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Observed decrease of summer sea-land breeze in Shanghai from 1994 to 2014 and its association with urbanization

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ABSTRACT

Sea-land breeze (SLB) is widely known as a common wind circulation in coastal cities, which plays an important role to heat transport and pollution diffusion. Using 21-year observation data, a continuous decrease of SLB is discovered in a Chinese metropolis city - Shanghai. In general, the thermodynamic difference between sea and land accounts for the magnitude of SLB. However, other factors associated with urbanization could also affect the SLB significantly, such as anthropogenic aerosol loading, surface roughness, heat release, and so on. This study statistically analyzes the influence of these factors on SLB under the background of global warming. As expected, the decrease of SLB is a combined effect of global warming and great urbanization in Shanghai. The latter, which affects the circulation in both thermodynamic and dynamic ways, is consisted of three parts: temperature increase with urbanization, change of atmospheric radiative forcing, and variation of the underlying surface. At night, the urbanization effect and global warming effect play the similar role by decreasing the temperature gap between sea and land, which would cause the decrease of land wind. At day, decreasing downwelling solar radiation partially offsets the temperature increase caused by both global warming and urbanization although the increasing trend of temperature remains. Different from the expected increasing trend of sea breeze based on the increasing temperature in Shanghai, sea breeze demonstrates a decreasing trend, which could be caused by the dynamic effect from increased surface roughness in Shanghai along with the cooling contribution from radiation-influential factors such as anthropogenic aerosols.

1. Introduction

With the increasing attentions to anthropogenic pollution and urbanization, wind field in urban agglomeration has been the interest of many researches for the importance of their interaction (Li et al., 2008; Yang et al., 2016). It has been revealed that different wind patterns, including the wind direction (Kim and Guldmann, 2011) and wind speed (Kim and Lee, 2015), play critical roles in the pollution status and transport along with their impacts on the regional climate change (Garrett et al., 2010; Yang et al., 2018; Garrett and Zhao, 2006). The impacts of wind field on the environment have been investigated in both observation-based statistical analysis (Xu et al., 2014) and model simulation studies (Dusica et al., 2016). Recent studies found that large-scale climate change, such as Asian monsoon (Li et al., 2016), can also interact with a number of local meteorological factors and then influence the air pollution. Vertical mixing and dispersion of aerosols are inhibited under low wind speed conditions during winter monsoon season in India (Verma et al., 2014). It is also found that multi-day pollution episode tends to burst when anti-cyclonic conditions prolong after the northeast monsoon surges (Hien et al., 2011). As global warming raises more and more concerns, heat wave problems in megacities have also become more severe threatens to people's health (Liu et al., 2010; Dematte and Mara, 1998). To better understand how living environment changes in megacities, it is very important to learn the change of wind field, such as sea-land breeze (SLB).

For coastal areas where many well-known metropolis and city agglomeration are located, one unique and important way of pollution transport and heat wave dispersion is sea-land breeze circulation (Puygrenier et al., 2005; Bouchlaghe et al., 2007; Rajib and Heekwa, 2010; Nai et al., 2018). The SLB is a kind of wind circulation driven directly by the thermodynamic difference between the sea and land. Due to the larger diurnal variation of temperature over land than over

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ocean, the wind comes from offshore during day while from onshore at night. Since the 1960s, numerous observations have shown that SLB circulation is a common phenomenon over coastal areas of all latitudes (Qiu and Fan, 2013). Though this circulation only affects limited area, stretching to dozens of kilometers at most (Rajib and Heekwa, 2010), it contributes a lot to the meteorological conditions near the coastal area. Not only does it have a great influence on local climate change (Yu et al., 1987), but also it is meaningful to fishery industry and wind power utilization (Chen and Yu, 1989). There is no doubt that SLB circulation is quite important to public health and pollution dispersion in coastal cities.

A number of researches have been carried out to investigate the characteristics of SLB from different aspects, including using planes to track SLB (Fisher, 1960), lidar data inverse analysis (Kingsmill, 1995), early-time pure theoretical derivation (Jefferys, 1922), and model simulation studies. There are studies which examine how SLB changes when underlying surface condition changes (Lin et al., 2001; Ding et al., 2004; Mcpherson, 1970; Ma et al., 2013) using small-scale modeling. There are also studies focusing on the structure and characteristics of SLB circulation in different coastal areas around the world (Zhou et al., 1987; Kraus et al., 1990; Finkele et al., 1995; Rani et al., 2010). We are now witnessing an era of fast urbanization globally. A lot of studies have been carried out to investigate how SLB circulation changes and influences climate and weather in coastal cities with a combined urban heat island effect (Yoshikado, 1992; Kusaka et al., 2000; Kawamoto, 2017). Model experiment showed that urban heat island effect could enlarge the temperature gap between sea and land as a result of which the SLB circulation is strengthened (Ma et al., 2013). Urban heat effect was also found to have a deep impact on the stretch of marine wind frontal surface (Sarker et al., 1998). Differently, Xu et al. (2013) found that strong heat island is unfavorable to the stretch of marine wind into inner land if the magnitude of temperature difference is larger than 2.6 °C based on statistical analysis. Although there are a lot of SLB related studies, most of these existing studies are only for case study or short period investigation. Few studies have focused on the long-term variation of SLB, which might have a strong relation with human activities and global climate changes. In this study, we investigate the long term change of SLB in Shanghai, China, and try to answer how sea-breeze wind changes in the long term as local environment changes as great urbanization proceeds.

As we all know, China is one of the world's fastest growing economies with a tremendous urbanization progress. Shanghai, a well-known metropolis since the beginning of 20th century, is now the kernel of Yangtze River Delta (YRD), one of the biggest urban agglomeration in the world. Ranking the first in Gross Domestic Product (GDP) of Chinese cities, Shanghai is right in the center of urbanization progress. During the past decades of 1994–2014, Shanghai had undergone a period of great urbanization as well as pollution. It has been found that most pollution originates from human activities (Wang, 2007). In addition, meteorological conditions and chemical reactions also contribute to the accumulation of pollutants in cities (Zhao et al., 2018; Zheng et al., 2017). This is typical of China's national conditions when looking into fast-developing cities after the 1978 Open and Reform. It is of great reference value for the study of wind changes in coastal urban agglomeration. For most coastal areas, summer is the season when SLB is most prevalent (Qiu and Fan, 2013). In this study, we will show in detail how SLB changed in summer from 1994 to 2014 in Shanghai and investigate the superimposed impact of factors due to urbanization on sea-land breeze in addition to the inevitable influence of global warming background.

The paper is organized as follows. Section 2 describes the data and methodology. Section 3 shows the specific results of the study and gives further discussion on this research. A summary of this study is given in Section 4.

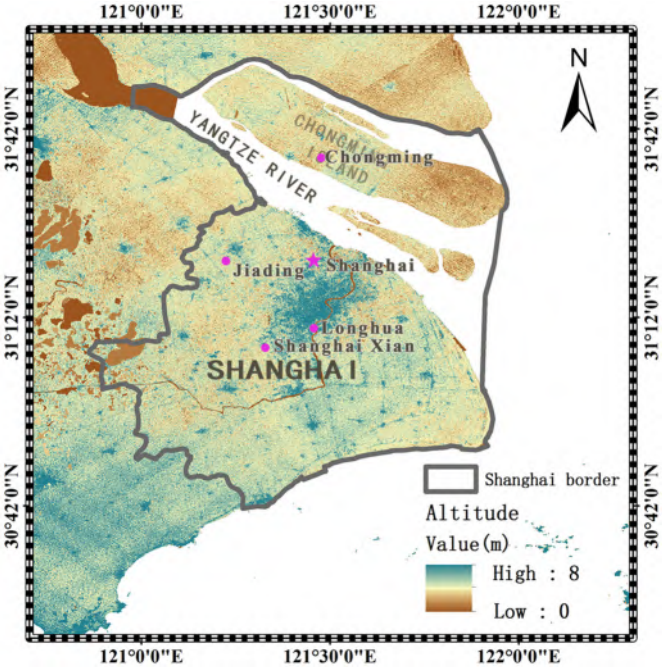

Fig. 1. The meteorological station locations used in this study, which include the Shanghai site (pink star flag) and the other four sites of Chongming, Jiading, Longhua and Shanghai Xian (pink dots). Also shown here is the map of Yangtze River Delta (YRD) along with the ground altitude information. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Data and method

2.1. Region and station

SLB analysis is carried out based on observations at an urban site (121.48°E, 31.4°N) in Shanghai. Fig. 1 shows the site location with a pink star flag along with the map of YRD region and the landscape of Shanghai. Shanghai is in the eastern corner of YRD, and right in the coastal area of east China plain to the west of East Sea. With an average altitude of less than 50 m, Shanghai is not surrounded by any large mountain. Thus, Shanghai is a typical plain region which could be mainly influenced by the SLB circulation. The urban site named Shanghai, site No. 58362 according to the China Meteorological Administration (CMA) national station database, is located in Baoshan district which is in the northeastern part of Shanghai. Meteorology observations at other four stations in Shanghai have also been used for comparison regarding the temporal variation of wind speed, which are Chongming site (No.58366, 121.45°E, 31.62°N), Jiading site (No.58365, 121.25°E, 31.38°N), Longhua site (No.58367, 121.43°E, 31.17°N) and Shanghai Xian site (No.58361, 121.38°E, 31.12°N). These four sites are also marked in Fig. 1 with small pink dots. However, there are no radiation observations at these four sites. In addition, most of these four sites were outside of Shanghai urban area for most time of the study period. Therefore, except for the temporal variation of wind speed, our analysis are only based on the observations at Shanghai site in this study.

2.2. Data

In this study, we mainly use 21-year meteorological data from 1994 to 2014 provided by the China Meteorology Administration. They can be downloaded online (http://data.cma.cn) with a registered account. All observation data has been rectified and undergone official quality control. Three sets of data are used in this study, which include, 1)

Daily maximum and minimum air temperature of 2 m; 2) Hourly wind speed of 10 m; 3) Daily ground-received radiation.

In order to reveal the temporal variation of urbanization accompanied by increasing human activities in Shanghai, we make use of the remote sensing dataset, the Nighttime Lights Time Series from the Operational Line-scanning System (OLS) of the Defense Meteorological Satellite Program (DMSP) operated by U.S. Department Of Defense. DMSP has been carried out since 1965 with the aim to get precise information of cloud, hurricane and weak light. The nighttime lights time series are detected with the help of OLS sensor which is advanced in magnifying weak optoelectronic signals in order not to ignore any light source. The annually averaged nighttime light data are adopted in this study from 1994 to 2013. The data have excluded the natural light spot such as forest fire and reflection of moonlight, which makes it reliable for detecting nighttime light signals and heat emissions from human activities (Elvidge et al., 1997; Henderson et al., 2003; Gallo et al., 2004).

2.3. Method

2.3.1. Identification of SLB circulation from large-scale wind field

The SLB circulation is a secondary circulation induced by the thermodynamic difference between sea and land. During daytime, the land becomes warmer than the ocean with the solar heating due to its lower heat capacity. Thus, the air above warmer land surface ascends and the air above cooler sea surface descends. In order to offset the pressure differences caused by this process, there would be onshore wind in the ground layer. The situation at night is opposite to that during daytime. This natural phenomenon is well known to the public and so far has been described by many studies (Haurwitz, 1947; Estoque, 1962; Nester, 1995; Prtenjak and Grisogono, 2007; Rani et al., 2010). Coastal areas in East China are often influenced by a large-scale wind field at the same time. For instance, East Asia monsoon prevails in this region in summer, bringing great amounts of water vapor from the Pacific (Zhou et al., 2018). Southeast wind serves as the prevailing wind in summer, having a great impact on coastal climate. Thus, the background of the large-scale prevailing system such as East Asia monsoon should be excluded first when focusing on the SLB circulation variation. A method is developed in this study to separate small-scale SLB circulation form large-scale wind field which is described as below.

The in-situ observed wind can be decomposed into U and V using vector decomposition. We take U as an example and get following equations:

$$U_{DS} = \overline{\sum_{i=1}^{24} U_i} \tag{1}$$

$$U_{HO} = U_{HL} + U_{DS} \tag{2}$$

$$U_{HL} = U_{HO} - U_{DS} \tag{3}$$

where U_i means hourly observed wind component U, U_{DS} is the mean value of U_i which means the daily large-scale wind, U_{HO} means the hourly observed wind which consists of the large-scale wind U_{DS} and small-scale local wind U_{HL}. U_{HL} is the local wind at observation time and is what exactly we need.

Assumptions have been applied to the derivation of U_{HL}. As far as Shanghai is concerned during summer time, the major large-scale wind system is summer monsoon. In general, the large-scale wind lasts for a long period of time with relatively weak temporal variation. In this study, we simply assume that the large-scale wind have almost no variation within a day, and daily average of local thermal-driven winds approaches zero. Under this assumption, the local SLB circulation can be easily obtained by subtracting the daily mean winds from the observed winds. This assumption could bring errors/uncertainties into our analysis. However, for long-term trend analysis, these first order estimates of sea-land breeze could provide us valuable statistical findings. Actually, this method has also been used by previous studies (e.g., Qiu and Fan, 2013).

Based on rules of vector decomposition, we can easily calculate the wind speed magnitude of SLB circulation and figure out its coming direction as follows,

$$\theta_{HO} = arcSIN\,(U_{HO}/VV_{HO}) \tag{4}$$

$$V_{HO} = VV_{HO}\cos(\theta_{HO}) \tag{5}$$

where U_{HO} and V_{HO} are the components of hourly wind speed magnitude of SLB circulation in X and Y axis direction respectively at each observation time,$\theta_{HO}$is the angle between wind vector and Y axis and VV_{HO} is the vector sum of U_{HO} and V_{HO}. In the field of meteorology observation, the Y axis is defined as running southwards and x-axis as running westwards. For example, for the north wind, the θ_{HO} is zero.

According to previous studies (e.g., Chen and Yu, 1989), the direction of SLB should be defined according to the shoreline trend. Based on the shoreline trend of Shanghai shown in Fig. 1, we could define the direction of SLB as either SE-NW or SW-NE in Shanghai region. However, it might be inappropriate to choose SW-NE direction in this study because the Shanghai site lies southwest of the intersection of Yangtze River and ocean. Furthermore, Chongming Island lies in the north-east of the Shanghai site. The constructions and the industrial emissions on Chongming Island, the temperature of Yangtze River, and the ships gathered at the estuary of East China Sea, could also contribute to the SLB in the direction of SW-NE, making the SLB in that direction more complicated and challenging to investigate. For simplicity, we here only define the SLB in the direction of SE-NW. Note that we have extracted the weak thermal circulation from large scale circulation using Eqs. (1)–(3). While uncertainties could exist, including the potential contributions from thermal gradients at directions other than SE-NW, the dominance of SLB in the direction of SW-NW may imply that these contributions are weak.

2.3.2. Definition of the SLB day

There are several kinds of definitions of SLB days according to the sampling site and study purpose (Yu et al., 1987; Xue et al., 1995; Borne et al., 1998). The most common way used in China coastal area defines the SLB day by dividing a single day into 4 time series (Yu et al., 1987): 0:00–8:00 as land wind time, 13:00–20:00 as marine wind time, 9:00–12:00 and 21:00–24:00 as converting time. Similar method has also been adopted in other region studies (Cuxart et al., 2014). Previous observation-based studies (Jin, 1988; Li et al., 2007) have statistically analyzed the general prevailing time of land wind and marine wind in different parts of coastal regions in China. It has been found that the prevailing time varies as observation location changes.

This study focuses on long-term variation of the SLB and the factors that contribute to the SLB variation. One influential factor is the sea and land temperature difference, particularly the differences of the highest temperature during day and the lowest temperature at night. Considering that the highest temperature generally occurs around 2 PM and the lowest temperature occurs around 5 or 6 AM, we proposed the criteria in this study for classification of SLB days as follows: when the offshore land winds occur in the time period of 01:00–06:00 with total occurrence time more than 2 h, and the onshore marine winds occur in the time period of 10:00–15:00 with total occurrence time more than 2 h, the day is counted as a SLB day. Also, since we are going to use the radiation data to learn the impact of it on SLB, the marine wind time is shortened and advanced compared to the criterion used in former studies mainly to exclude the time period when radiation from the Sun cannot be detected. As a result of this, the lowest occurrence time changes from 4 to 2 times. The magnitude of SLB is measured only on SLB days.

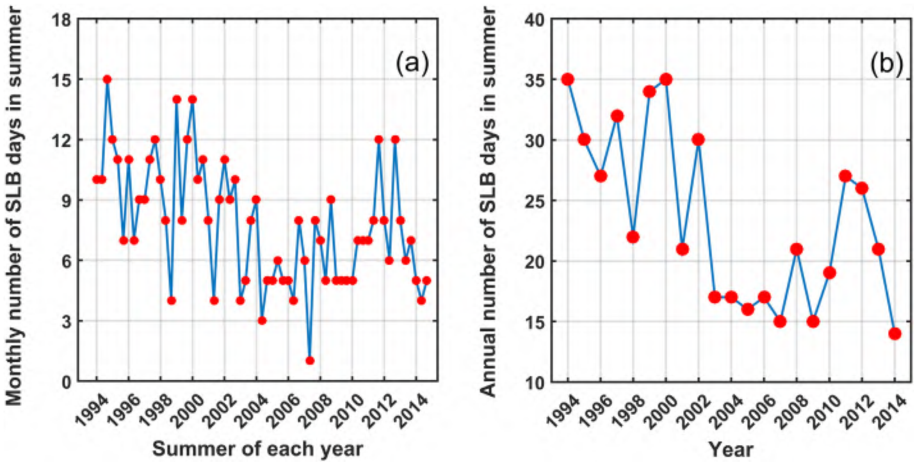

Fig. 2. (a) Monthly and (b) annual variation of SLB day number in summer from 1994 to 2014.

3. Results and discussion

In this part, we first analyze the temporal variation of the frequency of SLB days, and the magnitude of marine and land wind speeds over the Shanghai region from 1994 to 2014. Then we analyze the temporal variations of potential influential factors that contribute to the change of sea-land temperature difference and land surface roughness, which include the observed land surface temperature, the long-time sea and land temperature variation trend associated with the global warming, the downwelling direct solar radiation, the urbanization rate and the progress of urbanization. Finally, we discuss in detail how these influential factors contribute to the temporal changes of SLB circulation.

3.1. Variation of SLB days

The variation of SLB days has been investigated in this study over the past 21 years from 1994 to 2014. Fig. 2a displays the specific number of SLB days in each summer month (June, July and August) during the study period. It shows that the number of SLB days varies with time, with a generally deceasing trend, particularly for the time period from 1994 to 2014. The number of SLB days is the largest in August of 1994 while the smallest in July of 2007. There are comparatively low but stable values of SLB day number from 2003 to 2010, with an average of 5 days each month. After 2010, the SLB day number has a quick rise in 2011 and 2012, reaching approximately 10 days each month, though it continues to decrease in 2013 and 2014. The fast upward fluctuation of SLB days in 2011 and 2012 is probably due to the 'La Nina' event. According to the observation record, year 2010 is a 'La Nina' year. The augmented large-scale trade wind in 'La Nina' year (Huang and Tao, 1992) from the direction of south-east could probably interact with the small-scale SLB circulation, causing the increase of SLB day number. Even though, from a long-term statistical view, the temporal trend found in Fig. 2a is most likely reliable. The annual number of SLB days in summer even shows a more obvious decreasing trend than that shown with monthly data for the period from 1994 to 2014. Similarly, there is a low value period in 2003–2010 for the number of SLB days in Fig. 2b. Of course, there are weak fluctuations of the SLB day number during this period. Roughly, the number of SLB days accounts for about one third of the totals in summer 1994, while accounts for less than one sixth of the totals in summer 2014.

In short summary, the SLB circulation is becoming increasingly uncommon in summer during last two decades while weak fluctuations still exist, which may be responsible for the increasing heat wave found in metropolis of Shanghai (Tan et al., 2007). However, we should note that the trend shown here is based on limited time period dataset. More reliable trend analysis about the SLB day number could be obtained in future when longer time period data are available.

3.2. Variation of SLB magnitude

We also investigate the changes of SLB circulation magnitude in summer over Shanghai region. In order to have a clear view on the temporal variation of SLB magnitude, a histogram analysis is carried out for both marine and land hourly wind speeds by dividing the two-decade period into five 4-year time periods, which are shown in Fig. 3. The histogram analysis shows the similar decreasing trends with time for both marine and land winds. The histogram distribution width for marine wind speed is slightly larger than that for land wind speed, which indicates that the temporal variability of marine winds is larger than land winds. After 2010, most of the wind speed decreases with time with the values mainly within the interval of 0–2 m/s. Still, the land wind speed has a slightly more centralized distribution whereas the marine wind speed has slightly larger values. Consistent with the decreasing trends of wind speed, the distribution width of histograms for both marine and land wind speeds is becoming smaller with time. In other words, the distribution of wind speed is becoming increasingly centralized. Moreover, Fig. 3 demonstrates that the summer average values of both marine and land winds which are represented by pink lines have a decreasing trend (shifting to the left) with time. For all time periods, the mean value of marine wind speed is greater than that of land wind speed, which is consistent with previous findings (Chen and Yu, 1989). However, their temporal variation differs slightly from each other. For marine wind, there is only a slight decrease of wind speed from 1.75 m/s to 1.72 m/s for the first two time periods. After the second time period, there is a continuous decreasing trend of summer average marine wind speed, which is approximately 0.15 m/s every 4 years. For the whole 21-year period, the summer average marine wind speed decreases more than 0.5 m/s, which accounts for more than 25% of the mean value at the initial time stage examined. By contrast, the summer averaged land wind speed has only a very tiny change between the second and third time period, decreasing from 1.40 m/s to 1.38 m/s. After the third period, there is also a continuously decreasing trend of summer-averaged land wind speed. In general, the marine wind speed decreases faster than the land wind speed over the years. More interestingly, the reduce rate of mean wind speed value accelerates slightly with time, changing from approximately 0.03 m/s per 4 years (marine wind) and 0.07 m/s per 4 years (land wind) at early stage to 0.15 m/s per 5 years (marine wind) and 0.19 m/s per 5 years (land wind) at recent stage. The summer-averaged marine wind speed and land wind speed are about 1.25 and 1.11 m/s respectively for the period 2010–2014, which are about 0.50 and 0.36 m/s less than that for the period 1994–1997. In summary, from 2002 to 2014, there is continuous

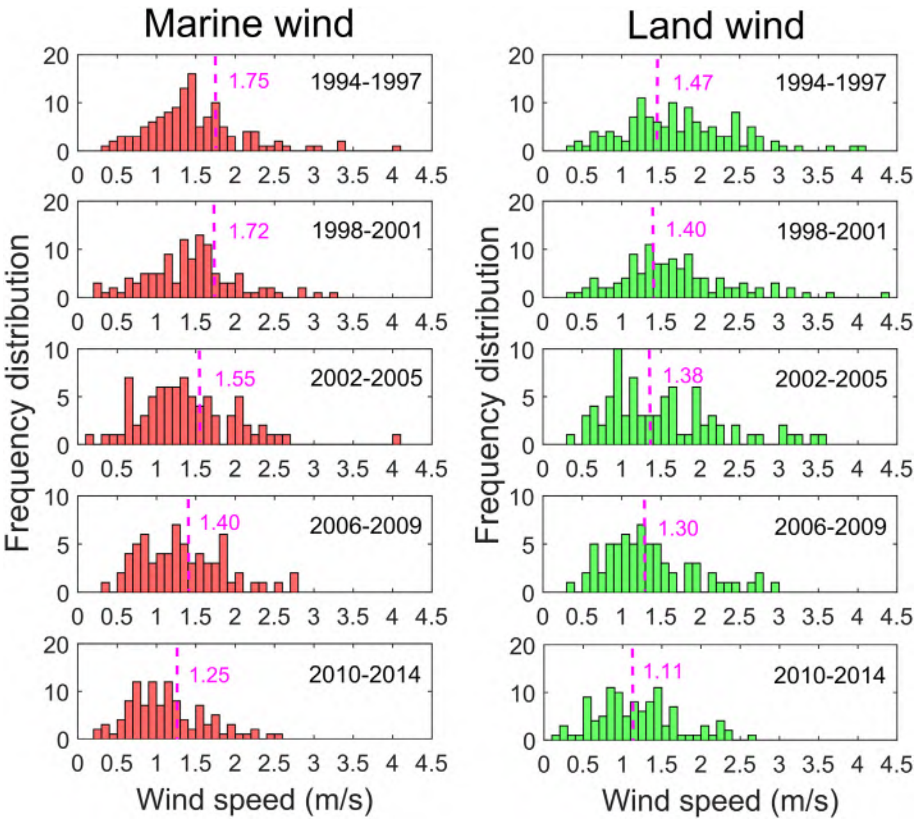

Fig. 3. Histogram of hourly marine wind speed and land wind speed for five 4-year periods in summer from 1994 to 2014. The pink lines represent the mean wind speed values for each time period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and obvious weakening of wind speed in both marine and land wind.

In order to eliminate the in-situ contingency caused by instrument or nearby construction, we also examine the variation of SLB magnitude using wind data from other four sites in Shanghai region. All the criteria of SLB day judgement are the same as what we use for Shanghai site. Figs. 4 and 5 show the histogram results for hourly marine winds and land winds, respectively, at the other four sites. In spite of the different temporal variation rates, the SLB magnitudes at three sites of Jiading, Shanghai Xian and Longhua also show the general decreasing trends over the study period for both marine and land winds, which suggests that the finding of weakening SLB over the whole Shanghai region is robust. It is interesting to notice the SLB magnitude at Chongming site does not show obvious decreasing trend compared to other three sites. Fig. 1 has shown that Chongming site is over the Chongming Island, and the winds at that site are more complicated and influenced by various factors. This might also imply the complexity of SLB at the direction of NE-SW, supporting our choice of SLB at the direction of NW-SE in this study. It should be also noted that uncertainties could be introduced by our SLB classification method shown in Section 2.3, while we think it should be small for these statistical analyses. In the following analysis, we focus on the SLB at Shanghai site only.

Fig. 6 shows the temporal variation of both land wind speed (left) and marine wind speed (right) in daily (upper panels), monthly (middle panels) and yearly (bottom panels) means for summers SLB days from 1994 to 2014. All the analyses shown in Fig. 6 demonstrate the significant decreasing trends of both marine and wind speeds during the last 21 years, all of which pass the student *t*-test (95%) with *p* value less than 0.01. The linear regression analysis shows that the decreasing trends of land wind speed are about 0.0009 m/s per summer SLB day, 0.006 m/s per summer month, and 0.019 m/s per summer. In contrast, linear regression analysis shows that the decreasing trends of marine wind speed are about 0.0013 m/s per summer SLB day, 0.011 m/s per summer month, and 0.033 m/s per summer. For both land wind speed and marine wind speed, the quantitative decreasing trend values for monthly average and summer average are consistent with each other. Note that the decreasing trend values for summer monthly average and whole summer average are also consistent with that for summer SLB daily average for both marine and land wind speeds, since SLB day number is generally around 20 in summer (7 days per month) while it varies with time. Based on these results, we estimate the decreasing trends of marine and land wind speeds as 0.033 and 0.019 m/s per summer, respectively. Moreover, the marine wind speed has a much faster (about twice) decreasing trend than the land wind speed. We should also note that there are temporal fluctuations in both marine and land wind speeds in addition to their decreasing trends. Particularly, both marine and land wind speeds have a comparatively more obvious descending period after the year of 2004, which are the same as that indicated in Fig. 3. The results of temporal variations in both marine and land winds of SLB shown here should be related to the temporal variation in thermal differences between sea and land, which will be analyzed in detail in next sections.

3.3. Difference in land surface air temperature trends between day and night

As mentioned in Section 2, the SLB circulation is driven by the thermal differences between sea and land. Since greenhouse gases play a warming effect by trapping longwave radiation instead of solar radiation, we assume that the warming trends are similar between day and night over relatively clean ocean regions. Then we investigate the difference of near surface air temperature trends between day and night over land, which may imply the contribution from the city heating. The city heating indicated here includes the potential urban heat island effect. Actually, as indicated later, there are almost the synergetic development over the whole YRD region which makes the temperature difference between Shanghai Site and other four sites too weak to

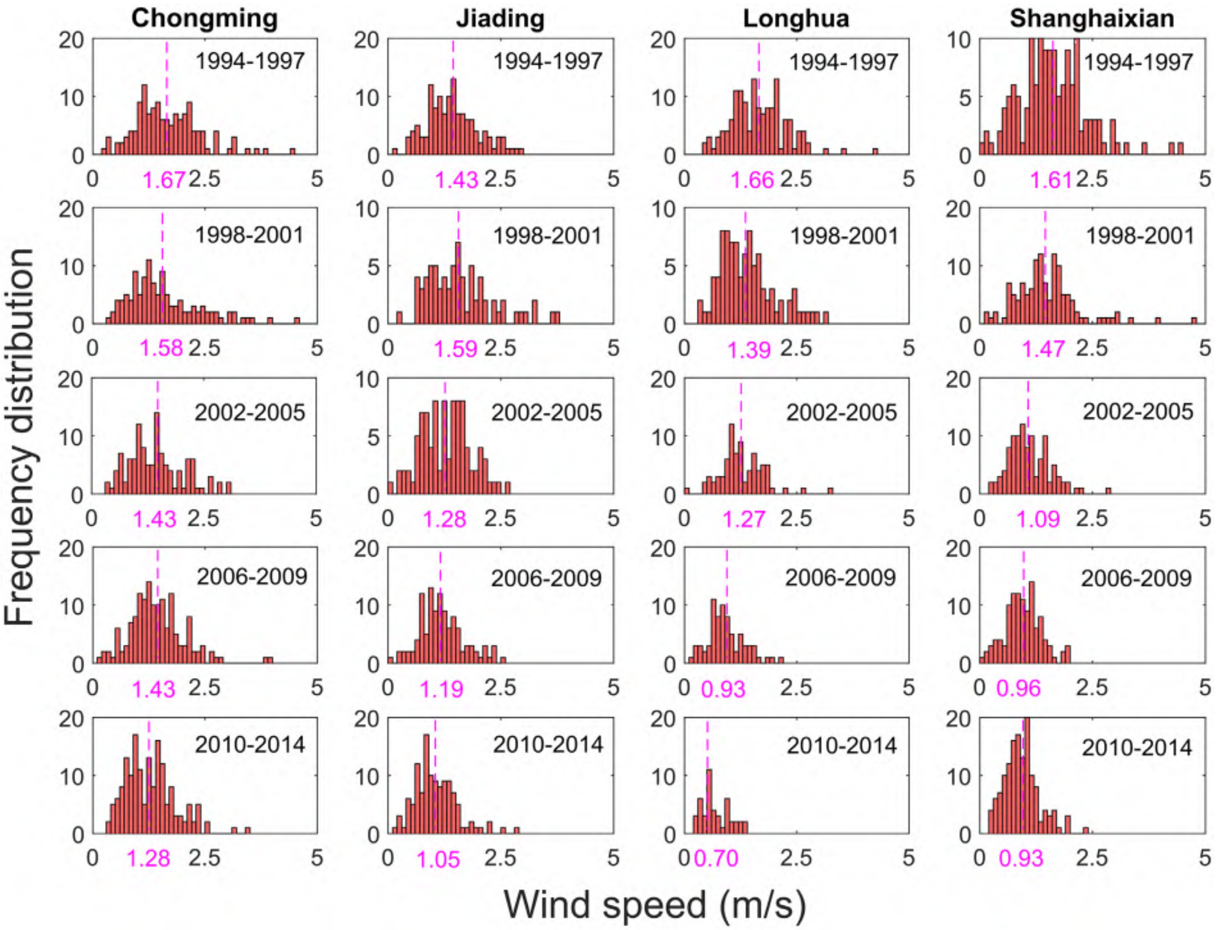

Fig. 4. Histograms of the marine wind speed of SLB in summer from 1994 to 2014 at other four sites in Shanghai: (a) Chongming, (b) Jiading, (c) Longhua, (d) Shanghai Xian. The pink lines represent the mean wind speed values for each time period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

identify the urban heat island effect. The temporal variation of land surface air temperature from in-situ observation at Shanghai site on SLB days is shown in Fig. 7. Consistent with the overall background of global warming and urban heating, both day and night temperatures at Shanghai site on SLB days show clear increasing trends during the past 21 years, which passes the significance test with p values smaller than 0.01. Using linear regression analysis, we find that the day temperature has a faster increasing rate than the night temperature. The increasing rate of day temperature is about 0.4 °C/decade while that of night temperature is about 0.3 °C/decade. The contribution of these different warming trends between day and night to SLB will be discussed in Section 3.7. We can also find that there are some extreme high temperatures during day time. For example, on some SLB days in 2004, the day temperatures are almost 40 °C. Note that the day and night temperatures here are obtained from the record of daily maximum and minimum temperatures, respectively.

3.4. *Difference of warming trends between land and sea*

Since the beginning of 21st century, the trends of both regional and global near surface temperature have been reported by many studies, such as the IPCC fifth annual report (IPCC, 2014). Several sets of data show that the warming trend tends to accelerate after 1900, which may be mainly due to human activities. Su et al. (2016) found that with a trend of periodic rise, the global mean surface temperature undergoes an acceleration of rise from 1970s to 2000s. Not only has the land surface temperature changed but also the marine surface temperature has changed (IPCC, 2014), which could have an effect on the SLB circulation. Su et al. (2016) divided the past 40 years into two parts, pointing out that 1998 is a watershed after which the global warming trend has transited into a comparatively lag phase.

Xu et al. (2017) showed that from 1998 to 2014, the daily mean air temperature over most of the YRD region, including Shanghai, is rising at the rate of about 0.2–0.4 °C/decade, while it varies at different rates in most regions of China from 1985 to 1997. Tan et al. (2016) used several datasets to analyze the temporal trends of sea surface temperature close to East China. Both ICOADS (from NOAA) and COBE-SST (from Japan Meteorological Agency) data show that before 1998, the sea surface temperature of East China Sea is rising at the rate of about 0.1–0.2 °C/decade, while after 1998, in despite of the continuous warming trend of global sea surface temperature, the sea surface temperature of east China offshore region shows a decreasing trend of about − 0.5 °C/decade. Table 1 lists the temporal trends of land surface temperature over east China and sea surface temperature of east China offshore region as described above.

During the time period studied in this article, the difference in temporal trends of temperature between sea and land on a timescale of decades could definitely affect the SLB. Without observations of temperature over ocean, we here simply adopt the values indicated above from the literature as the difference of temporal trends of temperature between sea and land while their locations are close to each other. We have to note that the temperature over ocean is gained through buoy observation rather than air temperature over ocean surface. Because it is apparent that there is no possibility to build observation station over sea surface. In a word, Shanghai is becoming warmer compared to its offshore sea when considering long-time and large-scale background of

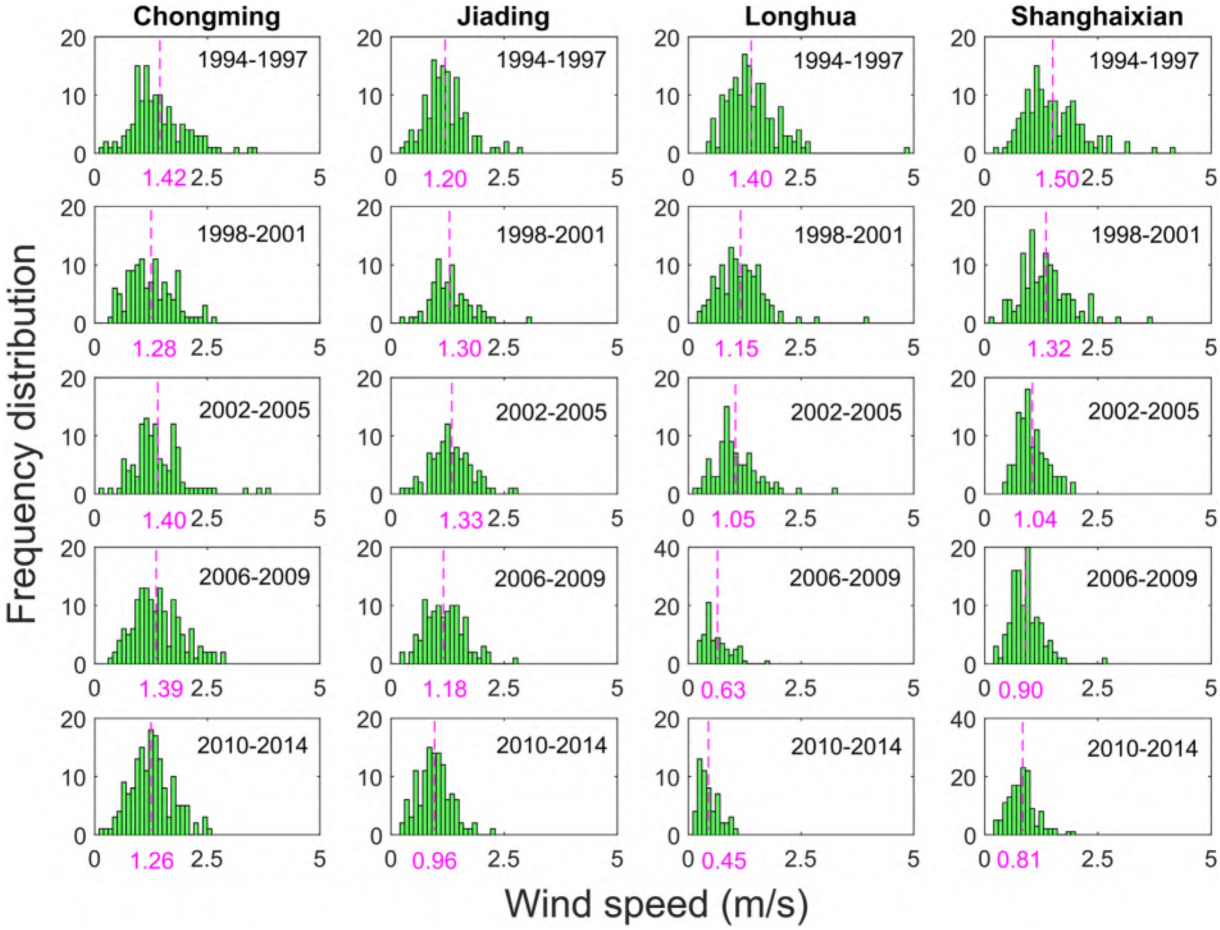

Fig. 5. Histograms of the land wind speed of SLB in summer from 1994 to 2014 at other four sites in Shanghai: (a) Chongming, (b) Jiading, (c) Longhua, (d) Shanghai Xian. The pink lines represent the mean wind speed values for each time period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climate changes. In this respect, the magnitude of SLB circulation could enhance during day time while weaken at night.

3.5. Variation of in-situ shortwave radiation

As well known, the surface temperature is highly influenced by the surface radiation balance, particularly the downwelling solar radiation. Great urbanization may cause increasing pollution which further affects the radiation reaching the surface by absorbing and scattering solar radiation. Particularly, the particles released to the atmosphere in urban cities, called as aerosols, could have a strong scattering effect to solar radiation. Fig. 8 shows the temporal variation of SLB-day averaged daily direct solar radiation reaching the surface at Shanghai site every summer from 1994 to 2014. As shown in Fig. 8, there is a very clear decreasing trend for the direct solar radiation reaching the surface at Shanghai site, which passes the significance test with a confidence level of 95%. We also note that there are strong annual variations of the summertime direct solar radiation reaching the surface, with the occurrence of high values every few years as indicated with the yellow dots in Fig. 8.

The occurrence of high downwelling direct solar radiation every several years might be a result of East Asia monsoon variation. According to the previous studies (e.g., Fang et al., 2014), year 1994, 2000, 2006, 2010, and 2013 are all years during a period of low monsoon index or are years with a relatively lower monsoon index compared to the average during the study period. Actually, year 2006, 2010, and 2000 are ranked among the 10 years with the lowest summer monsoon index observed in 1979–2011. Zhao and Zhang (1996) pointed out that the rain band distribution is closely related to monsoon index. Weaker summer monsoon is often accompanied with a rain band in a more southern place than normal summer monsoon. Accordingly, in years with weak summer monsoon index, rain band is harder to reach YRD region. The less precipitation and then clouds in YRD during the weak summer monsoon years could cause less solar radiation reflected and more radiation reaching the surface. Fig. 8 shows that there is significant decreasing trend of daily down-welling direct solar radiation reaching the surface during the past 21 years. Actually, even for those high values of down-welling direct solar radiation with weak summer monsoon effects, they also show a clear decreasing trend with time, with the maximum value of 12 MJ/m^2 in summer of 1994.

The linear fitting regression of the decreasing trend of surface downwelling direct solar radiation is $y = -0.14x + 8.8$, where y and x represent summer SLB-day mean daily surface downwelling direct solar radiation in each summer in unit MJ/m^2 and year, respectively. This is most likely associated with the variation of aerosol pollution in this region. There have been numerous reports claiming that China has been carrying out tremendous urbanization since the 1978 Great Open and Reform. Especially after the year of 2000, there is a rapid acceleration of aerosol pollution as the urbanization goes up to a higher level (Kong et al., 2017). Using the remote sensing data from NASA, Zhou et al. (2017) showed that, from 2000 to 2011, PM$_{2.5}$ pollution increases rapidly and then becomes stable in this region. The center of pollution has an east-toward moving trend and the YRD region is one of the highest pollution areas (Zhou et al., 2017). It should be acknowledged that the decreasing downwelling direct solar radiation could be a result of the combined effect of aerosols and cloud, which can be called the

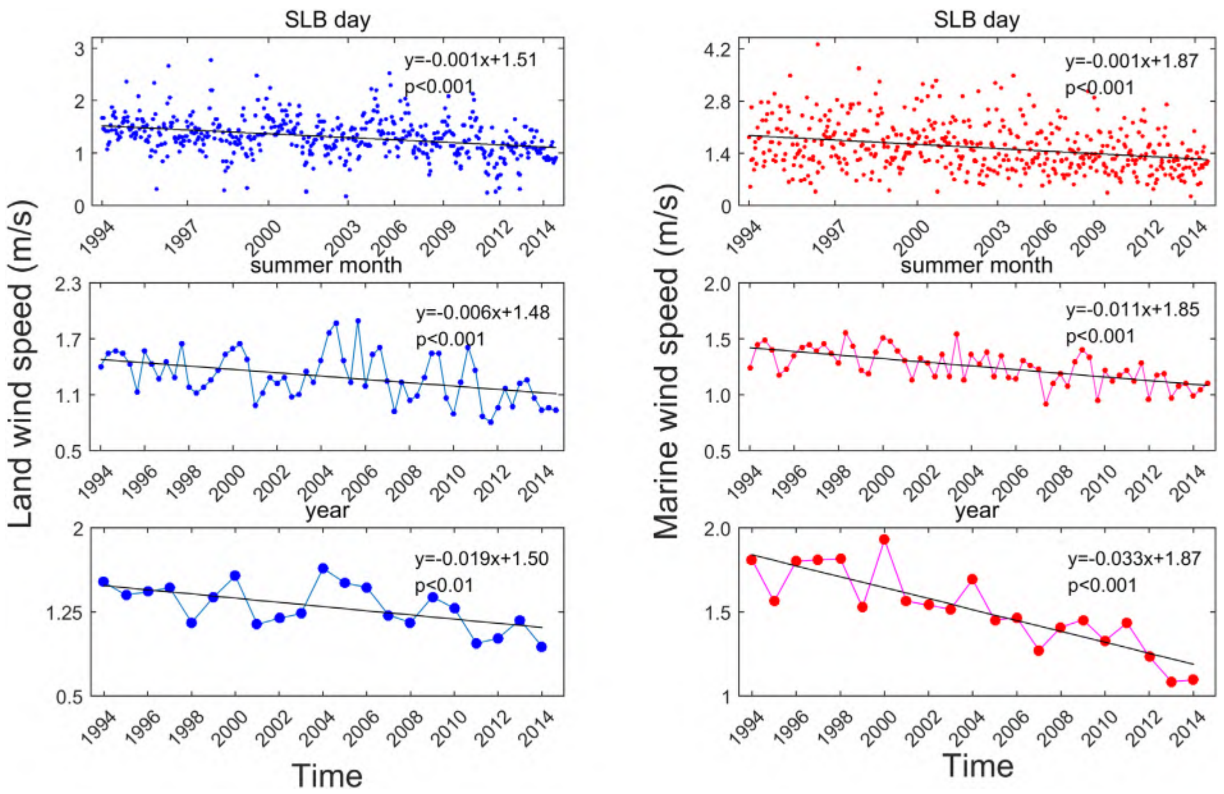

Fig. 6. Temporal variation of both land wind speed (left) and marine wind speed (right) in daily (upper panels), monthly (middle panels) and yearly (bottom panels) means for SLB days.

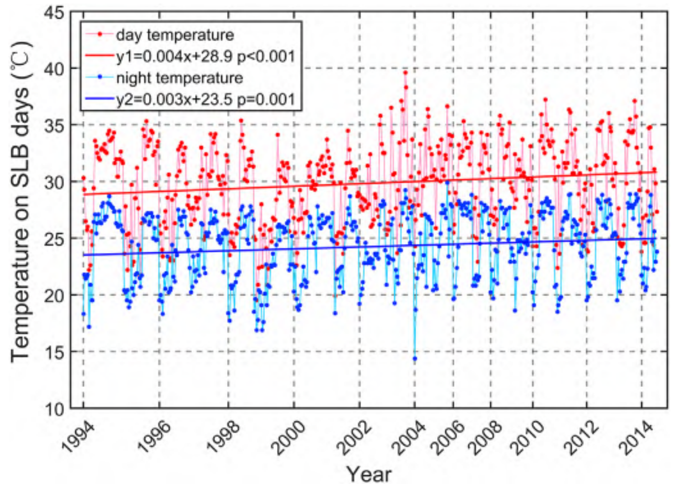

Fig. 7. Temporal variation of day (maximum value) and night (minimum value) near surface air temperature measured at Shanghai site on SLB days from 1994 to 2014. The linear regression lines are obtained based on yearly average temperature during day and night time, respectively.

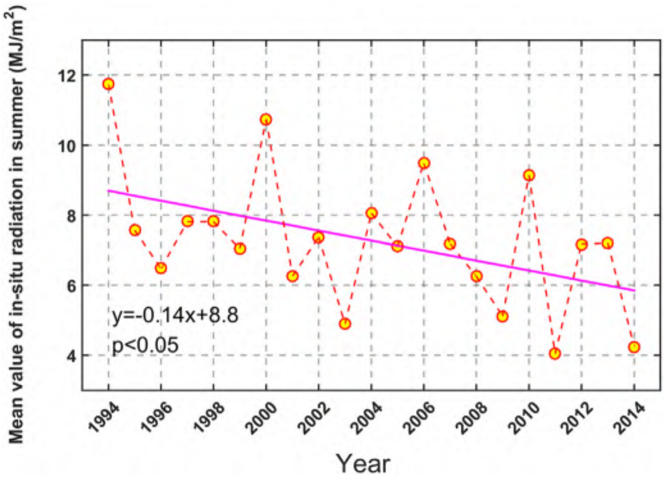

Fig. 8. Temporal variation of SLB-day averaged daily direct solar radiation reaching the surface at Shanghai site in each summer from 1994 to 2014. The temporal trend of the downwelling direct solar radiation was also shown in the pink line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

'Umbrella Effect' of aerosols and cloud, while the change of aerosol and cloud radiation forcing effect is not investigated individually in this study. The decrease of received shortwave radiation at the surface is unfavorable to the in-situ temperature rise found in Section 3.3. Instead, the aerosol effects on solar radiation could reduce the warming trend over the land area during day time, partially offsetting the positive effect on the SLB magnitude.

Table 1
The temporal trends of land air temperature over east China and sea surface temperature of east China offshore region obtained from literature.

Time period	Sea temperature trend	Land temperature trend	Land – sea temperature difference	Literature
1994–1998	0.1–0.2 °C/decade	0.2–0.4 °C/decade	+ 0.1–0.2 °C/decade	Xu et al. (2017)
1998–2014	− 0.5 °C/decade	0.2–0.4 °C/decade	+ 0.7–0.9 °C/decade	Tan et al. (2016)

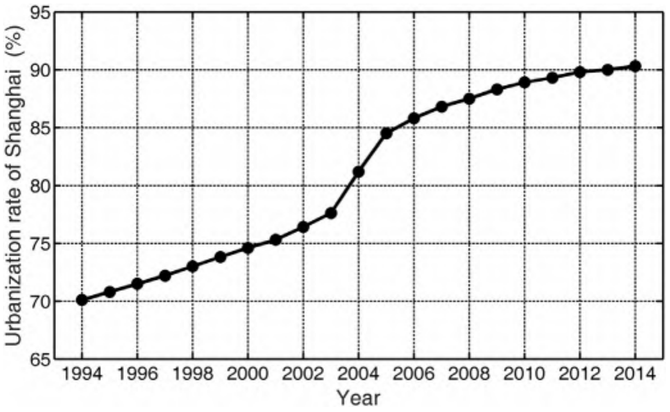

Fig. 9. Temporal variation of urbanization rate over whole Shanghai region from 1994 to 2014 based on the data from Shanghai Statistical Yearbook.

3.6. Expansion of urban area and increasing human activities

As mentioned before, great urbanization has a close relation with temperature rise and radiation variation. Here we look into the specific changes of urbanization. Fig. 9 shows the temporal variation of urbanization rate over whole Shanghai region from 1994 to 2014 based on the data from Shanghai Statistical Yearbook. Urbanization rate represents the ratio of city population to total population in Shanghai. The urbanization rate of Shanghai has been continuously increasing during the study period, rising about 20% from 70% in 1994 to over 90% in 2014. The rate undergoes an acceleration period around the year of 2004.

The urbanization progress can also be further investigated based on the annual change of nighttime light in the eastern part of YRD region, which is shown in Fig. 10. The nighttime light data are retrieved from the satellite of DMSP observations and can directly show the expansion pattern of urban areas. In Fig. 10, the abbreviations of SH, SZ and JX represent the three main cities of Shanghai, Suzhou, and Jiaxing in this area, respectively. Most of the light shown in the maps comes from human activities and urban infrastructure like office buildings or street lamps. In contrast, the dark areas represent the rural areas such as farmland or forestland which have few light source at night. The increasing nighttime light regions (increasing brightness) indicate the expansion of urban area over the years in the YRD region, which could definitely have a significant influence on the SLB circulation.

In addition to the increasing area of nighttime light, the distribution pattern of urbanization has also changed over the years. From the very beginning, the light areas are small like bright dots scattering over the region. As time passes, there appears a trend of centralization of the light area. Starting from 2004, the dotted bright regions show a sign of congregation, which is in accordance with the steep acceleration of urbanization rate shown in Fig. 9. After 2010, the dotted bright regions finally congregate with each other. Till 2013, almost all light regions have been connected with each other, especially in the direction of NW-SE. There are only sparse black areas to the south west of Shanghai. Associated with the fast urbanization, the land utilization should also be changing to urban construction, which could affect the surface roughness and then the near surface winds.

3.7. Analysis of the influential factors to SLB change

As mentioned in Section 2, the temperature difference between land and ocean can directly affect the SLB circulation. We can define the factors that influence the land or ocean temperature which further affect the SLB circulation as thermodynamic factors. In addition to the thermodynamic factors, the surface condition could also affect the SLB circulation by influencing the surface roughness, which can be defined as dynamic factors. We next discuss the potential contributions from different influential factors.

Figs. 3–6 have shown that the magnitude of both land and marine wind speed has a decreasing trend from 1994 to 2014 over the Shanghai region. The urbanization of Shanghai during this period should play a positive contribution, which increases the area of urban constructions and makes the surface roughness increase, causing more frictions to both land and marine wind. Thus, the dynamic effects associated with the urbanization could play an important role for the decreasing trends of both land and marine wind speed in Shanghai from 1994 to 2014.

In addition to the dynamic effects, temporal changes of land-sea surface temperature difference could also play important roles. Multiple factors could affect the land-sea temperature differences, including the different temporal trends of land and sea temperatures associated with large-scale and long-time background signal such as global warming, the heat release from cities, the downwelling solar radiation, the surface albedo, and so on.

We first discuss the potential effects from the aspect of climate and heat releases from cities. As indicated by Jones et al. (1990), urbanization has a positive effect on temperature increase in megacity which has a continuous increase in population. Fig. 7 shows that nighttime and daytime temperatures have warming trends of 0.3 °C/decade and 0.4 °C/decade, respectively. Assuming the climate signals associated with the large background are the same for regions over the land of Shanghai between day and night, the contribution from city heat release should be larger during day time than during night time. This should be reasonable since there are generally more human activities and heat sources in cities during day time. Table 1 has indicated that the long-term regional temperature rise associated with the large background is about 0.2–0.4 °C/decade over the land, whose rate is slightly lower than that found in Fig. 7. Thus, the warming effect associated with the city heat release is likely to be roughly less than 0.1 °C/decade on SLB days, though it may be a little different during day time and at night time. The day-night difference in land near surface temperature trends could imply that the temporal variation of land surface temperature contributes more changes to daytime marine wind than nighttime land wind. Table 1 further indicates that the increasing trend of air temperature over land is larger than surface air temperature over offshore sea, which could help increase the marine wind speed and decrease the land wind speed. However, Fig. 3 shows that there are larger decreasing rates for the temporal variations of marine wind speed than that for land wind speed. This implies that there must be some other factors which play a more important role in weakening marine wind.

We then discuss the potential radiation effects from the atmospheric components, such as aerosols and clouds. As indicated in Fig. 8, there are significant decreasing trend of downwelling direct solar radiation, for which the aerosol cooling effect should be one of the important contributing factors. Without considering the change of surface heat capacity and albedo, this would have a negative effect on the surface temperature increase in Shanghai during day time. This would help contribute to the decreasing trend of marine wind speed during day time. Note that the change of surface albedo and heat capacity due to urbanization is not discussed here, which need further study in the future.

Fig. 11 summarizes the physical mechanisms when considering the change of SLB circulation, including both the thermodynamic and dynamic factors discussed above. The intersection of the horizontal arrow and the vertical solid line means the original point whose left and right sides represent weakening and strengthening magnitude of SLB, respectively. The left part is for night time and the right for day time. The dash lines on the left represent the decreasing trends of both land wind speed and marine wind speed from observations, with larger decreasing trend during day time. From the long-time and large-scale aspect of temperature variation, the faster warming trend of air temperature than

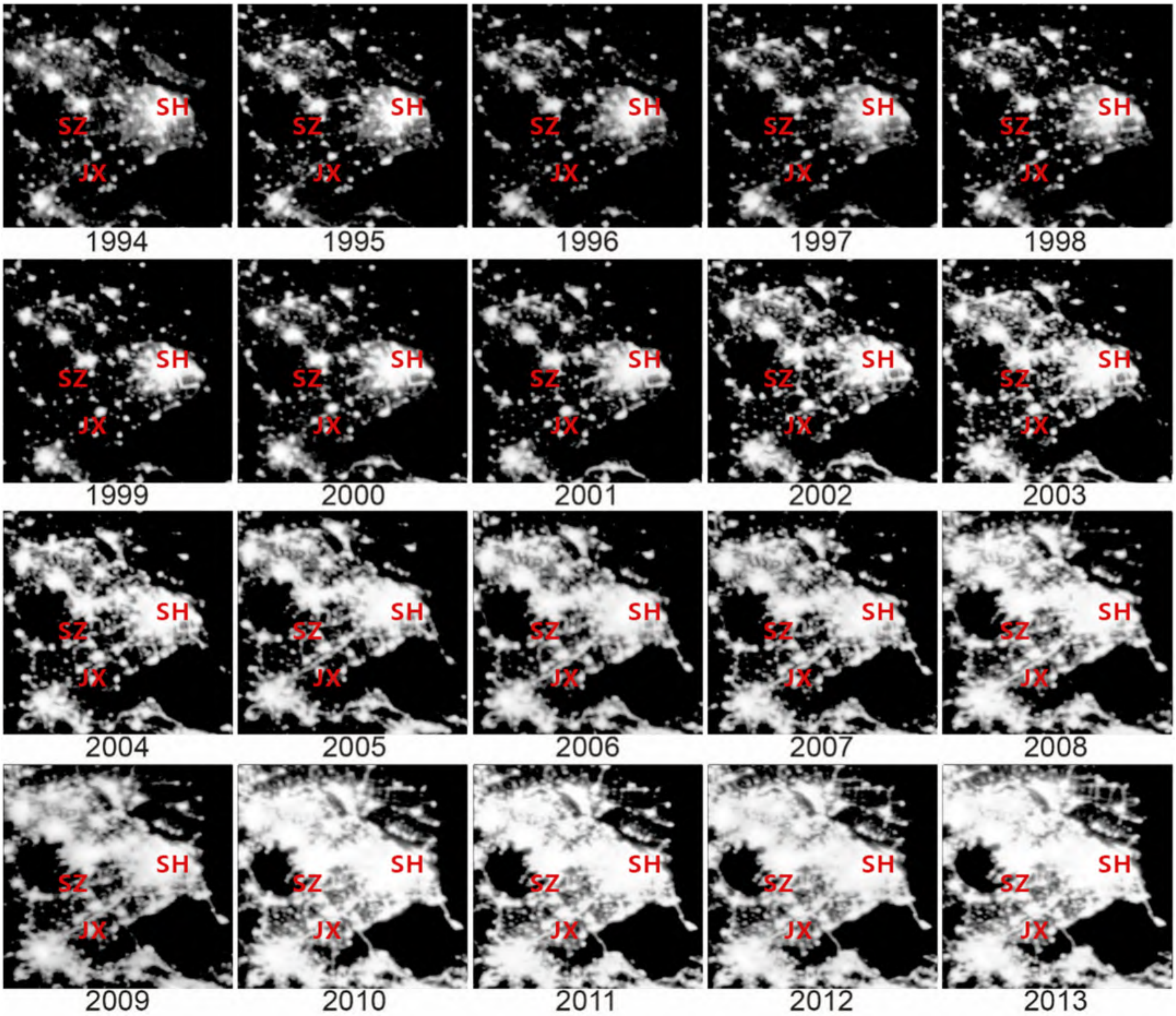

Fig. 10. Annual change of nighttime light distribution in the YRD region from 1994 to 2013. The abbreviations of SH, SZ and JX represent the three main cities of Shanghai, Suzhou, and Jiaxing in this area, respectively.

sea surface temperature in the study region contributes to the increase of marine wind speed and decrease of land wind speed. The heat release due to urbanization could also contribute to increase of marine wind speed during day time and decrease of land wind speed during night time. Differently, the decreasing surface solar radiation should contribute to the decrease of marine wind speed. The increase of surface roughness due to urbanization, which is included in dynamic effects, should have an important contribution to the decrease of both land and marine wind speeds. Considering that the decreasing trend of marine wind speed is larger than that of land wind speed, the contribution of dynamic effects should be larger during day time than that at night time. There were at least two likely reasons for this. First, as Fig. 1 shows, the observation station is located to the north of the central urban area of Shanghai, so the incoming marine wind has to go through a large area where urban buildings are located. While at night, according to previous observations, land wind often encroaches less than 20 km (Pokhrel and Lee, 2011). Accordingly, the offshore land wind goes through less central urban areas with a high surface roughness where a great amount of urban buildings were located. As a result, the blocking effect mainly due to increasing surface roughness as urbanization proceeds is larger at day than at night. Secondly, there are more human activities and human heat releases during day time than that at night time, which could cause stronger turbulence friction during day time. This is also part of the dynamic factors. We should note that the quantitative estimations about the relative contributions to the decreasing trend of SLB circulation from the various influential factors have not been investigated here, which could be done in future.

4. Conclusion

The magnitude of SLB circulation depends on both the thermodynamic effects from the land-sea temperature difference and the dynamic effects from the surface conditions. This study analyzes the impacts of urbanization on the SLB circulation from both thermodynamic and dynamic aspects.

This study first statistically analyzes the temporal variations of SLB days, the marine and land wind speeds, the in-situ air temperatures during day and night, the large-scale and long-time land-sea

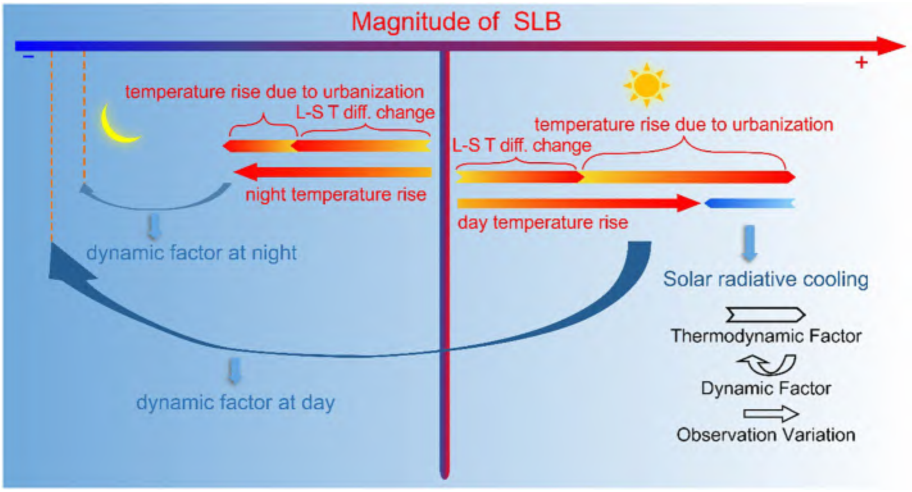

Fig. 11. A diagram for the physical mechanisms that contribute to the change of SLB circulation, including both the thermodynamic and dynamic factors. The 'L-S T diff. change' is short for 'Land and sea temperature difference change'.

temperature variation trends and their differences, the downwelling direct solar radiation, and the urbanization rate over the Shanghai region from 1994 to 2014. It is found that the magnitude of both marine and land wind speeds has decreasing trends from 1994 to 2014 at the Shanghai site, which are 0.033 and 0.019 m/s per summer, respectively. The temperature analysis shows that nighttime and daytime land surface air temperatures have warming trends of 0.3 °C/decade and 0.4 °C/decade, respectively. A literature review shows the faster warming trend over land than over nearby ocean over the YRD region when considering the signal of global warming background. Further analysis using remote sensing data shows the urbanization expansion of Shanghai city from 1994 to 2014.

This study further discusses the potential influence of urbanization and global warming on the change of SLB circulation. The warming trend is larger over land than over nearby ocean, contributing to increase of marine wind speed during day time and decrease of land wind speed during night time. Similarly, the warming effect associated with the urbanization could also contribute to increase of marine wind speed during day time and decrease of land wind speed during night time. On the other hand, the increase of surface roughness due to urbanization, which is included in dynamic effects, could have a great contribution to the decrease of both land and marine wind speeds. The larger decreasing trend of marine wind speed implies that the contribution of dynamic effects should be larger during day time than that at night time, which could be related to the observation site location, the direction of urbanization, and human activities during day time.

Acknowledgement

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