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To what extent can urban ventilation features cool a compact built-up environment during a prolonged heatwave? A mesoscale numerical modelling study for Hong Kong

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ABSTRACT

Recent advances in numerical tools and data for the study of urban microclimates have helped to evaluate countermeasures for urban heat in heterogeneous and high-rise cities such as Hong Kong. Thus, two ventilation strategy designs, point ('oases') and linear ('corridors') features, were numerically simulated during a typical heatwave using the multi-layer coupled MesoNH-SURFEX-TEB mesoscale atmospheric model.

These strategies proved to be effective at night with respect to thermal comfort but caused a localised increase in heat stress during the day in the ventilated areas, which were less shaded. There was no significant deterioration in the wind performance around the developments that were redesigned to accommodate the displaced population due to the construction of the ventilation features; however, an improvement was observed in thermal comfort during the daytime. The simulated impacts were relatively localised, suggesting the importance of increasing porosity across the entire urban fabric. The corridors, especially when built along the axis of the prevailing winds, exhibited better ventilation at the pedestrian level than the oases. Nevertheless, the oases remain interesting features in the context of progressive urban ventilation planning that involve the implementation of isolated, connected, and eventually a network of features to provide benefits at the megalopolis scale.

1. Introduction

To accommodate the ever-increasing urban population, cities worldwide are adopting high-density and high-rise urban forms. Compactly built environments are efficient in land and energy use, highly accessible to services and facilities, and provide opportunities for social and cultural exchange (Jabareen, 2006). However, they often face urban climate issues such as urban heat islands (UHIs), poor air quality due to reduced ventilation, and floods/droughts due to changes in precipitation patterns and land cover. Such problems are exacerbated by extreme weather events, such as heatwaves, which are increasing and intensifying owing to climate change (Masson, Lemonsu, Hidalgo & Voogt, 2020). Therefore, to protect citizens from future climate risks and ensure the quality of urban living, governments must take action to build climate resilience in urban areas (Rosenzweig et al., 2018).

In recent years, there has been abundant research on UHI mitigation. Aleksandrowicz, Vuckovic, Kiesel and Mahdavi (2017) revealed that the most common countermeasures for urban heat are greening (tree shading, ground vegetation, green roofs) and the use of cool materials. However, a set of urban heat mitigation studies are examining how buildings and structures can be better arranged within a city – strategies collectively referred to as 'urban design' (Gago, Roldan, Pacheco-Torres & Ordóñez, 2013). Amongst them, the design of street geometry with respect to air flow and solar radiation is particularly relevant for alleviating excess urban heat the densely populated cities. The consideration of wind flow in urban design is not a new idea and has been gaining attention in the planning of rapidly urbanising cities. Germany was a pioneer in developing 'wind corridors' (*Ventilationbahn*; Kress, 1979) that allow cool and fresh 'country breezes' (*Flurwind*; Barlag & Kuttler, 1991) from the mountains to flow into the urban areas. Since then,

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ventilation quality has been an important factor in influencing the urban development of many German cities (Katzschner, 1988; Barlag & Kuttler, 1991; Matzarakis & Mayer, 1992) and was subsequently incorporated into their national planning guidelines (VDI, 1997). Learning from the studies conducted in Germany, 'wind paths' (*kaze-no-michi*; Kagiya & Ashie, 2012) were introduced into the planning of Japanese cities to harness the cooling effect of thick sea breezes in coastal high-rise districts (e.g., Tokyo Bay). In the last decade, an increasing number of Chinese cities have adopted the concept of 'urban ventilation corridors' in their local planning (Ren, 2016). Following successful implementation in pilot cities, the Chinese government has formulated a technical guide (CMA, 2018) to establish the standard protocols for analysing the wind characteristics and developing urban ventilation corridors at the early planning stage. More recently, He, Ding and Prasad (2019) proposed the classification of urban typologies into different 'precinct ventilation zones' according to their compactness, building height, and street structure, to further facilitate ventilation performance-based planning.

In Hong Kong, compact high-rise urban development has led to heightened urban air temperatures (Chen et al., 2012; Shi, Katzschner & Ng, 2018), weakened wind flow at the pedestrian level (Peng et al., 2018), and a deterioration in the urban air quality (Yim, Fung, Lau & Kot, 2009). Poor urban ventilation also increases the transmission of airborne infectious diseases, such as severe acute respiratory syndrome (SARS) and COVID-19 (Coccia, 2020; Ng, 2009). Wang et al. (2021) found that poor urban ventilation, represented by high frontal area density, was significantly associated with all-cause mortality in Hong Kong during 2008–2014. Alerted by the SARS outbreak in 2003, the Hong Kong government initiated several projects aimed at improving the quality of high-density residential environments. Consequently, an air ventilation assessment (AVA) system was established to evaluate the impacts of major developments on their neighbouring wind environment (Ng, 2009). Furthermore, based on the wind tunnel experiments and computational fluid dynamic (CFD) modelling studies (Ng, Yuan, Chen, Ren & Fung, 2011; Yuan & Ng, 2012), sustainable planning principles focussing on air ventilation, such as air paths, street orientations, and building permeability, were introduced into the corresponding urban planning and building design guidelines (HKBD, 2016; HKPlanD, 2015).

Till date, most modelling studies on urban wind flows in Hong Kong have relied on CFD models. They focussed on the relationship between urban morphology and pedestrian-level ventilation (Letzel et al., 2012; Yuan & Ng, 2012) or air pollutant dispersion (Yim et al., 2009; Yuan, Ng & Norford, 2014). Although hindered air flow is a major contributing factor to UHI formation (Nuruzzaman, 2015), thermal effects of urban ventilation strategies have not been investigated. Owing to the high computational cost of CFD models, these studies are often limited to idealised street canyons or small study areas. Stationary inflow boundary conditions are commonly used to perform short-period parametric studies (e.g., 2 h averages in Letzel et al., 2012). Advanced data extraction and mesh generation techniques (Blocken, 2015) allowed researchers (Du, Mak & Ai, 2018; Wang, Xu, Ng & Raasch, 2018; Zhang et al., 2021) to more realistically model urban wind flows for AVA purposes in various neighbourhoods. Additionally, the CFD software ENVI-met, which can model urban ventilation, radiation, greening, air pollution, and thermal comfort in an integrated manner (e.g., Lan, Lau, Shi & Ren, 2021; Morakinyo & Lam, 2016; Xing, Brimblecombe, Wang & Zhang, 2019), has become a popular simulation tool for microclimate studies (Liu et al., 2021; Toparlar, Blocken, Maiheu & Van Heijst, 2017). However, this building-resolving model requires high computational power and time, making it impractical for large study areas. Such simulations also require initialisation or forcing by weather data from nearby stations or field experiments. The recently developed multi-layer coupling between the mesoscale atmospheric model Meso-NH and Town Energy Balance (TEB; Schoetter et al., 2020), as along with advances in urban surface characterisation (Kwok, De Munck, Schoetter, Ren & Lau, 2020), allow to more holistically model the microclimatic effects of urban ventilation strategies more holistically for a larger spatial (district to city scale) and temporal (few days to weeks) scale, although with less precision, than microscale studies. Another advantage of this coupled model is the consideration of the two-way feedback between physical processes in the urban canopy and synoptic weather conditions.

In the present study, MesoNH-TEB was employed to examine the effects of two ventilation strategy designs on the urban thermal conditions and wind performance at the pedestrian level in Hong Kong. The study was conducted to envisage a 'realistic' urban development scenario for the metropolis in the future during a representative heatwave period (Kwok et al., 2021). The scenarios to be examined, with isolated and connected open/green spaces, were designed with reference to the concept of wind corridors (Matzarakis & Mayer, 1992) and recommendations given in the Hong Kong Planning Standards and Guidelines (HKPSG; HKPlanD, 2015). The implications are discussed with respect to the practical principles for urban planning in high-rise, high-density cities and the technical capabilities of the model. This study is expected to contribute to the development of urban heat mitigation strategies through climate-responsive urban design.

2. Methodology

2.1. Model configuration

Numerical modelling was conducted using the mesoscale non-hydrostatic atmospheric model Meso-NH (Lac et al., 2018). Given the highly heterogeneous surface cover and high-rise urban environment in Hong Kong, the land surface model SURFEX (Masson et al., 2013) was coupled with Meso-NH to solve the surface energy balance of sea, rural, urban, and inland water surfaces following a tile approach. Urban areas were modelled by the urban canopy model TEB (Masson, 2000), which was coupled to Meso-NH at multiple atmospheric levels (Schoetter et al., 2020). Particularly, the drag force and wind shear due to the presence of tall buildings and the release of heat and moisture fluxes within the urban boundary layer were considered. This coupling approach also allows a refinement of the model vertical resolution, which increases by 15% from 2 m at the surface for every grid up to 500 m. The high-resolution operational forecast analyses of the Integrated Forecasting System (IFS) from the European Centre for Medium-Range Weather Forecasts were downscaled by Meso-NH via four intermediate domains (D1–D4) to the study area (D5) with a horizontal resolution of 125 m that covers the major urban areas in Hong Kong (Kowloon Peninsula and Hong Kong Island; Fig. 1). The IFS analyses were used as boundary conditions for the largest model domain every six hours from 17th to 31st May 2018, with a model spin-up that was 36 h ahead.

The investigated period represents an extreme high-temperature episode, which is expected to be frequent in the future (Ginn, Lee & Chan, 2010). This period is characterised by sunny and largely rain-free conditions, with urban air temperatures exceeding 25 °C and reaching over 33 °C for 15 consecutive days (HKO, 2018). A hindcast simulation for this prolonged heatwave period has been previously conducted by employing the same model configuration with a detailed urban surface database of Hong Kong as of, 2018 (Kwok et al., 2020). The study yielded a satisfactory model performance (Kwok et al., 2021; Schoetter et al., 2020). Table 1 presents a summary of the evaluation metrics for the modelled air temperature, relative humidity, and wind speed at weather stations within D5 (Fig. 2). Details of model configuration, meteorological situation, and comprehensive model evaluation can be found in Schoetter et al. (2020) and Kwok et al. (2021).

The model input data varied according to the three surface databases of the urban environment of Hong Kong before and after the implementation of ventilation strategies. As planning of large-scale ventilation features is time-consuming and the urban areas would have evolved by the time they could be implemented, they were evaluated against a future baseline. The baseline (named FUTURE after Kwok et al., 2021)

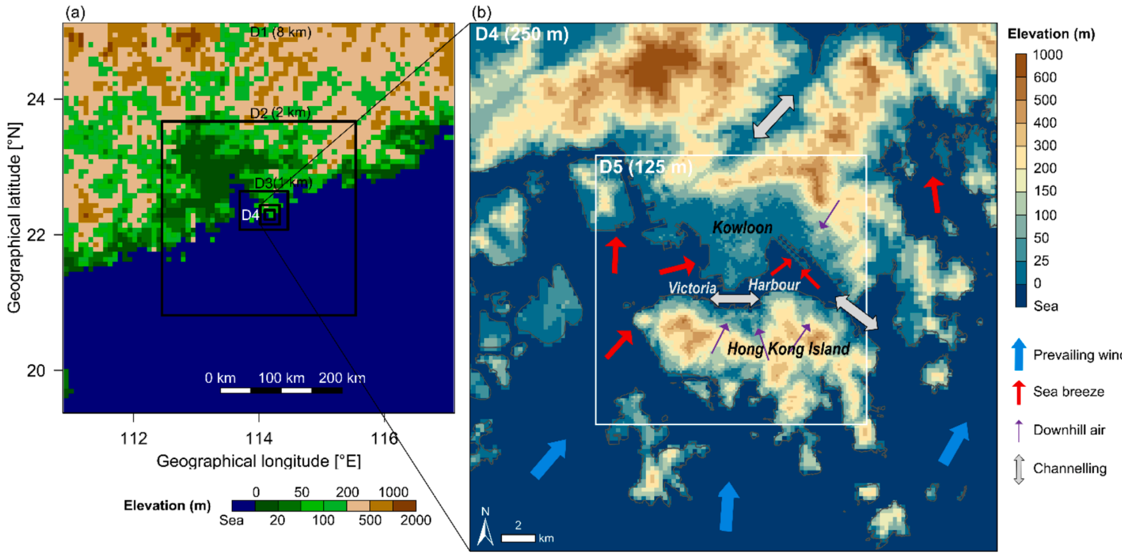

Fig. 1. Extent, resolution, and topography of (a) model domains D1-–D4 (modified from Schoetter et al., 2020) and (b) the study area (D5) with summarised wind information for the selected meteorological situation.

Table 1
Evaluation metrics of modelled air temperature and relative humidity at 1 m, and wind speed at the anemometer heights for all weather stations within D5 based on the hindcast simulation for the investigated period. RMSE is the root mean square error. Note that not all meteorological variables are measured at all stations.

	Air temperature (°C)		Relative humidity (%)		Wind Speed (m/s)	
Station	Bias	RMSE	Bias	RMSE	Bias	RMSE
Average of all stations	0.522	1.12	−3.91	6.92	0.127	1.27
CP1	–	–	–	–	−0.580	1.29
GI	–	–	–	–	0.633	1.63
HKO	0.727	1.12	−5.74	7.50	−0.741	1.13
HKP	0.528	1.05	–	–	–	–
HKS	1.40	1.58	−5.59	7.31	0.431	0.896
HPV	0.284	0.967	–	–	–	–
KLT	0.007	0.987	–	–	–	–
KP	0.657	0.986	−2.95	5.66	−0.271	0.717
KTG	0.541	1.03	–	–	–	–
LAM	–	–	–	–	1.12	1.66
SE1	0.569	1.14	–	–	0.831	1.44
SKW	0.958	1.44	–	–	–	–
SSP	0.740	1.01	–	–	–	–
TC	0.014	1.21	−2.36	8.05	−0.411	1.43
TY1	0.652	1.10	−2.92	6.10	–	–
VP1	−0.186	1.07	–	–	–	–
WTS	0.416	0.952	–	–	–	–

represented a 'realistic' urban development scenario of Hong Kong ~30 years from the present (~2050). It was constructed based on the 2018 urban database (Kwok et al., 2020) with the addition of planned (re) developments, e.g., new developments at the old Kai Tak Airport. The old urban areas within D5 were expected to densify (with respect to building volume and energy use) with an assumed redevelopment rate of ~1%/year. Details of scenario construction and input parameters are provided in Kwok et al. (2021) and Fig. S1 in the Supplementary Material.

2.2. Urban ventilation scenarios

The comparison of the modelled microclimatic conditions in the two ventilation scenarios of urban oases (OAS) and wind corridors (COR) with FUTURE forms the base of the analysis and discussion of this study.

2.2.1. Disposition of the urban oases and corridors

A qualitative climate analysis was conducted by examining the near-surface wind fields and air temperature of FUTURE, along with the observed wind during the heatwave period (Fig. 2; Kwok et al., 2021) to identify suitable locations of the oases and corridors. The prevailing wind direction for the investigated period was mainly from the south-west and south (Fig. 1), which coincides with the summer background wind direction of Hong Kong (Yan, 2007). Smaller-scale circulations, such as sea breezes, were observed coming from the west along the western coastline of Kowloon and from the southwest to the north-western part of Hong Kong Island. When the winds are southerly, wind channelling occurs between the narrow eastern inlet of Victoria Harbour, resulting in south-eastern wind flowing onto the Kowloon Peninsula (Fig. 2). Supplementary summer wind information was obtained from the Urban Climatic Analysis Map of Hong Kong (UC-AnMap; HKPlanD, 2012), which has been developed from past observations, MM5/CALMET simulated wind data,[1] and expert evaluation for a typical summer situation. Additionally, topography-induced channelling effects along the Shing Mun Valley to the north of Kowloon (outside D5) and potential downhill air movements from the hilly region of Hong Kong Island to the neighbouring urban areas in the north were shown by the UC-AnMap. Ren et al. (2018) also laid out guidelines for the planning of ventilation corridors in Chinese cities by linking the city centre to cool fresh air sources, such as water bodies and greenery areas. The COR layouts (Fig. 3b) were therefore designed to allow sea breeze from Victoria Harbour and land breeze coming downhill into the urban areas (Fig. 1).

As construction of wind corridors would induce dramatic changes to the urban surface, the OAS scenario (Fig. 3a), with isolated open spaces in alignment with the corridors, was proposed. Oases were placed strategically in areas with relatively high building surface fraction (BLD) and wall density to break down the extensive hot spots in these areas, especially at night in central Kowloon Peninsula. A roughly even distribution of oases across areas with varied characteristics (e.g., coastal, inland, open settings, compact settings, residential areas, commercial areas) was ensured, with a minimum distance of ~1 km between two

[1] Wind fields of 100 m resolution from the prognostic fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) coupled with the diagnostic California Meteorological Model (CALMET).

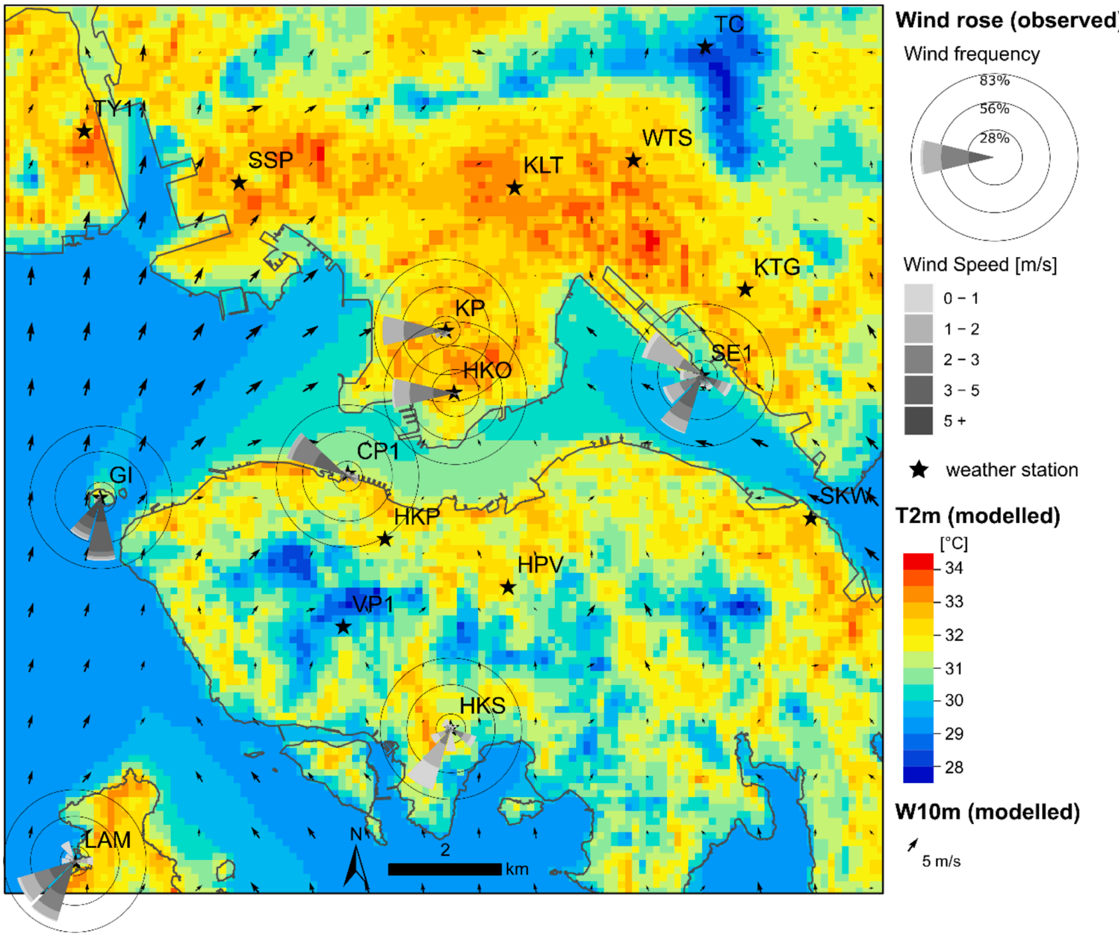

Fig. 2. Modelled 2-m air temperature and 10-m wind fields of the FUTURE scenario for a representative day of the simulated meteorological situation (21st May 2018, local time 1100–1600) and wind roses showing observed wind during the investigated period at selected weather stations within D5.

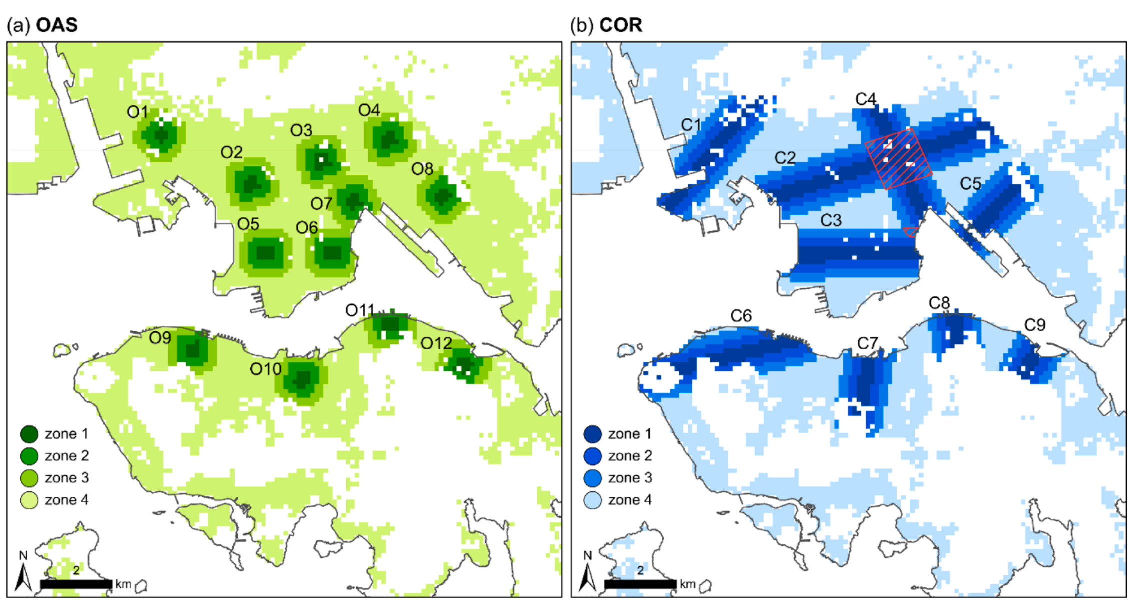

Fig. 3. Locations of (a) urban oases (OAS) and (b) wind corridors (COR) and the definition of zones for analysis extracted from the surface input maps of TEB. Refer to Fig. S1 in the Supplementary Material for corresponding urban parameters at the oases and corridors. Areas overlapped by two corridors were removed from the analyses of individual corridors and are shaded in red in (b).

oases (Fig. 3a).

2.2.2. Implementation of the oases/corridors and associated assumptions

For urban spaces to serve as ventilation paths, Matzarakis and Mayer (1992) provided a list of specific requirements for their lengths (at least 1000), widths (at least 50 m and 2–4 times the height of neighbouring urban canyons), size of obstacles in the path (<10% of the width of the path), height of obstacles in the path (<10 m), and aerodynamic surface roughness length (<0.5 m). Accordingly, the geometry of the oases/-corridors was therefore set as follows (Fig. 4):

- Considering the effective resolution of the coupled model MesoNH-TEB, the cross-sectional width of the oases/corridors was set to ~500 m (~4 model grids), which was according to the recommended width of the major ventilation corridors in Chinese cities (CMA, 2018).
- The length of the corridors was determined by the extent of the urban areas that they intersect with. All corridors were over 1000 m in length, except C8 and C9, which terminated at the foot of an undeveloped mountain close to the coastline. The length of the oases was assumed to be the same as the width, forming roughly circular oases.
- BLD was reduced to 0.1 for grids with $BLD_{future} > 0.1$; otherwise, it was kept the same as in FUTURE.
- The removed BLD (BLD_{rm}) was replaced by low vegetation (LVEG), which had an aerodynamic roughness length of 0.01 m in TEB (Lemonsu, Masson, Shashua-Bar, Erell & Pearlmutter, 2012).
- Building height (BH) was reduced to 6 m for grids with $BH_{future} > 6$ m; otherwise, it was kept the same as in FUTURE. This height was set arbitrarily to represent low-rise buildings (~2 storeys) while maintaining a low surface roughness.
- Impervious surface fraction (ROAD) was kept the same as in FUTURE and had an aerodynamic roughness length of 0.05 m in TEB (Schoetter et al., 2020).

The model input parameters were modified accordingly in a geographic information system (GIS). Since the two urban ventilation scenarios were created assuming that the residents moved from the locations of oases and corridors were relocated within the urban areas in D5 (resembling an urban redevelopment without counter-urbanisation), the total building volume within D5 for OAS and COR was the same as in FUTURE. The removed building volume ($BLD_{rm} \times 125^2 \times BH$) from the oases/corridors was distributed evenly amongst all the other grids where $0 < BLD_{future} < 0.6$. This resulted in an increase of 2 m and 7 m in BH for OAS and COR, respectively, while the BLD in the non-oasis/corridor grids remained unchanged (Fig. 4). Final maps of the BLD and BH of D5 for OAS and COR are shown in Fig. S1 in the Supplementary Material.

Another important urban input parameter in the TEB, which was difficult to obtain, was the wall density (WD; i.e., the ratio between the vertical facade area and the horizontal plan area). The WD of the oases/corridors was calculated assuming a square building footprint for the buildings within them. For the other grids of D5 with buildings, the WD was estimated from BLD, ROAD, and BH using a multiple linear regression model (Eq. (1)).

$$WD_{new} = 4.27\, BLD + 0.17\, ROAD + 0.03\, BH - 0.56 \quad (1)$$

This model was developed from the data of ~5000 grid points with $BLD_{future} > 0.05$ and had an R^2 of 0.52. Although the R^2 is relatively low, the model was validated using 116 other randomly selected grid points from FUTURE. There was a good agreement between the predicted WD (WD_{new}) and the ground-truth (WD_{future}) WD for values <3 but a general underestimation for larger values. Therefore, the original WD_{future} was used if $WD_{new} < WD_{future}$ at grids with $WD_{future} > 3$, while negative values of WD were manually corrected to 0.05 for OAS and 0.1 for COR. The details of the regression model are presented in Supplementary Material S1.

2.3. Analysis approach

2.3.1. Universal thermal climate index

The Universal Thermal Climate Index (UTCI) was developed to assess the thermo-physiological effects of the atmosphere on humans (Bröde et al., 2012). It is derived from the offset of the reference air temperature caused by the air and mean radiant temperature (MRT), wind speed, and humidity of the actual conditions. Therefore, it is a useful composite index to summarise the surface meteorological variables responsible for human outdoor thermal comfort. In MesoNH-TEB, the UTCI was calculated from the air temperature (T2m) and specific humidity (Q2m) at 2 m, wind speed at 10 m (W10m), and the weighted average MRT of the shaded and sunlit parts of the street canyon (Supporting Information S2 of Kwok et al., 2019). Moreover, UTCI values can be categorised according to the corresponding human physiological responses to evaluate thermal stress (Błażejczyk et al., 2013). Maps of UTCI and its constituting variables for two different time periods, daytime (local time (LT) 1100–1600) and night-time (LT 0100–0600), were analysed and compared for both scenarios in Section 3.1.

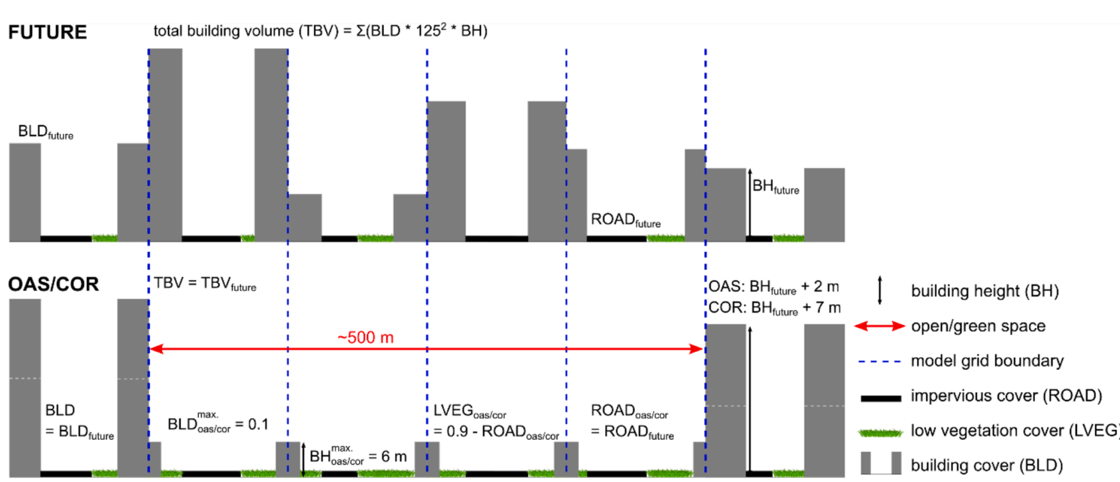

Fig. 4. Schematic diagram of the cross-sectional geometry and model input parameters of the oases/corridors. Only the model grids concerned in the implementation of the oases/corridors and one on either side are shown. BH is building height, BLD, ROAD, and LVEG are the building, impervious, and low vegetation surface fractions, respectively.

2.3.2. Effective area analysis

To examine the areal extent of the effects of oases and corridors, box plots of the difference in the surface meteorological variables (T2m and W10m) relative to FUTURE were plotted for the four zones (Fig. 3). The boxes represented the data extracted from buffers around the oases or on the two sides of the corridors that were defined to analyse impacts with respect to an increasing distance from the features: zone 1 covers the oases/corridors themselves, zone 2 is the area within 250 m from zone 1, and zone 3 is the area within 250 m from zone 2. All other areas with a dominant urban surface cover were defined as zone 4. A further analysis was conducted for each oasis/corridor focussing on the night-time T2m and daytime W10m to understand the ways to achieve the highest cooling and ventilation effects. Buffers of corridors C2, C3, and C4 overlapped at certain locations (shaded in red in Fig. 3b). Data from these overlapping areas were removed to analyse the effects of each individual corridor.

2.3.3. Wind performance analysis

Wind performance along the corridors was assessed using the wind velocity ratio (VR), which is defined as $W_{pedestrian}/W_{infinity}$, where $W_{pedestrian}$ is the wind speed at 2 m (W2m) and $W_{infinity}$ is the wind speed near the top of the urban boundary layer (~500 m for Hong Kong; W500m) that is unaffected by urban roughness. It is the ratio of the wind that is experienced by pedestrians to the background wind availability and is commonly used for the AVA of proposed developments in Hong Kong (HKHPLB & HKETWB, 2006). Previous studies have found negative correlations between the wind VR and built-up density indicators, such as frontal area density (Ng et al., 2011) and building ground coverage (Kubota, Miura, Tominaga & Mochida, 2008), providing a reference for planners to design urban environments with good ventilation. Considering the weak wind conditions of the urban areas of Hong Kong, it is generally perceived a higher wind VR indicates a better wind performance (Ng, 2009). The time series of the average wind VR in the four zones of COR was compared with those in the urban areas of FUTURE during the investigated period. The wind performance for two groups of corridors with different orientations (C2 and C3, C4 and C7; Fig. 3b) was then discussed for two selected days (24th and 30th May) with prevailing winds from different directions.

3. Results

3.1. Urban thermal environment

The average daytime and night-time UTCI values in the urban areas of D5 are shown in Fig. 5. Strong to very strong heat stress was observed over almost all urban areas in the day during the investigated period for all scenarios. Daytime heat stress was the strongest in the open spaces of the OAS. At night, even without solar radiation, the UTCI remained remarkably high in urban areas, especially in the FUTURE scenario of Kowloon, where strong heat stress prevailed in the inner-city neighbourhoods. The only areas with no thermal stress were on the sparsely built and vegetated slopes located at the borders of the urban areas. The OAS and COR helped to reduce the nocturnal thermal stress by breaking down the areas with strong heat stress into smaller discontinuous patches.

Fig. 6 shows the difference in average UTCI between OAS/COR and FUTURE. The effects of the oases and corridors were mostly localised, as evidenced from the well-defined zones of elevated UTCI in the day and reduced UTCI at night. The UTCI increased by 3.6 K on average (up to 7 K) during the day in the open spaces in OAS. The UTCI on the extended open spaces in COR also increased, but to a lesser degree (2.6 K on average). In most of the other urban areas, the UTCI reduced slightly owing to the overall increase in BH, causing the formation of shade in urban canyons; this was attributed to the assumption that the residents

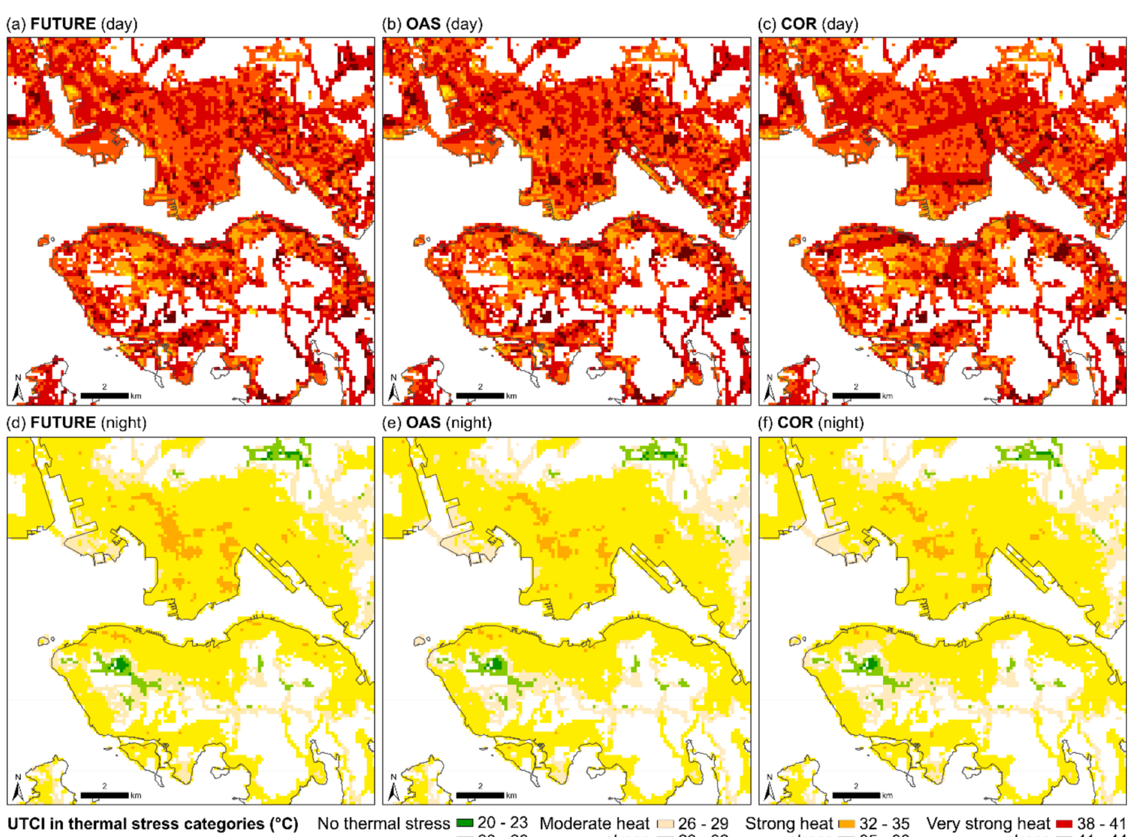

Fig. 5. Average (a–c) daytime (LT 1100–1600) and (d–f) night-time (LT 0100–0600) Universal Thermal Climate Index (UTCI) in urban areas of D5 during the investigated period for FUTURE, OAS, and COR.

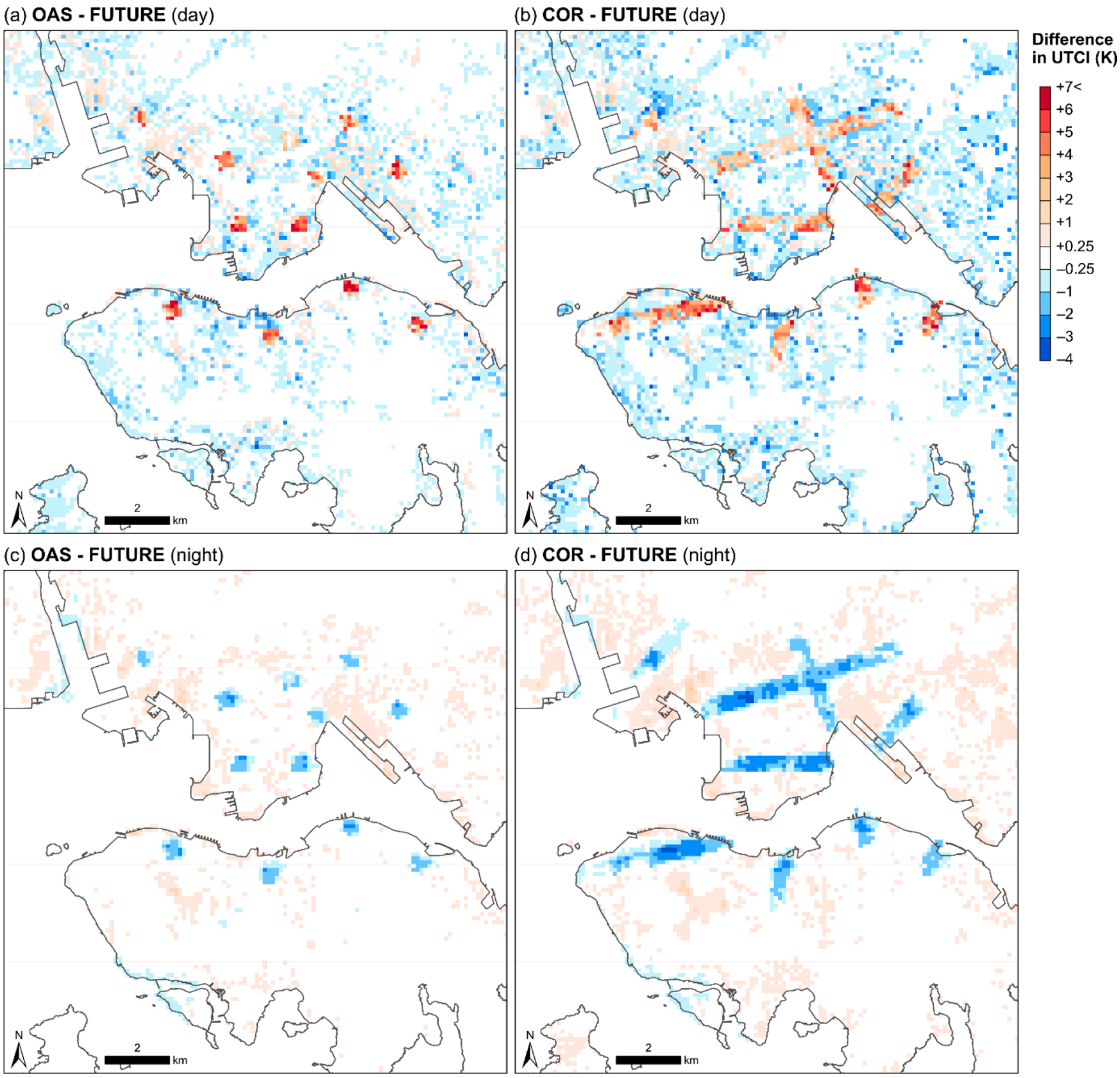

Fig. 6. Difference in average (a and b) daytime and (c and d) night-time Universal Thermal Climate Index (UTCI) in the urban areas of D5 during the investigated period for OAS and COR relative to FUTURE.

(building volume) that were moved to create the oases/corridors were accommodated by slightly taller buildings in other areas of D5. Patches of lower UTCI were observed downwind of corridor C1 and to the northeast of the intersection of corridors C2 and C4 (Fig. 6b), probably owing to the combined effects of lower MRT and higher wind speed (Figs. S3 and S5). At night, the UTCI reduced by 1–2 K (2–4 K) in the oases (along the corridors). For COR, the changes in UTCI along corridors extended for a larger and more continuous area than that of the daytime changes (see Section 3.2). Small increases in UTCI (< 1 K) were observed across other urban areas of D5 because of the higher heat release from the increased volume of building materials; however, the difference was small compared to the decrease in daytime UTCI for these areas.

To further explain the observed differences in UTCI between the scenarios, the constituting factors of UTCI were examined (Table 2; maps of the difference in MRT, T2m, W10, and Q2m are in the Supplementary Material). UTCI is strongly influenced by radiation intensity and is found to increase by ~3 K for every 10 K rise in MRT (Bröde et al., 2012). The pattern of differences in MRT between OAS/COR and FUTURE corroborates that of the UTCI, particularly during the day (Fig. S3). The main source of daytime net radiation is the sun, while night-time net radiation is due to the longwave radiation dissipated from the warm urban materials that have heat stored from the day. Therefore, the magnitude of change in the daytime MRT (up to +30 K in the oases/corridors without shading) is much larger than that in the night-time MRT (approximately −5 K in the oases/corridors). Air temperature (Fig. S4) is also positively related to UTCI (Bröde et al., 2012). A small local increase (decrease) in daytime (night-time) T2m was observed in the oases. Slight increases in daytime T2m (<0.5 K) were scattered along the corridors, except for a hot spot in the high-rise

Table 2
Qualitative summary of the daytime (LT 1100–16) and night-time (LT 0100–0600) differences in the surface meteorological variables affecting the Universal Thermal Climate Index (UTCI) at the oases and corridors between OAS/COR and FUTURE.

	Expected correlation with UTCI (Bröde et al., 2012)	Simulated differences with FUTURE	
		Daytime	Night-time
MRT	Strongly positive	+	–
T2m	Positive	+	–
W10m	Negative	+	+
Q2m	Slightly positive	+	Variable
Resulting UTCI		+	–

commercial district in the north-western part of Hong Kong Island. At night, cooling up to 2 K was observed for a larger area along and near the corridors.

At air temperatures <35 °C, wind contributes to lowering it, and thus lowering the UTCI (Bröde et al., 2012). The urban ventilation features (oases and corridors) were effective in increasing the local W10m, but the increased BH in non-oasis/corridor areas caused a slight reduction in wind flow owing to the higher building drag (Fig. S5). The increase in W10m due to increased diffusion of air masses through greater urban porosity provided by the oases is about two times smaller than that along the corridors. In the latter, the coupled effects of wind channelling between tall buildings and the entry of sea breezes allow momentum-driven wind flow over longer distances, resulting in a stronger increase in W10m. This occurred especially along corridors C1, C2, and C3 in Kowloon and C6 on Hong Kong Island (Figs. 3b and S5). Such an increase in W10m could counteract the increase in MRT along these corridors, resulting in a smaller increase in daytime UTCI for COR than that of OAS (Fig. 6a and b). Humidity slightly increases the UTCI in warm climates (Bröde et al., 2012). The higher Q2m in the oases and corridors during the day was probably due to the increased evapotranspiration by low vegetation in the building areas, but the differences between scenarios were generally small (within ± 0.5 g/kg; Fig. S6).

3.2. Spatial extent of effects

The size and extent of the thermal and ventilation effects of oases and corridors were studied from the changes in T2m and W10m in the different zones of OAS and COR relative to FUTURE. The average daytime warming (Fig. 7a) and night-time cooling (Fig. 7b) effects caused by the oases and corridors were similar. The daytime increase in T2m was mainly restricted to zone 1 (comprising the oases and corridors), which was directly exposed to solar radiation. Daytime T2m in zones 2–4 remained largely similar to that in FUTURE despite the increased shade casted by the taller buildings. However, the cooling effect at night also extended to zone 2, and marginally to zone 3 for COR, benefiting areas up to 500 m away from the open spaces (i.e., four model grids on each side). T2m reduced by ~0.5 K in zone 1; the effect was approximately halved in zone 2 and was even less in zone 3. The increase in daytime W10m was greater along the corridors (average of 1.2 m/s and up to 3 m/s) than in the oases (average of 0.8 m/s and up to 2 m/s; Fig. 7c). Based on local outdoor thermal comfort surveys (Cheng et al., 2012), an increase of 1 m/s in wind speed was found to increase the neutral air temperature (i.e., temperature at which subjects were thermally comfortable) by ~2 K. Therefore, considerable cooling effect was observed in the zone 1 of both OAS and COR, which could potentially improve thermal sensations from 'hot/slightly warm' to 'slightly warm/neutral' (Ng & Cheng, 2012). However, the effect in zone 2 was variable, and W10m was observed to be marginally higher only for COR. Further away from the oases and corridors, W10m was generally slightly lower than that in FUTURE. Similar patterns of a smaller magnitude were observed during the night (Fig. 7d).

The effects of individual oases/corridors located in various urban environments were further investigated (Figs. S7–10). The differences in night-time T2m and daytime W10m for oases O1, O4, O10, and O11 are used for the discussion here (Fig. 8); the wind performance of selected corridors is presented in the next section. The largest reduction in night-time T2m was found at O11 (also O9), which was close to the sea and had a relatively more reduced in building surface cover compared to that in FUTURE (Fig. S1); comparatively less reduced building surface cover was observed at O4 (also O3), probably owing to its further inland location. O4 (also O3 and O8) also had the least increase in daytime W10m, probably owing to its distance from the sea. Therefore, any sea breeze reaching it would have been slowed down by the upwind built-up areas. The cooling effect in zone 2 of O10 was more obvious than that in the other oases. Higher wind speeds from both the sea to the north and the vegetated valleys to the south of O10 were likely to have more efficiently advected the cooler air mass over the oasis to its neighbouring areas. O1 was originally an area with open settings and low-rise buildings. Therefore, the oasis benefited from a moderate increase in daytime W10m, but its surrounding areas (zones 2–3) suffered from a clear reduction in the W10m due to the relatively large increase in surface roughness with increased BH to accommodate the displaced population. Notably, the range of differences in T2m and W10m generally decreased with increasing distance from zone 1, indicating that areas further from the oases/corridors were less influenced by the change in urban morphology and exhibited more homogenous microclimate characteristics.

3.3. Wind performance along corridors

Overall, the wind performance at the pedestrian level, represented by the wind VR, improved along the corridors (zone 1) for all days of the investigated period when compared to FUTURE (Fig. 9a). A daily variation was observed in the increase in wind VR that corresponded to different background wind conditions and prevailing wind directions. For example, the corridors performed better on average at the beginning and end of the prolonged heatwave and worse in between (24–27 May). The wind conditions in zones 2–4 of COR were generally similar to, or not much worse than, that of FUTURE. In days when the background wind speed estimated at ~500 m, was relatively low and only formed a light breeze (~3 m/s, Beaufort Scale), the wind VR in zone 1 could exceed 1, suggesting that wind accelerated near the surface along the corridors. This leads to a discussion on whether the relatively high wind speeds at the pedestrian-level on such days would cause discomfort or danger. Penwarden (1973) determined the comfort and safety thresholds of wind speed in towns by observing and calculating the wind pressure on human bodies, the unbalancing effect of wind force, the energy required to walk against the wind, and the characteristics of particles lifted by the wind (Arens & Ballanti, 1977). The probability of exceeding the common wind comfort threshold of 5 m/s along all corridors was <2% of the time during the investigated period, which was therefore considered 'good' for all activities (traversing, strolling, and sitting) (Stathopoulos, 2009).

All wind corridors were designed with specific orientations based on the climatic analysis (Section 2.2.1) but corridors C2 and C3, and C4 and C7, which showed contrasting orientations, were selected to describe the varied effectiveness of different wind situations. Corridors C2 and C3 had an almost east-west orientation and extended from the western coast of Kowloon Peninsula to the mountains in northeast Kowloon (C2) and to the eastern coast of Kowloon Peninsula (C3). Corridors C4 and C7 had an almost north-south orientation. C4 crossed C2 at a right angle in the central-eastern part of Kowloon, while C7 connected the northern coast and the vegetated valley in the central part of Hong Kong Island. During the first week and towards the end of the investigated heatwave period, prevailing winds were south-westerly. However, in the middle of the heatwave period, the prevailing wind direction became southerly. Two representative days of these two wind situations (24th and 30th May; Fig. 10) were analysed with respect to the wind VR in the selected corridor pairs (Fig. 9b and c).

On 24th May, C2 and C3 were particularly ineffective owing to a gentle to moderate breeze (~5.5 m/s, Beaufort Scale) from the south-southeast (Fig. 10a), which was not aligned with the long axis of these corridors. The southern background wind was obstructed by the topography of Hong Kong Island and thus flowed around it, resulting in wind channelling near the ground from the southeast through the eastern entrance of the Victoria Harbour towards Kowloon (Fig. 10b). This resulted in a low baseline (FUTURE) mean wind VR (~0.3), which did not improve for COR at C2 and C3 (Fig. 9b). When Kowloon experienced southerly wind (Fig. 9b), the average W2m in the built-up area remained below 1 m/s as the wind was unable to enter the open spaces of C2 and C3, which were almost perpendicular to the wind direction. Instead, it is likely that a skimming flow forms above the high-density

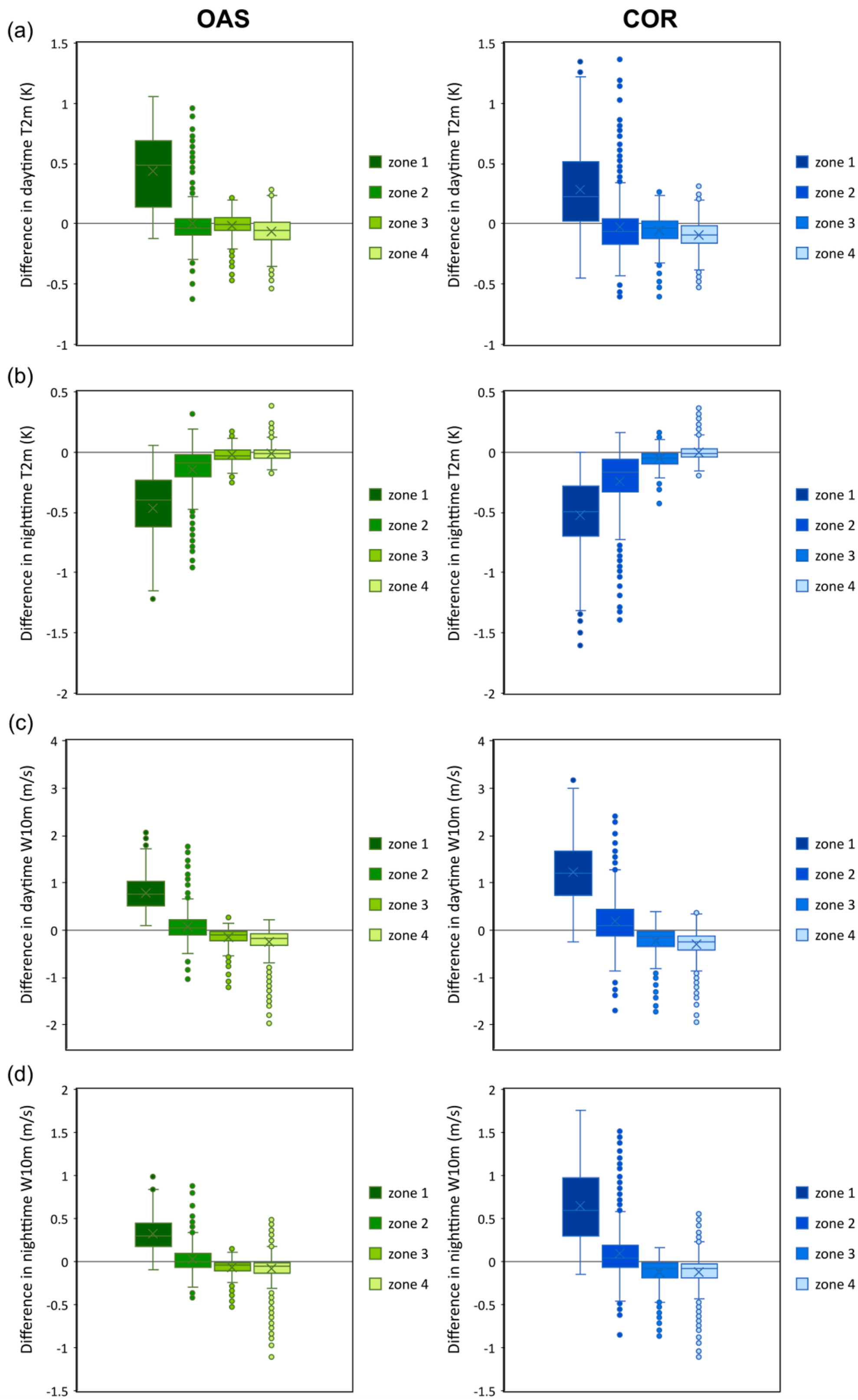

Fig. 7. Boxplots of the differences in (a) daytime and (b) night-time 2-m air temperature (T2m) and (c) daytime and (d) night-time 10-m wind speed (W10m) for zones 1 to 4 of OAS and COR relative to FUTURE. Boxes show the median and the first and third quartiles; whiskers show the maximum and minimum values within 1.5 the interquartile range; outliers are plotted as circles; mean values are marked as crosses.

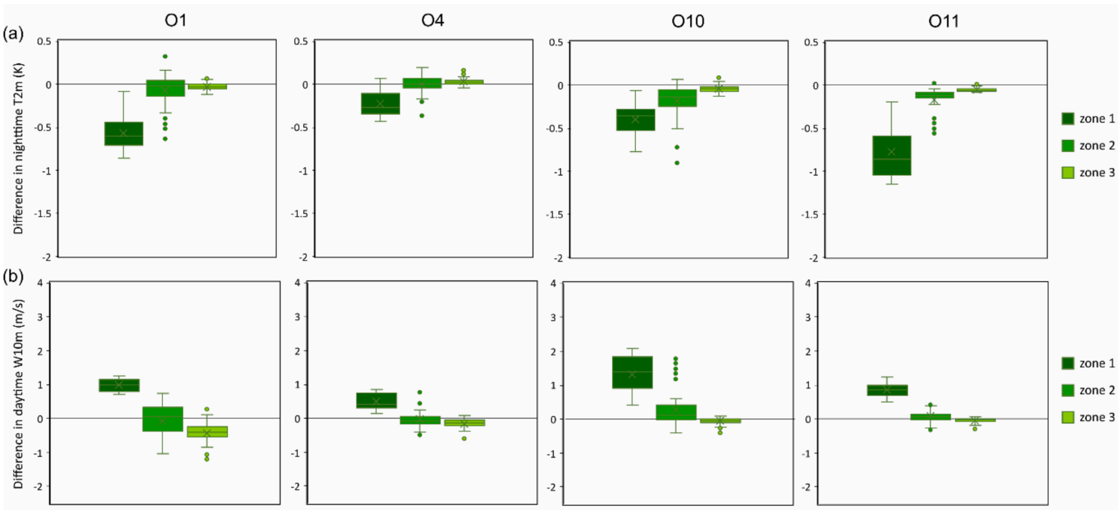

Fig. 8. Boxplots of the differences in (a) night-time T2m and (b) daytime W10m relative to FUTURE for zones 1–3 of selected oases (O1, O4, O10, O11). Refer to caption of Fig. 7 for a description of elements in the boxplots.

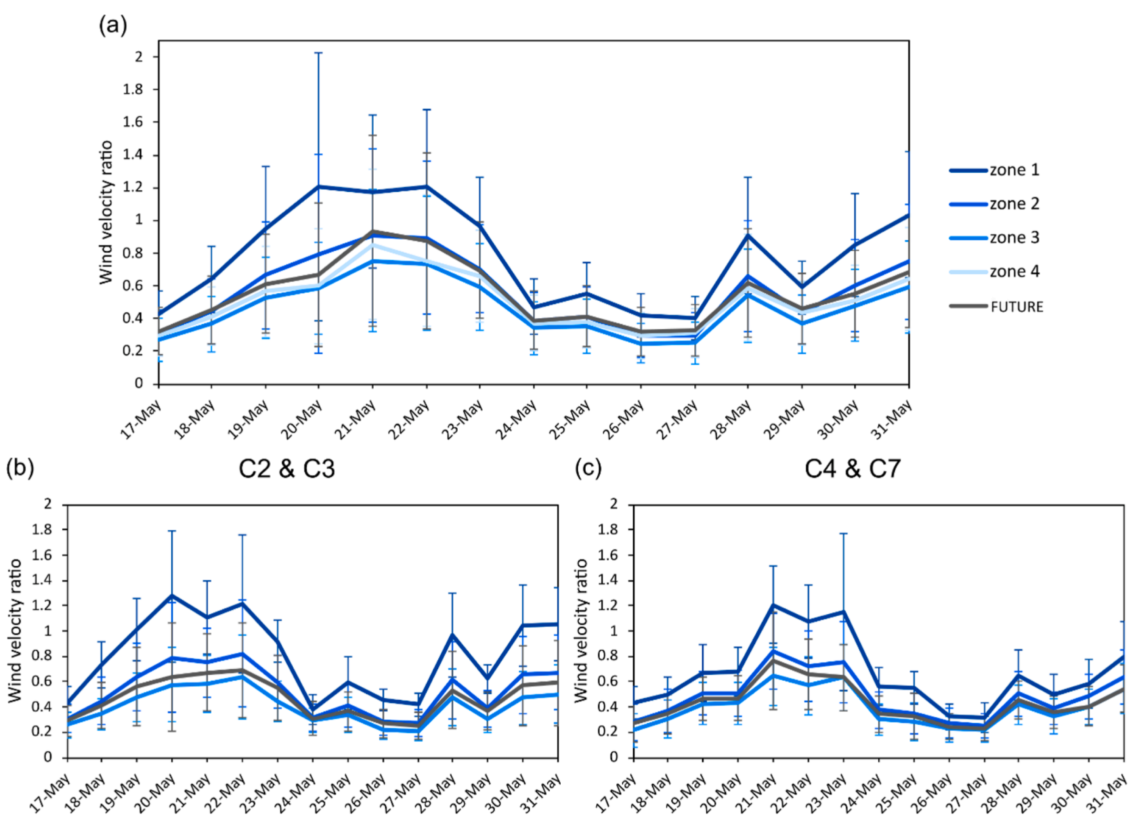

Fig. 9. Daily time series of the daytime wind velocity ratio in zones 1–4 for (a) all corridors in COR and in zones 1–3 for corridors (b) C2 & C3 and (c) C4 & C7. The wind velocity ratio in the corresponding urban areas of FUTURE is also plotted for comparison. Error bars show one standard deviation above and below the average wind velocity ratio.

urban environment with deep urban canyons (Oke, 1987; Zajic et al., 2011). However, the mean wind VR at C4 and C7 increased from ~0.3 in FUTURE to ~0.6 in COR (Fig. 9c). Because C4 and C7 were orientated at a small angle relative to the prevailing wind direction, some wind could flow along the corridor near the surface (Fig. 10b). Furthermore, a slightly accelerated surface wind (W2m) compared to the background wind (W500m) was observed through C7 towards the Victoria Harbour (Fig. 10a and b).

The background wind on 30th May was a gentle breeze (~4 m/s, Beaufort Scale) from the southwest (Fig. 10c). The surface wind flowed around the north-western corner of Hong Kong Island and sped up before reaching the western coast of the Kowloon Peninsula. Facilitated by the corridors of low roughness that were orientated along the incoming sea breeze direction (C2 and C3), the wind penetrated through the densely built urban areas of Kowloon. The wind VR along C2 and C3 increased from ~0.5 in FUTURE to ~1 in COR (Fig. 9b). The wind VR in neighbouring areas (zone 2) was also increased compared to that in FUTURE (also observed in other days with a similar wind situation, e.g.,

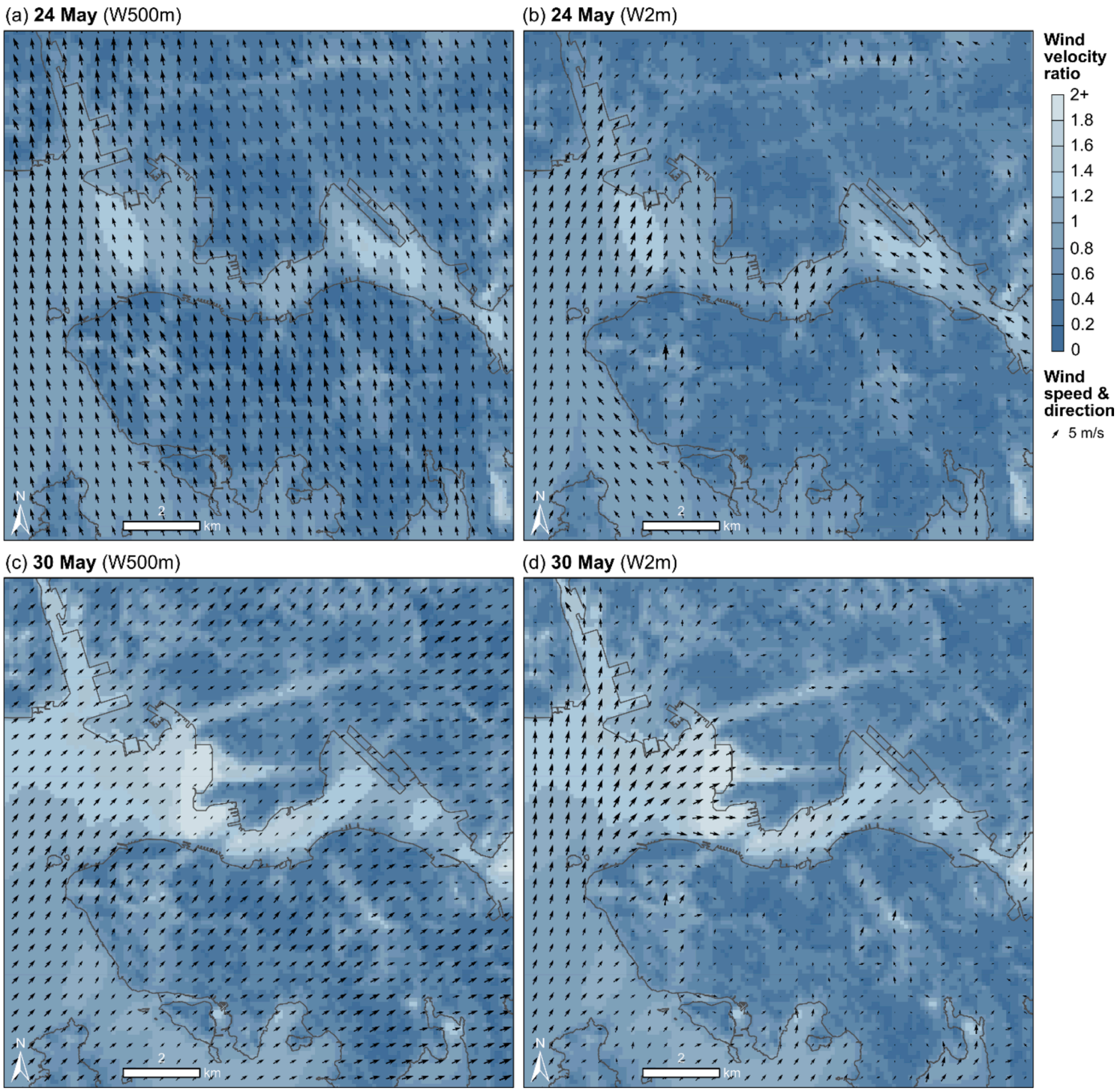

Fig. 10. Background (W500m) and pedestrian-level (W2m) wind fields overlain on the wind velocity ratio of D5 for COR on (a,b) 24 May and (c,d) 30 May.

20th–23rd and 31st May). Wind can travel long distances via relatively strong momentum-driven wind flow, which improved the urban wind environment of Kowloon at the district scale. However, C4 and C7 were much less effective owing to the difference in the corridor orientation and wind direction on 30th May.

4. Discussion

4.1. Model capability and interpretation of findings

Investigation of the microclimatic effects of urban oases and corridors relies on the ability of the coupled model to capture the differences in surface energy balance and flow dynamics over heterogeneous surfaces and urban canyons with different geometries. While the mesoscale atmospheric model accounts for mesoscale atmospheric conditions, the coupled surface parameterisations aim at representing the neighbourhood-scale processes which occur within each model grid (Section 2.1). The present study demonstrates the model capability and potential application of the new multi-layer coupling between Meso-NH and the urban canopy model TEB (Schoetter et al., 2020) in cities with complex urban forms. The results showed that this coupling approach realistically simulated wind flow channelling over urban surfaces with low roughness and horizontal advection of warm/cool air masses within urban areas, which could not have been achieved using the original single-layer version of TEB.

Moreover, due to the provision of detailed urban surface and building data derived from GIS data, the dynamical effects of the heterogeneous urban geometry on wind flow within the urban environment can be fully represented. Therefore, the model results may be interpreted with confidence to reveal the intra-urban variation of microclimate conditions at the scale of 125 m, which is suitable for district-scale urban planning applications.

4.2. Urban planning for better ventilation

The design concept of urban ventilation scenarios is discussed in this section. Recommendations for climate-responsive urban planning are then reviewed with the support of the study findings.

4.2.1. From point-line-plane approach to real-life applications

Points, lines, and planes are the basic elements of art and design (Kandinsky, 1926). The two ventilation scenarios examined in this study also originate from these geometrical elements – points (oases) and lines (corridors). This approach can be applied to the district-scale urban planning principles for better ventilation (Table 3): (1) urban green/-open spaces (points) provide urban porosity to facilitate air movement

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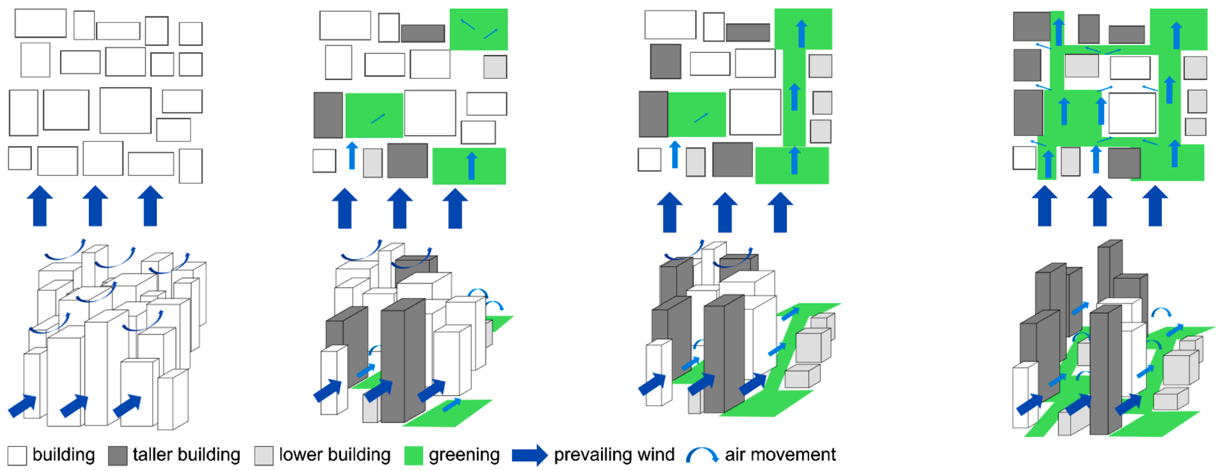
Table 3
Schematic diagrams (not drawn to scale) and characteristics of the ventilation features and urban wind environment following the point-line-plane approach. Each rectangle may represent an urban plot or building block.



High-density, high-rise urban area	Improved urban design with ventilation features		
	'Point'	'Line'	'Plane'
- Deep & narrow street canyons - Wind skims over building tops - Stagnant pedestrian wind environment	- Urban oases: low building ground coverage, low building heights, highly vegetated - Light air movements can reach oases	- Wind corridors/air paths: connected urban oases aligned with the prevailing wind - More greening at grade, some taller buildings - Wind can flow along and cool corridors	- Ventilation network: evenly distributed oases and corridors forming a diverse urban environment - More greening at grade, some taller buildings - Wind can penetrate the entire neighbourhood/district

and sites of relief/variation amidst the high-density cites; (2) the linkage of urban green/open spaces by roads or other linear features with low surface roughness (e.g., rivers) can serve as air paths and wind corridors (lines); (3) strategically placed oases and corridors form a well-ventilated network that potentially cools an entire neighbourhood/district (plane). These three types of ventilation features are increasingly effective, but are also difficult to implement, especially in developed areas. Therefore, when incorporating these principles in urban design, planners can start by creating/maintaining urban oases to ultimately connect them and enhance the district-scale wind environment.

The point-line-plane concept has been applied in the 'Conserving Central' initiative proposed during the 2009–2010 Policy Address of Hong Kong (HKSAR, 2009). The main purpose of this concept was to extend cultural and heritage conservation from several identified historic buildings (points) to the neighbouring streets (lines) and the entire Central district (plane) (HKAAB, 2014). Thus, historical sites that had low building heights and open settings were preserved and served as urban oases. Based on the urban climatic map analysis, experts further suggested widening and intensifying greening along streets (lines) connecting the historical sites (former Police Married Quarters 'PMQ', former Central Police Station Compound 'Tai Kwun', and Central Market) to reduce the expected heat stress frequency by 60% (Ng, 2011). To further enhance air ventilation in the busy Central commercial district, the Urban Renewal Authority adopted 'Central Oasis' as the theme for revitalising the Central Market, aiming to introduce more greenery and connected public space for better overall environmental quality and pedestrian comfort.

Another example is the AVA conducted to assess the potential impacts on ventilation due to new BH restrictions in the Wan Chai area (Ng & Wang, 2010). Following expert evaluation, the Planning Department incorporated some mitigation measures into the revised planning scenario by connecting areas with lower building heights, open spaces, and non-building areas along the north-south orientated streets to form air paths that allow the penetration of valley breezes into urban areas. The locations of the studied features, though at a smaller scale, coincide with O10 and C7 (Fig. 3) in the present study, where their effectiveness in reducing the nocturnal urban heat and enhancing wind flow was well simulated by the model (Figs. 8 and 10b).

4.2.2. From simulations to urban planning recommendations

Analyses of the changes in T2m and W10m, induced by the implementation of oases/corridors, indicates that their urban climate effects were rather localised (Section 3.2). Therefore, it is more desirable to place oases at a higher frequency and distribute corridors (or at a smaller scale, air paths) evenly across the city to allow their benefits to reach a larger extent and greater variety of areas, eventually achieving a 'plane' of enhanced ventilation (Section 4.2.1, Table 3). The findings of the present study also showed the importance of orienting wind corridors along the prevailing wind directions to maximise the urban ventilation effect and facilitate momentum-driven wind flow along the corridors (Section 3.3, Table 3). At a smaller scale, this effect can be emulated by an array of main streets orientated parallelly or at an angle up to 30° to the direction of the main prevailing winds, as recommended in the HKPSG (HKPlanD, 2015). Another useful finding is that while the urban ventilation and nocturnal thermal environment improved at the oases/corridors, the slightly increased BH in the non-oasis/corridor areas of D5 did not have significant negative impacts (Figs. 7–9). Similarly, Kwok and Ng (2018) noted that BH ceases to be the main factor affecting pedestrian-level ventilation when wind flow enters the skimming flow regime in the AVA of the Mong Kok area, a compact inner-city area with deep street canyons in Kowloon. Planners can therefore focus on opening up wind corridors and providing open/green spaces at grade, even if they result in the influx of urban population into the nearby taller buildings. Moreover, creating more open spaces and varying BH offer diversity and choices of thermal and wind comfort for urban dwellers with different preferences (Table 3). Nevertheless, the UTCI analysis showed very strong heat stress in the oases and corridors during the day during the simulated prolonged heatwave period. This can be mitigated by planting trees to provide more shade in these open spaces (Morakinyo & Lam, 2016; Morakinyo, Kong, Lau, Yuan & Ng, 2017). However, a comprehensive assessment regarding the benefits of planting trees along the streets is required, as they might also reduce ventilation and trap pollutants within the urban canyons (Gromke & Ruck, 2009). Such analysis would require the selection of suitable tree species and determination of the optimal balance between ventilation and shading in the urban open spaces and wind corridors.

4.2.3. Feasibility of scenarios

Owing to the limitations in the effective spatial resolution of the state-of-the-art mesoscale models, the oases and corridors in this study were designed in a large-scale (width of ~500 m) for the high-density urban areas of Hong Kong, where typical street blocks are only ~50 m wide. Although these scenarios would be almost impossible to be carried out in reality, they demonstrated the potential district-wide impacts of creating urban oases and wind corridors that can be insightful for future urban planning of large-scale new development areas, such as the artificial islands of East Lantau Metropolis (HKPlanD, 2016; Kwok et al., 2021). In the existing urban areas, the ventilation effects of a wide wind corridor may be emulated by a network of narrower but evenly distributed air paths that are designed according to the principles as recommended in Section 4.2.2. Such air paths can be readily constructed along existing major roads and around urban parks, as well as by widening the streets that are aligned to the prevailing wind directions and connect areas with relatively low building density and BH. Wong, Nichol, To and Wang (2010) identified several potential ventilation corridors in the Kowloon Peninsula using a least-cost path analysis on a map of building frontal area. Three major potential pathways along the east-west orientation provided by the (1) Boundary Street, (2) Argyle Street and Cherry Street, and (3) Ho Man Tin Road, Gascoigne Road, and King's Park show a remarkable resemblance to the corridors C2 and C3. Supported by the findings of the present study, these existing features need to be maintained, strengthened, and developed into wind corridors in the future city planning of Kowloon.

4.3. Study limitations and further work

Apart from the limitation of model spatial resolution and thus the scale of ventilation features discussed in Section 4.2.3, several other study limitations need to be noted. First, in relation to the urban airflow modelling, the specification of sub-grid scale canyon orientations (available in Lemonsu et al., 2012) has not yet been implemented in the multi-layer TEB (Schoetter et al., 2020). The current assumption of an isotropic frontal area may have led to an underestimation of the effective areas of the oases/corridors because the alignment of street grids between two oases/corridors was not considered. The wind flow within urban areas is therefore only accounted for in the first order and does not truly represent the realistic and detailed wind dynamics within street canyons and at road junctions. These aspects can only be addressed using CFD models at a much smaller scale. Second, the simulated ventilation scenarios in this study did not investigate the impact of street trees in open spaces, as the multi-layer TEB currently uses a big-leaf approach to model urban trees. Their impact can be further studied when developments incorporating the radiative and drag effects of street trees in TEB (Redon, Lemonsu & Masson, 2020) are integrated within the model. Third, the microclimatic effects of individual ventilation features simulated in this study should be scaled down by microscale models (e.g., CFD) for the detailed planning of neighbourhoods.

For a more comprehensive understanding of the impacts of oases/corridors under different wind regimes, further work should be undertaken to study the seasonal variation of prevailing winds, as well as both extreme (e.g., heatwaves, as in the present study) and typical meteorological situations. Simulations at the microscale and with idealised wind conditions may also be required at the detailed planning stage of specific development areas. Furthermore, it would be useful to examine the interaction and combined effects of the different UHI mitigation strategies, including but not limited to ventilation features (a network of both point and line features), greening (especially street trees), cool materials, and urban water bodies, to identify the most suitable urban environmental solutions for specific districts and cities.

5. Conclusion

In the present study, the potential effects of two urban heat mitigation strategies by urban design, namely, oases (isolated 'points' of open/green space) and corridors (connected 'lines' of open/green space) on the thermal and wind comfort at the pedestrian-level in a compactly built environment were investigated. The novelty of this study lies in the application of a newly developed multi-layer coupling between the urban canopy model TEB and the mesoscale atmospheric model Meso-NH to quantify the effectiveness of district-wide urban heat mitigation strategies. The study implies that the proposed point-line-plane approach of enhancing urban ventilation is of practical value for the planning of new development areas.

Enabled by the recent development of coupling the mesoscale atmospheric model (Meso-NH) to the urban canopy model (TEB) at multiple atmospheric levels, the impacts of changes in the urban morphology on the microclimate conditions can be simulated holistically in a district to city scale. This study focusses on the most urbanised areas of Hong Kong (Kowloon and Hong Kong Island) and employs three detailed surface datasets representing the baseline and two redeveloped future (~2050) scenarios with strategically placed oases and corridors. For the simulated prolonged heatwave period, a strong heat stress was expected in almost all urban areas within the study domain. Although the open spaces created by the oases and corridors have a higher MRT in the day, they can reduce the urban heat and cool neighbouring areas (up to a distance of 500 m from the corridors) at night. Surface wind availability increased throughout the day by both the urban ventilation features, and corridors that were aligned with the prevailing wind direction were found to be particularly effective in facilitating momentum-driven wind penetration into the city. In high-density urban settings, such as that of Kowloon, the improvement in surface wind environment by creating more open spaces at the ground level was found to outweigh the slight deterioration of the wind performance induced by fewer but taller buildings. The findings of this study provide important information for local governments and planners to consider in climate-responsive planning during future urban development.

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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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2021.103541.

References

Aleksandrowicz, O., Vuckovic, M., Kiesel, K., & Mahdavi, A. (2017). *Current trends in urban heat island mitigation research: Observations based on a comprehensive research repository, 21* pp. 1–26). Urban Climate.

Antiques Advisory Board (HKAAB). (2014). Report on the policy review on conservation of built heritage.

Arens, E., & Ballanti, D. (1977). Outdoor comfort of pedestrians in cities. Paper presented at the. In *Proceedings of the conference on metropolitan physical environment* (pp. 115–129).

Barlag, A., & Kuttler, W. (1991). The significance of country breezes for urban planning. *Energy and Buildings;(Switzerland), 15*(3/4), 291–297.

Błażejczyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., et al. (2013). An introduction to the universal thermal climate index (UTCI). *Geographia Polonica, 86*(1), 5–10.

Blocken, B. (2015). Computational fluid dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Building and Environment, 91*, 219–245.

Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., et al. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology, 56*(3), 481–494.

Buildings Department (HKBD). (2016). Practice note for authorized persons, registered structural engineers and registered geotechnical engineers - Sustainable building design guidelines. (No. APP-152).

Chen, L., Ng, E., An, X., Ren, C., Lee, M., Wang, U., et al. (2012). Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: A GIS-based simulation approach. *International Journal of Climatology, 32*(1), 121–136.

Cheng, V., Ng, E., Chan, C., & Givoni, B. (2012). Outdoor thermal comfort study in a sub-tropical climate: A longitudinal study based in Hong Kong. *International Journal of Biometeorology, 56*(1), 43–56.

China Meteorological Administration (CMA). (2018). *Specifications for climatic feasibility demonstration – Urban ventilation corridor* 气候可行性论政规范 城市通风廊道 *(in Chinese). (No. qx/t 437).*中国气象局.

Coccia, M. (2020). An index to quantify environmental risk of exposure to future epidemics of the COVID-19 and similar viral agents: Theory and practice. *Environmental Research, 191*, Article 110155.

Du, Y., Mak, C. M., & Ai, Z. (2018). Modelling of pedestrian level wind environment on a high-quality mesh: A case study for the HKPolyU campus. *Environmental Modelling & Software, 103*, 105–119.

Gago, E. J., oldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews, 25*, 749–758.

Ginn, W., Lee, T., & Chan, K. (2010). Past and future changes in the climate of Hong Kong. *Journal of Meteorological Research, 24*(2), 163–175.

Gromke, C., & Ruck, B. (2009). On the impact of trees on dispersion processes of traffic emissions in street canyons. *Boundary-Layer Meteorology, 131*(1), 19–34.

He, B., Ding, L., & Prasad, D. (2019). Enhancing urban ventilation performance through the development of precinct ventilation zones: A case study based on the Greater Sydney, *Australia. Sustainable Cities and Society, 47*, Article 101472.

Hong Kong Observatory (HKO). (2018). The weather of May 2018. https://www.hko.gov.hk/en/wxinfo/pastwx/mws2018/mws201805.htm.

Housing Planning and Lands Bureau (HKHPLB), & Environment Transport and Works Bureau (HKETWB). (2006). Technical guide for air ventilation assessment for developments in Hong Kong. (Technical Circular No. 1/06).

Jabareen, Y. R. (2006). Sustainable urban forms their typologies, models, and concepts. *Journal of Planning Education and Research, 26*(1), 38–52.

Kagiya, K., & Ashie, Y. (2012). National research project on Kaze-no-michi for city planning: Creation of ventilation paths for cool sea breezes in Tokyo. *Journal of Heat Island Institute International, 7*(2), 33–41.

Kandinsky, W. (1926). *Point and line to plane*.

Katzschner, L. (1988). The urban climate as a parameter for urban development. *Energy and Buildings, 11*(1–3), 137–147.

Kress, R. (1979). *Regionale luftaustauschprozesse und ihre bedeutung für die räumliche planung.* Bundesminister für Raumordnung, Bauwesen und Städtebau.

Kubota, T., Miura, M., Tominaga, Y., & Mochida, A. (2008). Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. *Building and Environment, 43*(10), 1699–1708.

Kwok, Y. T., De Munck, C., Schoetter, R., Ren, C., & Lau, K. K. (2020). Refined dataset to describe the complex urban environment of Hong Kong for urban climate modelling studies at the mesoscale. *Theoretical and Applied Climatology, 142*, 129–150.

Kwok, Y.T. & Ng, E. (2018). Term consultancy for expert evaluation on air ventilation assessment (PLN ava 2015): For Mong Kong planning area. (No. final report). Hong Kong: Planning Department.

Kwok, Y. T., Schoetter, R., de Munck, C., Lau, K. K., Wong, M. S., & Ng, E. (2021). High-resolution mesoscale simulation of the microclimatic effects of urban development in the past, present, and future Hong Kong. *Urban Climate, 37*, Article 100850.

Kwok, Y. T., Schoetter, R., Lau, K. K., Hidalgo, J., Ren, C., Pigeon, G., et al. (2019). How well does the Local Climate Zone scheme discern the thermal environment of Toulouse (France)? An analysis using numerical simulation data. *International Journal of Climatology, 39*(14), 5292–5315.

Lac, C., Chaboureau, J., Masson, V., Pinty, J., Tulet, P., Escobar, J., et al. (2018). Overview of the Meso-NH model version 5.4 and its applications. *Geoscientific Model Development, 11*, 1929–1969.

Lan, H., Lau, K. K., Shi, Y., & Ren, C. (2021). Improved urban heat island mitigation using bioclimatic redevelopment along an urban waterfront at Victoria Dockside, *Hong Kong. Sustainable Cities and Society, 74*, Article 103172.

Lemonsu, A., Masson, V., Shashua-Bar, L., Erell, E., & Pearlmutter, D. (2012). Inclusion of vegetation in the town energy balance model for modelling urban green areas. *Geoscientific Model Development, 5*(6), 1377–1393.

Letzel, M. O., Helmke, C., Ng, E., An, X., Lai, A., & Raasch, S. (2012). LES case study on pedestrian level ventilation in two neighbourhoods in Hong Kong. *Meteorologische Zeitschrift, 21*(6), 575–589.

Liu, Z., Cheng, W., Jim, C. Y., Morakinyo, T. E., Shi, Y., & Ng, E. (2021). Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Building and Environment, 200*, Article 107939.

Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorology, 94*(3), 357–397.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., et al. (2013). The SURFEXv7. 2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geoscientific Model Development, 6*, 929–960.

Masson, V., Lemonsu, A., Hidalgo, J., & Voogt, J. (2020). Urban climates and climate change. *Annual Review of Environment and Resources, 45*, 411–444.

Matzarakis, A., & Mayer, H. (1992). Mapping of urban air paths for planning in Munich. *Wiss. Ber. Inst. Meteor. Klimaforsch. Univ. Karlsruhe, 16*, 13–22.

Morakinyo, T. E., Kong, L., Lau, K. K., Yuan, C., & Ng, E. (2017). A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. *Building and Environment, 115*, 1–17.

Morakinyo, T. E., & Lam, Y. F. (2016). Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. *Building and Environment, 103*, 262–275.

Ng, E. (2009). Policies and technical guidelines for urban planning of high-density cities–air ventilation assessment (AVA) of Hong Kong. *Building and Environment, 44* (7), 1478–1488.

Ng, E. (2011). Oases, boulevards and our city (powerpoint presentation to the executive council of the government of the Hong Kong SAR).

Ng, E., & Cheng, V. (2012). Urban human thermal comfort in hot and humid Hong Kong. *Energy and Buildings, 55*, 51–65.

Ng, E., & Wang, Y. (2010). Term consultancy for expert evaluation and advisory services on air ventilation assessment (PLNQ 37/2007): Wan Chai Area. (No. Final Report). Hong Kong: Planning Department.

Ng, E., Yuan, C., Chen, L., Ren, C., & Fung, J. C. (2011). Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong. *Landscape and Urban Planning, 101*(1), 59–74.

Nuruzzaman, M. (2015). Urban heat island: Causes, effects and mitigation measures-a review. *International Journal of Environmental Monitoring and Analysis, 3*(2), 67–73.

Oke, T. R. (1987). *Boundary layer climates*. Routledge.

Peng, L., Liu, J., Wang, Y., Chan, P., Lee, T., Peng, F., et al. (2018). Wind weakening in a dense high-rise city due to over nearly five decades of urbanization. *Building and Environment, 138*, 207–220.

Penwarden, A. D. (1973). Acceptable wind speeds in towns. *Building Science, 8*(3), 259–267.

Planning Department (HKPlanD). (2012). Urban climatic map and standards for wind environment - Feasibility Study. (No. final report).

Planning Department (HKPlanD). (2015). Hong Kong planning standards and guidelines - Urban Design guidelines. (No. chapter 11).

Planning Department (HKPlanD). (2016). Hong Kong 2030+ towards a planning vision and strategy transcending 2030 - Preliminary Concepts for the East Lantau metropolis.

Redon, E., Lemonsu, A., & Masson, V. (2020). An urban trees parameterization for modeling microclimatic variables and thermal comfort conditions at street level with the town energy balance model (TEB-SURFEX v8. 0). *Geoscientific Model Development, 13*(2), 385–399.

Ren, C. (2016). In C. Ren (Ed.), *Assessment and air path plan - Creating 'breathing cities" (in Chinese)*. China Architecture and Building Press.

Ren, C., Yang, R., Cheng, C., Xing, P., Fang, X., Zhang, S., et al. (2018). Creating breathing cities by adopting urban ventilation assessment and wind corridor plan–the implementation in Chinese cities. *Journal of Wind Engineering and Industrial Aerodynamics, 182*, 170–188.

Rosenzweig, C., Solecki, W.D., Romero-Lankao, P., Mehrotra, S., Dhakal, S., & Ibrahim, S.A. (2018). Climate change and cities: Second assessment report of the urban climate change research network. Cambridge University Press.

Schoetter, R., Kwok, Y. T., de Munck, C., Lau, K. K. L., Wong, W. K., & Masson, V. (2020). Multi-layer coupling between SURFEX-TEB-V9.0 and Meso-NH-v5.3 for modelling the urban climate of high-rise cities. *Geoscientific Model Development, 13*, 5609–5643.

Shi, Y., Katzschner, L., & Ng, E. (2018). Modelling the fine-scale spatiotemporal pattern of urban heat island effect using land use regression approach in a megacity. *Science of the Total Environment, 618*, 891–904.

Stathopoulos, T. (2009). Wind and comfort. Paper presented at the. In *Proceedings of European–African conference on wind engineering (EACWE 5)*. Florence, Italy: International Association for Wind Engineering.

The Hong Kong Special Administrative Region (HKSAR). (2009). 2009-2010 Policy address breaking new ground together. https://www.policyaddress.gov.hk/09-10/eng/index.html.

Toparlar, Y., Blocken, B., Maiheu, B., & Van Heijst, G. (2017). A review on the CFD analysis of urban microclimate. *Renewable and Sustainable Energy Reviews, 80*, 1613–1640.

VDI. (1997). VDI-Guideline 3787 environmental meteorology - Climate and air pollution maps for cities and regions. (No. part 1). Beuth Verlag, Berlin: The Association of German Engineers.

Wang, P., Goggins, W. B., Shi, Y., Zhang, X., Ren, C., & Lau, K. K. (2021). Long-term association between urban air ventilation and mortality in Hong Kong. *Environmental Research, 197*, Article 111000.

Wang, W., Xu, Y., Ng, E., & Raasch, S. (2018). Evaluation of satellite-derived building height extraction by CFD simulations: A case study of neighborhood-scale ventilation in Hong Kong. *Landscape and Urban Planning, 170*, 90–102.

Wong, M. S., Nichol, J. E., To, P. H., & Wang, J. (2010). A simple method for designation of urban ventilation corridors and its application to urban heat island analysis. *Building and Environment, 45*(8), 1880–1889.

Xing, Y., Brimblecombe, P., Wang, S., & Zhang, H. (2019). Tree distribution, morphology and modelled air pollution in urban parks of Hong Kong. *Journal of Environmental Management, 248*, Article 109304.

Yan, Y. Y. (2007). Surface wind characteristics and variability in Hong Kong. *Weather, 62*(11), 312–316.

Yim, S. H., Fung, J. C. H., Lau, A. K., & Kot, S. C. (2009). Air ventilation impacts of the "wall effect" resulting from the alignment of high-rise buildings. *Atmospheric Environment, 43*(32), 4982–4994.

Yuan, C., & Ng, E. (2012). Building porosity for better urban ventilation in high-density cities–A computational parametric study. *Building and Environment, 50*, 176–189.

Yuan, C., Ng, E., & Norford, L. K. (2014). Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies. *Building and Environment, 71*, 245–258.

Zajic, D., Fernando, H., Calhoun, R., Princevac, M., Brown, M., & Pardyjak, E. (2011). Flow and turbulence in an urban canyon. *Journal of Applied Meteorology and Climatology, 50*(1), 203–223.

Zhang, S., Kwok, K. C., Liu, H., Jiang, Y., Dong, K., & Wang, B. (2021). A CFD study of wind assessment in urban topology with complex wind flow. *Sustainable Cities and Society, 71*, Article 103006.