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Influence of extreme 2022 heatwave on megacities' anthropogenic CO_2 emissions in lower-middle reaches of the Yangtze River

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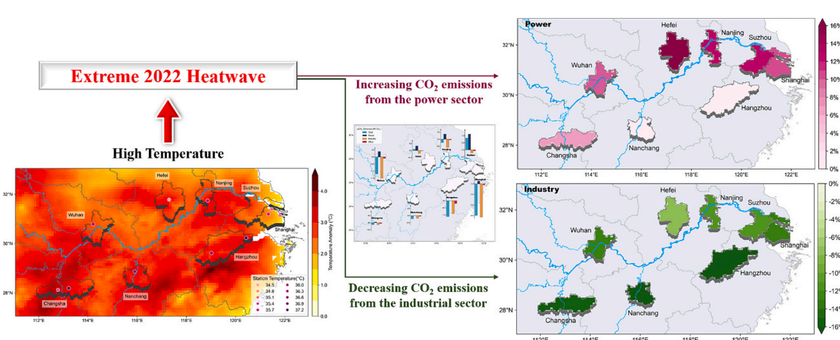
HIGHLIGHTS

- An unprecedented heatwave hit the Yangtze River Basin in August 2022.
- Power emissions showed strong linear relationships with temperatures in megacities.
- The heatwave led to a total increase in power emissions of about 2.70 Mt CO_2.
- Industrial emissions down linked to China's policy to ensure household power supply.
- Industrial emissions decreased by 8.45 Mt CO_2, offsetting rise in power emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

An unprecedented heatwave hit the Yangtze River Basin (YRB) in August 2022. We analyzed changes of anthropogenic CO_2 emissions in 8 megacities over lower-middle reaches of the YRB, using a near-real-time gridded daily CO_2 emissions dataset. We suggest that the predominant sources of CO_2 emissions in these 8 megacities are from the power and industrial sectors. In comparison to the average emissions for August in 2020 and 2021, the heatwave event led to a total increase in power sector emissions of approximately 2.70 Mt CO_2, potentially due to the increase in urban cooling demand. Suzhou experienced the largest increase, with a rise of 1.12 Mt CO_2 (12.88 %). Importantly, we observed that changes in daily power emissions exhibited strong linear

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Extreme 2022 heatwave
Lower-middle reaches of Yangtze River

relationships with temperatures during the heatwave, albeit varying sensitivities across different megacities (with an average of 0.0076 ± 0.0075 Mt d^{-1} $°C^{-1}$). Conversely, we find that industrial emissions decreased by a total of 8.45 Mt CO_2, with Shanghai seeing the largest decrease of 4.71 Mt CO_2, while Hangzhou experienced the largest relative decrease (−21.22 %). It is noteworthy that the majority of megacities rebounded in industrial emissions following the conclusion of the heatwave. We convincingly suggest a tight linkage between the reductions in industrial emissions and China's policy to ensure household power supply. Overall, the reduction in industrial emissions offset the increase in power sector emissions, resulting in weaker emissions for majority of megacities during the heatwave. Despite remaining uncertainties in the emissions data, our study may offer valuable insights into the complexities of anthropogenic CO_2 emissions in megacities amidst frequent summer heatwaves intensified by greenhouse warming.

1. Introduction

The global atmospheric carbon dioxide (CO_2) concentrations have increased from pre-industrial 280 ppm to approximately 417.9 ppm in 2022 (WMO, 2023), with global surface temperature increase of 1.07 °C (IPCC, 2021). Human-induced greenhouse gases (GHGs) emissions are the main driver of the global warming which can increase the frequency and intensity of regional climate extremes (Hugh et al., 2018; Matthews et al., 2009; Yang et al., 2021).

Human-induced CO_2 emissions mainly come from fossil fuel combustion and industrial processes (IPCC, 2021). China has been the world's largest consumer of primary energy and emitter of CO_2 since 2005 (Duan et al., 2022b; Guan et al., 2009; Lin et al., 2020; Lu et al., 2022). It is estimated that China's CO_2 emissions from fossil fuel combustion and cement production amounted to 2.49 Gt C (Liu et al., 2015), producing 33 % of global CO_2 emissions (Crippa et al., 2022). Furthermore, approximately about 85 % of China's emissions originate from urban areas (Shan et al., 2017). At the general debate of the 75th session of the United Nations General Assembly, China proposed to adopt more powerful policies and measures to make CO_2 emissions peak before 2030 and strive to achieve "carbon neutrality" before 2060 (Dong et al., 2022; Zhang et al., 2021).

A premise of achieving "carbon neutrality" is to fully understand the stability of terrestrial carbon sources and sinks. However, global warming, with frequent climate extremes, such as droughts and heatwaves, will not only greatly affect natural ecosystem carbon sinks (Ciais et al., 2005; El-Madany et al., 2020; Krasnova et al., 2022), but also affect human activities and industrial production. Extreme heatwaves increase the use and intensity of refrigeration and air conditioning equipment, resulting in a significant increase in electricity demand (Hu et al., 2023; Larcom et al., 2019). The average increase in electricity demand is approximately 6.35 % for every 1 °C increase in daily temperatures (Hatvani-Kovacs et al., 2016). Rising demand and consumption of electricity are contributing to increased CO_2 emissions (Qin et al., 2020; Zuo et al., 2015). However, direct studies investigating the impact of heatwaves on anthropogenic CO_2 emissions are still lacking.

In August 2022, central and eastern China experienced an unprecedented and protracted regional heatwave, with the Yangtze River Basin (YRB) most severely affected (Jiang et al., 2023). This event caused the most severe decline in vegetation greenness and photosynthesis since 2000 (Wang et al., 2023c), but it remains unclear whether the event had a significant impact on urban anthropogenic CO_2 emissions. Therefore, we aim to investigate the changes of anthropogenic CO_2 emissions in major megacities in lower-middle reaches of the YRB during the extreme 2022 heatwave, using the near-real-time Global Gridded Daily CO_2 Emissions Dataset (GRACED) (Dou et al., 2022, 2023; Liu et al., 2020a, b).

2. Data and methods

2.1. Anthropogenic CO_2 emission data

Anthropogenic CO_2 emissions in megacities are from GRACED (Dou et al., 2022, 2023) with a global spatial resolution of 0.1° by 0.1° and a temporal resolution of 1 day. GRACED is developed using near-real-time daily national CO_2 emission estimates from Carbon Monitor (Huo et al., 2022; Ke et al., 2023; Liu et al., 2022), combined with the spatiotemporal patters of multi-source spatial activity data and satellite nitrogen dioxide (NO_2) retrievals. The GRACED dataset contains seven sectors, including power sector, industrial sector, residential sector, ground transportation sector, international aviation sector, international shipping sector and domestic aviation sector. Our study considers power and industrial sectors, with the remaining factors categorized into the "other" sector. CO_2 emissions were calculated by multiplying the activity data by the corresponding emission factors. For the power sector, the dataset uses data from the National Bureau of Statistics (NBS) and Wind Information Co., Ltd.. CO_2 emissions were calculated from daily thermal power generation in China and daily coal consumption by six Chinese power companies. There are four sub-categories of the industrial sector, including the iron and steel industry, the cement industry, the chemical industry and other industries. For each category, it is obtained from the website of the NBS website and the World Steel Association website for monthly production data, from which the corresponding month-on-month growth rates are calculated accordingly. Emissions from industrial production during fossil fuel combustion are calculated by multiplying the activity data (*i.e.*, fossil fuel consumption data for the industrial sector) by the corresponding emission factor for the fuel type. Uncertainties in the dataset were analyzed according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The overall uncertainty of the dataset is ±7.2 %, with uncertainties of ±14.0 % and ± 36.0 % for the power and industrial sectors, respectively.

The 2022 extreme heatwave also occurred in Sichuan province and Chongqing in the upper YRB in August. But the GRACED has relatively larger uncertainty on the power generation side due to its reliance on the electricity consumption data (Liu et al., 2020a). Notably, both Sichuan province and Chongqing boast substantial power generation capacities. Moreover, it is worth mentioning that these two provinces grappled with severe COVID-19 in August, which led us to exclude them in this study.

2.2. Meteorological data

The meteorological station data comes from the Internal Sequencer Data-Lite (ISD-Lite) by the National Climatic Data Center (NCDC) for August 2020, 2021 and 2022. We have selected 11 stations in 8 megacities with a time resolution of 1 h/3 h (Table S1). We obtained the daily maximum temperature at each station to serve as an indicator of temperature for the corresponding city, and calculated the monthly average temperature. For cities with 2 or 3 stations, the average of multiple stations was taken. As no data were available for the Suzhou site in 2022, we used temperatures from HONGQIAO INTL (Code ID: 583670), the closest station to Suzhou. According to the China Meteorological Administration (CMA) High Temperature Warning Signal, yellow warning is for daily maximum temperature to rise above 35 °C for three consecutive days, orange and red warnings are for daily maximum temperature to rise above 37 °C and 40 °C respectively within 24 h. In this study, we consider the city to have experienced an extreme heatwave event when the daily maximum temperature reaches 35 °C for

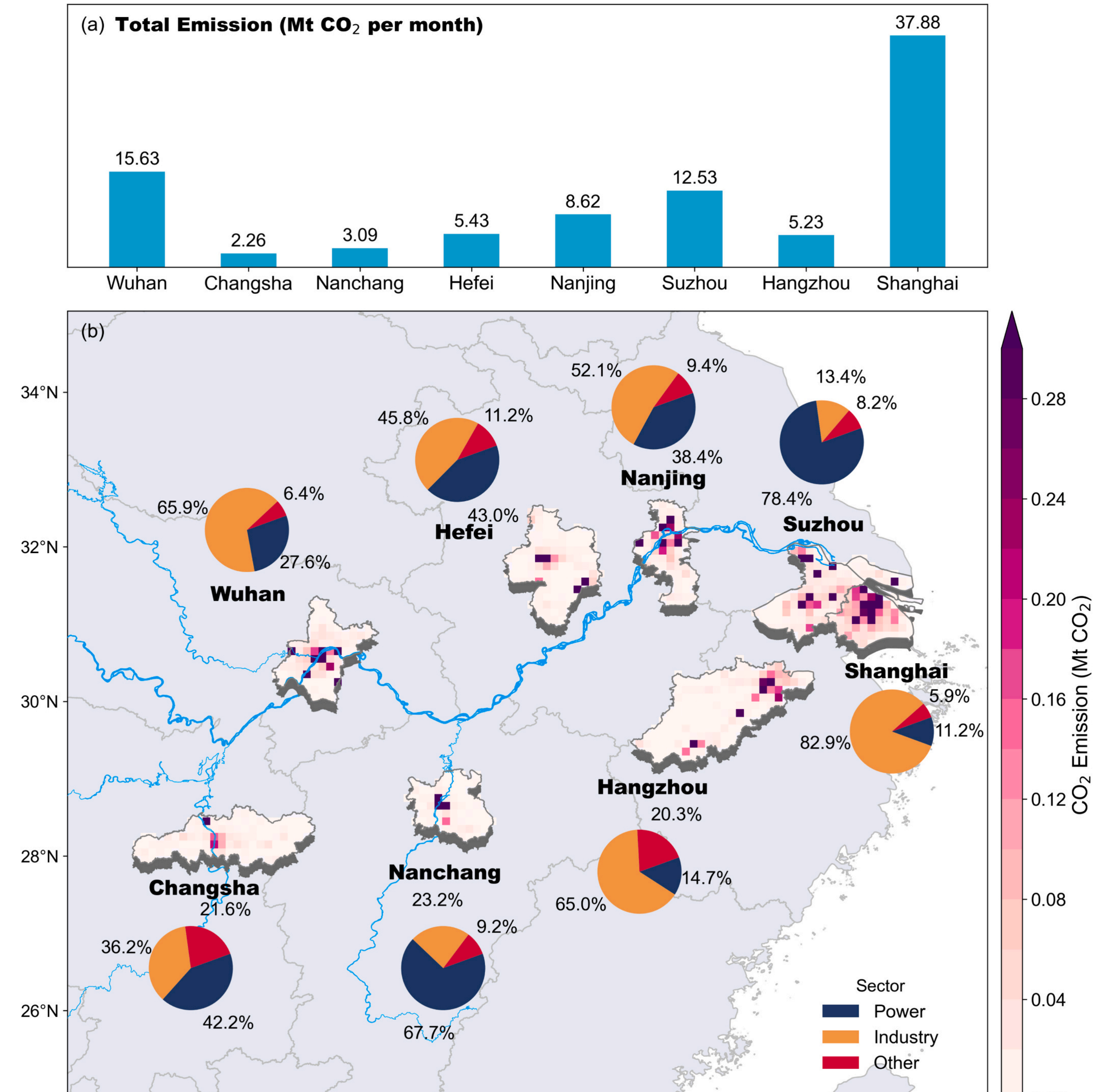

Fig. 1. Anthropogenic CO_2 emissions in megacities in August 2022. (a) Total CO_2 emissions in these 8 megacities in Mt CO_2. (b) Spatial distribution of average CO_2 emissions (Mt CO_2) and proportions (%) of emissions by sectors in each megacity.

three consecutive days (yellow warning) or above 37 °C (orange warning) (Table S2).

The regional meteorological data are derived from the monthly average ERA5-Land data, provided by the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Muñoz Sabater, 2019). ERA5-Land is the land component of the ERA5 climate reanalysis of the ECMWF, combined with global observations by replaying the ECMWF ERA5 climate reanalyzes into one global dataset with a grid of 0.1° × 0.1°. In this study, the anomaly of temperature is calculated by removed the long-term climatology.

3. Results

3.1. Anthropogenic CO_2 emissions and the heatwave over megacities

Fig. 1 shows the anthropogenic CO_2 emissions and temperatures in megacities in August 2022. We focus on emissions from 8 megacities, which together account for approximately 30.84 % of the total emissions from these provinces. The strongest emitter among these megacities is Shanghai, with 37.88 Mt CO_2 emissions in August 2022, followed by Wuhan with 15.63 Mt CO_2 and the smallest emitter is Changsha with about 2.26 Mt CO_2 (Fig. 1a).

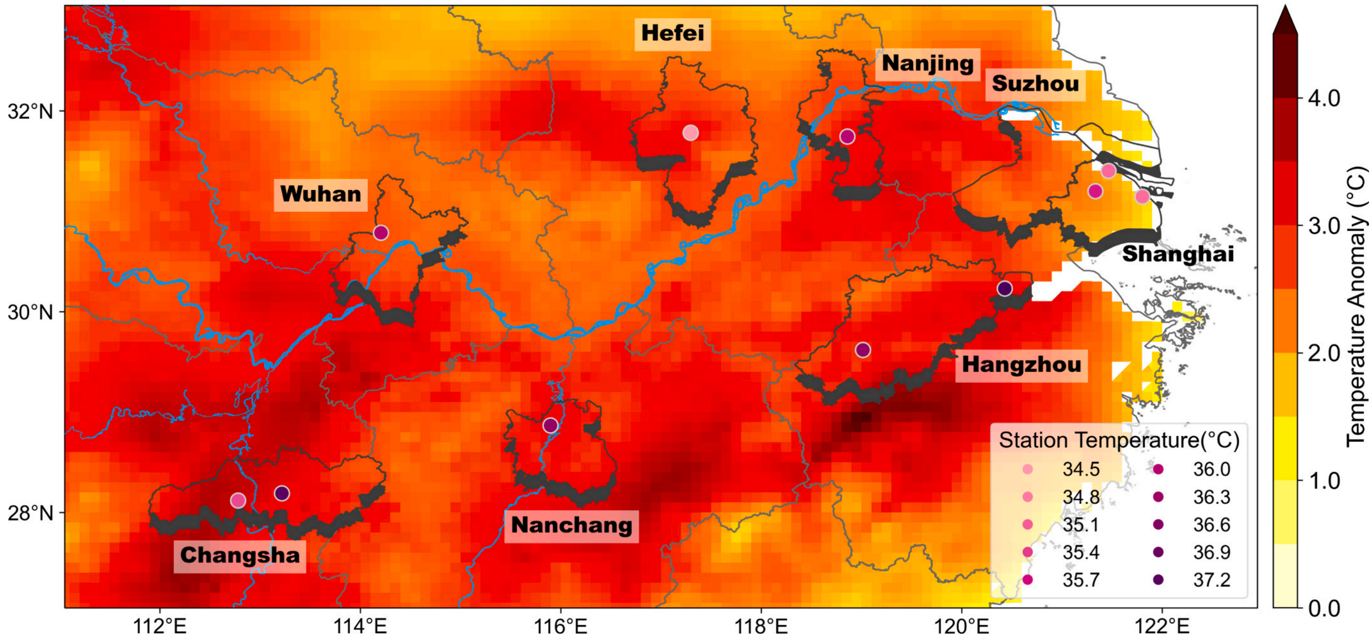

Fig. 2. Gridded temperature anomalies and station temperatures in August 2022. The temperature at the meteorological stations represents the monthly average maximum temperature.

Importantly, the emissions profile in 5 out of the 8 megacities is dominated by the industrial sector, with proportions varying from 45.8 % in Hefei to an imposing 82.9 % in Shanghai. In contrast, the remaining cities (Changsha, Nanchang, and Suzhou) are primarily characterized by the power sector, where proportions range from 42.2 % to 78.4 % (Fig. 1b). Broadly speaking, power and industrial sectors in these megacities account for over 78 % of CO_2 emissions, with Shanghai reaching an even higher percentage of 94.1.

In August 2022, the YRB experienced a record-breaking heatwave, characterized by its unprecedented intensity (Ma and Yuan, 2023; Wang et al., 2023c), with temperatures surging by approximately 2 °C compared to historical records (Fig. 2). Notably, the monthly average maximum temperatures surpassed 35 °C across all cities, except for Hefei, where temperature reached 34.5 °C (Fig. 2). Remarkably, seven cities experienced extreme heatwaves, defined as daily maximum temperature surpassing 35 °C for three consecutive days or above 37 °C, for at least 20 days during August 2022. Changsha and Nanchang recorded the longest duration of extreme heatwave, enduring 27 days, followed by Hangzhou with 23 days. Even Hefei, with the shortest duration, experienced the extreme heatwave for 19 days.

3.2. Impact of the heatwave on CO_2 emissions from the power sector

We analyzed the correlation between CO_2 emissions from the power sector and daily maximum temperatures at a daily scale in Fig. 3. Notably, there appears to be strong linear relationships between temperatures and CO_2 emissions from the power sector during the extreme heatwave, with p-values <0.05 and an average sensitivity of 0.0076 ± 0.0075 Mt d^{-1} °C^{-1}. However, it's important to acknowledge the presence of the large uncertainty, indicating notable variations in temperature sensitivity among different megacities (Fig. 3). In detail, Wuhan exhibited the highest sensitivity between temperature and power sector emissions during the heatwave, approximately 0.0251 Mt d^{-1} °C^{-1} ($R^2 = 0.26$, $p < 0.05$), followed by Suzhou and Shanghai with sensitivities of 0.0094 Mt d^{-1} °C^{-1} ($R^2 = 0.14$, $p < 0.05$) and 0.0068 Mt d^{-1} °C^{-1} ($R^2 = 0.19$, $p < 0.05$), respectively.

Although Wuhan, Changsha, and Hefei exhibited discontinuities around 35 °C, the underlying reasons varied. In Changsha, for instance, a daily maximum temperature of 33.25 °C was recorded on August 24, yet the power CO_2 emissions remained high. This anomaly occurred during an extreme heatwave, with daily maximum temperatures exceeding 37 °C in the days preceding and following this date, indicating that the emissions were still influenced by the ongoing heatwave. In Wuhan and Hefei, the increase or decrease in power sector CO_2 emissions corresponded with temperature fluctuations. Lower temperatures in these two cities in August followed the end of the heatwave, leading to a slow decrease in emissions. However, the emissions did not revert to pre-heatwave levels, as temperatures in Wuhan and Hefei remained in the 30 to 35 °C range. Notably, cooling demand already increases dramatically when the temperatures exceed 30 °C (Boudali Errebai et al., 2022; Duan et al., 2022a; Wang et al., 2023a). This indicates that even after the heatwave subsided, the continued high temperatures sustained high power emissions due to persistent cooling demand.

Therefore, high temperatures lead to the increase in emissions from the power sector across all megacities (Fig. 4). Among these megacities, Hefei witnessed the most substantial relative increase, registering an impressive 16.87 % rise, closely followed by Nanjing and Suzhou, each displaying a noteworthy increase of 12.88 %. Hangzhou, on the other hand, recorded the smallest relative increase at 0.05 %. In absolute magnitude, Suzhou exhibited the most significant increase in power sector, reaching 1.12 Mt CO_2, and Shanghai followed with an increase of 0.40 Mt CO_2. Wuhan, Nanjing and Hefei had similar emission increases, with 0.39, 0.38 and 0.34 Mt CO_2 respectively. In total, emissions from the power sector across these 8 megacities surged by 2.70 Mt CO_2. Additionally, the three megacities with the highest increase in power sector emissions during the heatwave correspond well to their highest temperature sensitivities (Fig. 3).

3.3. Impact of the heatwave on CO_2 emissions from the industrial sector

In GRACED, a linear relationship between daily industrial production and industrial fossil fuel use data is assumed for the calculation of emissions from the industrial sector. This approach decomposes monthly CO_2 emissions into daily emissions utilizing monthly industrial production statistics and daily electricity generation data (Liu et al., 2020a). As a result, compared to the power sector, daily CO_2 emissions from the industrial sector exhibit larger uncertainties. Consequently, our analysis focuses on examining CO_2 emissions from the industrial sector

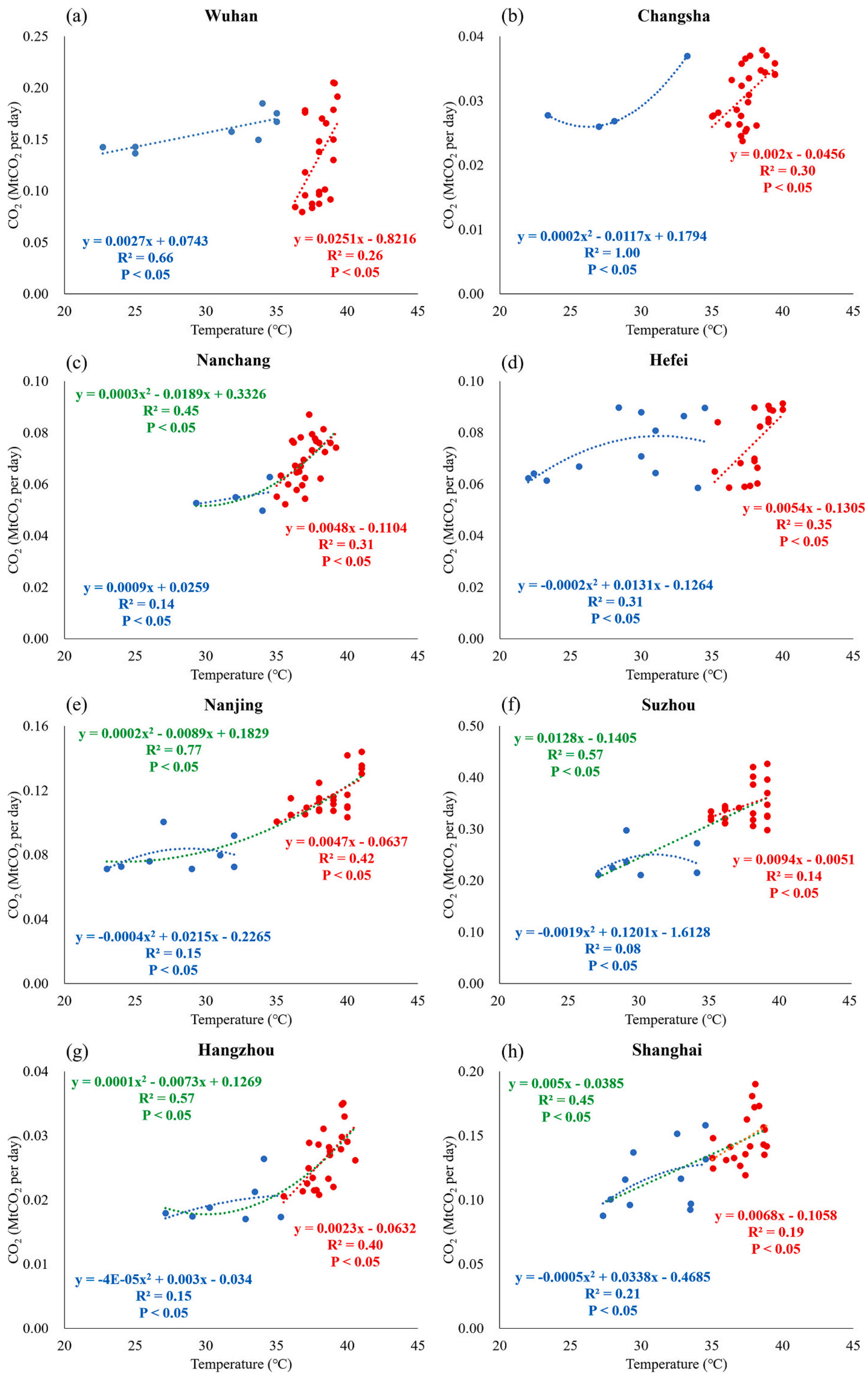

Fig. 3. Relationship between the daily maximum temperature and CO_2 emissions from the power sector in August 2022. Red indicates their relationship during the heatwave (daily maximum temperature surpassing 35 °C for three consecutive days or above 37 °C), blue indicates their relationship when daily maximum temperature maximum temperature did not achieve the high temperature warning standard, and green indicates the relationship in August 2022. Cities that clearly have two segments of variation, named Wuhan, Changsha, and Hefei, do not have extreme total temperature sensitivities. R^2 represents the coefficient of determination and significance levels (*p*-values) are estimated by the Student's *t*-test.

on a monthly basis rather than daily. It is clear that emissions from the industrial sector show a consistent downward trend in August 2022 compared to the average of August 2021 and August 2020 in all megacities (Fig. 5). More specifically, Hangzhou and Nanchang experienced the substantial relative decrease in industrial sector emissions of 21.22 % and 20.85 %, respectively. Changsha followed closely with a reduction of 15.46 %, while Hefei displayed the least pronounced relative decrease at 7.73 %. Emissions from the remaining three megacities fell by about 12 %.

Quantitatively, the most significant decrease in emissions occurred in Shanghai, amounting to −4.71 Mt CO_2, with Wuhan also contributing a substantial reduction of −1.50 Mt CO_2 (Fig. 6). Furthermore, five out of the eight megacities, namely Wuhan, Changsha, Nanchang, Hefei, and Hangzhou, had resumed their emissions in September, with all

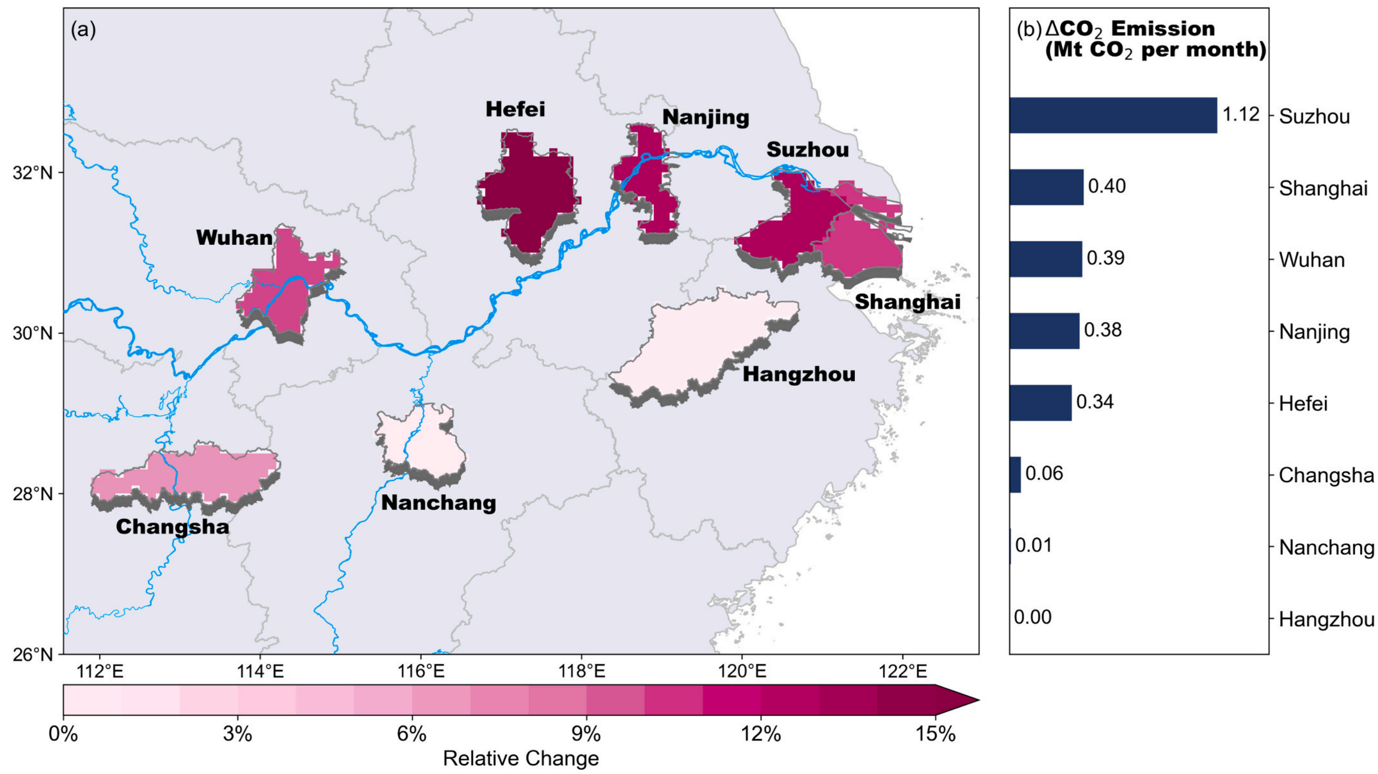

Fig. 4. Changes in CO_2 emissions from the power sector in August 2022 compared to the average of August 2021 and August 2020. (a) Absolute change in CO_2 emissions from the power sector. (b) Relative change in CO_2 emissions from the power sector.

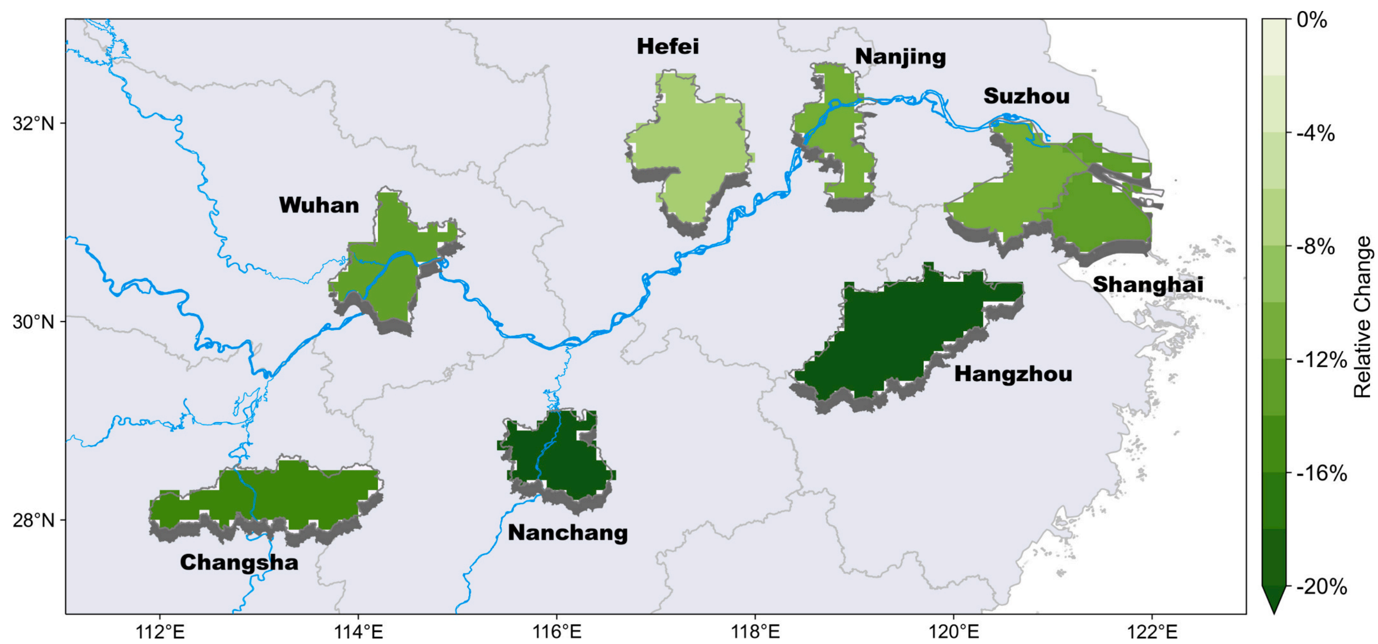

Fig. 5. Relative change in CO_2 emissions from the industrial sector in August 2022 compared to the average of August 2021 and August 2020.

megacities returning to their normal emission levels by October, or even surpassing previous years' levels. However, Nanjing, Suzhou and Shanghai continued to decrease their emissions in September, possible due to factors related to their industrial structure and urban resilience (Davoudi et al., 2013; Martin et al., 2016; Zhai et al., 2015). These three cities are positioned at the end of the industrial chain, and disruptions or reductions in production at upstream plants in August may result in a delayed recovery of capacity at downstream plants, ultimately leading to a continued decline in emissions. This requires detailed industrial data for further research and analysis.

3.4. Changes in total CO_2 emissions

Fig. 7 shows the absolute changes in CO_2 emissions by sectors in megacities. Comparing total CO_2 emissions in August 2022 to the average of August 2021 and August 2020, we find that emissions

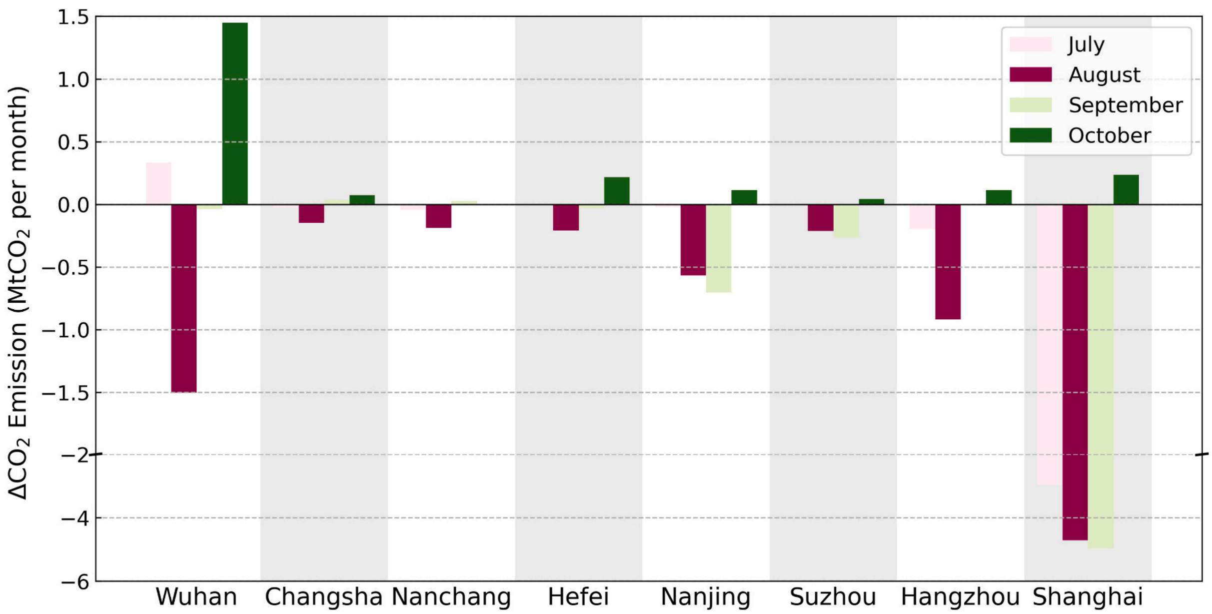

Fig. 6. Monthly absolute change in CO_2 emissions from the industrial sector in 2022 compared to the average of 2020 and 2021.

decreased in 6 out of the 8 megacities. Shanghai witnessed the largest decrease in CO_2 emissions, amounting to 4.46 Mt CO_2, followed by Wuhan and Hangzhou with a decrease of 1.21 and 1.12 Mt CO_2, correspondingly. Conversely, Suzhou and Hefei showed increases in emissions, totaling 0.84 and 0.11 Mt CO_2, respectively. We posit that these increases are likely attributed to increases in power demand, particularly noteworthy in Suzhou, where the power sector commands a substantial share of 78.4 % (Fig. 1). Furthermore, changes in CO_2 emissions from other sectors were relatively weak, with Hangzhou having the largest emissions from the other sector at only 0.15 Mt CO_2.

4. Discussion

4.1. Increase in power emissions

The increase in power emissions is primarily attributable to the upsurge in thermal power generation. Extreme heatwaves triggered a surge in cooling demand (Oliver et al., 2015; Van Vliet et al., 2016), affecting both electricity consumption and the energy mix (Paul Meier et al., 2017; Wang et al., 2023b; Zeighami et al., 2023). For instance, in Southern Europe, heatwave events between 1989 and 2019 led to a 3.5 % to 10.6 % increase in electricity demand, while wind power generation decreased by 30.89 % (Molina et al., 2023). Similarly, in the United States, there has been an increase in electricity production during extreme heatwave events, alongside a greater reliance on fossil fuels as the availability of clean energy sources dimishes (Zhao et al., 2023).

Notably, urban and rural residential electricity consumption in China surged by 33.5 % year-on-year in August 2022 (CEC Statistics and Data Centre, 2022). All seven provinces where megacities located showed a significant increase in thermal power generation in August 2022 compared to August in 2021 and 2020 (Fig. S1). Data from NBS (National Data, 2022) reveals that Anhui and Jiangsu province (where Hefei and Suzhou are located, respectively) experienced substantial year-on-year increases in thermal power generation, amounting to 6.51 and 5.41 billion kWh respectively. These figures were second only to Hubei province where Wuhan located, recording a staggering increase of 7.03 billion kWh (equivalent to 63.05 %) (Fig. S1 and Table S3).

On the other hand, the dramatic increase in thermal power generation in Hubei province was largely influenced by the decrease in the hydroelectric power generation. The Three Gorges Hydropower Station, the world's largest hydropower facility, typically generates over 80 % of the Hubei's hydroelectric power. However, the extreme 2022 heatwave coincided with droughts, notably affecting areas like Wuhan and Changsha, where precipitation significantly dropped compared to in previous years (Fig. S2). The upper YRB water level fell below historical levels, leading to a considerable reduction in power generation from the Three Gorges hydropower station, which decreased by around 50 % compared to August 2021 (Fig. S3). This severe drought-induced decline in hydroelectric power production, coupled with the heatwave-induced surge in electricity demand, placed substantial pressure on the power production of thermal power firms (Chowdhury et al., 2021; Yang et al., 2022). Consequently, the reduced hydroelectric power output and the increased demand for electricity both compelled power system operators to rely more on fossil fuel power plants (Brás et al., 2023; Zeighami et al., 2023). This reliance on fossil fuel ultimately translated into increased coal consumption, which in turn contributed to the rise in CO_2 emissions from power sector.

4.2. Decrease in industrial emissions

We speculate that the decline in industrial emissions was primarily attributed to government policies (Shanghai Municipal Commission of Economy and Informatization, 2022; Hangzhou Development and Reform Commission, 2022; PRC National Development and Reform Commission, 2011), with provincial and municipal authorities implementing measures to ensure stable household electricity supply during extreme heatwaves. These policies included limitations on commercial and industrial electricity use and implementation of staggered electricity usage in factories (Yu, 2022) (Fig. S4).

According to China Statistical Yearbook 2022 (National Bureau of Statistics, 2022), the lower-middle reaches of YRB only occupies 9.58 % of China's area, but contributes to 79.86 % of the regional GDP of the Yangtze River Economic Belt and 35.13 % of the national GDP in 2021. Data from the China Electricity Council (CEC) Statistics and Data Centre (CEC Statistics and Data Centre, 2022) reveals that in August 2022, the national manufacturing industry consumed 370.8 billion kWh of electricity, equivalent to 74 % of the national industrial electricity consumption. It represented a year-on-year decline of 1.3 % with the national manufacturing industry averaging 11.96 billion kWh/day, down by 160 million kWh/day. This reduction in national industrial electricity consumption reflects, to a certain extent, the constraints imposed on industry within the YRB due to the extreme heatwave.

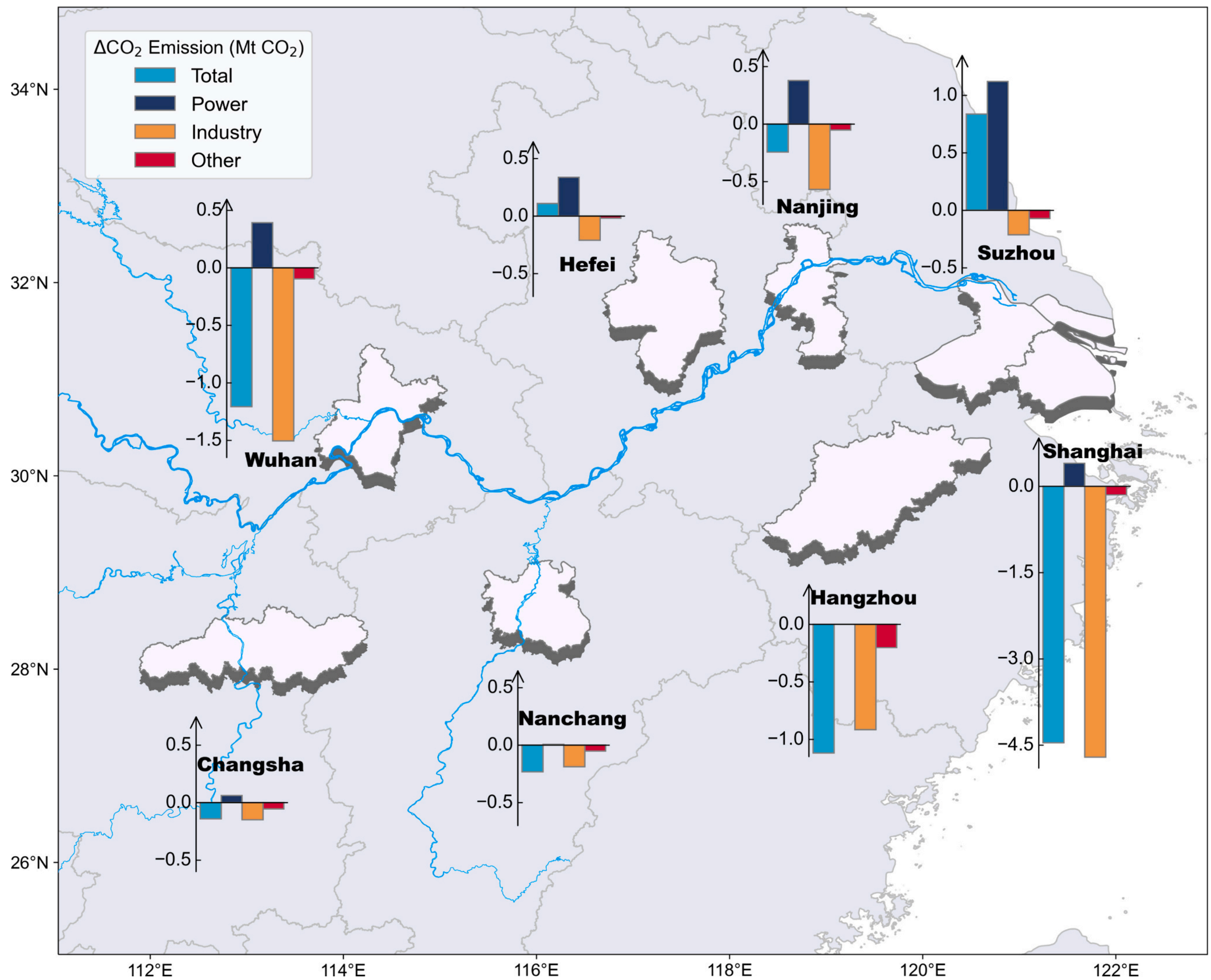

Fig. 7. Absolute changes in CO_2 emissions by sectors in megacities. Anomalies are derived by the emission difference between August 2022 and the average of August 2021 and August 2020.

Restrictions on industrial electricity consumption halted industrial production, impacting the output of industrial products and consequently causing a significant reduction in the CO_2 emissions produced during the manufacturing process. Data from NBS shows that the production of major industrial products (Fig. S5) such as cement and crude stee experienced widespread declines across seven provinces in August. Crude iron ore production in Anhui province dropped by 384,700 t, representing a decrease of 14.16 % compared to the past two years.

4.3. Economic situation and COVID-19

The International Energy Agency (IEA) (IEA, 2022) reported that China's emission in 2022 showed a reduction in industrial and transport emissions. It was attributed to factors such as sluggish economic growth and stringent COVID-19 measures.

However, upon comparing anthropogenic CO_2 emissions for the months of July and August across 8 megacities (Fig. 5), we discovered that emissions in all megacities, except Shanghai, experienced relatively stability in July 2022 compared to 2020 and 2021. Shanghai, affected by COVID-19 policies, exhibited weaker industrial emissions in July 2022. However, in August 2022, emissions across all megacities witnessed a significant decrease. Therefore, we can confidently assert that the decline in emissions from the industrial sector in August 2022 is very likely attributable to the impact of the extreme heatwave.

Furthermore, we queried outbreak case data for August 2022 (Table S4), 2021 (Table S5), and 2020 (Table S6) for these megacities from national and municipal government websites. In August 2022, there were no new confirmed cases in Nanchang, Hefei, and Suzhou. The remaining cities reported up to 10 new cases, with no more than 2 cases on any single day: Wuhan had 3 cases, Changsha and Nanjing had 5 cases each, Hangzhou had 3 cases, and Shanghai had 10 cases. In August 2020 and 2021, eight and five megacities, respectively, reported no new confirmed cases. Wuhan and Nanjing experienced a number of new cases for several consecutive days in early August 2021, but this had a limited impact on industrial production as it occurred toward the tail end of the outbreak. In addition, from August 2021 onwards, China's outbreak control strategy shifted to "precision prevention and control" (Liang et al., 2022), whereby the occurrence of several cases had minimal impact on industrial production, and thus on industrial emissions. Overall, in August 2022, as well as August 2020 and August 2021, new confirmed cases in all megacities were sporadic and did not impede industrial production.

5. Conclusion

In August 2022, the lower-middle reaches of YRB experienced an extreme heatwave, during which 8 megacities endured at least 19 days with daily maximum temperatures reaching 35 °C. We analyzed the impact of this extreme heatwave on anthropogenic CO_2 emissions in these megacities, especially focusing on the emissions from the power and industrial sectors.

We suggest that changes in daily power emissions are strongly linearly related to temperatures during the heatwave, albeit with varying temperature sensitivity among the megacities. The average temperature sensitivity was determined to be 0.0076 ± 0.0075 Mt d^{-1} $°C^{-1}$. Hence, compared to the average emissions for August in 2020 and 2021, this heatwave event triggered a collective increase of 2.70 Mt CO_2 from the power sector across these 8 megacities. This surge could be associated with heightened urban cooling demand, with Suzhou experiencing the most substantial increase of 1.12 Mt CO_2 (12.88 %).

Conversely, industrial emissions exhibited a contrasting response to the extreme heatwave, declining across all megacities. Shanghai registered the largest decrease of 4.71 Mt CO_2, while Hangzhou showed the most significant relative decrease of −21.22 %. It is worth noting that industrial emissions rebounded in most cities following the heatwave's conclusion. We suggest that the decrease in industrial emissions is most likely caused by China's policy aimed at ensuring household power supply under climate extremes. Overall, the decrease in industrial emissions offset the increase in power sector emissions, resulting in an overall reduction in emissions during the heatwave across most megacities. Our study offers valuable insights into the complexities of anthropogenic CO_2 emissions in megacities amidst frequent summer heatwaves intensified by greenhouse warming. By shedding light on the intricate dynamics between emissions and policy interventions, it contributes to our understanding of how urban areas respond to climate challenges.

CRediT authorship contribution statement

Jingye Tan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Jun Wang:** Writing – review & editing, Validation, Supervision, Funding acquisition, Formal analysis. **Haikun Wang:** Writing – review & editing, Formal analysis. **Zhu Liu:** Writing – review & editing, Resources, Data curation. **Ning Zeng:** Writing – review & editing. **Ran Yan:** Software, Formal analysis. **Xinyu Dou:** Writing – review & editing, Resources, Data curation. **Xunmei Wang:** Software. **Meirong Wang:** Writing – review & editing. **Fei Jiang:** Writing – review & editing. **Hengmao Wang:** Writing – review & editing. **Weimin Ju:** Writing – review & editing. **Jing M. Chen:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

CO_2 emissions from GRACED are available at https://carbonmonitor-graced.com/datasets.html.

The meteorological station data are provided at https://figshare.com/articles/dataset/Unexpected_Reduction_in_Megacities_Anthropogenic_CO2_Emissions_in_Lower_middle_Reaches_of_the_Yangtze_River_during_Extreme_2022_Heatwave/24126867.

The meteorological region data are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.68d2bb30?tab=form.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175605.

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