Building and Environment 145 (2018) 177–195

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Detection and evaluation of a ventilation path in a mountainous city for a sea breeze: The case of Dalian

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ARTICLE INFO

Keywords:
Ventilation path
Frontal area index
Computational fluid dynamics model
Planning strategies

ABSTRACT

In this study, an urban morphological method is introduced to detect ventilation paths to drain sea and mountain breezes to mitigate the urban heat island of Dalian, a typical coastal mountain city. Wind analysis shows that the dominant wind direction is south in summer, and north in winter; the wind is weak at night in the summer and autumn when mountain breezes could blow. The hindering effect of the mountain is included in the frontal area index calculation, and a reduction coefficient for the mountain's FAI is also presented in consideration of the differences of its shape from the building. Ventilation paths for both sea and mountain breezes are identified by mapping the frontal area index and the least cost path methodology based on a geographic information system (GIS) in a 100 m × 100 m grid. Four paths for south and four for north sea breezes are detected. The mountain breeze has a pattern similar to the sea breeze, but with several NW-SE direction paths. An advanced computational fluid dynamic model and field measurements are used to verify the wind paths detected. Field measurements are conducted to obtain air temperature, which average values are used to generate a temperature field in the GIS system. Corresponding planning mitigation policies are proposed according to the superimposed results of the least cost paths and air temperature field. Based on these findings, local governments and urban planners can improve living quality in the urban area.

1. Introduction

Mega-cities today are characterised by high building densities and floor area ratios. Because of the increase in impervious surface as land cover, smaller vegetated areas, and the impedance of air flow owing to the high density of buildings, cities generally produce urban heat islands (UHIs) with higher temperatures than the surrounding suburbs and an accumulation of air pollution [1–4]. In the future, the effects of UHIs and air pollution will combine with those of global warming, which will result in even greater adverse effects on the thermal comfort and health of city residents [5]. Urban planners are therefore increasingly concerned with methods to complete a quantitative and scientific assessment of the urban climate as a basis for mitigation and adaptation strategies [6,7].

Wind can significantly reduce the UHI effect, improve a city's thermal comfort, and promote the dispersion of pollutants [8,9]; if wind reaches a certain critical value, the UHI effect will disappear [1,10]. Urban ventilation paths such as rivers and green belts are prospective strategies to improve a city's overall ventilation, which can at the same time divide UHIs and prevent them from merging into one another and expanding [11,12]. The introduction of fresh, clean air via ventilation paths in the suburbs or above the sea can also promote air flow velocity and dispersion of pollutants under stagnant weather conditions. Therefore, the detection and development of ventilation paths have been applied in many cities such as Tokyo [13], Stuttgart [14], Hong Kong [15], Beijing [16], and Tainan [17].

Land cover and terrain have a considerable influence on the local climate. Sea-land breezes are thermally-induced winds that are caused by the difference in heat capacities between the land and the sea. The penetration distance of the sea breeze from the Bohai Sea, an innermost gulf of the Yellow Sea in the northeast of China, can be more than 100 km [18]. Another study shows that the sea breeze penetration distance on the Korea Peninsula, which is on the east of the Yellow Sea, is 25 km–30 km [19]. The mountain-valley breeze circulation occurs because of the inhomogeneous heating of the mountain and valley, similar to the sea-land breeze. The mountain has three main effects on sea breeze: 1) a mechanical forcing effect [20]; 2) an enhancing effect due to the upward valley breeze in daytime [21]; 3) a hindering effect due to the downward mountain breeze at night time [22,23]. According to the study by Federico, Dalu [23], when the height of the mountain is 500 m on a peninsula, the obstruction effect and the enhancing effect of mountain on the sea breeze is balanced, which means the intensity of

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https://doi.org/10.1016/j.buildenv.2018.09.010
Received 22 April 2018; Received in revised form 4 September 2018; Accepted 6 September 2018

the sea breeze is the same as on flat terrain. When the height is more than 500 m, the enhancing effect is dominant. Furthermore, as the German guideline on Environmental meteorology – Local cold air [24] pointed out, the thickness of the cold air above the mountain is usually from a few dozen to a hundred metres, while the thickness of the sea breeze is from several hundred to a thousand metres [25], which is much stronger and thicker. When the intensity of the sea breeze is greater than $3\,\mathrm{m\,s^{-1}}$, the cold air above the mountain does not persist.

The type of land use has a great influence on surface temperature in an urban district because of the variation in evaporative ability, heat capacities, and emissivity [26,27]. UHI intensity can be ameliorated by planning strategies such as increasing the area of vegetated land, green roofs, forests, and water bodies, and decreasing artificial and impervious surfaces [28–30]. A research simulation showed that if approximately 30% of roof areas could be covered by vegetation in the Baltimore-Washington metropolitan area, the surface UHI intensity would decrease by 1 °C [31]. Another study showed that the surface temperature of water-retentive concrete blocks was much lower than that of asphalt pavement. When the surface temperature of asphalt pavement was 56.1 °C, that of the water-retentive concrete was only approximately 38.5–48.9 °C [32].

The urban wind environment is mainly assessed using field measurements, wind tunnel tests, and numerical simulations [33,34]. Field measurements and wind tunnel tests are more accurate, but are time-consuming and costly. The urban climate numerical simulation method is divided into two main types: meso-scale and micro-scale. Meteorological models such as the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) [35] and the Weather Research and Forecasting (WRF) model [36] have an abundance of physics schemes and the coupled urban canopy models reproduce the processes of a boundary layer climate at a scale of 10^0 km–10^3 km such as land and sea breezes, UHIs, and pollutant dispersions. The effect of UHI mitigation strategies such as urban land use and albedo assessed using WRF have also been studied [37]. Computational fluid dynamics (CFD) can also be adopted in a wide range of applications, considering solar radiation, heat transfer, anthropogenic heat, and other factors, in urban design at a micro-scale of 10^2 metres [38,39]. CFD and meso-scale models require sophisticated configurations of boundary conditions and pose great challenges for urban planners and architects.

Compared to numerical simulation technology, parametric analysis of urban three-dimensional (3D) morphology using a Geographic Information System (GIS) becomes an important and simple method for wind environment assessment. Urban morphology is an interdisciplinary field of study that includes geography, architecture, and urban planning [40]. The most-acknowledged elements of urban morphology are 1) urban form, including the physical elements of buildings, and their open spaces and plots; 2) resolution, including the building or lot, street or block, city, and region; 3) time, which refers to the continuous evolution and redesign of cities. The first two elements (urban form and resolution) have been commonly used in many geographic studies where urban morphology is a general designation for aerodynamic or surface roughness parameters, such as zero-plane displacement height (Z_d), roughness length (Z_0), depth of the roughness sublayer, frontal area index (FAI), effective height (heff), building density, and urban porosity (P_h) [41–44]. In many other urban planning studies, urban morphology has been used in juxtaposition with surface roughness, where its meaning is closer to the third element (time), which refers to the use of design and planning measures to reconstruct or regenerate urban forms for the improvement of the environment [13,45,46]. In our study, the urban morphological method refers to the first two elements, that is, the aerodynamic parameters (such as FAI) related to urban forms. Urban morphological indexes have a good correlation with wind velocity in an urban environment; thus, many researchers use these parameters to evaluate wind environments or detect ventilation paths. For example, Gál and Unger [47] calculated roughness parameters such as Z_d, Z_0, and P_h for the city of Szeged, Hungary, using 3D building data and thereby located potential ventilation paths. Ratti, Sabatino [48] used digital elevation models (DEMs) to generate the roughness length and FAI of London, Toulouse, and Berlin. In these studies, the calculation of FAI is simple and widely used. However, most studies in the past have evaluated flat lands, ignoring the complicated terrain of mountainous cities, which may cause deviation in the results of ventilation paths. In the study in Hong Kong, Ng, Yuan [45] used MM5 simulation results to produce wind rose diagrams at a height of 60 m, which were used as the basis for calculating the average FAI, to reflect the effect of complex terrain on wind. Chen, Lu [49] developed an improved method of FAI calculation that introduced the impact of mountains into the quantification process of ventilation paths. However, in the study of Chen, Lu [49], the urban area was also flat and the difference of shape and scale between mountains and buildings is not considered; therefore, cities with more complicated topography such as Dalian need to be further studied.

The purpose of this study was to investigate a city with a complex terrain, and to identify ventilation paths that would introduce sea breezes and mountain breezes to decrease the UHI effect and pollution. An improved method to calculate the FAI of buildings and hills under complex terrain conditions was proposed. The difference of mountain and building was discussed and a reduction coefficient was presented. The wind roses of the study area were analysed and the influence of mountain breezes to the sea breezes was discussed. The FAI map was calculated using a grid of 100 metres, and the ventilation paths for sea breeze and mountain breeze were exploited using the least cost path (LCP) method. The results of the extraction of ventilation paths are verified using CFD-PHOENICS 2017, and field measurements. Air temperature measured from 45 points of the study area were used to generate a map based on GIS, to evaluate the thermal environment along the ventilation paths. Finally, corresponding mitigation planning measures were proposed according to different features of the ventilation paths.

2. Material and methods

2.1. Study area

Dalian (N38.9°, E121.6°) is a typical coastal mountain city in the southernmost part of the Liaodong Peninsula in China (Fig. 1). The city exhibits complex topography; 67% of its total area is mountainous. The urban constructed area of Dalian has gradually expanded over the past 60 years from 50 $\mathrm{km^2}$ (1950) to 396 $\mathrm{km^2}$ (2017) according to statistics from Dalian Municipal Bureau of Statistics [50]. Because of the expansion of the city and the high concentration of land use, the form features of high buildings and high-population density embodied in complex terrain have become established in the central urban area. The city of Dalian is on the southernmost part of Liaodong Peninsula, with a land depth only 7 km–22 km, smaller than the penetration distance of a general sea breeze [18,19]. Therefore, the land breeze does not form easily due to the small land area of the city. The Xinghai Bay, part of the Yellow Sea, is in the south of the study area, and the shortest distance from the study area to the Bohai Sea in the north is 20 km. Sea breezes often penetrate the city from both south and north at the same time, similar to many other peninsulas [19,51,52].

Meanwhile, in a mountainous peninsula city like Dalian, the sea breeze is substantially affected by the terrain. The terrain of the study area is quite complex, as it is mainly composed of three hilly areas (Fig. 1(c)). The Dading Mountain in the northwest has tree ridges, and the highest altitude is 250 m. There is an isolated mountain (Fuguo Park) with a height of 180 m in the centre of the study area. The eastern mountain is a part of Dalian Forest Zoo with an altitude of 190 m. The flattest area is the Xinghai Square and the Malan River valley in the east, where the wind breeze has lower resistance. The height of mountains in the city is between 100 m and 300 m, which indicates that most of the time, the intensity of the mountain-valley breeze is not