ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL112480

Increasing Sea-Land Breeze Frequencies Over Coastal Areas of China in the Past Five Decades

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Key Points:

- A comprehensive criteria for gridded reanalysis dataset to identify SLBDs is proposed
- SLB frequencies in coastal China have increased in the past five decades
- The rising land-sea temperature contrast drives the increase in SLB frequencies

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Huang, Y., Li, S., Zhu, Y., Liu, Y., Hong, Y., Chen, X., et al. (2025). Increasing sea-land breeze frequencies over coastal areas of China in the past five decades. *Geophysical Research Letters*, *52*, e2024GL112480. https://doi.org/10.1029/2024GL112480

Received 13 SEP 2024
Accepted 11 FEB 2025

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Abstract Sea-land breeze (SLB) is particularly important in coastal regions and can affect weather conditions and air quality. However, previous research on SLB has predominantly focused on specific locations, with varying methodologies used to identify SLB days (SLBDs), leading to a limited understanding of long-term SLB trends across extensive coastal areas. Here, a unified method for gridded reanalysis dataset to identify SLBDs is proposed for the first time, and the trend, influencing factors, and effects on air pollutant recirculation over coastal China are explored. The results demonstrate that SLBDs have increased in 70% of China's coastal areas in the past five decades. Key driving factors include the growing temperature contrast between land and sea, increasing solar radiation, and the weakening background winds. The study suggests that the increasing SLB frequency will enhance air pollutant accumulations, making it challenging to manage air quality effectively in these coastal areas.

Plain Language Summary Sea-land breeze (SLB), a prevalent local circulation driven by the temperature contrasts between land and sea, significantly impacts regional weather, urban environments, wind power generation, and fisheries. While detailed case studies have explored the local characteristics of SLB in different specific coastal regions, the long-term trends and underlying mechanisms of SLB have received less attention, particularly in the context of global warming. The rapid advancement of meteorological reanalysis data with high spatial and temporal resolutions now allows for a comprehensive analysis of these long-term trends across extensive coastal regions. This study introduces a novel method to identify SLB days (SLBDs) over coastal areas of China using gridded reanalysis datasets (ERA5). Over the past 53 years, we find that the frequencies of SLB have increased in more than 70% of coastal China. Rising temperature differences between land and sea, increasing solar radiation, and weakening wind fields are key factors contributing to the trend. A weakening recirculation index suggests that increased SLBDs may exacerbate air quality issues in coastal areas. The method proposed in this study for identifying SLBDs can be extended to other regions worldwide, yielding new insights into the regional dynamics of SLB and their broader environmental impacts.

1. Introduction

Sea-land breeze (SLB), a mesoscale local circulation occurs widely in coastal areas due to differences in the thermal properties of land and sea (X. Chen et al., 2016; Shen et al., 2021a). A sea-land breeze day (SLBD) specifically refers to any 24 hr period that features a distinct transition from sea breezes during the day to land breezes at night (Xiao et al., 2023). Variations in SLB are influenced by temperature difference between land and sea (Park & Chae, 2018), solar radiation (Shen et al., 2021b; Shen & Zhao, 2020), urbanization (Fan et al., 2020; Lyu et al., 2024; You et al., 2019), and background wind field (Allouche et al., 2023; Shen et al., 2022; Xu, Jia, et al., 2021), impacting local weather, climate, and ecosystem (Allouche et al., 2023; Shen et al., 2021b; Zhu et al., 2021). SLB also interacts with large-scale circulations (e.g., monsoons) and extreme events, modulating its intensity and dynamics (Bajamgnigni Gbambie & Steyn, 2013; Di Bernardino et al., 2023; Papanastasiou et al., 2010). For instance, SLB can enhance extreme rainfall events in coastal areas by intensifying local convection, as observed in studies of heavy precipitation along the South China (X. Chen et al., 2016). As a distinct coastal weather phenomenon, SLB significantly affects air quality of coastal cities (S. Han et al., 2023; Wang et al., 2023; Zheng et al., 2023), consequently influencing public health and living standards. Additionally, the

Writing – review & editing: Yuxuan Huang, Shuai Li, Yiming Liu, Xiao Lu, Qi Fan

periodic patterns of SLB have implications for wind power generation in coastal areas (Garvine & Kempton, 2008; Mazon et al., 2015). Given China's extensive coastline and dense coastal population, a deeper understanding of SLB circulation is essential for advancing the environmental sustainable development.

In recent decades, numerous studies have investigated SLB structure and characteristics using observational methods, including aircraft, weather towers and radar (Guo et al., 2023; Hunter et al., 2007; Jia et al., 2023; Liu et al., 2022; Prtenjak & Grisogono, 2007), as well as theoretical research (Fu et al., 2022; Miller et al., 2003) and numerical simulations (Davis et al., 2019; Drobinski et al., 2018; Hai et al., 2018; Liu & Chan, 2002; Wang et al., 2017). Shen et al. (2019) found a declining trend of SLBDs during summer in Shanghai (1994–2014), attributing these changes to the impacts of urbanization and global warming. In Tianjin, the number of SLBDs (2005–2019) also exhibited a slight downward trend (Xiao et al., 2023). Conversely, Lei et al. (2024) discovered a significant increase in SLBDs in Hong Kong over the past 50 years (1971–2020), with an average annual growth rate of 8%. Besides, SLB has a widespread impact on air quality by affecting the transport and dispersion of air pollutants (Coulibaly et al., 2021; Geddes et al., 2021; Hu et al., 2019; Nie et al., 2020; Wang et al., 2018). Zhao et al. (2022) examined how SLB circulation affects ozone pollution in the Yangtze River Delta (YRD) region, with nocturnal land breezes transporting ozone offshore and daytime sea breezes returning it to coastal areas, promoting the accumulation of pollutant.

Most studies on SLB have been limited to individual cities or regions, focusing predominantly on short- to medium-term trends of SLB (El-Geziry et al., 2021; Lei et al., 2024; Shen et al., 2019). Differences in geographical location, underlying surface conditions, and coastline distribution among various coastal areas, have led to divergent data application and identification methods of SLBDs (Borne et al., 1998; Shen & Zhao, 2020; Xu, Huang, et al., 2021). Recent advances in meteorological reanalysis datasets, particularly the fifth-generation European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA5), offer high spatial ($0.25° \times 0.25°$) and temporal (hourly) resolutions (Zhu et al., 2024). This enables detailed investigation of mesoscale weather systems over large areas and extended durations. In this study, we develop a comprehensive set of criteria for identifying SLBDs across all coastal areas in China based on ERA5 data. We aim to investigate the long-term trends of SLBDs across broader coastal regions and identify the main driving factors. The influences of SLB on air pollutants in coastal areas are further analyzed using a recirculation index as an indicator. The structure of this paper is as follows: Section 2 describes the data and methods, Section 3 presents the results and discussions, Section 4 provides the study limitations and future perspectives, and Section 5 summarizes the findings and discusses the implications.

2. Data and Methods

2.1. Meteorological Data

The meteorological data are from the ERA5 reanalysis dataset, provided by ECMWF, including hourly data with a spatial resolution of $0.25° \times 0.25°$, covering variables such as the 10 m u and v component of wind, 2 m temperature, sea surface temperature, surface solar radiation downwards, and total cloud cover. The study area encompasses the entire coastal regions of China (17.5°N–42°N, 107.5°E–126°E), characterized mainly by plains except for the mountainous regions flanking the Taiwan Strait (Figure S1 in Supporting Information S1). The study period spans from 1970 to 2022, totaling 53 years. Land use data from the Resource and Environmental Science Data Platform (RESDEP) are utilized to examine the impact of rapid urbanization.

2.2. Definition of Sea-Land Breeze Days

Previous research has primarily focused on defining SLB at individual stations using various methodologies (Table S1 in Supporting Information S1), limiting our understanding of long-term trends across extensive areas. Currently, there is no consensus on the criteria for defining SLBDs due to the difference in geographical locations and the lack of uniform observations. Zhu et al. (2024) evaluated the applicability of ERA5 data in the analysis of SLB characteristics and found that ERA5 data with long time series had a high correlation with observational data, making it suitable for SLBD statistics. In this study, we establish a comprehensive and unified standard for defining SLB events in coastal China. The key challenge of this method lies in accurately identifying the wind directions of sea and land breezes along different coastlines. A detailed flowchart of this method is presented in Figure S2 in Supporting Information S1.

The first step is to identify the coastal grids within the selected area (Figure S2a in Supporting Information S1). For each grid, we extend the area to include surrounding 80 grids, forming a 9 × 9 square (about 225 × 225 km). This range is chosen because most observations of SLB are conducted at urban meteorological stations located within an effective SLB zone, typically 50–150 km from the coastline (Davis et al., 2019; Xiao et al., 2023). Meanwhile, we compare the results using 10, 20, and 30 sea grids (Figure S3 in Supporting Information S1) and find requiring at least 20 sea grids ensures that the identified grids are located within tens of kilometers from the coastline, which is a more reasonable range for SLBD statistics. Thus, we define a coastal land grid such that the remaining 80 grids in the square must include at least 20 sea grids. Similarly, a coastal sea grid must be surrounded by at least 20 sea grids. Additionally, small islands are excluded from the analysis.

Next, we determine the wind direction of sea breeze by dividing the square into four triangular regions (east, south, west, and north) along the diagonal axes, assuming that each sea grid contributes equally within its respective triangular region (Figure S2b in Supporting Information S1). The number of sea grids in these regions is recorded as a1, b1, a2, and b2, respectively. The concentration direction of sea grids indicates the incoming direction of the sea breeze. We use the number of sea grids in the north-south and east-west directions as weights to calculate the angle between the sea breeze and *x*-axis. The formula is as follows, a more detailed calculation of this equation is included in Text S1 in Supporting Information S1.

$$\theta = atan\ 2(b2 - b1, a2 - a1) \tag{1}$$

Here, the range of θ is −180°–180°, where 0° represents due east, 90° represents due north, −90° represents due south, and ±180° represents due west. Ultimately, a total of 838 grids with specific sea breeze directions are identified (Figure S2c in Supporting Information S1). The wind speed component in the direction of sea breeze (θ) is calculated as follows:

$$w = u \cos\theta + v \sin\theta \tag{2}$$

Here, w represents the component of wind speed perpendicular to the coastline, where a positive value indicates wind blowing from the ocean toward the land, while a negative value represents wind blowing from the land toward the ocean.

Finally, a SLBD is determined by excluding the influence of background wind, requiring the 24 hr average daily wind speed to be below 10 m/s (Qiu & Fan, 2013; Sun et al., 2022; Zhang et al., 2024). According to previous studies, both sea and land breezes must occur simultaneously for over 4 hr each day in SLBD (Lei et al., 2024; Xiao et al., 2023). Therefore, a sea breeze is identified if the wind direction is positive and persists for more than 4 hr within 24 hr, while a land breeze is identified if the wind direction is negative and lasts for over 4 hr. If both transitions occur consecutively within a 24 hr period, the day is classified as a SLBD (Figure S2d in Supporting Information S1).

3. Results

3.1. Spatial and Temporal Characteristics of Sea-Land Breeze

Figure 1a presents the annual average number of SLBDs in coastal China from 1970 to 2022. The statistical analysis reveals an average of 27 SLBDs per year in these regions. Significant spatial variations are observed, with lower latitudes experiencing higher SLB frequencies, likely due to the influence of solar radiation (Xu et al., 2024). The highest annual averages (106 days), are predominantly concentrated in the southeastern coastal areas.

We also examine the seasonal characteristics of three key coastal regions: the Bohai Rim (BR) (37.75°N–41°N, 117.75°E–122°E), the YRD (27.25°N–33°N, 120.25°E–123°E) and the Pearl River Delta (PRD) (21°N–24°N, 110.5°E–117.5°E). In the BR, SLBDs are more frequent in spring and summer, accounting for about 57% of the total occurrences, and least in winter, likely influenced by strong cold air from Siberia (Xiao et al., 2023). In the YRD, SLBDs are relatively uniform year-round, with a slight increase in autumn. This contrasts with previous findings that indicated a summer peak in Shanghai (Shen et al., 2019), suggesting the difference may be due to the broader scope of this study. In the PRD, SLBDs peak in autumn, with an average frequency exceeding 35%, followed by winter. This pattern is associated with the large-scale wind field and air-sea turbulent heat fluxes

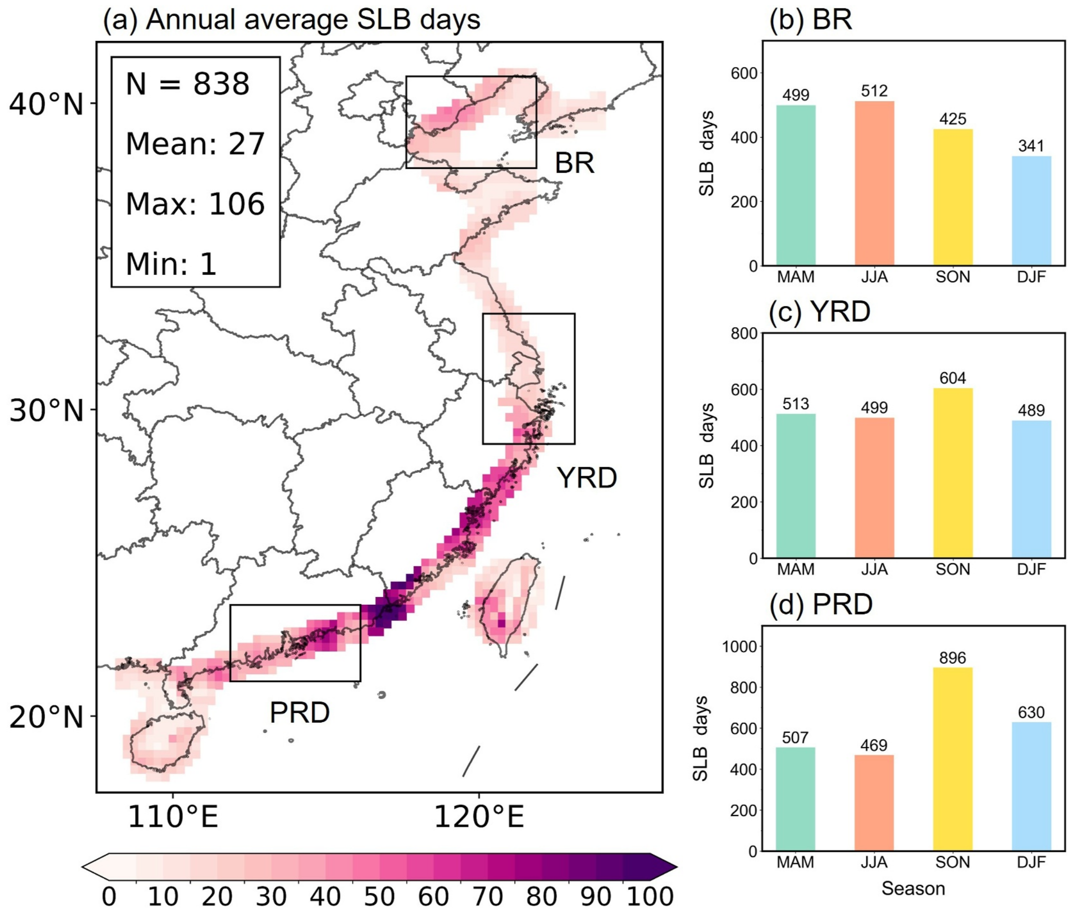

Figure 1. (a) Spatial distributions of annual average SLBDs at individual grids over coastal areas of China and the seasonal SLBDs in total in the (b) BR, (c) YRD, and (d) PRD from 1970 to 2022. Mean, maximum, and minimum values over the grids are shown inset. Three black boxes in (a) present the BR, YRD, and PRD respectively.

(THFs) (Shen et al., 2024). During autumn and winter, a weak ridge of continental cold high creates a weak background wind field in the PRD, favoring SLB occurrences (Lu et al., 2010; Zhang et al., 1999).

3.2. Increasing Sea-Land Breeze Frequency Over Coastal China

Figure 2a illustrates the decadal changes in the number of SLBDs over coastal China from 1970 to 2022. The analysis reveals that over 70% of the grids exhibit an upward trend in SLBDs, with an average growth rate of 0.6 days decade^{-1} (251 grids with p-value <0.05). Notably, regions with significant upward trends are concentrated in the BR, YRD, and PRD, with average decadal rises of 1.58, 1.38, and 2.58 days respectively (Figures 2b, 2d, and 2f). Meanwhile, we observe a significant upward trend with growth rates exceeding 18% in three regions from the 1970s to the 2010s (Figures 2c, 2e, and 2g). However, a downward trend in SLBDs is noted in Taiwan, possibly linked to factors like background wind fields, etc., as discussed in Section 3.3.

Compared to previous studies, our findings align with the analysis by Xiao et al. (2023) for the period 2005–2009, which indicated similar trends in the BR. Although Shanghai showed a slight upward trend in SLBDs over the past five decades, the decline observed during the summer from 1994 to 2014 is consistent with Shen et al. (2019). Besides, the significant increase observed in Hong Kong from 1971 to 2020 corresponds with the findings of Lei et al. (2024). These results affirm the feasibility of using ERA5 data to explore the variations of SLBDs.

3.3. Factors Influencing the Increasing Frequency

The SLB circulation is primarily driven by the heat difference between land and sea, making this differential the most critical factor affecting SLB intensity and frequency. In this section, we focus on analyzing the main factors

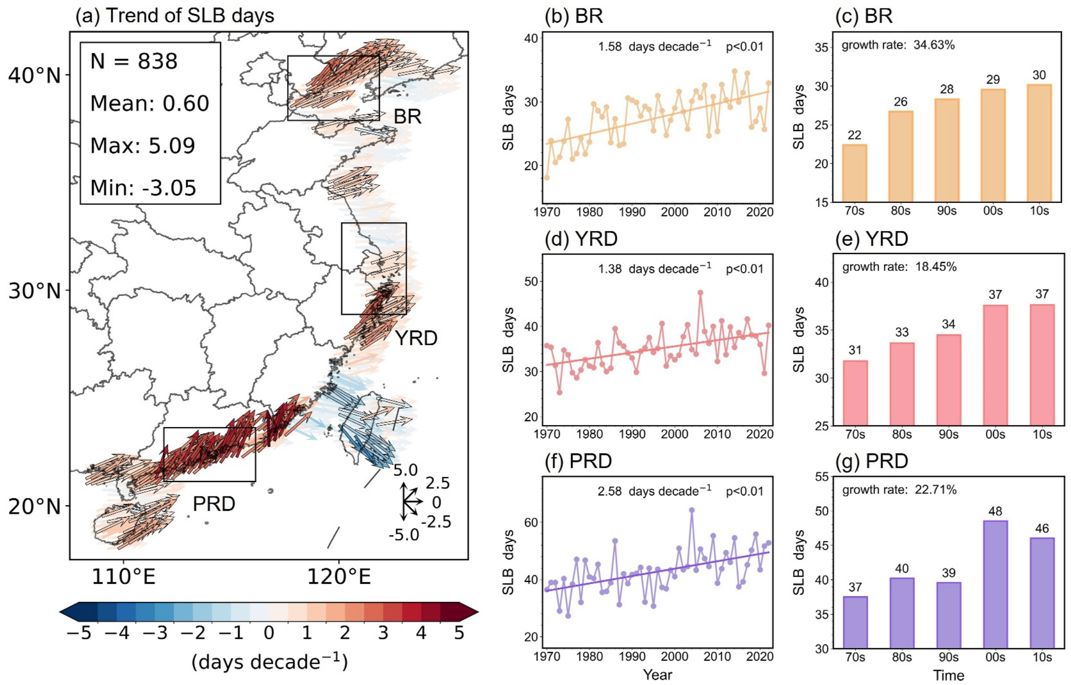

Figure 2. (a) Spatial distributions of long-term trends of SLBDs over coastal areas of China from 1970 to 2022. Black borders outside the arrow indicate sites with a p-value <0.05. Both directions and colors of the vectors indicate the trend of SLBDs. Mean, maximum, and minimum values over the grids are shown inset. Three black boxes in (a) present the BR, YRD, and PRD respectively. Time series of the annual trend of SLBDs in the (b) BR, (d) YRD, and (f) PRD from 1970 to 2022. Annual average SLBDs in the (c) BR, (e) YRD, and (g) PRD during the 1970, 1980, 1990, 2000, and 2010s.

contributing to the increasing frequency of SLB, including the sea-land temperature differences, solar radiation, background wind field, and total cloud cover (Shen et al., 2019; Xu et al., 2024).

According to the sixth IPCC Report, the 21st century experienced significant land-use expansion, intensified human activities, and rapid industrialization, all of which have driven a sustained rise in greenhouse gas emissions (e.g., CO_2, CH_4), exacerbating the global warming. This warming affects both land surface temperature (LST) and sea surface temperature (SST), which in turn influences the occurrence and development of SLB (Calvin et al., 2023; Yan et al., 2017). Additionally, the urban heat island (UHI) effect plays a notable role in modulating SLB dynamics. The UHI effect intensifies during the progress of urbanization (J. Y. Han & Baik, 2008), which may enhance SLB circulation by dragging surrounding air toward the urban center (S. Han et al., 2023; Shen et al., 2018).

We first analyze the trend of daytime surface temperatures in coastal regions of China (Figure 3a) and the trend of land-sea temperature differences in the BR, YRD, and PRD (Figures 3d, 3g, and 3j). We find that both SST and LST in coastal regions have increased during the day, with LST rising faster than SST, resulting in a larger sea-land temperature difference, which could create favorable conditions for the occurrence of SLB. At night, the land-sea temperature difference shows little change compared to daytime (Figure S4 in Supporting Information S1). In this respect, the SLB intensity could enhance during the daytime while weakening at night.

Surface temperature is largely affected by the balance of radiation at the surface, particularly solar radiation reaching the ground. Using land use data, we find significant increases in urban and rural residential land use in the Beijing-Tianjin-Hebei, YRD, and PRD regions over the past 40 years (Figure S5 in Supporting Information S1). Large-scale urbanization has likely led to increased pollution, which affects solar radiation by absorbing and scattering it (Shen et al., 2019; Xu et al., 2024). The analysis of solar radiation changes (Figures 3e, 3h, and 3k) shows an upward trend in the BR, YRD, and PRD, with the PRD experiencing the most significant increase (16.88 KJ/m^3 decade^{-1}). Changes in cloud cover (Figures S6 and S7 in Supporting Information S1) show a reduction across coastal areas in China, leading to an increase in solar radiation during the day, which enhances

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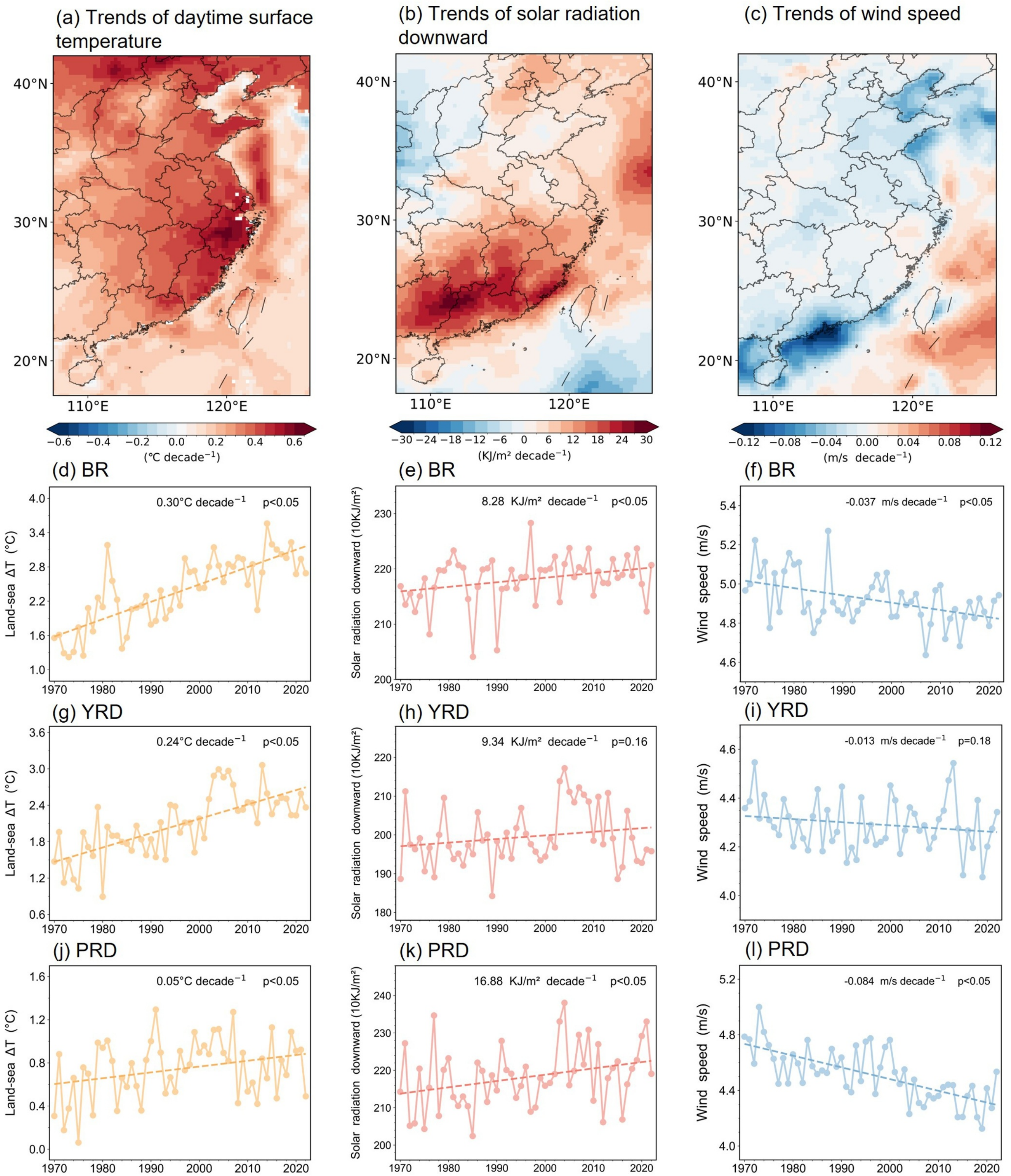

Figure 3. Spatial distributions of long-term trends of (a) daytime surface temperature, (b) solar radiation downwards, and (c) annual mean wind speed in the study area in 1970–2022. Time series of the annual trend of sea-land temperature difference in the (d) BR, (g) YRD, and (j) PRD. Annual trend of solar radiation downwards in the (e) BR, (h) YRD, and (k) PRD. Annual trend of wind speed in the (f) BR, (i) YRD, and (l) PRD. The dashed lines represent the linear trend. Trend per decade and p-values are shown inset.

the sea-land temperature difference and strengthens the occurrence of SLB. This also suggests that global warming is influencing SLB.

Figure 3c illustrates the trend in annual mean wind speed over coastal China. The PRD shows the most significant decrease in wind speed, with a reduction of 0.084 m/s per decade, followed by the BR and YRD (Figures 3f, 3i, and 3l), corresponding with the upward trend of SLBDs. Xu et al. (2006) reported that the annual mean wind speed over China decreased steadily by 28%, and the prevalence of windy days (daily mean wind speed >5 m/s) decreased by 58% from 1969 to 2000. The decreasing wind speed in China may be related to global warming and urbanization (Fu et al., 2011; Guo et al., 2011). Increased urbanization and human activities have raised surface roughness across significant portions of coastal China, contributing to weaker circulation patterns and more frequent SLBDs (Li et al., 2018).

However, a downward trend in SLBDs is observed in Taiwan. Our analysis shows a slight increase in wind speed in central inland regions over the past five decades, which may contribute to the downward trend in Taiwan. Besides, the eastern region of Taiwan is characterized by mountainous terrain (Figure S1 in Supporting Information S1), and thermal circulations become even more complicated over locations with complex topography due to the interactions between SLB and other local circulations including mountain-valley circulation and foehn wind (Bei et al., 2018; Gao et al., 2023; Huang et al., 2012).

The above findings are further supported by high correlation coefficients between these factors and the annual variations in SLBDs across the three main regions (Table S2 in Supporting Information S1), all of which are statistically significant. Specifically, the correlation coefficients between the sea-land temperature differences and SLBDs in the BR, YRD, and PRD are 0.51, 0.43, and 0.46, respectively. In the YRD and PRD, correlations between solar radiation and SLBDs exceed 0.5. Notably, the annual wind speed shows a significantly negative correlation with the SLBDs, with a correlation coefficient of −0.65 in the PRD. Moreover, we find that the intensity of various influencing factors not only increased or decreased significantly but also appeared more frequently in recent years (Figure S8 in Supporting Information S1). This suggests that there are now more days characterized by stronger sea-land temperature differences, higher solar radiation, and weaker wind speeds compared to earlier years, which further contribute to the rise in SLBDs. Additionally, other underlying mechanisms including complex topography, UHI effects, etc., may also affect the changes in SLB frequency. More detailed discussions are in Section 4.

3.4. Impact on Air Pollutant Recirculation

The periodic nature of SLB circulation significantly impacts the transport and dispersion of atmospheric pollutants in coastal areas, complicating pollution dynamics (Z. S. Han et al., 2023; Hu et al., 2019; Meng et al., 2024). At night, pollutants and their precursors over coastal cities are transported from inland areas to the sea by land breezes, and the next day, sea breezes may bring the pollutants back to the land (Zhao et al., 2022). This periodic shift in wind direction may have a substantial impact on air pollution in coastal areas.

To assess the effect of enhanced SLB on air quality, we introduce the recirculation index (R) (Allwine & Whiteman, 1994; Wu et al., 2016; Zhou et al., 2019), which evaluates the impact of local circulation on pollutant transport. The index R is defined as the ratio of the vector length from the origin to the end point of horizontal wind motion over a specified period, relative to the total trajectory distance. The local SLB circulations, driven by the different thermal properties of land and sea, typically follow a 24 hr cycle. Therefore, we calculate the 24 hr recirculation index (R_{24}) (X. Y. Chen et al., 2016):

$$R_{24} = \frac{\sqrt{\left(\Delta t \sum_{i=t-23\Delta t}^{t} u_i\right)^2 + \left(\Delta t \sum_{i=t-23\Delta t}^{t} v_i\right)^2}}{\Delta t \sum_{i=t-23\Delta t}^{t} \sqrt{{u_i}^2 + {v_i}^2}} \tag{3}$$

where R_{24} represents the 24 hr recirculation effect of the wind field at a given grid and time, indicating its ability to transport local pollutants. An R_{24} near one suggests effective downstream transport of pollutants leading to broader dispersion, while value near zero indicates that wind conditions promote pollutant accumulation and potential backflow, restricting the effective dispersion range. With stable daily emissions, lower R_{24} values correspond to smaller dispersion areas and potentially more severe local pollution.

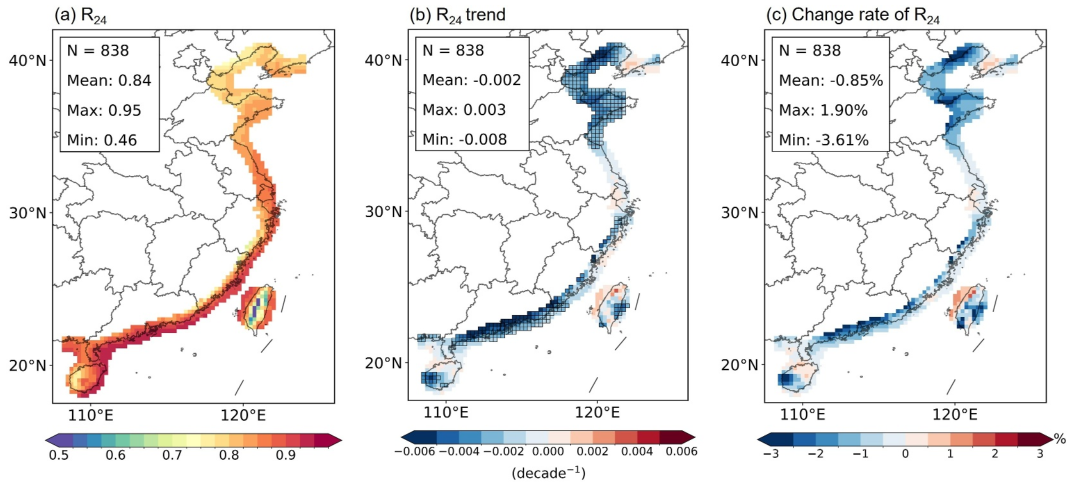

Figure 4. Spatial distributions of (a) R_{24}, (b) R_{24} trend, and (c) change rate of R_{24} in the study area from 1970 to 2022. Black borders in Figure (b) indicate sites with a p-value <0.05.

Figure 4a presents the average R_{24} of the past five decades in coastal China. The mean R_{24} is 0.84, with a gradual increase from high to low latitude, indicating stronger pollutant transport effects in the southern coastal areas. However, over the past 50 years, nearly 90% of the grids show a downward trend in R_{24} (Figures 4b and 4c), particularly in the PRD (Figure S9 in Supporting Information S1). This suggests that the rising SLB frequency enhances air pollutant accumulations in coastal areas, offers critical insights for air pollution prevention and control efforts in these regions.

4. Study Limitations and Future Perspectives

This study examines the long-term trends in SLBDs and the driving factors in coastal China over the past 53 years within the context of global warming and urbanization. The analysis of changes in the recirculation index provides insights into how SLB influence pollutant transport in coastal regions. However, there are certain limitations to this research. First, due to the absence of long-term observational data from coastal and ocean stations for validations, as well as the lack of other high-resolution reanalysis datasets for cross-examination, our findings are based solely on ERA5 reanalysis data, which may introduce discrepancies in identifying SLBDs. Comparisons with other reanalysis data were not feasible due to their lower temporal resolution. Nevertheless, the characteristics of SLBDs indicated by ERA5 data are consistent with previous studies focusing on specific locations, suggesting that our conclusions are reliable and reasonably accurate.

Furthermore, the underlying mechanisms driving the increasing SLB frequency remain to be fully explored. While we have provided explanations for the rise in SLBDs from thermodynamic perspectives, deeper factors such as changes in complex topography, the UHI effects, and aerosol radiation effects may also play a role. Complex topography affects the moving direction and development of SLB through dynamic processes: blocking, forced uplift, bypassing, etc (Barthlott & Kirshbaum, 2013; J. F. Miao et al., 2003; Qian et al., 2012). Meanwhile, the topography also affects sea and land breezes through thermal processes which may impose forcing or counteracting of SLB circulations (He et al., 2021; Y. Miao et al., 2015). Previous studies have indicated that the UHI effect can affect the SLB circulation by changing the thermal characteristics of urban areas (Shen et al., 2018; Xiao et al., 2023). Additionally, rapid urbanization may lead to increasing pollution, and aerosols released into the atmosphere from cities could have a strong scattering effect on solar radiation. Instead, the aerosol effects on solar radiation may reduce the warming trend over land areas during the day, partially offsetting the positive effect on SLB magnitude (Shen et al., 2019). Future research should prioritize quantitative analysis of these diverse influencing mechanisms, delving deeper into the underlying factors driving observed changes and exploring the complex interrelationships among them.

Lastly, the current study of SLB and its impact on air quality in coastal areas is primarily based on the recirculation index, without delving into the specific mechanisms involved. For instance, whether the increase in SLBDs enhances cloud processes and dry and wet deposition, thereby exerting a cleansing effect on pollutants, remains an open question. Future research should aim to perform a more comprehensive quantitative analysis of the influence of SLB on the transport and dispersion of pollutants in coastal areas. Additionally, future studies should also further investigate the interactions between SLB and large-scale atmospheric circulations, as well as the impacts of extreme events, under evolving climate conditions.

5. Conclusions

This study proposes a comprehensive set of criteria for identifying SLBDs across a wide range of coastal areas using ERA5 reanalysis data. We analyze the long-term trends and driving mechanisms of SLB in coastal China from 1970 to 2022, covering 838 grids. Our findings reveal that the region of highest annual average SLBDs is primarily concentrated in the southeastern coastal areas, with the BR, YRD, and PRD regions exhibiting distinct seasonal variations, driven by regional circulation patterns and seasonal wind speed variations. Notably, over 70% of grids show an upward trend in SLBDs. The PRD region, in particular, experiences a significantly higher increase in SLBDs compared to other regions.

A potential mechanism by which global warming and urbanization have influenced SLB circulation from both thermal and dynamic perspectives is summarized in Figure S10 in Supporting Information S1. From past to present, global warming has caused LST in most coastal areas to rise more rapidly than SST, leading to a continuous increase in land-sea temperature differential. Concurrently, reductions in cloud cover have allowed more solar radiation to reach the surface during the day, further exacerbating the land-sea temperature difference. Additionally, the expansion of urban areas has increased surface friction, leading to a decline in annual average wind speed across large coastal regions of China, promoting the formation of weak circulation patterns and rise in SLB frequency.

SLB also significantly impacts the transport and accumulation of air pollutants in coastal cities. Introducing the recirculation index (R_{24}), this study evaluates the influence of SLB on air quality. The results indicate that R_{24} has decreased across nearly 90% of China's coastal grids, with the PRD region experiencing the largest decline (up to 3.61%). This suggested that more frequent SLB circulation can exacerbate air pollutant accumulation, deteriorate the atmospheric environment, and increase environmental health risks for coastal residents. The interaction of SLB with anthropogenic emissions from land, ship emissions, and natural marine sources further complicates the formation and distribution of pollutants in coastal areas.

Besides, the method proposed in this study for identifying SLBDs can be applied to other regions globally, providing a valuable tool for similar research. Its broader application across diverse coastal areas may yield new insights into the regional dynamics of SLB and their broader environmental impacts.

Data Availability Statement

The meteorological data used in this study are from the ERA5 reanalysis dataset, provided by the European Center for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2023). The land use data are from the Resource and Environmental Science Data Platform (RESDEP) (Xu et al., 2018).

Acknowledgments
This research has been supported by the National Key Research and Development Program of China (2023YFC3710900), the Science and Technology Program of Guangdong Province (Science and Technology Innovation Platform Category) (2019B121201002), National Natural Science Foundation of China (42375182), Guangdong Basic and Applied Basic Research Foundation (2023A1515010162, 2024A1515510032), and Science and Technology Project of Guangdong Meteorological Service (GRMC2024M07, GRMC2023Q03).

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