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Study on the Applicability of ERA5 Reanalysis Data at Lake Taihu

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Abstract

Lakes are an important component of the earth climate system. They play an important role in the study of basin weather forecasting, air quality forecasting, and regional climate research. The accuracy of driving variables is the basic premise to ensure the rationality of lake mode simulation. Based on the *in-situ* observations at Bifenggang site of the Lake Taihu Eddy flux Network from 2012 to 2017, this paper investigated temporal variations in temperature, relative humidity, wind speed, radiation components at different time scales (hourly, seasonal and interannual). ERA5 reanalysis data were compared with *in-situ* observation to quantify the error and evaluate the performance of reanalysis data. The results show that: 1) On the hourly scale, the ERA5 reanalysis data described air temperature, and downward long-wave radiation more accurately. 2) On the seasonal variation scale, the ERA5 reanalysis data described air temperature, and downward long-wave radiation more accurately. However, the descriptions of wind speed, relative humidity and downward short-wave have large deviations. 3) On the interannual scale, the ERA5 reanalysis data show a good performance for temperature, followed by downward longwave radiation, downward shortwave radiation and relative humidity.

Keywords

Lake Taihu, ERA5 Reanalysis Data, Meteorological Variables, Comparison, Applicability

1. Introduction

As an important component of the earth climate system, lakes play an important role in regional and global climate change (Adrian et al., 2009). Firstly, evaporation from lakes is an important source of atmospheric water vapour (Wang et al., 2018), and the resulting lake effect can directly trigger heavy precipitation events such as heavy rainfall and snowstorms downstream (Samuelsson et al., 2010). Secondly, the specific heat capacity of lake water is greater than that of land, so when receiving the same amount of solar radiation, the warming rate of lakes will be slower than that of the surrounding land, acting as a buffer against temperature changes and slowing down the warming trend of the basin (Sills et al., 2011). Lakes are considered to be a source of atmospheric CO_2 and CH_4 and have a significant impact on the regional and global greenhouse gas cycle (Cole et al., 1994; Bastviken et al., 2011). Furthermore, the physical, chemical, biological and ecological processes of lakes respond significantly to climate change (Zhang, 2015) and can be indicative of climate change to some extent (Ke, 2004). In summary, the study of momentum, energy and material exchange processes between lakes and the atmosphere has important implications for scientific issues such as local weather, regional climate, the greenhouse gas cycle and climate change.

Compared with observational methods, lake dynamics model simulations can not only describe the physical and chemical processes of lakes in detail, but also expand the spatial and temporal scales of lake gas exchange studies (Liu et al., 2005; Zhang et al., 2020a; Wang et al., 2017; Wang et al., 2014). However, direct observations are mostly single-point observations in lake science, which have the disadvantages of small spatial coverage, limited representativeness, short time duration and discontinuous data records, making it difficult for single-point observations to fully reflect the true characteristics of lake gas exchange, especially in large lakes and lakes with high spatial heterogeneity (Lee et al., 2014). For this reason, academics in China and abroad have started to use reanalysis data to drive lake dynamics models (e.g. NCAR LISSS, National Center for Atmospheric Research, Lake, Ice, Snow, Sediment Simulator) to simulate the physical, biological, chemical and ecological processes of lakes and air exchange processes. Reanalysis data is a re-integration and integration of multiple categories and sources of short-term numerical weather prediction products and observations using the most complete data assimilation system (Zhao et al., 2010). Compared with fixed-point observations, reanalysis data have a wide spatial coverage, a large time span and a continuous data record, which can effectively compensate for the shortcomings caused by direct observation methods and make it possible to study the response of lake ecosystems to climate change on a larger spatial scale. Therefore, the accuracy and applicability of reanalysis data based on *in situ* observation data are crucial to quantitative assessment.

In recent years, scientists at home and abroad have conducted extensive and in-depth accuracy evaluation studies on the temperature, humidity and altitude fields of various reanalysis data based on observational data (Zhang et al., 2017; Liu et al., 2014; Fujihara et al., 2014; Zhao et al., 2013; Boilley & Wald, 2015; Berrisford et al., 2011; Dee et al., 2011; Yang et al., 2020; Gao & Hao, 2014; Xie et al., 2021), and have also conducted evaluation studies on ERA5 reanalysis data.

Meng et al. (2018) found that the ERA5 data had strong correlation between sea level pressure and temperature in Shandong; Zhang et al. (2020b) found that the mean relative humidity of the ERA5 simulations was better compared to NCEP-FNL when studying an atmospheric pollution process in the Sichuan basin in January 2018. Liu et al. (2021) used ERA5 data to analyse the climatic characteristics of regional 10 m height winds over mainland China during 1979-2018, and showed that the 10 m and 100 m wind speed were in good agreement with station observations in terms of spatial distribution and climatic characteristics evolving on annual and seasonal scales. Peng et al. (2021) used ERA5 to assess the feasibility of integrated water vapour trends (IWV) over the European continent. Nefabas et al. (2021) used ERA5 data to simulate the wind-powered electricity system of an Ethiopian wind farm, and the results showed good correlation between the measured and ERA5 simulated models. In summary, studies on the evaluation of the applicability of ERA5 reanalysis information have focused on land, and it is unclear how applicable ERA5 reanalysis information are on lakes due to the lack of long-term actual measurement data on lakes. Although the ERA5 reanalysis data are more accurate in describing the meteorological fields of a wide range of subsurfaces, the applicability in large shallow lakes such as Lake Taihu is not known.

Lake Taihu, the third largest freshwater lake in China, has an important influence of climate change on the Lake Taihu basin and the Yangtze River Delta region (Yang et al., 2013; Cao et al., 2015). Liu et al. (2013) found that the lake air exchange process in Taihu Lake enhances the heat island circulation in coastal cities. Ren et al. (2017) found that lake and air exchange processes in Taihu Lake change the distribution of surface heat and water vapour, thus affecting the development of nearby urban heat islands. It can be seen that the use of reliable data driven lake dynamic models to accurately simulate the lake air exchange process in Lake Taihu is important for weather forecasting, regional climate change prediction and air quality forecasting in the Lake Taihu basin. The driving variables that need to be input to a lake dynamic model (e.g. NCAR LISSS model) include temperature, wind speed, specific humidity, downward shortwave radiation, upward shortwave radiation and downward longwave radiation (Oleson et al., 2013). To carry out simulations of lake and air exchange processes on long time scales, reanalysis data must be used as the driving data source and the applicability of reanalysis data in Lake Taihu must be evaluated before numerical simulations and analysis of the results can be carried out. Due to the high spatial and temporal resolution, the long age of data accumulation and the widely validated accuracy, this paper, based on the meteorological and radiometric observations of the Lake Taihu mesoscale flux network shelter station (BFG) from 2012 to 2017, compares the ERA5 reanalysis data with the temperature, relative humidity, wind speed and radiation components of the BFG station at different scales (hourly, seasonal and interannual). A comparative analysis was carried out to assess the error and applicability of ERA5 at Lake

Taihu.

2. Data and Methods

2.1. Observed Station

2.1.1. Introduction of Lake Taihu

Lake Taihu is located at the southern edge of the Yangtze River Delta in China, in the economically developed and highly urbanized Yangtze River Delta urban agglomeration of China, and is surrounded by four large cities with a population of over one million, which named Wuxi City on the northern shore of Taihu Lake, Huzhou City on the southern shore, Yixing City on the western shore and Suzhou City on the eastern shore. The latitude range of Lake Taihu is 30˚55'40" - 31˚32'58"N and the longitude range is 119˚052'32" - 120˚036'10"E. Lake Taihu is a typical large subtropical shallow water lake with a surface area of 2400 square metres and average depth of 1.9 m (Qin et al., 2007; Huang & Xu, 2009). Lake Taihu belongs to a subtropical monsoon climate zone with significant weather variations in all seasons. In summer, the prevailing wind direction is southeasterly, with hot weather and abundant precipitation; in winter, the prevailing wind direction is northerly, with low temperatures and high wind speeds.

2.1.2. Introduction of Lake Taihu Mesoscale Flux Network Data

The meteorological and radiometric data used in this paper are provided by the BFG station (31.17˚N, 120.40˚E) at Lake Taihu, as shown in **Figure 1**, which is located in the eastern part of Lake Taihu and is part of the Lake Taihu Mesoscale Flux Network established by the Yale University-Nanjing University of Information Science and Technology Centre on Atmospheric Environment (Lee et al., 2014). As shown in **Table 1**, the BFG station equipped with a comprehensive

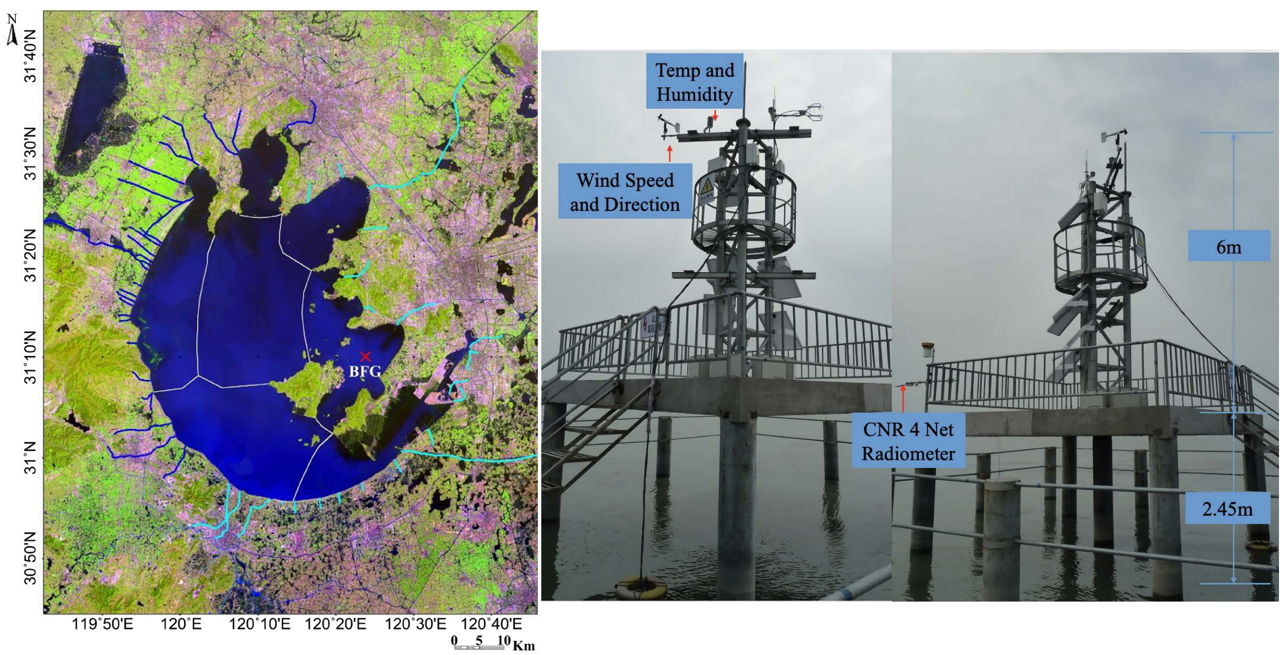


Figure 1. The geographical location of the Lake Taihu site and its observation system.

observation system, including microclimate observation system, CNR4 net radiometer, vorticity correlation system and water temperature gradient observation system (Lee et al., 2014). The data used in this paper are temperature Ta, relative humidity RH, mean wind speed U, downward short-wave radiation $K_{\downarrow}$ and downward long-wave radiation $L_{\downarrow}$ on a half-hourly scale from 2012 to 2017.

2.1.3. Microclimate and Radiation Observation System at the Shelter Station

Table 1. Basic information of the microclimate and radiation observation system at the Lake Taihu Meteorological Station.

Observation system	System Component	Instrument manufacturers and models	Observation elements	Height of erections
Microclimae	Temperature and humidity	HMP155A, Vaisala Inc.	Temperature T_a Humidity e_a	8.5 m 8.5 m
	Wind speed and direction	05103, R.M. Young Company	Average wind speed U	8.5 m
Radiation	CNR4Net Radiometer	CNR4, Kipp & Zonen B. V.	Downward shortwave radiation $K_{\downarrow}$ Upward shortwave radiation $K_{\uparrow}$ Downward longwave radiation $L_{\downarrow}$ Upward longwave radiation $L_{\uparrow}$	2 - 3 m

2.2. Reanalysis Data and Calculation Methods

2.2.1. Introduction of ERA5 Data

ERA5 reanalysis data is the fifth generation of global atmospheric reanalysis information implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), with data updated in real time every month usually. Compared to the ERA-interim data, ERA5 is a major improvement, with an increased spatial resolution of 31 km × 31 km, a vertical division into 137 layers, and a top pressure of 1 hPa; an upgrade of the Integrated Forecasting System (IFS) model from Cy 31r2 to Cy 41r2; and an increase in the number of variables provided by ERA5 from 100 to 240, which includes variables such as wave height and direction provided by the coupled wave models. The analysis product will be updated on an hourly scale from every 6 h to 1 h.

The ERA5 reanalysis data used in this paper are taken from the European Centre for Medium-Range Weather Forecasts website (https://www.ecmwf.int/). The downloaded meteorological element data include hourly and seasonal scale from air temperature Ta (2 m), dew point temperature Td (2 m), mean wind speed U, downward shortwave radiation $K_{\downarrow}$, to downward longwave radiation $L_{\downarrow}$. The hourly scale data were selected from 02, 08, 14 and 20 o'clock in Beijing time. The spatial resolution of the above meteorological elements is 0.1˚ × 0.1˚. According to the downloaded ERA5 reanalysis data which are closest grid points of the BFG station, we can calculate the mean value.

2.2.2. Calculation of ERA5 Data

The dew point temperature is an important parameter for characterizing atmospheric humidity. The saturation water vapour pressure calculated using the dew point temperature T_d and water vapour pressure e_a. The calculation formula is below.

$$e_a = 6.1078\exp\left[\frac{17.2693883(T_d - 273.16)}{T_d - 35.86}\right] \quad (1)$$

Saturated water vapour pressure is calculated using the actual temperature (T_a). The calculation formula is below.

$$e_s = 6.1078\exp\left[\frac{17.2693883(T_a - 273.16)}{T_a - 35.86}\right] \quad (2)$$

Relative Humidity (RH) is calculated as follows.

$$\text{RH} = \frac{e_a}{e_s} * 100\% \quad (3)$$

2.2.3. Statistical Parameters Formulae

In this paper, the correlation coefficient (R), root mean square error (RMSE), and relative deviation (BIAS) to assess the simulation capability of ERA5 reanalysis data for meteorological elements at BFG station, and each statistical parameter is calculated by the following equations.

$$R = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) * (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}\left[(x_i - \bar{x})^2 * (y_i - \bar{y})^2\right]}} \quad (4)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left[(x_i - \bar{x})^2 * (y_i - \bar{y})^2\right]}{n}} \quad (5)$$

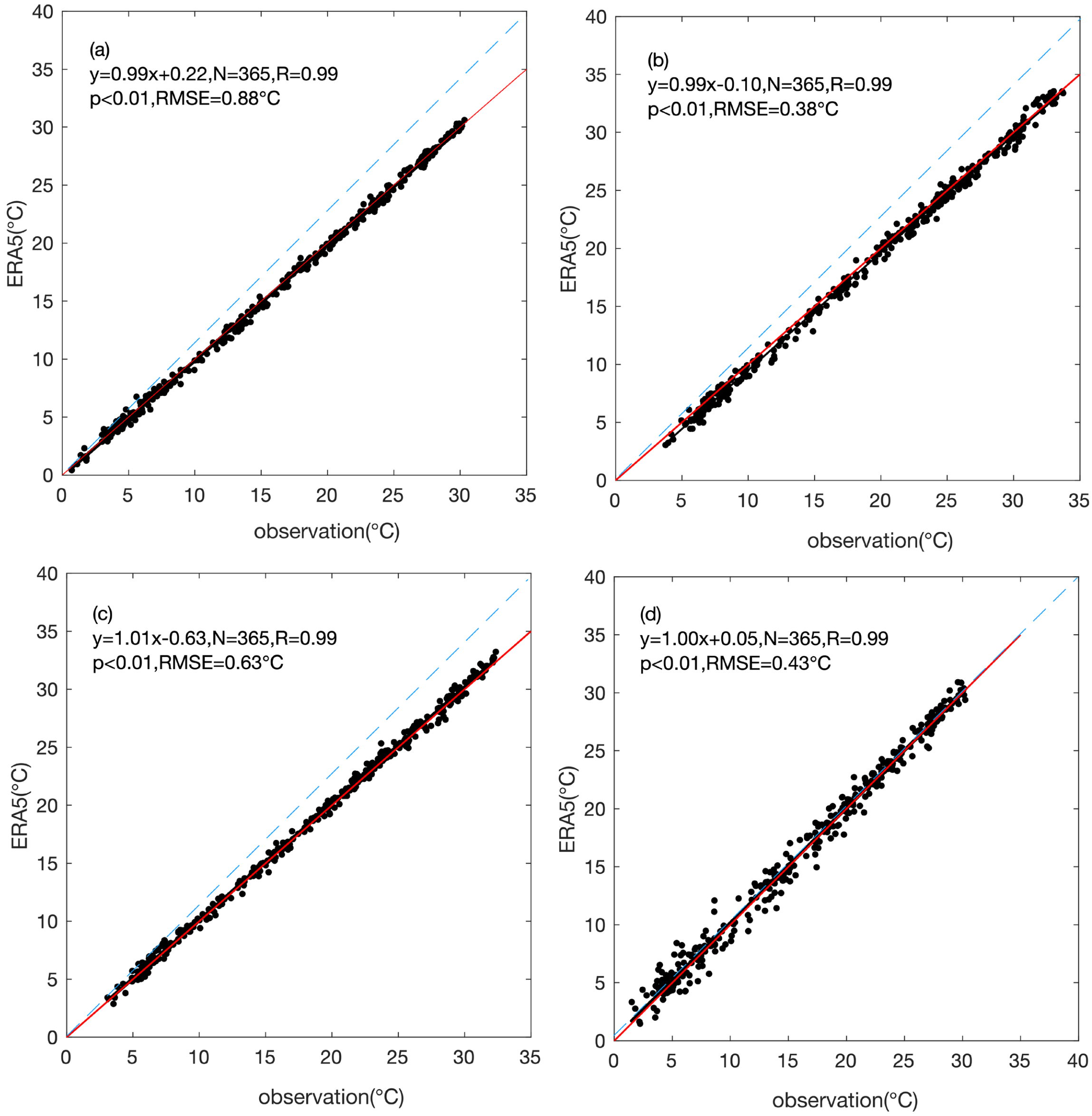
$$\text{BIAS} = \frac{\sum_{i=1}^{n} y_i - x_i}{\sum_{i=1}^{n} x_i} \quad (6)$$

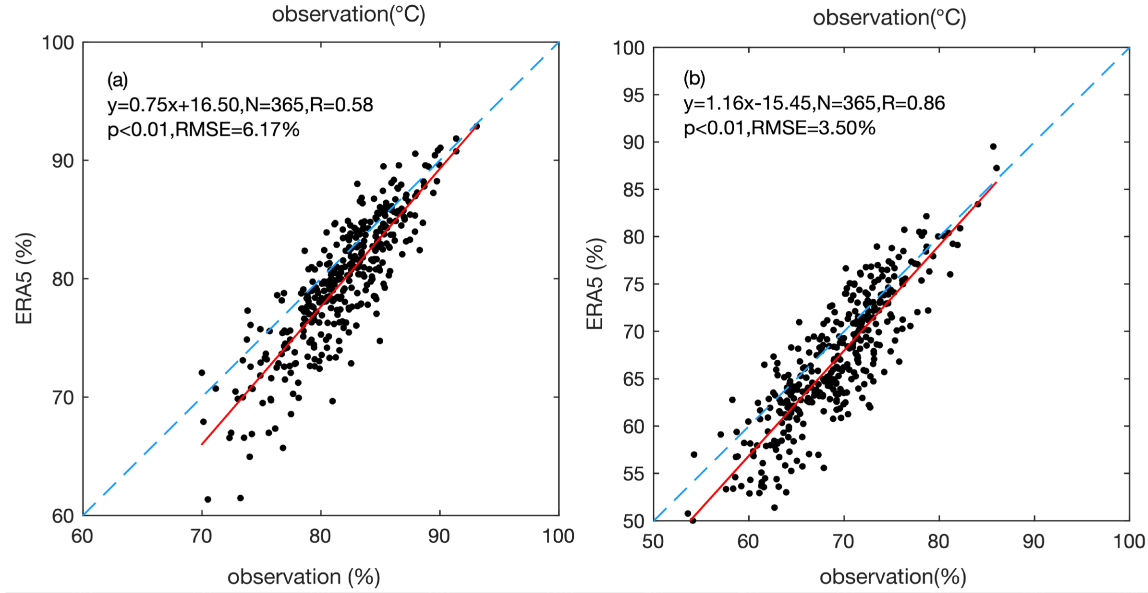
x and y represent ERA5 reanalysis information and observations respectively, and n is the number of samples used to calculate the statistical parameters.

3. Results and Discussion

3.1. Hourly-Scale Differences

For more visually represent the characteristics of ERA5 reanalysis data, we compared with observations on hourly scales, scatter plots were plotted on hourly scales using ERA5 reanalysis data and observations of five meteorological elements at the BFG site from 2012-2017, and linear regression analysis was done in this section. as shown in Figure 2, the ERA5 reanalysis temperature data at four times (02 o'clock, 08 o'clock, 14 o'clock and 20 o'clock) were all relatively close to the observed values at Lake Taihu, with the difference between the slope of the fitted equation and not exceeding 0.01, the intercept less than 0.63˚C, the correlation coefficient is 0.99, and all passed the significance test at the 0.01 level, and the root mean square errorless than 0.88˚C. The ERA5 relative humidity data


(a)
y=0.99x+0.22,N=365,R=0.99
p<0.01,RMSE=0.88°C
ERA5(°C)
observation(°C)
(b)
y=0.99x-0.10,N=365,R=0.99
p<0.01,RMSE=0.38°C
ERA5(°C)
observation(°C)
(c)
y=1.01x-0.63,N=365,R=0.99
p<0.01,RMSE=0.63°C
ERA5(°C)
observation(°C)
(d)
y=1.00x+0.05,N=365,R=0.99
p<0.01,RMSE=0.43°C
ERA5(°C)
observation(°C)


(a)
y=0.75x+16.50,N=365,R=0.58
p<0.01,RMSE=6.17%
ERA5 (%)
observation (%)
(b)
y=1.16x-15.45,N=365,R=0.86
p<0.01,RMSE=3.50%
ERA5 (%)
observation(%)

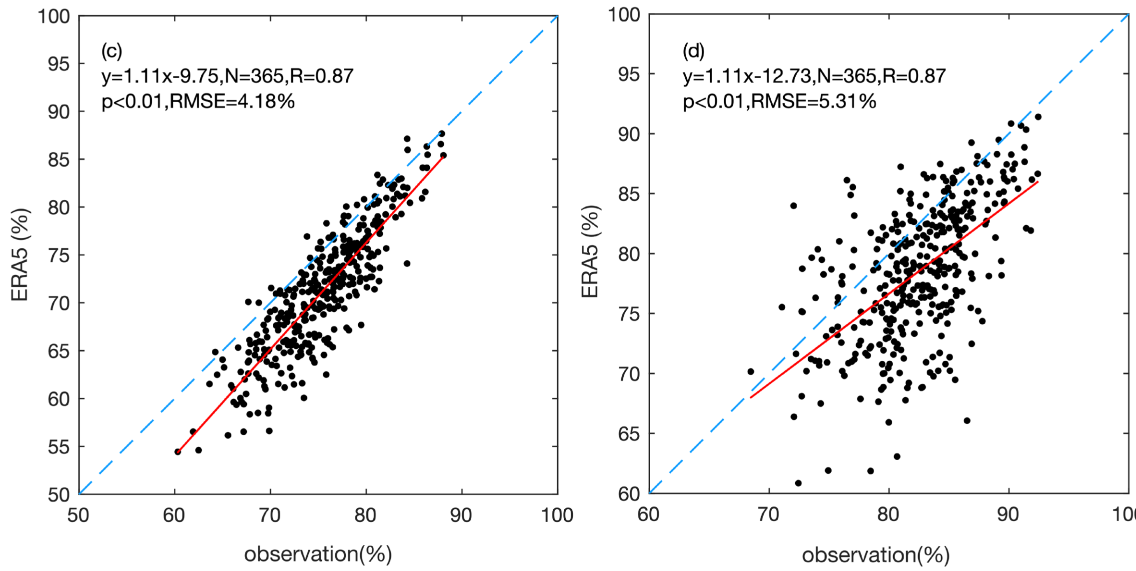


Figure 2. Linear regression relationship between ERA5 temperature and relative humidity data and observation in Lake Taihu BFG site at different times in 2012-2017 (a) 02 o'clock; (b) 08 o'clock; (c) 14 o'clock; (d) 20 o'clock.

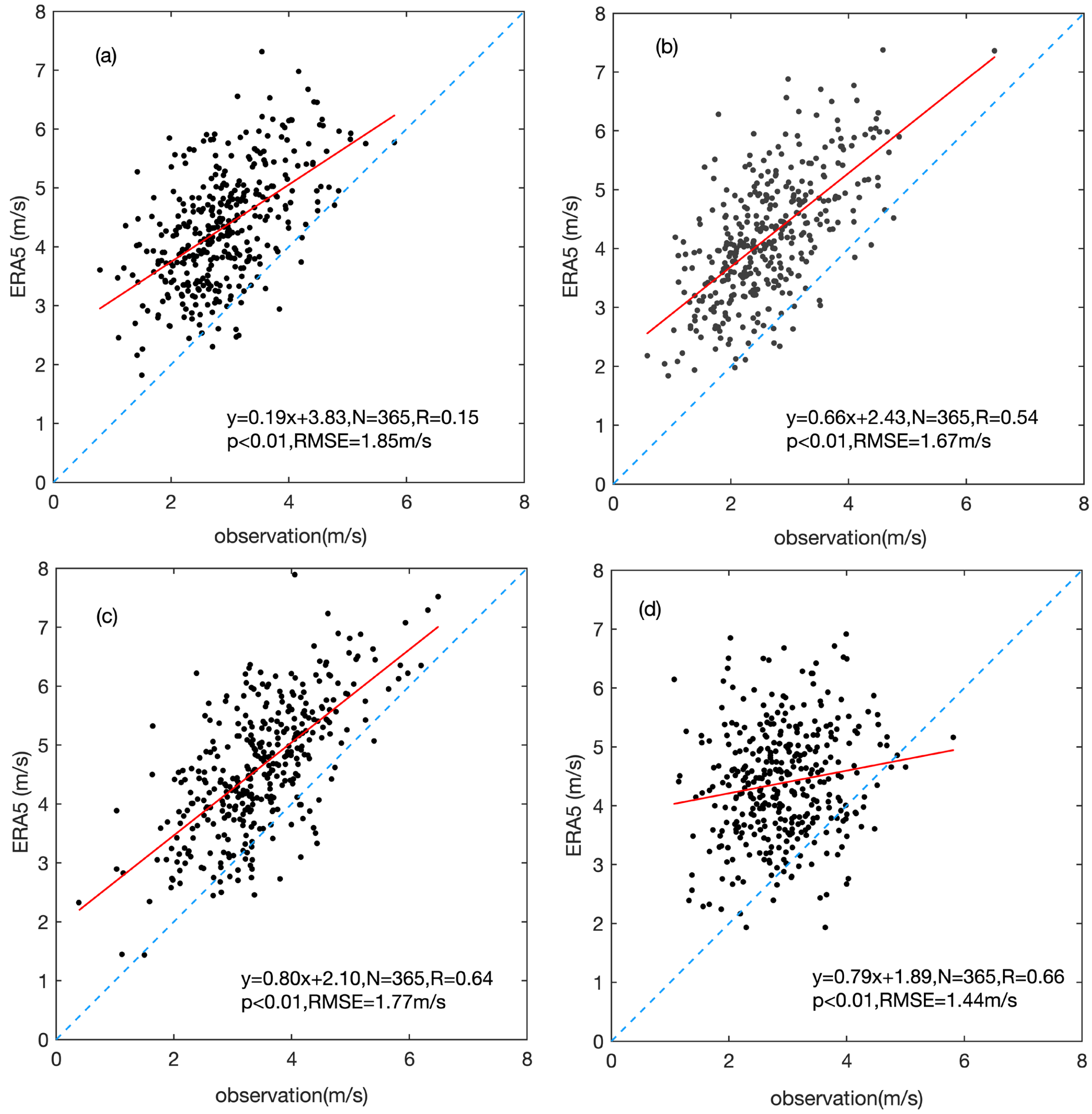
are more accurate at 08, 14 and 20 o'clock, with correlation coefficients greater than 0.86, but they all overestimate the relative humidity to some extent, by 16%, 11% and 11% respectively. There is a large error in the description at 02 o'clock, with a correlation coefficient of 0.58 and an RMSE of 6.17%, which needs to be revised before using.

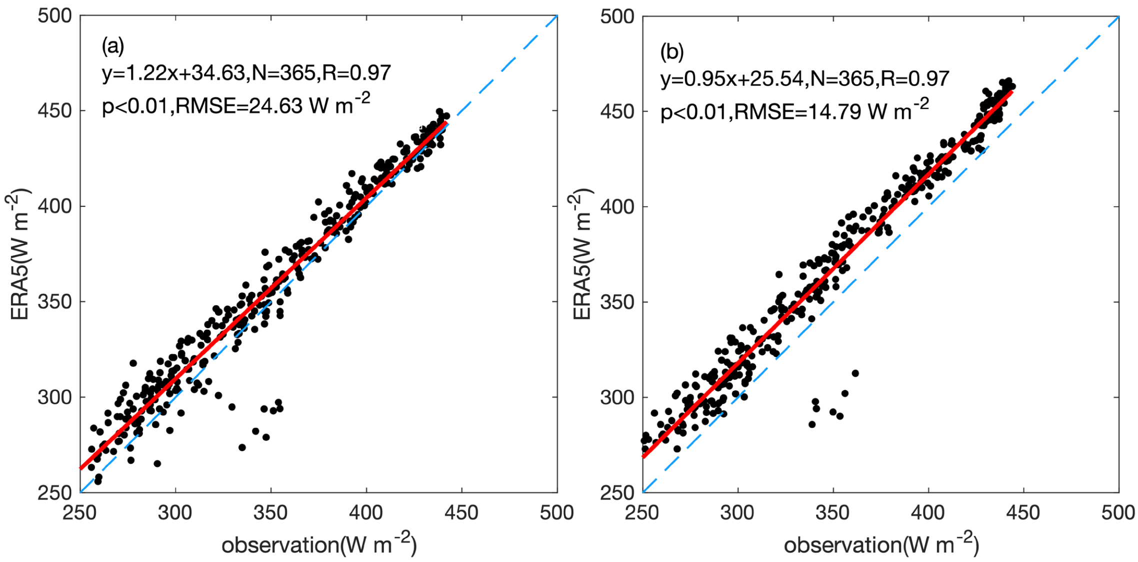
As shown in **Figure 3**, the ERA5 reanalysis data have large deviations in describing the wind speed characteristics of Lake Taihu at all four moments, with R less than 0.66 and RMSE greater than 1.44 m·s^{-1}, and all underestimate the wind speed at BFG station at all four moments by 81%, 34%, 20% and 21%, respectively. The downward longwave radiation ($L_{\downarrow}$) of the ERA5 reanalysis data at all four moments is closer to the observed value at Lake Taihu. The correlation coefficients were 0.97, 0.97, 0.98 and 0.98, which passed the 0.01 significance test, and the root mean square errors were 24.63 W·m^{-2}, 14.79 W·m^{-2}, 21.43 W·m^{-2} and 15.10 W·m^{-2}. The ERA5 reanalysis data can accurately describe $L_{\downarrow}$ of four moments.

As can be seen from **Figure 4**, the ERA5 reanalysis data generally overestimate the description of downward shortwave radiation ($K_{\downarrow}$), overestimating by 53% and 5% at 08 o'clock and 14 o'clock respectively. This is consistent with the findings of Zhao et al. (2013), and may be related to the underestimation of aerosols and clouds by the reanalysis data, as the ERA5 solar radiation data are larger than the bias generated by $K_{\downarrow}$ and its correction should be carried out to reduce the error when conducting the lake model simulation study.

3.2. Seasonal Scale Difference

In this section, the observed meteorological data provided by the BFG station and the ERA5 reanalysis data were used to average the five meteorological elements


(a)
y=0.19x+3.83,N=365,R=0.15
p<0.01,RMSE=1.85m/s
(b)
y=0.66x+2.43,N=365,R=0.54
p<0.01,RMSE=1.67m/s
(c)
y=0.80x+2.10,N=365,R=0.64
p<0.01,RMSE=1.77m/s
(d)
y=0.79x+1.89,N=365,R=0.66
p<0.01,RMSE=1.44m/s
ERA5 (m/s)
observation(m/s)
0
2
4
6
8
1
3
5
7


(a)
y=1.22x+34.63,N=365,R=0.97
p<0.01,RMSE=24.63 W m-2
(b)
y=0.95x+25.54,N=365,R=0.97
p<0.01,RMSE=14.79 W m-2
ERA5(W m-2)
observation(W m-2)
250
300
350
400
450
500

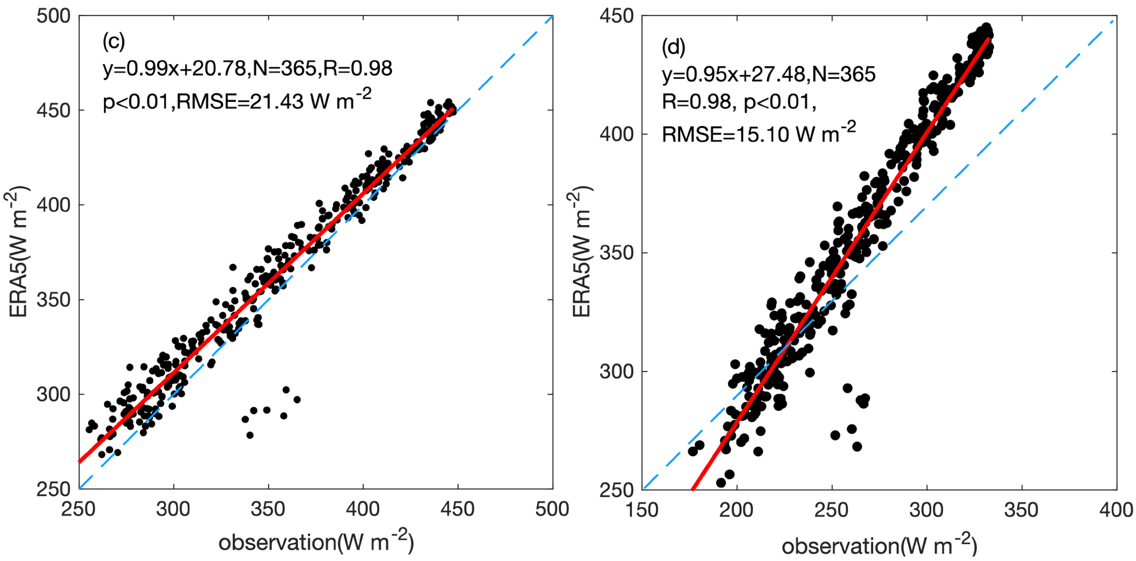


Figure 3. Linear regression relationship between ERA5 wind speed, downward long-wave radiation data and observation in Lake Taihu BFG site at different times in 2012-2017 (a) 02 o'clock; (b) 08 o'clock; (c) 14 o'clock; (d) 20 o'clock.

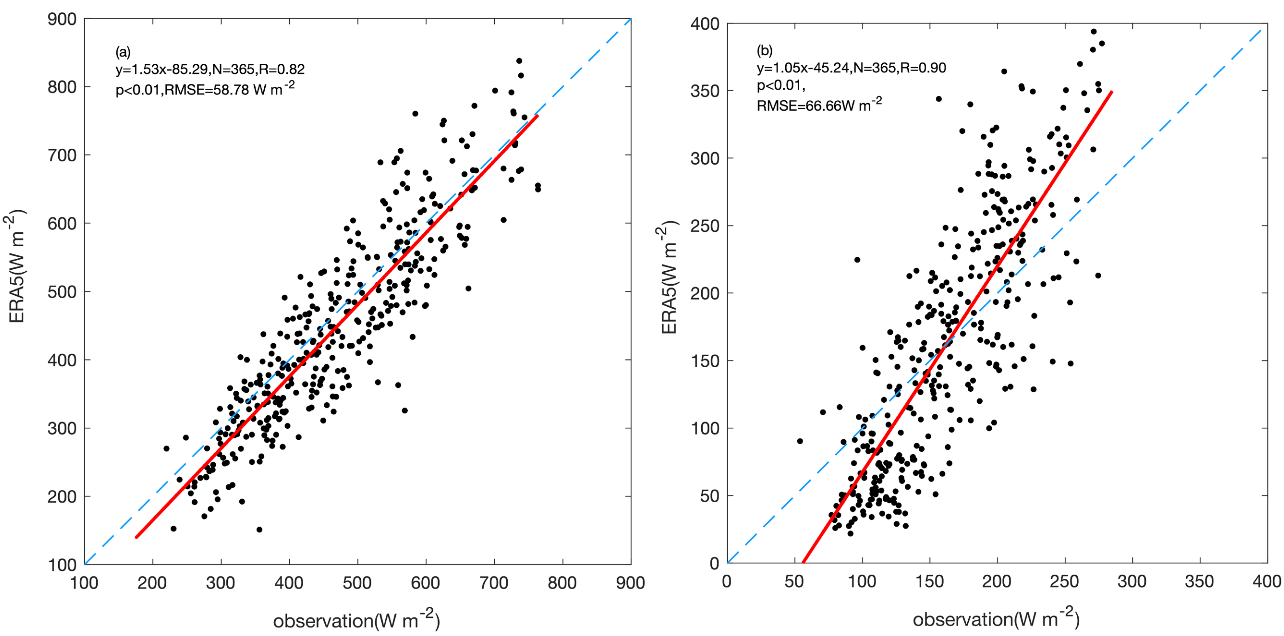


Figure 4. Linear regression relationship between ERA5 downward shortwave radiation data and the observational value of downward shortwave radiation from the Lake Taihu BFG site from 2012 to 2017 (a) 08 o'clock; (b) 14 o'clock.

(temperature, relative humidity, mean wind speed, downward shortwave radiation, downward longwave radiation) for each month from 2012 to 2017 respectively, so as to plot the difference between the ERA5 reanalysis data and the BFG station.

The comparison of meteorological elements with seasonal changes from 2012 to 2017 is shown in Figure 5, and Table 2 shows the evaluation of the simulation accuracy of ERA5 reanalysis data for the five meteorological elements in

Table 2. Evaluation of the simulation accuracy of ERA5 on 5 meteorological elements on different time scales.

elements	Spring (March-May)			Summer (June-August)			Autumn (September-November)			Winter (December-February)		
	R	RMSE	BIAS	*R*	RMSE	BIAS	*R*	RMSE	BIAS	*R*	RMSE	BIAS
Ta	0.99	0.41	0.026	0.99	0.25	0.002	0.99	0.19	−0.005	0.97	0.43	0.040
RH	0.84	3.38	0.036	0.76	3.31	0.012	0.87	3.22	0.022	0.74	4.91	0.054
u	0.63	3.21	−0.621	0.52	3.31	−0.623	0.60	2.57	−0.664	0.49	3.48	−0.762
$K_{\downarrow}$	0.96	23.58	0.142	0.96	16.37	0.063	0.95	14.85	0.087	0.77	28.03	0.264
$L_{\downarrow}$	0.90	26.11	−0.052	0.91	20.21	−0.029	0.91	32.77	−0.034	0.89	29.07	−0.075

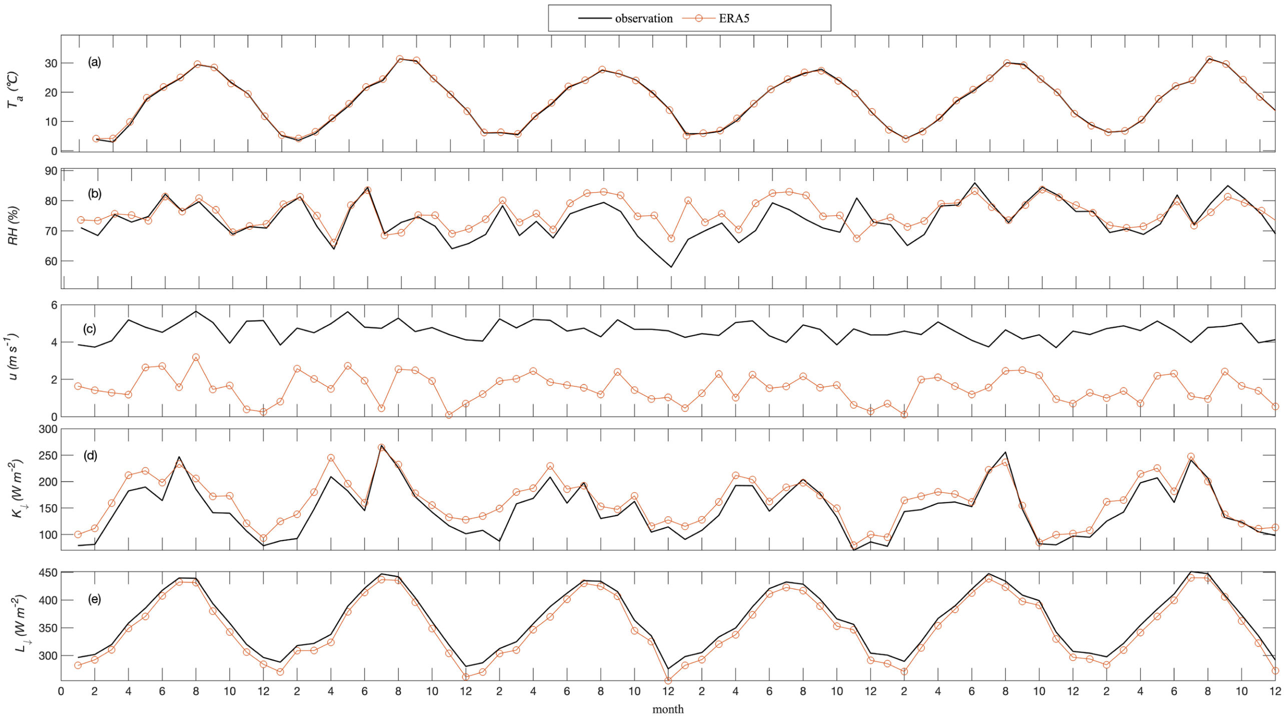


Figure 5. Comparison of the seasonal variation between the monthly average value of ERA5 reanalysis data from 2012-2017 and the measured value at Taihu BFG station (a) temperature; (b) relative humidity; (c) wind speed; (d) downward shortwave radiation; (e) downward longwave radiation.

different seasons. It can be seen that on the seasonal scale, the ERA5 reanalysis temperature data has high agreement with the BFG site's temperature. *R* is greater than 0.97 and RMSE is less than 0.43˚C. ERA5 data slightly underestimate temperature in autumn (BIAS = −0.005), overestimate temperature in spring, summer and winter (BIAS = 0.026, 0.002 and 0.040 respectively).The ERA5 reanalysis of relative humidity data show the same trend as the BFG station observations, with autumn (*R* = 0.87, BIAS = 0.022) being the most accurate, followed by spring (*R* = 0.84, BIAS = 0.036), summer (*R* = 0.76, BIAS = 0.012), and winter (*R* = 0.74, BIAS = 0.054).

The ERA5 reanalysis data all have large errors in the description of mean wind speed, with correlation coefficients ranging from 0.49 to 0.63, and BIAS less than

0. Overall. ERA5 data underestimate mean wind speed and have large errors that need to be revised before it can be used. This error may be caused by the low spatial resolution of the reanalysis data. The reanalysis data cannot accurately identify inland water bodies and distinguish between land and lakes, and since land is rougher than lake surface, the wind speed on land is smaller than that on lake surface, resulting in the reanalysis data underestimating the actual wind speed, which is consistent with the findings of Zhao & Xu (2014).

The ERA5 reanalysis data for downward shortwave radiation describe a consistent trend with high correlation in spring, summer and autumn, with correlation coefficients greater than 0.95 and BIAS of 0.142, 0.063 and 0.087 respectively, with the most accurate description for summer $K_{\downarrow}$. The description is most

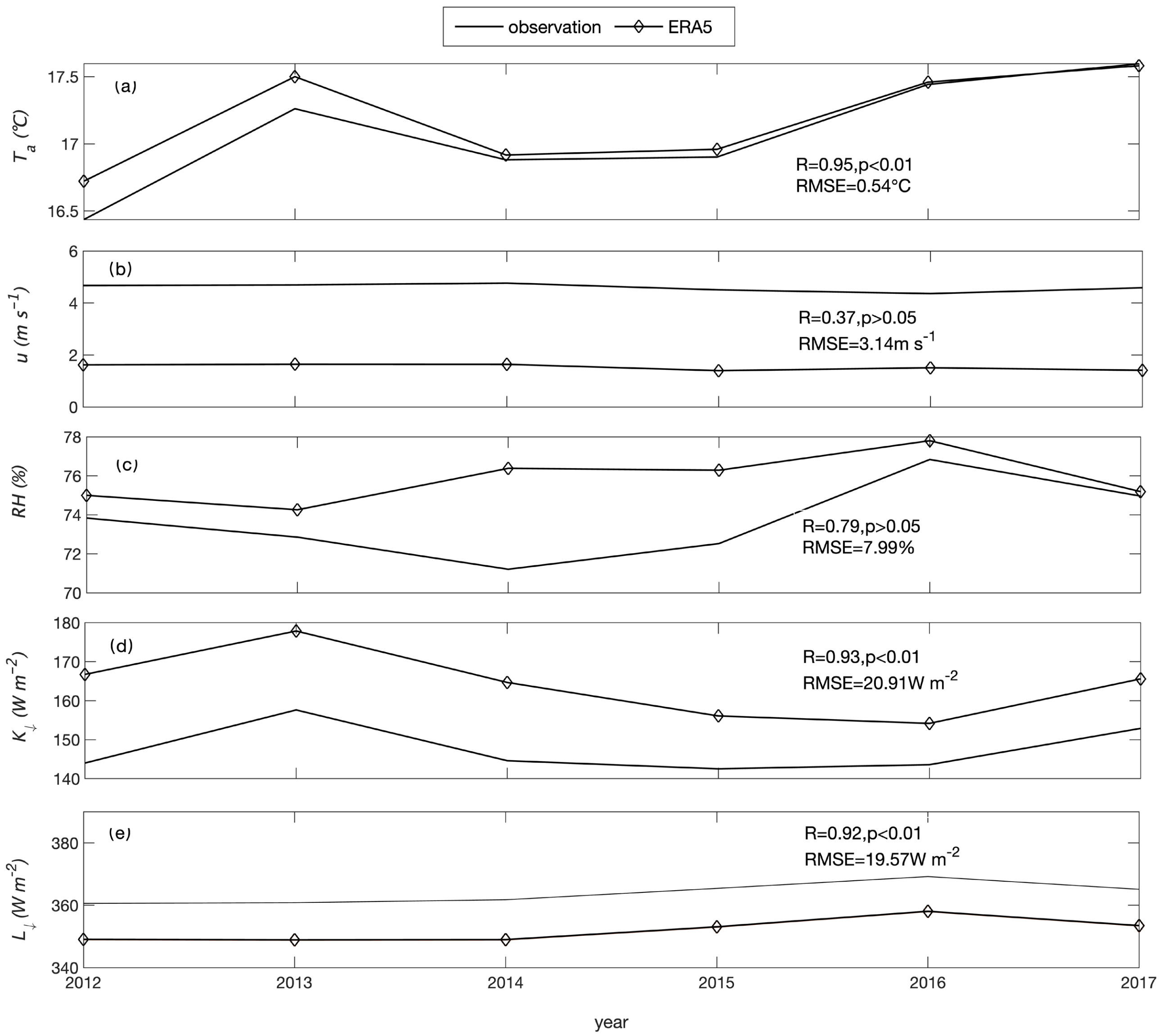


Figure 6. Comparison of the annual average value of ERA5 reanalysis data from 2012 to 2017 and the measured value of Taihu BFG station (a) temperature; (b) wind speed; (c) relative humidity; (d) downward short-wave radiation; (e) downward long-wave radiation.

accurate in summer. The ERA5 data description of downward longwave radiation is consistent in all four seasons, with $R > 0.89$, RMSE < 32.77 W·m^{-2} and for summer (R = 0.91, BIAS = −0.029) and autumn (R = 0.91, BIAS = −0.034) are more accurate.

3.3. Differences in Annual Means

This section uses meteorological observations provided by the BFG station and ERA5 information to average meteorological elements for each month from 2012-2017, respectively, so as to plot a comparison curve between ERA5 information and the BFG site for meteorological elements and interannual variability from 2012-2017 (**Figure 6**). On the interannual scale, ERA5 has the best ability to describe temperature (R = 0.95, RMSE = 0.54˚C), followed by downward longwave radiation (R = 0.87, RMSE = 20.91 W·m^{-2}), and downward shortwave radiation (R = 0.84, RMSE = 19.57 W·m^{-2}). The relative humidity (R = 0.79, BIAS = 0.28) and mean wind speed (R = 0.37, BIAS = −0.67) did not correlate significantly with the interannual trends of the BFG station observations.

4. Conclusion

This paper compares ERA5 reanalysis data with air temperature, relative humidity, mean wind speed, downward shortwave radiation and downward longwave radiation at different scales (hourly, daily, seasonal and interannual) based on meteorological and radiometric observations from the BFG station of the Lake Taihu mesoscale flux network from 2012 to 2017, quantifies the errors of ERA5 reanalysis data at Lake Taihu and assesses its applicability at different time scales, and the conclusions obtained are summarized as follows.

1) At the hourly scale, the ERA5 reanalysis data are more accurate for both temperature and downward long-wave radiation. The wind speed and downward shortwave radiation were described with a large deviation, with wind speed underestimated by 81%, 34%, 20% and 21% for the four moments at the BFG station, and downward shortwave radiation overestimated by 53% and 5% at 08 o'clock and 14 o'clock respectively.

2) At the seasonal scale, the temperature and downward longwave radiation of the ERA5 reanalysis data are closer to the measured values of Lake Taihu, with the correlation coefficients exceeding 0.90 (passing the significance test at the 0.01 level), among which the summer temperature and summer radiation are most accurately described. The ERA5 reanalysis data have more deviations in the description of wind speed, relative humidity and downward shortwave radiation in Lake Taihu, with RMSE greater than 2.57 m·s^{-1}, 3.22% and 14.58 W·m^{-2} respectively.

3) At the interannual scale, ERA5 temperature and downward longwave radiation reanalysis information is suitable as driving data to replace observations for interannual scale lake modelling studies. For mean wind speed, relative humidity, and downward shortwave radiation, ERA5 data must be revised based on

actual measurements, and the revised values can drive the lake model studies.

In summary, the ERA5 reanalysis data provide a more accurate description of Lake Taihu temperature and downward longwave radiation on hourly, seasonal and interannual scales. Due to the limitation of spatial resolution, the ERA5 reanalysis data cannot discriminate Lake Taihu, and therefore the description of the subsurface is biased, resulting in small wind speeds in the reanalysis data. Due to the underestimation of cloudiness and aerosols, the ERA5 reanalysis data have a large downward shortwave radiation and an inaccurate description of relative humidity. Therefore, the ERA5 reanalysis is not well suited to some of the meteorological elements of Lake Taihu and the reanalysis must be corrected based on actual measurements before it can be used to drive the model.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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