Effects of Mountains and Urban Areas on Daytime Local-Circulations in the Osaka and Kyoto Regions

Yukitaka OHASHI and Hideji KIDA

Department of Geophysics, Graduate School of Science, Kyoto University, Kyoto, Japan

(Manuscript received 21 November 2001, in revised form 25 February 2002)

Abstract

In the current study, the effects of topography and urbanization on the daytime local-circulations in the area of the Osaka–Kyoto plain were investigated using a mesoscale atmospheric model. The main results obtained from the numerical and observational data analyses are as follows:

1) The stagnation of the inland penetration of the sea-breeze front that occurs in the peripheral portion of the Tokyo urban area does not clearly occur in the peripheral portion of the Osaka urban area. The stagnation is attributed to the heat-island circulation that develops over the peripheral portion of the urban area. Because the northern peripheral portion of the Osaka urban area faces mountains, the valley circulation weakens the heat-island circulation; the about 600-m mountains surrounding the Osaka and Kyoto urban areas are the most suitable to cause the weakening of the heat-island circulation. The valley circulation also induces the surface-air-temperature increase over the plain, through an adiabatic process due to its downward flow; the temperature increase strengthens the horizontal pressure gradient between the sea-breeze circulation and inland areas.

2) The surface air over the suburban region between the Osaka and Kyoto urban areas remains drier than that over the Osaka and Kyoto urban areas, until the arrival of the sea-breeze front, even though urban areas were thought to be drier than suburban areas. This dryness results from the fact that the valley circulation transports drier air downward from the upper levels over the suburban area, and transports the surface-air moisture supplied from the ground surface into mountainous areas. The valley circulation also appears to play an important role in the transport of pollutants from the suburban area into mountainous areas.

3) A chain flow, which flows downward from the upper levels over the Osaka urban area to the lower levels over the Kyoto urban area, forms ahead of the sea-breeze front. This flow can result in the transport of pollutants emitted from the Osaka urban area into the inland Kyoto area prior to the transport of pollutants by the sea-breeze circulation. Additionally, the chain flow intensifies the downward flow of the valley circulation over the suburban region between the Osaka and Kyoto urban areas.

1. Introduction

During the daytime hours, local circulations, such as sea-breeze and valley circulations (referred to as SBC and VC, respectively), can develop in most regions of Japan. Such circulations will be influenced by the geometrical and thermal properties of a ground surface: buildings, paddies, forests and so on. Large urban areas exist over the Kanto and Nohbi plains in Japan, which can influence the local circulations that develop in these regions.

From observational and 2D-model experimental results, Yoshikado and Kondo (1989) and Yoshikado (1992) clarified that the deformation of the SBC which penetrates from...
Tokyo Bay was due to the Tokyo metropolitan area. Interactions between the SBC and the heat-island phenomenon caused the vertical wind speed of the SBC front and the depth of the SBC to increase, as compared with those without an urban area. Additionally, it was pointed out that a landward flow can be found in upper levels (~1 km) over the suburban area ahead of the SBC front; it appears as if the sea-breeze layer rises over the suburban area. Using a quasi-real 3D-model that included the Kanto plain and its surrounding areas, Kusaka et al. (2000) examined the effects of urbanization on the behavior of the SBC penetrating from Tokyo Bay. Results suggested that the SBC front remained stagnant for a long period of time due to the seaward horizontal pressure-gradient force opposing the SBC around the city of Saitama, located between the urban and suburban areas. Yoshikado and Kondo (1989) and Yoshikado (1992) also observed and simulated the stagnation of the SBC penetration.

Kitada et al. (1998) simulated the local wind and thermal environment over the Nohbi plain to investigate the influence of urbanization in the region. As the urban area was extended inland in the model, the zone of the daily maximum temperature gradually moved toward the inland suburban area. It was considered that as the mixed layer strongly developed over the peripheral portion of the urban area, corresponding to the convergence zone of the SBC and heat-island circulation (referred to as HIC), the air mass in this area was warmed via the top entrainment and the inlandward horizontal transport of heat emitted from the urban area by the SBC.

As mentioned above, the existence of urban areas affects the structure and behavior of the local circulations. The local circulations, in turn, control the temporal and spatial variations of temperature, humidity, and the concentration of air pollutants over the urban and its surrounding areas. Thus, it is important to investigate and clarify the interactions between the local circulations and the heat-island phenomenon.

The Osaka plain has a large urban area, similar to those found in the Kanto and Nohbi plains. For convenience, the northern portion of the Osaka plain, including the Kyoto basin area, is hereinafter referred to as the Osaka–Kyoto plain. The effects of the urban area on the structure and behavior of the local circulations in this region have not been well established, although observational and numerical studies were so far conducted by a number of researchers (e.g., Eguchi 1977; Mizuma 1995; Itoh 1995; Uno et al. 1996). Ohashi and Kida (2001) observed the structure of the SBC over the northern Osaka urban area, and suggested that the deformation of the SBC was due to this urban area. That is, a weak-wind region, with a horizontal scale equal to that of the urban area, formed ahead of the SBC front and moved inland with the SBC penetration. A similar feature also appeared in the SBC structure over the Kanto plain (Yoshikado and Kondo 1989; Yoshikado 1990). Subsequently, Ohashi and Kida (2002b), via numerical experiments, explained the relationship between the formation of the weak-wind region and the existence of an urban area.

In the Osaka–Kyoto plain, the SBC, which penetrates from Osaka Bay during the morning hours, passes over a large urban area and reaches within the Kyoto basin area by evening. This region has two geographic features not found in the Kanto and Nohbi plains. First, the plain gradually narrows toward inland regions (see Fig. 1). Second, two large urban areas, the cities of Osaka and Kyoto, exist on the plain, separated by some distance (see Fig. 2a). These features will affect meteorological conditions and air pollution, as well as the structure and behavior of the local circulations. The use of a mesoscale atmospheric model and numerous observational data will clarify how the above features are related to the local circulations in the Osaka–Kyoto plain, and how meteorological features differ from those that appear in the Tokyo and Nohbi urban areas.

2. Model descriptions

The mesoscale atmospheric model developed by Ohashi and Kida (2002a) was used in the current study. Descriptions of the model (the Dry Atmospheric Regional Demonstrations, referred to as DryARD) are summarized in Table 1. The DryARD employs land-use data, having a horizontal resolution of 100 m², with the land-use types divided into 11 categories. The calculations of surface fluxes require various parameters of the land-use properties, such
as the roughness length, albedo, and moisture availability. The land-use parameters employed in this study are listed in Table 2. The surface flux in each category is calculated by means of the bulk method. The weighted averages of the fluxes over a 2-km² area are estimated from the occupation rate of the land-use categories, according to Kimura (1989).

The temporal and spatial variations of anthropogenic heat are also considered in the current study. The anthropogenic heat is emitted from building site A which means large and tall buildings (skyscrapers, high-rise apartment complexes, etc.), and the transport site, at a height of \( z^* = 20 \text{ m} \). The anthropogenic heat data compiled by Shimoda et al. (1998) for the Osaka urban area and Morita (1993) for Kobe and Kyoto were used.

The model domains used in this study are presented in Fig. 1. The two-type domains, narrow and broad regions, are employed to examine the effects of the extended sea-breeze (Itoh 1995) on meteorological conditions in the Osaka–Kyoto plain. Figure 2 shows the land-use conditions for the Osaka–Kyoto plain and its surrounding areas. The areas consist mainly of building site A, building site B (small buildings such as family residence, etc.), rice paddy, and forest. It should be noted that two heavily urbanized areas are located on the Osaka–Kyoto plain—the Osaka urban area adjacent to Osaka Bay, and the Kyoto urban area located inland at a distance of 25–30 km from the peripheral portion of the Osaka urban area.

The simulation was started at a model time of 0300 LST 29 July, during the summer season. Initial conditions for potential temperature and relative humidity were taken from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis data, at 35\(^\circ\)N, 135\(^\circ\)E at 0300 JST on 29 July 1992. The initial wind condition was calm, and no synoptic-scale winds were assumed during the calculated model time. For the sea-surface temperature, use was made of the 29 July 1992 Advanced Very High Resolution Radiometer (AVHRR) data, from the National Oceanic Atmospheric Administration (NOAA) satellite at 1432 JST over Osaka Bay. The spatially averaged value over Osaka Bay was determined as 27.8\(^\circ\)C. The sea-surface temperature was fixed in time to this value, since the diurnal variation of the sea-surface temperature is small. On the above chosen date, the Osaka–Kyoto plain was under clear-sky and calm conditions.
3. Characteristics of the wind field and model validation

3.1 Observational data

The model validation should be verified by a comparison between the calculated results obtained from the DryARD and those observed from routine observatories, which clarify the characteristics of the actual meteorological fields. For the analysis, use was made of observational data which consist of wind, temperature, relative humidity, and the concentration of pollutants from the Air Quality Monitoring System (AQMS), along with wind, temperature, and the duration of sunshine from the Automated Meteorological Data Acquisition System (AMeDAS). The locations of the observational sites are indicated in Fig. 3. The aerological wind data at Shionomisaki and Yonago (see Fig. 1) were also used in the analysis.

Because focus is centered on the behavior of local circulations under calm conditions, the observational data should be chosen with the use of certain criteria. Two criteria for the choice of clear-sky and calm days, when local circulations will develop, are established as follows: 1) more than 6-hours duration of sunshine occurred at all of the Osaka, Hirakata, and Kyoto
AMeDAS sites; 2) wind speeds were less than 5 m s\(^{-1}\) at the 850-hPa level, at both 0900 and 1500 JST at the Shionomisaki and Yonago sites. Criterion 1) means that sufficient surface heating will be required to develop local circulations during the daytime. Takada and Tanaka (1996) reported that when the wind speeds were greater than 15 m s\(^{-1}\) at the

<table>
<thead>
<tr>
<th>Table 1. Specifications of the DryARD model (Ohashi and Kida 2002a).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Governing Equations</strong></td>
</tr>
</tbody>
</table>
| **Coordinate and Grid Structure** | • \(z^*\) coordinate and Arakawa-C staggered grid system.  
Vertical: 30 layers at heights of 3, 10, 30, 70, 150, \(\cdots\), and 4950 m.  
Horizontal: 2 km-grid size. |
| **Numerical Schemes and Smoothing** | • Finite-difference method.  
Temporal: Leap-frog solution for horizontal terms, 
and fully implicit solution for vertical terms.  
Spatial: Centered difference.  
• Time filter (Robert 1966), and 4th-order linear horizontal diffusion.  
• Top: No slip, and zero gradient for scalars.  
• Bottom: No slip, and surface temperature is diagnostically calculated 
from the surface heat-budget.  
• Lateral: Modified Orlanski's radiation condition (Miller and Thorpe 1981). |
| **Subgrid-Scale Turbulent Model** | • \(E-\varepsilon\) model (1.5-order closure).  
TKE and its dissipation rate are predicted.  
Parameters given by Takagi and Kitada (1994 and 1998) are used. |
| **Surface Fluxes** | • Bulk method.  
Stable: Approximate solution using Beljaars and Holtslag’s formula (Lee 1997).  
Unstable: Approximate solution using Dyer’s formula (Lee 1997). |
| **Atmospheric Radiations** | • Shortwave: Including Rayleigh scattering (Kondo 1976; Kimura 1984).  
• Downward longwave: Empirical formula (Kondo 1976). |
| **Soil Model** | • Multi-layered model (the heat-conduction equation).  
5 layers at depths of 0.05, 0.15, 0.4, 0.9, and 1.4 m |
| **PBL Height** | • Diagnostically calculated from the gradient Richardson number, 
including the frictional velocity (Vogelezang and Holtslag 1996) |
| **Pollutants Transport Model** | • Lagrangian particle dispersion model (LPDM),  
according to the Markov-chain process (McNider 1981; McNider et al. 1988) |
| **Others** | • Sponge layer above the height of 2450 m (Klemp and Lilly 1978)  
• Time increment: 10 sec. |
850-hPa level, local circulations did not develop in the Kinki district, including the Osaka–Kyoto plain. Around the Okayama plain area (located ~120 km west of the Osaka plain; see Fig. 1b), when the wind speeds at the 600-hPa level were less than 5 m s\(^{-1}\), the behavior and structure of the SBC were not deformed by synoptic-scale winds (Sahashi 1978). The use of criterion 2) is expected to extract days during which the SBC is not deformed. These criteria were applied to observational data over the months of July and August for the years 1992–1996. As a result, 14 days were chosen as clear-sky and calm days when the local circulations well developed in the Osaka–Kyoto plain.

3.2 Features of local winds near the ground surface

The temporal variations of observed winds are exhibited in Fig. 4 (the vectors on the upper lines). These are shown as the ensemble (14 days) average with the criteria employed as mentioned above. The indicated sites (see Fig. 3) are located along a line in the direction of the penetration of the SBC from Osaka Bay. It is clear that the SBC gradually penetrates inlandward from the Konohana site (Fig. 4a) near the coast to the inland Shimamoto site (Fig. 4d). The typical wind speed and direction of the observed sea-breeze are about 3 m s\(^{-1}\) and west or southwest, respectively. From the observational data, the penetrating speed of the SBC from Osaka Bay to the inland Kyoto area is estimated as 0.6–1.7 m s\(^{-1}\). On the other hand, the Mibu site (Fig. 4e), which is located the furthest inland of sites in Fig. 4, has a peak wind speed (~2 m s\(^{-1}\)) at noon. When the model urban areas are replaced with forests (the bottom-most line in Fig. 4e, and later termed the 3Dno experiment), no such peak appears and a quite weak (less than 1 m s\(^{-1}\))
southeasterly wind is persistently formed until sunset. Therefore, it is concluded that the southerly wind, which appears when urban areas exist, can be considered as a heat-island wind flowing into the city of Kyoto during the daytime. The heat-island wind was also confirmed by Tanaka (1984), being observed over the southern portion of the city of Kyoto, from midnight to the morning hours during the fall season. It is noteworthy, therefore, that the development of the heat-island wind can be statistically confirmed, even during the daytime on calm-summer days.

3.3 Model validation

The comparison between the observed and calculated data, prior to discussions concerning the model results, is conducted here. Figure 5 shows the comparison between the observed (the AMeDAS and AQMS sites located only over the plain area) and calculated daytime (from 0700 to 2000 LST) average wind-speeds and temperatures near the ground surface. The figure indicates that the calculated field agrees

---

**Figure 4**
Temporal variations of the observed horizontal-wind vectors (the upper lines; the mean value under calm conditions) at (a) Konohana, (b) SuitaW, (c) Ibaraki, (d) Shimamoto, and (e) Mibu sites, whose locations are shown in Fig. 3. The calculated horizontal-wind vectors (the lower lines) are shown for five grid-points: the grid-point (center) corresponding to the above-mentioned observational sites and four grid-points (east, west, south, and north) adjacent to the center grid-point. The bottom-most line in (e) is the result of the calculated 3Dno case (with no urban areas).

**Figure 5**
Scatter diagrams of the daytime (from 0700 to 2000 LST)-mean observed values versus the daytime-mean calculated values for (a) the wind speed and (b) the temperature near the ground surface. The various symbols (see the figure legend on the right) indicate the regions denoted in Fig. 3. The arrows indicate AMeDAS sites.
well with that observed (the correlation coefficients for the wind speed and temperature are 0.65 and 0.58, respectively). The calculated grid-point temperatures corresponding to the AMeDAS sites are quite consistent with those observed, whereas those corresponding to the AQMS sites are, to a small extent, underestimated as a whole. This is probably related to differences in the methods of measurement—for example, sampling methods, the type of instruments used, and the measurement environment—between the AMeDAS and the AQMS.

In Fig. 4, the temporal variations of the calculated winds (the vectors on the lower lines) and averaged observed-winds (the vectors on the upper lines) near the ground surface, at the sites within the Osaka–Kyoto plain, are displayed. The calculated wind variations indicate that the penetration of the SBC from Osaka Bay (Figs. 4a–d) and the daytime heat-island wind found in the city of Kyoto (Fig. 4e), as mentioned previously, are in good reproduction, as can be seen compared with the observed wind-variations. The horizontal distributions of the calculated surface-wind and temperature during the daytime hours are displayed in Fig. 6. These calculated results are considered as the standard run, and are referred to as the 3Dall case. From the above comparisons, it is concluded that the DryARD model can reproduce the meteorological features which appear in the Osaka–Kyoto plain not only qualitatively, but also quantitatively.

3.4 The extended sea-breeze
Itoh (1995), making use of a numerical model, demonstrated that an extended sea-breeze appeared in the Kinki region. Under clear-sky and calm conditions, this wind system, having a vertical scale of ~1 km, will entirely cover the Kinki region from Kii Channel, from late afternoon to midnight (Itoh and Kawazoe 1983; Mizuma 1985). Itoh suggested that the relative locations of the Japan Sea and the Kii and Tsurugi mountain districts produced a large-scale horizontal pressure-gradient, which resulted in the formation of the extended sea-breeze. It is important to examine how the extended sea-breeze interacts with the meteorological elements in the Osaka–Kyoto plain. Therefore, two types of model domain were employed, as shown in Fig. 1. They consist of the narrow domain that includes the Osaka–Kyoto plain, which alone cannot form an extended sea-breeze, and the broad domain that additionally includes the Japan Sea and the Kii and Tsurugi mountain districts, which can then form the extended sea-breeze.

Differences in the wind and temperature distributions between the results obtained from the narrow and broad domains at sites A and B (see Fig. 1) were examined. Site A is located in southern part of Awaji Island; the extended sea-breeze remarkably affects the wind and temperature variations at this site after 1500 LST (not shown). Site B, located on the Osaka plain, however, is not affected by the extended sea-breeze until sunset (not shown). Since the objectives of time and space in the current study are in the Osaka plain area during the daytime hours, the results obtained from the narrow domain are sufficiently valid. Consequently, the only use of the narrow domain experiments will be made in the following sections. Case runs conducted in this study are listed in Table 3.

4. Heat and moisture transport by the VC

4.1 Surface variations
Temporal and spatial variations of the calculated temperature (contours) and specific humidity (shading) near the ground surface for the 3Dall case are displayed in Fig. 7. This figure shows the following two features: a zone of maximum temperature appears in the Suita area and gradually moves inlandward with penetration of the SBC front; a relatively dry-air zone can be found in the inland suburban area ahead of the portion of the above-mentioned maximum-temperature zone. The dry-air zone appears over the suburban area between the coastal Osaka and inland Kyoto urban areas, although the air over urban areas is generally thought to be drier than that over suburban areas during the daytime (e.g., Aida et al. 1979; Oke 1988; Sakakibara 2001) if the advection is not considered. Subsequently, the surface air over the coastal Osaka urban area is affected by the SBC moisture with penetration of the SBC front, whereas the air over the suburban area is drier than that over the inland Kyoto urban area, which is still not influenced by the SBC. The mechanism for the formation
Fig. 6. Horizontal distributions of the wind vectors (left) and air temperature (right) at the height of $z' = 20$ m, for (a) 1200 LST, (b) 1400 LST, and (c) 1600 LST. The drawn region corresponds to the dashed square in Fig. 1a. Topographic contour-lines are drawn with a 200-m interval, and the degree of shading indicates the temperature (see the figure legend on the right).
of such temperature and moisture distributions will now be investigated.

From the observational data (Fig. 8), it is also revealed that the suburban areas between the northern Osaka and Kyoto urban areas—for example, the west Suita (SuitaW) and the south Takatsuki (TakatsukiS) sites—display drier conditions relative to the other regions during the daytime hours. The dry area exhibits a large amplitude in the diurnal change of water-vapor pressure. This feature implies that the suburban area is possibly affected

Table 3. List of experiments conducted in the current study.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Model Dimensions</th>
<th>Land-Use and Anthropogenic Heat</th>
<th>Topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D cases</td>
<td>2D model</td>
<td>See Fig. 15a</td>
<td></td>
</tr>
<tr>
<td>3Dall</td>
<td>3D model</td>
<td>Yes</td>
<td>Realistic</td>
</tr>
<tr>
<td>3Dflat</td>
<td>3D model</td>
<td>Yes</td>
<td>Flat</td>
</tr>
<tr>
<td>3Dno</td>
<td>3D model</td>
<td>No</td>
<td>Realistic</td>
</tr>
<tr>
<td>3Dflat-no</td>
<td>3D model</td>
<td>No</td>
<td>Flat</td>
</tr>
<tr>
<td>3Dhigh</td>
<td>3D model</td>
<td>Yes</td>
<td>50% increase in mountain height</td>
</tr>
</tbody>
</table>

Fig. 7. Horizontal distributions of the air temperature (contours) and specific humidity (shading, see legends on the right) near the surface, at (a) 1000 LST, (b) 1200 LST, (c) 1400 LST, and (d) 1600 LST. The regions drawn correspond to the dashed square in Fig. 1a. The dashed contour lines indicate a 200-m interval of topography. The dotted lines indicate the location of the sea-breeze front.
Fig. 8. Temporal variations of the mean water-vapor pressure under calm conditions, at various observational sites.
by local circulations which have a different mechanism from those in the coastal and inland urban areas. Figure 9 displays the temporal variations of the calculated temperature and specific humidity near the ground surface, at grid locations corresponding to the Sennari site in the coastal urban area (Fig. 9a), the TakatsukiS site in the inland suburban area between the Osaka and Kyoto urban areas (Fig. 9b), and the Mibu site in the inland urban area (Fig. 9c). When making a comparison between the 3Dflat (i.e., flat topography, dashed lines) and 3Dall cases (solid lines), it appears that mountains influence the diurnal variations of the meteorological elements, except for those at the coastal Sennari site. That is, the VCs, which develop over the mountains that surround the plain, most likely heat and dry the lower atmosphere over the plain. At the TakatsukiS site, the range of the diurnal change of moisture is greater than that at the other sites. This feature is consistent with that of the observed moisture (i.e., Fig. 8).

From examining Fig. 9, another feature can also be found; even in the case of no mountains (3Dflat), the atmosphere over the inland suburban TakatsukiS site is drier than that found over the inland urban Mibu site during the daytime hours. This fact suggests that the dryness over the suburban area between the Osaka and Kyoto urban areas can be attributed not only to the VCs, but also to another factor which will be discussed in section 5.2.

4.2 Heat and moisture budgets
To assess the heat budget over the peripheral portion of the Osaka urban area, which is surrounded by mountains, the accumulated sensible-heat in an atmospheric column ($Q_C$) and from the ground surface ($Q_H$), from 0700
LST to time $t$, can be calculated by

$$Q_H(t) = \int_{\theta_h}^{t} SH(t) \, dt,$$

(1)

and

$$Q_C(t) = c_p \rho \int_{z_t}^{z_g} [\theta(z, t) - \theta_{\text{ht}}(z)] \, dz.$$

(2)

Here, $c_p$ is the specific heat of air at constant pressure, $\rho$ the air density, $z_g$ the ground height, $z_t$ the height of the model top, and $SH(t)$ the surface sensible-heat flux. The symbol $\theta$ represents the potential temperature, and $\theta_{\text{ht}}(z)$ denotes the vertical profile of potential temperature at 0700 LST. The temporal variations of $Q_C(t)$ and $Q_H(t)$ at the grid point corresponding to the TakatsukiS site, which is located near the peripheral portion of the Osaka urban area, are shown in Fig. 10. In the 3Dflat case (Fig. 10a), the magnitude of $Q_C$ is smaller than that of $Q_H$ during the daytime hours, which suggests that the heat supplied from the ground surface diverges from the atmospheric column, or relatively colder air flows into the atmospheric column. The results reported by Kusaka et al. (2000), for the same analysis over the peripheral portion of the Tokyo urban area in the Kanto plain, were similar to those mentioned above (see Fig. 12 in Kusaka et al. 2000). This similarity is attributed to the fact that the Tokyo urban area extends over a large plain with no nearby mountains. On the other hand, for the 3Dall case (Fig. 10b) in the peripheral portion of the Osaka urban area, the magnitude of $Q_C$ is greater than that of $Q_H$. That is, the heat converges from the surrounding areas into the atmospheric column.

To clarify the sensible-heat transport described above, it is required to know the air motions in the suburban region between the Osaka and Kyoto urban areas. For this objective, Fig. 11 shows a trajectory analysis carried out with the Lagrangian Particle Dispersion Model (LPDM), until 1300 LST, which is prior to the arrival of the SBC front at the corresponding area. The trajectories drawn in this figure indicate the paths of the parcels within a 5-km width in the horizontal direction from the location of the cross section shown by the dash-dot line in Fig. 1a. The parcel marked by the symbol ▲, emitted near the ground surface over the plain around the suburban Hirakata area, is transported toward the mountain area located to the north until noon. The parcel marked by the symbol ○, released over the mountain area, is transported upward toward the upper levels. In the suburban area the parcel, marked by × emitted in the upper levels over the plain, is transported to near the ground surface by downward flow of the compensating air. These results indicate that upper-level air with high potential temperature and low specific humidity moves downward to near the ground surface, while moisture supplied from the ground surface is transported toward the mountains.

The downward transport of air appears to be related not only to the compensating flow of the
VC, but also to a combination of the turbulent mixed layer and quasi-mixed layer (as referred to by Kuwagata and Kimura 1997). The quasi-mixed layer develops due to subsidence heating by the downward flow of the VC. The apparent mixed layer is formed by the connection between the upper quasi-mixed layer and the lower turbulent-mixed layer. As a result, the height of the entire mixed layer is greater than that of an ordinary mixed layer, i.e., the lower turbulent-mixed layer. The combination of layers allows the upper air to be rapidly transported downward, as indicated in the rapid downward-motion of the upper-level parcel over the plain from 1100 to 1200 LST (the symbol $U$ in Fig. 11).

In Table 4, the mountain and urban contributions to the sensible- and latent-heat budgets, at the grid location corresponding to the Takatsuki site, are listed. In this table, $Q_{CS}$ denotes the accumulated sensible-heat defined by Eq. (2), while $Q_{CL}$ is the accumulated latent-heat calculated by

$$Q_{CL}(t) = \lambda \rho \int_{z_s}^{z_f} [q(z,t) - q_{7h}(z)] dz.$$  \hfill (3)

Here, $\lambda$ is the latent heat of water vaporization, and $q$ represents the specific humidity. The difference between the accumulated sensible- and latent-heat of the 3Dflat (with urban areas and no mountains) and 3Dflat-no (with forests instead of the urban areas, and no mountains) cases measures the influence of urbanization on the atmosphere; the difference between the 3Dall and 3Dflat cases indicates the influence of mountains. Both urbanization and mountains work to heat and dry the atmosphere. As can be seen in the ratio of $\Delta Q_{CS}$ (3Dflat–3Dflat-no) to $\Delta Q_{CS}$ (3Dall–3Dflat), the noontime atmospheric heating due to mountains is, to some extent, less than that due to urbanization. On the other hand, the dryness due to mountains is about twice as large as that due to urbanization. On the other hand, the dryness due to mountains is about twice as large as that due to urbanization, from the ratio of $\Delta Q_{CL}$ (3Dflat–3Dflat-no) to $\Delta Q_{CL}$ (3Dall–3Dflat). That is, these results imply that urbanization and mountains play main roles in the heating and drying of the atmosphere, respectively, in the Osaka–Kyoto plain.

4.3 Influence on atmospheric pollutants

The VC that develops around the suburban region between the Osaka and Kyoto urban areas also appears to affect the behavior of atmospheric pollutants. Figure 12 shows the
temporal variations in the hourly time rate of change of the suspended particulate matter (SPM) concentration observed on 27 July 1995, under calm conditions.

With respect to the concentration of pollutants, the Osaka–Kyoto plain can be divided into three areas:

1) The coastal Osaka urban area (Fig. 12a) found within region III (see Fig. 3). Here, the SPM concentration is invariant or, to a small extent, decreases with time, except that the arrival of the SBC front is accompanied by an increase in the SPM concentration.

2) The suburban area between the Osaka and Kyoto areas (Fig. 12b) found within region IV (see Fig. 3). In this area, the decrease in the SPM concentration prior to the arrival of the SBC front is more notable than in the other regions. As can be seen in Fig. 12b, this causes the SPM concentration to rapidly increase when compared with the coastal urban area (Fig. 12a), at the arrival of the SBC front. Concerning the magnitude of the SPM concentration, until around 1000 JST the value of the concentration over the suburban area is comparable to or somewhat greater than those over the coastal and inland urban areas; at 1400 JST the concentration over the suburban area, e.g., Takatsuki S, are reduced to 35 and 50% of those over the coastal and inland urban areas, e.g., Sennari and Mibu, respectively (not shown). The decrease of the SPM concentration prior to the arrival of the SBC front may be attributed to the VC. This phenomenon is due to the same mechanism as the transport of the heat and water vapor as described in the previous section; that is, less polluted air from upper levels is transported downward to near the ground surface by the compensating current of the VC, while polluted air is transported into the mountain area, as was shown in the trajectory analysis in Fig. 11. This phenomenon probably suppresses an increase in the accumulating concentration of anthropogenic pollutants that are emitted from the corresponding area.

3) The inland Kyoto urban area (Fig. 12c) found within region V (see Fig. 3). Here, no decrease in the SPM concentration such as those appearing in the suburban area occurs, and the SPM temporal variations are irregular.

Similar features appear in variations of the SO\textsubscript{2} concentration (not shown), whereas they do not occur in variations of the NO\textsubscript{x} and O\textsubscript{3} concentrations. It should be noted that NO\textsubscript{x} and O\textsubscript{3} can be produced or destroyed by photolysis and chemical reactions during the daytime.

Table 4. Accumulated sensible \(Q_{CS}\) and latent \(Q_{CL}\) heats (MJ/m\(^2\)) for each hour over the peripheral portion of the Osaka urban area for the various cases.

<table>
<thead>
<tr>
<th>LST</th>
<th>3Dflat-no</th>
<th>3Dflat</th>
<th>3Dall</th>
<th>3Dflat - 3Dflat-no</th>
<th>3Dall - 3Dflat</th>
<th>ΔQ\textsubscript{CS}</th>
<th>ΔQ\textsubscript{CL}</th>
<th>ΔQ\textsubscript{CS}</th>
<th>ΔQ\textsubscript{CL}</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.39</td>
<td>0.73</td>
<td>0.59</td>
<td>-0.69</td>
<td>+0.34</td>
<td>-1.16</td>
<td>+0.16</td>
<td>-0.30</td>
<td>1.55</td>
</tr>
<tr>
<td>10</td>
<td>0.68</td>
<td>1.26</td>
<td>1.28</td>
<td>-1.62</td>
<td>+0.58</td>
<td>-2.01</td>
<td>+0.87</td>
<td>-2.84</td>
<td>1.30</td>
</tr>
<tr>
<td>11</td>
<td>0.99</td>
<td>1.68</td>
<td>2.32</td>
<td>-2.73</td>
<td>+0.87</td>
<td>-2.84</td>
<td>+0.67</td>
<td>-5.05</td>
<td>1.23</td>
</tr>
<tr>
<td>12</td>
<td>1.30</td>
<td>2.46</td>
<td>3.67</td>
<td>-3.97</td>
<td>+1.16</td>
<td>-3.60</td>
<td>+0.93</td>
<td>-7.46</td>
<td>1.25</td>
</tr>
<tr>
<td>13</td>
<td>1.57</td>
<td>3.02</td>
<td>5.32</td>
<td>-4.70</td>
<td>+1.45</td>
<td>-4.11</td>
<td>+1.18</td>
<td>-10.02</td>
<td>1.23</td>
</tr>
<tr>
<td>14</td>
<td>1.79</td>
<td>3.50</td>
<td>8.64</td>
<td>-2.44</td>
<td>+1.71</td>
<td>-2.72</td>
<td>+1.58</td>
<td>-11.08</td>
<td>1.08</td>
</tr>
<tr>
<td>15</td>
<td>1.91</td>
<td>3.84</td>
<td>12.33</td>
<td>+0.47</td>
<td>+1.93</td>
<td>-0.47</td>
<td>+1.84</td>
<td>-10.53</td>
<td>1.05</td>
</tr>
<tr>
<td>16</td>
<td>1.96</td>
<td>3.93</td>
<td>15.72</td>
<td>-0.57</td>
<td>+1.97</td>
<td>+1.80</td>
<td>+1.74</td>
<td>-16.29</td>
<td>1.13</td>
</tr>
</tbody>
</table>

August 2002
Y. OHASHI and H. KIDA
5. The SBC penetrating from Osaka Bay

5.1 Penetrating speed of the SBC front

Figure 13 shows the distance of the inland penetration of the SBC front from Osaka Bay for several experimental cases and observations. As shown in this figure, the estimated penetrating speed for the 3Dall case is rather consistent with that observed (the mean value under calm conditions). In the experiment with no mountains (3Dflat), the inland penetration of the SBC front stagnates for approximately 2 hours in the afternoon around Suita, which is located in the northern peripheral portion of the Osaka urban area. On the other hand, in the experiment with no mountains and no urban areas (3Dflat-no), no such stagnation of the SBC front appears. The stagnation is caused by the heat-island wind, having an opposing direction to that of the sea breeze, which also appeared over the Kanto plain including the Tokyo urban area (Yoshikado and Kondo 1989; Yoshikado 1990; Kusaka et al. 2000). In the 3Dall case, no stagnation of the SBC front at Suita appears, and the front speed is greater than that in the 3Dflat-no case. Therefore, it is suggested that the mountains surrounding the Osaka–Kyoto plain, including the urban area, prevent the stagnation of the inland penetration of the SBC front. Two reasons for the acceleration of the SBC front are proposed in the following.

First, the inland penetration of the SBC front is accelerated due to inland atmospheric heating. As mentioned in the previous section, day-
time sensible-heat is supplied not only from the ground surface, but also from upper levels due to the local subsidence by the downward flow of the VC in a valley area (Kondo et al. 1989; Kugawata and Kimura 1995, 1997). Additionally, since the atmospheric volume in a valley area is generally smaller than that over a plain because of the surrounding mountains (e.g., Whiteman 1990), the air within the valley is warmed more than that over the plain by the sensible-heat supply from the ground surface. These effects combine to result in the atmospheric heating in a valley area being greater than that over a plain. This creates a greater depression in an inland surface-pressure (Fig. 14) relative to that in the case with no mountains. Consequently, the horizontal pressure-gradient force between the SBC front and an inland area ahead of the front then increases. From consideration of the theory of gravity currents (e.g., Benjamin 1968; Simpson 1969), it is thought that an increase in the density difference between the gravity and ambient currents accelerates the penetration of the gravity current, namely, the SBC. As can be seen from the results of the 3Dhigh case, the thermal effect of the mountains depends on the mountain height. The surface-pressure depression during the daytime hours increases as the mountain height is extended (Fig. 14). Therefore, the penetration of the SBC front is accelerated, as shown in Fig. 13.

Second, the inland penetration of the SBC front will accelerate due to the weakening of the HIC resulting from the development of the VC. To understand this phenomenon, it is important to examine how the HIC weakens, and the relationship between the degree of weakening of the HIC and the mountain height. The elucidation of this relationship through the previous 3D-experiments is difficult, due to the complex topography. To readily understand this effect, use was made of the 2D-version of the DryARD, which is assumed to be the simplest configuration and placement of urban and mountain areas, as schematically shown in Fig. 15a. The initial and boundary conditions given in the 2D experiments are the same as those in the previous 3D-experiments. Figure 15b shows the temporal variations of the horizontal wind speed around the peripheral portion of the urban area at a height of $z^* = 200$ m. The positive and negative values denote flows toward the mountain (hereinafter, the mountainward wind) and toward the urban area (hereinafter, the urbanward wind), respectively. As can be seen in the comparison among the 2Dflat and the other cases, mountains tend to weaken the urbanward wind, or change the urbanward wind to a mountainward wind. This results from the fact that the HIC, which is formed between the urban and forest areas, is directly weakened by the VC, since the wind directions of the HIC and VC oppose each other. Although the mountainward wind speed tends to increase with mountain height, it becomes insignificant at heights greater than 600 m. The mountainward wind found for the 600-m mountain height is the most persistent; this wind works to accelerate the SBC penetration. In the Osaka–Kyoto plain, mountains with heights of 500–600 m above ground level are found adjacent to the northward peripheral portion of the Osaka urban area. Consequently, the VCs developing over the mountains near the Osaka–Kyoto plain most effectively weaken the horizontal convergence of the HICs, which would decelerate the inland penetration of the SBC. In the afternoon, the urbanward winds develop gradually, as shown in the cases with urban and mountain areas. Lee and Kimura (2001) revealed that in the afternoon the local...
circulation induced by land-use difference predominates rather than that induced by topography. Over the Osaka–Kyoto plain, since the SBC covers the peripheral portion of the Osaka urban area in the afternoon, the local circulation induced by land-use difference, i.e., the HIC in the current study, disappears at that time.

The effect of this weakening of the HIC cannot be explained by a simple linear sum of the HIC and VC alone. Figure 15b shows that the wind speed from the result of the 2D model, with an urban area and a 600-m mountain (2D600 case), is greater than the sum of the wind speeds of the 2Dflat (no mountain; generating only the HIC) and 2Dmou (no urban area and with 600-m mountain; generating only the VC) cases. That is, the wind is intensified mountainward due to nonlinear effects. This intensification tends to be most remarkable and invariant independently of the mountain height, when the mountain height is greater than around 800 m. The reasons for the above features are beyond the scope of the current study. It is thought, however, that the features are possibly related to the vertical scale of the wind system and the depth of the developing mixed layer.

5.2 Deformation of the SBC due to urbanization

As was mentioned in section 1, a remarkable deformation of the SBC due to urbanization has been found in the Kanto plain under calm conditions. In the Osaka–Kyoto plain, a similar deformation of the SBC appears in this study. Figure 16 exhibits vertical cross-sections of results for the 3Dall (with urban areas, Fig. 16a) and 3Dno (with no urban areas, Fig. 16b), along the direction of the penetration of the SBC from Osaka Bay (the dotted line in Fig. 1a). In Fig. 16, it can be seen that the upward flow of the SBC front, and the vertical scale of the SBC for the 3Dall case, are greater than those for the 3Dno case. These features have also been found
in the 2D experiments of Yoshikado (1992) which was described in section 1. There is, however, a noteworthy feature that occurs over the Osaka–Kyoto plain; a downward flow from upper levels over the Osaka urban area to lower levels over the Kyoto urban area exists ahead of the SBC front. A particular feature of this flow is that it can transport atmospheric pollutants, especially those emitted over the peripheral portion of the Osaka urban area, into further inland areas before the SBC transports the pollutants. For example, see the trajectory analyses in Figs. 16a and 16b, which indicate the path of a parcel within a 5-km width in the horizontal direction from the location of the cross-section line, the trajectory of the parcel is not drawn. The location of the cross section is indicated in Fig. 1a (the dotted line). The numerals represent the time when the air parcels reach the indicated positions (denoted as 7 to 14, i.e., 0700 to 1400 LST). Dark and light lines denote the locations of the urban areas (left, Osaka and right, Kyoto) and Osaka Bay, respectively.

flows into the inland urban area, over the suburban area between the two urban areas, as the SBC front moves inland. This flow was termed the chain flow by Ohashi and Kida (2002a). Over the Osaka–Kyoto plain, the downward flow of the VC is intensified by the chain flow. Figure 17 indicates the downward-flow ratio of the 3Dall to 3Dno cases at \( z' = 500 \) m. As can be seen in this figure, the downward wind speed in the 3Dall case is 1.5–3.5 times greater than that in the 3Dno case, over the region from the inland area ahead of the SBC front to the south area of Kyoto. This means that the downward flow, found over the suburban areas between the Osaka and Kyoto urban areas, is intensified by the chain flow when the urban areas exist. In Fig. 9, the drying of the surface air over the suburban area between the Osaka and Kyoto urban areas was found even when no mountains existed. This dryness is caused by the chain flow that transports drier air downward from the upper levels.
6. Conclusions

In this study, the effects of topography and urbanization on the daytime local-circulations over the Osaka–Kyoto plain area, were investigated using a mesoscale atmospheric model. From discussions of the differences between features appearing in the Osaka–Kyoto and Kanto plains, focus was centered on 1) the interactions among the SBC, VC, and HIC, and on 2) the deformation of the SBC due to urbanization.

Results related to 1) can be summarized as follows. The stagnation of the inland penetration of the SBC front, such as found in the peripheral portion of the Tokyo urban area, does not clearly occur in the Osaka urban area. This stagnation is attributed to the HIC that develops over peripheral portions of urban areas. The northern peripheral portion of the Osaka urban area faces mountains. Consequently, the VC, which develops over the mountain area, results in two factors that contribute to the acceleration of the SBC front: 1) the HIC that would normally interfere with the inland penetration of the SBC is weakened by the VC, because the wind directions of the HIC and VC oppose each other; 2) the horizontal pressure-gradient between the SBC front and inland area is increased by the heating of the inland atmosphere; this heating is attributed to the transport of heat by the downward flow of the VC, and the smaller atmospheric volume in the valley area relative to that in the plain area.

The VC also greatly influences the moisture distribution over the Osaka–Kyoto plain. The suburban area between the Osaka and Kyoto urban areas is relatively dryer than the urban areas until the arrival of the SBC front; it also exhibits a greater range of diurnal change in water-vapor pressure. These features result from the VC transporting drier air downward from upper levels over the suburban area, while also transporting the moisture supplied from the ground surface into mountain areas. In addition, decreases in the nonreactive pollutant (e.g., SPM and SO₂) concentrations over the suburban area prior to the arrival of the SBC, are more notable than those over any of the other areas. The polluted air is transported out of the suburban area into mountain areas, and less polluted air descends from upper levels.

Results related to 2) can be summarized as follows. Both the upward flow of the SBC front and the vertical scale of the SBC are greater than those found in the case of no urbanization, which also appeared in the 2D-flat experiments that approximated the Kanto plain (Yoshikado 1992). In addition, in the Osaka–Kyoto plain, a chain flow (Ohashi and Kida 2002a), which flows downward from upper levels over the Osaka urban area to lower levels in the Kyoto urban area, forms ahead of the SBC front. This flow can transport atmospheric pollutants, especially those emitted over the peripheral portion of the Osaka urban area, further inland before the SBC transports the pollutants.

Thus, in the Osaka–Kyoto plain, VCs that develop in the surrounding mountains play an important role in the heat, moisture, and pollutant transport because of the narrowness...
of the plain. Consequently, this results in different meteorological features between the urban area in the Osaka–Kyoto plain and that in the Kanto plain.

It should be mentioned what meaning the results obtained in this study have. As was shown in Fig. 13, over the Osaka–Kyoto plain the SBC front does not stagnate at the peripheral portion of the urban area, and arrives at the Kyoto basin earlier, compared with the results from the case having no mountains. Additionally, the chain flow transports pollutants toward inland areas earlier, compared with the results from the case having no urban areas. These phenomena can induce the air pollution to an inland area earlier in time than if there were no mountains or no urban areas over the plain. The information obtained from the current study can be used to predict the meteorological features between the urban areas, and mountains, which, for example, will be necessary for urban planning and renewal.

Acknowledgments

Use was made of the GFD–DENNOU Library to draw many of the figures. The NCEP/NCAR reanalysis data were used to initialize the model profiles. The sea-surface temperatures, using the AVHRR data from the NOAA satellite, were provided by the Marine Information Science Laboratory, Kobe University of Mercantile Marine (http://misa.kaiyou.kshosen.ac.jp/). The meteorological data were made available by the Japan Meteorological Agency, Hyogo, Osaka, and Kyoto Prefectures along with relevant cities. The authors also wish to thank two anonymous reviewers for providing useful comments for the improvement of the manuscript.

References


McNider, R.T., 1981: Investigation of the impact of topographic circulations on the transport and


——— and ———, 2002a: Local circulations developed in the vicinity of both coastal and inland urban area—A numerical study with a mesoscale atmospheric model. J. Appl. Meteor., 41, 30–45.


