NOTES AND CORRESPONDENCE

Numerical Experiments on the Weak-Wind Region Formed Ahead of the Sea-Breeze Front

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Abstract

A weak-wind region, whose horizontal scale is comparable to that of an urban area, is occasionally formed ahead of the sea-breeze front, over a large coastal urban area (Yoshikado and Kondo 1989; Yoshikado 1990; Ohashi and Kida 2001). In this study, the characteristics and the formation mechanism of the weak-wind region were investigated, using a 2D mesoscale atmospheric model. The following results were obtained:

The weak-wind region is created by the development of the heat-island circulation over the urban area; the heat-island circulation (i.e., the urbanward pressure-gradient-force) weakens the inlandward ambient wind during the morning hours. At that time, the sea-breeze circulation is inessential in creating this weak-wind region. The weak-wind region cannot be created under the influence of the seaward ambient wind. Subsequently, the weak-wind region is persistently formed ahead of the sea-breeze front, and gradually moves inlandward. A long-term balance between the urbanward pressure-gradient-force, and the turbulent mixing, causes such a phenomenon. Thus, interactions among the sea-breeze circulation, heat-island circulation, and inlandward ambient wind play an important role in the above processes. The spatial scale of the weak-wind region strongly depends on the urban size (width), i.e., the spatial scale of the heat-island circulation developing over the urban area, during the daytime hours.

1. Introduction

Over an urban area adjacent to the sea, a sea-breeze circulation (hereinafter SBC) penetrating from the sea is most likely affected by the urban area (e.g., Takano 1977; Patrinos and Kistler 1977; Savijarvi 1985). In the Kanto plain, including the Tokyo metropolitan area, the inland penetration of the SBC front often stagnates over the inland periphery of the ur-

ban area, which was reported by Yoshikado and Kondo (1989, hereinafter YK89) and Yoshikado (1990, hereinafter Y90). Subsequently, a weak-wind region is formed ahead of the SBC front, over the inland suburban area. Y90 suggested a possibility of the urban heat-island effect that corresponds to a horizontal pressure difference between the urban and suburban areas. Also, over the Osaka plain, including a large urban area, Ohashi and Kida (2001, hereinafter OK01) observed a weak-wind region (wind speeds of less than 2 m s^{-1}) found just ahead of the inlandward moving SBC-front. The horizontal scale of weak, wind regions, observed in both the Tokyo and Osaka urban areas, was comparable to that of each urban area.

Yoshikado (1992, hereinafter Y92) simulated a SBC penetrating over an urban area adjacent

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to the sea, assuming the Kanto plain to be a two-dimensional situation. Y92 pointed out that the stagnation of the SBC-front penetration was caused by interactions between the SBC and the heat-island circulation (hereinafter HIC); as a result, a weak-wind region was created ahead of the SBC front. OK01 referred to the weak-wind regions mentioned above as *SRISH* (the Stagnant Region due to the Interaction between the Sea-breeze and Heat-island circulations), because these weak-wind regions probably form in association with the SBC and HIC.

However, the following two problems remain on the formation of the *SRISH*: 1) very few *SRISH*s are observed; there were only 3 *SRISH*-days in the Tokyo urban area, confirmed by YK89 and Y90, and only 1 day in the Osaka urban area, reported by OK01; 2) the experiments of Y92 were conducted assuming calm conditions, i.e., no synoptic winds; under such a situation, the *SRISH* cannot be identified and separated from the surrounding calm regions; therefore, it is difficult to explain the relationship between the urban size and the spatial scale of the *SRISH*; 3) although the above researchers suggested that the formation of the *SRISH* was related to the existence of an urban area, the formation mechanism of the *SRISH* is not still clarified for the present.

Consequently, we will here investigate the characteristics of the *SRISH*—especially, the dependence of the *SRISH* scale on urban size—and the formation mechanism of the *SRISH*.

2. Numerical model

The mesoscale atmospheric model developed by Ohashi and Kida (2002) was modified into the 2D version and was used for the current purpose. Basic equations used in the model are based on an incompressible fluid and are employing the hydrostatic approximation. Descriptions of the model in detail are summarized in Table 1. The schematic diagram of the model is depicted in Fig. 1. The total horizontal domain is 160 km with a grid interval of 2 km. While the sea region extends from the left edge of the model to 50 km, the land region from the coastline to 110 km, with an urban area adjacent to the sea. In the atmospheric region, 30 layers are assigned at heights of 3, 10, 30, 70, 150 to 1550 m with a 100-m interval, 1550 to 2550 m with a 200-m interval, and 2550 to 4950 m with

a 400-m interval. On the other hand, the soil region is divided into 5 layers assigned at depths of 0.05, 0.15, 0.40, 0.90, and 1.40 m.

The initial conditions for potential temperature, and relative humidity, are taken from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis data at 0300 LST at 35°N, 135°E (near the northern Osaka plain), on a certain clear and calm day in summer. For the sea-surface temperature, use is made of the Advanced Very High Resolution Radiometer (AVHRR) data from the National Oceanic Atmospheric Administration (NOAA) satellite at 1432 LST on the same day over Osaka Bay. The spatially averaged value over Osaka Bay is 27.8°C, which is fixed in time during the period of the model calculation.

The bottom boundary has a nonslip condition. The top boundary also has a nonslip condition, except that the scalar variables have a zero-gradient condition. At the lateral boundaries, a modified Orlanski (1976) radiation condition as proposed by Miller and Thorpe (1981), given as the two-level scheme, is used to allow the propagation of gravity waves through the interior model walls. The upper-half region of the model corresponds to a sponge layer, which can absorb the gravity-wave energy generated in the lower layers (Klemp and Lilly 1978).

The urban and suburban areas are assumed to consist of the buildings and fields, respectively. Calculations of the surface fluxes require parameters of the surface properties, such as the roughness length, albedo, and moisture availability, in each land-use type. The parameters, which are shown in Table 2, are adopted from values listed by Anthes et al. (1987), and Seaman et al. (1989). The size (width) of urban area, L , varies over the range between 6 and 38 km.

3. Experimental results

3.1 Formation of the *SRISH*

As can be seen in Fig. 2, there are differences in the vertical structures of the SBCs between the case with an urban area ($L = 14$ km, hereinafter Case [SBC, HIC]), and the case with no urban area (hereinafter Case SBC). When an urban area exists (Fig. 2b), the SBC front becomes clearer and the depth of the SBC more increasing than those for no urban area (Fig.

Table 2. Parameters of the surface properties.

	Roughness Length (m)	Albedo	Moisture Availability	Soil Heat Capacity ($\times 10^6 \text{ J/m}^3 \cdot \text{K}$)	Soil Thermal Diffusivity ($\times 10^{-7} \text{ m}^2/\text{s}$)
SUBURBAN AREA	0.10	0.17	0.50	2.11	5.30
URBAN AREA	1.00	0.20	0.05	2.11	7.20
SEA	Charnock (1955) and Wu (1980)		1.00		

2a). The HIC develops ahead of the SBC front and gradually moves inlandward with penetration of the SBC. These features are the same as those indicated by the Y92's experiments (cf., their Fig. 14). As was described in section 1, Y92 pointed out the formation of the SRISH over the inland suburban area, although the experiments were conducted assuming calm conditions, i.e., no ambient winds; if under the calm conditions, the SRISH cannot be identified and

separated from the surrounding calm regions, as the result of Case [SBC, HIC] indicates.

In the OK01's observation, a wind shear in height existed in the early morning prior to the appearance of the SRISH. The synoptic-scale wind, which was the same direction as the penetration of the SBC, prevailed in the upper layers during the daytime hours. The next experiments use the observational data of OK01 for the ambient wind (hereinafter AW) of the

Fig. 2. Vertical cross-sections of the wind vectors at 1300 LST for the cases (a) with no urban area under the calm condition, (b) with the urban area under the calm condition, (c) with no urban area under the influence of ambient winds, and (d) with the urban area under the influence of ambient winds. The urban size L is 14 km, which is nearly the same size as the Osaka urban area. Contour lines indicate the potential temperature for every 0.5°C .

Fig. 3. Vertical cross-sections of the wind vectors of (a) Case [HIC, AW] and (b) Case [SBC, HIC, AW], at 0900 LST (left) and 1300 LST (right). The light dotted-line shown in the right figure of (b) indicates the location of vertical profile in Fig. 4.

model, which linearly increases from 0 m s^{-1} at the ground surface to 5 m s^{-1} at a height of 1000 m. Figures 2c and 2d show results of the case with the inlandward AW. When no urban area exists (Fig. 2c, hereinafter Case [SBC, AW]), the SBC front is unclear due to the AW, and the wind distribution is almost uniform in the horizontal direction. When the urban area exists (Fig. 2d, hereinafter Case [SBC, HIC, AW]), however, the SBC front clearly appears around $X = 72 \text{ km}$, and a weak-wind region (defined as a region of weak winds compared with the surrounding regions, in the current study) is created just ahead of the SBC front. The weak-wind region appears in the early morning over the inland periphery of the urban area and subsequently moves inlandward with penetration of the SBC. At 1300 LST (Fig. 2d), this region can be distinctly separated from the surroundings and has spatial scales of about 500 m in depth, and 10–15 km in width. After this time, the weak-wind region gradually re-

duces both in the vertical and horizontal scales. This weak-wind region is defined here as the SRISH. Then, it is not until winds surrounding the SRISH exist that the SRISH can be found out, as shown in Fig. 2d. The surrounding winds correspond to the synoptic-scale winds in the Osaka observations reported by OK01, and the large-scale valley-winds (i.e., the plain-to-plateau wind system, Maunnouji 1982) in the Kanto observations reported by YK89 and Y90.

3.2 Formation Mechanism of the SRISH

We will here discuss the mechanism of that the SRISH is formed ahead of the SBC front and subsequently moves inlandward, as mentioned before. Figure 3 shows the vertical cross-sections of wind vectors of Case [HIC, AW] (i.e., only with the HIC and AW) and Case [SBC, HIC, AW]. At 0900 LST (left panels), a weak-wind region gradually develops over the inland periphery of the urban area, for both Case [HIC, AW] (Fig. 3a) and Case [SBC, HIC, AW] (Fig.

Fig. 4. Vertical profiles of each term of Eq. (1) for Case [SBC, HIC, AW], at 34 km from the coastline (the light dotted-line in Fig. 3b) at 1300 LST. The straight solid-line indicates zero values.

3b). At this time, the SBC does not contribute most to form the weak-wind region. Therefore, the origin of this weak-wind region is probably different from the SRISH, because as described in section 1, the SRISH should be created by the interaction between the SBC and HIC.

At 1300 LST (right panels), the features of the two cases are obviously different from each other. In the result of Case [HIC, AW], a weak-wind region can be found inland at a distance of about 30 km from the HIC convergence-zone appearing at the periphery of the urban area. Additionally, the lower part of the HIC clearly appears over the suburban area. On the other hand, in Case [SBC, HIC, AW] a weak-wind region is clearly formed just ahead of the SBC front, and gradually moves inlandward with penetration of the SBC front, which is consistent with the observational features; it means that the SBC is essential in forming and moving this weak-wind region at the stage. This weak-

wind region, formed ahead of the SBC front, can be considered as the SRISH, because as mentioned above, the SRISH should be created by the interaction between the SBC and HIC. A weak-wind region, which is created by both of the HIC and AW, gradually evolves into the SRISH as the SBC develops and moves inlandward. Therefore, all of the SBC, HIC, and AW are required for the formation of the SRISH.

In Case [SBC, HIC, AW], the SRISH moves inlandward with penetration of the SBC. We now investigate the mechanism of that the SRISH persistently exists ahead of the SBC front for many hours. Figure 4 shows the term balance for the horizontal momentum equation:

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - w \frac{\partial u}{\partial z} - \theta \frac{\partial \pi}{\partial x} + \frac{\partial}{\partial z} \left(K \frac{\partial u}{\partial z} \right) + fv, \quad (1)$$

ACCE HADV VADV HPRE VMIX

where each symbol is conventional. The ACCE on the left-hand side of Eq. (1) is the horizontal velocity acceleration. On the right-hand side, HADV, VADV, HPRE, and VMIX are the horizontal advection, vertical advection, horizontal pressure gradient, and vertical mixing terms of the horizontal velocity, respectively. The last term is the Coriolis force and can be neglected in this study. As can be seen in Fig. 4 which indicates the time when the SRISH appears, HPRE and VMIX within the SRISH (i.e., the height of less than ~500 m) are dominant among the terms, and the two terms balance each other; this results in the ACCE becoming nearly zero within the SRISH. Figure 5 denotes the temporal variations of each term of Eq. (1) at the same position as Fig. 4, but for a height of 200 m. For the result of Case [SBC, HIC, AW] (Fig. 5a), from around 1100 LST the absolute value of HPRE, which is dominant among the terms, becomes greater than that of VMIX which is another dominant term. This situation produces a seaward motion (the negative value of ACCE) and consequently works to weaken an inlandward AW; the process creates a weak-wind region. In the afternoon, an increment of the absolute value of HPRE becomes slow gradually. Subsequently, the magnitude of HPRE is nearly as large as that of VMIX for 1–2 hours. This situation produces a quasi-steady motion (the zero value of ACCE) and consequently works to maintain the weak-wind region; the

Fig. 5. Temporal variations of each term of Eq. (1) for (a) Case [SBC, HIC, AW] and (b) Case [SBC, AW], at the same location as Fig. 4 but for at a height of 200 m.

process plays an important role in the inlandward moving weak-wind-region with penetration of the SBC front. The result of Case [SBC, AW] which has no urban area is also indicated in Fig. 5b. From the comparison between Fig. 5a and Fig. 5b, values of HPRE and VMIX, which are found in Case [SBC, HIC, AW], prior to the arrival (1500–1530 LST) of the SBC front, are produced by the existence of the urban area. The negative value of HPRE is due to the horizontal pressure-gradient-force against the sea breeze, which is generated by the pressure difference between the urban and suburban areas. On the other hand, the positive value of VMIX is possibly due to the downward transport of the momentum of AWs, by the turbulent mixing associated with the development of the mixed layer during the daytime, and the frictional force over the land.

3.3 Dependence of the SRISH scale on urban size

Figure 6 shows the relationship between the spatial scale of the SRISH and the urban size L . It is noteworthy that the maximum develop-

ing-scale of the SRISH obviously depends on L , as the figure indicates. The maximum vertical scale (Fig. 6a) of the SRISH becomes logarithmically increasing as the urban area extends. Meanwhile the maximum horizontal scale (Fig. 6b) of the SRISH linearly increases with L until $L = 22$ km and is comparable to that of the urban area. This relation becomes insignificant, as long as the urban area is greater than 22-km size. The time when the SRISH scale reaches a maximum is also delayed with L . Both horizontal and vertical scales of the HIC are strongly subject not to the heat-island intensity but to the heat-island scale (Kimura 1975; Arita et al. 2000). Additionally, the intensity of interactions between the SBC and HIC becomes invariant when L exceeds 20 km (Yoshikado 1994). These facts support that the formation of the SRISH closely relates to the development of the HIC. Consequently, the spatial scale of the SRISH is determined by an urban size L , namely, the developing scale of the HIC.

In the Kanto plain, the vertical and horizontal scales of the observed SRISHs were 500–600 m and about 20 km, respectively, at around mid-

Fig. 6. Relationships between (a) the vertical scale of the SRISH and the urban size, and (b) the horizontal scale of the SRISH and the urban size. The solid line denoted in (a) is a logarithmic fitting curve.

day (YK89; Y90). As can be seen in Fig. 6, the experiments on the cases with the urban sizes of 30–38 km, which are comparable to the Tokyo urban size, show that the vertical and horizontal scales of the model SRISH grow similarly to those observed in the Tokyo urban area. In the experiments in which the urban size is assumed to be the Osaka one (10–18 km), the vertical and horizontal scales of the model SRISH are 300–500 m, and 12–16 km, respectively. The horizontal scale of the observed SRISH was 7–18 km (OK01), which is nearly the same as those of the simulated SRISH, whereas the vertical scale of the observed SRISH was occasionally twice greater than that of the simulated SRISH. Because the Osaka plain is narrow and

surrounded with mountains, the geographical complex distribution of the urban areas, mountains, and sea plays more important role in local circulations, compared with the Kanto plain; for example, the valley circulations, which develop over the surrounding mountains, more or less possibly affect the SRISH structure during the daytime.

4. Summary and conclusions

A weak-wind region formed ahead of the sea-breeze front was so far reported by the urban observations (Yoshikado and Kondo 1989; Yoshikado 1990; Ohashi and Kida 2001). Its horizontal scale was comparable to that of the urban areas. We investigated the characteristics and the formation mechanism of the weak-wind region, using a 2D mesoscale atmospheric model.

The weak-wind region is created by the development of the heat-island circulation (HIC) over the urban area; the HIC (i.e., the urbanward pressure-gradient-force) weakens the inlandward ambient wind (AW) during the morning hours. At that time, the sea-breeze circulation (SBC) is inessential in creating this weak-wind region. The weak-wind region cannot be created under the influence of the seaward AW. Subsequently, the weak-wind region is persistently formed ahead of the SBC front, and gradually moves inlandward. A long-term balance between the urbanward pressure-gradient-force and the turbulent mixing causes such a phenomenon. Thus, interactions among the SBC, HIC, and inlandward AW play an important role in the above processes; the weak-wind region found at this stage can be considered as “the stagnant region due to the interaction between the SBC and HIC” (SRISH), as was mentioned in section 1.

The spatial scale of the SRISH strongly depends on the urban size (width), i.e., the spatial scale of the HIC developing over the urban area during the daytime hours. Pollutants emitted from a coastal urban area concentrate in the upper levels over suburban areas and advance inland, due to the existence of the SRISH (Yoshikado 1994). Therefore, it can be considered that the spatial scale of the SRISH affects a height at which the maximum concentrations of pollutants appear; this height probably increases with the vertical scale of the SRISH.

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