

Mesoscale-to-LES Modeling of the Sea-Breeze Front and Its Interaction with Turbulent Flows over a Coastal City

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ABSTRACT: The sea-breeze front (SBF) intruding into coastal cities can lead to sudden changes in local weather and air quality. Its structures and disturbances over the urban surface with dense tall buildings have been a challenge for numerical modeling. In this study, we present the fine-scale structures of an actual SBF simulated by mesoscale-to-large-eddy simulation (LES) models at 3-m resolution in a 15-km domain of Sendai City, Japan. The head of SBF is shown to develop remarkable three-dimensional structures in the downtown area, where it interacts strongly with the microscale turbulent flows induced by buildings. Localized strong updrafts form at the lees of high-rise buildings within a few minutes just after the passing of the SBF, as ejections emerge in urban warm air mass surrounded by the cool air mass of the sea breeze. Downdrafts in the sea breeze are seen at the windward sides of high-rise buildings and help to increase wind speed in adjacent streamwise streets. After the passage of SBF, near-surface wind speeds exhibit high-frequency fluctuations with a period of 2–3 min, in good agreement with in situ observations in the downtown area. These results demonstrate the good capabilities of the building-resolving LES of both mesoscale weather conditions and microscale turbulent flows over a large city for the prediction of urban weather and environment in the streets.

SIGNIFICANCE STATEMENT: The sea-breeze front (SBF) has significant impacts on the local weather in coastal cities around the world. It is challenging to simulate the fine-scale structures of SBF and their interactions with turbulent flows over the cities. In this study, we present an improved building-resolving numerical simulation of an actual SBF that develops fine-scale structures in the downtown area with high-rise buildings. The SBF head is shown to be strongly disturbed by buildings and interacts with urban turbulent flows, which drive local strong updrafts and vertical transports of heat. The passing SBF also leads to high-frequency fluctuations in the simulated surface wind speed, in good agreement with observations. The results are helpful for improving our understanding and prediction of the local winds at street scales during the passing of the front.

KEYWORDS: Density currents; Updrafts/downdrafts; Sea breezes; Wind; Large eddy simulations; Numerical analysis/modeling

1. Introduction

The sea breeze has great influence on local weather and atmospheric environment in coastal cities, where a large portion of the global population lives. Its intrusion on land is characterized by the passage of the sea breeze front (SBF) that leads to sudden changes in temperature, pressure, winds, and aerosols (e.g., Simpson 1994). The marine cool air mass behind the SBF brings a drop in temperature and thus relief from the hot weather in summer (Inoue and Kimura 2004; Hu and Xue 2016). The passage of the SBF also increases the near-surface winds that favor wind energy and ventilation in cities. The updrafts at the SBF head act to enhance the vertical exchange of heat and momentum, as well as the dispersion of air pollutants

in the atmospheric boundary layer (Iwai et al. 2011). These frontal updrafts may sometimes induce cloud formation and convection initiation that favor local thunderstorms (Atkins et al. 1995; Moncrieff and Liu 1999; Fovell 2005; Boyouk et al. 2011; Saito et al. 2018; Ito et al. 2021). Detailed structures, dynamics, and impacts of the SBF particularly over coastal cities have been key scientific issues and societal applications (Miller et al. 2003; Crosman and Horel 2010).

The SBF, as a typical density current, has pronounced fine-scale structures, and its leading edge is featured by a number of localized updrafts/downdrafts at a scale of several hundreds of meters (Nakane and Sasano 1986; Simpson 1994; Mayor 2011; Chen et al. 2019). As the SBF penetrates the city, these fine-scale structures are likely subject to the local disturbances of dense buildings (Thompson et al. 2007). The built-up area of a large city has a horizontal extent of several tens of kilometers and a vertical extent of a few hundreds of meters that are comparable to the scales of the SBF. Turbulent flows can

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be highly active in urban boundary layers that may be organized into coherent structures depending on background weather conditions (Inagaki and Kanda 2010). In turn, the building-induced microscale disturbances may regulate the detailed structures of mesoscale weather, and thus we can expect that the SBF structures and induced surface winds become more complicated over the urban area than those on a flat surface (Jiang et al. 2017; Chen et al. 2019). Such an across-scale interaction between turbulent flows and the sea breeze is key for understanding the formation of SBF fine-scale structures, which will help the prediction of local weather in coastal cities (Thompson et al. 2007; Crosman and Horel 2010). Building disturbances have been well examined particularly under homogeneous ambient flows (e.g., Oke et al. 2017). Their activities over a large city-scale area under the density current type of flows with large gradients are less understood. A key question is how the building-induced turbulent flows develop on the SBF when passing a densely built-up area. Of particular interests are how localized updrafts/downdrafts and horizontal wind fluctuations form during the short period of SBF passage.

The mesoscale-to-microscale coupling has been a long-standing challenge for numerical modeling across scales (Atkinson and Zhang 1996; Muñoz-Esparza et al. 2014; Haupt et al. 2019). Mesoscale meteorological models are widely used to capture the dynamic processes of the atmosphere at horizontal scales ranging from a few to several hundreds of kilometers (e.g., Saito et al. 2006), and on the other hand, large-eddy simulations (LESs) serve for resolving microscale phenomena (e.g., Sha et al. 1991; Cunningham 2007). Recent studies have developed mesoscale-to-LES models, in which an LES model is coupled with a mesoscale model, for explicitly resolving both mesoscale weather and microscale turbulent flows under actual atmospheric conditions (Chen et al. 2011; Nakayama et al. 2012; Chen et al. 2015; Mazzaro et al. 2017; Muñoz-Esparza et al. 2018). Such mesoscale-to-LES modeling may offer good applications for studying across-scale interactions between the SBF and turbulent flows. For instance, Chen et al. (2019) reproduced the SBF that develops fine-scale structures with the pulsation of gravity current and turbulent flows in coastal areas, which are in good agreement with lidar observations. The buildings, though being low and scattered in coastal airport area, are shown to somewhat disturb the SBF. It is unclear how the fine-scale structures of SBF evolve in the downtown area where high-rise buildings may strongly disturb local winds and temperature patterns. The modeling of the SBF over a built-up area (as a density current type of flows intruding city) may provide us insights into the dynamics of SBF and its impacts on local weather (Thompson et al. 2007; Crosman and Horel 2010). Such numerical experiments require huge computational resources because refined meshes with a few meters of grid spacing are needed for resolving a large number of individual buildings over a large city tens of kilometers wide. Therefore, another benefit is to demonstrate the capabilities of a high-resolution CFD model in simulating the actual SBF when passing over a city with complex street and building structures.

In this study, we carry out mesoscale-to-LES modeling of an actual SBF that passes the city of Sendai, Japan, so that its interaction with urban turbulent flows and its impact on local

weather at the street scales can be clarified. The data, model configuration, and evaluation are briefly introduced in section 2. In section 3, we present the general structures of simulated SBF that develop over a densely built-up area by comparing the two numerical experiments with and without buildings. We further investigate the formation of the SBF's fine-scale structures in section 4, with emphasis on the detailed disturbances by high-rise buildings in the Sendai downtown. In section 5, we also examine the high-frequency fluctuations in surface winds during the SBF passage. Concluding remarks are given in section 6.

2. Data and methods

a. The SBF event targeted and data used in this study

In this study, we examine an SBF event that occurred at the Pacific coast of Japan on 19 June 2017, which was a typical summer event (Chen et al. 2015; Peng and Watanabe 2022). The fine weather conditions during daytime led to a fast surface warming and low pressure on land that drove the sea breeze (southeasterlies) at the coast of northeastern Japan (Figs. 1a,b). Previous studies have examined this event, with emphasis on the roll convection in afternoon hours that forms in the smooth flows of the sea breeze over Sendai Airport with scattered low buildings (Chen et al. 2015). Another interesting phenomenon of that day is the SBF that penetrated Sendai City earlier in the morning hours at about 1000 Japan standard time (JST). Such an intrusion of the SBF into the city is suitable for studying the urban turbulent flows that form over a densely built-up area under weather conditions with relatively large gradients, which is the scope of this study.

In this study, to describe the general features of the sea breeze, we use the Automated Meteorological Data Acquisition System (AMeDAS) data (i.e., surface meteorological station data) from the Japan Meteorological Agency (JMA). The hourly conventional observations of AMeDAS data over northeastern Japan were also applied for the data assimilation (DA) of the mesoscale model (Fig. 1b). For the vertical structures of the sea breeze, we use the lidar observation data that were collected by a field investigation over the Sendai Airport (Iwai et al. 2008). The velocity–azimuth display (VAD) analysis of lidar data provides us with the vertical profile of winds at the hour of interest (1000 JST). To detect the high-frequency fluctuations of near-surface winds in the built-up area, we also use the AMeDAS data in Sendai downtown at 1-min intervals provided by the Japan Meteorological Business Support Center. The AMeDAS is installed in the Sendai District Meteorological Observatory, about 1 km eastward from the Sendai railway station. These observation data of the sea breeze will be used to validate the output of numerical models.

b. Experiment settings of mesoscale-to-LES modeling system

In this study, we conduct the mesoscale-to-LES modeling on the SBF with individual buildings resolved for a large city domain. For a better prediction of both mesoscale conditions and

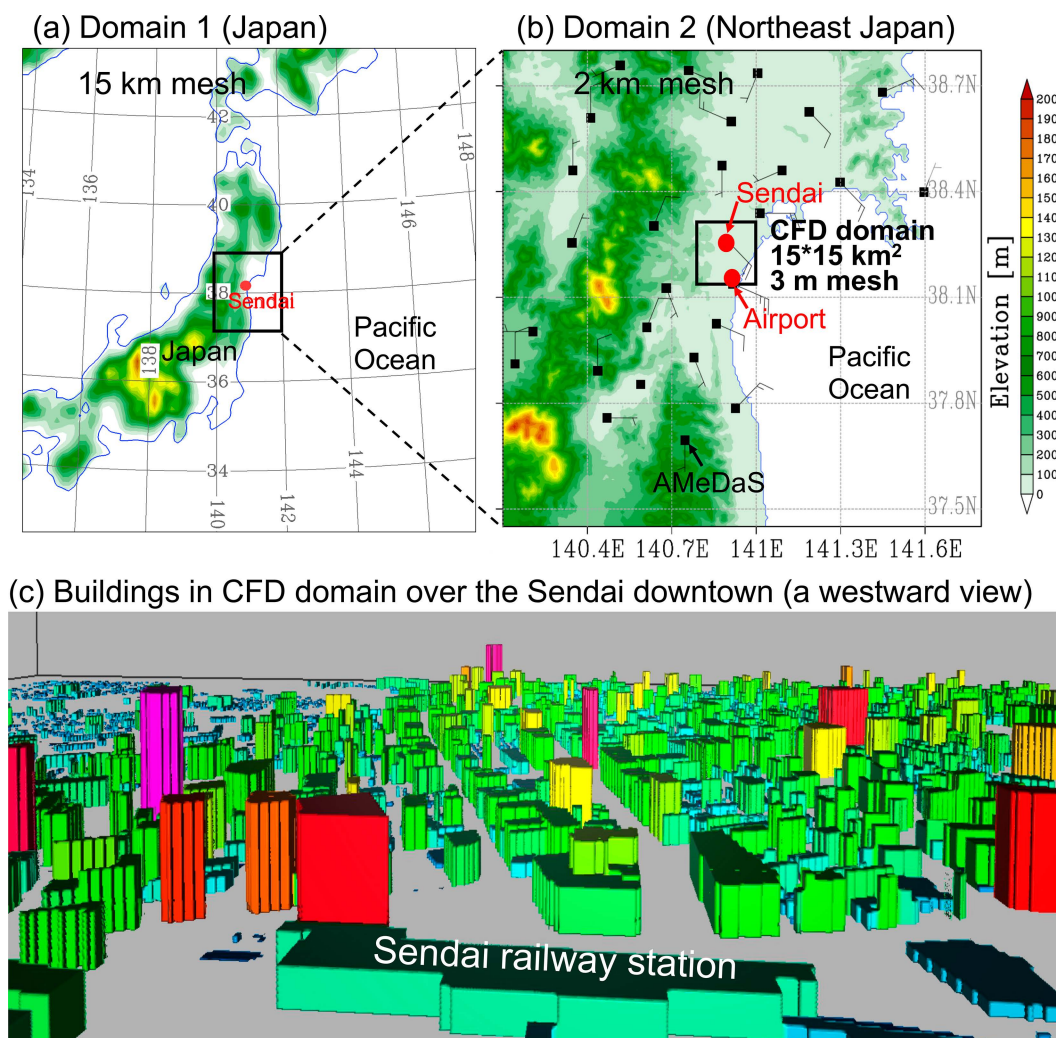


FIG. 1. Domains of this study for the mesoscale-to-LES modeling system. (a),(b) The domains are downscaling from JMA-NHM (Japan and its northeast areas) to the CFD model (Sendai domain). The surface winds (with a full wind barb denoting 2 m s^{-1} at 1000 JST) at AMeDaS sites are marked in (b). (c) The 3D visualization of the buildings in the CFD model at 3-m resolution in the downtown area of Sendai City.

microscale turbulent flows, we have developed an advanced modeling system, in which a computational fluid dynamics (CFD) model is one-way nested to a mesoscale meteorological model (Chen et al. 2015). First, the mesoscale conditions of SBF are derived by the JMA non-hydrostatic model (JMA-NHM) (Saito et al. 2006). The JMA-NHM is established using the fully compressible equations on hybrid terrain-following coordinates, which are implemented with physical processes (including cloud microphysics, surface processes, boundary layer scheme, convective parameterization, and atmospheric radiation). For an improved accuracy, we conduct JMA-NHM with a data assimilation scheme (Miyoshi and Aranami 2006; Seko et al. 2011). We perform data assimilation in the domain of Japan with a 15-km mesh and in that of Japan's northeastern region with a 2-km mesh (Figs. 1a,b), with 1-km resolution topography from GTOPO30. The data assimilations of these two domains are conducted by a two-way nested system using the

local ensemble transform Kalman filter. The temperature, winds, and humidity from conventional observation networks are assimilated. Then, the hourly assimilated data at 2-km mesh are used to make short-range forecasts at grid spacing up to 100 m. The forecasts of horizontal winds, vertical velocity, temperature, and pressure fields at 6-hourly cycles from JMA-NHM just before the intrusion of the SBF on Sendai downtown are used as the initial and lateral boundary conditions for driving the innermost CFD model.

A building-resolving CFD model is used to simulate the fine-scale structures of the SBF and turbulent flows in built-up areas (Sha 2002; Chen et al. 2015). The model is established in the 3D Cartesian coordinates, and so it can resolve steep topography and buildings. It solves the fully compressible Navier–Stokes equations using an algorithm of the semi-implicit method for pressure-linked equation revised code (Patankar 1980; Sha et al. 1991). The finite volume method on

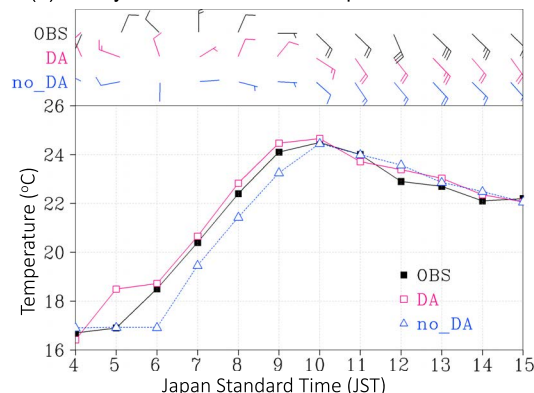
a staggered grid system is adopted as the discretization approach. A Lilly–Smagorinsky LES is used to resolve large eddies and to parameterize small eddies (Lilly 1962; Smagorinsky 1963). It uses the block-off technique to handle steep topography and buildings, so that the dynamic impacts of surface geometries are considered. The skin temperature is applied to the land surface and building walls, so that their thermal effect is taken into account, while moisture process and radiation heating are excluded. An improved Orlanski-type radiation condition is employed to handle lateral and upper boundaries (Orlanski 1976). These settings of the model had been tested in the Sendai area by previous studies (Chen et al. 2015, 2019).

The major advantages of this study are the numerical experiments at LES resolutions for a large city domain. A spatial resolution of 3 m is applied for a 15×15 km² domain with a total grid number of up to 5 billion (Fig. 1b). The vertical resolution of 3 m is also used in the layers up to 600 m AGL for explicitly resolving both individual buildings and SBF structures. The building data at meter resolution are provided by Zenrin Map Company, which are used for the CFD model and for 3D visualization by NCAR VAPOR (Li et al. 2019). A large number of high-rise buildings in the downtown near Sendai railway station can be explicitly resolved and visualized (Fig. 1c), which is the focus area of this study. Many buildings in the downtown area are 30–60 m high, and the tallest one is about 110 m high, while most one-family houses in the outskirt area are 6–10 m high. These building-resolving experiments for a city domain require a large computation source, and they are processed by 40 000 cores on the K computer, which was the former flagship supercomputer in Japan (Saito et al. 2023). The skin temperature of building walls is set as the urban ground temperature, which is prescribed by the mesoscale model at 100-m spacing grids. The lateral boundary conditions are also provided by the output from the mesoscale model, which is fixed for the short period of CFD modeling. In this study, we compare the control run with buildings and another test run with buildings removed but urban ground temperature kept, so that we may clarify how large the dynamic effects of buildings are on the fine-scale structures and progress speed of SBF.

c. Model evaluation against observations

In this study, we can evaluate the performances of mesoscale-to-LES modeling systems against the observations including the AMeDAS data at both 1-h and 1-min intervals and the lidar-derived wind profiles as introduced in section 2a. The southeasterly sea breeze was first recorded in the coastal area of Sendai Airport at 0900 JST and then intruded fast inland by a distance of ~ 16 km from coastline by 1000 JST (Fig. 1a). Figure 1a shows that, in the hours after sunrise (0600–0900 JST), surface temperature in the city of Sendai increased fast by ~ 2 K h^{−1}. The SBF passed the Sendai downtown at 1000 JST, with an increasing wind speed and a shifting wind direction from northerlies to southeasterlies (Fig. 1a). The sea breeze also led to a temperature drop after 1000 JST, in a robust contrast to the increasing temperature at other inland sites ahead of the SBF. In general, the mesoscale model simulates the passage of the SBF at 1000 JST.

(a) Hourly surface winds and temperature in Sendai City



(b) Vertical profile over Sendai Airport at 10:00 JST

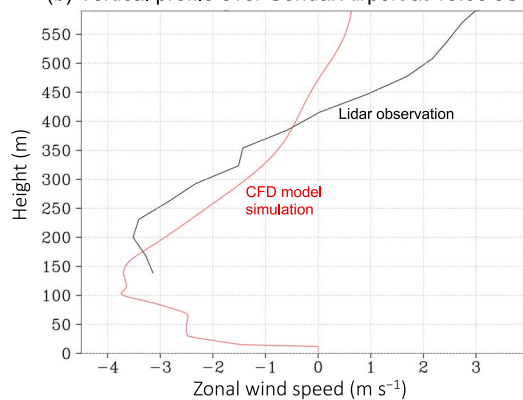


FIG. 2. Observation and modeling of the sea breeze on 19 Jun 2007. (a) Hourly variations of near-surface winds at 10 m AGL (with a full wind barb denoting 2 m s^{-1}) and temperature in Sendai City derived by the AMeDAS observation, mesoscale model with DA and without DA (no_DA). (b) Vertical profile of zonal wind over Sendai Airport at 1000 JST derived by lidar observation and the CFD model.

The model output with data assimilation was found in good agreement with the hourly observations of temperature and wind speed/direction. The bias in temperature was as small as 0.3 K, and that in wind speed was less than 1 m s^{-1} . It outperformed the model without data assimilation for most hours during 0600–1500 JST. We may expect this consistency because hourly observation data are assimilated.

We further evaluate the vertical structures of the sea breeze using the wind profile derived by the VAD analysis of lidar observation at 1000 JST at Sendai Airport, which is located upstream of Sendai City. Figure 2b shows that the sea breeze (easterly wind component) dominated in the lowest level below 400 m, while the return flow (westerly wind component) was seen aloft. The maximum easterly wind of 3.5 m s^{-1} at the height of 200–220 m was also noted as the height of the sea-breeze internal boundary layer (Iwai et al. 2008; Chen et al. 2015). The wind profile in the CFD model showed good agreement with that of the lidar observation, although the simulated height of maximum easterly wind was slightly lower than the observed one.

We also compared the simulated near-surface winds with the observation data at 1-min intervals in Sendai City. The detailed evaluation and analyses of building-induced disturbances on surface winds are shown in [section 5](#). The CFD model was found to simulate the high-frequency wind fluctuations with a period of 2–3 min that were observed in the built-up area. The simulated magnitude of wind fluctuations appears to be larger than the observed one because of different time resolutions. Overall, the mesoscale-to-LES modeling system captured reasonably well the event of the sea breeze in three aspects (inland progress, vertical structures, and wind fluctuations), and thus the simulation data are suitable for the in-depth analyses of this study.

3. General variations of the simulated SBF passing Sendai City

[Figure 3](#) shows the spatial patterns of simulated SBF and updrafts in the built-up area of Sendai City. At the early time steps (FCST = 140 s), the southeasterly sea breeze of about 5 m s^{-1} and 296.2 K reaches the southern outskirts of the city ([Fig. 3a](#)). The leading edge of the sea breeze is characterized by a narrow convergence line where the marine southeasterlies collide with the relatively warm ambient northeasterlies from the downtown area. It also leads to a well-defined belt of frontal updrafts that are orientated nearly west–east. In the latter time steps (FCST = 280 and 420 s), the sea-breeze southeasterlies are penetrating inland, and the SBF moves steadily northward into the built-up area of the city. The updrafts are greatly disturbed and become more scattered in the Sendai downtown. Some updrafts develop in the downtown area ahead of the SBF (northwest sector of the domain), and they denote the formation of urban turbulent flows. These prefrontal updrafts are organized by a secondary convergence boundary (SCB) in the ambient northeasterly flows with temperature differences between the downtown area ($\sim 298.4 \text{ K}$) and its northeast outskirts ($\sim 297.5 \text{ K}$). In contrast, the updrafts are less seen in the south sector of the domain where the cool air mass of the sea breeze dominates, though some localized updrafts appear less than 0.5 km behind the SBF.

[Figure 3b](#) shows that, in the experiment without buildings, the simulated SBF maintains its coherent pattern while moving northward. The SCB ahead of the SBF also becomes more pronounced. The updrafts of both SBF and SCB tend to be organized into line patterns rather than scattered distributions. The large differences between [Figs. 3a](#) and [3b](#) suggest that both the SBF structures and urban turbulent flows can be remarkably disturbed over the built-up area of the city.

[Figure 4](#) shows the vertical structures of SBF in the minutes when passing the Sendai downtown. In the early time steps ([Fig. 4a](#)), the relatively cool southerlies of the sea breeze are mainly seen in the layer below 200 m AGL, while the northerlies of the ambient flow occur in the upper levels above 300 m AGL. The isothermal surface of 297 K may distinguish the layer of the sea breeze from that of ambient flow. These vertical structures are in good agreement with lidar observations, as noted in [section 2c](#). The SBF shows the typical characteristics of a gravity current, with an elevated head of cool air

mass ($Y = 6.5\text{--}7.3 \text{ km}$) and a large temperature gradient at the leading edge. Strong updrafts of $2\text{--}3 \text{ m s}^{-1}$ occur at the leading edge of the SBF ($Y = 7.3 \text{ km}$), while downdrafts form in the upper levels behind the elevated head ($Y = 6.0\text{--}6.5 \text{ km}$). The depth of the sea breeze is relatively low behind the elevated head ($Y = 6.0\text{--}6.5 \text{ km}$), but it is re-enhanced in the south area ($Y = 5.0\text{--}6.0 \text{ km}$). These repeated perturbations in the sea-breeze height are related to the Kelvin–Helmholtz instability (e.g., [Miller et al. 2003](#); [Plant and Keith 2007](#)). More interestingly, local perturbations in temperature and vertical motion become pronounced in the near-surface layers below 150 m AGL in the built-up area. In the experiment with buildings removed, we see the similar patterns of gravity current with updrafts at the elevated head of the SBF ([Fig. 4c](#)). The leading edge of the SBF is displaced north to $Y = 7.4 \text{ km}$, and the maximum updraft is slightly larger. However, the local disturbances relating to individual buildings are absent from the near-surface layers in [Fig. 4c](#), compared to those in [Fig. 4a](#).

[Figure 4b](#) shows that in the latter time steps of the control run, the SBF moves to the northern location at $Y = 8.1 \text{ km}$. The head of the SBF is evidently disturbed as indicated by the isothermals, and the frontal updrafts become scattered and weak. Behind the SBF head, it is followed by another enhancement of the sea breeze with low temperature near the surface at $Y = 7.4 \text{ km}$. The microscale turbulent flows with temperature perturbations and updrafts are clearly seen in the low layers below 200 m particularly near high-rise buildings ahead of or behind the SBF such as at $Y = 7.35 \text{ km}$. We expect that the SBF is strongly interacting with turbulent flows and develops fine-scale structures when passing the Sendai downtown.

In the experiment without buildings ([Fig. 4d](#)), the SBF arrives at $Y = 8.3 \text{ km}$, which is about 200 m faster than that in the control run. Some eddies develop at the head of the SBF over the warm urban ground at $Y = 8.5\text{--}9.0 \text{ km}$, though the dynamic effects of buildings are absent. The updrafts at the frontal head are temporally intensified when they are merging with prefrontal turbulent flows (as shown by the arrow in [Fig. 4d](#)), in good agreement with those in the idealized experiment ([Jiang et al. 2017](#)). Nevertheless, the winds and temperature in the sea-breeze layer as well as the SBF head are less disturbed than those in the control run because of the absence of building-induced eddies. So, the less-disturbed sea breeze corresponds to a relatively fast inland progress of the SBF in [Fig. 4d](#), while the building-induced turbulent flows may act as a frictional effect slowing down the SBF in [Fig. 4b](#). The results agree with the observations of previous studies in that the SBF movement becomes relatively slow and uneven in the built-up area (e.g., [Thompson et al. 2007](#); [Miller et al. 2003](#)).

A key issue in urban weather modeling is the growth of turbulent flows over the city. We need to examine how fast the turbulent flows are generated in the domain of the CFD model because the relatively smooth flows from mesoscale model are used as initial conditions. [Figure 5a](#) shows the spectrum of turbulent kinetic energy (TKE) over the downtown area (dashed rectangle in [Fig. 3a](#)) in the control run with buildings. At the first time step, the TKE in the CFD model increases from the initial condition (gray line) as the buildings

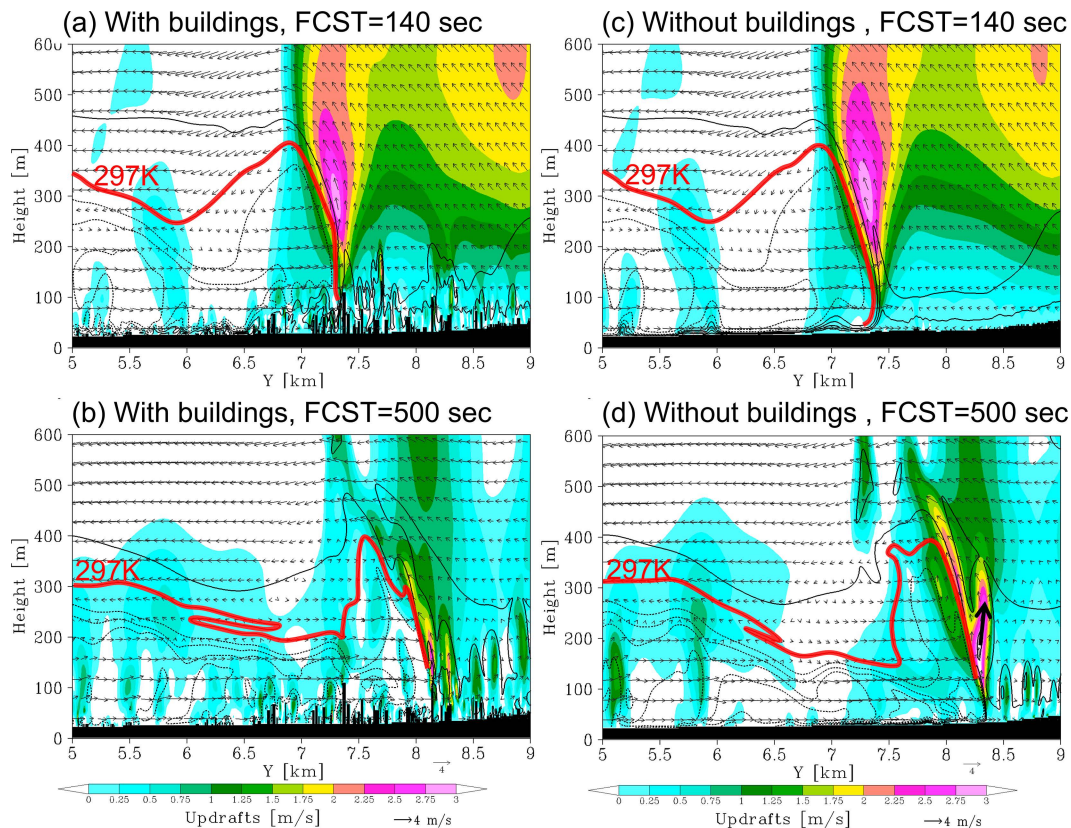


FIG. 4. Vertical section of updrafts (shading), horizontal winds (vectors), and temperature (solid contours for above 297 K and dashed for below 296.5 K) along the plane of $X = 6.85$ km simulated by the CFD model (a),(b) with buildings and (c),(d) without buildings. The bold contour in red highlights the height of the isothermal of 297 K, approximately denoting the depth of the sea breeze. The arrow in (d) denotes a growing updraft.

comparable to buildings. The deviation of the energy spectrum is also high at wavelengths larger than 400 m, which may suggest the thermally driven eddies being organized in coherent patterns. Such a growth of TKE at the low-wavenumber end of the spectrum may be related to the coming SBF and the growing SCB (Fig. 3a).

Figure 5b shows that, in the experiment without buildings, the CFD model also shows a growth of TKE but slower than the case with buildings. The simulated TKE reaches a quasi-steady state in about 5 min. The maximum energy is slightly higher for the low-wavenumber end of the spectrum in Fig. 5b (compared to that in Fig. 5a), which corresponds to the relatively strong SBF and SCB in Fig. 3b (compared to Fig. 3a). In contrast, the TKE spectrum is generally lower for the microscale disturbances with wavelengths smaller than 300 m. So, in the absence of buildings, the thermally driven eddies at a scale of several hundreds of meters seem more dominant, and they are less disturbed into the smaller-scale ones. These differences between the CFD runs with and without buildings are highlighted by the maximum TKE spectra (thick dashed lines in pink and blue in Fig. 5b), suggesting that the buildings are crucial for producing the active turbulent flows at microscale scales of 50–300 m. Meanwhile, it is interesting to see that the CFD model can simulate the growth of microscale

turbulent flows at a reasonable fast speed (about 5 min) particularly for those building-induced ones, so that a short-range forecast at relatively low cost can be applicable for analyzing the interactions between SBF and urban turbulent flows (Muñoz-Esparza et al. 2014; Jiang et al. 2017).

4. Interaction of SBF and microscale eddies over the built-up area

We pay more attention to the detailed variations of SBF structures in the Sendai downtown, where they may interact with building-induced turbulent flows. Figure 6 shows the three-dimensional patterns of air temperature near Sendai railway station, in which the cool isothermals denote the sea breeze and the warm isothermals denote urban air mass. At the early forecast time steps (Fig. 6a), the well-defined head of SBF comes from the left (south) and a large number of microscale eddies with warm perturbations are developing over the built-up area on the right (north). Figure 6c shows that in the experiment with buildings removed, the microscale eddies in warm air mass are less pronounced than those in Fig. 6a. Therefore, the urban eddies seem to develop the daytime boundary layer with moderate thermal instability, and they are highly promoted by the small disturbances of

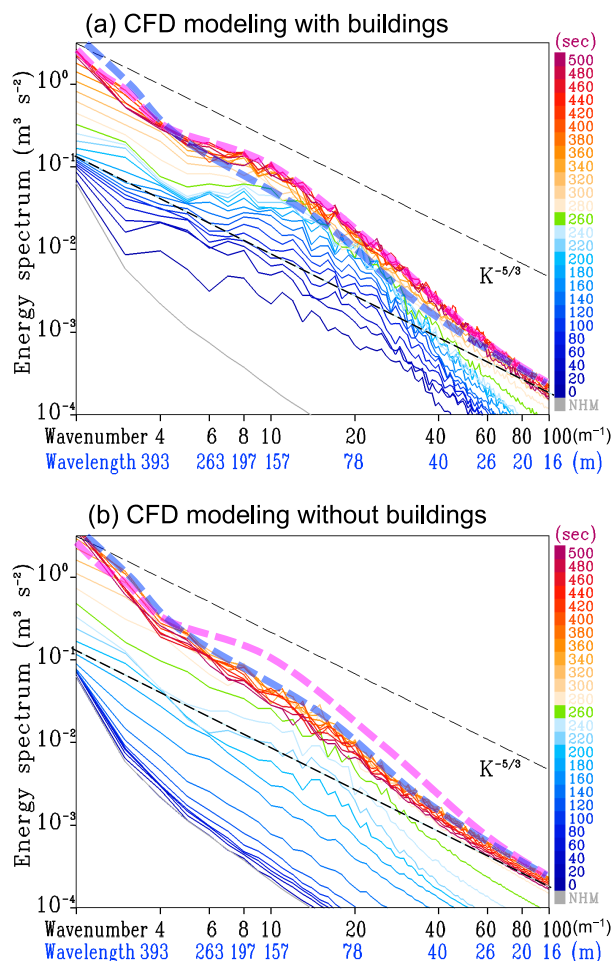


FIG. 5. Spectrum of TKE at 100 m AGL in the CFD model (a) with buildings and (b) without buildings. The analysis domain is shown by the dashed rectangle in Fig. 3a. The thick dashed line in pink denotes the maximum value in the run with buildings, and that in blue denotes the run without buildings. The thin dashed line in black denotes the Kolmogorov's $-5/3$ power law (i.e., $K^{-5/3}$).

inhomogeneous buildings, which will be quantified latter in Fig. 7.

Figure 6b shows that, at the latter time steps, the urban eddies with warm perturbations (thermal plumes) are fully developed, as also noted by TKE in Fig. 5a. The thermal plumes have a vertical extension of more than 300 m comparable to the height of the SBF head, which is about 4–5 times the building height. The plumes of warm air mass are evidently lifted by the updrafts at the SBF ahead, where the urban warm eddies are colliding with the SBF. The cool air mass of the sea breeze is also highly disturbed as shown by the perturbations and uneven movement of cool isothermal surfaces on the left. So, the SBF head develops remarkable three-dimensional structures as it moves to the downtown area of the city. Figure 6d shows that, in the experiment with buildings removed, the SBF head also develops its three-dimensional structures when colliding with the prefrontal warm eddies formed over the warm

urban ground. However, the disturbance features of both the SBF head and urban eddies are less pronounced in Fig. 6d than those in Fig. 6b. Therefore, the building-induced turbulent flows seem to play a key role in regulating the detailed structures of SBF, and thus they explain the pronounced TKE particularly at the small wavelengths of 50–300 m in Figs. 5a. Previous studies have observed the SBF structures that can be disturbed by the scattered low buildings in airport areas (Chen et al. 2019), and here we see the SBF can develop much more complicated structures in the densely built-up area of city downtown.

To further clarify the detailed disturbances of buildings on SBF structures, we examine the variations of vertical motions and associated heat fluxes in the internal boundary layer over the downtown area. We pay more attention to the local updrafts (w'_+) with low wind speed in the streamwise direction (u'_-) and the downdrafts (w'_-) with high wind speed (u'_+), which are so-called ejections and sweeps, respectively (Kanda et al. 2004; Inagaki and Kanda 2010). Of particular interest is that they may be coupled with local temperature perturbations during the passing SBF, so that we can clarify how the buildings induce kinetic buoyancy fluxes that contribute to the upward transport of heat and produce TKE (Moeng and Sullivan 1994).

Figures 7a–c show that the linear patterns of frontal updrafts just to the north of the SBF are disturbed when they pass the downtown area because of the blocking effects of buildings. Some updrafts appear behind the SBF and are formed locally at the northwestern lees of high-rise buildings (i.e., “B1” in Fig. 7a, “B2” in Fig. 7b, and “B3–B4” in Fig. 7c). They mostly occur with a lag of 1–3 min after the passing SBF, so that they are displaced from those frontal updrafts at the leading edge of the SBF. Figures 7d–f show that these local updrafts in wake flows (ejections) are closely coupled with the warm perturbations of the thermal plume. Therefore, the upward heat fluxes become locally strong at the building lees (i.e., B1 in Fig. 7d, B2 in Fig. 7e, and B3–B4 in Fig. 7f, as well as other buildings “B5”–“B6”), and they can last for about 1–3 min. These local maxima of heat fluxes by building-lee ejections are estimated as more than 2 K m s^{-1} , which are stronger than those by frontal updrafts at the leading edge of the SBF. In contrast, the sweeps occur in the open areas between buildings after the passing SBF (Figs. 7a–c), and they are closely coupled with cold perturbation (Figs. 7d–f). The upward heat transport averaging for a 1-km^2 area near B2 after the passing SBF in Fig. 7e is estimated as 0.31 K m s^{-1} . Therefore, the building-induced local disturbances can lead to the pronounced vertical transports of heat just behind the SBF head for a few minutes. Such kinetic buoyancy fluxes are also expected to generate eddies with pronounced TKE at the wavelength of 50–300 m in Figs. 5a, 6a, and 6b. In the experiment without buildings, the updrafts and associated heat fluxes are mostly confined at the leading edge of the SBF, while those disturbances behind the SBF are less pronounced (figures not shown). The upward heat transport averaged near B2 after the passing SBF decreases to 0.16 K m s^{-1} .

As high-rise buildings have an evident influence, we further examine the detailed variations of flows and temperature in the surrounding areas of six high-rise buildings (B1–B6).

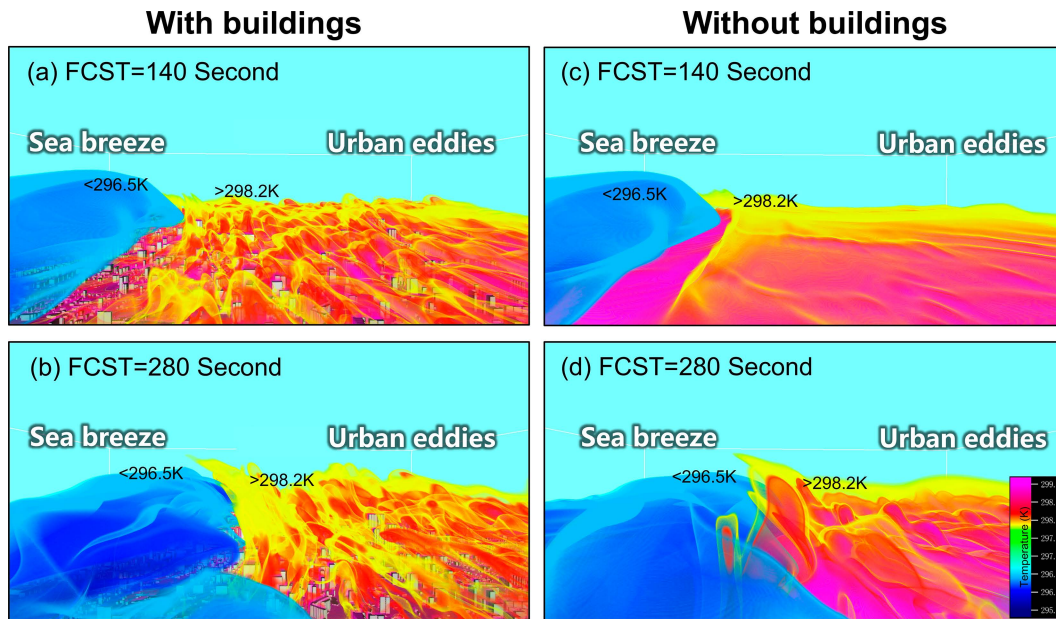


FIG. 6. The 3D visualization of isothermals (shading) in the downtown area simulated by the CFD model (a),(b) with buildings and (c),(d) without buildings. The isothermals below 296.5 K and above 298.2 K are shaded in light blue and yellow, which denote the sea breeze and warm urban air mass, respectively.

Figure 8 shows that the cool air mass of the sea breeze is moving fast in the upper layers above most buildings, while the wind speed is relatively low in the lees of high-rise buildings that are higher than adjacent buildings. The relatively warm air mass is thus trapped in the lees of high-rise buildings. Such a temperature difference between the warm air mass and the cool air mass aloft leads to a large thermal instability and thus helps to drive the updrafts. These building-lee updrafts (ejections) extend for hundreds of meters downstream from buildings, and they can last for a few minutes until the warm air mass is fully replaced by the cool air mass of the sea breeze. Therefore, both the dynamic disturbances of buildings on wind fields and the thermal conditions of large temperature gradients at the SBF head jointly contribute to the formation of local ejections during the passing SBF. In contrast, local downdrafts are formed at the windward side of high-rise buildings, likely due to blocking effects. Such downdrafts help to transport the cool air mass and associated momentum near the surface (Figs. 8e,f and B2 in Figs. 7e,f). These building-windward downdrafts or the sweeps in open areas can contribute to the upward heat fluxes at a magnitude of about 1 K m s^{-1} (Figs. 7e,f), though they are smaller than the building-lee ejections (up to 2 K m s^{-1}). Therefore, the high-rise buildings, that are outstanding in the urban canopy, can play a key role in producing the inhomogeneous fine-scale structures of SBF and local vertical motions.

5. Surface wind fluctuations during the SBF passage

We expect that surface meteorological conditions also undergo evident variations in the downtown area, where the fine-scale structures of SBF are disturbed by buildings. Figure 9

shows that the avenue of A–A' (National Route 286) has a fast progress of the sea breeze with a relatively large wind speed of southerlies/southeasterlies and a low temperature. This avenue is orientated nearly streamwise (southeast–northwest) with a large width, and thus it seems to serve as a channel suitable for the fast moving of sea-breeze airflows. Local wind speed is particularly large (up to 5 m s^{-1}) near high-rise buildings such as B2. Local minimum temperature is also seen at the windward and flank sides of building B2. These correspond well to the downdrafts at the windward sides of high-rise buildings that help to increase the wind speed and decrease the temperature near the surface as shown in Figs. 8d–f. Figure 9 also shows that the southerlies of the sea breeze are locally enhanced at another streamwise route of B–B' (railroads) to the east or south of the Sendai railway station, while the low wind speeds and relatively high temperatures are seen in the west. Overall, the simulation of the CFD model shows the fine-scale patterns of surface winds and temperature in the downtown area that are strongly regulated by the geometries of buildings and streets.

Figure 10a further shows the temporal variations of wind speed in the south–north cross section near the Sendai railway station during the SBF's intrusion. The wind speed increase is associated with the arrival of the SBF head, as shown by the arrow "A1." The wind speed shows some fluctuations at an interval of 2–3 min or about 200–300 m. The second round of wind speed is seen in the sea breeze behind the SBF, as denoted by the arrow "A2." It has a lag of about 3 min from the first one, and it is followed by the third one "A3" at similar intervals. Therefore, we can see the high-frequency fluctuations of wind speed at a regular period of $\sim 3 \text{ min}$ at given locations. More interestingly, wind fluctuations have the relatively high

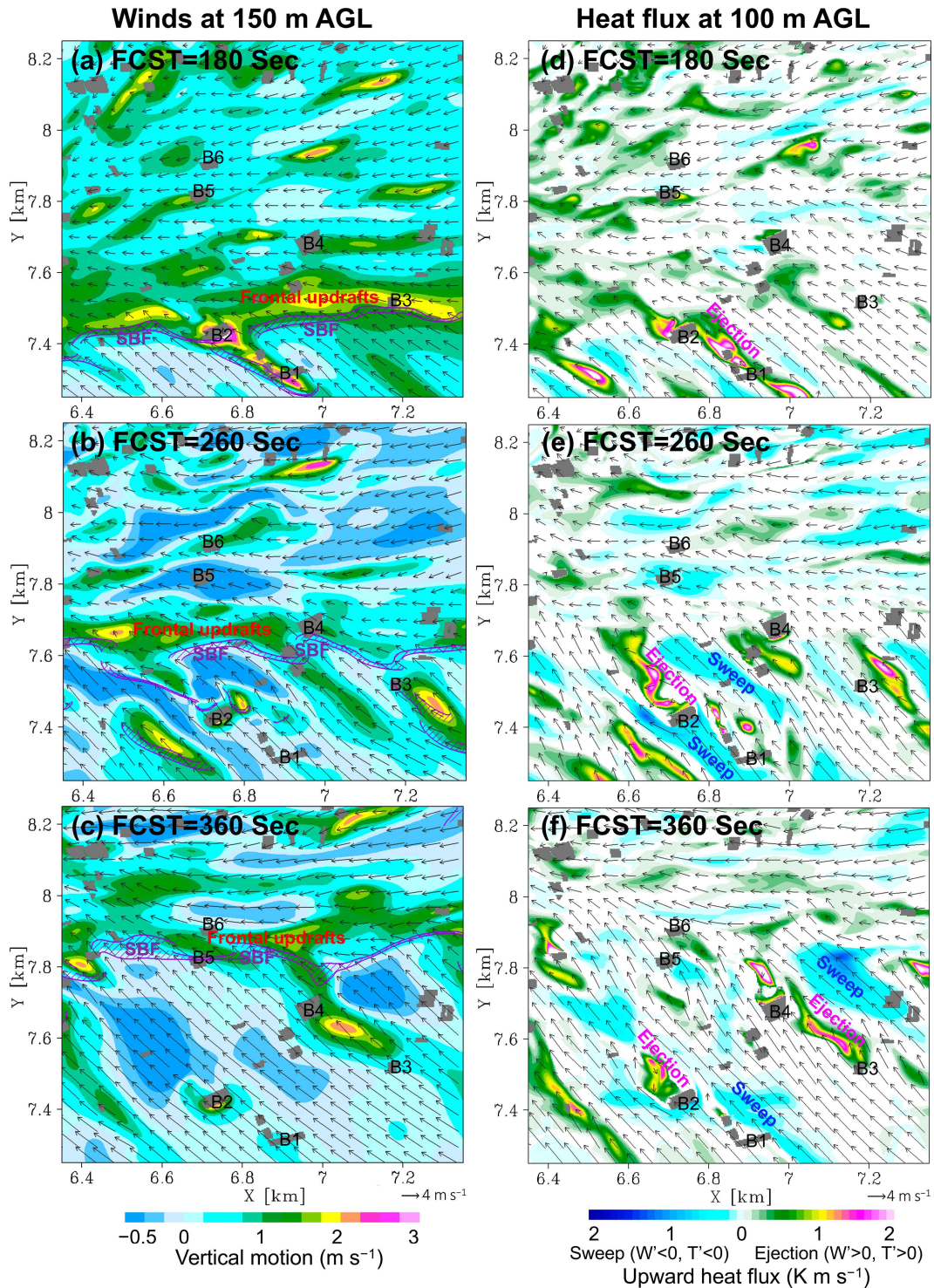


FIG. 7. Spatial patterns of winds and upward heat flux in the downtown area during the passing SBF. (a)–(c) Vertical motion (shading), horizontal winds (vectors), and SBF (hatched) at 150 m AGL. (d)–(f) Heat flux by ejections (warm shading) and sweeps (cold shading) at 100 m AGL. Blocks in gray denote the buildings higher than 75 m, and B1–B6 are selected to make Fig. 8.

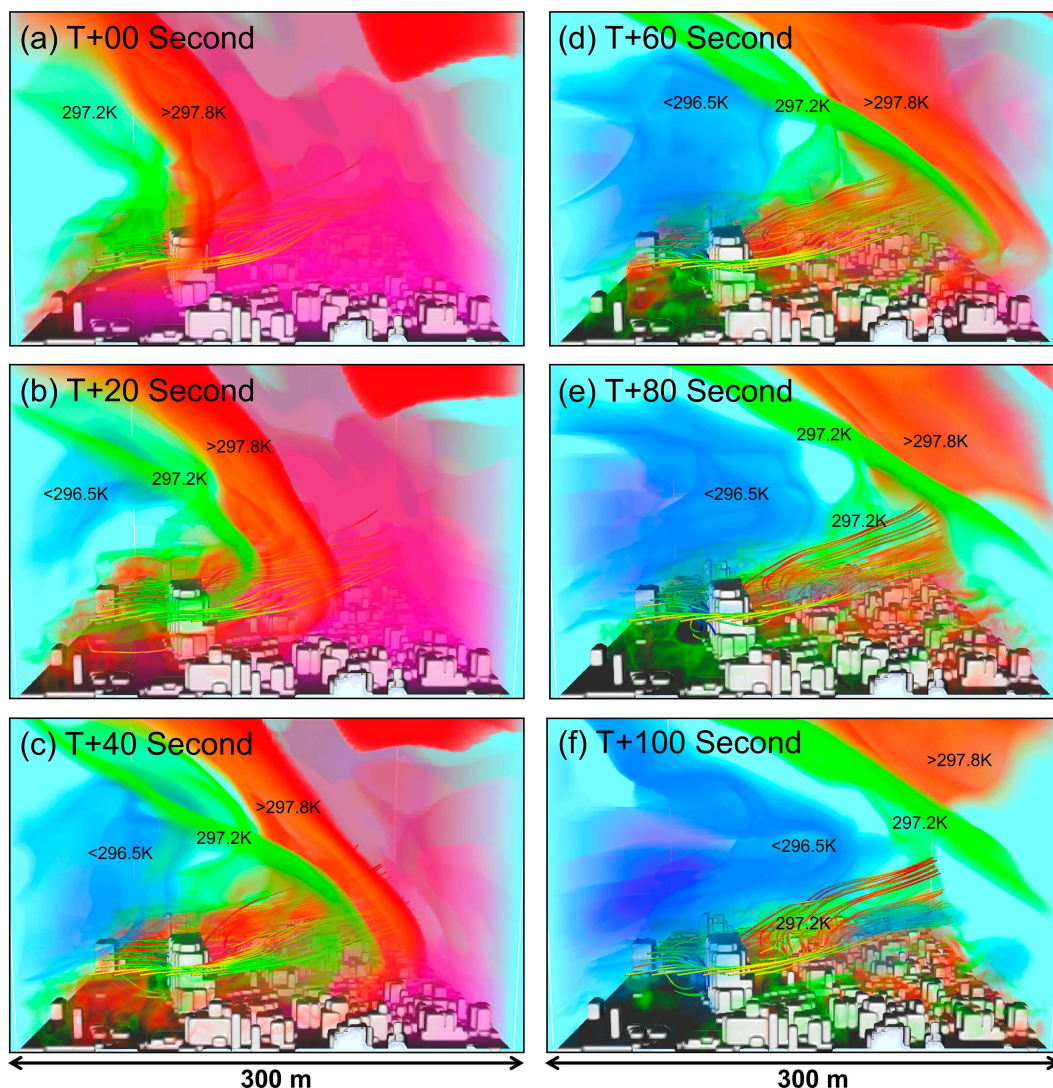


FIG. 8. The 3D visualization of isothermals (shading) and streamlines (with updrafts in red and downdrafts in blue) near high-rise buildings after the passing SBF. The seconds relative to the SBF arrival at the high-rise buildings are noted at the upper left corner. The sea-breeze air mass, its leading edge, and prefrontal warm air mass are denoted by the isotherms below 296.5 K, of 297.2 K, and above 297.8 K, which are shaded in blue, green, and red, respectively.

wind speed at the specific locations (such as at $Y = 7.2, 7.5$, and 7.8 km), probably in relation with the distributions of buildings. At these locations, the wind speed maximum at the SBF head (closed circles in Fig. 11a) is followed by another wind maximum with a lag of ~ 3 min (open circles in Fig. 11a). Figures 10b and 11a show that, in the experiment with buildings removed, the wind speed increases steadily with the SBF progress, but the high-frequency wind fluctuations become less pronounced. These results suggest that the influence of the disturbance of buildings on the passing SBF is key for producing the high-frequency fluctuations in near-surface winds.

Although the direct observation of SBF is unavailable for the densely built-up area, we may validate the simulation of their associated surface winds using observation data and

examine whether the wind fluctuations can be simulated by mesoscale-to-LES models. Figure 11b shows the temporal variations of surface winds at 1-min interval observed by the in-site sensor of AMeDAS about 1 km east of the Sendai railway station. The mean wind speed is as low as 2 m s^{-1} during the 40 min (0900–0940 JST) before the arrival of the SBF, and it has repeated fluctuations with a period of 8–10 min. After the passing of SBF at 0940 JST, the mean wind speed increases to more than 5 m s^{-1} . The wind speed shows the fluctuations with a period of about 10 min, and more interestingly, it also has some high-frequency fluctuations with a period of 2–3 min. These observed high-frequency wind fluctuations are similar to those in the CFD model, though the magnitude of observed fluctuations ($1\text{--}2 \text{ m s}^{-1}$) appears to be smaller than simulated ($2\text{--}4 \text{ m s}^{-1}$), probably because the observation data at 1-min

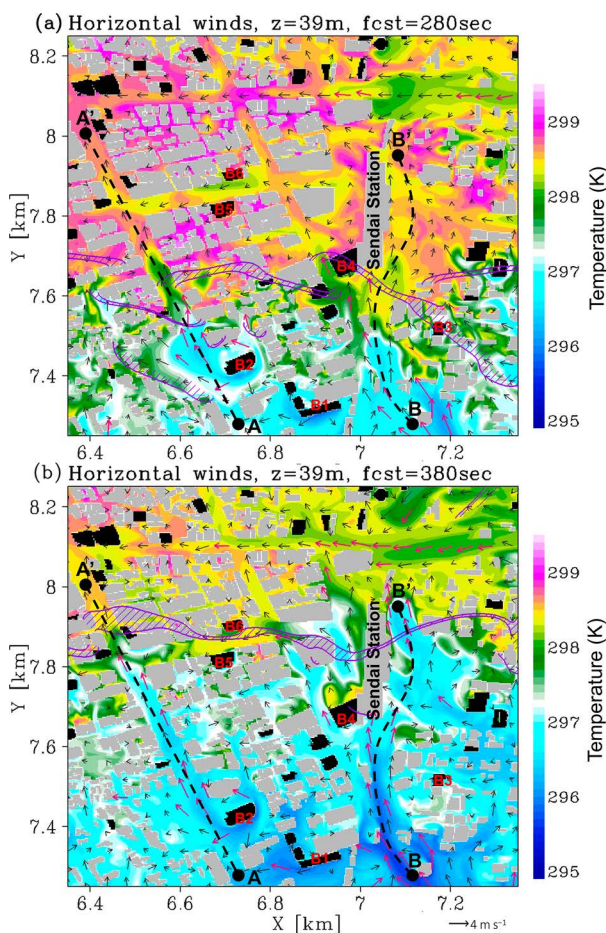


FIG. 9. Spatial patterns of near-surface temperature (shading) and horizontal winds (vectors) in the downtown area during the passing SBF (hatched in purple). Blocks in gray denote the buildings, and those in black are higher than 75 m. Dashed lines A–A' and B–B' denote the streamwise streets.

intervals are coarse relative to the model output at 20-s interval. Therefore, the mesoscale-to-LES models are shown to have a good performance in simulating the wind fields in the streets that become more disturbed after the passing SBF. The local winds in the streets seem to have a high predictability if we can resolve both the background weather conditions and the local disturbances of urban buildings.

6. Concluding remarks

In this study, we present the building-resolving simulation on an actual SBF that penetrates the coastal city using an advanced mesoscale-to-LES modeling system. We pay attention to how the SBF interacts with building-induced turbulent flows over the downtown area and how they affect surface winds in the streets. The main findings are summarized below.

The original SBF shows the linear characteristics of a gravity (density) current with an elevated head and frontal updrafts at its leading edge. As the SBF moves over the built-up

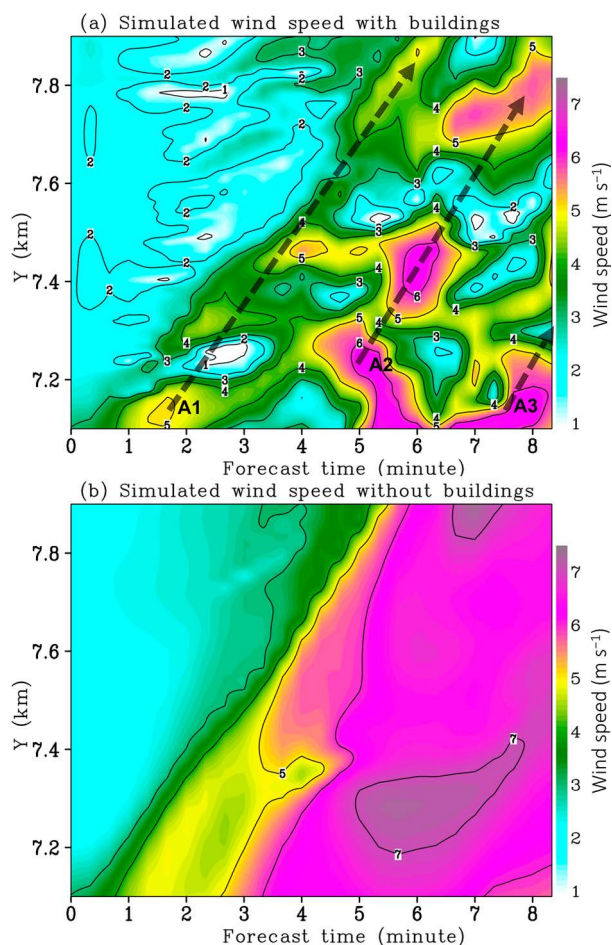


FIG. 10. Temporal variations of near-surface wind speed along the plane of $X = 6.6$ km near the Sendai Station in the CFD runs (a) with buildings and (b) without buildings. The dashed arrows A1, A2, and A3 denote the northward movement of wind fluctuations.

area of the city, it is disturbed by urban buildings and develops the three-dimensional structures with more localized updrafts, compared to the experiment without buildings. The updrafts become scattered both at the leading edge of the SBF and at the building lees just behind the SBF, suggesting a strong interaction between the SBF and urban turbulent flows. Those building-lee updrafts are closely associated with the building-induced turbulent flows at the wavelength of 50–300 m that become highly active in the control run, while the thermally driven eddies organized by convergence lines at wavelengths larger than 400 m are dominant in the experiment without buildings. The simulation of the CFD model shows that these turbulent flows reach their fully developed state in a short forecast time of less than 5 min. The SBF tends to move slowly and unevenly over the built-up area because of the frictional drag of active turbulent flows.

Over the downtown area with high-rise buildings, the passing SBF can lead to fast changes in the fine-scale patterns of local weather. In the upper layers higher than the level of

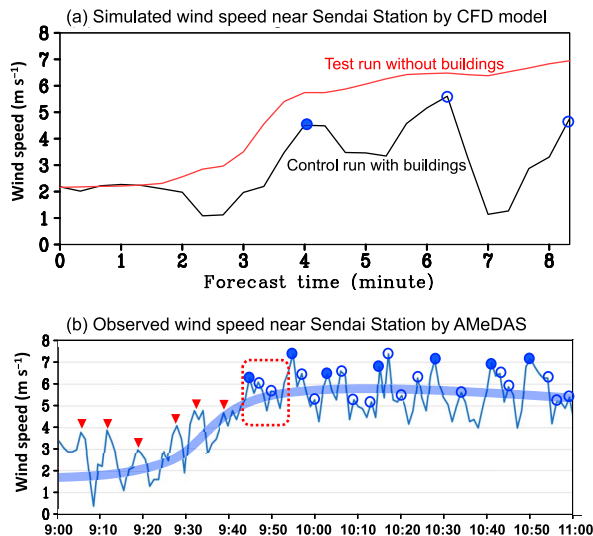


FIG. 11. Temporal variations of near-surface wind speed in Sendai downtown (a) simulated by the CFD model at $Y = 7.5$ km and (b) observed by AMeDAS at 1-min intervals. The closed circles denote the wind speed peaks at a period of ~ 10 min with a pronounced increase after the passing SBF, and the open circles denote the following peaks at a period of 2–3 min. The dashed rectangle in (b) denotes the arrival of the SBF around 0945 JST. The triangles denote the peaks of wind speed ahead of the passing SBF.

100 m AGL, the linear patterns of SBF are broken by the blocking of high-rise buildings. Unlike the frontal updrafts moving along with the SBF, some local updrafts develop at the lees of high-rise buildings where the relatively warm urban air mass is trapped and surrounded by the sea-breeze cool air mass aloft. These localized updrafts with the warm perturbation (thermal plumes) are formed at a lag of 1–3 min after the passing SBF. In contrast, the downdrafts with cold perturbations are established within the sea breeze in most of the open areas between buildings and in the windward side of high-rise buildings. These so-called ejections and sweeps play a key role in the vertical transport of heat and momentum in the internal boundary layer of the sea breeze. Near the surface, the airflow of the sea breeze moves relatively fast in the streamwise streets. The wind speed is particularly high in the wide avenue adjacent to high-rise buildings where the downdrafts act to transport cool air mass and associated momentum to surface layers. Near-surface wind speed increases after the passage of the SBF, and it also shows high-frequency fluctuations with a period of 2–3 min, which is related to the building-induced disturbances on the SBF. Such fluctuations in simulated surface winds are similar to those of in situ observations in the downtown area, though the magnitude of simulated fluctuations at finer time resolution appears to be larger than observed. The results demonstrate the good capabilities of mesoscale-to-LES models for the prediction of local weather in the streets.

The outflow from density current (such as the gusty wind from an MCS's cold pool) is well known as one of the typical conditions for producing severe winds (Houze 2004; Schumacher and

Rasmussen 2020). Our study has shown some promising simulations of density currents over the city, though the SBF is relatively gentle. Further modeling studies of density currents under severe weather conditions are needed to clarify the formation of damaging local winds particularly in the streets of cities. Another issue to be addressed is the uncertainty and predictability of local weather, as the inner CFD modeling is strongly affected by the initial/boundary conditions from outer mesoscale models and the complicated geometries of buildings (Muñoz-Esparza et al. 2014, 2018; Haupt et al. 2019). The sensitivity of the CFD modeling to both various atmospheric conditions and underlying surfaces (orography or buildings) should be evaluated by more numerical experiments and observation data. Some data-driven methods, such as deep learning, may also work with the CFD model to reduce the computation cost so that they may provide timely information at fine resolutions (Onishi et al. 2019; Shao et al. 2023; Yasuda et al. 2023). Our method may provide realistic training data for these methods. Such studies may help to pinpoint the prediction of local damaging winds in the streets, which will benefit disaster prevention for cities.

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Data availability statement. The hourly observations AMeDAS are provided by JMA (<https://www.data.jma.go.jp/stats/etrn/index.php>). The AMeDAS data at 1-min intervals are purchased from the Japan Meteorological Business Support Center (<https://www.jmbssc.or.jp/en/index-e.html>). Lidar observation data are collected by the field investigation of the sea breeze over Sendai Airport (Iwai et al. 2008). The building data are purchased from Zenrin Map Company (<https://www.zenrin.co.jp/>). The digital elevation GTOPO30 is found at the USGS EROS Archive (<https://doi.org/10.5066/F7DF6PQS>). The 3D visualization code is offered by NCAR VAPOR (<https://www.vapor.ucar.edu>).

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