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Sea surface temperature data from coastal observation stations: quality control and semidiurnal characteristics

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Abstract

Sea surface temperature (SST) data obtained from coastal stations in Jiangsu, China during 2010–2014 are quality controlled before analysis of their characteristic semidiurnal and seasonal cycles, including the correlation with the variation of the tide. Quality control of data includes the validation of extreme values and checking of hourly values based on temporally adjacent data points, with 0.15°C/h considered a suitable threshold for detecting abnormal values. The diurnal variation amplitude of the SST data is greater in spring and summer than in autumn and winter. The diurnal variation of SST has bimodal structure on most days, i.e., SST has a significant semidiurnal cycle. Moreover, the semidiurnal cycle of SST is negatively correlated with the tidal data from March to August, but positively correlated with the tidal data from October to January. Little correlation is detected in the remaining months because of the weak coastal–offshore SST gradients. The quality control and understanding of coastal SST data are particularly relevant with regard to the validation of indirect measurements such as satellite-derived data.

Key words: sea surface temperature, data quality control, semidiurnal cycle, tidal movement, coastal observations

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1 Introduction

As one of the most important components of Earth's climate, the oceans are not only a regulator of the environment, but also an indicator of global climate change. Sea surface temperature (SST) is an important fundamental physical property of the ocean, and its variation has an important role in both oceanography and climate research (Schluessel et al., 1990; Donlon et al., 2002; Mochizuki and Kida, 2006; Kawai and Wada, 2007; Liu et al., 2013). Anomalies of SST have been found to have important influence on, for example, the El Niño-Southern Oscillation, tropical cyclones, and the East Asian Monsoon (Cai and Whetton, 2001; Kent and Kaplan, 2006; He et al., 2007; Wu et al., 2010; Qiu et al., 2016).

One method of observing SST is in situ measurements, including the direct measurement with thermometers. While the direct measurement of water temperature is economical and can provide results used widely in observational investigations, sensors must be calibrated at regular intervals to avoid producing errors resulting from sensor drift. Temperature–salinity probe can be used for long-term fixed observations as they generally have sensitive yet stable operation. Another method of observing SST is the indirect measurement via the retrieval of satellite remote sensing data, which enables real-time and continuous observations of large sea areas, but with a precision limited by the nature of the inversion model, atmospheric conditions, as well as other oceanographic parameters (Mao et al., 2003).

Generally, SST data measured at nearshore coastal stations have the characteristics of being long term and continuous, and play an important role in the study of SST changes in the coastal environment. Moreover, such field observations can be used for the validation of both satellite-derived data and numerical model results. As the data from coastal observational stations can be easily affected by factors such as the environment and the precision of instrumentation, data should be reviewed and quality controlled prior to use in analysis. For example, research into the quality control of SST data has yielded some useful results (McClain et al., 1985; Emery et al., 2001; O'Carroll et al., 2008; Dash et al., 2010). In addition, NOAA has developed an online iQuam system (Xu and Ignatov, 2014) which can perform near real time quality control of *in situ* SST measurements and it has been applied in many recent studies (Koner et al., 2016; Zhang et al., 2016; Liao et al., 2017).

Quality control has direct impact on the usability of data, with extreme value and consistency checks widely used for observational data (Meek and Hatfield, 1994; Feng et al., 2004; Tu et al., 2013), which are usually based on statistical methods. However, there is no unified standard of quality control or specific operational methodology for particular types of observational data. Therefore, as the investigation of quality-control techniques is still a worthwhile undertaking, in this study, we discuss the quality control of SST data using observational data of coastal stations in Jiangsu (China) and analyze the characteristics of SST variation over different timescales.

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2 Data description

2.1 *Data collection and management*

Observational data were collected from observational stations of the Ministry of Natural Resources of China. Considering the continuity and integrity of these data, datasets from the four stations shown in Fig. 1 were selected for this study. Table 1 presents the names and locations of these four stations, with the temporal range of the SST and tidal datasets shown in Table 2.

2.2 *Validity check*

The validity check of this study focused on data from the Yangkou Station, with the datasets from the Lvsi, Zhugensha and Huoxingsha Stations used to aid the analysis. The maximum number of hourly data from Yangkou Station from 2010 to 2014 was 43 824 (i.e., the number of hours during this period). In fact, the datasets actually comprised 43 042 measurements, i.e., 782 observations (1.8% of the total) were missing. Some reasons for the missing data include power failure and the exposure of the temperature probe to air (Table 3). The amount of missing data per year is shown in Table 4.

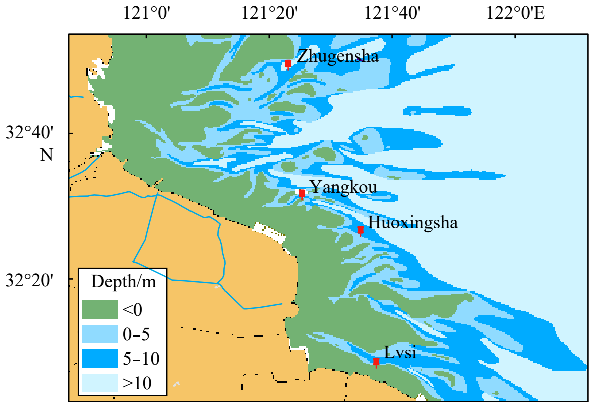

Fig. 1. Position of observation stations.

Table 1. The offshore distance of observation stations

Station	Offshore distance/km
Yangkou	11.0
Lvsi	4.2
Zhugensha	42.0
Huoxingsha	17.7

3 Quality control

3.1 *Inter-comparison of four stations*

Figure 2 illustrates the seasonal cycle of the multi-year mean sea surface temperature of four stations, illustrating a consistent behavior, with significant seasonal variations. Comparison of the four stations through scatter plots of the normalized SST values in Fig. 3 shows values of Pearson's correlation coefficient $r > 0.95$, suggesting a high correlation for each station.

Table 2. Specifications of hourly SST and tidal datasets

Dataset	Year	Manufacturer	Instrument type	Precision	Resolution	Depth/m
SST	2010–2014	National Ocean Technology Center	Temperature–salinity probe/YZY4-3	±0.2°C	0.05°C	0.3
Tide	2010–2014	HYDROWISE	Tidal sensor/SCA11-3A	±1 cm	0.1 cm	—

Table 3. Causes of missing SST data

Months with missing data	Cause
Jul., Aug., Sep. 2010; Jan. 2011	temperature–salinity probe fault
Apr. 2011; May 2012	power failure
Aug. 2011	temperature–salinity probe fault
Oct. 2011; Jun., Jul., Oct., Nov. 2013; Jun., Jul., Aug., Sep., Oct. 2014	temperature–salinity probe exposed to air
Jan., Mar., Apr. 2012	temperature–salinity probe fault
Jun. 2012	instrument calibration
Apr. 2013	transmission failure

Table 4. Amount of missing SST data

Year	Time/h	Ratio/%
2010	65	0.74
2011	20	0.23
2012	102	1.16
2013	19	0.22
2014	576	6.58
Total	782	1.78

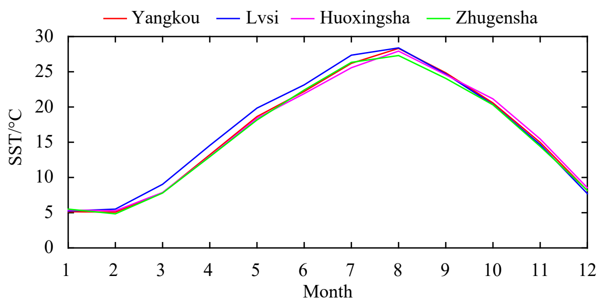

Fig. 2. Time series of monthly mean SST for the years 2010–2014 for the four stations: Yangkou, Lvsi, Huoxingsha, and Zhugensha.

3.2 *Extreme value analysis*

The extreme values and ranges of measurements, which have their own physical characteristics, were analyzed based on the guidelines of Ding et al. (2011). From 2010 to 2014, the maximum SST recorded at Yangkou was 31.8°C, which was observed at 20:00 Chinese Standard Time (CST) on August 9, 2013, with a minimum SST of 1.4°C observed at 05:00 and 06:00 CST on January 18, 2011. It is worth noting that this minimum SST is the lowest value observed during the measurement history.

To verify whether the SST extreme values of Yangkou are

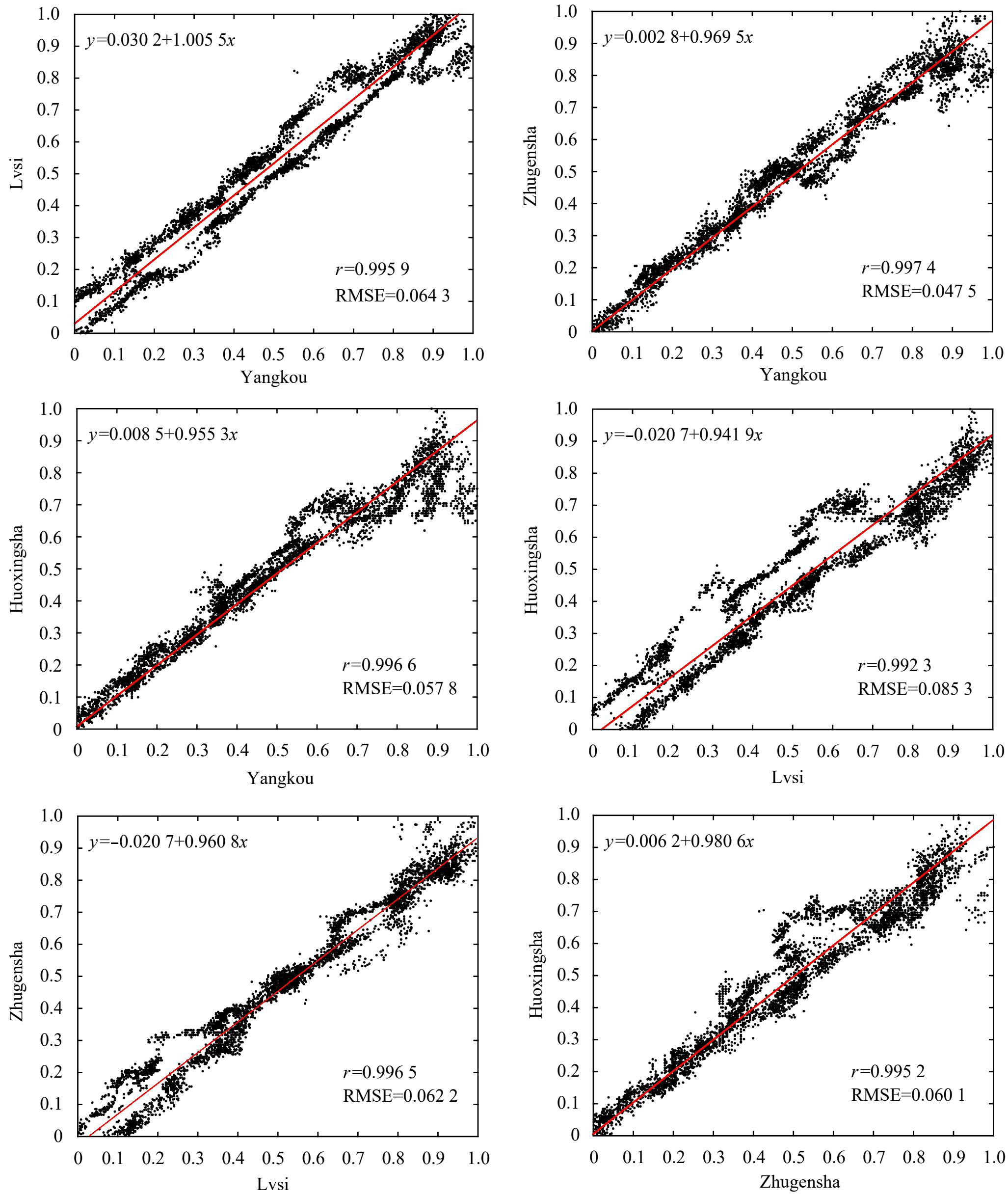

Fig. 3. Scatter plots of normalized SST from the four stations. Also indicated are the lines of best fit, the value of r, and the root-mean-square error (RMSE).

within the allowable range, we consider the SST data acquired during the same period of at the adjacent Lvsi Station. The extreme SST values of both stations, shown in Table 5, exhibit similar behavior. The extreme air temperature values give a maximum at Yangkou of 38.1°C (August 2013), with a minimum of −5.2°C (January 2010), and the next lowest temperature of −4.2°C (January 2011). The extreme values of SST are consistent with hydrological and meteorological trends, leading us to conclude that the maximum and minimum values of Yangkou are not outliers.

Table 5. The annual SST (°C) extremes of the Yangkou and Lvsi Stations

Year	SST max		SST min	
	Yangkou	Lvsi	Yangkou	Lvsi
2010	30.6	31.6	1.9	1.9
2011	29.4	30.5	1.4	1.4
2012	30.4	30.8	2.5	3.2
2013	31.8	32.4	2.8	2.7
2014	29.6	29.8	4.1	3.5

Our analysis confirms that the SST data of Yangkou are in the expected range of values. While the long-term time series of the representative regional characteristics do not illustrate any abnormal values, a more accurate quality control analyzes SST data on a smaller time scale.

3.3 *Detection of outliers*

The quality of data from coastal stations is liable to be influenced by the type and location of the instrumentation, as well as the prevailing hydro-meteorological conditions. Moreover, early SST data were observed subjectively at a specific time, so the quality may also have been reduced by subjective factors. Although the preliminary screening of the data was performed by checking the extreme values, as described in Sections 3.1 and 3.2, a method for verification of temporal consistency is presented here for further quality control of SST data.

For hourly observed data, two adjacent values must have some degree of continuity, so outliers can be determined initially using a time-continuity check (Tu et al., 2013). The time-continuity check can be calculated following Eq. (1):

$$\Delta T = \frac{|V_2 - (V_3 + V_1)/2|}{(t_3 - t_1)/2}, \tag{1}$$

where V_2 is the value to be judged at time t_2, and V_1 and V_3 are the observed values at times t_1 and t_3, respectively. Here, if ΔT is greater than a certain critical value, V_2 is suspected to be an abnormal value.

The hourly SST data from Yangkou Station indicate an hourly variation of SST of between −1°C and 1°C. Because the precision of SST data is 0.1°C, ΔT was tested for critical values of 0.1, 0.15 and 0.2°C/h, with histograms of the value of Delta T according to Eq. (1) shown in Fig. 4. Combined with the variation of SST and previous experience with the instrumentation, we find a value of ΔT = 0.15°C/h produce the most reasonable number of suspected outliers. In this way, it is possible to detect abnormal values for continuous processes, while also retaining the characteristics of the variation of SST. For example, the results from the Yangkou Station on January 12 and August 4, 2012 are shown in Fig. 5, where the examination of the temporal continuity indicates ΔT = 0.15°C/h as the optimal value for detecting outliers.

The changes in SST data after quality control are compared with those without quality control in Fig. 6, with quality-controlled results retaining the monthly and inter-annual variations of SST, while abnormally high values and low values are detected. The difference in monthly mean SST before and after quality control is −0.1°C to 0.3°C. The maximum value is approximately 0–0.6°C higher than that without quality control, with the minimum value approximately 0–0.5°C lower. The annual and seasonal mean SST values change little after quality control, with the difference only 0.1°C.

4 Multi-scale variation characteristics analysis

According to the hydrological climate (Chen et al., 1992; Guo et al., 2005), winter extends from January to March, spring is from April to June, summer covers from July to September, and autumn extends from October to December. The seasonal mean

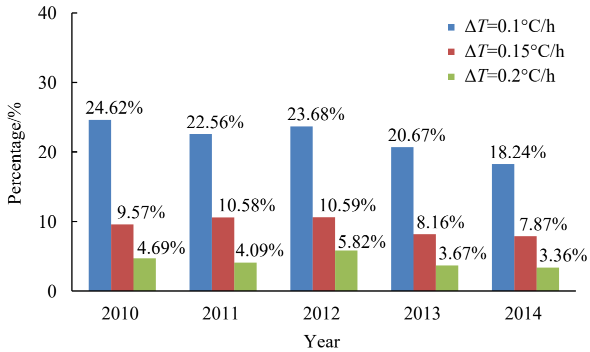

Fig. 4. Histograms of percentage of outliers for different critical values of Delta T for hourly SST at Yangkou Station.

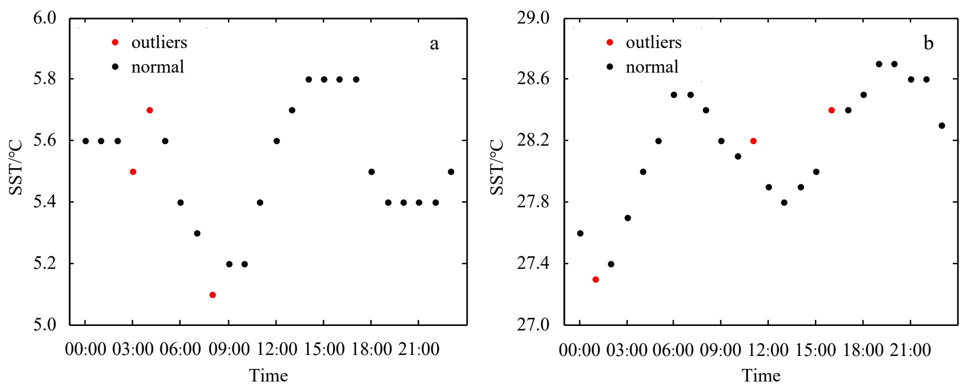

Fig. 5. The quality-controlled results of SST on January 12, 2012 (a) and August 4, 2012 (b).

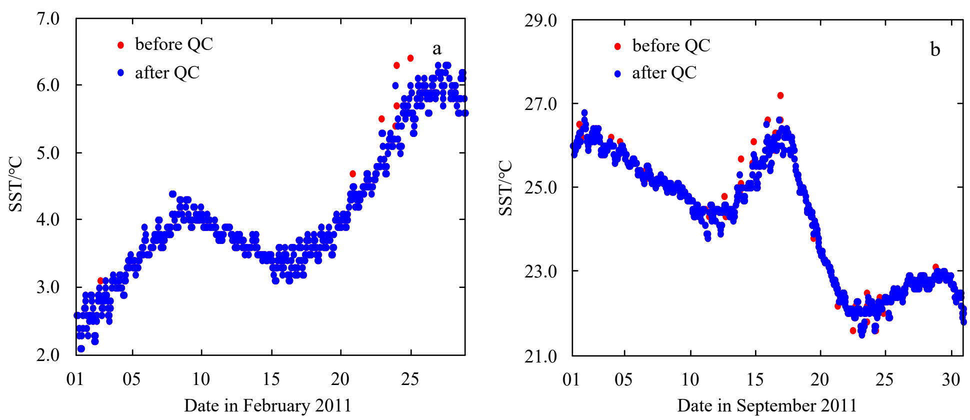

Fig. 6. Before (red) and after (blue) quality control (QC) of SST data for February 2011 (a) and September 2011 (b).

values of SST of the four stations are given in Table 6, showing a consistent seasonal variation. The temperature differences of the transition periods from winter to spring and from summer to autumn are large, giving a temperature change of about 13°C, while those from spring to summer and from autumn to winter are smaller, with the seasonal change of about 9°C. The seasonal variation of SST is controlled by solar radiation, and is less affected by anthropogenic activities.

Hourly averaged values of SST from the Yangkou Station are shown in Fig. 7. The highest value occurs from 13:00–15:00 CST in autumn and winter, but from 18:00–20:00 CST in spring and summer. The specific heat of the sea is larger than that of the air and therefore the highest daily value of SST usually lags behind the maximum daily air temperature. Moreover, the highest values are found later in the day in spring and summer than in autumn and winter. The characteristic cycles of hourly SST data in spring and summer are delayed compared with stations in the northern area of the Yellow Sea (Peng et al., 2014); however, they are similar in autumn and winter.

Table 6. The seasonal mean SST (°C)

Station	Spring	Summer	Autumn	Winter
Yangkou	17.5	26.7	14.6	5.4
Lvsi	18.8	27.1	14.4	6.0
Zhugensha	17.9	26.0	14.2	5.7
Huoxingsha	17.3	26.4	15.1	6.4

The diurnal range of SST, presented in 0.5°C intervals in Table 7, shows ranges greater than 2°C mostly occur from March to August. In most months, the highest frequency of diurnal range is 0.5–1.0°C, followed by 1.0–1.5°C. The diurnal range of SST is greater in spring and summer than in autumn and winter, with the maximum range reaching 3.6°C, but only 2.4°C in autumn and winter. The diurnal range of SST is affected by many external factors which have a greater effect than the SST itself.

The diurnal cycle of SST at the Yangkou Station display a bimodal structure on most days, which we analyzed with consideration of the variation with the tidal data (Fig. 8), as the semidiurnal cycle of SST is strongly influenced by the tide, which also has an obvious semidiurnal cycle.

The semidiurnal cycle of SST is formed because of the existence of the horizontal gradient of water temperature, coupled with the periodic movement of the tidal current. The semidiurnal variation of SST correlates well with the tide level on most days, with the positive and negative phases appearing alternately. The alternation of flood and ebb tides is responsible for the semidiurnal cycle of coastal SST. From late February to August, the nearshore SST is higher than the offshore SST. Therefore, the relationship between them is out of phase, implying that rising and falling tides correspond to the reduction and increase in SST, respectively. While in January and from the end of September to December, the offshore SST is higher than the nearshore SST, and the semidiurnal cycles of SST and tide have synchronized phases. It indicates that the rising and falling tides correspond to

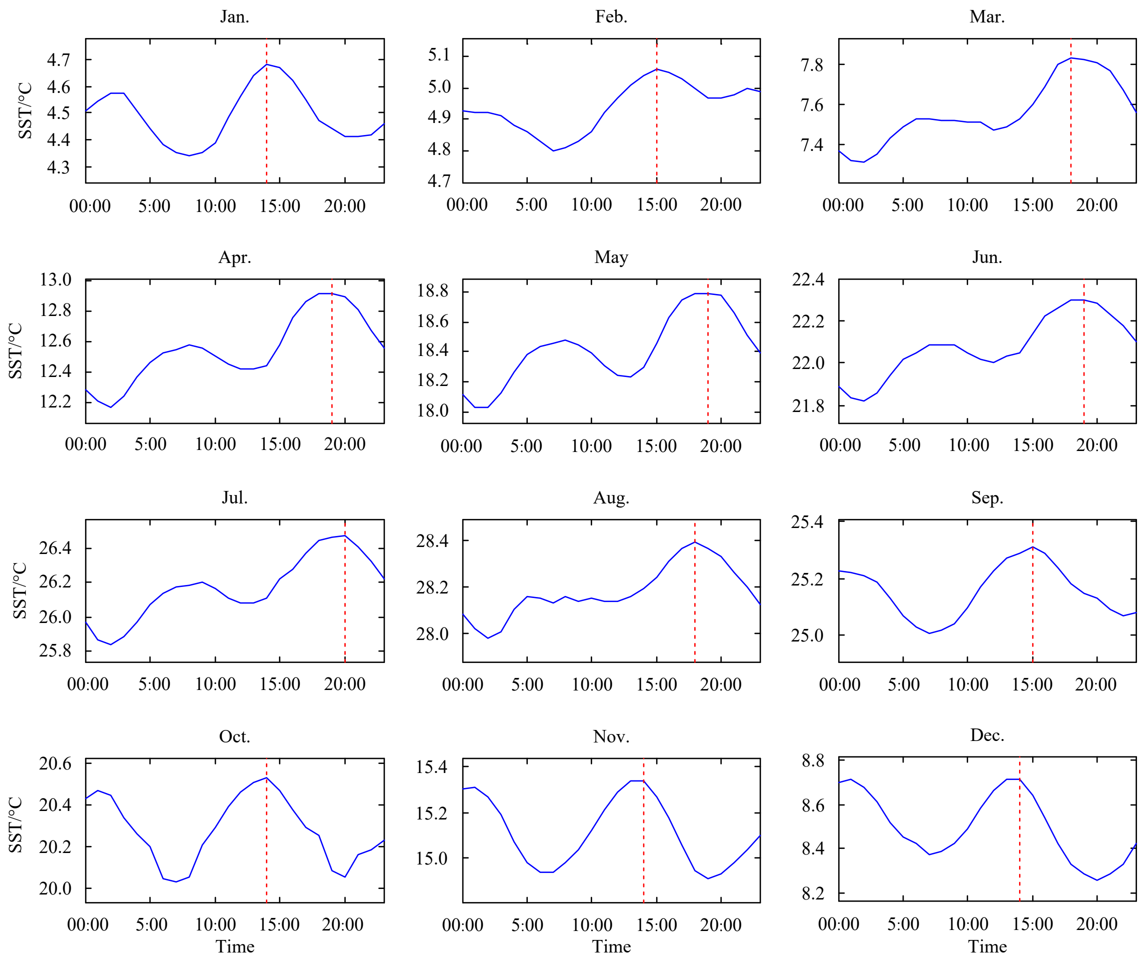

Fig. 7. Hourly averaged SST (°C) for each month of the year.

Table 7. Distribution (%) of the range of SST in 0.5°C intervals

	[0, 0.5)	[0.5, 1.0)	[1.0, 1.5)	[1.5, 2.0)	[2.0, 2.5)	[2.5, 3.0)	[3.0, 3.5)	[3.5, 4.0)
Jan.	22.58%	49.46%	19.35%	8.60%	–	–	–	–
Feb.	35.29%	43.53%	18.82%	2.35%	–	–	–	–
Mar.	12.22%	42.22%	24.44%	12.22%	6.67%	1.11%	1.11%	–
Apr.	1.14%	21.59%	30.68%	30.68%	7.95%	5.68%	2.27%	–
May	6.45%	13.98%	27.96%	24.73%	13.98%	7.53%	–	5.38%
Jun.	3.33%	28.89%	34.44%	26.67%	6.67%	–	–	–
Jul.	2.33%	5.81%	30.23%	32.56%	15.12%	10.47%	2.33%	1.16%
Aug.	13.58%	46.91%	24.69%	11.11%	2.47%	1.23%	–	–
Sep.	18.60%	60.47%	18.60%	2.33%	–	–	–	–
Oct.	11.11%	65.43%	23.46%	–	–	–	–	–
Nov.	4.44%	33.33%	40.00%	15.56%	6.67%	–	–	–
Dec.	1.09%	21.74%	43.48%	28.26%	5.43%	–	–	–

Note: "–" means the calculation result is 0 in the interval.

the increase and decrease in SST, respectively. The transitional period from the positive phase to the negative phase occurs in February, whereas the transitional period from the negative phase to positive phase occurs in September, as indicated by the lack of correlation between the SST and tide during these months. The cause of the phase changes in February and September is the small coastal–offshore SST gradients in these months, which weakens the semidiurnal variation of SST. In contrast, the semidiurnal cycle of SST resulting from the tidal motion is significant in other months with larger coastal–offshore SST gradients.

To further investigate the semidiurnal period of SST and its relationship with tidal changes, empirical mode decomposition (EMD) analysis (Huang et al., 1998) was conducted on the SST data, whereby nonstationary data are decomposed into intrinsic mode functions (IMFs) and a residue based on trends and fluctuations at different scales. Since the EMD algorithm was established, it has received wide attention with applications in many fields (Wan et al., 2005; Liu et al., 2008; Wang et al., 2016; Pan et al., 2018).

The average hourly SST at the Yangkou Station was decomposed using the EMD method into nine modes (eight IMFs and one trend) (Fig. 9). Table 8 shows the averaged period of the first four IMF components, with the averaged period of the IMF2 and IMF3 components significant at 12 h and 24 h, respectively, where 12 h is close to the period of the tide in the Jiangsu sea area. The monthly variance contribution of the first four IMF components characterizes their impact on the overall SST signal, with the correlation between each IMF component and the SST shown in Table 9. The contribution of IMF2 to the variation of SST is the largest in each month, indicating this component contains most of the information of SST. The correlation coefficients of the IMF2 and IMF3 components with the SST signal are significant at the 95% and 90% significance levels, respectively, implying the IMF2 component has a higher similarity with the SST series, which indicates that there is a significant semidiurnal periodic variation of coastal SST.

5 Summary and discussion

The SST data of long-term time series observed by coastal stations are valuable for investigation of changes in the marine environment, which means the quality control of such data is important. This study examined observational datasets collected from coastal observational stations of Jiangsu (China), with particular consideration of the quality control of SST observed at the Yangkou Station, and it investigated the semidiurnal variation of SST. The results show that SST extremes are consistent with the actual changes expected of the marine environment, with the minimum SST value increasing year by year since 2011. We recommend that the quality control of SST data be mainly focused on a continuity check based on relatively short time scales, such as the semidiurnal variation, where abnormal values are detected in our data when the critical value of 0.15°C/h is exceeded, which is considered a reasonable value for SST data. As the diurnal variation of coastal SST is affected by many factors, the range can be relatively large, with the variation at Yangkou reaching to 3.6°C in spring and summer, and 2.4°C in autumn and winter.

The diurnal variation of SST has the bimodal structure on most days, although this structure exhibits obvious seasonal variation. The semidiurnal variation of SST correlates well with the tide level, with the positive and negative phases appearing alternately, largely attributable to a commensurate variation of heat exchange with the coastal water; however, the exact mechanism is complex. The alternation of flood and ebb tides is responsible for the bimodal structure of coastal SST. Therefore, further study of the physical processes is needed to understand the semidiurnal change of the SST, with special attention of this tidal phenomenon using a greater range of SST data in coastal waters to help validate datasets of larger spatial resolution, such as from remote sensing observations.

This study enable the further understanding of the quality and characteristics of SST data observed by coastal observing stations, indicating the necessity for appropriate quality control of SST data, including with regard to the analysis of specific features prior to the use of such data for the validation of other datasets. However, our study could be considered somewhat rudimentary given the complicated coastal dynamic environment of the study area. Detailed examination of the mechanisms of SST semidiurnal variation may highlight several topics worthy of further study in the future. For example, we note that some rivers flow into the Jiangsu shoal area, although the discharge is not large (Zhang, 2014). Both Kako et al. (2016) and Park et al. (2011) have discussed the effects of Changjiang River discharge on SST in the East China Sea on a seasonal timescale using a global ocean general circulation model. In a following study, we intend to use runoff data to study the multiscale temporal characteristics of the effects of runoff on SST. Furthermore, during this study, we have paid attention to the effect of wind on the semidiurnal variability of SST. Other studies have found that the diurnal warming of SST can be significant in many cases (Kawai and

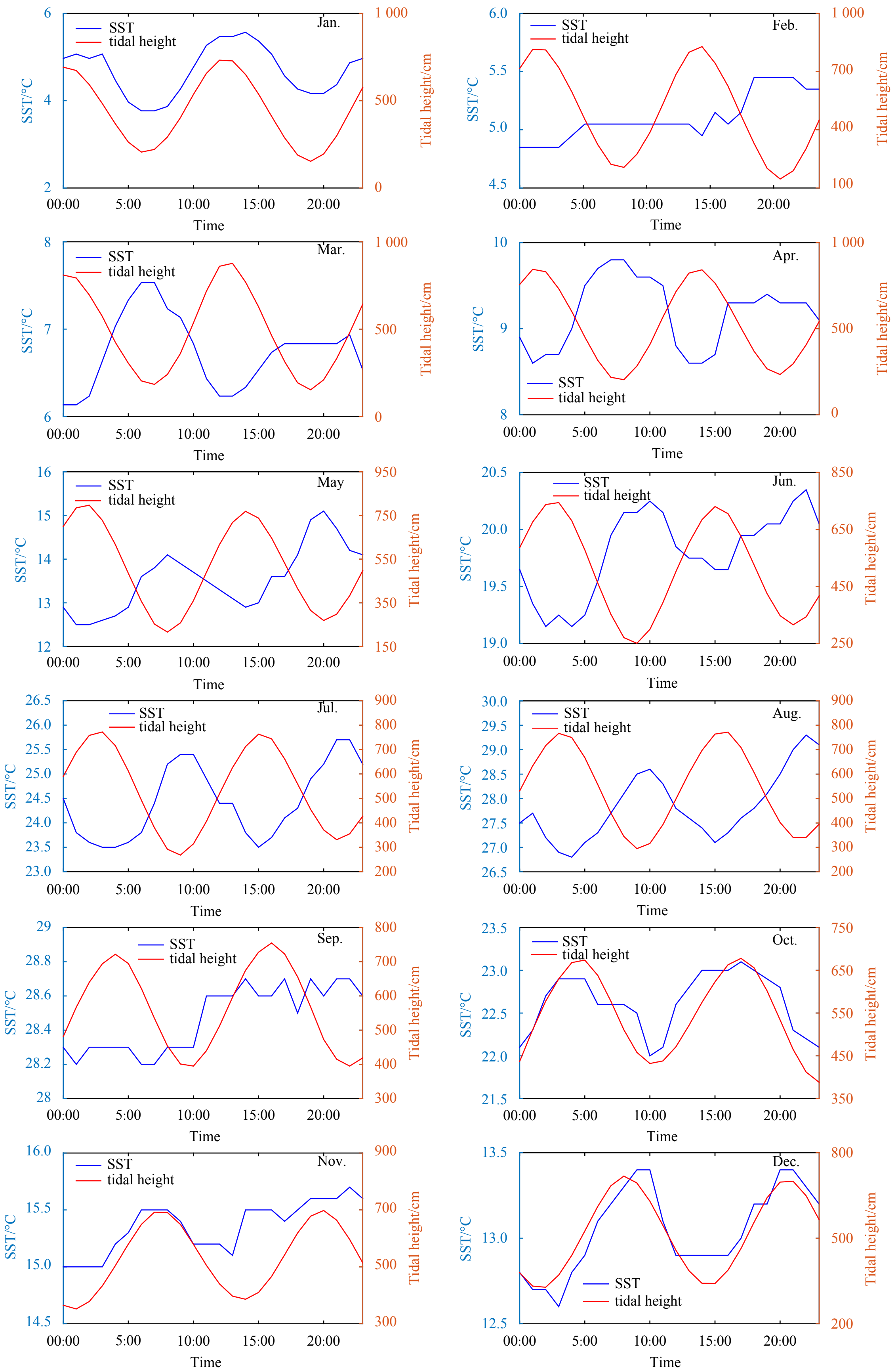

Fig. 8. Correlation between semidiurnal cycles of SST and tidal height on the first day of each month in 2010.

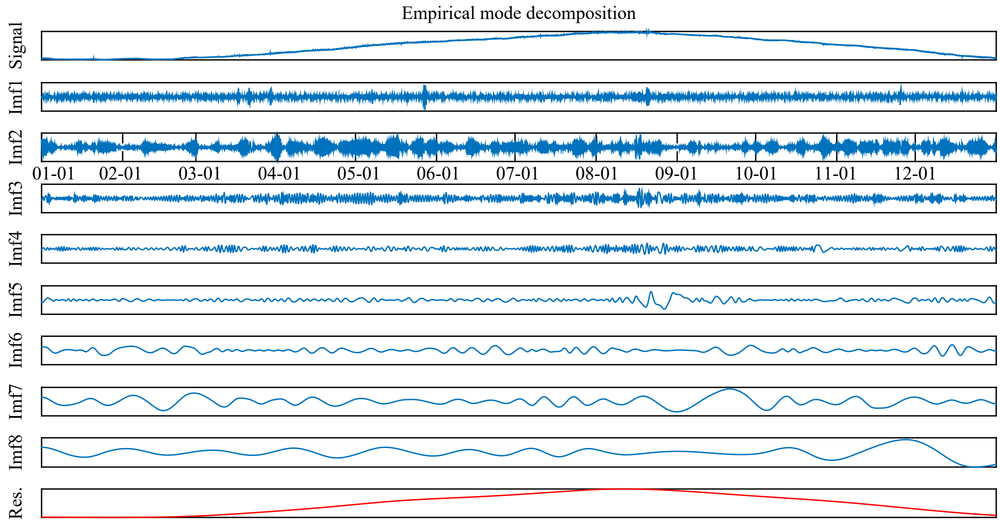

Fig. 9. Results of the EMD analysis, showing the original averaged hourly SST at the Yangkou Station and its first eight IMF components. The residual is shown in the lowest panel.

Table 8. The period (h) of the first four IMF components of the SST at the Yangkou Station

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
IMF1	12	11.789	12	3.103	12	6.154	4.088	3.979	3.478	4.326	13.846	12
IMF2	12	12.218	12	12	12	12	12	12	12	12	12	12
IMF3	24	24	24	24	24	24	24	24	24	24	24	24
IMF4	43.765	84	24	72	74.4	65.455	24	46.5	42.353	33.818	45	57.231

Table 9. The variance contribution of the first four IMF components and correlation coefficient between the IMF components and the original SST signal

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
IMF1	Variance ontribution/%	11.84	0.73	19.20	4.13	28.62	4.26	6.27	6.32	4.20	2.19	10.25	12.11
	Correlation coefficient	0.207	0.081	0.112	0.051	0.112	0.036	0.062	0.126	0.037	0.025	0.022	0.038
IMF2	Variance ontribution/%	27.19	3.95	40.18	35.94	52.94	36.69	25.02	17.63	24.54	24.51	71.47	34.91
	Correlation coefficient	0.297	0.150	0.135	0.145	0.110	0.122	0.109	0.241	0.115	0.119	0.120	0.086
IMF3	Variance ontribution/%	5.11	1.72	23.94	19.13	16.77	15.86	13.66	15.18	31.45	7.85	16.08	7.35
	Correlation coefficient	0.146	0.142	0.104	0.110	0.072	0.125	0.062	0.223	0.107	0.038	0.015	0.068
IMF4	Variance ontribution/%	1.64	1.09	11.38	2.86	1.67	2.79	6.12	8.26	14.57	1.75	2.21	5.60
	Correlation coefficient	0.039	0.072	0.019	0.058	0.026	0.007	0.068	0.048	0.018	0.025	0.007	0.123

Kawamura, 2002; Stuart-Menteth et al., 2003; Pimentel et al., 2008; Filipiak et al., 2012; Lin et al., 2014) . In addition, Tanahashi et al. (2003) verified that diurnal warming of SST occurs under conditions of high insolation and weak wind speeds. We suspect the influence of wind on the amplitude of diurnal variation of SST is greater than that on the cycle of SST variability. Therefore, the influence of wind, solar radiation, and other factors on the amplitude of the diurnal variation of SST is worthy of study.

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