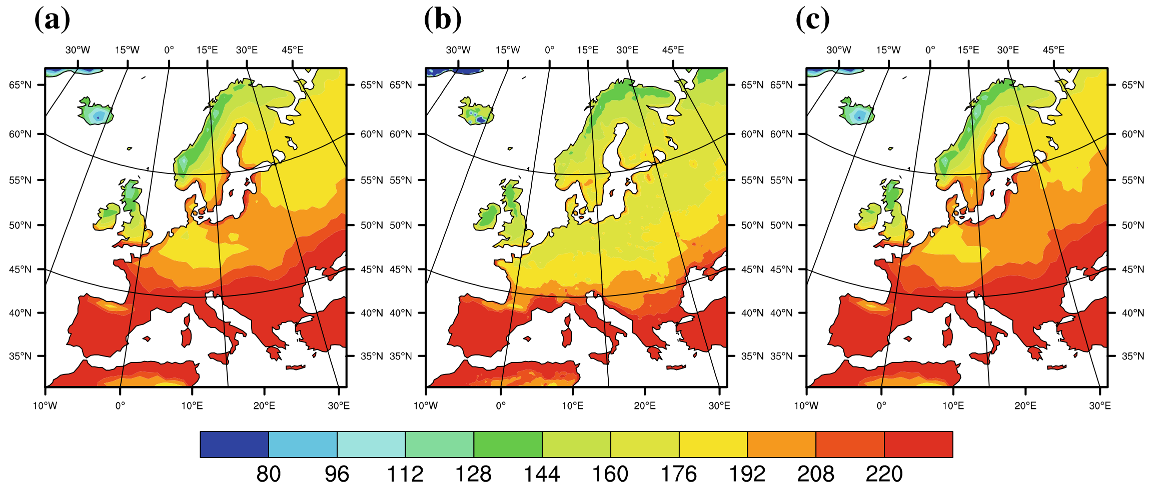


Fig. 9 The mean shortwave radiation at the surface in Europe from 1992 to 2013 in the boreal summer (JJA): **a** CESM1 control modeling results without AHR; **b** ERA 5 data results; **c** CESM1 modeling results with AHR (unit: W m^{-2})

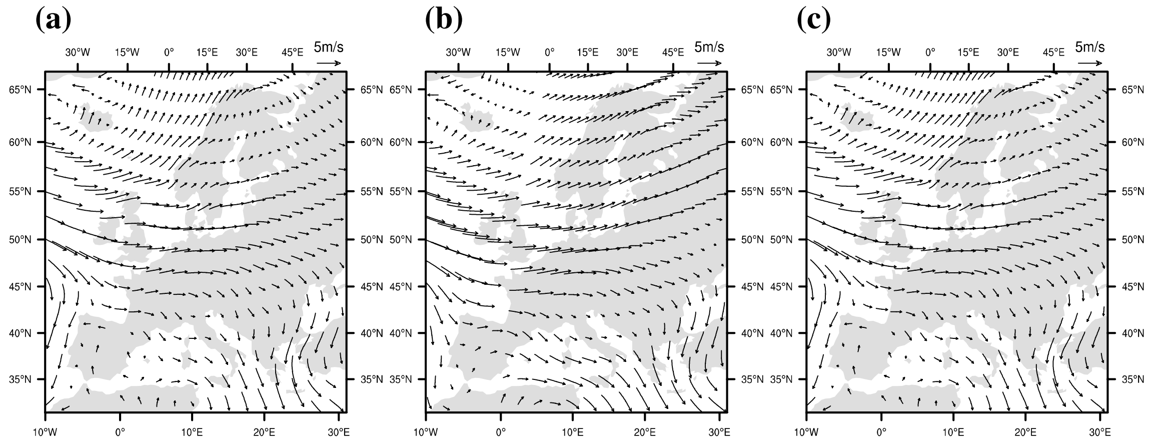


Fig. 10 Mean horizontal wind (U, V) at 850 hPa (unit: m s^{-1}) in Europe from 1992 to 2013 in the boreal summer (JJA): **a** CESM1 control modeling results without AHR; **b** NCEP/NCAR Reanalysis 1 data results; **c** CESM1 modeling results with AHR

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Author contributions BC and XL developed the idea. BC and TL performed most of the analysis. BC drafted the manuscript. All the authors discussed the concepts and edited the manuscript.

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Data availability The energy consumption statistics for Europe from 1965 to 2019 provided by BP are available at http://www.bp.com/statisticalreview. The NOAA DMSP/OLS data are publicly available at http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html, and the data on the annual mean distribution of AHR in Europe from 1992 to 2013 are available:https://drive.google.com/file/d/1T2ZClEkoOzm0NKD1PamkWyE9nEFcdkJM/view?usp=sharing. The ERA 5 data are publicly available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The CRU data are publicly available at https://sites.uea.ac.uk/cru/data. The CPC data are publicly available at https://www.cpc.ncep.noaa.gov. The NCEP/NCAR Reanalysis 1 data are publicly available at: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

Declarations

Conflict of interest The authors declare no competing interests.

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