

Received November 18, 2020, accepted December 1, 2020, date of publication December 4, 2020, date of current version December 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3042548

Analogs of Future Climate in Chinese Cities Identified in Present Observations

CONG YIN^{1,2}, FEI YANG^{1,3}, AND JUANLE WANG¹

¹State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

²College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

³Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China

Corresponding author: Fei Yang (yangfei@igsrr.ac.cn)

This work was supported in part by the Key Research Program of Frontier Science of Chinese Academy of Sciences under Grant QYZDY-SSW-DQC007, in part by the Construction Project of China Knowledge Center for Engineering Sciences and Technology under Grant CKCEST-2020-2-4, and in part by the Strategic Priority Research Program of the Chinese Academy of Sciences under Grant XDA20030302.

ABSTRACT There seems to be a gap between the public and complex climate prediction models that reduces public awareness of and participation in climate change research. Therefore, it is necessary to describe the trends of future climate change with more concise conclusions. Climatic analogs are an effective method used to measure the similarity between two climate scenarios. By mapping a given climate scenario to another, familiar climate scenario and measuring their similarity, complex climate prediction models can be simplified and made easier to understand. In this study, we used climatic analogs of 378 cities in China and the suitable future climate area of China to study climatic novelty in China. The results show that (1) climatic novelty in the North China Plain, Xinjiang, Tibet, and parts of southern China is relatively high, and these areas may experience more drastic climate changes than other areas; (2) most cities have climatic analogs to the south, hundreds of kilometers away, indicating that the climates of these cities may change significantly; and (3) China's suitable climate area will change significantly in the future, and these changes are closely related to whether effective emission reduction measures are taken. The results of this study have repeatedly proven the need for effective emission reduction measures that will significantly delay climate change.

INDEX TERMS Climatic analogs, climatic novelty, climate change, emission reduction.

I. INTRODUCTION

Future climate simulation results show that global warming will intensify further [1], [2]. Climate change is a threat to life on earth [3]. If no emission reduction measures are taken, without immigration, it is expected that in the next 50 years, one-third of the world's population will live under high temperatures, with average annual temperatures exceeding 29 °C [4]. Climate change has already attracted the attention of governments, organizations and scholars, but the public has a limited understanding of the effects of climate change. This not only increases the cost of implementing climate change policies (such as emission reduction measures) but also reduces the public's ability to respond to the effects of climate change (such as extreme climate events) [5]–[8]. An effective way to solve this problem is to describe research results with plain conclusions. A successful case of this is the statement “the global average temperature will rise by

3 °C” [9]–[11]. In this study, to enhance public awareness of climate change, we are committed to answering the following three questions in response to public concerns about climate change: (1) which areas of China will have the most severe future climate change? (2) How do researchers find contemporary climate scenarios that are most similar to the future Chinese urban climate? (3) Which areas in China will be suitable for human habitation in the future?

An effective way to answer these questions is to map climate scenarios in different periods; that is, to find climate analogs, the most similar climate scenarios between two different periods. Climatic analogs are used to quantify the similarity of the climate in one period/location relative to another and are mainly used in the identification of novel climate scenarios or of climate scenarios that are similar to the scenario being studied [9], [12]–[14]. Williams *et al.* used climatic analogs to study the emergence of new climate scenarios and the disappearance of existing climate scenarios in 2100 and to assess the impacts of climate change on species distributions and ecosystem processes [15]. Hallegatte *et al.*

The associate editor coordinating the review of this manuscript and approving it for publication was Weimin Huang¹.

used three indicators, monthly average temperature, annual total precipitation and monthly average precipitation, to study climatic analogs in 17 European cities and to assess the economic costs of adapting to climate change [16]. Most studies have focused on the similarities between current and future climates, and Beniston *et al.* applied climate analogs to current and past climates to assess the northward shift of isotherms in Europe over the past decade [17].

To assess the climatic novelty of North America in the late 20th century, Mahony *et al.* first proposed the σ dissimilarity, which they based on the Mahalanobis distance. The σ dissimilarity was used to measure the dissimilarity between the predicted climate at the end of the 21st century and the observed climate at the end of the 20th century in a certain location. The greater the σ dissimilarity is, the higher the dissimilarity between the predicted climate and the observed climate is, and the more novel the predicted climate is. The results showed that by the end of the 21st century, the southern coastal regions of North America and the western Arctic will have widespread novel climates [12]. The σ dissimilarity has been widely used in relevant studies on climate novelty [18]–[20]. Based on the σ dissimilarity, Fitzpatrick *et al.* studied the climatic analogs of 540 cities in North America by using 12 variables, including average daily maximum temperature, average daily minimum temperature and total precipitation in 4 seasons. The results showed that the climate of most cities will change significantly, either becoming closer to the modern climate hundreds of kilometers away, mainly in the southern region of North America, or that there will be no areas similar to the modern climate [9]. Nguyen *et al.* assessed climate similarity in Southeast Asia based on the improved σ dissimilarity and the monthly average temperature and precipitation and found a significant trend of climate migration to warmer regions [18].

Today, China is the world's second largest economy and the largest emitter of greenhouse gases. Global environmental problems cannot be solved without China's engagement (<https://www.worldbank.org/en/country/china/overview>). Therefore, it is necessary to study the future climate change trends in China. In addition, improving public awareness of climate change is also important for advancing carbon reduction measures. In this study, we used contemporary climate data from 1970–2000 and climate prediction data from the 2050s and 2080s to quantify climate similarity on an annual scale using the σ dissimilarity to study future climatic novelty and climatic analogs in China. In addition, while previous studies mostly mapped the future climate to the contemporary climate, we mapped the climate of the contemporary residential area to the future, thus identifying the future suitable climate area.

II. DATA AND METHODS

A. DATA

Climatic analog calculations based on the σ dissimilarity require three climate datasets: contemporary climate data, climate prediction data, and meteorological station observation

data. Meteorological station observation data include three indicators: daily average maximum temperature, daily average minimum temperature, and total precipitation [9], [12]. First, we used the WorldClim (<https://www.worldclim.org/>) monthly weather data from 1970 to 2000 as the contemporary climate data, which were obtained from CRU-TS-4.03 data after downscaling and bias correction based on WorldClim 2.1 deviation [21], [22]. The resolution of this dataset is 2.5 minutes. To ensure consistency with the climate prediction data and reduce the calculation burden, we resampled this data to a 5-minute resolution. Second, we used the BNU-ESM climate prediction data under RCP4.5 (a mitigated emissions scenario) and RCP8.5 (an unmitigated emissions scenario), including data from the two periods of the 2050s and 2080s (<http://www.ccafs-climate.org/>). These data were downscaled and debiased using a delta method or change-factor method, and spatial interpolation techniques were used to assign the climate anomalies with a resolution of 5 minutes [23]. Third, we used a monthly dataset of China's surface climatic data from the National Meteorological Data Center (<http://data.cma.cn/>) as the meteorological station observation data; this dataset contains monthly data from China's 613 surface meteorological observation stations from 1951 to the present. We used the data collected from January 1981 to December 2019.

B. METHODS

We used the σ dissimilarity (based on the Mahalanobis distance) proposed by Mahony *et al.* to measure the dissimilarity of two climate scenarios. The Mahalanobis distance is an effective method used to calculate the similarity between two sample sets [24]. Unlike the Euclidean distance, it considers the relationships between variables and eliminates the variance inflation caused by correlation, and it is scale-invariant. The Mahalanobis distance can be expressed by the probability of a chi distribution with n degrees of freedom, where n is the number of climate variables. The σ dissimilarity represents the percentile of the given Mahalanobis distance in this chi distribution [9]. We consider a σ dissimilarity of two (2σ , the 95th percentile of the chi distribution) to be a moderate degree of novelty and 4σ dissimilarity to be extreme novelty. If the σ dissimilarity is larger, it indicates less similarity between the two climate scenarios, or that the predicted climate scenario is so novel that it is difficult to find a similar climate scenario. We rewrote the calculation process using Python, which is more concise and easier to use than the R-based method used by Mahony *et al.* [12].

The source data used to calculate the Mahalanobis distance include (a) contemporary climate data, among which a_i is an n -dimensional array of contemporary climate variables at position i , and n is the number of climate variables; (b) projected climate data, among which b_j is the n -dimensional array of predicted climate variables at position j ; and (c) meteorological station observation data, among which c_j is the $n \times t$ climate variable matrix formed by the meteorological station observation values closest to position j , and $t = 39$ represents

the timespan of the meteorological observation record (1981–2019). In this study, a_i , b_j and c_j are n -dimensional arrays formed by the corresponding maximum air temperature, minimum air temperature and total precipitation, and V_j is the covariance matrix of c_j . The formula for calculating the Mahalanobis distance M_d is as follows:

$$M_d = \sqrt{(b_j - a_i) V_j^{-1} (b_j - a_i)^T} \quad (1)$$

In this study, we used a total of 12 variables, the daily average maximum temperature, daily average minimum temperature and total precipitation in four seasons, to describe a climate scenario, and we used the σ dissimilarity to measure the similarity between two climate scenarios. We used the Python software package *scipy* (<https://scipy.org/>) to calculate the Mahalanobis distance and σ dissimilarity. The core code for calculating the Mahalanobis distance and σ dissimilarity is as follows:

$$M_d = \text{scipy.spatial.distance.mahalanobis}(b_j, a_i, V_j^{-1})$$

$$M_p = \text{scipy.stats.chi.cdf}(M_d, n)$$

$$M_x = \text{scipy.stats.chi.ppf}(M_p, 1)$$

where M_p is the cumulative distribution function value corresponding to M_d and degrees of freedom n under the chi distribution; and M_x is the percentile value corresponding to M_p and the degree of freedom 1 in the chi distribution, that is, the σ dissimilarity. Therefore, when calculating the σ dissimilarity in this study, three n -dimensional climate variable arrays must be input: a_i , b_j and the inverse of the covariance matrix of c_j , V_j^{-1} .

III. RESULTS

A. MAPPING THE CLIMATIC NOVELTY IN CHINA

Figure 1 shows the predicted climatic novelty in China in the 2080s under the RCP4.5 and RCP8.5 scenarios. We calculate the minimum σ dissimilarity of each pixel and define it as climatic novelty. If the minimum σ dissimilarity of a pixel is large, it means that it is difficult to find a similar climate scenario in the contemporary era; that is, the climate scenario of the pixel is more novel, which indicates areas with severe climate change. In the RCP4.5 scenario, 78.66% of the regions have a minimum σ dissimilarity less than 2σ , which indicates that similar contemporary climate scenarios can be found for most regions. The minimum σ dissimilarity of the North China Plain is between 2σ and 4σ , indicating medium climatic novelty, while some regions, such as Xinjiang and Tibet, have higher minimum σ dissimilarity values, indicating highly novel climate regions; thus, the climates of these regions may undergo drastic changes. In the RCP8.5 scenario, only 50.73% of the regions have a minimum σ dissimilarity less than 2σ , which indicates that in the absence of emission reduction measures, nearly half of the regions in China will have novel climate scenarios. The minimum σ dissimilarity values of the North China Plain, Xinjiang, Tibet and parts of southern China (a total of 15.23% of the area) are greater than 4σ . These areas show high degrees of climatic novelty

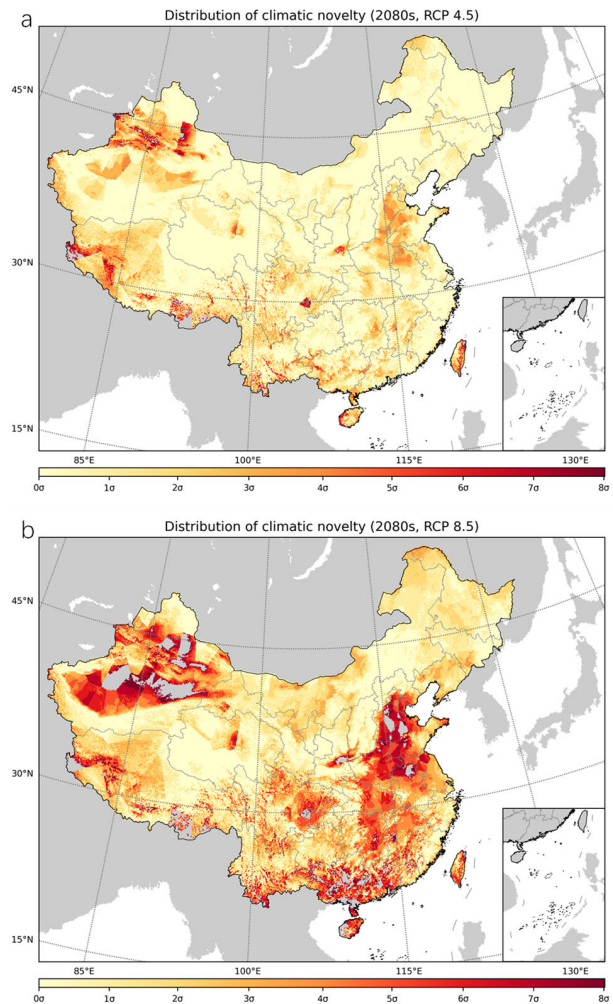


FIGURE 1. Distribution of climatic novelty under (a) RCP4.5 and (b) RCP8.5 in the 2080s. If the value is larger, it means that it is more difficult to find a climatic analog in the contemporary era; that is, the climate scenario of the pixel is more novel, which indicates an area with severe climate change.

and may become regions with drastic climate changes in the future. Ecosystems in these regions may face greater challenges, and human life and production activities will also be greatly affected. In the comparison of the results of the two scenarios, we found a significant decrease in climate similarity and a significant increase in climatic novelty in RCP8.5 compared to RCP4.5, which indicates the need for emission reduction measures.

B. MAPPING CLIMATIC ANALOGS OF CHINESE CITIES

Figure 2 and Figure 3 show the climatic analogs of Beijing and Shanghai in the 2080s under the RCP4.5 and RCP8.5 scenarios. The best climatic analogs of the two cities are south of each corresponding city, which indicates that the future climates of Beijing and Shanghai will become warmer. At the same time, the distance between Beijing and its best climatic analog is greater than that between Shanghai and its

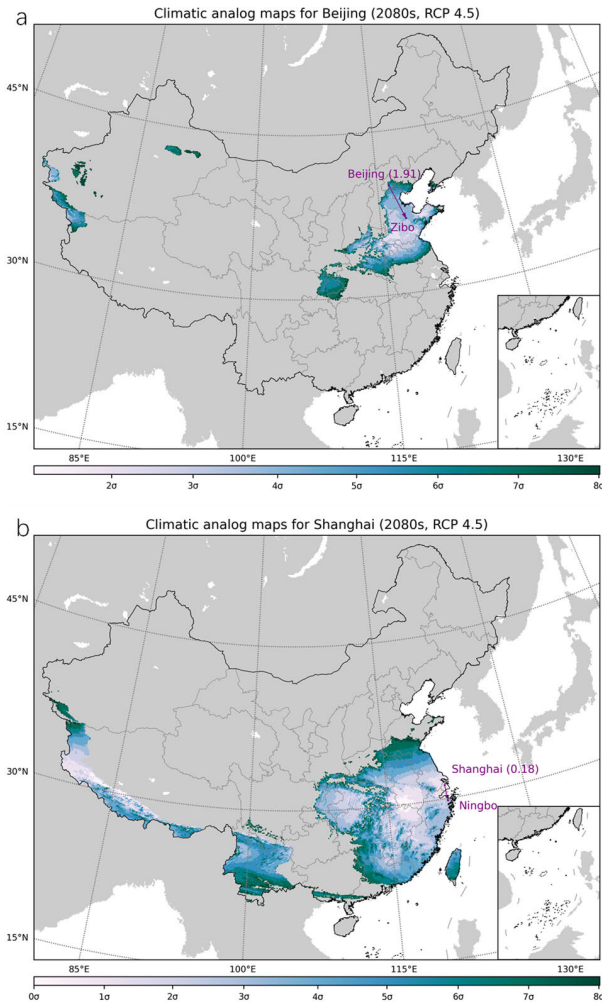


FIGURE 2. Climatic analog maps for (a) Beijing and (b) Shanghai in the 2080s under RCP4.5. The arrows connects each city and their corresponding best climatic analog with a minimum σ dissimilarity.

corresponding climatic analog, and the minimum σ dissimilarity of Beijing is greater than that of Shanghai, indicating that Beijing will experience more severe climate change than Shanghai will. Under the RCP4.5 scenario, the climatic analog area of Beijing in the 2080s is mainly distributed in the North China Plain. The σ dissimilarity in almost all areas is greater than 2σ , and the best climatic analog of Beijing is Zibo, Shandong (σ dissimilarity = 1.906). The climatic analog area in Shanghai is mainly distributed in the middle and lower reaches of the Yangtze River. The 10.25% area has a σ dissimilarity less than 2σ , and the best climatic analog of Shanghai is Ningbo, Zhejiang (σ dissimilarity = 0.1758).

Under the RCP8.5 scenario, the climatic analog area for the 2080s shrank and continued to move south, and the σ dissimilarity was greater than 2σ . The best climatic analog of Beijing is Shiyan, Hubei (σ dissimilarity = 6.5484), and the best climatic analog of Shanghai is Fuzhou, Fujian (σ dissimilarity = 2.1349). A more concise explanation for this result is

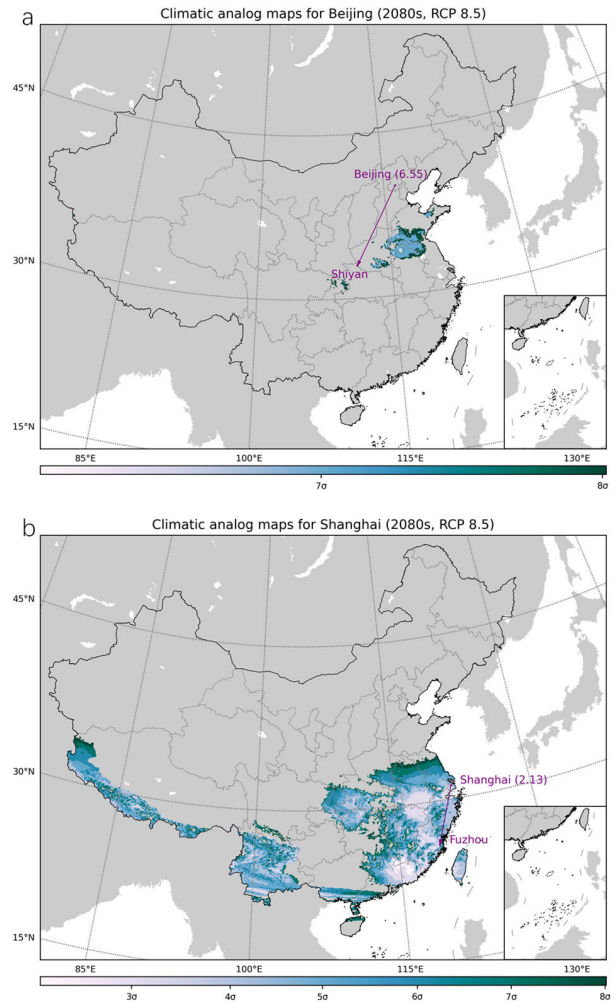


FIGURE 3. Climatic analog maps for (a) Beijing and (b) Shanghai in the 2080s under RCP8.5.

that in a mitigated emissions scenario (RCP4.5), the climate of Beijing in the 2080s will be most similar to that of Zibo today, with a large climatic analog area. In an unmitigated emissions scenario (RCP8.5), the climate of Beijing in the 2080s will be most similar to that of Shiyan today but with a lower degree of similarity and a smaller climatic analog area. Without effective emission reduction measures, it will be more difficult for Beijing residents to migrate in the future to find a climate scenario for their long-term adaptation. In addition, compared with RCP4.5, the climatic analog area under the RCP8.5 scenario is smaller, and the minimum σ dissimilarity is greater, which also indicates more dramatic climate change under the RCP8.5 scenario.

Figure 4 shows climatic analogs of 378 Chinese cities in the 2080s under the RCP4.5 and RCP8.5 scenarios. The best climatic analogs for cities in eastern, central and western China tend to move southwest, north and northwest, respectively. In the RCP4.5 scenario, 79.56% of the best climatic analogs are located south of each corresponding city, with an average

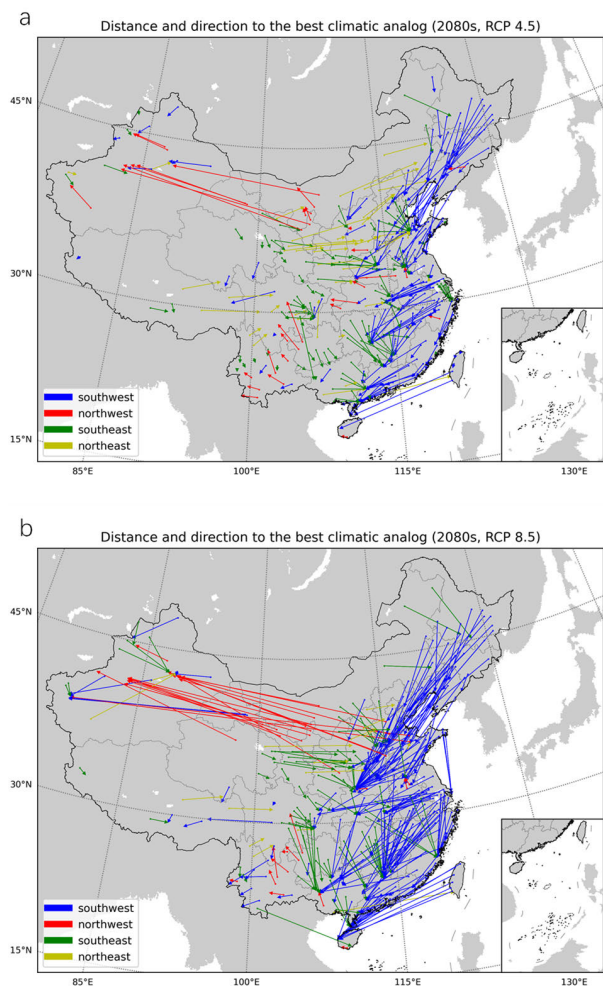


FIGURE 4. Distance and direction to the best climatic analog under (a) RCP4.5 and (b) RCP8.5 in the 2080s. Different colors are used to represent the direction of the best climatic analogs.

distance of 298.17 kilometers; this indicates that most residents of the cities need to migrate nearly 300 kilometers south to find an adaptable climate scenario. In the RCP8.5 scenario, 86.67% of the best climatic analogs are south of each corresponding city, with an average distance of 624.52 kilometers, which is twice that of the RCP4.5 scenario. In addition, the distances between the best climatic analogs in northern China and the corresponding cities are generally greater than those in the south. There are two possible reasons for this result. First, from the perspective of climatology, several studies have found that climate change in northern China is more drastic than that in southern China [25]–[27], which leads to northern cities being farther away from their best analogs. Second, technically, the densities of cities in northern China are lower than those in the south, and the climate types in the north are more diverse, which makes it more difficult for northern cities to find their best analogs in a relatively close range. The best climatic analogs and corresponding

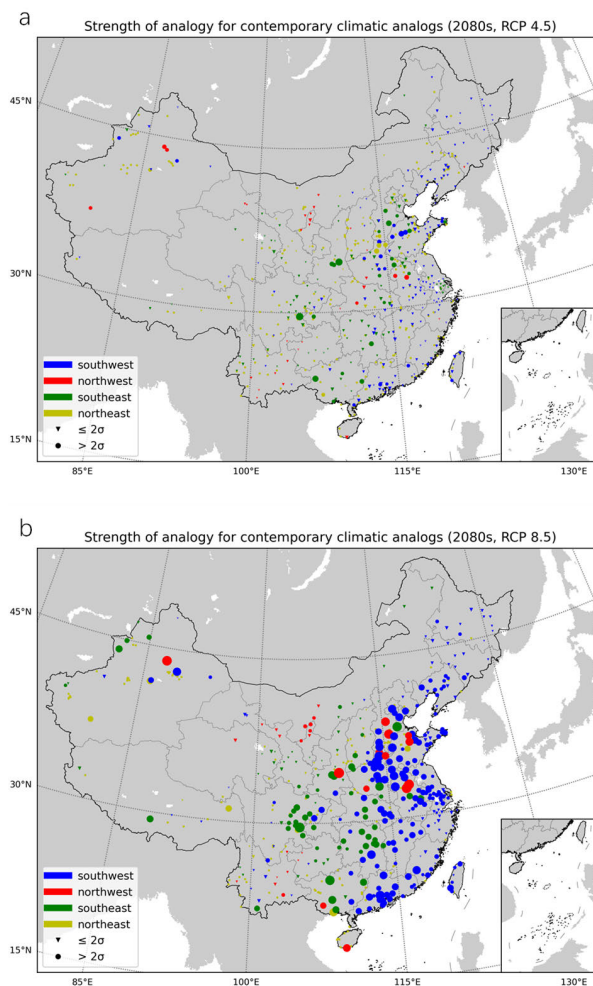


FIGURE 5. Strength of the analogy of contemporary climatic analogs in the 2080s under (a) RCP4.5 and (b) RCP8.5. The size of the marker represents different values, and different colors represent the direction of the best climatic analogs.

cities tend to have similar natural environments (e.g., the best climatic analogs of Taiwanese cities are in Hainan, and the best climatic analogs of Gansu cities are in Xinjiang). If a city is in a unique climate area (such as the Qinghai-Tibet Plateau), the distance between the best climatic analogs and the corresponding city is smaller, which shows the effectiveness of the climatic analog method.

Figure 5 shows the minimum σ dissimilarity of each city under the two scenarios. In Figure 5, the size of the marker represents different values, and different colors are used to represent the position of the best climatic analogs. The smaller the minimum σ dissimilarity is, the better the climatic similarity is. Obviously, the minimum σ dissimilarity under the RCP8.5 scenario is generally greater, which means that it is more difficult for most cities to find a climate scenario similar to the contemporary scenario under the RCP8.5 scenario. In the RCP4.5 scenario, 86.38% of the cities have a minimum σ dissimilarity less than 2σ , which is considered the limit of



FIGURE 6. Contemporary residential area. A contemporary residential area is defined as an area with a population density of more than 1 person per square kilometer.

a similar climate, while in the RCP8.5 scenario, only 36.39% of the cities have a minimum σ dissimilarity less than 2σ . We found that it is difficult to obtain similar contemporary climate scenarios for most of the cities in eastern China, which are economically developed and densely populated. This again reminds us of the need to implement effective emission reduction measures.

C. MAPPING SIMILAR CLIMATE AREA OF CONTEMPORARY RESIDENTIAL AREA IN THE LATE 21ST CENTURY

For thousands of years, humans have concentrated on a surprisingly narrow subset of Earth’s available climates, and climate change will significantly affect future suitable climate areas [4], [28]. Figure 7 and Figure 8 show the similar climate areas of contemporary residential area in different periods and under different scenarios. A contemporary residential area is defined as an area with a population density of more than 1 person per square kilometer. The population density data comes from SEDAC (Socioeconomic Data and Applications Center, <https://sedac.ciesin.columbia.edu/>). Due to the harsh natural conditions of the Tibetan Plateau and the Taklimakan Desert in northwestern China, these areas are not suitable for human habitation. Therefore, the contemporary suitable climate areas are mainly distributed in areas other than northwestern China, accounting for 69.99% of the country.

A future suitable climate area is defined as an area with a climate similar to that of a contemporary residential area. We used climatic analogs to map the climates of the contemporary residential areas in the future. When the σ dissimilarity is less than 2σ , the area is defined as a highly similar climate area; when the σ dissimilarity is between 2σ and 4σ , the area is defined as a moderately similar climate area; when the σ dissimilarity is between 4σ and 8σ , the area is defined as a lightly similar climate area; and when the σ dissimilarity is greater than 8σ , the area is defined as

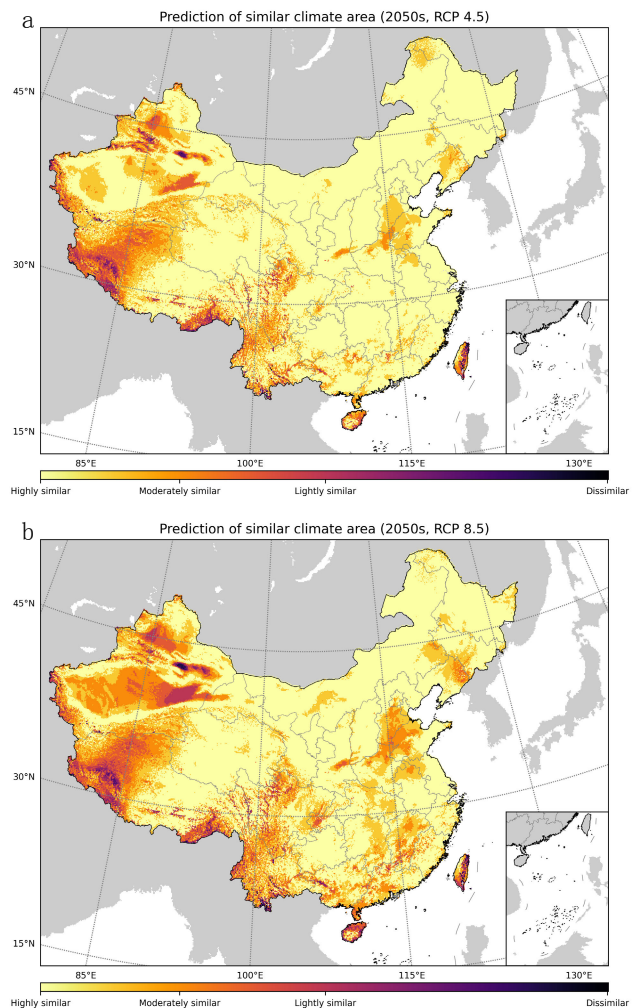


FIGURE 7. Prediction of the similar climate areas of contemporary residential area in the 2050s under (a) RCP4.5 and (b) RCP8.5. When the σ dissimilarity is less than 2σ , the area is defined as a highly similar climate area; when the σ dissimilarity is between 2σ and 4σ , the area is defined as a moderately similar climate area; when the σ dissimilarity is between 4σ and 8σ , the area is defined as a lightly similar climate area; and when the σ dissimilarity is greater than 8σ , the area is defined as a dissimilar climate area.

a dissimilar climate area. In the 2050s, under the RCP4.5 scenario, due to the climate becoming warmer and wetter, the area of highly similar areas in northwest China greatly expanded, while the similarity of some areas in eastern and southern China decreased, and some moderately similar areas appeared; under this scenario, highly similar and moderately similar areas account for 88.74% and 10.57% of the national area, respectively. Under the RCP8.5 scenario, the highly similar areas in northwest China are similar to those in the contemporary era, and the moderately similar areas in northern China and southern China continue to expand, accounting for 80.64% and 18.4% of the national area, respectively.

In the 2080s, under the RCP4.5 scenario, the moderately similar areas in northern China and northwest China expanded, with highly similar areas and moderately similar areas accounting for 80.85% and 18.23% of the national

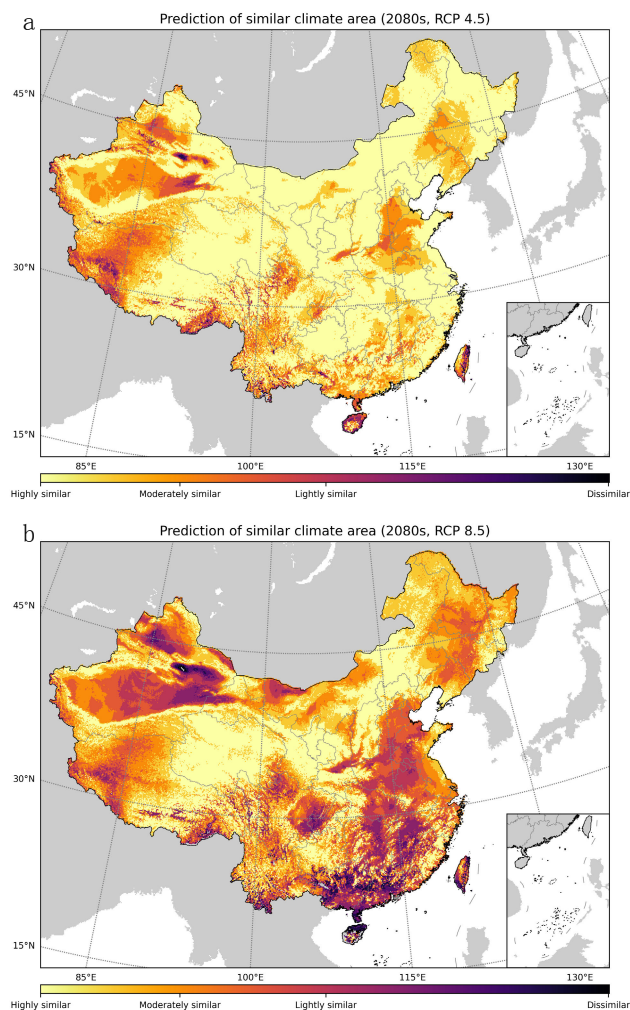


FIGURE 8. Prediction of the similar climate areas of contemporary residential area in the 2080s under (a) RCP4.5 and (b) RCP8.5.

area, respectively. Under the RCP8.5 scenario, large moderately similar and dissimilar areas appear in eastern China and northwest China, with highly similar areas and moderately similar areas accounting for 50.97% and 42.35% of the national area, respectively. In general, under the influence of climate change, some contemporary cold and arid regions may become suitable for human habitation, while contemporary suitable climate areas may become unsuitable. Due to human migration and changes in climate adaptability, this result is not a prediction of the future population distribution, but instead indicates areas where the climate is changing drastically; if no effective emission reduction measures are taken, by the 2080s, the suitable climate area of the most densely populated region of eastern China will decrease.

IV. DISCUSSION

Climate change has already had a wide-ranging impact on human life and production activities [29]–[32], but compared

to extreme climate events (such as heat waves, droughts, and floods) that directly threaten human life and the security of property, it is more difficult to attract public attention to climate change [9], [33]–[35]. This is because climate change is a long-term and gradual process, and it is challenging for climate change to have a direct impact in a short time frame [36]–[38]; in addition, the public often has difficulty understanding complex climate models and professional terminology. Climatic analogs are a method used to measure the similarity of two climate scenarios. A representative question climate analogs can answer is whether “the climate of a certain location in the future is most similar to the climate of a contemporary location”. Clearly, climatic analogs provide realistic scales and references that can help the public better understand the impacts of climate change, which is of great significance for improving public awareness and participation to address climate change. Climatic analogs can intuitively show areas with drastic climate changes, which is of great value for improving the coping ability of these areas.

In this study, we studied climatic novelty in China using climatic analogs of 378 cities in China and determined the suitable climate area of China in the future. It is worth noting that the climate of the densely populated and economically developed areas in eastern China (especially the North China Plain) will change drastically, which is reflected in the high climatic novelty in the region (Figure 1), and even in the 2080s, if effective emission reduction measures are taken, the suitable climate area will decrease (Figure 8a). Through the comparison of climatic analogs under two scenarios, RCP4.5 and RCP8.5, we found that the implementation of emission reduction measures is essential for mitigating the adverse effects of climate change. Under the RCP8.5 scenario, the novel climate area and uninhabitable area are several times larger than those of the RCP4.5 scenario. All of eastern China will become a novel climate area and an uninhabitable area, and urban residents will need to travel more than 600 kilometers to find a similar climate scenario to the one they have adapted to for a long time; this distance is twice that of the RCP4.5 scenario. It is time to take effective measures to reduce emissions.

Since the study area is limited to China and the best climatic analogs may be located outside the study area (for example, the area with the best climate similarity to southern China may occur in Southeast Asia), this may lead to a large σ dissimilarity [9]. This does not reduce the practical significance of the research results. Due to the impact of immigration policies and economic costs, the difficulty of international migration far exceeds that of domestic migration [4]. Therefore, finding the best similar climate within the country is the concern of most people. In addition, the prediction of suitable climate areas does not correspond with the future population distribution; it only considers the climatic conditions and assumes that human adaptability to climate remains unchanged. Due to the increased ability of human beings to cope with climate change (such as the use of air conditioners) and other socioeconomic factors that affect

population distribution (such as cost of living), more in-depth research is needed to predict the future population distribution [28], [39]–[41].

Our results have repeatedly emphasized the importance of adopting stringent emission reduction measures to curb climate change. The RCP4.5 scenario requires that the radiation forcing should not exceed 4.5 w/m^2 and the CO_2 concentration should not exceed 650 ppm by 2100 [42]. The scheme requires that CO_2 emissions begin to decline by approximately 2045 and reach approximately half of the 2050 level by 2100, which is considered to be intermediate and achievable (<https://ar5-syr.ipcc.ch/>). In recent years, China has proposed “ecological civilization construction” and promised to reduce carbon dioxide emissions per unit of GDP by 40%–45% by 2020 compared with the emissions in 2005. Scholars have also carried out in-depth research in the field of climate change. The key to emission reductions lies in the public and in enterprises; this is due to the lack of public awareness of climate change and the fact that enterprises tend to pursue economic interests and give up ecological value. Therefore, improving public participation and strengthening enterprise supervision are an important links in achieving the goal of emission reduction.

V. CONCLUSION

This study uses the climatic analog method to study climatic novelty in China, climatic analogs of 378 cities in China, and the suitable climate area of China in the future. The results of the study show that compared with the RCP4.5 scenario, the RCP8.5 scenario has a larger novel climate area, fewer climatic analogs, and a smaller suitable climate area. This indicates that more dramatic climate changes will result under the RCP8.5 scenario, which repeatedly emphasizes the need for effective emission reduction measures. In addition, climate change is expected to be more intense in the densely populated and economically developed North China Plain and in southeastern China as well as in the ecologically fragile Qinghai-Tibet Plateau. Especially in the North China Plain, the climate of the region is highly novel, and even under the scenario incorporating emission reduction measures (RCP4.5), the suitable climate area will decrease, indicating that the region is facing greater climate change challenges.

REFERENCES

- [1] T. L. Root, J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and J. A. Pounds, “Fingerprints of global warming on wild animals and plants,” *Nature*, vol. 421, no. 6918, pp. 57–60, Jan. 2003, doi: [10.1038/nature01333](https://doi.org/10.1038/nature01333).
- [2] P. M. Cox, R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell, “Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model,” *Nature*, vol. 408, no. 6809, pp. 184–187, Nov. 2000, doi: [10.1038/35041539](https://doi.org/10.1038/35041539).
- [3] S. F. Pileggi and S. A. Lamia, “Climate change TimeLine: An ontology to tell the story so far,” *IEEE Access*, vol. 8, pp. 65294–65312, 2020, doi: [10.1109/access.2020.2985112](https://doi.org/10.1109/access.2020.2985112).
- [4] C. Xu, T. A. Kohler, T. M. Lenton, J.-C. Svenning, and M. Scheffer, “Future of the human climate niche,” *Proc. Nat. Acad. Sci. USA*, vol. 117, no. 21, pp. 11350–11355, May 2020, doi: [10.1073/pnas.1910114117](https://doi.org/10.1073/pnas.1910114117).
- [5] I. Lorenzoni and N. F. Pidgeon, “Public views on climate change: European and USA perspectives,” *Climatic Change*, vol. 77, nos. 1–2, pp. 73–95, Aug. 2006, doi: [10.1007/s10584-006-9072-z](https://doi.org/10.1007/s10584-006-9072-z).
- [6] L. Scruggs and S. Benegal, “Declining public concern about climate change: Can we blame the great recession?” *Global Environ. Change*, vol. 22, no. 2, pp. 505–515, May 2012, doi: [10.1016/j.gloenvcha.2012.01.002](https://doi.org/10.1016/j.gloenvcha.2012.01.002).
- [7] T. M. Lee, E. M. Markowitz, P. D. Howe, C. Y. Ko, and A. A. Leiserowitz, “Predictors of public climate change awareness and risk perception around the world,” *Nature Climate Change*, vol. 5, no. 11, p. 1014, Nov. 2015, doi: [10.1038/nclimate2728](https://doi.org/10.1038/nclimate2728).
- [8] A. Drummond, L. C. Hall, J. D. Sauer, and M. A. Palmer, “Is public awareness and perceived threat of climate change associated with governmental mitigation targets?” *Climatic Change*, vol. 149, no. 2, pp. 159–171, Jul. 2018, doi: [10.1007/s10584-018-2230-2](https://doi.org/10.1007/s10584-018-2230-2).
- [9] M. C. Fitzpatrick and R. R. Dunn, “Contemporary climatic analogs for 540 North American urban areas in the late 21st century,” *Nature Commun.*, vol. 10, no. 1, pp. 1–7, Feb. 2019, doi: [10.1038/s41467-019-08540-3](https://doi.org/10.1038/s41467-019-08540-3).
- [10] S. van der Linden, E. Maibach, and A. Leiserowitz, “Improving public engagement with climate change: Five ‘best practice’ insights from psychological science,” *Perspect. Psychol. Sci.*, vol. 10, no. 6, pp. 758–763, Nov. 2015, doi: [10.1177/1745691615598516](https://doi.org/10.1177/1745691615598516).
- [11] S. A. Nicholson-Cole, “Representing climate change futures: A critique on the use of images for visual communication,” *Comput., Environ. Urban Syst.*, vol. 29, no. 3, pp. 255–273, May 2005, doi: [10.1016/j.compenvurbysys.2004.05.002](https://doi.org/10.1016/j.compenvurbysys.2004.05.002).
- [12] C. R. Mahony, A. J. Cannon, T. Wang, and S. N. Aitken, “A closer look at novel climates: New methods and insights at continental to landscape scales,” *Global Change Biol.*, vol. 23, no. 9, pp. 3934–3955, Sep. 2017, doi: [10.1111/gcb.13645](https://doi.org/10.1111/gcb.13645).
- [13] S. Kopf, M. Ha-Duong, and S. Hallegatte, “Using maps of city analogues to display and interpret climate change scenarios and their uncertainty,” *Natural Hazards Earth Syst. Sci.*, vol. 8, no. 4, pp. 905–918, Aug. 2008, doi: [10.5194/nhess-8-905-2008](https://doi.org/10.5194/nhess-8-905-2008).
- [14] G. Rohat, S. Goyette, and J. Flacke, “Characterization of European cities’ climate shift—An exploratory study based on climate analogues,” *Int. J. Climate Change Strategies Manage.*, vol. 10, no. 3, pp. 428–452, 2018, doi: [10.1108/ijccsm-05-2017-0108](https://doi.org/10.1108/ijccsm-05-2017-0108).
- [15] J. W. Williams, S. T. Jackson, and J. E. Kutzbach, “Projected distributions of novel and disappearing climates by 2100 AD,” *Proc. Nat. Acad. Sci. USA*, vol. 104, no. 14, pp. 5738–5742, Apr. 2007, doi: [10.1073/pnas.0606292104](https://doi.org/10.1073/pnas.0606292104).
- [16] S. Hallegatte, J.-C. Hourcade, and P. Ambrosi, “Using climate analogues for assessing climate change economic impacts in urban areas,” *Climatic Change*, vol. 82, nos. 1–2, pp. 47–60, Mar. 2007, doi: [10.1007/s10584-006-9161-z](https://doi.org/10.1007/s10584-006-9161-z).
- [17] M. Beniston, “European isotherms move northwards by up to 15 km year⁻¹: Using climate analogues for awareness-raising,” *Int. J. Climatol.*, vol. 34, no. 6, pp. 1838–1844, May 2014, doi: [10.1002/joc.3804](https://doi.org/10.1002/joc.3804).
- [18] T. Nguyen-Thi et al., “Climate analogue and future appearance of novel climate in Southeast Asia,” *Int. J. Climatol.*, pp. 1–18, Jun. 2020, doi: [10.1002/joc.6693](https://doi.org/10.1002/joc.6693).
- [19] J.-F. Bastin, E. Clark, T. Elliott, S. Hart, J. van den Hoogen, I. Hordijk, H. Ma, S. Majumder, G. Manoli, J. Maschler, L. Mo, D. Routh, K. Yu, C. M. Zohner, and T. W. Crowther, “Understanding climate change from a global analysis of city analogues,” *PLoS ONE*, vol. 14, no. 7, Jul. 2019, Art. no. e0217592, doi: [10.1371/journal.pone.0217592](https://doi.org/10.1371/journal.pone.0217592).
- [20] C. Carroll, S. A. Parks, S. Z. Dobrowski, and D. R. Roberts, “Climatic, topographic, and anthropogenic factors determine connectivity between current and future climate analogs in North America,” *Global Change Biol.*, vol. 24, no. 11, pp. 5318–5331, Nov. 2018, doi: [10.1111/gcb.14373](https://doi.org/10.1111/gcb.14373).
- [21] I. Harris, P. D. Jones, T. J. Osborn, and D. H. Lister, “Updated high-resolution grids of monthly climatic observations—the CRU TS3.10 dataset,” *Int. J. Climatol.*, vol. 34, no. 3, pp. 623–642, Mar. 2014, doi: [10.1002/joc.3711](https://doi.org/10.1002/joc.3711).
- [22] S. E. Fick and R. J. Hijmans, “WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas,” *Int. J. Climatol.*, vol. 37, no. 12, pp. 4302–4315, Oct. 2017, doi: [10.1002/joc.5086](https://doi.org/10.1002/joc.5086).
- [23] J. Ramirez-Villegas and A. Jarvis, “Downscaling global circulation model outputs: The delta method decision and policy analysis,” *Int. Center Tropical Agricult., Cali, Colombia, Working Paper 1*, 2010.

- [24] P. C. Mahalanobis, "On the generalised distance in statistics," *Sankhya-Ser. A-Math. Statist. Probab.*, vol. 80, pp. 1–7, Dec. 2018, doi: [10.1007/s13171-019-00164-5](https://doi.org/10.1007/s13171-019-00164-5).
- [25] L. Liang, L. Ma, Q. Feng, T. Liu, B. Sun, and Y. Zhou, "Responses of abrupt temperature changes/warming hiatuses to changes in their influencing factors: A case study of Northern China," *Meteorol. Appl.*, vol. 27, no. 4, p. e1937, Jul. 2020, doi: [10.1002/met.1937](https://doi.org/10.1002/met.1937).
- [26] Y. He, A. Lu, Z. Zhang, H. Pang, and J. Zhao, "Seasonal variation in the regional structure of warming across China in the past half century," *Climate Res.*, vol. 28, no. 3, pp. 213–219, 2005, doi: [10.3354/cr028213](https://doi.org/10.3354/cr028213).
- [27] Z.-Z. Hu, "Long-term climate variations in China and global warming signals," *J. Geophys. Res.*, vol. 108, no. D19, pp. 1–13, 2003, doi: [10.1029/2003jd003651](https://doi.org/10.1029/2003jd003651).
- [28] R. McLeman and B. Smit, "Migration as an adaptation to climate change," *Climatic Change*, vol. 76, nos. 1–2, pp. 31–53, Jun. 2006, doi: [10.1007/s10584-005-9000-7](https://doi.org/10.1007/s10584-005-9000-7).
- [29] S. Caney, "Cosmopolitan justice, responsibility, and global climate change," *Leiden J. Int. Law*, vol. 18, no. 4, p. 747, 2005.
- [30] S. Caney, "Human rights, climate change, and discounting," *Environ. Politics*, vol. 17, no. 4, pp. 536–555, Aug. 2008, doi: [10.1080/09644010802193401](https://doi.org/10.1080/09644010802193401).
- [31] K. M. Brander, "Global fish production and climate change," *Proc. Nat. Acad. Sci. USA*, vol. 104, no. 50, pp. 19709–19714, Dec. 2007, doi: [10.1073/pnas.0702059104](https://doi.org/10.1073/pnas.0702059104).
- [32] A. J. McMichael, J. W. Powles, C. D. Butler, and R. Uauy, "Food, livestock production, energy, climate change, and health," *Lancet*, vol. 370, no. 9594, pp. 1253–1263, Oct. 2007, doi: [10.1016/S0140-6736\(07\)61256-2](https://doi.org/10.1016/S0140-6736(07)61256-2).
- [33] J. C. Semenza, D. E. Hall, D. J. Wilson, B. D. Bontempo, D. J. Sailor, and L. A. George, "Public perception of climate change: Voluntary mitigation and barriers to behavior change," *Amer. J. Preventive Med.*, vol. 35, no. 5, pp. 479–487, Nov. 2008, doi: [10.1016/j.amepre.2008.08.020](https://doi.org/10.1016/j.amepre.2008.08.020).
- [34] K. W. Knight, "Public awareness and perception of climate change: A quantitative cross-national study," *Environ. Sociol.*, vol. 2, no. 1, pp. 101–113, Jan. 2016, doi: [10.1080/23251042.2015.1128055](https://doi.org/10.1080/23251042.2015.1128055).
- [35] H. Yu, B. Wang, Y.-J. Zhang, S. Wang, and Y.-M. Wei, "Public perception of climate change in China: Results from the questionnaire survey," *Natural Hazards*, vol. 69, no. 1, pp. 459–472, Oct. 2013, doi: [10.1007/s11069-013-0711-1](https://doi.org/10.1007/s11069-013-0711-1).
- [36] K. E. Kunkel *et al.*, "Monitoring and understanding trends in extreme storms: State of knowledge," *Bull. Amer. Meteorol. Soc.*, vol. 94, no. 4, pp. 499–514, Apr. 2013, doi: [10.1175/bams-d-11-00262.1](https://doi.org/10.1175/bams-d-11-00262.1).
- [37] R. S. Vose *et al.*, "Monitoring and understanding changes in extremes: Extratropical storms, winds, and waves," *Bull. Amer. Meteorol. Soc.*, vol. 95, no. 3, pp. 377–386, Mar. 2014, doi: [10.1175/bams-d-12-00162.1](https://doi.org/10.1175/bams-d-12-00162.1).
- [38] B. McKibben, "Climate change impacts in the United States: The third national climate assessment," *New York Rev. Books*, vol. 61, no. 12, pp. 46–48, Jul. 2014. [Online]. Available: <http://WOS:000337338400018>
- [39] R. Reuveny, "Climate change-induced migration and violent conflict," *Political Geogr.*, vol. 26, no. 6, pp. 656–673, Aug. 2007, doi: [10.1016/j.polgeo.2007.05.001](https://doi.org/10.1016/j.polgeo.2007.05.001).
- [40] R. Black, S. R. G. Bennett, S. M. Thomas, and J. R. Beddington, "Migration as adaptation," *Nature*, vol. 478, no. 7370, pp. 447–449, Oct. 2011, doi: [10.1038/478477a](https://doi.org/10.1038/478477a).
- [41] C. Mortreux and J. Barnett, "Climate change, migration and adaptation in Funafuti, Tuvalu," *Global Environ. Change*, vol. 19, no. 1, pp. 105–112, Feb. 2009, doi: [10.1016/j.gloenvcha.2008.09.006](https://doi.org/10.1016/j.gloenvcha.2008.09.006).
- [42] A. M. Thomson, K. V. Calvin, S. J. Smith, G. P. Kyle, A. Volke, P. Patel, S. Delgado-Arias, B. Bond-Lamberty, M. A. Wise, L. E. Clarke, and J. A. Edmonds, "RCP4.5: A pathway for stabilization of radiative forcing by 2100," *Climatic Change*, vol. 109, nos. 1–2, pp. 77–94, Nov. 2011, doi: [10.1007/s10584-011-0151-4](https://doi.org/10.1007/s10584-011-0151-4).



edge service of disaster risk reduction, and data driven model and big data mining in geoscience.



Dr. Wang received several academic awards, including the Bronze Award of Excellent Map Works Pei Xiu Award, in 2018, the Remote Sensing Image Atlas of Environmental Change in China, the Second Prize of National Science and Technology Progress Award of China, in 2014, National Earth System Science Data Sharing Platform Construction, Key Technology and Services Application, the Outstanding Instructor Award, in 2014, the Data sharing Cup contest supported by National Science and Technology Infrastructure, and the First Prize of Henan Province Science and Technology Progress Award, in 2013, the Earth System Science Data Sharing Key Technology Research and Application.



Dr. Wang received several academic awards, including the Bronze Award of Excellent Map Works Pei Xiu Award, in 2018, the Remote Sensing Image Atlas of Environmental Change in China, the Second Prize of National Science and Technology Progress Award of China, in 2014, National Earth System Science Data Sharing Platform Construction, Key Technology and Services Application, the Outstanding Instructor Award, in 2014, the Data sharing Cup contest supported by National Science and Technology Infrastructure, and the First Prize of Henan Province Science and Technology Progress Award, in 2013, the Earth System Science Data Sharing Key Technology Research and Application.

Dr. Wang received several academic awards, including the Bronze Award of Excellent Map Works Pei Xiu Award, in 2018, the Remote Sensing Image Atlas of Environmental Change in China, the Second Prize of National Science and Technology Progress Award of China, in 2014, National Earth System Science Data Sharing Platform Construction, Key Technology and Services Application, the Outstanding Instructor Award, in 2014, the Data sharing Cup contest supported by National Science and Technology Infrastructure, and the First Prize of Henan Province Science and Technology Progress Award, in 2013, the Earth System Science Data Sharing Key Technology Research and Application.

• • •