仙台夏期海風の基本特性と屋外温熱快適性に及ぼす影響に関する研究
(The basic characteristics of summer sea breeze events in Sendai, Japan and their effects on outdoor thermal comfort)

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The modern way of life brings convenience to people, but also brings gradually deteriorating living environment. This study takes Sendai, Japan as the main research object. On the premise of clarifying the characteristics of summer sea breeze in Sendai, the cooling effect of sea breeze on urban temperature rise is quantified. Finally, the outdoor thermal comfort is quantitatively evaluated, aiming at providing guidance in urban planning. All the data were simulated by the Weather Research and Forecasting (WRF) model. After detailed data analysis, ArcGIS Pro was used to visualize the data. Finally, Rayman software was used to quantitatively evaluate the outdoor thermal comfort. The results show that inland rivers have a positive effect on sea breeze speed and cooling intensity. The sea breeze is slower along the coast and increases as it travels further inland. The retreat of the sea breeze slows down significantly when it is close to highly urbanized areas. The duration of the sea breeze is longest in the direction of the retreating sea breeze. Sea breeze cooling capacity shows a negative correlation with distance from the coast, with points closer to inland rivers having a longer cooling distance. Comfort is always lowest in urban areas on either sea or west breeze days, highest in coastal areas on sea breeze days and highest inland on west breeze days. The intensity of improvement in thermal comfort is greatest at 13:00 on sea breeze days; regionally, the coastal areas lasted the longest and had stronger improvements.

1. Introduction

Due to global warming and urbanization, high-temperature events—which frequently occur in cities—are presenting an increasing threat to the daily lives of human beings [1]. In coastal cities, sea breezes can cool the near-surface and improve the urban environment to some extent. Understanding the cooling characteristics of sea breeze in the urban environment is informative for improving and mitigating the urban heat island (UHI) effect.

This thesis discusses in detail the effects of sea breezes on the coastal urban environment, using Sendai, Japan as the study area. All data were obtained using Weather Research and Forecasting (WRF) model simulations. And the measured temperature and WRF simulation results are also evaluated with observations. The results show little difference between the two. I analyze the basic characteristics of the timing of the cooling effect of sea breeze in urban summer based on the long-term multi-point measurements of air temperatures. Additionally, the Weather Research and Forecasting (WRF) model is used to show the influence of sea breeze on cities in terms of the cooling action time. The amount of cooling produced by the sea breeze on Sendai over the time of the cooling effect is also calculated. The variation over time of the cooling effect produced by the sea breeze on the coastal city was analyzed by using hourly units. All the data were visualized in a distribution map through ArcGIS Pro and detailed data analysis was carried out.

2. A method of using computers to simulate and visualize meteorological data

In this study, I used the Advanced Research Weather Research and Forecasting (ARW-WRF) model developed by the National Center for Atmospheric Research (NCAR) and the National Center for Environmental Prediction (NCEP) to numerically simulate the Sendai urban area. This simulation used three nested domains (Fig.1). The outer square is domain 1, which consists of 37 × 28 grids with a spatial resolution of 9 km. Domain 2 consists of 43 × 34 grids with a spatial resolution of 3 km. The main analysis do-main is domain 3, which consists of 31 × 28 grids with a spatial resolution of 1 km. A horizontal resolution of 1 km is widely used in numerical studies of urbanization and sea breeze.

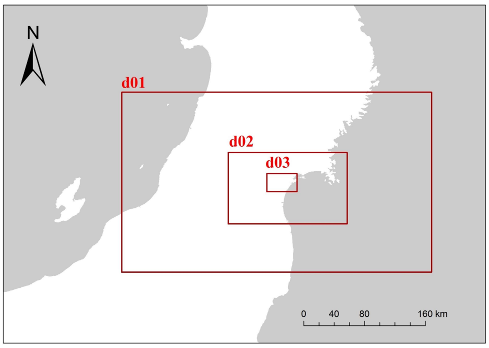

***Fig. 1** Definition of the three domains for the WRF model.*

The number of vertical layers used in this study was 30, and the urban canopy model and WSM 6-class graupel scheme were used (Table 1). Many planetary boundary layers (PBL) schemes are available, and some researchers have made detailed comparisons of the different schemes. This simulation used the Mellor–Yamada–Janjic model [2]. The Rapid Radiative Transfer Model for General circulation models (RRTMG) longwave scheme and Dudhia shortwave scheme in the general circulation model were used. The land data utilized data from the Digital Land Information released by the Japanese government in space with a resolution of 1 km. The initial boundary conditions for the simulations were generated from the final operational global analysis data (FNL) from the National Center for Environmental Prediction (NCEP).

***Table 1** Domains and Parameterization schemes used in WRF model experiments.*

Calculation period	09:00 (JST) on August 1, 2016, to 09:00 (JST) on August 10, 2016 (sea breeze day) 09:00 (JST) on August 5, 2013, to 09:00 (JST) on August 15, 2013 (west breeze day)
Vertical grid	30 layers
Horizontal grid	Domain 1: 9 km, dimension 37 × 28 Domain 2: 3 km, dimension 43 × 34 Domain 3: 1 km, dimension 31 × 28
Meteorological data	NCEP re-analysis of global objective data
Land data	Digital national land information (resolution of 1000 m)
Microphysics	WSM 6-class graupel scheme
Radiation: Longwave	Rapid radiative transfer model
Shortwave	Dudhia shortwave
PBL scheme	Mellor-Yamada-Janjic TKE scheme
Surface scheme	Urban canopy model

Two data simulations were conducted for this study, with calculation periods from 1 to 10 August 2016 and 5 to 15 August 2013. The specific dates of sea breeze day and west breeze day were determined based on meteorological characteristics. The date of 5 August 2016 was sea breeze day and the date of 10 August 2013 was west breeze day. The simulated data in domain 3 finally generate 31 × 28 points data, and each point datum contains the values of temperature at 2 m above ground and specific humidity at 2 m above ground. The frequency of the numerical output is 10 min, which is the same as the measured data.

With WRF mode simulation of the generated data, Ncview and NCL can be used to query and export visual images. Because the data needs to be calculated and analyzed, ArcMap is used to export the simulated data. The data exported in Excel format are temperature, specific humidity, wind speed, and direction with geographic information. Finally, ArcGIS Pro was selected to visualize the data. ArcGIS Pro can easily visualize and perform advanced analysis of data with geographic information in 2D,3D, and 4D modes.

3. Recreate the process of sea breeze movement in Sendai

In this study, the sea breeze days were determined by meteorological observatory data downloaded from the Japan Meteorological Agency. Therefore, the sea breeze day can be determined by the generation of sea breeze and the characteristics of changes in meteorological variables after the occurrence of sea breeze. In addition, to exclude the interference of other factors, clear days were chosen to determine the sea breeze days in this study. Specifically, these include the following. With 40% or more of the possible sunshine hours, less than 5% cloud, and no rainfall, wind blowing from the sea to the land lasting at least 2 hours, a drop in temperature lasting 1 hour or more after the start of the sea breeze.

Before using the simulated data, the reproducibility of the WRF model data was analyzed in this study. The reproducibility analysis of the WRF model data was done using simulated data paired with actual measured point data for comparative analysis. Each measured point data is compared with the nearest simulated point data. Bias, RMSE, and correlation were calculated separately using SPSS. In urban environments, different geographical locations and urban settings have different degrees of influence on the simulated values of mesoscale urban climate. To evaluate the errors between numerical simulations and measured values at different locations, at different times, I defined the study area as a coastal area, urban area, and inland area based on distance. I made a dynamic analysis of the errors in each of the three areas 24 hours a day (Fig.2).

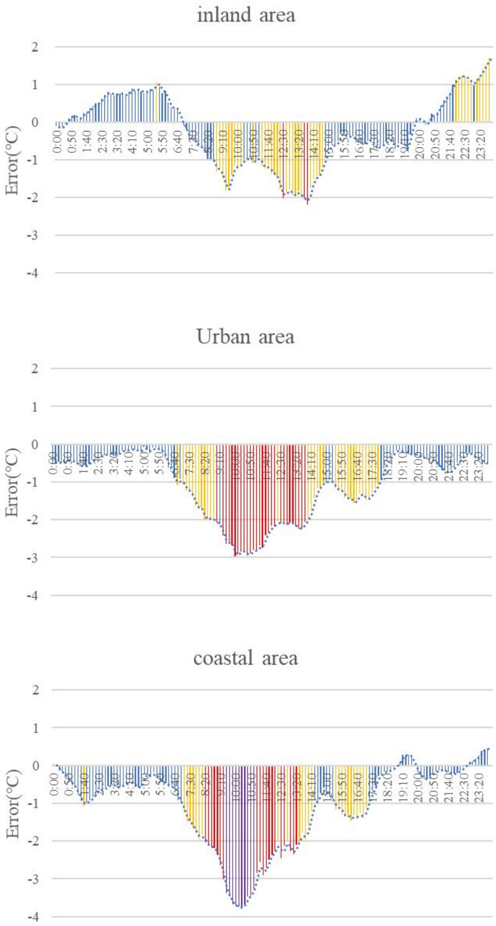

***Fig. 2** The error dynamic curve for the inland/urban/coastal area.*

The calculation results show that the correlation is strong at all points. Among the three areas, the urban area has the highest difference value. In the error dynamics analysis, the simulated values are always lower than the measured values in the rest of the area, except for the local period in the inland area. During the day, higher errors always occur around the 10:00-12:00 time period. And among the three areas, the coastal area locally presents higher error values and the inland area has the lowest error values.

A three-year study period (August 2018 to 2020, period B) was compared with a twelve-year study period (August 2010 to 2021, period A) for both periods. It is concluded that this study period is a good representation of the temperature characteristics of the summer sea breeze days in Sendai. Finally, August 5, 2016, was selected as the case study day.

In contrast to the previous definition of sea breeze arrival and retreat times by wind conditions, this study determines the arrival and retreat times of sea breeze based on the variation of sea breeze daily temperature and specific humidity (Fig.3). When the sun rises, the temperature of the land begins to rise, forming a pressure difference with the sea, and the air begins to move from the sea to the land. The wind blowing from the direction of the sea brings cold air to the land, so this study defines the point in time when the temperature starts to drop after sunrise as the time when the sea breeze arrives. The continuous rise in temperature is suppressed when the sea breeze arrives, at which point it lowers the temperature of the city. Additionally, it also brings humidity. The temperature fluctuates in a constant range, and the humidity rises again after a significant drop at midday due to strong sunlight. Because of the weakening of insolation, the temperature starts to exceed the constant range, and the rate of decrease increases significantly. At this point, the specific humidity also drops sharply once again, and we define this moment as the time of retreat of the sea breeze.

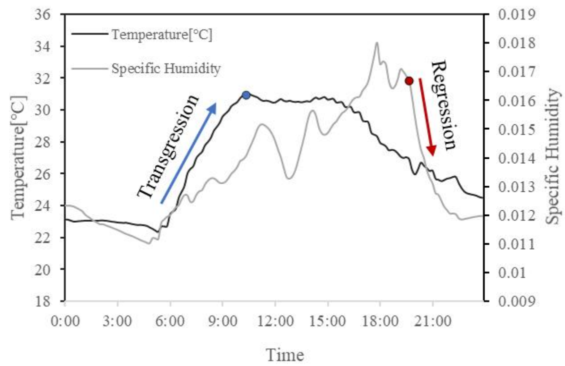

***Fig. 3** The points pointed by the arrows show the time of arrival (blue points) and retreat of the sea breeze (red points).*

After determining the arrival time of the sea breeze and the retreat time of the sea breeze at each point, the duration of the sea breeze was obtained. ArcGIS Pro was used to generate sea breeze arrival distribution, sea breeze retreat distribution, and sea breeze persistence distribution (Fig.4). When analyzing sea breeze arrival time and sea breeze retreat time, the main concern is the speed of sea breeze and the length of sea breeze duration. So I do this by placing points on the distribution that represent distances. The points are distributed in a fixed linear direction, and each point is evenly spaced 1.5 km apart.

It turns out that in the coastal part, the sea breeze blows landward at a slower rate, and the rate increases with penetration inland. The arrival time of sea breeze is strongly influenced by inland rivers.

From the map of sea breeze retreat time distribution, the direction of sea breeze retreat is related to the area of compact mid-rise and compact Low-rise and urban topography. The retreat of the sea breeze slows down significantly when it is close to highly urbanized areas. Until it is close to the coastal part, the sea breeze retreat speeds up. From the map of sea breeze duration distribution, the sea breeze duration is relatively evenly distributed in area, and the sea breeze duration is the longest in the direction of sea breeze retreat.

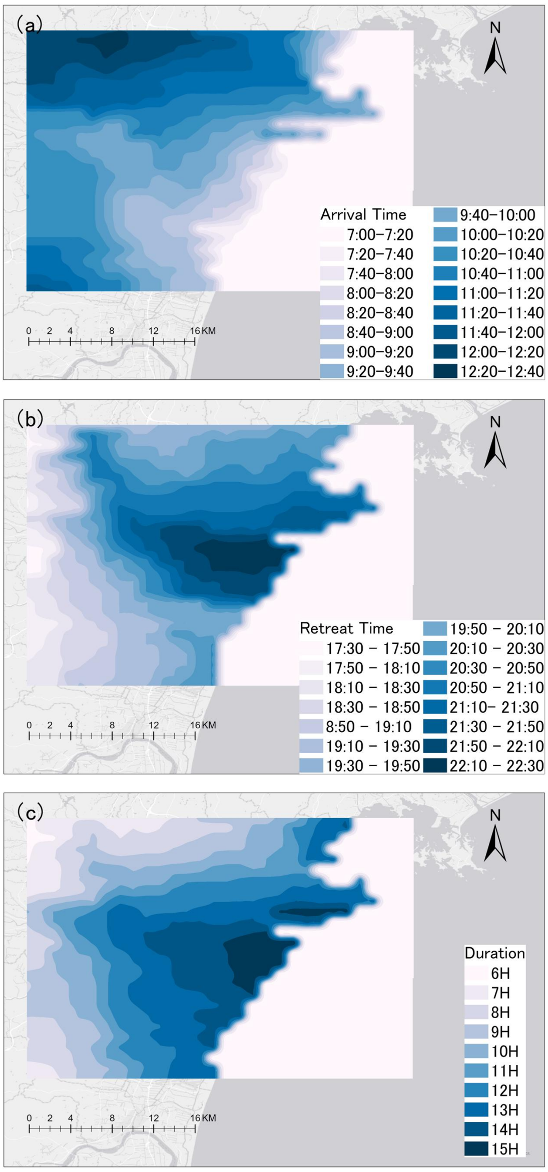

Fig. 4 (a) Sea breeze arrival time map; (b) Sea breeze retreat time map; (c) Sea breeze duration time map;

4. Draw the distribution diagram of cooling capacity under the action of sea breeze and quantitatively analyze the cooling capacity of sea breeze and outdoor thermal comfort

On a sea breeze day, the sea breeze moves through the city, and during the whole continuous process from the sea breeze reaching the land to the sea breeze retreating from the land, the sea breeze exerts a restraining effect on the rising temperature of the city. In this study, the days with the west breeze blowing in weather conditions are similar to those of sea breeze days as the subject of the study. Through the meteorological observation data downloaded by the Japan Meteorological Agency, chose August 10, 2013, as the research object of west breeze day. Sea Breeze Day is on August 5, 2016.

Simulated data for west breeze days were obtained in the same way as for sea breeze days. The same way includes using the WRF model and applying the same settings. The difference between the simulated temperature data on a sea breeze day and a west breeze day was then calculated to quantify the cooling capacity of the sea breeze in coastal cities.

The difference in temperature between a sea breeze day and a west breeze day represents, under similar weather conditions, how much cooler the city is on a sea breeze day compared to a west breeze day, and define this difference as the cooling capacity of the sea breeze on the coastal city.

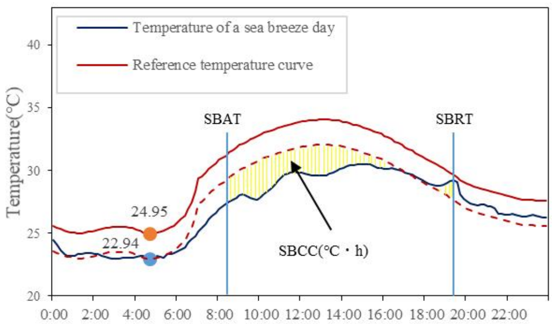

***Fig. 5** Sea breeze day (5 August 2016) temperature profile at the Sendai simulation point in the study area, west breeze day (10 August 2013) temperature profile and adjusted temperature profile. Yellow parts represent sea breeze cooling capacity.*

Sea breeze cooling capacity (SBCC) is the difference between the integration in time of the temperature on a west breeze day (WESTA) and the integration in time of the temperature on a sea breeze day (SEA). SBCC (°C h) is defined as the product of sea breeze cooling and the cooling duration (Fig.5). The calculation is described in Eq. (1).

$$SBCC=WESTA-SEA \quad 1)$$

Where WESTA is the time integral of the adjusted westerly daily temperature profile and SEA is the time integral of the sea breeze daily temperature profile. They are defined by defining Eq.(2) and (3):

$$WESTA = \sum_{i=2}^{n} \frac{\left(T_{west(i-1)} + T_{west(i)}\right) \times \Delta t}{2} \quad 2)$$

$$SEA = \sum_{i=2}^{n} \frac{\left(T_{sea(i-1)} + T_{sea(i)}\right) \times \Delta t}{2} \quad 3)$$

Where $T_{west(i)}$ and $T_{sea(i)}$ are the west-adjusted daily temperature profile and the sea breeze-daily temperature profile at time step i, respectively, Δt is the time interval between adjacent time steps in the sea breeze event, and n is the number of time steps. The time step at each point is defined as the sea breeze duration at each point, calculated from the time of sea breeze arrival until the time of sea breeze retreat.

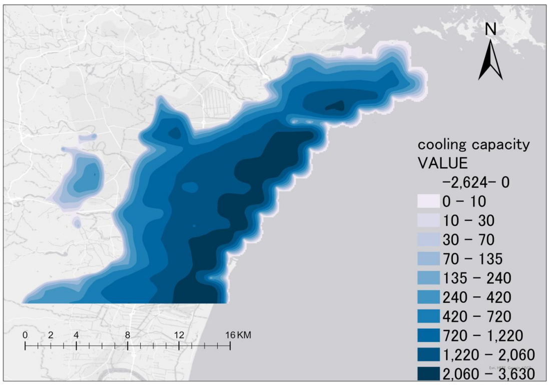

Fig. 6 *Plan view of all sea breeze cooling generated during the time of sea breeze action.*

Table 2 *Sea breeze cooling capacity and cooling area per hour.*

Time	cooling capacity (℃.h)	Cooling area (km²)
7:00	2092.99	30.6
8:00	12489.48	115.26
9:00	28891.49	222.36
10:00	37989.61	277.44
11:00	33062.05	261.12
12:00	28331.30	236.64
13:00	29149.13	236.64
14:00	22974.94	221.34
15:00	17250.13	180.54
16:00	13565.42	153
17:00	8760.34	116.28
18:00	7150.46	93.84
19:00	4600.70	76.5
20:00	1888.38	32.64
21:00	400.04	21.42

After calculating the sea breeze cooling at each point, the sea breeze cooling is then imported into ArcGIS Pro to obtain a visual plan view of the sea breeze cooling in the simulated area (Fig.6). The sum of cooling capacity under sea breeze and the hourly variation from the beginning to the end of sea breeze are analyzed by calculating results. After analyzing the data therein statistically, it was found that the sea breeze cooling capacity and the sea breeze cooling area both show an increasing and then decreasing trend. At 10:00, the sea breeze cooling capacity reached a maximum value of 37,989.61°C.h and the cooling area reached a maximum range of 277.44km² (Table 2).

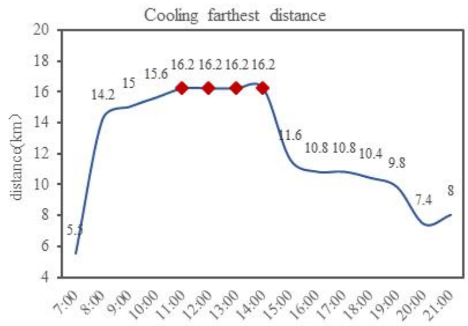

Fig. 7 *Furthest cooling distance and time.*

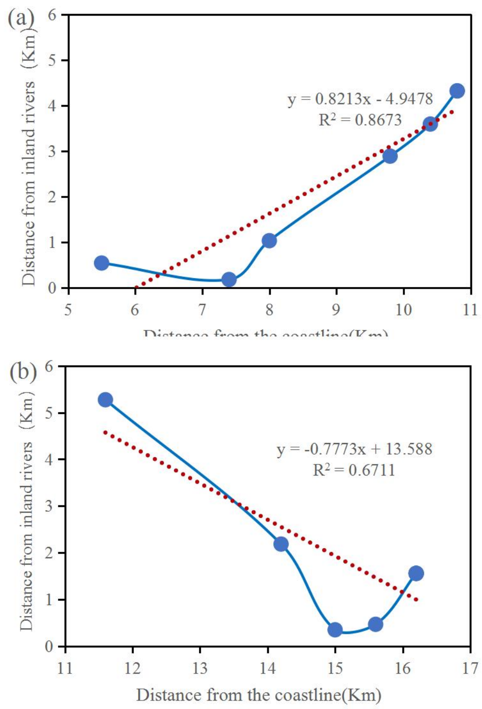

Fig. 8 *(a)The cooling area within a distance of 5 - 11 km, the furthest cooling point to an inland river; (b) The cooling area within a distance of 11 - 17 km, the furthest cooling point to an inland river.*

To analyze the permeability of the cooling effect of sea breeze in the study area, this study measured the distance from the coast to the farthest point of the sea breeze cooling range per hour. The farthest distance for cooling at 7:00 was 5.5km, and the distance grew rapidly to 14.2km at 8:00 and reached a maximum distance of 16.2km for cooling at 11:00 (Fig.7). Analyzing the distance between the farthest point of the sea breeze cooling range and inland rivers and time, as the time value increases, the distance to the inland river gets closer. The closer the point is to the inland rivers, the further the sea breeze cooling distance is when the sea breeze cooling distance is more than 11km (Fig.8). The furthest range of sea breeze cooling exceeds 11km from 08:00-15:00. The hourly cooling capacity and cooling area analysis shows that of all the times with sea breeze cooling effect, the higher cooling capacity and the cooling area is found between 9:00-13:00. Therefore, inland rivers have a positive influence on the cooling effect of sea breezes.

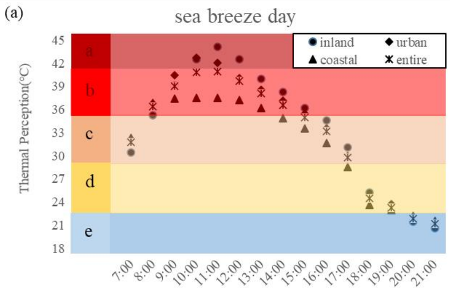

Fig. 9 Thermal sensing of PET averages for (a) sea breeze day and (b) west breeze day in each area of the study area.

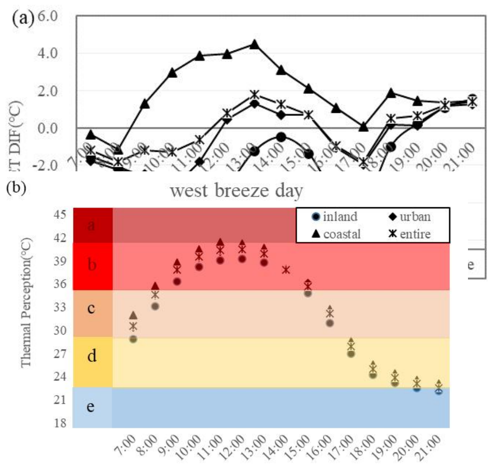

***Fig. 10** Hourly average of PET DIF by area;*

Outdoor thermal comfort is an important criterion to measure the overall comfort of the outdoor environment. In this study, the PET (Physiological Equivalent Temperature) values were calculated for sea breeze days and west breeze days using Rayman software. By entering the initial parameters in the Rayman software: air temperature, humidity, wind speed, cloud cover, date and time of the calculation, geographical location of the calculation site, as well as the characteristics of the person, the intensity of the activity and the thermal resistance of the clothing, the PET value for that thermal environment parameter is obtained. The input initial parameters for this study are air temperature, relative humidity, radiation, and wind speed. The source of all data is obtained from the direct output of the WRF mode simulation, or the calculation of the output values. Physiological Equivalent Temperature (PET) is the equivalent temperature of air temperature in a specific location (outdoor or indoor) to a typical indoor environment with core and skin temperatures equal to the temperature under the conditions assessed. The comfort was analyzed and evaluated by PET heat stress levels on sea breeze days and west breeze days.

The following conclusions were finally drawn:

(a) There are differences between sea breeze day and west breeze days in terms of underlying environmental factors. The basic environmental factors include temperature, radiation, wind speed and relative humidity; (b) On sea breeze day, there are large effects of wind direction and radiation values on outdoor thermal comfort; on west breeze day, there are large effects of temperature and relative humidity on outdoor thermal comfort; (c) On sea breeze days, the distribution of heat perception is territorial; on west breeze days, the distribution of heat perception is more similar in all regions (Fig. 9); （d） Comfort is always lowest in urban areas on either sea or west breeze days, highest in coastal areas on sea breeze days, and highest inland on west breeze days (Fig. 10); (e) On sea breeze days there are different degrees of outdoor thermal comfort improvement values in different areas, with the longest duration and strongest degree of improvement in the coastal area. At 13:00, the strongest improvement in outdoor thermal comfort was obtained;

References

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