Toward Improved Forecasts of Sea-Breeze Horizontal Convective Rolls at Super High Resolutions. Part II: The Impacts of Land Use and Buildings

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ABSTRACT

Horizontal convective rolls form in coastal areas around Sendai Airport during sea-breeze events. Using a building-resolving computational fluid dynamics model nested in an advanced forecast system with a data assimilation scheme, the authors perform a series of sensitivity experiments to investigate the impacts of land use and buildings on these rolls. The results show that the roll positions, intensities, and structures are significantly affected by variations in land use and the presence of buildings. Land-use heterogeneity is responsible for generating rolls with evident regional features. Major rolls tend to develop downwind of warm surfaces, and they dominate over neighboring rolls; thus, a heterogeneity-scale mode is imposed on the inherent roll wavelength. The roll’s rapid growth is attributable to warm surfaces that initiate a strong coupling among turbulent thermals, convective updrafts, pressure perturbations, and secondary flows in sea breezes. The heterogeneity-induced features differ considerably from the nearly homogeneous features that form over uniform surfaces. Additionally, the wake flow behind buildings helps organize near-surface warm air into streamwise bands that drive streaky ejections. The building-induced turbulence acts to modify secondary flows and displace roll updrafts toward building wakes. Such effects are most effective over villages with scattered houses that are aligned with the ambient wind. Building signatures are elongated in downwind open areas due to sustained secondary circulations. An analysis of turbulent kinetic energy shows that both land use and buildings regulate energy generation and transport, resulting in a clear response in roll growth. Thus, including complex surfaces in forecast models helps determine detailed characteristics and structures of roll convection over coastal regions.

1. Introduction

Horizontal convective rolls (HCRs) are a typical pattern of boundary layer convection that greatly influences local weather and environment (e.g., Atkinson and Zhang 1996; Young et al. 2002). As a type of shallow convection, HCR formation and growth can be strongly affected by the thermal and/or mechanical properties of the underlying surfaces (Weckwerth et al. 1997; Raasch and Harbusch 2001; Miao and Chen 2008; Inagaki and Kanda 2010). Analyzing roll convection over small-scale complex surfaces is likely to improve our understanding of both land–atmosphere interaction and local weather variation (Maronga and Raasch 2013). Because of the limited knowledge on roll convection and the difficulties in resolving complex surfaces, a substantial challenge is realistically forecasting sea-breeze HCRs over coastal cities (Ashie and Kono 2011; Chen et al. 2015, hereafter Part I).
Complex surfaces are defined by two major aspects: land use and geometry. Land-use heterogeneity is associated with variability in surface temperature, humidity, and roughness. Previous studies suggest that inhomogeneous land use can generate convective phenomena that are notably distinct from those over uniform surfaces (Letzel and Raasch 2003; Prabha et al. 2007; Kang and Bryan 2011). The induced circulation becomes evident as the heterogeneity increases to a scale comparable to or larger than the depth of the convective boundary layer (CBL; Hadfield et al. 1992; Shen and Leclerc 1995; Avissar and Schmidt 1998). Active turbulence usually develops above or downwind of the heat flux maxima. When background wind exists, the secondary circulation of roll convection is responsive to surface heat patterns depending on the CBL wind direction (Raasch and Harbusch 2001). Such heterogeneity-induced turbulence contributes to vigorous energy transport and greatly modifies the CBL structure. Thus, including real land-use heterogeneity in forecast models is a key step to reproducing the regional features of CBL turbulence and CBL mean characteristics (Huang and Margulis 2009; Maronga and Raasch 2013).

Over urban/suburban areas, complex geometry, such as buildings, also strongly regulates local winds, temperature, and dispersion in the boundary layer (e.g., Roth 2000; Collier 2006). Flow patterns can change significantly in the presence of buildings (Smith et al. 2001; Baik et al. 2009). Idealized experiments show that turbulent organized structures, such as low-speed streaks with ejections, may form over a building array (Kanda et al. 2004; Kanda 2006). The coherent structures can reach a scale that is several times larger than the individual buildings and can greatly affect the weather variables in the urban boundary layer (Castillo et al. 2011; Inagaki et al. 2012; Park and Baik 2013). The low-speed streaks are usually aligned streamwise to form larger-scale horizontal vortices (Inagaki and Kanda 2010; Park and Baik 2014). The persistent HCRs are in fact often observed to develop in the CBL over urban/suburban areas and downstream (Kropfli and Kohn 1978; Newsom et al. 2008; Miao and Chen 2008). Although many numerical studies have analyzed the effect of idealized buildings on local flows and turbulent structures, the interaction between building-induced eddies and roll convection is not fully understood. In particular, the major issue of how complex land use and buildings regulate mesoscale shallow convection in the CBL, such as HCRs under realistic weather, has not been addressed.

During an observational campaign over Sendai Airport in 2007, HCRs that occurred in sea breezes were well detected by dual-Doppler lidar and helicopter measurements (Iwai et al. 2008; Oda et al. 2010). The HCRs tended to initiate in coastal areas; then, they became more evident over built-up areas than over rice paddy fields. Because rolls are strongly associated with underlying surfaces, they present a good opportunity for studying the impacts of land use and buildings on shallow convection in the sea-breeze internal boundary layer (IBL). To simulate these sea-breeze HCRs, in the first part of this study (Part 1), we design a Down-Scaling Simulation System (DS³) that derives reliable mesoscale conditions to drive a building-resolving computational fluid dynamics (CFD) model. The verification using intense observations over Sendai Airport shows that the rolls can be reproduced with reasonable good accuracy. Therefore, using DS³, it is feasible to further expose and clarify the detailed impacts of complex surface features on roll characteristics, such as intensities, structures, wavelength, and positions.

In this study, we perform more numerical experiments to illustrate how small-scale land use and buildings regulate the activities of sea-breeze HCRs. The goal is achieved by comparing a series of sensitivity experiments that express the thermal/dynamic effects of different land use and buildings. Section 2 describes the settings of the numerical models and experiments. In section 3, the characteristics of the simulated HCRs over various surfaces are examined, and the associated physical processes are discussed. The final section presents the conclusions.

2. Surface processes in DS³ and design of the sensitivity experiments

a. Treatment of land use and buildings in DS³

In this study, HCRs are simulated using DS³, in which a CFD model is nested in an advanced forecast downscaling system with a data assimilation scheme. The detailed configuration and performance of DS³ are described in Part I. First, weather conditions associated with roll formation are derived using a mesoscale model with a convective-scale data assimilation scheme. The mesoscale model is the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM; Saito et al. 2006, 2007). The data assimilation scheme is a two-way nested system based on the local ensemble transform Kalman filter (LETKF; Seko et al. 2011, 2013). The analysis data can adequately capture the inland penetration of a sea breeze and the related wind/temperature variations over Sendai Airport during the daytime on 19 June 2007. The analysis data are used as the initial conditions for the mesoscale model to produce a short-range forecast. Then the forecast is applied to drive a building-resolving CFD model over an urban-scale area at a resolution of a few meters (Sha et al. 1991; Sha 2002, 2008). As shown
in Fig. 1 of Part I, the simulations are downscaled using five nested grids centered at Sendai Airport, with horizontal resolutions of 15 km, 2 km, 400 m, 100 m, and 10 m. The mesoscale simulations with data assimilation are conducted in the outer two grids. The extended mesoscale forecast is conducted in the third and fourth grids. The CFD simulations are performed in the innermost grid over a 10-km domain. In this respect, the simulation of local weather can be achieved at a super high resolution with reasonably good precision. Here we numerically modify the land use and buildings used in the numerical models at the forecast stage and examine the corresponding change in the simulated HCRs.

As we focus on the effects of land use and buildings, an important issue is the treatment of surface processes in numerical models. In the mesoscale model JMA-NHM, the land-use data with a 100-m resolution are obtained from the Geospatial Information Authority of Japan. There are nine categories of land cover in the vicinity of Sendai Airport. The major categories include rice paddy fields and concretelike surfaces, such as built-up areas, airport runways, industrial lands (mostly for parking), and roads. These categories are used to determine surface parameters, such as albedo, wetness, roughness, heat capacity, and conductivity for the surface processes in JMA-NHM (Table 1). A major difference between rice paddy fields and concretelike surfaces is wetness, which greatly affects the thermal conditions of the land surface. Under fair weather, these two land-use types approximately denote the cool and warm states, respectively, of the land surface. Ground temperature forecasts in JMA-NHM present the surface thermals that correspond to the applied land use.

In the CFD model, thermal properties of the land surface are given by a prescribed ground temperature from the outer mesoscale model. In a short-term run, the ground temperature undergoes minimal change; thus, it is fixed at the given initial value. Regarding the surface geometry, the buildings are treated as cubical blocks using a block-off technique. Similar to solid blocks, these cubical blocks have thermal properties but no wind/pressure variables. The location, shape, and height of individual buildings are obtained from GIS data so that the mechanical effects of buildings are explicitly described. Note that, unlike JMA-NHM, the CFD model does not employ a surface process scheme, assuming that it explicitly resolves fine surface geometry and induced eddies. As the radiation scheme is excluded, the temperature of building roofs and walls is set to the prescribed temperature of the underlying land surface. The shade effect of buildings is not considered. Surface heat fluxes are estimated by the heat transfer between air mass and building/land surfaces.

b. Design of sensitivity experiments

The experiments are set up to study the sea-breeze HCRs that occurred around Sendai Airport at 1305 Japan standard time (JST; JST = UTC + 9 h) 19 June 2007 (Iwai et al. 2008; Oda et al. 2010). In the first numerical experiment (EXP1), real land use and buildings are incorporated to describe their combined effect on the rolls (Fig. 1a). Land use is applied to the outer four grids of the mesoscale model at the finest spatial resolution of 100 m. Forecasts of atmospheric variables and ground temperature are used to drive the inner building-resolving CFD model with a 10-km domain at a 10-m grid spacing. In the CFD model, the prescribed ground temperature reflects the surface thermals of heterogeneous land use, while an explicit resolution for the building geometry presents the mechanical effects of the buildings. The integration time is 10 min, with a time step of 1 s. Because model equations are solved iteratively for obtaining converged solutions, variable fields are adjusted for many cycles at each time step. As shown in Part I, the CFD solution, with weak/uniform disturbances from the mesoscale model, can reproduce strengthened rolls with evident regional features over real surfaces. In a very shallow sea-breeze layer, only a 5-min forecast time is needed for rolls to fully develop and reach a quasi-steady state in the CFD domain. The

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**Table 1. Land-use categories and surface parameter settings around Sendai Airport.**

<table>
<thead>
<tr>
<th>Land use</th>
<th>Albedo</th>
<th>Wetness (m)</th>
<th>Roughness</th>
<th>Conductivity (m² s⁻¹)</th>
<th>Heat capacity (J² s⁻¹ K⁻² m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0 × 10⁻³</td>
<td>1.3 × 10⁻⁶</td>
<td>1.9 × 10⁶</td>
</tr>
<tr>
<td>River/lake</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0 × 10⁻³</td>
<td>1.3 × 10⁻⁶</td>
<td>1.9 × 10⁶</td>
</tr>
<tr>
<td>Runway/industry</td>
<td>0.13</td>
<td>0.15</td>
<td>0.02</td>
<td>1.0 × 10⁻⁶</td>
<td>1.4 × 10⁶</td>
</tr>
<tr>
<td>Traffic line</td>
<td>0.13</td>
<td>0.02</td>
<td>0.1</td>
<td>1.0 × 10⁻⁶</td>
<td>1.4 × 10⁶</td>
</tr>
<tr>
<td>Built-up area</td>
<td>0.13</td>
<td>0.02</td>
<td>1.0</td>
<td>1.0 × 10⁻⁶</td>
<td>2.0 × 10⁶</td>
</tr>
<tr>
<td>Waste land</td>
<td>0.2</td>
<td>0.2</td>
<td>0.01</td>
<td>6.0 × 10⁻⁷</td>
<td>1.7 × 10⁶</td>
</tr>
<tr>
<td>Forest</td>
<td>0.1</td>
<td>0.2</td>
<td>0.95</td>
<td>6.0 × 10⁻⁷</td>
<td>1.7 × 10⁶</td>
</tr>
<tr>
<td>Cropland</td>
<td>0.2</td>
<td>0.4</td>
<td>0.02</td>
<td>6.0 × 10⁻⁷</td>
<td>1.7 × 10⁶</td>
</tr>
<tr>
<td>Rice paddy field</td>
<td>0.1</td>
<td>0.8</td>
<td>0.03</td>
<td>7.0 × 10⁻⁷</td>
<td>1.7 × 10⁶</td>
</tr>
</tbody>
</table>

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instantaneous fields at that time step are the focus here. The simulated roll-scale updrafts are consistent with those observed by dual-Doppler lidar and helicopter flights. Thus, the rolls in EXP1 may serve as a benchmark for evaluating the other sensitivity tests. As in Part I, we note an underestimate of small-scale turbulence in the CFD domain probably for lack of resolved inflow turbulence (Mirocha et al. 2014; Muñoz-Esparza et al. 2014a,b). Such a deficiency has little effect on our conclusions, since the onset/growth of the coastal rolls closely relates to the organized turbulence newly growing from the underlying surfaces (e.g., Atkinson and Zhang 1996), which can be simulated in the CFD model as shown later.

In the second experiment (EXP2), the settings are identical to those in EXP1 except that the buildings are removed (Fig. 1b). Without buildings, EXP2 expresses the thermal effect of heterogeneous land use. Because the building thermals in EXP1 are the same as those of the underlying land surfaces in EXP2, a difference between EXP1 and EXP2 mainly represents the mechanical effect of buildings. In the third experiment (EXP3), all of the land-use categories are artificially replaced by uniform rice paddy fields in JMA-NHM (Fig. 1c). The prescribed ground temperature is used to drive the CFD model on the topography (flat near airport) without buildings, so that the EXP3 run represents the effect of land surfaces in a cool state. In contrast, in the fourth experiment (EXP4), ground temperature in the CFD model is prescribed by JMA-NHM using uniform industrial lands, that is, the land surfaces in a warm state (Fig. 1d). The difference between EXP3 and EXP4 thus expresses the thermal forcing of uniform land surfaces in different thermal states, while the discrepancy between EXP2 and EXP3–4 highlights the impact of land-use heterogeneity.

FIG. 1. (a)–(d) Configuration of land use and buildings in the vicinity of Sendai Airport in four numerical experiments using mesoscale and CFD models.
3. Results and discussion

a. General and regional features of the roll convection over various surface conditions

First we examine the spatial patterns of horizontal winds and vertical velocity simulated by the CFD model. Figure 2 shows that longitudinal bands of roll updrafts generally initiate in coastal areas and grow inland. The roll axis is stretched downwind from southeast to northwest. In all four experiments, the HCRs feature inland growth and a streamwise orientation. Regarding regional features, Fig. 2a shows that, in EXP1, active updrafts originate from two major built-up areas: Sendai Airport at the domain center and the residential village in the south (Fig. 1a). In contrast, updrafts are less evident over and downwind of the rice paddy fields. The intensity and positions of roll convection are strongly associated with the underlying surfaces. These regional features of simulated HCRs agree well with those observed by dual-Doppler lidar and helicopter flights, as shown in Part I. Figures 2a and 2b show that the rolls have similar general features in EXP1–2. In contrast to the updrafts evolving smoothly in EXP2, those in EXP1 exhibit more local features, indicating building-induced eddies. Regarding individual rolls, Figs. 2a and 2b also reveal some slight discrepancies in EXP1–2 regarding the updraft intensity and positions, particularly near built-up areas. Although the buildings are low in the vicinity of the airport, they seem to affect the detailed behavior of roll convection within a shallow sea-breeze layer.
Over uniform surfaces, most updrafts are weak in EXP3 (Fig. 2c), whereas they become much stronger in EXP4 (Fig. 2d). Such a difference is expected because land thermal conditions greatly determine the intensity of convection. Updrafts are generally spaced at a regular distance of ~500 m, indicating a homogenous roll wavelength. The updrafts have comparable intensities. The roll growth thus exhibits small regional differences in EXP3–4, in contrast to that in EXP2 in which the active updrafts grow downwind of the warm surfaces. Figures 2c and 2d also show that most of the individual rolls have different positions in EXP3–4. The roll positions seem less fixed over the uniform surfaces compared with those with a strong surface dependence in EXP2. An overview of EXP2–4 highlights that the thermal states and heterogeneous features of land use may greatly influence the intensity and regional differences in roll convection.

To clarify the turbulent structures, Fig. 3 shows vertical profiles of the variances in the velocity components and temperature. The profile represents a southeast–northwest cross section, which displays an inland evolution in the streamwise direction. Four experiments appear to produce the new turbulence induced by land surfaces and its upward growth associated with the onset/growth of coastal HCRs. Figure 3a shows that, in EXP1, the vertical motion variance $\sigma_u^2$ usually increases from the coast, with a maximum in the middle of the growing mixed layer. Combined with a deepening temperature variance $\sigma_T^2$, an inland growth of thermally driven updrafts and downdrafts is manifested. Evident growth occurs at $X = 3–4.5$ km (i.e., downstream of the built-up areas). Figure 3b shows that the streamwise velocity variance $\sigma_u^2$ is large near the surface where building-induced eddies and wind speed streaks are active (Foster et al. 2006; Iwai et al. 2008; Inagaki et al. 2012). The variance extends upward at $X = 3–4$ km where the rolls are deep. Figure 3b also shows that the spanwise velocity variance $\sigma_w^2$ has two peaks, with a major peak near the surface and a secondary peak at the upper IBL. These peaks represent the bottom and upper branches of the secondary circulation in the crosswind plane, similar to earlier studies (Moeng and Sullivan 1994; Prabha et al. 2007; Maronga and Raasch 2013). The upper branch becomes visible and grows upward at $X = 3–4$ km, which indicates a deepening secondary circulation along with roll growth. To the west of $X = 3$ km, large variance dominates a vertical range of 140–300 m AGL, implying that the height of secondary flows may vary considerably among inland rolls.

Figures 3c and 3d show that the general patterns of the variances in EXP2 are similar to those in EXP1, while some local discrepancies are visible. For instance, the vertical velocity variance is larger in EXP2 at $X = 4–5$ km (Fig. 3c), whereas it becomes slightly stronger in EXP1 at $X = 2–3$ km (Fig. 3a). The streamwise velocity variance is somewhat large in EXP1 near the surface due to building effects (cf. Figs. 3b and 3d). A relatively large variance in the streamwise velocity also occurs in EXP1 in the IBL, particularly at $X = 3–4$ km, implying obvious streaky structures. These differences in EXP1–2 point to a possible influence of buildings on turbulent structures and roll convection.

Figures 3e and 3f show that the variances in the four variables are small in EXP3 and demonstrate inactive turbulence over cool surfaces. In contrast, Fig. 3g shows that the vertical velocity variance is much stronger in EXP4, with evident growth at $X = 3–5$ km. To the west of $X = 3$ km, the obvious variance reaches ~230 m AGL, with a maximum at ~100 m AGL. Additionally, the spanwise velocity variance at the upper IBL becomes clear at $X = 5$ km and grows upward while inland, as shown in Fig. 3h. The variance magnitude is somewhat smaller than that in EXP2 (cf. Figs. 3h and 3d), suggesting an enhancement of the spanwise velocity variance over heterogeneous surfaces (Raasch and Harbusch 2001; Prabha et al. 2007). The variances in the three velocity components in EXP4 also have vertical extents that are lower than those in EXP2 (cf. Figs. 3g,h and 3c,d). The updrafts/downdrafts and secondary circulations seem to be confined to a relatively low layer over uniform surfaces but grow higher over heterogeneous surfaces. From Fig. 3, we see that the turbulent thermals, updrafts, streamwise speed streaks, and secondary circulations experience an adjustment that notably differs among the four experiments during the inland evolution of roll convection. A further investigation focuses on these IBL disturbances over different surface features to clarify the impacts of land use and buildings on rolls.

To understand the IBL environment associated with roll convection, we examine the inland evolution of the mean temperature and wind speed. Figure 4 shows that, in all four experiments, the sea breeze has similar mean structures along the coastline ($X = 7$ km). The low temperature, that is, below 294.5 (292) K, has a depth of ~220 (~100) m. The wind speed maximum is 6–6.5 m s$^{-1}$ at ~150 m AGL, and it exhibits a moderate wind shear below. As revealed in Part I, a combination of thermal instability and wind shear is favorable for roll formation. Along with roll growth, the IBL structure undergoes inland transition, as shown by the changing profiles of temperature and wind speed to the west of $X = 6$ km. Figures 4a and 4b show that EXP1–2 exhibits a similar transition above 50 m AGL in relation to
FIG. 3. Vertical profiles of the variances in the velocity components (streamwise: $\sigma_u^2$, spanwise: $\sigma_y^2$, and vertical: $\sigma_w^2$) and potential temperature ($\sigma_\phi^2$) from the southeast coast to the northwest inland area. The section is averaged over a 4-km zone, as marked in Fig. 2c. The coastline is located around $X = 7$ km.
comparable turbulent mixing (Figs. 3a–d). Some discrepancies are seen below 50 m AGL. In the presence of buildings, a shallow layer of warm air is established near the surface in EXP1 (Fig. 4a). The wind speed is also low near the surface; and thus, wind shear remains obvious at the lowest level of the IBL. Such wind shear and thermal instability sustain IBL structures that potentially modulate roll convection above and downwind of the buildings.

Figure 4c shows that sea breezes exhibit a weak inland transition in EXP3, as indicated by a lower temperature to the west of $X = 6$ km than that in other experiments. This feature corresponds to weak turbulent mixing due to the suppressed roll convection over the rice paddy fields (Fig. 3e). The wind profile also changes slowly, with a maximum speed remaining at 150 m AGL. The wind shear thus maintains some strength in the lower IBL. In contrast, sea breezes are modified rapidly over warm surfaces in EXP4 (Fig. 4d). The temperature profile over inland areas exhibits a well-mixed feature that relates to active turbulence (Fig. 3g). The wind speed maximum, originally located at 150 m AGL at $X = 6$–7 km, is established near the surface to the west of $X = 4$ km. This shift indicates that the roll convection has played an active role in energy transport and modification of the IBL structure. These features support the general understanding that roll convection growth is tightly linked to the CBL structure, while roll-induced momentum and heat fluxes in turn greatly regulate the CBL’s mean characteristics (e.g., LeMone 1976; Weckwerth et al. 1997). An overview of Figs. 2–4 suggests that the interaction between sea breezes and roll convection considerably varies with different surface conditions. In the following sections, we examine the roll growth in the context of this interaction to illustrate roll structures and characteristics over various surfaces.

b. Impacts of buildings on roll characteristics

To highlight building impacts, we examine the variable differences between the simulations with and without buildings (EXP1 vs EXP2). Note that the differences mainly express the mechanical effect of buildings because the same surface thermals are applied in EXP1–2. Figure 5 shows an overall difference in the vertical motion at 25 m AGL in the vicinity of Sendai Airport. The disturbances, in the form of a pair of rising/sinking motions, are clearly seen at the lees of major buildings. The disturbances stretch downwind over open areas at a distance of 1–2 km; thus, they extensively influence the downstream convection. Because these streaky disturbances occur near the roll axis, they manifest a building-induced displacement of roll updrafts or downdrafts. To illustrate the detailed effects of different building morphologies, the flow pattern and temperature disturbances in four subdomains in Fig. 5 are enlarged in Fig. 6. These subdomains represent four building types: coastal building clusters (S1), dense industrial compounds (S2), downstream isolated buildings...
(S3), and a residential village with scattered single-family houses (S4). We focus on two levels (5 and 25 m AGL) that correspond to the building canopy layer and the IBL above roof height, respectively.

Figure 6a shows that, over the coastal village (S1), rising motion appears above the rooftop heights on the windward sides of building clusters, while sinking motion occurs immediately within the near-wake areas, due to the local mechanical effect of building obstacles. Remarkably, several elongated bands of rising motion occur downstream of buildings. The strongest band originates from the center of the buildings’ zone, while the other two bands are established at the lateral sides. The bands can stretch downwind 500–1000 m, which is several times larger than the scale of the building clusters. These bands coincide with the streaky patterns of low wind speed and warm air. Such coherent structures (low wind speed with rising warm air and high wind speed with sinking cool air) play an important role in the vertical transport of momentum and heat in the IBL (Inagaki et al. 2012; Park and Baik 2014). Figure 6b shows that, near the surface, as the airflows encounter buildings, they are deformed similar to a horseshoe eddy. Warm air accumulates at the wake zone as a result of surface heating and convergent flow related to lateral vortices (Smith et al. 2001). Based on Figs. 6a and 6b, the near-ground warm air stretches from building clusters and subsequently ascends in downwind areas to drive updrafts. These disturbances with streaky structures appear to regulate the initiation of roll convection in coastal areas, which explains the newly formed rolls that are attached to the lees of buildings. Similar features are seen at the lees of another coastal village in the south (Fig. 5).

Figure 6c shows that, over the dense industrial compounds (S2), there are two modes of rising motion over the streamwise and spanwise orientations, respectively. In contrast to spanwise lifting over windward buildings, streamwise updrafts develop with low-speed streaks and warm disturbances. These streaky updrafts correspond to turbulent coherent structures that are similar to those over building arrays in idealized experiments (Kanda et al. 2004; Inagaki and Kanda 2010; Inagaki et al. 2012; Park and Baik 2013). Figure 6d shows that the near-surface airflows are blocked by major buildings, such as those labeled 1. Slow-moving warm air is present over streets with dense buildings (labeled 2–5). Together, Figs. 6c and 6d suggest that warm air near the surface emerging from the dense buildings’ zone is lifted to form coherent ejections over downwind streets (north of

![Figure 5](image-url)
FIG. 6. Differences in the winds and temperature between EXP1 and EXP2 in the four subdomains.
(a), (c), (e), (g) Differences in the horizontal winds (vector), vertical motion (shaded), and temperature (contours) at 25 m AGL. The contour interval is 0.3 K, in which solid (dashed) lines are positive (negative).
(b), (d), (f), (h) Temperature difference and horizontal winds in EXP1 at 5 m AGL. The locations of the four subdomains S1–S4 are marked in Fig. 5. In (h), the long dashes mark the village axis; the short dashes mark the cross sections at the upstream and midstream areas of the village in Fig. 7.
building 5). Such turbulent structures are analogous to the inherent properties of HCRs: the updraft originates from a convergent band of near-surface warm air. Therefore, these structures help establish roll updrafts on the lee streets of dense buildings. In contrast, over the open areas between buildings 1–2 and 6, the airflow is relatively fast and the temperature remains low (Fig. 6d).

Figure 6e shows that, in the downstream open area with isolated buildings (S3), a streaky disturbance induced by upstream buildings stretches from the southeast. The coherent feature is disturbed when passing by the building near the subdomain center. This disturbance is distinct from another disturbance in the northeastern corner that is sustained over a flat area. Figure 6f shows that the change in the vertical motion disturbance is associated with a temperature disturbance shift from a cold bias to a warm bias at the building lees. The isolated building, by trapping warm air in the wake flow, adjusts the existing roll convection and deforms updraft toward the lee side. The signatures are less evident at other buildings at southern and western boundaries, which are far from roll convection. In contrast to their coastal counterparts (Fig. 6a), these inland buildings are incapable of producing new rolls on their own (Fig. 6e).

Figure 6g shows that, over the residential village with scattered single-family houses (S4), a well-defined band of rising motion and low-speed streak is elongated from southeast to northwest over the village. The band is initiated in the upwind area of the village, it strengthens just at the lee of the village center, and it is sustained farther downstream. The pattern is collocated with the village axis (long dash) and is parallel to the mean wind direction. Figure 6h shows that the disturbance of rising motion is facilitated by near-surface warm air over the village, where building drag continues to inhibit airflow and enhances convergence. These structures are more coherent than those over other building morphologies, as shown in Fig. 6. Thus, building signatures may accumulate effectively where the scattered buildings are parallel to the ambient wind. Another difference between Figs. 6g and 6c is that the streaky disturbances are enhanced continuously above the scattered buildings (S4), while they are initially interrupted by the dense buildings and then reformed over the leeward street (S2). These differences may arise from the local winds and temperature patterns (Figs. 6d,h) that vary with the mechanical effects of different building morphologies. Similarly, Kanda et al. (2004) reported in idealized experiments that the preferred locations of turbulence are different over sparse and dense building arrays.

To clarify the response of roll convection to buildings, we examine the structure of secondary flows and thermal disturbances over the residential village. The cross-roll sections, which are normal to the village axis, are analyzed in upstream, midstream (just at the lees of most houses), and downstream areas of the village (Fig. 6h). These sections correspond to the growth, mature, and maintenance stages of the building-induced disturbances, respectively. Figure 7a shows that upstream of the village, a temperature disturbance is established over the area near the village axis. A warm bias, with a maximum of ~1 K, is mainly concentrated at the rooftop level (15 m AGL). Rising motion, while still
weak, develops above the rooftop heights in the warm zone where near-surface flows are convergent.

Figure 7b shows that the building-induced temperature disturbance strengthens and reaches a maximum of 1.1 K at the midstream of the village. An obvious warm bias extends ~50 m deep and reflects an accumulation of warm air at the lees of the village houses. Additionally, the disturbance of rising motion strengthens significantly over this warm zone. The rising motion extends up to 100 m AGL, with a maximum of ~0.5 m s\(^{-1}\) at 35 m AGL. The sinking motion of relatively cold air, as the return branch of a secondary circulation, strengthens at a neighboring side to the right. The rising and sinking motions are linked by the cross-sectional flows with a speed of 1 m s\(^{-1}\) near the surface. This secondary circulation has a magnitude comparable to that of roll convection. Because the rising (sinking) motion corresponds to roll updrafts in EXP1 (EXP2), the building-induced turbulence displaces the roll updraft toward the village axis. The displacement is ~100 m, as indicated by the distance between the rising and sinking motions in Fig. 7b.

Figure 7c shows that the warm air diminishes near the surface but it remains above the rooftop level in the downstream areas far from the village. This feature reflects the decaying confluence of surface warm air over open areas without buildings. Accordingly, the disturbance of rising motion slightly weakens and narrows. In the adjacent zone to the right side, a cold bias dominates near the surface as sinking motion draws cool air downward. As the near-surface secondary flows converge toward the warm area, they continue to gather warm air into the updraft zone. While the secondary circulation is sustained, the updrafts and downdrafts seem to be organized and maintain their strength (Prabha et al. 2007). As a result, building signatures persist downstream at a considerable distance and extensively influence the roll convection, as shown in Figs. 5 and 6g. The features are somewhat similar to the idealized experiments on building arrays: the building-induced turbulence may behave like the coherent structures of rising warm air and sinking cool air. Such a concept seems applicable to the realistic complex buildings in the sea-breeze simulations here. This study further shows that the effectiveness of such building impacts vary across the different morphologies of building densities, alignments, and locations. As these induced disturbances are weak and elongated, they play a role in regulating the local structures of roll convection. Over coastal areas, the disturbances seem to anchor the initiation of roll convection to the lees of buildings. Inland, the disturbances may interrupt the existing coherent structures over buildings and then rebuild/displace rolls in the wake zone.

c. Impacts of land use on roll characteristics

In this section, we examine the impacts of land-use characteristics (thermal state and heterogeneity) on the rolls under realistic sea breezes. The objective is achieved by comparing the simulated rolls over real land use (EXP2) and over artificially uniform surfaces in cool (EXP3) and warm (EXP4) states. Because these experiments are designed to expose and clarify land-use effects, the buildings are excluded for convenient interpretation of the results. The difference between EXP2 and EXP3–4 highlights the effects of land-use heterogeneity; the difference between EXP3 and EXP4 highlights the effects of surface thermal states.

To illustrate thermal disturbances over various land-use types, we examine the spatial distributions of the surface and air temperature in the vicinity of Sendai Airport. Figure 8a shows that the near-surface air temperature perturbations are wind-parallel bands that stretch from southeast to northwest in EXP2. Perturbations originate in coastal areas and grow inland. These perturbations are regularly spaced at a scale of several hundred meters, implying an inherent mode of the roll wavelength. The perturbations are associated with a confluence of warm air masses via near-surface flow structures, particularly low-speed streaks, as shown in Part I. A comparison of Figs. 8a and 2b reveals that these thermal fluctuations are exactly collocated with the bands of rising motion. Arguably, the warm air in the low-speed streaks, through localized buoyancy, help initiate the coherent sheets of convective updrafts (Khanna and Brasseur 1998). The findings also explain why the observed updrafts of sea-breeze HCRs mainly originate in low-speed streaks (Iwai et al. 2008; Oda et al. 2010).

Figure 8b shows that, at the low IBL, temperature disturbances occur downwind of major built-up areas. Specifically, three major bands occur downstream of the airport, while another appears downstream of the village. Therefore, turbulent thermals mainly originate
FIG. 8. Ground temperature (shaded) and mean air temperature (hatched for 293 and 293.5 K) in (a),(b) EXP2; (c),(d) EXP3; and (e),(f) EXP4. (a),(c),(e) 0–50 m AGL and (b),(d),(f) 50–100 m AGL.
from relatively warm surfaces. These features coincide well with the major rolls that have strong updrafts (Figs. 8b and 2b). The coexistence of vertical motion and temperature disturbances indicates an active heat flux over warm surfaces and downstream, with a maximum flux of \( \sim 1.5 \text{ K m s}^{-1} \). Turbulence usually becomes vigorous above or downwind of heat flux maxima, while it is weaker above or downwind of heat flux minima (Hadfield et al. 1992; Prabha et al. 2007). Heat flux variations induced from heterogeneous surfaces are thus connected to the regional differences in roll convection. The features are similar to those over other cities where active rolls tend to occur over urban surfaces rather than over rural areas (Kropfli and Kohn 1978; Miao and Chen 2008; Ashie and Kono 2011). Figure 8b also shows that two areas of strong turbulent thermals are separated by \( \sim 2 \text{ km} \) in response to the configuration of the airport and village. Land-use heterogeneity seems to produce a relatively large mode of roll wavelength superimposed on the inherent wavelength. The land-use-induced features usually become evident when the heterogeneity has a scale comparable to or larger than the CBL depth (Shen and Leclerc 1995; Avisser and Schmidt 1998). In this study, the sea breeze is very shallow (200–300 m deep); accordingly, the land-use effect on roll convection is evident at a small scale.

Because of the link between thermal disturbances and roll convection, we further examine roll characteristics over other land-use conditions. Figures 8c and 8e show that near-surface thermal bands are evident in the experiments with uniform surfaces (EXP3–4). The bands similarly exhibit coastal initiation and inland growth, even though they are slightly active over uniform industrial land (EXP4). A comparison of Figs. 8c,e and 2c,d suggests that these perturbations match the corresponding updraft positions in each experiment. It is also noted that the specific locations of the thermal bands vary considerably between EXP3 and EXP4, which produce the positions of the individual rolls with less dependence on uniform land surfaces.

At the lower IBL, thermal disturbances are weak in EXP3 (Fig. 8d), whereas they are much stronger in EXP4 (Fig. 8f). This difference corresponds to the intensity of the roll updrafts that are significantly different in EXP3–4 (Figs. 2c,d). Therefore, the IBL thermal disturbances over various surfaces greatly influence the overall intensity of the roll updrafts. As stated previously, such a thermal effect on the roll intensity seems locally applicable to real land use in EXP2, in which strong updrafts form downwind of warm surfaces. Another feature in EXP3–4 that is distinct from EXP2 is that the individual thermal bands have comparable strengths and have regular spacing (Figs. 8d,f). The uniform thermal disturbances seem to produce roll updrafts with nearly homogenous features in EXP3–4 (Figs. 2c,d), which considerably differs from those with regional features in EXP2 (Fig. 2b).

To clarify the vertical structure of the rolls over heterogeneous and homogenous surfaces, we examine the thermal/pressure perturbations and secondary flows in EXP2 and EXP4. A cross section is analyzed at \( X = 4 \text{ km} \) in (a),(b) EXP2 and (c),(d) EXP4. The solid (dashed) contour denotes the vertical velocity of 0.5 \( \sim 0.5 \text{ m s}^{-1} \).
EXP2, four rolls occur downstream of the village and airport ($Y = 2.8, 4.5, 5.1,$ and $5.7\,\text{km}$). These rolls have obvious upward motion ($w \approx 0.5\,\text{m}\,\text{s}^{-1}$), with a vertical extent ranging from 130 to 200 m AGL. The rolls feature turbulent thermals and secondary flows at corresponding strengths. Figure 9b shows that near the updraft zone, low pressure disturbances occupy the lowest level and high pressure disturbances occupy the upper IBL. Local pressure gradient forces, which drive convergent surface inflow and divergent outflow aloft, sustain the secondary circulations and roll updrafts. It is noteworthy that two low pressure centers are slightly displaced from each updraft maximum because the pressure perturbation can be divided into density and potential temperature perturbations (Saito et al. 2007), in which the effect of high temperature partly offsets that of low density in the convective updraft. This process seems to drive stronger surface inflow on the low pressure side (e.g., at $Y = 5.2\,\text{km}$), which may explain the asymmetry of the secondary circulations. Figures 9a and 9b show that the thermal/pressure disturbances and secondary circulation are well defined in a few major rolls. Therefore, a strong coupling of thermal and dynamic processes supports the rapid growth of major rolls. In particular, for the roll updraft at $Y = 2.8\,\text{km}$ that passes the village center, both thermal and pressure disturbances are dominant. The intensified local circulation allows this roll to gather more heat than its neighboring rolls, sustaining a strong thermal band downwind of the village (Fig. 8b). In contrast, the updrafts are relatively weak at $Y = 2.3, 3.4,$ and $3.9\,\text{km}$, downstream of the rice paddy fields (Figs. 9a,b). Here the thermal/pressure disturbances and secondary flows are less evident; thus, the weaker feedback process results in the slower growth of roll convection.

In contrast to the rolls in EXP2 with evident regionality, Fig. 9c shows that roll updrafts in EXP4 exhibit comparable strengths and heights, in which $w \approx 0.5\,\text{m}\,\text{s}^{-1}$ extends to $\sim 150\,\text{m}\,\text{AGL}$. In each updraft, both turbulent thermals and secondary flows have nearly uniform magnitudes and have regular spacing of $\sim 670\,\text{m}$ (equivalently $\sim 490\,\text{m}$ in cross-roll plane). The pressure disturbances share similar features and thus maintain secondary flows at a uniform intensity, as shown in Fig. 9d. The findings strongly suggest that the individual rolls compete with each other over homogeneous surfaces. A comparison of Figs. 9a,b and 9c,d shows that, although roll convection occurrence increases in EXP4, the major rolls are much weaker than those in EXP2. In particular, the roll updraft downstream of the village ($Y = 2.8\,\text{km}$) may strengthen and extend higher in EXP4 than in EXP4. As stated previously, over heterogeneous land-use areas, major rolls can become dominant over their neighboring rolls. This heterogeneity-related process in EXP2, despite the weaker mean surface heat, seems to produce stronger local updrafts than observed in EXP4.

It is known that the thermal conditions of a land-use configuration can greatly modify turbulent structures (e.g., Courault et al. 2007; Huang and Margulis 2009; Kang and Bryan 2011). When background wind exists (typically for roll convection), the induced circulation is more evident when land-use heterogeneity is aligned with the mean wind direction (Letzel and Raasch 2003; Prabha et al. 2007). Realistically, the flows tend to feel the surface heat pattern in a streamwise direction, generating roll-like convection. Over inland regions, time averaging and resembling mean are often used to distinguish the heterogeneity-induced circulation from background turbulence (Maronga and Raasch 2013). At Sendai Airport, the land-use configuration is not a streak or chessboard layout that typically affects roll convection. However, less background turbulence to distract roll convection is present within the sea breezes in coastal areas. The regional features of roll convection clearly result from the different growth speeds of individual updrafts over various surfaces during their inland evolution. Arguably, based on Figs. 8–9, warm surfaces may initiate strong feedback processes among IBL disturbances, triggering a rapid growth in roll convection downstream compared with cool surfaces. An implication of this surface dependence is the good predictability of the individual rolls over coastal areas.

**d. Roll energy production over various surface conditions**

HCR formation and growth are often linked to buoyancy and shear forces in the CBL (Asai 1964, 1970; LeMone 1973; Moeng and Sullivan 1994; Weckwerth et al. 1997). As cool marine air flows over warm land, a sea breeze sets up a moderately unstable IBL and wind shear favorable for roll convection growth (Fig. 4). To clarify roll forcings of various surfaces, we investigate the budget of the resolved roll-scale turbulent kinetic energy [TKE; Eq. (1) in Part I]. In addition to the TKE generation by buoyancy ($\frac{\partial \overline{\rho u_w}}{\partial z}$) and shear ($\overline{\rho w_0 \partial U/\partial z}$), the TKE variations induced by turbulent transport ($-\overline{\partial w E/\partial z}$) and pressure transport ($-\overline{\partial w p/\partial z}$) are also included to illustrate the roll’s upward growth. Note that the transport terms only redistribute TKE vertically because their integration through the CBL is exactly zero (Lenschow et al. 1980; Moeng and Sullivan 1994; Lin 2000). The formation mechanisms of sea-breeze HCRs are illustrated in Part I. Here, we focus on the similarities and differences in the TKE budget among four sensitivity experiments and
then link them to roll characteristics. To describe inland evolution, the TKE budget is estimated over the major built-up areas (X = 5 km) and downstream areas (X = 4 and 3 km). Because the mean flows are horizontally inhomogeneous due to the sea-breeze transition, the related linear component is identified via linear regression and is removed before defining the perturbation quantities in the TKE budget estimation.

First, we examine profiles of the TKE productions in the experiments with and without buildings (EXP1–2), as shown by the first and second columns in Fig. 10. In both experiments, the height of positive buoyancy

![Fig. 10. Production of TKE by buoyancy B, shear S, turbulent transport T, and pressure transport P in the four experiments. The triangles at the vertical coordinates approximately mark the top of the internal boundary layer, as diagnosed from the inversion in Fig. 4. The profiles estimated at (a)–(d) X = 5, (e)–(h) X = 4, and (i)–(l) X = 3 km, which display the inland evolution from southeast to northwest, as shown by the rectangle in Fig. 2c.](image-url)
increases steadily inland along with a deepening IBL (from 120 m at $X = 5$ km, 180 m at $X = 4$ km, to 240 m at $X = 3$ km). The maximum buoyancy occurs in the middle IBL, where the updrafts are most intense. Small negative buoyancy appears at the IBL top due to entrainment. Figures 10a and 10b show that, over the built-up areas ($X = 5$ km), the buoyancy term is somewhat smaller in EXP1 than in EXP2. Because the buoyancy is directly linked to convective updrafts, it explains a suppression of roll convection over the buildings’ zone arising from mechanical interruption of coherent growth of the existing rolls. Buoyancy in EXP1 is smaller than that in EXP2 at $X = 4$ km (Figs. 10e,f), but it becomes marginally stronger downstream at $X = 3$ km (Figs. 10i,j). Thus, although the roll updrafts are temporarily interrupted over the buildings’ zone, they undergo relatively fast growth in the downstream areas, as shown in Figs. 3a and 6–7.

Figures 10a and 10b show that the shear term of the TKE production is significantly large in EXP1, particularly near the surface, compared with that in EXP2. The term expresses an evident dynamic effect of strong shear due to building drag (Fig. 4a) and large momentum flux due to building-induced ejections (Fig. 11a). Such shear force contributes to organizing near-surface turbulences into roll-like coherent structures in the wake zone, as shown in Fig. 6. Previous studies noted that enhanced wind shear above the building canopy helps trigger turbulent organized structures over idealized building arrays (Kanda et al. 2004; Park and Baik 2014). The results here confirm that this hypothesis may also hold for realistic complex buildings. Figures 10e and 10f show that, in both EXP1–2, the shear term of the TKE production declines with decaying wind shear in the middle IBL (Figs. 4a,b), despite enhanced momentum flux (Fig. 11e). The shear production maintains strength in the upper IBL where the momentum flux and wind shear coexist (Figs. 11e and 4a,b). The shear term helps establish streaky structures in the upper IBL to support roll growth, as shown by the strengthening velocity variances (Figs. 3b,d).

The first and second columns in Fig. 10 also show that EXP1 and EXP2 share similar transport terms. The turbulent transport is negative at the lower half of the IBL and positive at the upper half of the IBL because the kinetic energy fluxes ($w'u'^2 + w'v'^2 + w'^2$), particularly $w'^2$, are usually maximized in the middle of the IBL (Figs. 11b,c,f,g,i,k). The vertical convergence thus leads to a local TKE gain in the upper IBL. Although vertical motion is slightly weak in EXP1 at $X = 4$–5 km, there is an enhanced flux of horizontal kinetic energy that is related to ejections (Figs. 11b,f). As a result, the difference in the turbulent transport in EXP1–2 is small.

Moreover, pressure transport produces a TKE gain near the surface and a TKE loss in the middle of the IBL (Figs. 10a,b,e,f,i,j), which expresses a dynamic effect because pressure perturbations are collocated with updrafts/downdrafts (Fig. 9b). The TKE production by pressure transport becomes positive at the top of the IBL (Figs. 10a,b,e,f,i,j) due to flux convergence (Figs. 11d,h,l). This process is related to the establishment of high pressure perturbations in the upper IBL (Fig. 9b), where vertical gradients aloft are favorable for overshooting updrafts. In quasi-steady experiments, the TKE gain by pressure transport is largely offset by negative buoyancy at the top of the CBL (Lenschow et al. 1980; Moeng and Sullivan 1994; Lin 2000). Here, the sum of the transport terms is much larger than the buoyancy term. Therefore, the two transport terms, particularly pressure transport, provide extra energy at the top of the IBL for driving upward growth of roll convection. The comparable magnitudes and vertical extents of the transport terms in EXP1–2 explain the similar upward growth of rolls, despite differences in the buoyancy and shear terms. Note that the transport terms are mainly localized to some rolls, as shown by the pressure perturbations over inhomogeneous surfaces (Fig. 9b), and thus contribute to the fast upward growth of dominant rolls.

We proceed to examine the TKE budget over various land-use conditions by comparing EXP2–4. Figures 10c, 10g, and 10k show that the buoyancy term in EXP3 is smaller in magnitude and lower in vertical extent than that in other experiments. The weak buoyancy seems to explain the less-developed updrafts (Figs. 2c, 3e, and 8d). Near the surface, the shear term of the TKE production has a magnitude that is comparable to the buoyancy term, which is typical for the initiation of roll convection (e.g., Weckwerth et al. 1997). The near-surface shear term in EXP3 is strongest among the three experiments without buildings (EXP2–4). Weak turbulent mixing in EXP3 (Fig. 3e) allows for sustained wind shear in the sea breeze (Fig. 4e). With moderate shear and enhanced momentum fluxes (Figs. 11a,e,i), the shear production of the roll energy can maintain strength and sustain roll-type convection. Figures 10c, 10g, and 10k also show that the two transport terms are near zero at the top of the IBL. A combination of weak buoyancy and transport terms thus explains that roll convection undergoes a relatively slow upward growth over cool surfaces.

Figures 10d, 10h, and 10l show that, in EXP4, the maximum buoyance in the middle IBL is very large and corresponds to the roll’s uniform height, as indicated in Fig. 3g. The shear term in the lower IBL decays fast and even becomes negative at inland regions at $X = 3$–4 km.
The suppressed shear term results from the decaying wind shear (Fig. 4d) and momentum fluxes (Figs. 11e,i). The two transport terms, particularly pressure transport, are positive at the top of the IBL, providing a local TKE gain for upward roll growth. However, the height of the TKE gain remains somewhat lower than that in EXP2 (cf. Figs. 10h,l and 10f,j), which explains the slower upward growth of roll convection over uniform surfaces, in contrast to that over heterogeneous surfaces. Meanwhile, a large pressure transport term appears near the surface, where regular low pressure perturbations help form updrafts (Figs. 9d and 11h,l). Thus, it is inferred that pressure transport near the surface contributes to sustaining roll-type convection despite the rapidly
decaying shear term in EXP4. As revealed in sections 3b,c, the roll growth is associated with strong coupling among the turbulent thermals, convective updrafts, pressure perturbations, and secondary flows. Here, it is further shown that buoyancy and shear forces work effectively as the streaky thermals to drive roll-like updrafts, while transport processes become important as the updrafts couple with kinetic energy and pressure perturbations to support the upward growth of rolls. Such variable forcings in EXP1–4 clearly reflect the energetics of various surfaces that regulate roll characteristics.

4. Conclusions

The convective rolls in sea breezes near Sendai Airport have been numerically investigated using a CFD model nested in a mesoscale model with a data assimilation scheme. Sensitivity experiments are compared to reveal and understand the impacts of different surface features on roll positions, intensities, and structures. The results suggest that roll convection intensity depends primarily on the thermal condition of the land surface, and it is strongly modified by land-use heterogeneity. Major rolls develop downwind of built-up areas, rather than over rice paddy fields. Two areas of major updrafts separated by ~2 km correspond to a configuration of the airport and a village. Such a heterogeneity-induced mode is superimposed on the inherent mode of the roll wavelength of ~500 m. These regional features over the actual land use are distinct from the homogeneous features that occur over uniform surfaces. An analysis of the vertical structures shows that roll convection growth is facilitated by a positive feedback, in which turbulent thermals drive convective updrafts, produce pressure perturbations, and enhance secondary flows that in turn strengthen thermal disturbances. With an effective feedback initiated by warm surfaces, roll convection undergoes faster growth than the neighboring areas, forming dominant rolls downstream. The importance of land-use heterogeneity on rolls is also highlighted by the local intense updrafts over inhomogeneous surfaces, despite a lower mean surface temperature compared with uniform industrial land.

The experiments with and without buildings are compared to highlight the mechanical effects of the buildings. The results show that the rolls prefer to initiate in the wake zone of coastal buildings, where a confluence of warm air is established. The coherent growth of preexisting roll structures can be interrupted by the presence of buildings, but they redevelop at the lees of buildings. The convergent warm air emerging from the buildings’ zone stretches downstream due to wake flows, triggering turbulent coherent structures in the form of low-speed and rising-motion streaks. The building-induced structures may vary with the different morphologies of building densities and arrangements. The most effective accumulation of warm air is observed over the village with scattered single-family houses that are aligned with the ambient wind direction, where building drag continues to slow the wind speed. In this area, the thermally driven rising motion and counterrotating secondary circulation tend to displace roll updrafts toward the village axis. The sustained secondary circulations and organized updrafts/downdrafts allow the building-induced signature to maintain its strength over the downstream open areas at a considerable distance of 1–2 km from buildings.

An analysis of the TKE budget shows that buoyancy and shear forces work together to organize near-surface warm air into sheets, which are then carried aloft by buoyancy and evolve into roll-type updrafts. Such forcing mechanisms in sea-breeze HCRs support the general understanding of other rolls (e.g., Moeng and Sullivan 1994; Weckwerth et al. 1997). We also found that the strength of TKE generation varies with different surfaces, and the transport processes at the top of the IBL greatly regulates the upward growth of rolls. Buoyancy and shear forces remain comparable over cool surfaces, producing weak roll updrafts. The buoyancy term is enhanced over warm surfaces to produce more active updrafts. In the presence of land-use heterogeneity, the growth of some rolls is distinctly facilitated by both local buoyancy and TKE gain by transport processes at the top of the IBL. Specifically, convective updrafts driven by enhanced buoyancy over warm surfaces maintain their roll patterns with the help of pressure perturbations and secondary flows. Thus, a strong thermal–dynamic coupling localizes turbulent energy to drive major rolls that grow higher than their neighbors. In the presence of buildings, the shear production of TKE increases significantly, arising from the strong wind shear and momentum fluxes. Although roll structures may be displaced or degraded by the mechanical effects over building zone, the enhanced shear and wake flows help organize warm air into streamwise streaks and redevelop the coherent roll structures at the lees of the buildings. As a result, roll convection can undergo a rapid recovery over downstream open areas.

HCR formation and growth are closely associated with mesoscale weather conditions (e.g., Weckwerth et al. 1997). It is speculated that the predictability of mesoscale weather may help determine predictable dynamics of HCRs. In Part I, adequately capturing sea breezes is shown to lead to improved simulations of the general features of roll convection, such as strength,
orientation, wavelength, and regional differences. In
Part II, the behaviors of individual rolls are further
shown to clearly respond to land use and buildings that
locally affect IBL disturbances. A description of complex
surfaces in numerical models is thus essential for fore-
casting detailed structures of roll convection. Consider-
Part I and Part II together, it is argued that individual
HCRs with less distracting background turbulence in
coastal areas can be reproduced with reasonably good
accuracy, in contrast to treating them as eddies with low
predictability. Note that it is not necessary to use de-
terministic forecasting, as is used in this study. To con-
sider uncertainties, an ensemble forecast of HCRs is
feasible by using the ensemble members of mesoscale
weather and surface thermals to drive the CFD model.
Other solutions, as noted in Part I, involve improved
mesoscale modeling at gray-zone resolutions (Dorrestijn
et al. 2013; Shin and Hong 2013; Beare 2014; Ching et al.
2014) and advanced nesting strategies to bridge the
transition from mesoscale to microscale models for
simulating small-scale turbulence (Mirocha et al. 2014;
Münoz-Esparza et al. 2014a,b). Nevertheless, more
studies on HCRs in various weather and surface condi-
tions are required to identify and correct the model de-
ficiencies in predicting roll convection and mean
properties in the CBL. Such studies will further promote
our understanding of land–atmosphere interactions and
local weather over coastal cities; this information would
be valuable for research communities, forecast purposes,
and related societal applications.

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