CLASSIFICATION OF VERTICAL PROFILES OF WIND VELOCITY AND TEMPERATURE IN TOKYO AREA USING WRF RESULTS AND CLUSTER ANALYSIS

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ABSTRACT

Sea breeze in summer has an effect of mitigating heat island phenomena in coastal urban areas. The effect depends on the characteristics of the sea breeze, especially the vertical distributions of wind velocity and temperature. In order to take full advantage of using the sea breeze in urban planning for mitigating heat island phenomena, it is necessary to understand the characteristics of the sea breeze. The authors investigated the vertical profiles of velocity and temperature in sea breeze using meteorological data from meso-scale numerical simulation for the area of Tokyo. The profiles were classified into eight representative patterns by using cluster analysis, and hence the frequency of occurrence for each pattern was investigated, and also the relationship to weather condition for each pattern was clarified.

Key Words: Urban heat island, Sea breeze, Meso-scale modeling, Cluster analysis

1. INTRODUCTION

Urban heat island effects have been observed in many cities located near the Japanese coast. Many researchers have reported various countermeasures for mitigating heat island phenomena. The approach is to control the heat balance within urban areas to reduce overheated air temperature¹)~⁹). One strategy is to utilize sea breeze by leading cool air into urban canopies. However, the effectiveness of this strategy depends on the characteristics of the sea breeze, particularly the vertical profiles of wind velocity and temperature. Thus, it is necessary to understand the characteristics of sea breeze. Recently, CFD simulations have been applied to real urban cities in order to examine the effects of various countermeasures to heat island phenomena⁷)~⁹). However, such simulations require appropriate vertical profiles at the inflow boundary, which is another reason to investigate the vertical profiles of wind velocity and temperature. Furthermore, if we can obtain some representative profiles and their occurrence frequencies, they could be used for statistical long term evaluation of wind and thermal environment (not just one moment or one day). Many field observation researches have shown that the vertical profile of mean wind speed under strong wind conditions follows a power law relationship. However, the vertical profile under weak wind conditions, in which heat island phenomena become severe, has not yet sufficiently been clarified. Although many studies have been conducted in Tokyo area that address the characteristics of the sea breeze by observations and meso-scale simulations¹)¹⁰), the information is limited to some specific days. In this study, meso-scale simulation was conducted from August 1st to August 31st of the years 2006, 2007, and 2008 in the area of Tokyo in order to obtain spatial distributions of velocity and temperature data. Based on the obtained data, the vertical patterns of velocity and temperature were classified using cluster analysis and the occurrence frequencies of the patterns were examined.

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2. OUTLINE OF MESO-SCALE SIMULATION

The Weather Research and Forecasting Model (WRF) is a next-generation meso-scale numerical weather prediction system designed for serve both operational forecasting and atmospheric research needs. It has been developed by the national Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), and the National Centers for Environmental Prediction (NCEP), etc. In this study, the Advanced Research WRF (ARW) dynamic solver was used for obtaining spatial distribution of wind velocity and temperature. NCEP global analysis data (resolution; 1°), real-time global sea surface temperature analysis data (resolution; 0.5°), Moderate Resolution Imaging Spectroradiometer (MODIS) 20-land use category, and USGS topographic data were used for the initial and boundary conditions. The default physical parameterizations of the WRF were used, and some of the representative physical parameterizations are shown in Table 1. With regards to urban area (from MODIS land use data), single layer urban canopy model (SUCM) proposed by Kusaka\(^{11}\) was adopted. The SUCM default settings for commercial area were used for the simulation. The roughness length of the urban area was set as 0.5 m according to MODIS 20-land use dataset. However, these parameters should be further examined, which will be studied in our future work, for more appropriate parameter settings in order to reflect the real situation of Tokyo area, which will be done in our future works.

The simulation was run in 3-nested domains as shown in Figure 1 and Table 2. The grid widths of the 3 domains were 9 km, 3 km and 1 km, respectively. The vertical computational domain was up to 20 km high and it was divided into 55 vertical levels (28 levels from surface to 2 km high) with non-uniform distribution. Target points for the investigation are shown in Figure 1. Two points were selected for comparing the vertical patterns of wind velocity and temperature on the sea and inland. The inland point (P1) is located in the center of Tokyo with an observation point of wind velocity on a high-rise building. The observation data were used for validating the WRF simulation. The observation height was 96m from the ground, and until 2009, the approaching wind was well recorded as no high-rise buildings were around the observation points. The simulation was performed from August 1\(^{st}\) to August 31\(^{st}\) of the years 2006, 2007, and 2008. Every 10-minutes data of each point were extracted from the output of WRF calculation. In this study, we only focused on the Y-component (south-to-north component) of the wind velocity because wind direction around south-to-north was predominant during summer in Tokyo. The Y-component of all wind velocity data (144×93days = 13,392 data at 28 vertical levels from surface to 2 km high) were used for the cluster analysis, which will be described in the next section.

3. OUTLINE OF CLUSTER ANALYSIS

Cluster analysis is a convenient method for grouping large amounts of data into categories that have similarity between them. Ward’s method\(^{13}\) was selected for the clustering procedure in this study. Ward’s approach is based on the sum of the squared deviation within a cluster. The first step in classifying the vertical profile of the wind velocity using Ward’s method is to make a matrix of velocity data and obtain the sum of squares between every two sets of data as follows.
\[ S_{ij} = \sum_{i=1}^{n} (V_{ik} - \bar{V}_k)^2 + (V_{jk} - \bar{V}_k)^2 \]  

(1)

where, \(i\) and \(j\) represent time, \(k\) represents vertical height level; \(V_{ik}\) = velocity component in south-to-north direction at height \(k\), at time \(i\); \(V_{jk}\) = velocity component in south-to-north direction at height \(k\), at time \(j\); \(\bar{V}_k\) = average velocity at height \(k\) between times \(i\) and \(j\). \(\bar{V}_k = (V_{ik} + V_{jk}) / 2\); \(n = 28\) (total number of height level for clustering, from surface to 2 km high).

Two sets of data of which \(S_{ij}\) was the smallest were merged into a cluster. After that, two sets of clusters (or data) were merged so as to increase the sum of squares \(\Delta S\) become smallest.

\[ \Delta S = S_{AB} - S_A - S_B, \quad S_A = \sum_{j=1}^{n_A} \sum_{k=1}^{n} (V_{A,j,k} - \bar{V}_{A,k})^2, \quad S_B = \sum_{j=1}^{n_B} \sum_{k=1}^{n} (V_{B,j,k} - \bar{V}_{B,k})^2, \quad S_{AB} = \sum_{j=1}^{n_A} \sum_{k=1}^{n} (V_{AB,j,k} - \bar{V}_{AB,k})^2 \]  

(2)

where, \(S_A\) and \(S_B\) = sum of squares in clusters \(A\) and \(B\). (if \(A\) or \(B\) is not a cluster but data, \(S_A=0, S_B=0\)), \(S_{AB}\) = sum of squares in cluster \(AB\) (merged clusters of \(A\) and \(B\)), \(n_A\) = number of data in cluster \(A\), \(n_B\) = number of data in cluster \(B\), \(V_{A,j,k}\) = velocity component in south-to-north direction at height \(k\) and at time \(j\) in cluster \(A\), \(\bar{V}_{A,k}\) = average velocity at height \(k\) in cluster \(A\).

This procedure was continued until all the clusters were merged into one cluster. In this study, velocity data at the sea point was analyzed by the cluster analysis, but the temperature data at the sea point and both velocity and temperature data at inland point (P1) was not examined by the cluster analysis. They were treated as the reference of the velocity at the sea point.

4. RESULTS

4.1 COMPARISON OF WRF RESULTS AND OBSERVATION DATA

Figure 2 shows comparison of the WRF results with observation data at P1 (see fig.1, observation height: 96 m) from August 16th to August 31st of 2006. The wind speed and wind direction calculated by WRF are in approximate agreement with the observation data. Figure 3 shows the vertical profiles of 1-hour averaged wind speed of WRF and observation data at Katsuura. The observation data were obtained from Wind profiler Network and Data Acquisition System (WINDAS) of Japan Meteorological Agency. The vertical profiles of wind speed calculated by WRF agree well with those of the observation. Although Figure 3 shows only three examples, most of the other calculated results among the whole period were in overall agreement with the observation results.
4.2 DETERMINATION OF THE NUMBER OF CLUSTERS

Figure 4 shows the cumulative sum of squares for each number of clusters. The cumulative sum of squares has large increment for smaller cluster number, which implies the loss of characteristics of the clusters. It would be appropriate to determine the number of clusters at the moderate change along the curve of cumulative sum of squares. Thus, eight clusters were selected as the reasonable number of clusters for this investigation.

4.3 VERTICAL PROFILE AND OCCURRENCE FREQUENCY OF EACH CLUSTER

The results of cluster analysis for August of 2006, 2007, and 2008 are shown in Figures 5 to 8 in which the average and standard deviation of velocities and temperatures in four representative clusters, with the occurrence frequency of each cluster are given. (Other four clusters are not shown in this paper due to the limitation of pages.) In these figures, positive and negative values in wind velocity indicate south-to-north and north-to-south direction, respectively.

In Figure 5, cluster 1 illustrated a weak wind pattern at both the sea and the inland locations. The wind pattern at sea location represented the beginning of sea-breeze pattern. The occurrence frequency of cluster 1 was 16.1% of all clusters, and 50% of cluster 1 occurred between sunrise (5:00AM) and noon (12:00AM).

In Figure 6, average wind velocity of cluster 2 over the sea increased up to 60 m height and then decreased with height above 60 m. For inland location, the average velocity increased up to 200 m height. The maximum average wind velocity of cluster 2 decreased from sea to inland and the wind direction reversed over 1.4 km from the surface. The difference between the temperatures of sea and inland was 3.3°C near the surface (lowest vertical height, 12.6m). This pattern frequently occurred in the afternoon on sunny or cloudy (from weather map of JMA) with the highest occurrence frequency (20.2%) of all clusters. Thus, the pattern of cluster 2 is considered to be a typical sea breeze circulation.

In cluster 3 (Figure 7), the sea breeze layer was thicker and the velocity was higher than those of cluster 2. The temperature difference between sea and inland for cluster 3 was 5.4°C near the surface (lowest vertical height, 12.6m), which was higher than that of cluster 2. This pattern mostly occurred after cluster 2 in the afternoon on very hot sunny days (from weather map of JMA) and it had 14.7% occurrence frequency.

The pattern of cluster 4 is shown in Figure 8. Cluster 8 was reversed wind pattern (wind blows from north to south in lower vertical levels). It frequently occurred from the beginning of the night through the morning and the occurrence frequency was 17.0%. According to the weather map of Japan Meteorological Agency, this pattern was dominating on those days which are effected by the high pressure in the north of Japan territory.
Figure 5. Average and standard deviation of velocity and temperature profiles for cluster 1 with diurnal occurrence distribution (●: Velocity, ▲: Temperature)

Figure 6. Average and standard deviation of velocity and temperature profiles for cluster 2 with diurnal occurrence distribution (●: Velocity, ▲: Temperature)

Figure 7. Average and standard deviation of velocity and temperature profiles for cluster 3 with diurnal occurrence distribution (●: Velocity, ▲: Temperature)

Figure 8. Average and standard deviation of velocity and temperature profiles for cluster 4 with diurnal occurrence distribution (●: Velocity, ▲: Temperature)
5. CONCLUSIONS

Meso-scale simulation was conducted for the area of Tokyo for the months of August of 2006, 2007, and 2008 to obtain spatial distribution of wind velocity and temperature data. Using the obtained data, we classified the vertical patterns of wind velocity and temperature in sea breeze by cluster analysis. The frequency of occurrence of each pattern was investigated and the relationship to weather condition of each pattern was clarified. It was found that eight clusters were captured the possible vertical patterns of sea breeze in the area of Tokyo for summer. The four representative clusters were shown in this paper. The cluster 2 and 3 were considered to be typical sea breeze circulation in which the wind direction was reversed over 1 km, and their total occurrence frequency was about 35% in all analyzed period. This study is a new challenge to clarify the vertical patterns of wind velocity and temperature in Tokyo using WRF results and cluster analysis. However further investigations are necessary for more appropriate WRF parameter settings in order to reflect real situation of Tokyo area and more appropriate classification methods, which will be done in our future works. After these investigations, we would like to propose the general function of each pattern in the future study.

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