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The effect of background wind on summertime daily maximum air temperature in Kowloon, Hong Kong

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ABSTRACT

The increased intensity of extreme weather events (e.g., heatwaves) that is predicted to occur due to global climate change could significantly impact human health, biodiversity, and infrastructure integrity in cities. As one of the most densely constructed cities in the world, Hong Kong has been experiencing increasingly intense heatwaves in recent years. However, the city presents a challenging site for studying urban climate due to its complex topography. Using observed weather data for clear summer (June to August) days from 2000 to 2020, we examine the relationship between background wind and daily maximum temperature in Kowloon, Hong Kong, and investigate how this relationship is affected by geographical location, land cover, and topography. We reveal the distribution of near-surface wind fields under calm weather conditions, which provides a basis for the analysis of relationship between background wind and maximum temperature in urban areas under windy conditions. We find that the maximum surface air temperature in coastal regions is significantly influenced by the background wind direction. For weather stations located in the Kowloon Peninsula, a larger background wind speed is associated with a faster increase in daily maximum temperature when the background temperature rises. We find that the mountain warming effect is influential in areas at the foot of a mountain, even though the maximum terrain height is only approximately 500 m a.s.l. These findings on the daily maximum temperature behavior under different background wind conditions provide a possible way to predict extreme high-temperature patterns in different regions of Hong Kong.

1. Introduction

Scientists agree that climate change will proceed quickly and violently in the next 20 years [1]. Furthermore, global warming is generally more rapid in urban regions [2]. As the urban population continues to increase worldwide, maintaining a healthy urban environment is increasingly important for people's lives [3]. Urbanization has been accompanied by decreasing urban wind speeds [4], rising urban air temperatures [5,6], and intensified urban heat island (UHI) effects [7,8].

As a key component of the urban climate, wind regulates urban ventilation, dissipates heat, and dilutes airborne pollutants in cities. Studies have shown a strong correlation between urban air ventilation and human mortality [9]. Additionally, wind significantly affects the outdoor thermal comfort of pedestrians. For example, people become more tolerant of high humidity when there is sufficient wind speed [10]; when the wind speed decreases from 1.5 to 0.5 m/s, the concurrent air temperature needs to drop by more than 2 °C to maintain the same level of thermal sensation [11]. Furthermore, at the mesoscale, background wind affects UHI circulation [12]. The observed increase in the number of haze days and the decrease in visibility are largely due to the decline of the mean wind speed in the lower troposphere in cities, e.g., those in the Beijing-Tianjin-Hebei region [13].

As a subtropical coastal city, Hong Kong is famous for its extremely hot and humid summer weather. Between 2000 and 2020, the average daily temperature is around 28.7 °C in summer and the average relative humidity is over 80%. In this city, it is difficult to avoid thermal discomfort when performing outdoor activities. A recent study showed that local extreme heat events in Hong Kong are associated with increased human mortality [14], and the frequency, length, and intensity of extreme heat events in the city have increased in the last few decades [7].

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Owing to the city's limited land resources and large population, buildings in Hong Kong are usually compact, blocky, and high-rise [15]. Moreover, the increase in impervious surface area that has occurred due to continuous urban development has deteriorated the urban thermal environment [16]. These factors not only negatively impact Hong Kong's urban thermal environment but also create challenges for the understanding of its urban climate. Furthermore, Hong Kong's irregular urban shape, with mixtures of commercial, industrial, and residential land uses also complicates the study of regional temperature behavior [17,18]. Moreover, the built-up area is unevenly divided by mountains and bays, and the interaction between sea breezes, mountain slope winds, and urban thermal plumes greatly aggravates the difficulty of urban climate studies [19].

Hong Kong's urban climate has been widely studied [4,7,20,21]. In the last five decades, there has been a significant reduction in wind speed in the Kowloon area due to land reclamation and urbanization, and in some parts of this area, the average pedestrian-level wind speed was 67% lower in 2010 than in 1964 [4]. Wang et al. investigated the interaction between sea breezes and UHI circulation in Hong Kong for different land-use types, and found that anthropogenic heat enhances the circulation and that the 2-m air temperature at 14:00 local time is 0.5 °C higher in the convergence zone compared to the non-anthropogenic heat case [20]. Urban ventilation corridors have been found to impact UHI intensity [21]. Additionally, it has been shown that during extreme heat events, the windward and leeward effects are important factors affecting the distribution of urban heat/cool island intensity [7]. However, a systematic analysis of the impact of background wind on the summertime urban air temperature in Hong Kong has not been conducted.

This study uses scatterplots on a revised traditional wind rose (wind star plot) and linear regression to investigate the relationship between the background wind and the daily maximum temperature in different areas of Kowloon. It focuses on background environmental variables including wind speed, wind direction, and background temperature, as well as daily maximum temperature and wind data at weather stations throughout Kowloon. The results first reveal the distribution of near-surface wind fields under calm weather conditions, which provides a basis for analyzing the relationship between background wind and maximum temperature in urban areas, and the impact of geographic and anthropogenic factors is carefully considered in the analysis. The results indicate that the maximum temperature in coastal areas, peninsular areas, and areas at the foot of a mountain respond differently to background meteorological factors. The possible causes of these observations are also analyzed and discussed.

2. Data and method

2.1. Dataset

Fifteen weather stations of the Hong Kong Observatory were selected as they adequately cover the whole of Kowloon and surrounding areas (Fig. 1). Some of the selected weather stations are not geographically or administratively located within Kowloon. Hourly wind data are available for 11 stations and daily maximum temperature data are available for eight stations. These eight stations were classified into three categories based on their geographical locations (Table 1). Hourly air temperature and wind data from the Waglan Island station (WGL) were used to analyze the background meteorological conditions as this station is located far from the city in the open sea and is thus less likely to be affected by urban areas [22].

The data before 2000 were discarded to minimize the effect of urbanization on the daily maximum temperatures while ensuring an adequate data volume. The amount of data varies between stations as some of them came into service in different years.

2.2. Data pre-processing

Data from June, July, and August for the years from 2000 to 2020 (i.e., data for 21 years) were extracted from the datasets of the 15 weather stations. The filtering conditions included that the daily bright sunshine hours should be more than 8 h to guarantee sufficient sunlight and the daily total rainfall should be less than 0.05 mm to exclude the effects of rain. Table 2 illustrates the proportion of the number of selected days to the number of non-rainy days (rainfall< 0.05 mm) at HKO (Table 2).

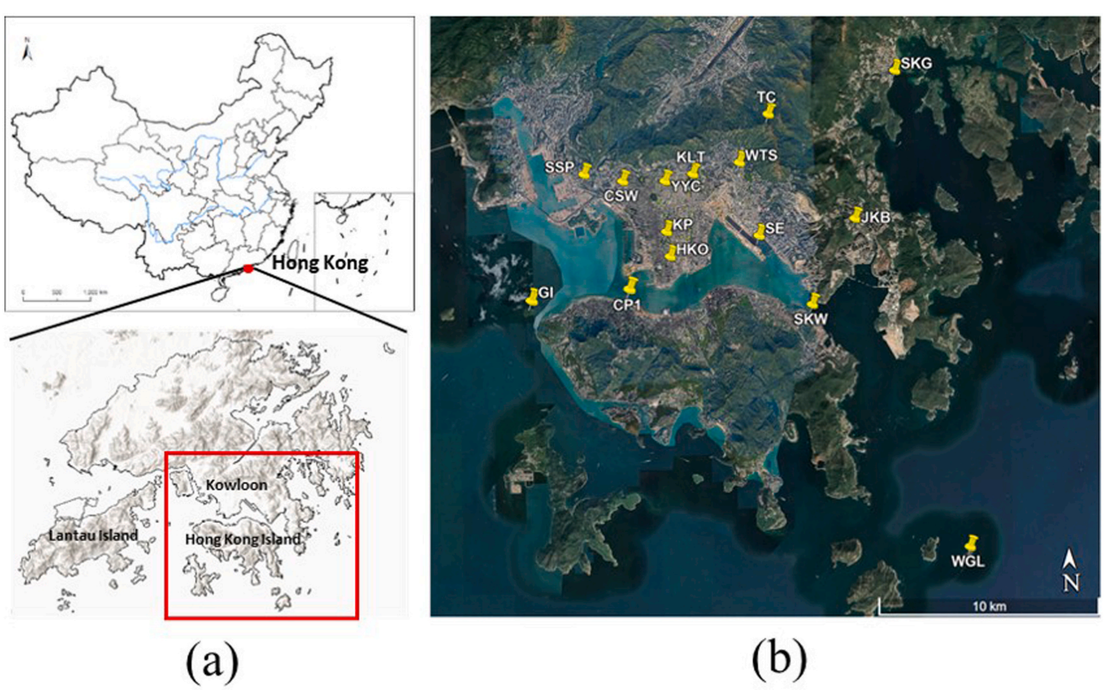


Fig. 1. (a) The location of Hong Kong within China (top) and a terrain map of Hong Kong (bottom). (b) The locations of the weather stations used for analysis; the pin symbols represent the locations of the weather stations and the text represents their abbreviations.

Table 1
Details of the 15 weather stations in Hong Kong that were used for the analysis.

Category	Full Name, Coordinates	Abbreviation
Coastal stations	Sham Shui Po station, 22°20′09"N, 114°08′13" E	SSP
	Sai Kung station, 22°22′32"N, 114°16′28"E	SKG
	Tseung Kwan O station, 22°18′27"N, 114°15′20"E	JKB
	Shau Kei Wan station, 22°16′54"N, 114°14′10"E	SKW
Peninsular stations	Hong Kong Observatory Headquarter station, 22°18′07"N, 114°10′27"E	HKO
	King's Park station, 22°18′43"N, 114°10′22"E	KP
Foothill stations	Kowloon City station, 22°20′06"N, 114°11′05"E	KLT
	Wong Tai Sin station, 22°20′22" N, 114°12′19" E	WTS
Background station	Waglan Island station, 22°10′56"N, 114°18′12"E	WGL
Other stations	Cheung Sha Wan station, 22°19′58"N, 114°09′14"E	CSW
	Yau Yat Chuen station, 22°19′57"N, 114°10′21"E	YYC
	Kai Tak station, 22°18′35"N, 114°12′48"E	SE
	Tate's Cairn station, 22°21′28"N, 114°13′04"E	TC
	Green Island station, 22°17′06"N, 114°06′46"E	GI
	Central Pier station, 22°17′20"N, 114°09′21"E	CP1

The daily rainfall and bright sunshine hours data from the Hong Kong Observatory Headquarter station (HKO) were used to screen for days with sufficient solar insolation and with very low or zero rainfall.

Table 2
A comparison between the number of selected days (rainfall <0.05 mm and bright sunshine hours >8 h) and the number of non-rainy days (rainfall <0.05 mm) on typical and very hot summer days for HKO during 2000–2020.

Meteorological parameters	No limitation	Rainfall <0.05 mm (a)	Rainfall <0.05 mm and bright sunshine hours >8 h (b)	Proportion (a/b)
No limitation	1862[a]	770	520	0.68
Maximum temperature ≥33 °C	369	264	216	0.82
Maximum temperature ≥34 °C	92	69	59	0.86
Maximum temperature ≥35 °C	17	12	10	0.83

[a]) There are a total of 1932 observation days during the study period, and data on 70 of these days are not available or were lost, e.g., due to faulty sensors or station maintenance.

The daily maximum temperature was chosen as the temperature indicator for the following reasons. The daily maximum temperature belongs to a suite of indices used to rationalize and standardize the quantification of extreme weather events developed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) [23]. The definition of a very hot day in Hong Kong is a daily maximum temperature ≥33 °C [24]. Besides, the difference in the daily maximum temperature from day to day is larger than the difference in the daily or daytime average temperature, which facilitates the determination of the association between the daily maximum temperature and background meteorological variables.

At HKO, the daily maximum temperature occurs on average at approximately 15:00 on the selected days (rainfall <0.05 mm and bright sunshine hours >8 h). On the other hand, the commercial activities such as electricity load of commercial buildings starts to increase at 07:00 in Hong Kong [25]. To study the effect of background wind on the daily maximum temperature, we used hourly data from 07:00 to 15:00 to calculate the vector-average wind data for the day. The vector averaging method is presented below.

$$\overline{X} = \frac{1}{N}\sum_{t=t_0}^{t_1} S_t\, sin(A_t) \tag{1}$$

$$\overline{Y} = \frac{1}{N}\sum_{t=t_0}^{t_1} S_t\, cos(A_t) \tag{2}$$

$$A_v = arctan\left(\frac{\overline{X}}{\overline{Y}}\right) \tag{3}$$

A_v is the vector-average wind direction in that period; S_t and A_t are the wind speed and direction at each time-node, respectively; $\overline{X}$ and $\overline{Y}$ are the average wind speeds in the east-west and south-north directions, respectively; and N is the number of data.

Similarly, to reflect the day's background temperature, we calculated the weighted average temperature $T_v$using the hourly temperature data from WGL as a benchmark to compare the urban temperature with the upstream temperature for days with a vector-average daily wind direction between 30° and 270°. With such winds, the urban areas unlikely affect the air temperature in WGL. The weighted average temperature better considers background wind effects compared to the daily maximum temperature or hourly average temperature.

$$T_v = \frac{\sum_{t=t_0}^{t_1} T_t S_t}{\sum_{t=t_0}^{t_1} S_t} \tag{4}$$

where T_t is the air temperature at each time-node and the weight is the hourly wind speed S_t. The multiplication of T_t and S_t indicates that more weight is taken when high temperature and large wind speed co-exist.

Using the above calculation, a refined daily-resolution dataset was developed for subsequent analysis.

3. Results and discussion

3.1. Characteristics of the near-surface wind field under calm background conditions

Fig. 2 shows the correlation between the background wind speed and the wind speed observed at 10 stations. All the wind data presented here were processed by the vector-averaging method. The two axes show the wind direction: an easterly wind is shown by a positive U component when the V component is zero, and a southerly wind is shown by a negative V component when the U component is zero. We particularly focus on the difference when the wind direction switches between generally easterly or westerly following the significant effect of the westerly sea breeze for the Kowloon Peninsula. A generally easterly wind refers to wind with a positive U component and a generally westerly wind refers to wind with a negative U component. Fig. 2 may be understood as a composition of two wind vector plots, one for the background and one for the measurement station concerned. On each wind vector plot, each point represents a wind vector showing both direction and wind speed. Such a wind vector plot shows the monitored wind conditions at a station. In analog with traditional wind rose plot, we refer this wind vector plot as wind star plot. Fig. 2 contains two wind star plots, one for the background station and one for the measurement station. When there is no change in the general wind direction on the day when the maximum temperature occurred, we draw a gray dashed line between the background station data point and the measurement station data point. When the wind at the measurement station changes to an easterly direction while the background station wind stays westerly, we draw a yellow line, and when the opposite change occurs, we draw a green line.

Fig. 2 was used to determine the possible ground wind distribution in different districts of Kowloon under calm or mild (<2 m/s) background

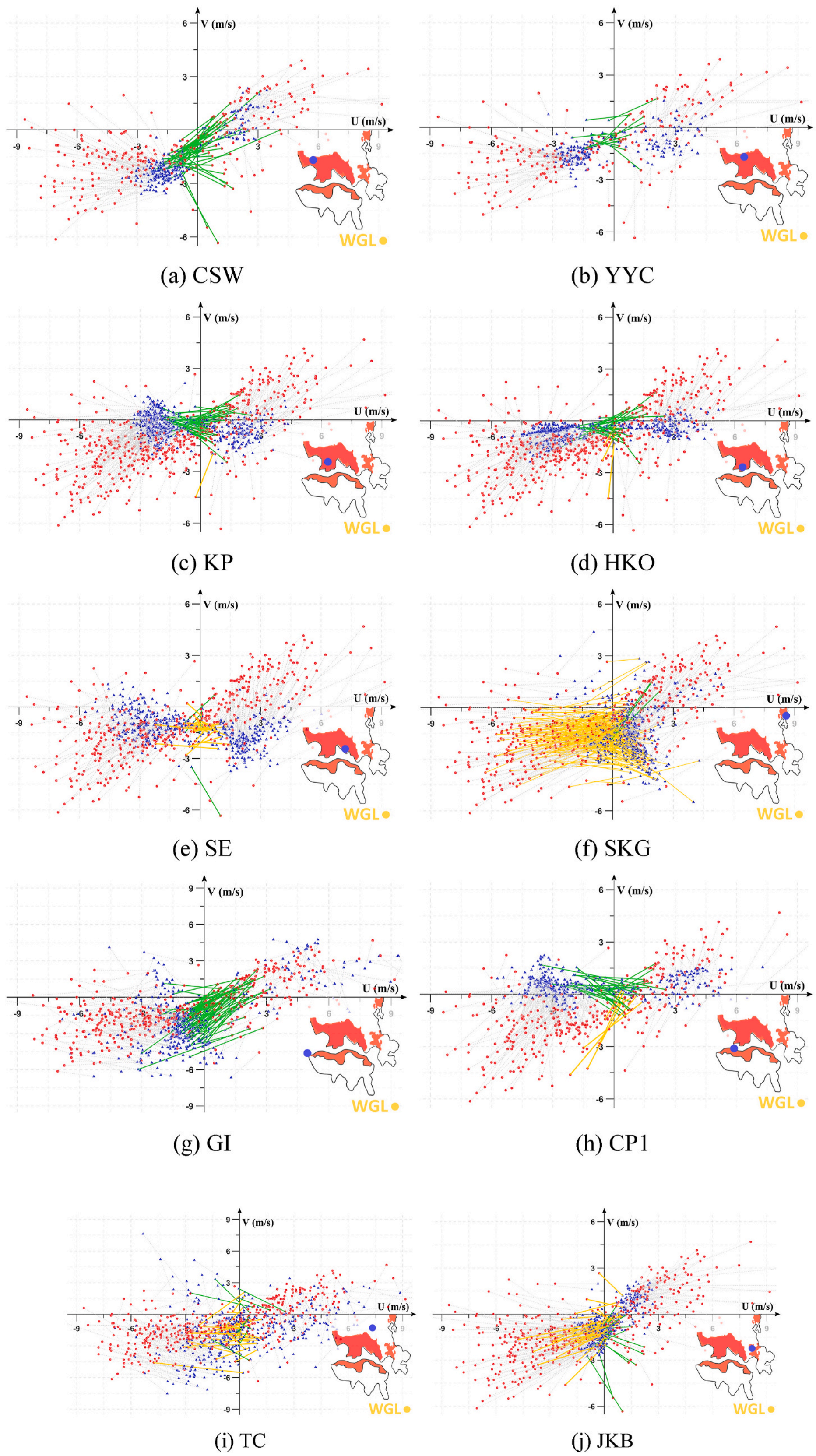


Fig. 2. Scatterplots of wind data on a vector plot from the measurement stations (blue triangles) and the background wind data (red dots, Waglan Island station [WGL]). Lines connect the red dots and blue triangles from the same day. Gray lines indicate that both data points are located at U < 0 or U > 0. Yellow lines indicate that the background wind is westerly and the measured wind is easterly, meaning that the background wind is located at U < 0 and the measured wind is located at U > 0. Green lines indicate that the background wind is located at U > 0 and the measured wind is located at U < 0. That is, yellow and green lines indicate that the wind direction at the measurement station is different from that at WGL. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

wind conditions. Fig. 2a–d shows the data for four urban stations in Kowloon, i.e., Cheung Sha Wan station (CSW), Yau Yat Chuen station (YYC), King's Park station (KP), and HKO. Many green lines are plotted on some days, meaning that the wind at the four stations became westerly (as shown by a blue triangle on the left side of the y-axis) when the background wind was mild and easterly (as shown by a red dot on the right side of the y-axis). At these four stations, when the background wind is very weak, the dominant wind directions are westerly or southwesterly, which is mainly because of the sea breeze from the waters of western Kowloon. There are only four yellow lines at KP and HKO, while there are none at CSW and YYC. This means that during the 21 years of the study period, there were only four days when the wind directions at KP and HKO changed from the westerly at WGL to easterly. Such a rare occurrence suggests the expected weak sea breeze from the east for the Peninsula.

The wind directions at the background station during the selected days are mostly southwesterly or northeasterly. The relatively concentrated cluster of blue triangles from the red dots in Fig. 2a–d suggests that the wind speed in urban areas is significantly weakened due to blockage by hilly terrain but that it is most weakened by dense concentrations of high-rise buildings [4]. The wind directions vary among the four stations: at KP and HKO, the wind is westerly or easterly; at CSW, it is southwesterly or northeasterly; and at YYC, it is southwesterly or approximately easterly.

For the Kai Tak station (SE) in the middle of Kowloon, a mild south-southeasterly wind can be inferred to be the prevailing wind under calm background conditions (Fig. 2e). When the background weather is calm, the Sai Kung station (SKG) at the northeastern end of Kowloon is affected by the sea breeze from the southeast (Fig. 2f). At the Green Island station (GI), under calm background conditions, the wind does not blow straight toward Hong Kong Island but follows a south-southwest direction towards Kowloon (Fig. 2g). Inevitably, part of the airflow passing GI will be entrained by the UHI plume and mountain slope wind in Hong Kong Island. Thus, the predominant wind for the Central Pier station (CP1) is westerly to northwesterly (Fig. 2h). When different background wind conditions are applied, the wind field distribution at Tate's Cairn station (TC) is relatively sparse as the winds at mountain peaks can be unstable (Fig. 2i). Meanwhile, for the Tseung Kwan O station (JKB), the colored lines intersect and are equivalent in number. Thus, it is challenging to predict the wind behaviors at TC and JKB under static background wind conditions (Fig. 2j).

Based on the above results, Fig. 3 shows a schematic diagram of the distribution of the daytime near-surface wind in Kowloon under calm wind conditions on days when the daily maximum temperature occurred (15:00). A possible airflow convergence zone can be observed in the east of the Kowloon Peninsula; this can be explained by sea breezes from both sides of the peninsula meeting and rising within this zone, as reported by Wang et al. [20] in their WRF-BEP-BEM simulation of wind patterns in Hong Kong. Under strong prevailing background wind conditions, the wind distribution is comparatively consistent with the prevailing wind directions (not shown).

3.2. Characteristics of the daily maximum temperature in coastal areas

Fig. 4 shows scatterplots of the daily maximum temperature at four coastal weather stations (SKG, JKB, SKW, and SSP) under different background wind conditions that are displayed by a wind star plot, like in Fig. 2 but in a polar coordinate system. Each dot (star) on the wind star plot shows a wind vector at background station with information on both wind speed and direction. The star color shows the daily maximum temperature at the station of concern. We refer the illustration in Fig. 4 as a temperature wind star plot. Such a temperature wind star plot provides a direct visual inspection of the effect of background winds on the daily maximum air temperature at a particular location.

SKG, JKB, and SKW are located in the east of Kowloon, near the vast expanse of water to the east of Hong Kong, while SSP is located in the west of Kowloon, close to a small stretch of sea surrounded by Lantau Island, Hong Kong Island, and the Kowloon Peninsula (Fig. 1a).

The daily maximum temperature at these four stations is strongly correlated with the background wind direction. At SKG, JKB, and SKW, the daily maximum temperatures are lower when the background wind is northeasterly to easterly than when the background wind is southwesterly to westerly (Fig. 4a–c). In contrast, the SSP station is negatively affected by the east-northeasterly winds, and only the winds from a small angular range close to the southwest benefit the station, though the difference in daily maximum temperature is not as large as at the three above-mentioned stations (Fig. 4d).

Furthermore, the temperature difference between the daily maximum temperatures at measurement stations and the weighted average temperature at WGL are plotted in Fig. 5. A similar trend is found at SKG as a strong temperature distinction appears when opposite background wind conditions are applied (Fig. 5a). For JKB and SKW, the general distinction between the two opposite prevailing winds is still discernible. The temperature difference is smaller when the background wind contains an easterly component. For background wind from the west and southwest, there is no correlation between the background wind speed and the temperature difference. Instead, JKB and SKW show larger temperature differences for the westerly background winds, and the temperature difference gradually decreases when the wind direction shifts to the southwest (Fig. 5b and c). This reflects the impact of the upstream environment on the study area, including possible pre-heating in the Victoria Harbour area and bypass flow around Hong Kong Island.

The distribution of the temperature difference at SSP follows the same pattern as the daily maximum temperature, i.e., the temperature difference is smaller when the wind blows directly from the sea with

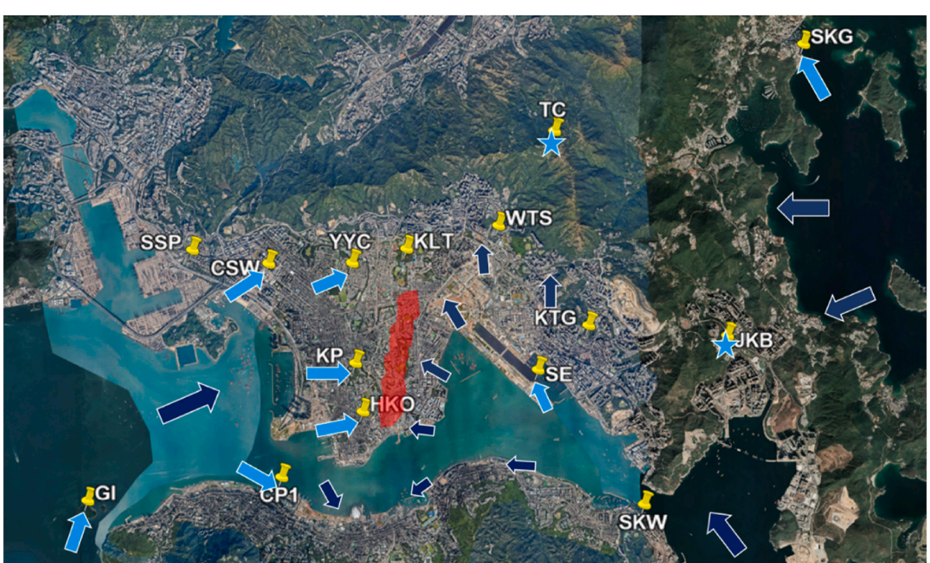


Fig. 3. A schematic diagram of the distribution of daytime near-surface wind in Kowloon under calm wind conditions. The light blue arrows represent actual wind data, and the dark blue arrows represent inferred wind. The light blue stars mean that the wind direction at the station could not be determined. The red region in the east of the Kowloon Peninsula represents a possible airflow convergence zone. Base image courtesy of Google Maps. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

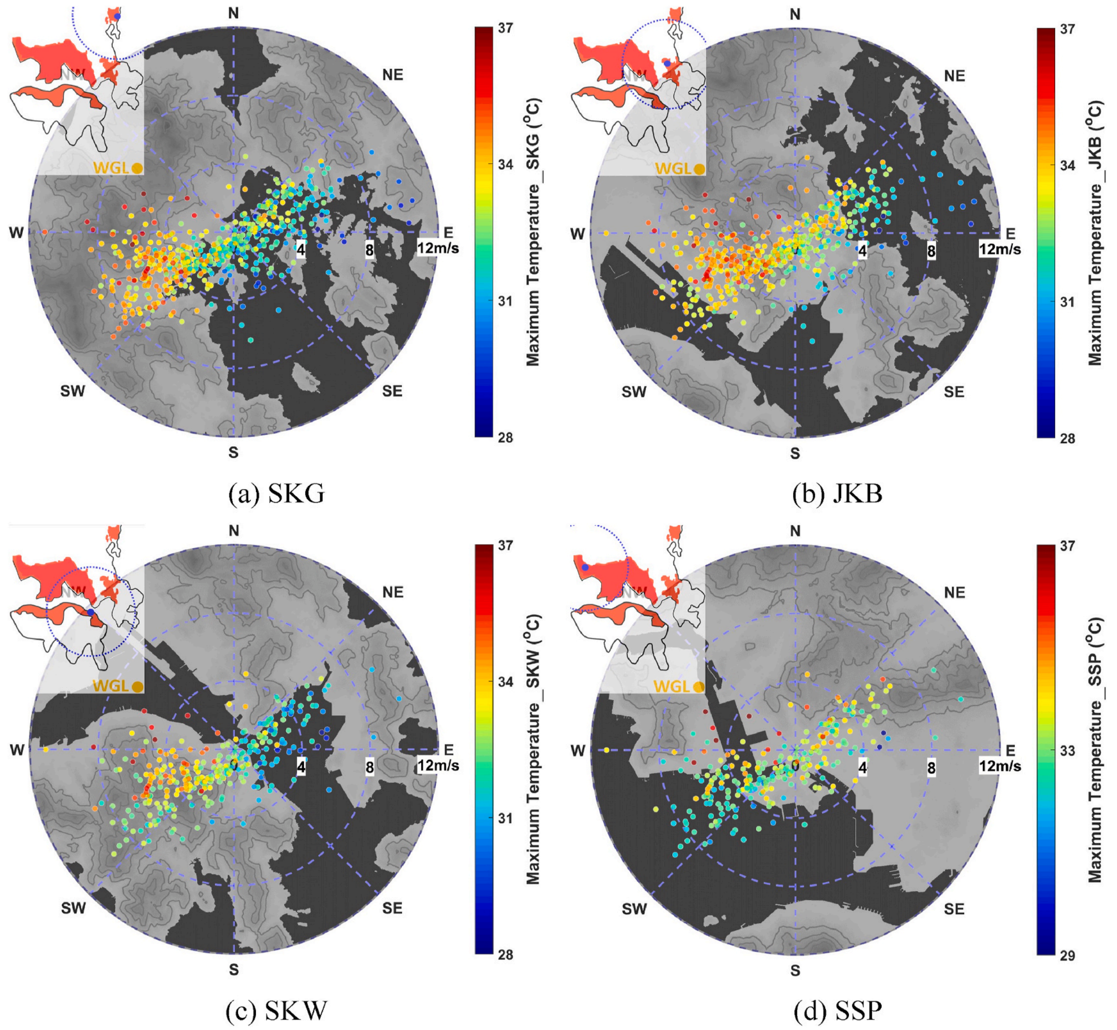


Fig. 4. The daily maximum temperatures plotted on top of the background wind (measured at WGL) (a) at SKG, (b) at JKB, (c) at SKW, and (d) at SSP. The location of each dot shows the wind speed and direction at the background station, and the daily maximum temperature is indicated by the color of the dot. The base image is a combination of a hydrographic map and a contour map with an interval of 100 m. Gray and black areas represent land and sea, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

limited interference (Fig. 5d).

A linear correlation is observed between the background wind speed and the daily maximum temperature at SKG for wind directions between 180° and 270°. With the increase in the background wind speed, both the daily maximum temperature and the temperature difference increase (Fig. 6). When the wind speed increases by 1 m/s, the daily maximum temperature and temperature difference at SKG rise by 0.29 °C and 0.50 °C, respectively.

These findings show that both the daily maximum temperature and the temperature difference are strongly correlated with the background wind direction at SKG, JKB, SKW, and SSP. Furthermore, the daily maximum temperature and temperature difference at SKG is linearly correlated with the background wind speed for wind directions between the southwest and west; such a linear correlation does not exist at other stations.

3.3. Characteristics of the daily maximum temperature in urban areas in the Kowloon Peninsula

HKO and KP are located in the heart of the Kowloon Peninsula (Fig. 1b) and are influenced by the westerly sea breeze in static background wind conditions. Due to the geographical features of the peninsula, the background wind from the west and southwest directly affects the area. Meanwhile, to the southeast of the peninsula lies Kowloon Bay and a short channel called Lei Yue Mun, where airflow can freely pass through under the east-southerly background wind. Thus, given the similar characteristics of such background winds, we discuss the possible connections between the daily maximum temperature and background wind variables other than the wind direction.

Fig. 7 shows the correlation between the background temperature and the daily maximum temperature at KP and HKO for background wind speeds of less than or equal to 6 m/s and background wind directions of southeast (112.5°–157.5°), southwest, and west (202.5°–270°). We only analyzed wind speeds of $\leq$6 m/s, as background wind speeds of >6 m/s from these directions ensure relatively low the daily maximum temperatures at both stations (data not shown). Three wind speed ranges were considered: light (0–2 m/s), gentle (2–4 m/s), and moderate (4–6 m/s). A linear least-squares regression was performed for each range. In all three wind speed groups, there is a weakly positive correlation between KP and HKO, and the slope increases as the wind speed increases. This means that a hotter background environment will result in a higher urban daily maximum temperature if all other meteorological conditions are approximately equal [26]. But surprisingly, when the background temperature is relatively high, a larger wind speed does not guarantee a lower daily maximum temperature in a certain wind speed range (0–6 m/s), even though the city ventilation has

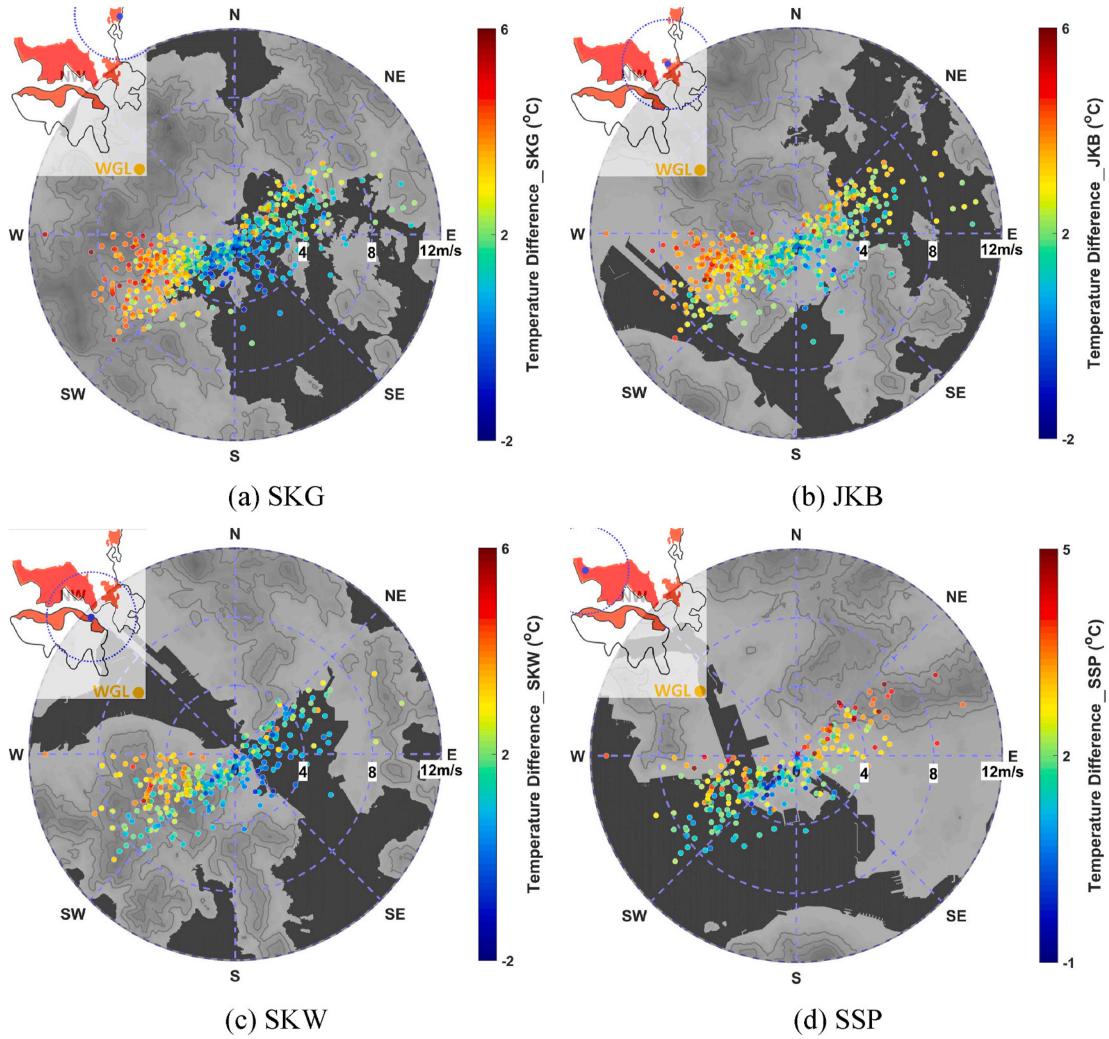


Fig. 5. The temperature difference between the daily maximum temperatures at measurement stations and the weighted average temperature at WGL plotted on the top of the background wind (measured at WGL) (a) at SKG, (b) at JKB, (c) at SKW, and (d) at SSP. The base image is a combination of a hydrographic map and a contour map with an interval of 100 m. The gray and black areas represent land and sea, respectively.

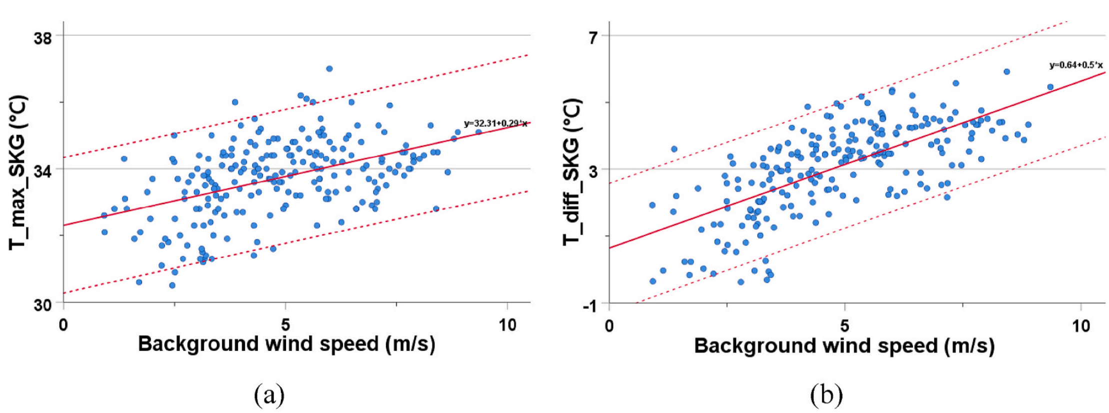


Fig. 6. The linear correlation between the background wind speed and (a) daily maximum temperature and (b) temperature difference at SKG.

improved due to the increased background wind speed. We suspect that this may be due to the heat advection caused by the high-temperature background wind. We also find that when the background temperature is low, a larger wind speed tends to be associated with a lower daily maximum temperature at KP and HKO. Thus, we identify a critical background temperature of around 30 °C that suggests whether the effect of wind speed on the daily maximum temperature in the Kowloon Peninsula area is positive or negative.

The relatively small distinction in daily maximum temperature between the three different wind speed ranges at HKO might be caused by the disturbance of Hong Kong Island, which is located relatively close to the station. Although high background temperature is rarely

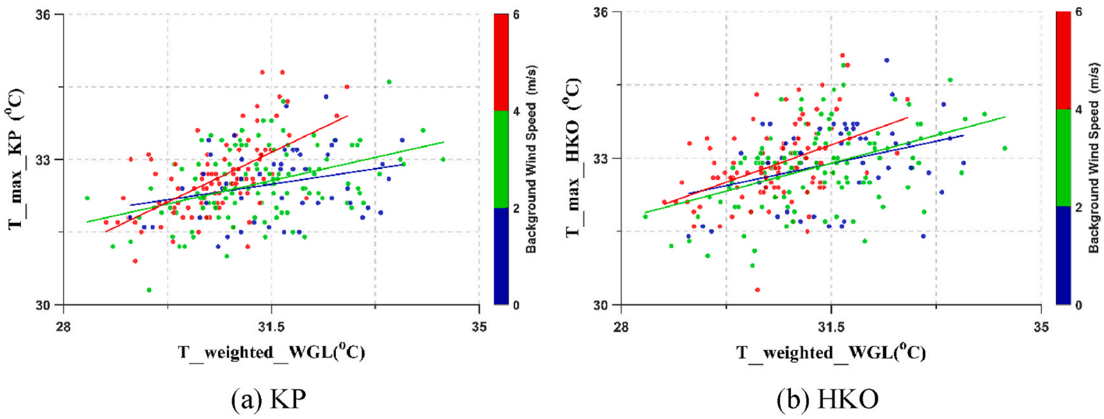


Fig. 7. The correlation between the background temperature and the daily maximum temperature for three ranges of background wind speed (0–2, 2–4, and 4–6 m/s) at (a) KP and (b) HKO. The best-fitting lines are obtained by the linear least-squares regression of the data points of the corresponding color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

accompanied by moderate wind speed in Hong Kong, this phenomenon to be cautioned against in the future considering the continuing warming of the global climate and sea surface temperature [27].

3.4. Characteristics of the daily maximum temperature in foothill areas

KLT and WTS are located at the foot of the mountain that sits to the north of the Kowloon Peninsula and half surrounds the Kowloon area. Unlike HKO and KP, these two stations are relatively far from the west coast of the Kowloon Peninsula, and thus, the sea breezes only have a limited impact on these stations under calm conditions (Fig. 8). However, at KLT and WTS, the daily maximum temperature tends to decrease when the southwesterly wind speed reaches 4 m/s or higher; conversely, the westerly and northwesterly winds significantly deteriorate at least not mitigate the daily maximum temperatures at these two stations.

Regarding the winds containing an easterly component, the analysis focuses on WTS as it is located in a more typical geographical position. The maximum terrain height within 6 km of WTS is obtained if we set WTS as the vertex of the angle and the angle increases in the clockwise direction with due north as 0° (Fig. 9a). The terrain height remains at around 500 m a.s.l. from 20° to 90°, which provides an approximate two-dimensional condition for studying the synergistic effects of mountain, city, and sea, as the mountain length is long enough to avoid bypassing flow. Then, at 100°, the height drops sharply to 300 m a.s.l. before increasing to 400 m a.s.l. at 110° and subsequently descending to zero. To investigate the effect of the background wind on the daily maximum temperature at WTS, a scatterplot of these two variables is shown in Fig. 9b (note that wind speeds greater than 8 m/s are excluded as this is the upper limit for possible mountain heating). In this figure, three simple linear regression lines are plotted according to the different datasets, with a black dashed line corresponding to weak wind days (triangles), the solid red line representing hot windy days (red circles), and the blue solid line corresponding to cool windy days (blue circles). The median background temperature on windy days (30.2 °C) represents the critical point in deciding coolness or hotness of the day. As shown in Fig. 9b, the daily maximum temperature on light-wind days tends to be higher than that on windy days regardless of the wind direction or background temperature. On windy days, the co-occurrence of high background temperature and northeasterly to east-northeasterly wind causes a high daily maximum temperature in the Wong Tai Sin area. On windy days (circles), the daily maximum temperature drops sharply when the angle exceeds 90°, which shows a trend similar to that of the maximum terrain height. This suggests that the height of the mountains may be positively related to the warming effect in this region. Similar warming effects have been reported on Lantau Island, Hong Kong, when the prevailing wind directions were east to

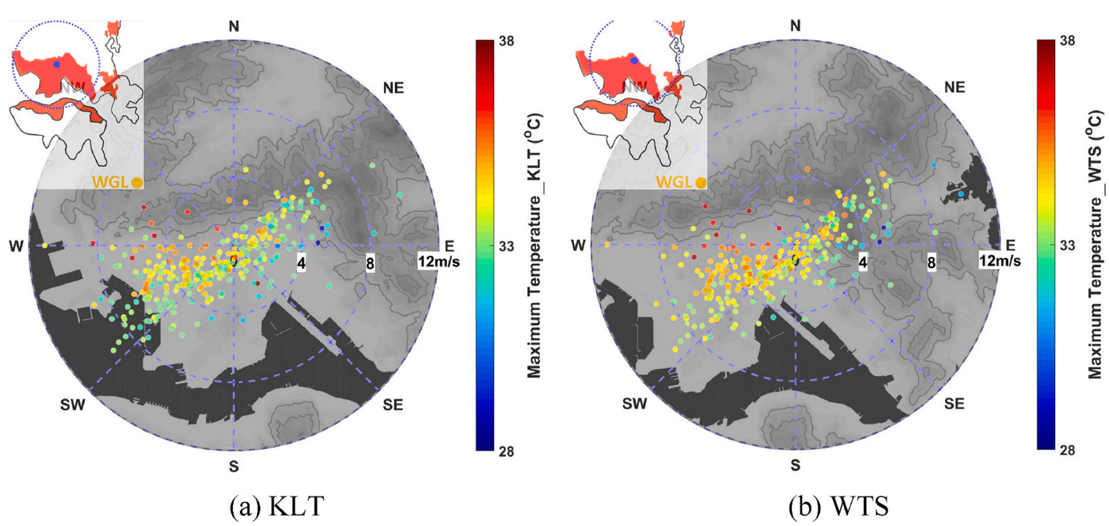
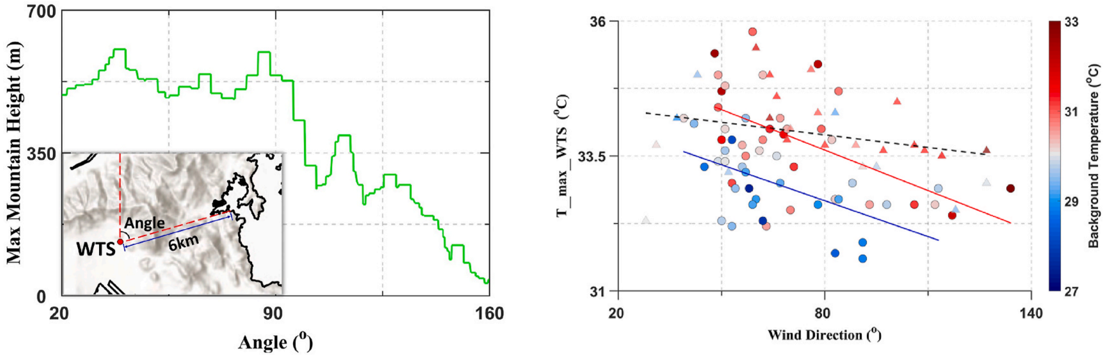


Fig. 8. The daily maximum temperature plotted on top of the background wind (measured at WGL) (a) at KLT and (b) at WTS. The base image of the figures is a combination of a hydrographic map and a contour map with an interval of 100 m. The gray and black colors represent land and sea, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



(a) (b)

Fig. 9. (a) The maximum terrain height within 6 km from WTS at the angle indicated in the figure; (b) the correlation between the background wind direction and the daily maximum temperature at WTS. The triangles indicate that the background wind speed on that day was less than 2 m/s, while the red circles and blue circles show the days with >2 m/s background wind speed. The triangles and circles are colored based on the day's background temperature. The black dashed line shows the best-fitting linear regression of the weak wind days (triangles), the red solid line the hot windy days (red circles), and the blue solid line the cool windy days (blue circles). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

southeasterly and the inversion layer was located at approximately 1 km above the sea surface, Chan et al. [28] clearly illustrated the occurrence of foehn wind using meteorological data from Hong Kong International Airport. Thus, the possible presence of foehn or foehn-like winds in the Wong Tai Sin area will be explored in a future study. Meanwhile, Wong et al. identified wind corridors stretching from the Wong Tai Sin area to the Kowloon Peninsula when the background winds were from the northeast [21], which means that this warming mechanism may exist further downstream in the Kowloon Peninsula area.

4. Discussion

This study clarifies how the daily maximum air temperature in Kowloon, Hong Kong, is associated with background weather variables (see Fig. 10) and provides a simple framework to understand and explore the mechanism behind extremely hot weather events. In Fig. 2, the fact that the wind speeds at the measurement stations are lower than those at the background station strongly suggests that the wind weakening phenomenon exists in Hong Kong. As shown in Fig. 2, the change of wind direction is often dominated by either sea breezes or UHI-induced winds. These results agree well with those of Ng and Ren [29]. The results of the present study imply that, in Hong Kong, the background wind synergizes with UHI-induced flows and sea breezes to impact the daily maximum temperature.

Luo and Lau [30] revealed the importance of mesoscale anticyclone circulation over Southern China for the occurrence of extreme hot weather events, indicating that mesoscale weather conditions can significantly impact extreme hot weather events in Hong Kong. Our findings on the importance of the background environment when performing weather analysis in Hong Kong are in line with the results of these authors. At the urban scale, land-use heterogeneity in Hong Kong has influenced the air circulation and the urban air temperature, showing that anthropogenic heat in urban areas may lead to a decrease in surface temperature in coastal regions due to intensified sea breeze [20]. The relative wind and temperature distinctions between different stations in Kowloon observed in the present study demonstrate the need

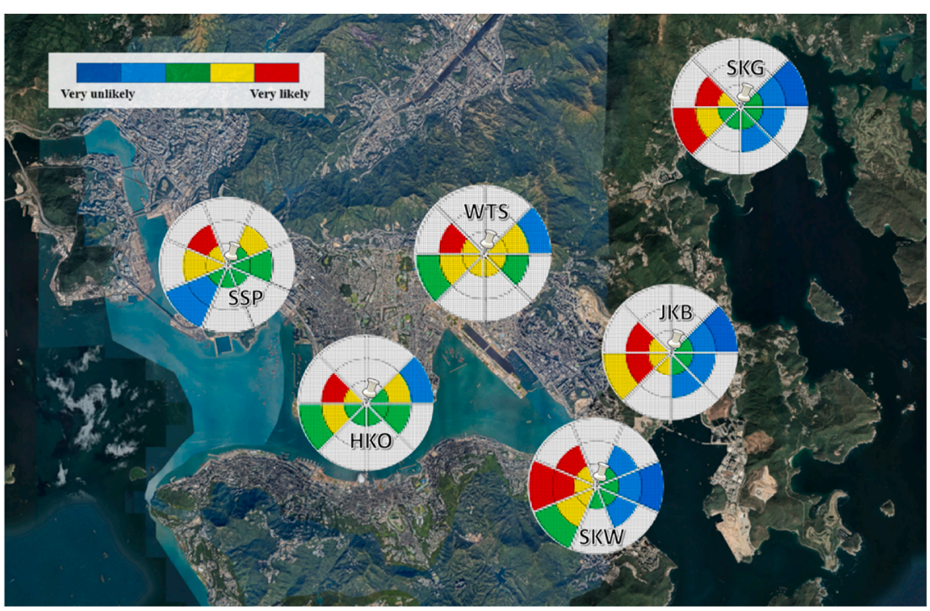


Fig. 10. The likelihood of occurrence of high daily maximum temperature in various areas of Hong Kong under different background wind conditions when the background air temperature is relatively high. Each wind disc is divided into eight directions and three wind speed levels, i.e., weak (0–2 m/s), medium (2–6 m/s) and strong winds (≥6 m/s). Base image courtesy of Google Maps.

to consider the background weather conditions and geographical features such as mountains that can block the winds when analyzing extreme weather events.

Ng and Ren [31] revealed different ventilation mechanisms in various densely built areas of Hong Kong and reported the summertime surface wind distribution; their findings agree well with our results. Furthermore, Wong et al. [21] reported a high-intensity UHI region in the west of the Kowloon Peninsula during a typical winter night, which was mainly due to the densely built urban area in the Yau Tsim Mong District. The possible cause of the convergence zone identified in this paper (see Fig. 3) is different from the cause of the high-intensity UHI region reported by Wong et al.in the winter nights as the convergence of the sea breeze from both sides of the Kowloon Peninsula leads to a relatively stagnant zone in eastern Kowloon; this occurs because the easterly sea breeze is weaker than the westerly one and the air temperature near the surface of Kowloon Bay is higher than that near the surface of the sea body to the west of Kowloon as the bay is tightly surrounded by artificial areas.

Ren et al. [7] evaluated the relationship between wind and the UHI effect in Hong Kong, and found that southeasterly winds dominate the selected stations (HKO, KP, JKB, and Tsak Yue Wu station [TYW]) during days without extreme heat, while winds with directions between west and southwest occur more frequently on extremely hot days. The eastward and westward components of the wind were shown to be very important for the temperature behavior. The findings of the present study can be combined with simulations and real-time observations to provide a simple way to predict the distribution of extreme heat.

The limitation of this study is that all the analyzed data have a temporal scale of one day, whereas the analysis of certain extreme hot days should use data with at least an hourly resolution. It is also questionable whether the selected weather stations can sufficiently represent the climatic features of certain urban regions as some stations are too close to open water (SKG and SKW). Finally, in addition to bright sunshine hours, other meteorological factors (e.g., clouds and humidity) have been shown to strongly affect urban weather [32,33]. Subsequent research will consider these factors and different synoptic weather types, as well as the possible foehn wind effect caused by low-altitude mountains under certain meteorological conditions.

5. Conclusion

The daily maximum temperature in different areas of Kowloon under various background conditions was investigated by analyzing observational data. The study examines the prevailing wind direction at the selected weather stations under calm wind conditions and then obtains the daytime near-surface wind distribution in Kowloon, Hong Kong. Our analysis confirms that coastal areas of Hong Kong are subject to sea breezes and suggests the existence of a convergence zone in the Kowloon Peninsula. The four stations that are located on the east and west coasts of the peninsula (SKG, JKB, SKW, and SSP) have higher daily maximum temperatures when open-sea areas are downwind of them. Besides, the daily maximum temperature and temperature difference are proportional to the background wind speed at SKG. For KP and HKO, a higher background temperature tends to result in a higher daily maximum temperature when the background winds are southeasterly (112.5°–157.5°), south-westerly, or westerly (202.5°–270°). Moreover, when the background temperature is high, larger background wind speeds are associated with higher daily maximum temperatures compared to lower wind speeds. The temperature of inland foothill areas near KLT and WTS is negatively affected by the mountains when the background winds blow from the northeast and under calm background weather conditions. Although rare, west-northwesterly winds in summer are unfavorable in temperature context for all the stations we studied.

In summary, a large effect of the background wind exists on the maximum temperature in different parts of the city. Whether a certain background wind is a good or "ill" wind for a specific region deserves a further and more in-depth study.

CRediT authorship contribution statement

Cheng Zhang: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Qun Wang:** Methodology, Validation, Writing – review & editing. **Pak Wai Chan:** Writing – review & editing, Data curation. **Chao Ren:** Writing – review & editing. **Yuguo Li:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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