NOTES AND CORRESPONDENCE

Interaction of the Sea Breeze with Urban Heat Islands of Different Sizes and Locations

By Hiroshi Yoshikado

National Institute for Resources and Environment, 16-3 Onogawa, Tsukuba, Ibaraki 305, Japan
(Manuscript received 26 July 1993, in revised form 25 October 1993)

Abstract

The interactions of the sea breeze with urban heat islands (UHI) are examined with use of a two-dimensional numerical model. The strength of the interaction depends on the intensity of the sea breeze, the intensity of the heat island circulation that develops over the inland side of the urban area, and the penetrating speed of the sea breeze. These factors are basically controlled by three characteristics of the urban area—the size or width, the distance from the sea, and the intensity of the UHI.

1. Introduction

Numerous investigations have been devoted to the urban heat island (UHI) effect—the higher air temperatures found in urban areas or cities compared with those of the surrounding area. Most studies of the UHIs have dealt with those that develop during nighttime, since they are more clearly defined. Recently, the importance of the daytime UHI has been recognized in view of the relationships with human activity and the urban environment.

The present author has examined the following characteristics of daytime UHIs (Yoshikado, 1992; hereafter referred to as Y92). When the basic field is calm, its depth is often much greater than that of the nighttime UHI, even if the daytime UHI is only just observable at ground level. Therefore, the daytime UHI can induce local circulations of larger scale than the nighttime UHI. However, if the basic field is not calm, the UHI circulation is readily distorted and dissipated as the velocity of external flow increases. For this reason the UHI circulation, or corresponding convergent flows near the surface, are not very often detected during the daytime when large-scale flows tend to prevail.

In contrast with the cases with large-scale flows, the daytime UHI can persist under the influence of the sea breeze, and interacts with the sea breeze. The most important point is that the sea breeze

front tends to remain over the city due to the UHI effects. This tendency can cause convergent flow patterns (*e.g.*, see Fujibe and Asai, 1980) to appear more frequently and clearly over coastal cities.

In Y92, a two-dimensional model was used to simulate the interaction between the sea breeze and the UHI, roughly corresponding to the conditions for Tokyo. The major observed features were well simulated. The present work attempts to clarify the features of the system when the variables pertaining to the city are changed, namely, when the size, the distance from the shore, and the heating anomaly of the city differ from the Tokyo case.

2. Numerical model

The numerical model employed here is based on the NIRE mesoscale model (Kondo, 1989) as was used in Y92. Yasuraoka (1993) performed a comparative test of four boundary-layer models, including the present model, and obtained satisfactory agreement among the results for the same heating conditions that occur during a calm daytime.

The structure of the present experiments is as follows. A Cartesian coordinate system is used with the x axis aligned from the sea inland, the y axis parallel to the shoreline, and the z axis upward. All properties are assumed to be homogeneous in the y direction, *i.e.*, $\partial/\partial y = 0$.

Calm conditions and a thermal stratification of $\partial\theta/\partial z = 0.007 \text{ K m}^{-1}$ are taken as the basic field,

Fig. 1. The given pattern of surface potential temperature, for (a) Temporal variations, and (b) the horizontal distribution.

Fig. 2. Diurnal variations of the sea breeze component u at a height of 100 m along the x axis, from the shore to a point 70 km inland, for (a) the control case with no city, and (b) the case with the city width of $L = 24$ km.

where θ is the potential temperature.

The mesh sizes are $\Delta x = 2$ km and $\Delta z = 50$ m, with the depth of the surface layer being 50 m. The sea surface is represented by 40 grid points, where $\theta = \theta_s$, a constant value of 298 K. A total of 60 adjoining grid points serves as the land, which experiences a diurnal variation $\theta = \theta_s + 10 \sin w(t - 6)$, where t is the local time (LT) in hours. From five to 22 consecutive grid points of the land surface are assumed as the city, where the number of points is changed corresponding to the size of the city in each experiment. The urban temperature excess represented by $\Delta\theta$ is specified throughout the day (Fig. 1).

The time integrations start with a quasi-equilibrium state corresponding to 0600 LT, at which time the surface temperature is uniform except for the city, and continue until 1800 LT.

3. Results

3.1 Control case without the UHI

A control experiment consisting of the pure sea

breeze was first performed by specifying a uniform land surface, *i.e.*, $\Delta\theta = 0$. The maximum sea breeze component u appears near the shore at 1500 LT. After the maximum u is reached, the surface stress reduces over the land, and another maximum appears in the gravity current-like inland low near 1800 LT (Fig. 2a). The latter has a value of about 5.7 ms^{-1} and is almost invariable, even when $\Delta\theta > 0$ is specified. The value of the former maximum is denoted as $u_{\max}$ in the following cases.

3.2 Effect of the UHI intensity

The intensity of the UHI is varied by specifying different values for $\Delta\theta$. As shown in Fig. 3b, $u_{\max}$ gradually increase as $\Delta\theta$ increases. The explanation of this relationship can be given as follows for a sufficiently large city located along the shore. The increase in $\Delta\theta$ values directly results in an increase in the land-sea temperature difference, which intensifies the sea breeze.

The vertical velocity in the circulation also increase with $\Delta\theta$. The maximum vertical velocity,

Fig. 3. The distributions of (a) $w_{\max}$ and (b) $u_{\max}$ as a function of the UHI intensity, $\Delta\theta$, for the cases with the city located along the shore and a width of $L = 24$ km.

$w_{\max}$, is attained in the convergence zone of the sea breeze and the UHI circulation growing over the inland side of the city. The appearance time of $w_{\max}$ is around 1200 LT, which is earlier than that of $u_{\max}$, although fairly large deviations occur from case to case. A sharp increase in $w_{\max}$ occurs when $\Delta\theta$ exceeds 1.5 K (Fig. 3a), in which case the sea breeze front is distinctly defined. In other words, a smaller value of $\Delta\theta$ induces a weaker UHI circulation, while the sea breeze is also weaker and the time it takes to penetrate the urban area is longer, and therefore they only slightly interact. When $\Delta\theta$ has a value of about 1.5 K, the UHI circulation becomes intense enough not to be overwhelmed by the sea breeze and the convergence zone is maintained. However, the value of 1.5 K is not definitive for such changes to occur, but probably varies when the size of the city changes.

Additionally, the increase in the surface heat flux due to the specification of $\Delta\theta > 0$, when averaged over the width of the city, is approximately proportional to $\Delta\theta$. The excessive urban heating accumulated from 0600 to 1800 LT was 7.53 MJm^{-2} for $\Delta\theta = 1.5$ K, 2.34 MJm^{-2} larger than that of the control case.

3.3 Effect of the size of the UHI

When a city located along the shore expands in the inland direction, $u_{\max}$ increases only gradually as the city width L increases (Fig. 4b). As in the previous sub-section, $u_{\max}$ basically depends only on the sea breeze, whereas $w_{\max}$ represents the extent of the interaction of the sea breeze and the UHI circulation.

The value of $w_{\max}$ sharply increases over the range of L between 10 and 20 km (Fig. 4a). Major changes in the flow pattern occur in this area; a stagnant region persists on the inland side of the city, apparently preventing the sea breeze from advancing inland, whereas the sea breeze front becomes more definite and develops to a deeper extent (Fig. 2b). Here, $\Delta\theta$ was set at 2 K and uniform over the city. If this value increases, the range of L over which the

Fig. 4. The distributions of (a) $w_{\max}$ and (b) $u_{\max}$ as a function of the city width, L , for the cases with the city located along the shore (solid lines). The dashed lines indicate the cases with the city of the same width as the cases indicated by the solid triangles on their left ends but at various distances from the shore. In all cases, $\Delta\theta = 2$ K.

flow pattern changes can shift to somewhat smaller values, and *vice versa*.

When L exceeds 20 km, the increase in $w_{\max}$ lessens and $w_{\max}$ then decreases, because both circulations make contact in their decaying stage during the afternoon. The ultimate values of $u_{\max}$ and $w_{\max}$ when L is sufficiently large are 5.3 ms^{-1} and 0.39 ms^{-1} , respectively, for $\Delta\theta = 2$ K.

Variations in the lowest (50 m) temperature at the point 30 km from the shore (referred to as Point A) are shown in Fig. 5. For the case with $L = 24$ km, the point becomes warmer compared with the control case (corresponding to $L = 0$), and the temperature anomaly is maintained at 1 K, even at 1800 LT. This difference arises from the delay of inflow air of the sea breeze and, even after it arrives, the urban heating that the sea breeze experiences. Furthermore, adiabatic heating or cooling that accompanies vertical motions influence the temperature pattern in a complicated manner.

When $L = 36$ km, it is consistently warmer than in the control case, which is natural since Point A is now located within the city. An interesting result is that when $L = 24$ km, almost the same high temperature occurs as in the case of $L = 36$ km after 1500 LT or so. Namely, over the inland suburban area, the delay of the sea breeze due to the UHI effect causes a warmer evening as if the city had been expanded to that area.

In contrast with the inland expansion of the city that results in the above-mentioned change in the temperature variation, seaward expansion can also

Fig. 5. Diurnal variations of the potential temperature at the lowest level (50 m), at a point 30 km inland (bold lines). The city widths in km are indicated for the various lines. The thin dash-dotted line represents the variation at the 42 km point for the case of $L = 36$ km. In all cases, the city is located along the shore and $\Delta\theta = 2$ K.

be assumed. In this case, the position of Point A changes from 30 km to 42 km from the shore. In Fig. 5, the temperature variation at the 42 km point (B) is also indicated. The warmer evening is further remarkable, and it is concluded that seaward expansion of urban areas can affect the inland climate more significantly than urbanization of the inland area.

3.4 Effect of the distance from the shore

The results from the cases in which the city is located away from the shore are also exhibited in Fig. 4.

As mentioned above, when the city is located along the shore, the urban temperature excess increases the land-sea temperature contrast, intensifying the sea breeze. As the city is shifted inland, the UHI effect on the sea breeze intensity is reduced, so that $u_{\max}$ gradually decreases to the value found in the control case.

However, $w_{\max}$ increases to some extent as the distance from the shore increases, for the smaller values of L . This behavior can be interpreted as follows. Large values of $w_{\max}$ are expected when the sea breeze and the UHI circulation on the inland side of the city make contact in their mature stage. When the city is small and located along the shore,

the UHI circulation does not develop sufficiently before the sea breeze arrives. When the city is located some distance from the shore, the UHI circulation can develop further.

4. Concluding remarks

Although realistic predictions of the UHI effect for any particular area can be obtained by modeling the detailed topography and other conditions, here the fundamental features have been examined with the use of a two-dimensional model.

For some large urban areas, situations can occur such that the average surface air temperature is higher by about 2 K, or the accumulated daytime heating larger by about 3 MJm^{-2} than those found in the surrounding areas. When such heavily urbanized regions exceed 10 km in width, the interaction between the UHI and the sea breeze becomes significant and influences the local climate. The inland advance of the sea breeze is delayed and the upward motion associated with the sea breeze front is intensified. Other important effects follow, such as the alteration of the mixed-layer height and the transformation of the structure of the urban air pollution, although these features are beyond the scope of the present study.

Acknowledgements

The author wishes to express thanks to his colleague, Dr. H. Kondo who produced the original version of the NIRE mesoscale model. The numerical computations were performed on the FACOM M780 of the RIPS in the Agency of Industrial Science and Technology, MITI.

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大きさや位置の異なる都市ヒートアイランドと海風の相互作用

吉門 洋

(資源環境技術総合研究所)

2次元局地循環モデルにより、海風と都市ヒートアイランド循環の相互作用の基本的な性質を調べた。相互作用の状態は、都市の大きさ(幅)、海岸からの距離、都市と郊外の温度差、の三つをパラメータとする以下の三つの要素—海風、および都市の内陸側にできる循環の発達度合、海風がそこに到達する速度—に支配される。