Role and Impact of the Urban Environment in a Numerical Forecast of an Intense Summertime Precipitation Event over Tokyo

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Abstract

Heavy precipitation fell over Tokyo in the afternoon of 26 August 2011, leading to flooding and major disruptions for the population, businesses, and authorities. Over 150 mm of precipitation was observed over the city center on that day, with hourly accumulations reaching values as high as 90 mm in late afternoon. Numerical forecasts of this case were performed with a 250-m grid spacing version of the Global Environmental Multi-scale (GEM) model in the context of the Tokyo Metropolitan Area Convection Study (TOMACS). Although initialized only from a global 25-km upper-air analysis, results indicate that GEM can produce the intense precipitation over Tokyo at about the right location and time.

A sensitivity test in which the urban surface scheme is switched off and replaced with tall grass suggests that the urban environment might have had considerable impact on precipitation intensity, but not on its occurrence or its timing. Based on diagnostics from the GEM integrations, the increased intensity of precipitation seems more related to an enhancement of lateral inflow of low-level moist static energy from Tokyo Bay than to augmented surface fluxes of heat and humidity from the city itself. The existence of low-level bands with locally high values of equivalent potential temperature indicates that the additional moist energy is distributed unevenly through the Tokyo area, an aspect of the simulation which is speculated to have directly contributed to the increase in precip-
1. Introduction

Because of their geometrical features with very distinct dynamical, thermal, and radiative properties, cities have been known and shown to have a substantial effect on meteorology, at least at the local scale. They have for instance a substantial impact on near-surface air temperature as often reported in studies related to urban heat islands (e.g., Oke 1982; Stewart and Oke 2012). Turbulent exchanges of heat, moisture, and momentum are also influenced by the city fabric, leading to development of surface and boundary layers specific to urban areas (Roth 2000; Martilli 2002; Falasaca et al. 2016). This has an impact on atmospheric mixing in the lower atmosphere, an aspect of considerable interest for air quality and dispersion applications (Hanna et al. 2006). The different surface fluxes also lead to local pressure perturbations with production of secondary circulations influencing larger-scale circulations as well as more local-scale flows such as sea or lake breezes (Lemonsu et al. 2006; Leroyer et al. 2006, 2014; Chen et al. 2011).

Recognizing that urban populations can be quite vulnerable to intense precipitation due to safety and security issues and due to disruption of economic activity, and recognizing that cities have been observed early on to influence the occurrence and severity of such events directly or indirectly, the relationship between precipitation and urban areas has been examined for quite some time already.

As summarized in Shepherd (2005), such studies go back to pre-modern meteorology era as can be seen in the works of Horton (1921), Landsberg (1956), and Atkinson (1968) who have provided evidence that large urban areas could affect precipitation formation and patterns. Later investigations from Changnon (1968) and Landsberg (1970) provided further evidence of the role that cities could play in this regard and paved the way to the Metropolitan Meteorological Experiment (METROMEX, Changnon et al. 1977) which was held in the 1970s and which provided observational material for several studies on the subject, including Huff and Vogel (1978), Changnon (1981), Changnon et al. (1991). This effort was followed many years later by another wave of interest on the subject, which further validated conclusions from earlier studies (e.g., Balling and Brazel 1987; Bornstein and LeRoy 1990; Jaurequi and Romales 1996).

Combined with findings from more recent observational and numerical studies, the physical mechanisms that have been put forward to explain the urban impact on precipitation are listed below.

(1) Low-level convergence: the larger roughness associated with the urban environment has been found to increase low-level convergence upwind, within, and downwind of cities with an impact on convective activity (e.g., Bornstein and Lin 2000; Rozoff et al. 2003).

(2) Vertical destabilization: although sometimes offset by a moisture depression due to reduced surface evaporation in cities, the urban heat island effect often results in an increase of thermodynamic energy in the urban boundary layer with larger values of convective available potential energy and leading to greater precipitation amounts and more intense precipitation (e.g., Miao et al. 2011; Zhong and Yang 2015).

(3) Changes to storms structure and movement: dynamical effects have been hypothesized to alter the structure and trajectory of incoming storms; many have been observed to lose their integrity and split into smaller convective cells upwind of cities, often accompanied with merging and re-intensification downwind (Miao et al. 2011; Niyogi et al. 2011); other storms have been found to bifurcate and move around the cities (Bornstein and Lin 2000).

(4) Interaction with local circulations: through their impact on turbulent exchanges of heat, moisture, and momentum with the atmosphere, many investigators have argued that cities could enhance local or mesoscale circulations such as breezes (for coastal cities) and cold fronts, resulting in increased low-level convergence and precipitation over urban areas (Yang et al. 2014; Zhong and Yang 2015; Ryu et al. 2016).

(5) Atmospheric aerosols: typically in greater concentrations in and around cities, aerosols play a complex role and influence the production of precipitation through radiative (direct) and microphysics...
(indirect) effects (Shepherd 2013). Cooling at the surface and warming of the cloud layers through aerosols-induced modification of radiative transfers have been shown to reduce precipitation (Jin et al. 2011). Depending on their type and concentration, aerosols were also argued to accelerate or delay cloud formation through collision-coalescence with impact on the timing and intensity of precipitation (Van den Heever and Cotton 2007; Han et al. 2012).

The role and impact of built-up areas on precipitation are obviously complex and differ for each city, depending on many factors related to its form and characteristics as well as its location with respect to latitude, orography, and proximity to large water bodies (e.g., coastal cities). In this study, numerical experiments for a case study over the city of Tokyo, Japan, are used for the investigation.

Covering a very large area, densely built-up, and with a population well over 10 million people, Tokyo has been shown to have a substantial effect on its local weather. Its urban surfaces have often been argued to locally increase summertime precipitation (e.g., Fujibe et al. 2009) as a result from an increase in low-level convergence over the city associated with enhancement of the Tokyo Bay breeze (e.g., Souma et al. 2013; Kusaka et al. 2014). In other meteorological situations, the city has been shown to lead to the opposite effect, i.e., to a decrease in precipitation (i.e., Matheson and Ashie 2008).

Based on the above, the main objective of this study is to evaluate the impact of the urban environment on the development of an intense precipitation event that occurred over Tokyo on 26 August 2011. To achieve this, a state-of-the-art numerical atmospheric model with grid spacing of 250 m, including a one-layer urban scheme and a two-moment microphysics cloud scheme is used to test several hypotheses related to the role of the urban environment on the presence and intensity of precipitation.

2. Modeling system and experimental setup

2.1 Atmospheric modeling system

The numerical forecasts presented in this article were performed with the Global Environmental Multi-scale (GEM) model (Côté et al. 1998a, b). This model integrates the non-hydrostatic primitive equations with a two-time level fully implicit scheme and a three-dimensional semi-Lagrangian scheme. It also features finite-element discretization on an Arakawa-C grid together with variable-resolution vertical discretization based on Charney-Phillips staggering (Girard et al. 2014).

For its physical processes, GEM considers surface fluxes of heat, moisture, and momentum over 5 types of surfaces (natural soil and vegetation, urban areas, water, sea-ice, and glaciers). Over natural land areas, surface processes are represented with the Interactions between Surface, Biosphere, and Atmosphere (ISBA) scheme in which surface temperature and soil moisture evolve according to a force-restore approach (Noilhan and Planton 1989; Bélair et al. 2003a, b).

Over cities, interactions between the surface and the atmosphere are simulated by the Town Energy Balance (TEB) scheme (Masson 2000). Based on a single canopy layer (Oke 1981), TEB prognostically represents the evolution of roofs, walls, and roads temperatures with individual surface energy budgets combined with heat diffusion transfer. Streets orientation is assumed isotropic and radiative forcing considers shadow and trapping effects. Turbulent exchanges between the urban environment and the atmosphere are represented over roofs and urban canyons following a network of aerodynamic resistances depending on wind speed and stability conditions.

The TEB scheme has been extensively tested since its early development over a wide variety of cities and climate conditions (e.g., Lemonsu and Masson 2002; Masson et al. 2002; Hamdi et al. 2012). Several of these studies have been performed with GEM or its offline component GEM-Surf, as described in Lemonsu et al. (2009) and Leroyer et al. (2011).

As is the case for most numerical atmospheric models in operational meteorological centers, GEM diffusive processes are treated separately for the horizontal and vertical directions. Horizontal diffusion is numerical in nature and based on a $\nabla^4$ operator whereas vertical diffusion is associated with atmospheric turbulence determined from a Turbulent Kinetic Energy (TKE) scheme (Mailhot and Benoit 1982; Benoit et al. 1989; Bélair et al. 1999). The vertical diffusion coefficients for conservative temperature and water variables, as well as for momentum are proportional to a turbulent mixing length $\lambda$ and to the square root of TKE.

A purely three-dimensional (3D) diffusion in the style of what is used in Large Eddy Simulation models for small-scale isotropic turbulence (Smagorinsky 1963; Moeng 1984; Mason 1994) is not available in GEM. What is used instead is a so-called quasi-3D approach in which the turbulent mixing length in the TKE scheme is written as:

$$\lambda = 0.23(\Delta x \Delta y)^{1/2},$$  \hspace{1cm} (1)
to establish a more appropriate balance between horizontal and vertical processes. In (1), \((\Delta x, \Delta y)\) is for the horizontal grid sizes in the \(x\) and \(y\) directions.

It is recognized that this method might not be ideal for simulations from numerical models with 250-m horizontal grid spacing. But it must be acknowledged that these scales (resolving at best circulations with dimensions of 1000–1500 m, i.e., 4–6 \(\Delta x\)) are also likely to be too large for a purely 3D-isotropic approach. And more importantly, results presented below were not found to be significantly sensitive to this aspect of the model.

In contrast, one aspect for which the atmospheric simulations presented in this study are sensitive to is the representation of clouds and precipitation. In GEM, four different schemes can be used simultaneously for clouds and precipitation (Bélair et al. 2005): as a diagnostic from the boundary-layer turbulence scheme, from shallow and deep convection schemes, and from cloud microphysics. The first three types simulate the effect of implicit (subgrid-scale) clouds whereas the last one, cloud microphysics, is for explicit (grid-scale or resolved) clouds. Because of its subkm grid spacing, GEM’s option for deep convection is not activated in the present study.

As described in Bélair et al. (2005), a unified cloudiness-turbulence scheme called MoisTKE has been implemented in GEM following Bechtold et al. (1992, 1995) and Bechtold and Siebesma (1998). This scheme features vertical diffusion of conservative thermodynamic variables and considers the mixing effect of boundary layer clouds through a buoyancy flux. Statistical relationships are used to determine the clouds characteristics (subgrid-scale cloud fraction, total cloud water, and a flux-enhancement factor).

The shallow convection scheme is called Kuo Transient and is also described in Bélair et al. (2005). In this variation of convective schemes from the Kuo family (Kuo 1965, 1974; Anthes 1977; Bougeault 1985), assumptions of quasi-stationary shallow cumulus clouds and of an environment in quasi-equilibrium are made, leading to a straightforward formulation for the convective tendencies expressed as relaxation toward a cloudy environment provided by a simple plume model from Louis (1984).

While the full impact or effect of the two above implicit cloud schemes is not completely understood in subkm-scale atmospheric models, there is no doubt about the importance of representing grid-scale microphysical processes. In this study, the two-moment version of the bulk microphysical scheme introduced in Milbrandt and Yau (2005) is used. This multi-moment scheme (it can also be integrated in single- or triple-moment modes) considers the prognostic evolution of 6 hydrometeor categories, which makes it a complex scheme with 12 independent variables (in its two-moment configuration). The Milbrandt-Yau microphysics has been extensively tested in various meteorological situations in the last decade (Milbrandt et al. 2010; Mailhot et al. 2010; Milbrandt and Morrison 2013) and for many years now has been part of Environment and Climate Change Canada (ECCC)’s km-scale numerical weather prediction (NWP) system over Canada.

2.2 Experimental setup

The numerical integrations were performed on the domain shown in the upper-left panel of Fig. 1, centered on the South Kanto region of Japan, and more specifically on the greater Tokyo area. The grid spacing is approximately 250 m and the number of grid points is 1024 \(\times\) 1024. The number of vertical levels is 57, with the lowest thermodynamic and momentum atmospheric levels at 5 m and 10 m, respectively. The time step of the integrations is 12 s. The runs are 24-h long and are initialized at 1200 UTC 25 August 2011 (local time is UTC + 9h in Japan, i.e., 0900 pm, in the evening preceding the intense precipitation event).

It is important to mention that the atmospheric initial conditions were produced with a four-dimensional ensemble-variational data assimilation (4DEnVar) system implemented in Fall 2014 at ECCC (Buehner et al. 2015). A retrospective analysis cycle was performed for summer 2011 on a global 25-km uniform horizontal resolution grid. Compared with the four-dimensional variational data assimilation (4DVar) system previously operational at ECCC, 4DEnVar features improved treatment of radiosonde and aircraft observations, better bias correction procedures, additional satellite data, a four-dimensional incremental analysis update approach (Bloom et al. 1996; Polavarapu et al. 2004), and recycling of a few crucial physical variables. The 25-km upper-air analyses are then gradually downscaled through a horizontal nesting process, featuring integrations with 10-km, 2.5-km, 1.0-km, and finally 250-m grid spacing.

As evidenced in the rest of the article, this downscaling approach is effective in producing local and intense precipitation over the Tokyo region. It can be expected that generation of the local-scale atmospheric circulations partially arises from nonlinear and multi-scale wave-wave interactions. But in this specific case forcing from natural and urban features exerted through surface fluxes of heat, moisture, and


momentum is also playing an important role.

The land surface geometric, thermal, and radiative characteristics that contribute to this downscaling were directly produced on the 250-m computational grid. The roads and buildings fractional coverages were specified using information from OpenStreetMap, a worldwide collaborative project that gathers various types of information from Global Position System device, aerial photographs, and local sources to provide free editable maps. OpenStreetMap’s detailed continental and island contours were also used to specify the land/water coverage fractions required by GEM. This information was complemented by other sources for building height (visual inspection, specialized inventories). Vegetation characteristics such as albedo, emissivity, rooting depth, and thermal characteristics were obtained through look-up tables using land use/land cover information from the GlobCover database (Bontemps et al. 2011), while the vegetation height is from lidar altimetric measurements (Simard et al. 2011).

The general layout of the 250-m integration domain is presented in Fig. 1, featuring the heavily urbanized and vast region of the greater Tokyo area west and north of Tokyo Bay and the mountainous regions to the west. The other three panels in Fig. 1 center on the urban areas, showing the mean building height and the fractional coverages of pavement/roads and of buildings.

Two numerical experiments are presented in this study. The control (CTRL) run includes all the features described above, while the sensitivity experiment NO_URB has the TEB scheme deactivated to remove the impact of urban areas. In NO_URB, roads and buildings have been replaced by low vegetation (tall grass) similar to that of the ECCC’s global forecasting system, which does not include any urban effect.

3. Control forecast of the 26 August 2011 case

Severe weather was observed over the greater Tokyo area on 26 August 2011 with strong winds and hourly precipitation accumulations over 90 mm at
Haneda airport and neighboring stations (Saito et al. 2013, 2014). As it occurred over densely populated areas the flooding associated with this case was highly disruptive to local government, industries, and population. This event has been selected as one of the main study cases of the Tokyo Metropolitan Areas Convection Study for Extreme Weather Resilient Cities (TOMACS, Maki et al. 2012; Nakatani et al. 2013).

Without being compelling, there is evidence of dynamical support from the large-scale environment for the development of convective precipitation over the Tokyo metropolitan area. As shown in Fig. 2’s left panel, a surface low pressure center was analyzed by the Meteorological Service of Canada northeast of Japan. This analysis is valid at 0600 UTC 26 August 2011, just prior to the intense precipitation over Tokyo (timing will be evidenced below). From the surface low center a weak pressure trough extends southwest over Japan’s main island with an associated band of relatively humid air exhibiting specific humidity values over 14 g kg$^{-1}$ (at 850 hPa) over southern Japan. The upper-air environment as depicted in Fig. 2’s right panel is consistent with this picture, showing a large-scale trough just north of Japan supporting the development of the surface low.

Evidence of intense precipitation for that case is presented in Fig. 3 which shows Japan Meteorological Agency (JMA)’s 12-h and 1-h precipitation analyses based on radar and rain gauges surface networks. The 12-h precipitation analyzed between 0000 UTC and

![Fig. 2. Meteorological situation for the 26 August 2011 case over Tokyo, valid at 0600 UTC 26 August 2011. The left panel shows sea-level pressure (contours, hPa) with 850-hPa specific humidity (colors, g kg$^{-1}$). The right panel shows 500-hPa temperature (colors, K) and geopotential height (contours, dm).](image)

![Fig. 3. The left panel shows JMA’s precipitation analysis (mm) based on radar and rain gauges for the 12-h period between 0000 UTC and 1200 UTC 26 August 2011. The right panel shows the same product but for hourly precipitation (mm) from 0600 to 0700 UTC 26 August 2011. The background for the right panel is from OpenStreetMap Contributors.](image)
1200 UTC (0900 to 2100 local time) 26 August 2011 reveals very large accumulations over Tokyo with values over 150 mm at some locations. The maps of urbanized areas provided in Fig. 1 can be used to geographically locate the precipitation events. According to Fig. 3’s right panel a large portion of this precipitation over Tokyo fell in a short amount of time in mid-afternoon, just after 0600 UTC (1500 local time). Precipitation accumulations over 90 mm in a single hour are portrayed by JMA’s analysis for that period.

In comparison, the precipitation produced by the GEM 250-m control run is shown in Fig. 4. Although not as intense and as spatially wide as JMA’s analyses, the atmospheric model is able to produce large amounts of precipitation over Tokyo for that day. Over 12h (0000 UTC to 1200 UTC, corresponding to 12h to 24h forecasts) a widespread area over and near Tokyo is predicted to receive precipitation with local maxima over 125 mm. The area of intense precipitation is smaller for the model prediction (cf. Figs. 3, 4).

It is also interesting to note from Fig. 4’s right panel that the model is also successful in predicting the intense precipitation in mid-afternoon over Tokyo, with a linear band of hourly precipitation showing rates as large as 70–80 mm h\(^{-1}\). It should be noted that this corresponds to 18h to 19h forecasts. The area covered by intense precipitation is smaller in the model forecasts than in the analyses. And it can also be seen that the model failed to capture the bow-like shape of the precipitation at that time. Nevertheless, the results presented in Fig. 4 are offered here as an example of an excellent short-range numerical forecast, considering the current state of operational NWP for that type of extreme events.

As investigated in the rest of this article, the intense precipitation event appears to have occurred as the result of a complex chain of events. Some basic aspects of this process are displayed in Figs. 5 and 6 which show observed, predicted, and conceptual surface flows. In the model run, intense precipitation is initiated late in the afternoon at the confluence of three surface circulations: a) northerly flow associated with the large-scale environment, b) southeasterly breeze from Tokyo Bay developing early in the afternoon, and c) northeasterly circulation associated with sea-breeze development over the east coast of Japan. While the last two items are well represented by the GEM 250-m numerical forecast, the strength of the northerly flow seems to have been overestimated by the model. This confluence process is illustrated in Fig. 6, including the approximate location of a convergence line crossing the Tokyo area.

4. Role and impact of the urban environment

The quality of the modeling results described in the preceding section depends on many factors. These aspects include the horizontal resolution, the atmospheric initial conditions, the surface forcing, and finally the representation of certain physical processes like cloud microphysics, implicit or subgrid-scale

Fig. 4. Same as Fig. 3 but for the 250-m experiment with GEM (CTRL experiment). The 12-h precipitation accumulations (mm (12 h)\(^{-1}\)) presented in the left panel are based on 12h to 24h forecasts (0000 UTC to 1200 UTC 26 August 2011). The hourly precipitation (mm h\(^{-1}\)) in the right panel is based on differences between 18-h and 19-h forecasts (from 0600 UTC to 0700 UTC 26 August 2011). The black square in the right panel indicates the area used for the time series presented in subsequent figures. The background for the right panel is from OpenStreetMap Contributors.
convection, and boundary layer mixing. The focus in the present study is on the surface forcing, and more particularly on the role that urban areas might have had on the intense precipitation event over Tokyo. Assessing the impact of the Tokyo urban area on the numerical forecast of this case is attempted by comparing the CTRL run with results from the NO_URB sensitivity experiment.

The outcome of this comparison is first displayed in Fig. 7 which like Fig. 4 shows horizontal maps of accumulated precipitation but for Exp. NO_URB (i.e., without the urban effect represented by TEB). It can first be noticed that GEM produces a wide region of intense precipitation even when the urban component is removed from the model, implying that for this case urban surfaces do not determine the occurrence or non-occurrence of the event. But juxtaposition with Fig. 4 indicates that 12-h precipitation accumulations are smaller in Exp. NO_URB (left panels). And the impact of urban surfaces on hourly precipitation at maximum intensity (right panels) is even more obvious. The precipitation band is narrower at this time, shifted southwest away from Tokyo center, and with smaller maxima if urban surfaces are not part of the numerical integration.

The temporal evolution of observed and predicted precipitation over the Tokyo area for this case is conveyed by Fig. 8. In this figure, the fractional coverage of hourly precipitation greater than certain thresholds, taken over the region indicated by the black square in Figs. 4 and 7, is plotted as a function of time. Observed precipitation is represented by histograms.

The lower panel for the weaker intensity threshold (1 mm hourly) reveals that the precipitation event started shortly before 16h integration (0400 UTC or 1300 local time) and ended approximately 8 hours later (1200 UTC or 2100 local time). According to JMA’s precipitation analysis, and as pointed out by
Fig. 8’s other panels, fractional coverages as large as 40\%, 30\%, 25\%, and 10\% of the designated square area experienced hourly rainfall greater than (respectively) 10 mm, 20 mm, 30 mm, and 50 mm at the time of maximum precipitation, around 19 h integration (0700 UTC or 1600 local time).

As shown by Fig. 8’s lower panel, model forecasts for the CTRL and NO_URB experiments are quite similar in their ability to predict the occurrence of precipitation, all intensities included, reinforcing the earlier conclusion that urban surfaces do not appear to be an important factor for this specific aspect. It can be noted from this same panel that both model versions incorrectly predict an earlier precipitation event between 9 h and 12 h integration. Also, the fractional coverage area for this low precipitation threshold is overestimated in both experiments in the later stage of the event, after 20 h integration.

Larger differences between the two numerical experiments are found in Fig. 8’s other panels. The CTRL version of GEM predicts substantially larger fractional areas of more intense precipitation. For thresholds of 10 mm hourly and more, the precipitation area predicted in CTRL is about double the area predicted in NO_URB. This increase for intense precipitation fractional area leads to a better agreement with JMA’s analysis. But even so the model still severely underestimates the area with precipitation rates greater than 20, 30, and 50 mm hourly.

There could be several reasons for the precipitation intensification associated with the presence of the Tokyo urban environment, as seen in Exp. CTRL vs
Exp. NO_URB. This intensification is linked with an increase in available convective energy over the area of interest. Figure 9 shows evidence of this with vertical profiles of equivalent potential temperature ($\theta_e$) for both the CTRL and NO_URB experiments averaged over the land portion of the black boxes drawn in Figs. 4 and 7. Profiles for both numerical experiments exhibit a well-mixed high-$\theta_e$ layer in the lower 500 m, where most of the energy (heat and humidity) for convective activity comes from. At 0530 UTC (i.e., 17.5 h integration), just before the intense phase of the precipitation event (see Fig. 8), this layer is found to have larger $\theta_e$ values (0.5 to 1.0 K) in the CTRL experiment, indicating that the presence of the urban area has indeed the effect of increasing the vertical instability over the specified region.

Several mechanisms could be raised to explain the increase of convective instability over Tokyo. They include: a) the direct influence of surface fluxes of heat and moisture over the city area, b) lateral flow of energy associated with surface pressure perturbations and breezes, or c) other dynamical enhancement effects related to city-induced circulations could also play a role in the precipitation enhancement.

To examine the first of these three items, a), Fig. 10 provides time series of surface sensible and latent heat fluxes spatially averaged over the land portion in the square shown in Figs. 4 and 7. As revealed by the upper panel, the sensible heat fluxes over Tokyo city are similar for both experiments except for a small time delay for Exp. CTRL. The sensible heat fluxes are smaller in the morning hours (from 9 h to 15 h integration times in Fig. 10) and larger afterwards due to the city geometrical and shadowing effects and due to thermal properties of its surfaces that are quite different from natural vegetation and soils. Although the surface heat fluxes over the city might be underestimated in Exp. CTRL due to imperfect modeling or incorrect representation of anthropogenic heat fluxes, maximum values close to 225 W m$^{-2}$ seem reasonable considering that they are averaged over a large area. Latent heat fluxes given in the lower panel of Fig. 10 are found on the other hand to have much larger values during daytime for the run without TEB, due to an increase of evapotranspiration by vegetation.

These differences between the two numerical experiments quite typically represent the impact of the urban environment on surface fluxes, i.e., time delay of heat release with drier conditions, and do not suggest that the presence of the city would lead in this case to an increase of low level energy and heavy precipitation. The opposite is in fact implied from this result, with a low-level environment that should be warmer and more humid in Exp. NO_URB.

The second cause, b), depends on the production or amplification of low-level circulations that could enhance low-level moist energy over the urban area where intense precipitation occurs. To support this hypothesis, Fig. 11 shows the differences of surface pressure and air temperature between the CTRL and NO_URB experiments (CTRL minus NO_URB)
as well as near-surface horizontal winds from Exp. CTRL. These fields are displayed at 16.5 hours of integration (i.e., 0430 UTC), before the precipitation event.

The upper panel shows that the main temperature differences between the two experiments occur over land, with positive values located over the Tokyo city area. The difference field displays substantial spatial variability. Differences on the order of 1K to 4K are observed over the urban area. The lower panel indicates that negative surface pressure perturbations of the order of a few tenths of hPa are produced in association with the surface air temperature signal, again mostly over the city. It could be argued that these perturbations might have helped to increase the intensity of the breezes from Tokyo Bay and from the East coast, also evidenced by the low-level winds in Fig. 11.

To determine if such an increase in the lateral transport of moist energy took place in Exp. CTRL, the horizontal flux of moist static energy (MSE), given by

\[
MSE_{\text{flux}} = \rho V_{\text{ortho}} (c_p T + g z + L_v q),
\]

and with units of W m\(^{-2}\) is displayed in Fig. 12. In (2), \(\rho\) is the air density, \(V_{\text{ortho}}\) is the horizontal wind speed orthogonal to the plan indicated by the thick black lines in Fig. 11, \(c_p\) is the specific heat capacity at constant pressure, \(T\) is the air temperature, \(g\) is the acceleration of gravity, \(z\) is the height above the surface, \(L_v\) is the latent heat of vaporization, and \(q\) is the specific humidity. The last factor in (2) represents the MSE with units of J kg\(^{-1}\). In Fig. 12, only fluxes for line “1” in Fig. 11 are shown, with positive values designating horizontal fluxes toward land and the city, and away from the Tokyo Bay. Fluxes across line “2” were also calculated but are not shown here because they are quite similar for both experiments.

The main differences in Fig. 12 between the two experiments are found near the surface. At 0430 UTC, prior to the precipitation event and at the same time as the pressure perturbations displayed in Fig. 11, large positive values of MSE flux are produced in Exp. CTRL compared with near-zero or negative values for Exp. NO_URB. As the heat and humidity fluxes over Tokyo Bay are similar for the two experiments (not shown), this increase of horizontal transport of MSE toward land and Tokyo (caused by urban processes) is related to a strengthening of the horizontal wind speed toward the city (i.e., intensification of the breeze).

One hour later, at 0530 UTC, a flow reversal occurs and mostly neutral fluxes are predicted in the CTRL experiment, in contrast with the negative horizontal MSE fluxes in the NO_URB experiment that indicate energy fluxes away from land and city. Most of these differences occur prior to or in the early stages of the intense precipitation event. At 0630 UTC, during the intense precipitation phase of the event (see Fig. 8), the vertical profiles of MSE horizontal fluxes are quite similar for both experiments. It should be mentioned that these differences in low-level flow circulations might explain the slower propagation of the convective system when the city is considered, i.e., with a position slightly more to the southwest in the NO_
URB integration (cf., Figs. 4, 7).

The third cause examined in this study, c), is prompted by the production of near-surface bands of moist energy found to be propagating over the Tokyo urban area in the CTRL run. This phenomenon, less evident in the NO_URB integration, is illustrated in Fig. 13 which shows maps of $\theta_e$ and winds approximately 100-m above the surface from the CTRL experiment.

In the early stages of the precipitation event, as shown in Fig. 13’s upper panels valid at 0430, 0500, and 0530 UTC, a band of high-$\theta_e$ air (A) is propagating over the city, parallel to the coast, and away from Tokyo Bay. It is accompanied by a quasi-stationary band (B) with the same orientation as (A) but which remains close to the Tokyo Bay coast. These near-surface dynamical structures evolve into something quite different during the intense precipitation event as shown in the lower panels valid at 0600 and 0630 UTC. At that time, the previous high-$\theta_e$ bands (A and B) have mostly dissipated or moved away from the city. Two other bands (C and D) are now predicted, but with a different orientation (orthogonal to the coast) and in association with the northeasterly breeze dominating at that time.

To highlight the role that urban areas might have played in the generation of these low-level bands, Fig. 14 shows equivalent results for Exp. NO_URB at the early stages of the precipitation events (0430 and 0500 UTC). By comparing with Fig. 13, it first appears that the contrast of low-level $\theta_e$ between land and water surfaces is less in the NO_URB integration. The northeasterly flow (“c” in Fig. 6) is more intrusive over the Tokyo Bay, and the southeasterly breeze (“b” in Fig. 6) is much weaker. Apart from the dominant high-$\theta_e$ features associated with convergence along the Tokyo coast, band or linear structures are difficult to discern over the Tokyo city area for this numerical experiment, in contrast with what was described in Fig. 13 for Exp. CTRL. The spatial structures of low-level $\theta_e$ appear to be more wavy and cellular in NO_URB.

Although it is not clear based on the results presented in this study what is exactly the physical and dynamical nature of the near-surface waves or bands, it can be argued that their presence along with the corresponding low-level convergence and vertical motion might have contributed to the production of the more intense precipitation in CTRL.

Only considering the thermal aspect of these perturbations, Fig. 15 presents cumulative distribution func-
tions (CDFs) for $\theta_e$ vertically averaged over the lowest 400 m for both experiments, with their $\theta_e$ differences as a function of percentile in the right panel. Looking at the main statistical characteristic, both distributions have mean values that are quite similar, but the $\theta_e$ distribution for the CTRL experiment is wider, with larger values of standard deviation (1.15 K versus 1.06 K), and with a larger skewness (0.25 versus 0.13). This last aspect could be of crucial importance, as it is reflected in a significant increase in the number of high-$\theta_e$ values, which might help explain the increase in precipitation intensity for CTRL with full urban representation.

5. Summary and conclusions

In this study, the impact of urbanized surfaces on the development of an intense precipitation event over Tokyo is investigated. Comparisons of two numerical

Fig. 13. Maps of equivalent potential temperature (K) and winds (m s$^{-1}$) at approximately 100-m above the surface from the CTRL experiment, valid at 0430, 0500, 0530, 0600, and 0630 UTC (respectively 16.5 h, 17.0 h, 17.5 h, 18.0 h, and 18.5 h of integration). The thick dashed lines indicate the location of convergence bands propagating away or parallel to the coast. The bands are labeled “A”, “B”, “C”, and “D” in the figure.
forecasts produced with a 250-m version of the GEM atmospheric model, including a control run with full physics and another without the effect of urban surfaces on the atmosphere, indicate that for this specific case urban areas could lead to an increase of precipitation intensity although they do not appear to have a substantial impact on the timing and overall area of precipitation.

A few hypotheses are proposed to explain the greater severity of the precipitation event due to urban effects. The numerical results presented in this study suggest that changes in surfaces fluxes of heat, humidity and momentum associated with the Tokyo urban area do not directly contribute to a more thermodynamically unstable environment over the Tokyo area. The precipitation intensification seems to be linked with a strengthening of the horizontal flow of thermodynamic energy at low levels from Tokyo Bay. Another contributing aspect could be linked with the production of low-level waves first propagating away from the Tokyo Bay coast and then in the orthogonal direction (toward the southwest) during the most intense phase of the precipitation event.

It must be mentioned at this point that these conclusions are drawn from a single case study, over a single city, with a single atmospheric model. As argued by others, the impact of urban areas on precipitation (occurrence and intensity) depends on many factors including the meteorological situations and the layout of the city with respect to its surrounding environment.

Since conclusions of this study are obtained from numerical integrations, the fact that their validity might depend on the atmospheric model must be considered. Other models might reveal a different impact of urban areas on precipitation, due to different repre-
presentation of surface-atmosphere interactions, as well as atmospheric dynamical and physical processes. It should be also pointed out that the role of atmospheric aerosols (direct and indirect) is not very well represented in the specific version of GEM used for this study. The same can be said for anthropogenic heat and humidity fluxes over the Tokyo metropolitan area, which could certainly be improved with additional data for that specific city.

Regardless, the mechanisms argued in this article for precipitation intensification over Tokyo are quite plausible. For instance, breezes produced in urban coastal areas can play a crucial role in the production and intensification of precipitation. Further investigation of this aspect is no doubt required, using both observational and modeling means.

Similarly, the low-level waves that are argued here to potentially have a role in the intensification of precipitation deserve more attention. For this meteorological event, the waves could be the result of complex interactions between the two different breezes and the surface urban canopy. Combined with modulation by late afternoon turbulent activity and influence by convective cold pools, this makes this aspect of the 250-m GEM run deserving of additional tests and diagnostics. Future studies should also attempt to provide evidence or absence of this type of wave activity for other cities and cases, and provide a better understanding of their role in organizing clouds and precipitation.

One of the major reasons for this kind of study (at least for these authors) is to pave the way for the next generation of operational short-range, local, NWP systems. To improve weather forecasts for urban areas, many other aspects of numerical prediction models must be examined and improved. They include resolution (horizontal and vertical), numerical methods, surface-atmospheric interactions, atmospheric diffusion, and turbulence, cloud physics, atmospheric radiation, as well as the production of better initial conditions for the atmosphere, land, and water surfaces.

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