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Local Climate Change Induced by Urbanization on a South China Sea Island

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Abstract: The South China Sea is a hotspot for regional climate research. Over the past 40 years, considerable improvement has been made in the development and utilization of the islands in the South China Sea, leading to a substantial change in the land-use of the islands. However, research on the impact of human development on the local climate of these islands is lacking. This study analyzed the characteristics of local climate changes on the islands in the South China Sea based on data from the Yongxing Island Observation Station and ERA5 re-analysis. Furthermore, the influence of urbanization on the local climate of the South China Sea islands was explored in this study. The findings revealed that the 10-year average temperature in Yongxing Island increased by approximately 1.11 °C from 1961 to 2020, and the contribution of island development and urbanization to the local warming rate over 60 years was approximately 36.2%. The linear increasing trend of the annual hot days from 1961–2020 was approximately 14.84 days per decade. The diurnal temperature range exhibited an increasing trend of 0.05 °C per decade, whereas the number of cold days decreased by 1.06 days per decade. The rapid increase in construction on Yongxing Island from 2005 to 2021 led to a decrease in observed surface wind speed by 0.32 m s^{-1} per decade. Consequently, the number of days with strong winds decreased, whereas the number of days with weak winds increased. Additionally, relative humidity exhibited a rapid decline from 2001 to 2016 and then rebounded. The study also found substantial differences between the ERA5 re-analysis and observation data, particularly in wind speed and relative humidity, indicating that the use of re-analysis data for climate resource assessment and climate change evaluation on island areas may not be feasible.
Key words: local climate; climate change; Yongxing Island; a South China Sea island; climate change induced by urbanization
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1 INTRODUCTION

The South China Sea is a crucial passage for maritime routes in the Far East and Southeast Asia, serving as one of the busiest sea lanes globally. Additionally, the South China Sea plays a considerable role in the formation and development of the East Asian summer monsoon. As a result, the climate of the South China Sea is a research focus in regional climate studies [1-4]. Ding et al. emphasized the importance of studying the South China Sea monsoon in the context of monsoon and climate change research. Over the years, the unique characteristics of the South China Sea monsoon activity have been revealed through the collaborative efforts of scientists globally [5]. Wu et al. conducted a study using the South China Sea monsoon intensity index and found periodic variations in monsoon intensity over 25 years and its correlation with rainfall in Guangdong Province [6]. Lau et al. introduced early results of a South China Sea monsoon experiment, suggesting that the extension of the southwest monsoon flow over the South China Sea may have contributed to disastrous floods in the Yangtze River Basin in June 1998 [7]. The South China Sea is dotted with numerous islands that have historically provided crucial rest stops for fishing and navigation. Currently, these islands play vital roles in supporting maritime production, shipping logistics, and scientific research. Despite extensive knowledge of the oceanic climate in the South China Sea, the climatic characteristics of the islands in the region remain unclear.

The islands in the South China Sea are extremely unique land surfaces surrounded by vast expanses of ocean, and their spatial scale is almost negligible compared to that of the sea. Extensive research has been

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conducted to assess offshore climate resources [8-11]. Abramic et al. pointed out that the number and scale of offshore wind farms are expected to increase in the future [12]. Robertson et al. provided a quantitative analysis of offshore wind and wave conditions and highlighted that offshore wind and wave energy resources could be utilized to produce renewable energy and mitigate the impacts of climate change [13]. However, these studies did not consider the influence of islands on ocean surface meteorological parameters. This is partly owing to the scarcity of long-term observational data from island-based stations and partly because the spatial scale of the islands is much smaller than that of the ocean. Re-analysis data, an essential foundation for analyzing climate resources and climate change, has limitations. Even with high-resolution global re-analysis data, the grid resolution in low-latitude regions is typically approximately 26.7 km (15°N), whereas the majority of the South China Sea islands have spatial scales ranging from approximately 100–1000 m. The numerical models used to produce the re-analysis data have difficulty in considering and describing small-scale islands below its grid resolution. In particular, when focusing on the local climate changes of the islands, physical characteristics such as heat capacity, roughness, and albedo of the islands cannot be ignored. However, these elements have not been adequately described in the models used to produce the re-analysis data.

Over the past 40 years, there has been considerable development and utilization of the islands in the South China Sea, accompanied by a substantial change in the land-use of the islands. To manage the various social activities on the islands effectively, China established Sansha City in 2012. Since then, the development of the South China Sea islands has accelerated. According to local media reports, the population of Sansha City was approximately 400 in 2010. By the end of 2022, the total population of Sansha City reached 2,200, with the majority residing on Yongxing Island, where the city government is located. Since the 1980s, Yongxing Island has experienced significant development. In order to accommodate more population and create more development space, the land use types on the island have undergone significant changes, and the number of buildings has also increased significantly.

Considerable evidences have shown that urbanization is one of the substantial contributors to local climate change [14-22]. In some rapidly urbanized areas, urbanization has been found to account for over 80% of the local temperature increase. Qiao et al. highlighted that from 1988 to 2017 (or 2008 to 2017), urbanization had a positive impact on urban warming, with an increase of 0.02 °C (0.26 °C) every decade. They also observed that the contribution of urbanization to urban warming increased from 58.74% to 61.21%, indicating that urbanization is a primary driver of urban warming [23]. Deng et al. studied the long-term spatiotemporal evolution patterns of urban heat island effects using the spatio-temporal clustering (STC) model and emerging hotspot analysis; their study revealed that urban expansion has influenced changes in the urban heat island index in the Greater Bay Area, establishing a coupling relationship between the two factors [24]. However, existing literature on the impact of urbanization on local climate primarily focuses on the terrestrial environment, with limited research on the impact of human development on the local climate of island areas.

The meteorological observation station on Yongxing Island has provided data since the late 1950s. Based on the data from this station, it is possible to analyze the local climate change characteristics of the islands of the South China Sea. This analysis is essential not only for understanding specific climate changes in the South China Sea islands but also for gaining insights into the impact of urbanization on the local climate of remote sea islands.

2 DATA AND METHODS

2.1 *Ground observation data and ERA5 re-analysis data*

The data used in this study were obtained from the Yongxing Island, South China Sea, China, which is located approximately 280 km from the Chinese mainland, as shown in Fig. 1. The area of Yongxing Island is in a spatial scale of several km^2, which is much smaller compared to the grid scale of the ERA5 re-analysis data (0.25° × 0.25°). The meteorological observation station on Yongxing Island was established in 1957 for long-term observations of local

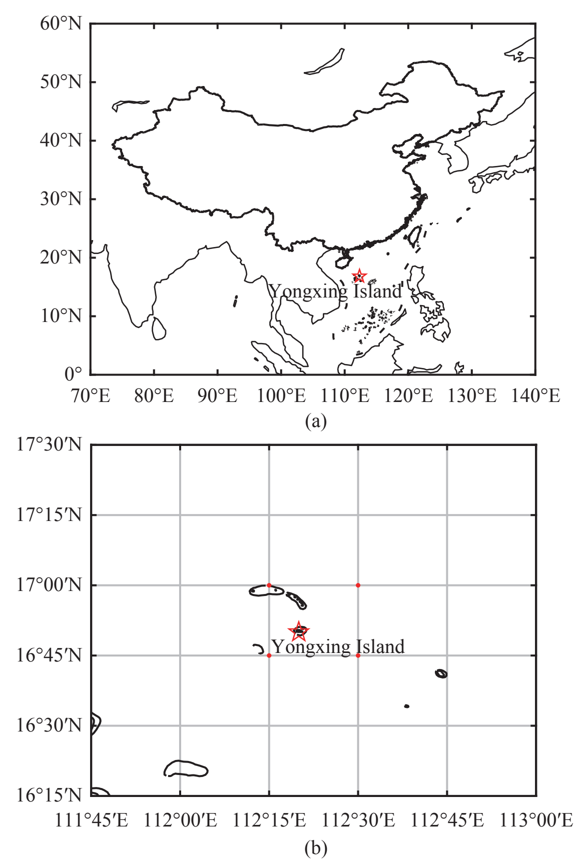

Figure 1. Geographic location of Yongxing Island (a) and the position of Yongxing Island within the grid area of 16°15′N–17°30′N and 111°45′E–113°E (b).

meteorological parameters. Observations are conducted at four local standard time points of 02:00, 08:00, 14:00, and 20:00 per day and have been continuously recorded since 1957 without interruption. In order to confirm and verify the observation results of Yongxing Island, the observation data of Coral Island during the period of 1975 to 2020 were compared with the data of Yongxing Island. Coral Island is about southwest to Yongxing Island, which is smaller than Yongxing Island. Like Yongxing Island, Coral Island has also had significant land-use change and new buildings since 1975.

Atmospheric re-analysis data are gridded datasets generated by assimilating and merging various observations such as radiosondes, surfaces, satellites, and other unconventional measurements using numerical models. In this study, we used ERA5 re-analysis data, which is the latest generation of re-analysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).

ERA5 represents a significant upgrade over its predecessor, ERA-Interim. It has a higher horizontal resolution, which improves from approximately 80 km in ERA-Interim to 0.25° × 0.25° in ERA5. The vertical layers have been increased to 60 levels, and the temporal resolution has been updated to 1 h. ERA5 includes 60 different physical parameters, including common variables such as air temperature, precipitation, and wind speed, as well as other comprehensive data such as the type of high vegetation, convective snowfall, wave spectral kurtosis, and wave spectral peakedness.

For this study, we used ERA5 data for surface parameters, including 2-m temperature, 2-m relative humidity, sea-level pressure, and 10-m wind speed. The period of the ERA5 data used in this study coincided with ground observation data from Yongxing Island, covering the period from 1961 to 2020.

2.2 *Research methods*

2.2.1 PRE-PROCESSING OF GROUND OBSERVATION DATA

In processing ground observation data, the first step involved data quality control, where missing data and outliers were removed from the dataset and excluded from the statistical analysis. The quality control process indicated that the data quality of the ground observations of Yongxing Island was relatively high, and the proportion of suspicious data to the total data did not exceed 0.01%.

Based on daily observations, annual data from 1961–2020 were calculated based on the following parameters: mean temperature, hot days (the number of days with high temperatures exceeding 30 °C), cold days (the number of days with low temperatures below 20 °C), mean diurnal temperature range, mean wind speed, number of days with strong winds, number of days with weak winds, and mean relative humidity.

2.2.2 SELECTION AND PROCESSING OF ERA5 RE-ANALYSIS DATA

In this study, we accessed ERA5 re-analysis data from the ECMWF data retrieval system, available at https://cds. climate. copernicus. eu/cdsapp#;/home. The data were downloaded at hourly intervals from 1961 to 2020. The selected variables included 2-m temperature, 2-m relative humidity, 10-m eastward wind speed, and 10-m northward wind speed. To obtain the relevant data for Yongxing Island, a grid size of 0.25° × 0.25° was selected, specifically covering the geographic coordinates of Yongxing Island, ranging from 112°15′E–112°30′E longitude and from 16°45′N–17°N latitude, as shown in Fig. 1b. We extracted the meteorological parameter values at four grid points representing the location of Yongxing Island. We then calculated the average values of the data from the four grid points to estimate the meteorological values for Yongxing Island. This method allowed us to obtain representative and meaningful estimates of the meteorological parameters for Yongxing Island within a grid [25].

2.2.3 STATISTICAL ANALYSIS METHODS

In this study, re-analysis data were used to represent the climate of the region where the island is located, whereas ground observation data were used to represent the local climate. The differences between the two were used to reflect the impacts of island development and urbanization on the local climate.

Several statistical parameters were calculated during the analysis to describe the relationship between the two datasets. These include the correlation coefficient (R), root mean square error (RMSE), mean bias (bias), and linear slope. R is a statistical measure of the strength of the linear relationship between two variables, and its calculation formula is as follows:

$$R = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \tag{1}$$

For the temperature relationship between the observation station and the reanalysis data sequence, this study utilized the correlation coefficient of two detrended sequences.

The RMSE was used to measure the magnitude of the error between the observed values and the re-analysis data. The calculation formula is as follows:

$$\mathrm{RMSE} = \frac{\sqrt{\sum_{i=1}^{n}(X_i - Y_i)^2}}{n} \tag{2}$$

Bias is the average difference between the observed values and re-analysis data. The calculation formula is as follows:

$$\mathrm{Bias} = \frac{\sum_{i=1}^{n}(X_i - Y_i)}{n} \tag{3}$$

In the above formulas, n represents the number of samples, X represents the observed values, and Y represents ERA5 re-analysis data.

Linear Least Squares Regression (LLSR) is employed to establish a linear regression model between meteorological variables and years in the current study. The details of the LLSR method can be found in the study of Li et al. [26].

3 RESULTS AND DISCUSSION

3.1 *Annual mean temperature*

Figure 2 depicts the variation in temperature on Yongxing Island based on ground observations from 1961 to 2020 and compares these data with the ERA5 re-analysis data for the same period. The RMSE between the re-analysis temperature and observed data is 0.07, whereas the bias is 0.52, indicating that the ground observations exhibit higher temperatures compared to the re-analysis data. Further analysis reveals that both the re-analysis and observed data exhibited a warming trend over the 60 years, with a high correlation coefficient (0.95) between the two datasets, while the detrended correlation coefficient is 0.94. These statistical results suggest a strong relationship between local temperature variations on Yongxing Island and the background climate changes represented by the re-analysis data. By comparing the data from Yongxing Island and Coral Island, we found that the temperature variability of Coral Island is almost the same as that of Yongxing Island. Although the spatial scale of Coral Island is smaller than that of Yongxing Island, and its development level is not as much as that of Yongxing Island, urbanization still influences it. Therefore, its observation data confirm that the data from Yongxing Island are reliable.

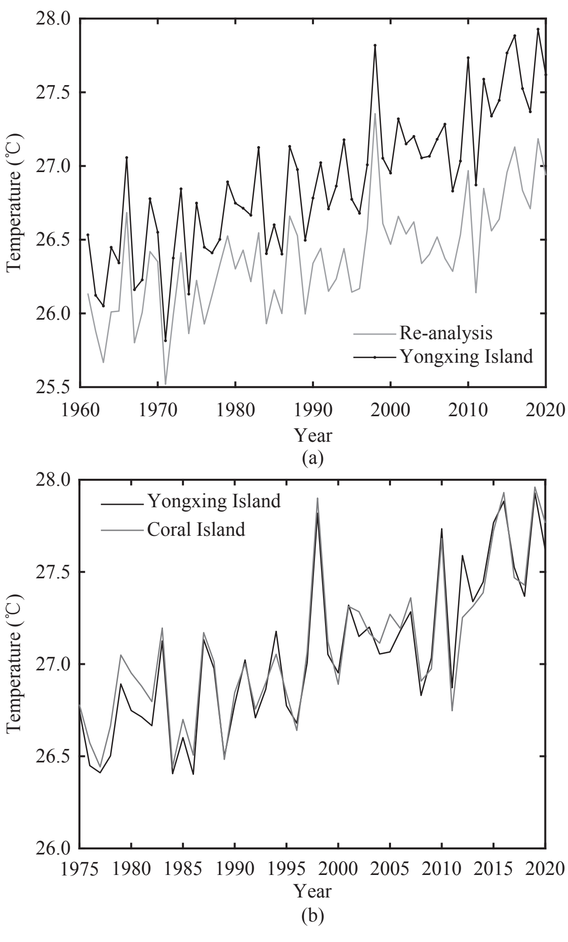

Figure 2. Comparison of annual mean temperature between re-analysis and observation data of Yongxing Island from 1961 to 2020 (a) and the comparison of annual mean temperature between the Coral Island observation station and the Yongxing Island observation station from 1975 to 2020 (b).

However, the warming rates reflected by the datasets from the re-analysis data and the observation data from Yongxing Island were not identical because the ground observation data showed a greater warming magnitude than the re-analysis data. According to the ground observation data, the average temperature on Yongxing Island was approximately 26.43 °C from 1961 to 1970, whereas it increased to approximately 27.53 °C in the period from 2011 to 2020. From 1961 to 2020, the 10-year average temperature increased by approximately 1.11 °C.

Based on the linear fitting of the time series from the ground observation data, the local temperature warming rate on Yongxing Island is estimated to be approximately 0.23 °C per decade. In contrast, the linear trend of the background climate reflected by the re-analysis data is approximately 0.15 °C per decade. It is worth noting that warming trends from the two datasets were statistically significant at a confidence level of 0.01, as determined using significance tests.

The IPCC Sixth Assessment Report indicates that global temperatures have experienced rapid warming since the 20^{th} century. The global average temperature during the period from 2011 to 2020 increased by approximately 1.1 °C compared to that in the late 19th century. Interestingly, the local warming on Yongxing Island over 60 years reached the same magnitude as the global average temperature increase over 120 years. By comparing the warming rates from the ground observation data and background climate warming rate reflected in the re-analysis data, it can be inferred that the contribution of island development and urbanization to local warming on Yongxing Island was approximately 36.2%. This contribution was smaller than the impact of rapid urbanization in the Pearl River Delta region. However, Yongxing Island is a small island with an area of less than 4 km^2, surrounded by a vast ocean with significant heat capacity and climate regulation ability. This indicates that even in regions far from the mainland, where the sea has become the dominant factor influencing climate, development, and land-use change on the natural underlying surface can still have a considerable impact on local climate.

Based on a comparison between the satellite remote sensing images from Google Earth from 2005 and 2021 (images not provided in the current paper), a significant increase in the number of buildings on Yongxing Island can be observed in recent years. Such changes to the island's surface may have important implications for various meteorological parameters in the area. The presence of buildings may lead to an increase in energy consumption and change the original physical properties of the underlying surface, which may have contributed to the rise in temperature on Yongxing Island.

3.2 *Hot and cold days*

Based on the defined criteria, in this study, a natural day is considered a “hot day” if the daily maximum temperature exceeds 30 °C and a “cold day” if the daily minimum temperature falls below 20 °C. Using this definition, the annual variations in the number of high- and low-temperature days on Yongxing Island were calculated separately based on both ground observation and ERA5 re-analysis data.

The results in Fig. 3 demonstrate that after 1971, the number of hot days on Yongxing Island gradually increased. The average annual number of hot days from 1961 to 1970 was 93.4 days, whereas it reached an average of 167.6 days from 2011 to 2020. The linear increasing trend in the number of hot days from 1961 to 2020 was 14.84 days per decade. However, the ERA5 re-analysis data did not accurately reflect this increasing trend, and ground observation data showed that the number of cold days on Yongxing Island showed a linear decreasing trend of 1.06 days per decade. The number of cold days, as shown by the ERA5 re-analysis data, also showed a decreasing trend.

3.3 *Diurnal temperature range*

Figure 4 shows that the diurnal temperature range of the observed data is notably larger than that of the reanalyzed data. After fitting, the diurnal temperature range of the observed data showed an upward trend at 0.05 °C per decade, which passed the significance test at 0.01 level. Some studies have indicated that although there was a global decrease in the diurnal temperature range during the latter half of the 20th century, the trends in the annual average diurnal temperature range in western and eastern Europe have shifted from decreasing in the 1970s to increasing. The trend in the diurnal temperature range may primarily be influenced by changes in emissions and related variations in incoming solar radiation [27].

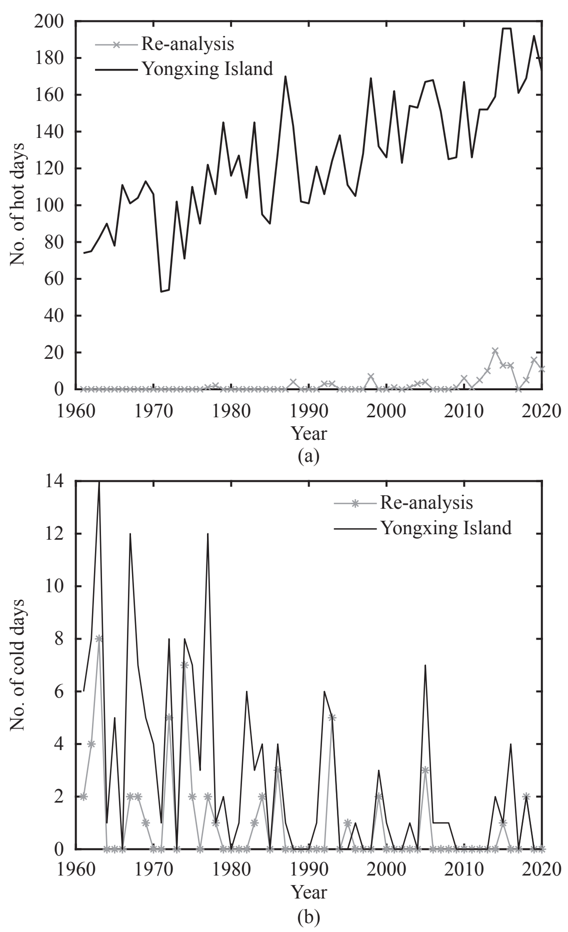

Figure 3. Comparison of the average annual number of hot days (a) and cold days (b) between re-analysis and observation data of Yongxing Island from 1961 to 2020.

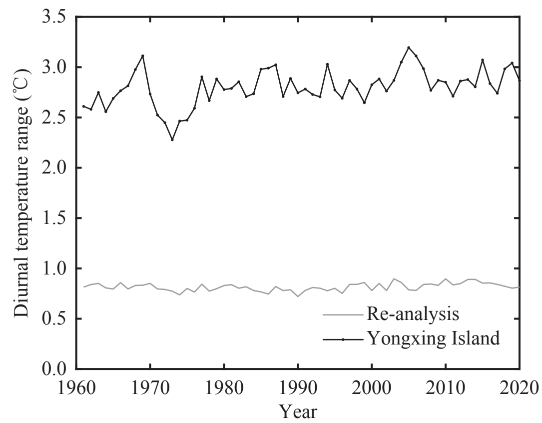

Figure 4. Comparison of annual mean temperature diurnal range between re-analysis and observation data of Yongxing Island from 1961 to 2020.

As development and construction on Yongxing Island progressed, the built-up area increased, likely resulting in a gradual increase in the diurnal temperature range. A comparison between the background and observed diurnal temperature ranges indicates that the urbanization on the island may have contributed to the increasing diurnal temperature range under the premise of a relatively small background diurnal temperature range. In contrast, the re-analysis data exhibited extremely small diurnal temperature ranges. In the background, which largely comprises tropical marine regions, the temperatures at 14:00 and 02:00 are nearly the same, and sometimes night-time temperatures may even be higher than daytime temperatures. This phenomenon may be related to the unique climatic and environmental conditions of tropical marine areas. However, the correlation coefficient between the observed and re-analysis data’s diurnal temperature range was hardly 0.21, and it did not pass the significance test at a level of 0.05; therefore, the re-analysis data representation of the diurnal temperature range in tropical marine island regions might be very limited.

3.4 *Annual mean wind speed*

Figure 5 shows the variations in the annual average wind speed. The re-analysis data indicate a relatively stable annual average wind speed of approximately 7 m s^{-1}, showing no significant changes over the past 60 years. However, the annual average wind speed calculated from ground observations exhibits a downward trend over the years, declining from 5.50 m s^{-1} in the early 1960s to a minimum of 3.18 m s^{-1} in 2018. The average wind speed was approximately 5.16 m s^{-1} in the period from 1961 to 1970 and decreased to 3.54 m s^{-1} in the years

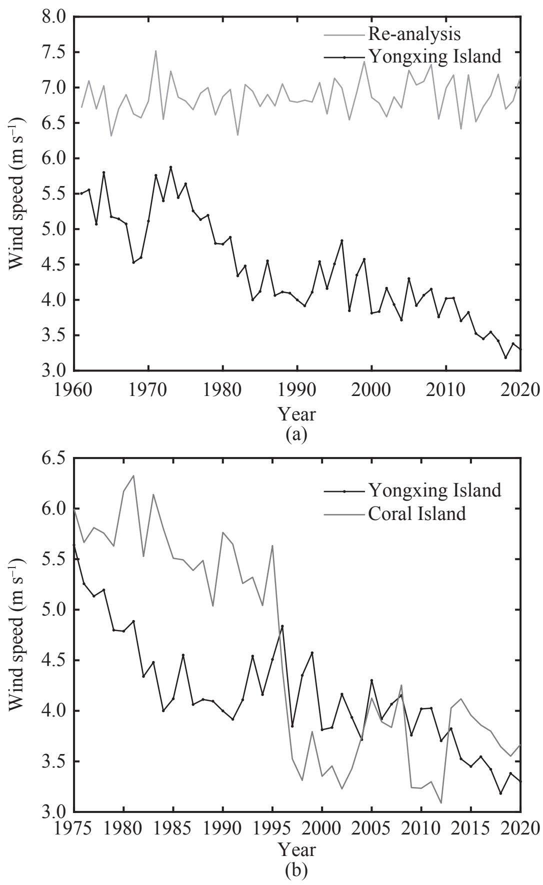

Figure 5. Comparison of annual mean wind speed between re-analysis and observation data of Yongxing Island from 1961 to 2020 (a) and a comparison of annual mean wind speed between the Coral Island observation station and the Yongxing Island observation station from 1975 to 2020 (b).

from 2011 to 2020. The linear fit of the ground observation data indicates a decrease of 0.32 m s^{-1} per decade.

The correlation coefficient between the re-analysis and ground observation data was 0.12, failing to pass the significance test at the confidence level of 0.05, indicating a low correlation between the two datasets. The comparison between the re-analysis and ground observation data suggests that although the background wind speed in the vicinity of Yongxing Island did not show significant changes over the 60 years, the island's average wind speed significantly decreased because of local development. To accommodate the rapidly increasing population and meet the growing port functions, there has been an increase in the number of buildings on Yongxing Island, leading to increased surface roughness, which dissipates near-surface airflow kinetic energy. By comparing the wind speeds at the Yongsxing Island Observatory and the Coral Island Observatory, we observed a more pronounced decrease in wind speed at Coral Island. This suggests that for smaller-scale islands, the impact of increased buildings on wind speed may be more noticeable.

3.5 *Days with strong winds and days with weak winds*

Figure 6 illustrates the variations in the number of days with strong and weak wind on Yongxing Island based

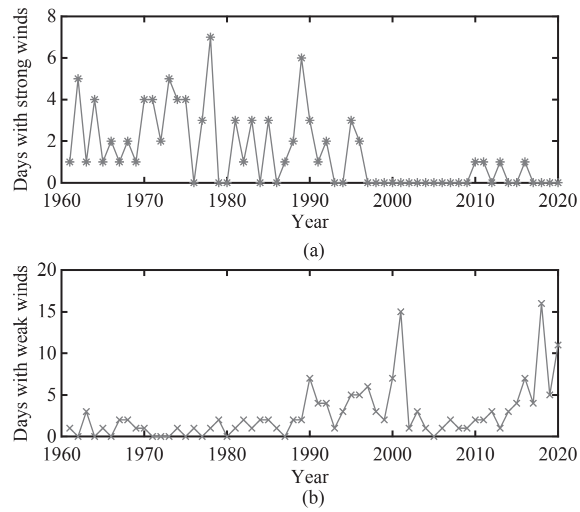

Figure 6. Annual total number of days with strong (a) and weak wind (b) in Yongxing Island observed data from 1961 to 2020.

on the defined criteria of natural days with wind speed exceeding 17.2 m s^{-1} for days with strong wind and daily maximum wind speed below 1.6 m s^{-1} for days with weak wind, using ground observation data.

Figure 6 shows that during the 1960s, Yongxing Island recorded at least one day with strong wind each year. From the 1970s to 1996, although there were some years without recorded days with strong wind, most years had such days. However, starting in 1997, the number of days with strong wind rapidly decreased, and in most years, no days with strong wind were recorded. In rare years, when a day with strong wind was recorded, there was usually one occurrence alone. Statistical analysis indicated a linear decreasing trend of approximately 0.5 days per decade for the number of days with strong wind, which passes the significance test at a confidence level of 0.01.

Conversely, the number of days with weak wind showed an increasing trend, rising by approximately 0.9 days per decade, and this upward trend also passed the significance test at a confidence level of 0.01. The simultaneous increase in days with weak wind and hot days has led to a decrease in climatic comfort on Yongxing Island.

3.6 *Annual mean relative humidity*

Research has indicated that an increase in impermeable surfaces during urbanization reduces the water-holding capacity of the underlying surface and, consequently, lowers the relative humidity [28]. Fig. 7 presents the variations in relative humidity on Yongxing Island since 1961. It is evident from Fig. 7 that the relative humidity from the re-analysis data remained consistently higher than the ground observation values, with the annual average relative humidity consistently maintained above 88%, which is a typical representation of maritime climates with high relative humidity. The RMSE and bias between the ground observations and the re-analysis data were relatively large, with a bias of −9.15, indicating that the observed values were significantly lower than those from the re-analysis data.

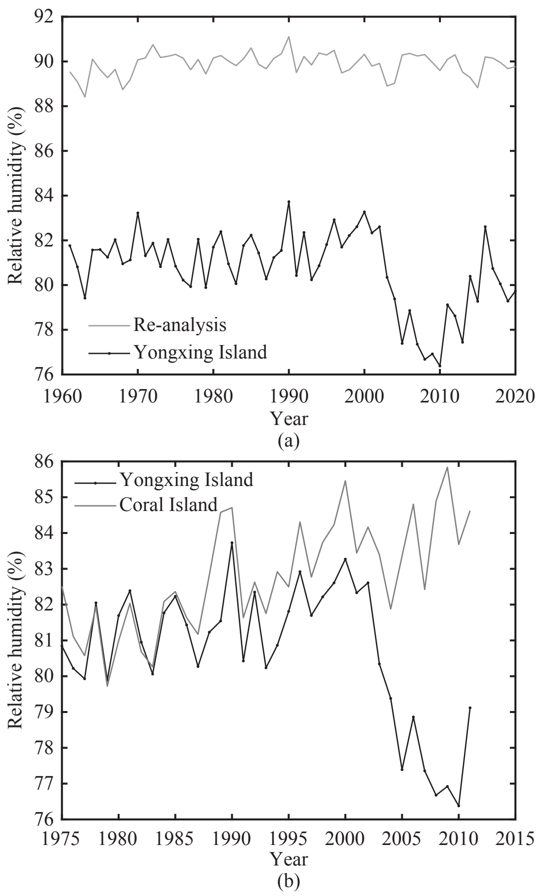

Figure 7. Comparison of annual mean relative humidity between re-analysis and observation data of Yongxing Island from 1961 to 2020 (a) and a comparison of annual mean relative humidity between the Coral Island observation station and the Yongxing Island observation station from 1975 to 2011 (b).

A comparison of the time series data revealed that the relative humidity obtained from ground observations remained consistently lower than that from the re-analysis data. This indicates that despite the small size of Yongxing Island, its local environment exhibits more land characteristics, resulting in a significant impact on its relative humidity from the land environment. Additionally, ground observations of relative humidity exhibited a sharp declining trend between 2002 and 2010, followed by a rapid increase after 2010, returning approximately to the average level before 2002. Local meteorological authorities confirmed that the period from 2002 to 2010 corresponded to a peak in the development and construction of Yongxing Island, with many new buildings being constructed. Clearly, these development and construction activities led to an increase in hardened surfaces on the island, resulting in a rapid decline in the local relative humidity. From 2011 onwards, the open spaces were utilized for planting various tropical plants, including coconut trees, leading to a rapid improvement in the island's ecological environment compared to that before 2010. Consequently, the relative humidity returned to normal levels in the short term.

Comparing Fig. 2 with Fig. 7, it is evident that relative humidity is more sensitive to human developmental activities than temperature. The response speed was rapid, which, to some extent, reflected the vulnerability of the island's climate. Additionally, some previous studies conducted on land have also indicated that during the 2000–2020 period, there was indeed a characteristic trend of relative humidity changing from decreasing to increasing. Still, the rate of change was not as notable as that observed on Yongxing Island [26]. The humidity comparison between the Yongxing Island Observatory and the Coral Island Observatory indicates that Coral Island consistently maintains good continuity, possibly due to the relatively fixed and continuous nature of its observation point. At the same time, there is an upward trend in humidity on Coral Island, suggesting that the warming effect has led to increased evaporation of water vapor, and this effect is more pronounced on smaller-scale islands.

3.7 *Comparison of re-analysis data with ground observation data*

Table 1 provides some statistics for ground observation data and reanalysis data. The differences between ground-based observations and re-analysis data indicate that the use of re-analysis data for climate resource assessment and climate change evaluation in the South China Sea islands is not feasible. It is essential to consider the possible impact of changes in the island's surface roughness on wind power resources. When evaluating meteorological conditions, the use of re-analysis data may also differ considerably from the actual situation in terms of the number of hot and cold days, diurnal temperature range, relative humidity, and other aspects.

3.8 *Comparison with other studies*

Table 2 provides a comparison of the climate variability of Yongxing Island with the climate variability recorded at several coastal stations beside the South China Sea. Through comparison with other cities, it can be observed that the rate of temperature rise of Yongxing Island is between those of Hong Kong and Shenzhen, which shows that urbanization have had a significant impact on the local climate of the South China Sea island since both cities are renowned for their significant impact of urbanization on their local climates [26].

4 CONCLUSION

Based on the analysis of ground observation and ERA5 re-analysis data, as well as the study of local climate change

Table 1. *R*, RMSE, and bias between observed values and ERA5 re-analysis data for temperature, wind speed, and relative humidity. In the table, an asterisk (*) indicates that the result passed the significance test at the 0.05 level, and a double asterisk (**) indicates that it passed the significance test at the 0.01 level.

Physical quantity	*R*	RMSE	Bias
Temperature (°C)	0.9375**	0.0703	0.5164
Wind speed (m s^{-1})	0.1177	0.3285	–2.4424
Relative humidity (%)	0.2596*	1.1948	–9.1104

Table 2. Comparison of warming rate and the contribution of urbanization to the warming rate and wind speed variability between Yongxing Island and other regions. The warming rate and contribution of urbanization to the warming rate for Shenzhen and Hong Kong are cited from Li et al. [26]. The warming rates and contribution of urbanization to the warming rate for Macao are quoted from Fong et al.'s study [29]. The wind speed variability for Shenzhen, Hong Kong, and Macao is cited from Ren et al.'s study [30].

Regions	Warming rate (°C $10a^{-1}$)	Contribution of urbanization to the warming rate (%)	Wind speed variability (m s^{-1} $10a^{-1}$)
Yongxing island (small island)	0.23	37.6	0.32
Shenzhen (megacity)	0.35	81.4–85.1	0.25–0.42
Hong Kong (large city)	0.10	42.3	0.25–0.42
Macao (small city)	0.10	–	0.25–0.42

on Yongxing Island, the following conclusions were drawn.

(1) The ground observation data shows that the 2-m temperature on Yongxing Island exhibits a linear trend of approximately 0.23 °C per decade. In contrast, the ERA5 re-analysis data hardly displays a temperature trend of around 0.15 °C per decade. This indicates that human development and utilization have a significant impact on the local climate of the island.

(2) Since 1971, the number of hot days in Yongxing Island has gradually increased. The linear increasing trend in the number of hot days from 1961 to 2020 was approximately 14.6 days per decade. Ground observation data indicate a declining trend in the number of cold days on Yongxing Island, with a linear decrease of approximately 0.2 days per decade.

(3) The diurnal temperature range from the observed data reveals an upward trend of approximately 0.06 °C per decade, based on linear fitting. In contrast, the re-analysis data have a small diurnal temperature range.

(4) The ground observation data on Yongxing Island revealed a linear trend of approximately 0.32 m s^{-1} decrease in wind speed per decade. The wind speed reached its lowest value of 3.18 m s^{-1} in 2018. This declining wind speed trend is likely related to the island′s development and land-use changes, which have increased the surface roughness of Yongxing Island.

(5) The observation data analysis indicates that Yongxing Island has experienced a linear decrease in the number of days with strong winds (approximately 0.5 days per decade). In contrast, the number of days with weak winds has shown an increasing trend of approximately 0.9 days per decade. Both trends were statistically significant at a confidence level of 0.01.

(6) The relative humidity on Yongxing Island remained consistently lower than that represented by the background marine conditions throughout the entire period from 1961 to 2020. The rapid decrease and subsequent increase in relative humidity from 2000 to 2020 can be attributed to the urbanization and the greening in the region. Rapid fluctuations in relative humidity suggest that the island's climate is influenced by both natural climatic changes and human-induced factors, making it a dynamic and vulnerable environment in terms of relative humidity variations.

(7) It is not feasible to evaluate the climate resources and climate change of the South China Sea islands using re-analysis data.

(8) A comparison with other cities reveals that temperatures on Yongxing Island are rising at a rate between Hong Kong and Shenzhen and that urbanization have a significant impact on the local climate of the South China Sea island.

These conclusions indicate that Yongxing Island exhibits notable trends in temperature, wind speed, and humidity, highlighting distinct climate change. However, the limited applicability of the ERA5 re-analysis data is evident for specific meteorological parameters. These findings are of significant importance for gaining a deeper understanding of the climatic characteristics and trends of the South China Sea Islands and their potential impacts on related fields. Nevertheless, these conclusions are based on an analysis of existing ground observations and ERA5 re-analysis data, which may be subject to data limitations and other influencing factors. Future studies should further explore the variations in upper-air meteorological elements on Yongxing Island. Specifically, incorporating radar-sounding data to discuss changes in wind speed will help to enhance our understanding and predictive capabilities of climate change in the upper level of this region.

REFERENCES

[1] FAN Y, ZHU S P, WANG L J, et al. Subseasonal dynamical prediction of South China Sea summer monsoon [J]. Atmospheric Research, 2022, 278: 106347, https://doi.org/10.1016/j.atmosres.2022.106347

[2] LAU K M, YANG S. Climatology and interannual variability of the southeast Asian summer monsoon [J]. Advances in Atmospheric Sciences, 1997, 14: 141–162, https://doi.org/10.1007/s00376–997–0016-y

[3] WANG B, ZHANG Y, LU M M. Definition of South China Sea monsoon onset and commencement of the East Asia summer monsoon [J]. Journal of Climate, 2004, 17(4): 699–710, https://doi.org/10.1175/2932.1

[4] LIU C W, YANG Q H, XU M, et al. Response of sea surface heat fluxes to the South China Sea summer monsoon onset in 2021 [J]. Atmospheric Research, 2023, 282: 106513, https://doi.org/10.1016/j.atmosres.2022.106513

[5] DING Y H, LI C Y, LIU Y J. Overview of the South China sea monsoon experiment [J]. Advances in Atmospheric Sciences, 2004, 21: 343−360, https://doi.org/10.1007/BF02915563

[6] WU S S, LIANG J Y. Intensity index of South China Sea

monsoon and its variation characteristics [J]. Journal of Tropical Meteorology, 2002, 8(1): 1−9, https://jtm.itmm.org.cn/en/article/id/20020101

[7] LAU K M, DING Y H, WANG J T, et al. A report of the field operations and early results of the South China Sea Monsoon Experiment (SCSMEX) [J]. Bulletin of the American Meteorological Society, 2000, 81(6): 1261−1270, https://doi.org/10.1175/1520–0477(2000)081<1261:AROTFO>2.3.CO;2

[8] HE J Y, CHAN P W, LI Q S, et al. Mapping future offshore wind resources in the South China Sea under climate change by regional climate modeling [J]. Renewable and Sustainable Energy Reviews, 2023, 188: 113865, https://doi.org/10.1016/j.rser.2023.113865

[9] THOMAS B, COSTOYA X, DECASTRO M, et al. Downscaling CMIP6 climate projections to classify the future offshore wind energy resource in the Spanish territorial waters [J]. Journal of Cleaner Production, 2023, 433: 139860, https://doi.org/10.1016/j.jclepro.2023.139860

[10] COSTOYA X, DECASTRO M, CARVALHO D, et al. Climate change impacts on the future offshore wind energy resource in China [J]. Renewable Energy, 2021, 175: 731–747, https://doi.org/10.1016/j.renene.2021.05.001

[11] COSTOYA X, DECASTRO M, CARVALHO D, et al. On the suitability of offshore wind energy resource in the United States of America for the 21st century [J]. Applied Energy, 2020, 262: 114537, https://doi.org/10.1016/j.apenergy.2020.114537

[12] ABRAMIC A, CORDERO-PENIN V, HAROUN R. Environmental impact assessment framework for offshore wind energy developments based on the marine Good Environmental Status [J]. Environmental Impact Assessment Review, 2022, 97: 106862, https://doi.org/10.1016/j.eiar.2022.106862

[13] ROBERTSON B, DUNKLE G, GADASI J, et al. Holistic marine energy resource assessments: A wave and offshore wind perspective of metocean conditions [J]. Renewable Energy, 2021, 170: 286−301, https://doi.org/10.1016/j.renene.2021.01.136

[14] HAO M Q, GAO C, GU C X, et al. Numerical simulation of the impact of urbanization on climate in Taihu Lake Basin [J]. Ecological Indicators, 2023, 154: 110522, https://doi.org/10.1016/j.ecolind.2023.110522

[15] ZHAO Q K, GAO L, MENG Q Y, et al. Nonlinear causal relationships between urbanization and extreme climate events in China [J]. Journal of Cleaner Production, 2024, 434: 139889, https://doi.org/10.1016/j.jclepro.2023.139889

[16] DENG Z F, WANG Z L, WU X S, et al. Strengthened tropical cyclones and higher flood risk under compound effect of climate change and urbanization across China's Greater Bay Area [J]. Urban Climate, 2022, 44: 101224, https://doi.org/10.1016/j.uclim.2022.101224

[17] REN Z B, FU Y, DONG Y L, et al. Rapid urbanization and climate change significantly contribute to worsening urban human thermal comfort: A national 183-city, 26-year study in China [J]. Urban Climate, 2022, 43: 101154, https://doi.org/10.1016/j.uclim.2022.101154

[18] YUAN J C, LIN Q Y, CHEN S S, et al. Influence of global warming and urbanization on regional climate of Megacity: A case study of Chengdu, China [J]. Urban Climate, 2022, 44: 101227, https://doi.org/10.1016/j.uclim.2022.101227

[19] JIA W Q, REN G Y, SUONAN K Z, et al. Urban heat island effect and its contribution to observed temperature increase at Wuhan station, central China [J]. Journal of Tropical Meteorology, 2019, 25(1): 102–113, https://doi.org/10.16555/j.1006–8775.2019.01.010

[20] WANG Z Q, XIAO Z X, TAM C Y, et al. The projected effects of urbanization and climate change on summer thermal environment in Guangdong-Hong Kong-Macao Greater Bay Area of China [J]. Urban Climate, 2021, 37: 100866, https://doi.org/10.1016/j.uclim.2021.100866

[21] WANG W W, ZHOU W, NG E Y Y, et al. Urban heat islands in Hong Kong: statistical modeling and trend detection [J]. Natural Hazards, 2016, 83(2): 885–907, https://doi.org/10.1007/s11069–016–2353–6

[22] GRIMM N B, FAETH S H, GOLUBIEWSKI N E, et al. Global change and the ecology of cities [J]. Science, 2008, 319: 756–760, https://doi.org/10.1126/science.1150195

[23] QIAO Z, WANG N, CHEN J Y, et al. Urbanization accelerates urban warming by changing wind speed: Evidence from China based on 2421 meteorological stations from 1978 to 2017 [J]. Environmental Impact Assessment Review, 2023, 102: 107189, https://doi.org/10.1016/j.eiar.2023.107189

[24] DENG X D, GAO F, LIAO S Y, et al. Spatiotemporal evolution patterns of urban heat island and its relationship with urbanization in Guangdong-Hong Kong-Macao greater bay area of China from 2000 to 2020 [J]. Ecological Indicators, 2023, 146: 109817, https://doi.org/10.1016/j.ecolind.2022.109817

[25] YAN Z W, WANG J, XIA J J, et al. Review of recent studies of the climatic effects of urbanization in China [J]. Advances in Climate Change Research, 2016, 7(3): 154−168, https://doi.org/10.1016/j.accre.2016.09.003

[26] LI L, CHAN P W, WANG D L, et al. Rapid urbanization effect on local climate: intercomparison of climate trends in Shenzhen and Hong Kong, 1968–2013 [J]. Climate Research, 2015, 63(2): 145−155, https://doi.org/10.3354/cr01293

[27] MAKOWSKI K, WILD M, OHMURA A. Diurnal temperature range over Europe between 1950 and 2005 [J]. Atmospheric Chemistry and Physics, 2008, 8(21): 6483−6498, https://doi.org/10.5194/acp-8–6483–2008

[28] GRIMMOND S. Urbanization and global environmental change: local effects of urban warming [J]. The Geographical Journal, 2007, 173(1): 83−88, https://www.jstor.org/stable/30113496

[29] FONG S K, WU C S, WANG A Y, et al. Analysis of surface air temperature Change in Macao during the period 1901–2007 [J]. Advances in Climate Change Research, 2010, 1(2): 84−90, https://doi.org/10.3724/SP.J.1248.2010.00084

[30] REN L, JI J C, LU Z J, et al. Spatiotemporal characteristics and abrupt changes of wind speeds in the Guangdong-Hong Kong-Macau Greater Bay Area [J]. Energy Reports, 2022, 8: 3465−3482, https://doi.org/10.1016/j.egyr.2022.02.224

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