Abstract

The Tokyo Metropolitan Area Convection Study (TOMACS) for extreme-weather-resilient cities is a research and development project (RDP) of the World Weather Research Programme (WWRP). TOMACS provided a multiplatform and high spatiotemporal resolution dataset for the present research on three episodes of deep convection in the Tokyo Metropolitan Area (TMA) under its heat island effect and sea breeze circulations. Heavy rainfall episodes of August 26, 2011, and July 23 and August 12, 2013, were simulated with (and without) the tropical town energy budget (T-TEB) model coupled with the advanced regional prediction system (ARPS). The T-TEB/ARPS system used initial and boundary conditions from the Japan Meteorological Agency (JMA) mesoscale analysis data for 24-hour integration runs at 5-km resolution over Japan and at 1-km resolution over TOMACS area. The 1-km resolution hourly rainfall field simulations were verified against the respective automated meteorological data acquisition system (AMeDAS) rain gauge network measurements. Statistics of the Contingency tables were obtained to estimate the critical success index (CSI), probability of detection (POD), and false alarm rate (FAR) as well as the root mean square error (RMSE). The T-TEB/ARPS simulations improved the south and east sea breeze circulations of TMA and its urban heat island effect. The time evolution of CSI scores improved within the advective time scale, whereas dissipation (phase) errors on precipitation RMSE increased with the integration time and were larger than the dispersion (amplitude) errors. The initial and boundary conditions of JMA greatly improved the simulations as compared to the previous ones performed with the outputs of NCEP’s global forecast system as indicated by the TOMACS datasets. Thus, the results represent
temporal and spatial evolutions of the atmospheric conditions leading to the development of a deep convection within TOMACS region. Furthermore, TMA is a good testbed to evaluate the urban surface schemes, such as T-TEB in this study.

**Keywords** ARPS; T-TEB; TOMACS; thunderstorms; JMA

1. **Introduction**

Tokyo Metropolitan Area (TMA) and the metropolitan area of Sao Paulo (MASP) are among the five largest megacities of the planet where intense and extensive urban growth has occurred in the past decades. Both metropolitan areas are also similar weather-wise with regard to extreme episodes of flash floods, strong winds, hail, and lightning induced by sea breezes and heat island circulation in summer. Spring and summer thunderstorms in MASP can reach a 6-km altitude above the average ones in the rural areas (Pereira Filho et al. 2013). Higher urban sensible heat fluxes, which are caused by surface temperature gradients greater than 10°C towards the urban center (Flores Rojas et al. 2016), along with the ocean moisture advection and increased environmental shear associated with the incoming sea breeze in mid-afternoons (Vemado and Pereira Filho 2016) increases moist instability and updrafts (Pereira Filho 2012). Furthermore, the rich cloud condensation nuclei resulting from urban environment pollution changes the drop spectra, with the observed rainfall rates being higher than those for similar deeper thunderstorms in the Amazon Forest (Pereira Filho et al. 2013). These induced anthropic severe weather episodes are increasingly detrimental to the society and government resulting in loss of life and property and concomitant negative economic impacts. Forecasting and nowcasting local severe weather anywhere are an operational challenge demanding (but not limited to) infrastructure, science, technology, and management.

Tokyo Metropolitan Area Convection Study (TOMACS) for extreme-weather-resilient cities (Nakatani et al. 2015) is a unique opportunity to verify simulations with mesoscale models at very high spatio-temporal resolutions. Summer convection simulations with the advanced regional prediction system (ARPS; Xue et al. 2000) in MASP were performed using the global forecast system (GFS) of the national centers for environmental prediction (NCEP) only as the initial and boundary conditions without any further cycle of data assimilation. The surface flux scheme over urban areas was treated originally in ARPS as a simple layer of sand at the bottom of the urban surface boundary layer (SBL). The tropical town energy budget (T-TEB; Karam et. al. 2010) code was implemented in ARPS (Flores Rojas et al. 2016) to improve the simulations of the urban heat island of metropolitan area of Sao Paulo-MASP. The T-TEB was implemented in the ARPS system for simulation over MASP, but with far fewer datasets for verification. Indeed, major hurdles in verifying urban SBL and their models arise from the lack of a dense automatic weather station (AWS) network and limited number of sounding sequences for characterizing of the urban planetary boundary layer (PBL) in the majority of tropical metropolitan areas such as MASP. A full set of three-dimensional (3D) data is considered necessary for short assimilation cycles, which are used in nowcasting, and for model verification. In previous studies on MASP, the verification was limited to weather radar and satellite precipitation estimation. More recently, Flores Rojas et al. (2017) verified ARPS/T-TEB system performance in MASP with only few AWSs. Currently, ARPS/T-TEB can be verified with TOMACS 4D datasets that were made available for the present study.

Thus, this research on severe weather modeling in urban environments takes advantage of the TOMACS measurement and processing systems to verify the ARPS/T-TEB system performance under severe weather conditions induced by sea breezes and heat island circulations in an ultra-dense data region such as Japan. The ARPS system is an important component of a hydrometeorological forecast system (HFS) for MASP. It also includes a mobile x-band polarimetric Doppler weather radar (XPOL; Pereira Filho 2012), a sparse network of rain gauges and AWSs, and distributed hydrologic modeling (Pereira Filho and Santos 2007). Sea breeze and heat island features and their induced heavy rainfall episodes over MASP were recently simulated with the T-TEB/ARPS system with GFS-only initial and boundary conditions without further data assimilation. Weather radar hourly rainfall accumulation estimation was the only data available with adequate spatiotemporal resolution to verify the simulations. Given the environmental and summer-
weather similarities between TMA and MASP, T-TEB/ARPS-numerical simulations of extreme events under sea breeze and heat island forcing can be now verified using TOMACS ultra-high density datasets. The ARPS/T-TEB system was initialized with Japan Meteorological Agency (JMA) high-resolution analyzed fields. The AMeDAS rainfall fields were used to verify ARPS/T-TEB performance as a step toward being applied in forecasting.

Crosman and Horel (2010) made an extensive review on modeling sea and lake breeze circulations. They indicated the numerical and computational problems as the major limiting factors. Sea breezes and urban heat islands were studied in many cities of the world, such as Baltimore-Washington (Ryu et al. 2016) where surface heterogeneities were incorporated into the weather research and forecasting (WRF) model; Taiwan (Lin and Chen 2016) to account for the soil moisture in WRF simulations; Beijing (Miao et al. 2015) for urban and mountain-valley circulation studies with the WRF system; São Paulo (Vemado and Pereira Filho 2016) where the heat island strongly interacts with the local sea breeze in a manner similar to that in TMA; Shanghai (Kang et al. 2014) that was affected by the heat island characterized with a surface network; Osaka-Kyoto (Takane et al. 2013) for interactions at the synoptic scale; Seoul (Ryu and Baik 2012) where the heat island and sea breeze were simulated with the WRF model; London (Chenel and Sokhi 2012) for a case study simulation of heat island and sea breeze with the WRF model; Brussels (Hamdi and Degrauwe 2012) where a version of TEB was implemented to study the heat island effects; Montreal (Leroyer et al. 2011) for a study of heat island with the Canadian external urban and land surface modelling system (GEM-SURF) system; and Kumamoto (Tomita et al. 2007) for thermal geometric controls on surface air temperature. In addition, many observational studies were conducted for TMA to analyze two mesocyclones with the surface network and weather radar during TOMACS (Saito et al. 2013); the urban canopy and winds (Kondo et al. 2008); wind profiles, static stability, and convergence leading to the development of thunderstorms (Mikami et al. 2011); multilayer winds and sea breezes measurements with the Doppler weather radar (Tsunematsu et al. 2009); aerosols and sea breeze studies with the Doppler LIDAR (Iwai et al. 2011); thermal and geometric studies on surface air temperature (Tomita et al. 2007); effects of the Tokyo Bay sea surface temperature on urban temperature (Oda and Kanda 2009); climatology of synoptic winds and surface temperatures (Yoshikado 2013); and lee winds and rainfall in TMA (Inamura et al. 2011). Further, many numerical simulations were conducted to study the impacts of land use and alteration on Tokyo surface temperature and sea breeze (Kusaka et al. 2000), increased precipitation (Kusaka et al. 2013), energy balance and heat modeling (Ooka et al. 2011), local heavy rainfall (Saito et al. 2014), Tokyo morphology (Adachi et al. 2014), and advanced data assimilation systems (Saito et al. 2016, 2018; Kawai-bata et al. 2011, 2013, 2014). Thus, many advanced research studies on convection has been conducted in Japan. This work uses the TOMACS datasets to test the ARPS/TEB system for areas where the local circulation has been extensively studied and are similar to the ones elsewhere, such as in the MASP.

A preliminary study with the ARPS system over Japan (Fig. 1) using GFS-only 14-day forecast at 1.0°-resolution as the initial and boundary conditions was conducted for the summers between 2011 and 2013. The ARPS was run continuously for 24 h at 12-km horizontal resolution with GFS-only boundary and initial conditions over Japan domain (192 × 183 grid points) with similar ARPS settings for MASP.

Fig. 1. Area domain of ARPS simulations with 5-km and 1-km (smaller square) horizontal grid resolutions. The color scale of latitudes, longitudes, and topography have been indicated. The red star indicates the location of Tateno sounding site, Tsukuba-shi, Ibaraki, code 47646, (36°03.5′; 140°07.5′).
a hyperbolic grid spacing in 43 vertical levels. The Kain–Fritsch (1993) cumulus parameterization was used in the 12-km resolution domain, and cloud microphysics by Lin et al. (1983; hereafter LIN) without cumulus parameterization was used in the 2-km resolution domain. Section 2 describes the area domain of simulations, ARPS system, T-TEB scheme, and datasets of the three events during TOMACS. Results are depicted and discussed in Section 3, followed by the conclusion in Section 4.

2. Methods

2.1 The ARPS system

The ARPS system is a three-dimensional mesoscale non-hydrostatic model in a terrain-following coordinated and developed by the center for analysis and prediction storms (CAPS) at the University of Oklahoma (Xue et al. 2000). The ARPS model uses a minimum of approximations in its governing dynamic and thermodynamic equations. Several advanced numerical techniques are implemented in this model as monotonic advection schemes for scalar transport and variance conserving fourth-order advection for other variables. Some equations represented by a split-explicit scheme allow distributed memory for massive parallel computation. The ARPS takes advantage of high-performance parallel processing.

The ARPS system includes physical parameterization schemes for the explicit simulation of thunderstorms and associated flow (Xue et al. 2000). The force restore scheme (Noilhan and Planton 1989; Jacquemin and Noilhan 1990) determines the state of the land surface energy and moisture budgets. The stability and roughness-length-dependent surface flux model that was proposed by Businger et al. (1971) and further modified by Deardorff (1972) is also available in ARPS. The urban heat flow parameterization scheme TEB developed by Masson (2006) was further developed for tropical regions (T-TEB) by Karam et al. (2010) and used in the TMA simulations described in Section 2.2.

2.2 The T-TEB scheme

The scheme developed by Masson (2006) called town energy budget (TEB) is the simplest of the single-layer models. It simulates surface turbulent heat, momentum, and mass fluxes attributed to buildings, roads, or any artificial material into the atmosphere over urban areas. The TEB parameterizes urban surfaces and the roughness sub-layer so that the atmospheric model needs to handle only the constant flux in its lower boundary. The scheme reproduces the damping of the daytime turbulent heat flux by the heat storage flux observed at core of the city area. The ARPS simulations for TMA used the tropical town energy budget (T-TEB) scheme by Karam et al. (2010). They implemented modifications into the original equations of Masson (2006) to simulate different surface conditions, such as the Monin–Obukhov similarity (MOS) framework in the inertial sub-layer (Monin and Obukov 1954); increased aerodynamical conductance toward more unstable conditions in the roughness sub-layer; modified urban subsurface drainage system to transport runoff by roofs to the roads; and introduced local scaling for flux-gradient relationships.

The MOS was used to calculate the turbulent fluxes in the surface layer and sub-layer generated by the heterogeneous nature of the elements of the urban canopy (rows, houses, trees, etc.). Thus, MOS represents complex urban area surface drag in the atmospheric flow. T-TEB uses the Penman–Monteith equation (Penman 1948; Monteith 1973) to estimate the urban latent heat flux over a limited-capacity stormwater reservoir that quickly drains excess water from roofs to roads to underground channels and so on.

Figure 2 depicts the schematics of the coupling procedure between ARPS and T-TEB. T-TEB variables are transferred to the ARPS main driven and surface physics modules. T-TEB receives the dynamic and radiative variables of urban-type vegetation in ARPS.

The parameters for TMA are listed in Table 1. Some parameters for construction materials are depicted in Masson (2006) and Oke (1987). Other T-TEB parameters for TMA were arbitrarily set and related to the building height, canyon, building aspect ratios, and traffic and industrial heat releases. Parameters were the same for the three convective episodes simulated with ARPS/T-TEB system. Building height was 15 m. The aspect ratio was 1.5 at each point over the urban surface.

T-TEB couples the output temperatures of roofs, walls, and roads with the surface temperature used by ARPS to estimate the surface energy fluxes with the following soil temperature equation (\( t_{\text{soil}} \)):

\[
T_{\text{soil}} = a_{\text{bhd}} \cdot T_{\text{roof}} + (1 - a_{\text{bhd}}) \cdot T_{\text{can}},
\]

where \( T_{\text{roof}} \) is the roof surface temperature (°C); \( a_{\text{bhd}} \) is the fractional area of buildings; and \( T_{\text{can}} \) is the canyon temperature (°C).

The roof surface temperature is obtained as a solution of the surface energy balance (SEB) over each urban canyon surface. The canyon temperature is driven by the entrainment of the urban boundary
layer air into the urban canopy (UC), anthropic heat and humidity fluxes, and the divergence of radiation (infrared) density flux through the UC surfaces (Nunez and Oke 1976).

The T-TEB scheme also estimates the water content of soil \(q_{soil}\) as follows:

\[
q_{soil} = a_{bld} \cdot q_{roof} + (1 - a_{bld}) \cdot q_{can},
\]

where \(q_{roof}\) is the roof water moisture, and \(q_{can}\) is the canyon air specific humidity (g kg\(^{-1}\)).

The fraction of roof area corresponding to the accumulation of rainwater is used to calculate the specific
humidity of the roof weighted between the equilibrium value on a water surface and the atmospheric value above the urban canopy (first level of the atmospheric model above the CLS). During the rain event, the evapotranspiration (surface turbulent flux) is potential, and the specific moisture is the equilibrium value (saturation). After rainfall, the water accumulated on the roofs is drained according to the rate of drainage of the duct that transports the water from the roof to the street, according to the TEB-proposal: the variation of the height of the roof water is obtained from the difference between the inlet and the outlet water. The area covered by water is assumed to be proportional to the accumulated height, and it is updated with each time step. The specific roof moisture tends to be the specific moisture value of the first level of the atmospheric model above the urban canopy when the roof area is dry, i.e., well after rainfall events.

The canyon-air specific humidity results from the entrainment of urban boundary layer into the UC. Additionally, the canyon air specific humidity ($q_{can}$) as a function of the turbulent and anthropic water vapor fluxes modulates the surface specific humidity ($q_{sfc}$). Surface variables modified by T-TEB ($T_{sfc}$, $q_{sfc}$, and $q_{sfc}$) are updated at every time step and the surface heat fluxes, momentum, and moisture are calculated using a stability and roughness-length dependent surface flux model based on modified Businger’s formulation (Businger et al. 1971). It is transferred to the ARPS system. Heat fluxes by traffic and industry are constants that are added to the surface energy fluxes (Table 1).

### 2.3 ARPS Simulations

The first ARPS control simulations runs over Japan were 24-h runs that were conducted between July and September of 2011, 2012, and 2013. They were used to evaluate the ARPS-performance with the initial and boundary conditions given by GFS 1° horizontal resolution in its nested one-way runs at 2-km and 2-km resolution grids. The diurnal cycle of convection for these nine summer months was analyzed at the 12-km horizontal resolution, while the performance of the 2-km ones were verified using contingency tables and indices such as critical success index (CSI), probability of detection (POD), and false alarm ratio (FAR) (Wilks 1995) using 1,310 AMeDAS rain gauges data. The main results of the control run for July, August, and September of 2011, 2012, and 2013 indicated better (worse) performance for September (August), characterized by the diurnal cycle of inertial circulation and rainfall with shear (north) and static moist energy (south) out of phase. High precipitation accumulation over Japan’s mountains was overestimated. The overall skill precipitation accumulation scores were under 30 % for no precipitation accumulation thresholds as verified with more than 1300 AWSs over the entire Japan. Furthermore, time-longitude analysis of CMORPH (CPC MORPHing technique)-hourly precipitation (not shown) indicated that convection over Japan is associated with westerlies with an average span, duration, and phase speed of 550 km, 10 h, and, 17 m s$^{-1}$, respectively. The three convective episodes in TMA occurred during weak synoptic forcing and were strongly affected by heat island and sea breeze circulation. The succeeding section describes the simulation area domain of the ARPS system, the T-TEB scheme, and datasets of the three selected events within TOMACS. The simulations of these convective episodes in TMA were performed with nested grids at 5-km and 1-km resolution centered in the Tokyo downtown. The ARPS was set to 43 vertical hyperbolic tangent layers with more levels close to the surface and less towards the top of the troposphere. The first level is at 10 m, with a minimum vertical grid spacing of 20 m and maximum altitude at about 21 km. Each of the three convective episodes were simulated for a control run with a semi-desert type of surface as specified by ARPS and another for the surface conditions specified by the T-TEB scheme over TMA. JMA datasets were used at 15 standard pressure levels between 1000 and 100 hPa at 3-h and 5-km resolutions. JMA datasets were interpolated to 43 h with boundary and initial conditions at 5-km horizontal. All simulations used JMA soil and SST analysis. ARPS includes LIN microphysics and Kain–Fritsh cumulus parameterization only for the 5-km grid. The initial time of each of the simulations was 2100 UTC (0600 LT). JMA 30-min precipitation analysis was used to verify all simulations. A brief description of the three episodes is provided in the succeeding section.

### 2.4 Convective episodes

Thunderstorms that occurred over TMA on August 26, 2011, July 23, 2013, and August 12, 2013 were associated with diurnal surface heating yielding a deep convection in the afternoon hours. Figure 3A shows that a jet stream occurred to the north of the TMA on August 26, 2011. The area of maximum rainfall accumulation occurred at the equatorial entrance of the jet where divergence aloft and surface convergence yield a dynamically unstable atmosphere. The Tateno sounding (not shown) lift index was $-4.40^\circ$C at 0000 UTC (0900 LT), and the total precipitable water was
58 mm, indicating high instability. The heat island increased CAPE and updrafts and decreased CIN over TMA, resulting in more intense and severe thunderstorms. Note that the environment was already unstable even without the heat island effect. Therefore, the CAPE and updrafts increased. Thus, convection was more intense than it would have been without the heat island effect.

The divergence aloft and surface convergence features at mid-pressure levels shown in Fig. 3B for...
July 23, 2012, are distinct from those of the August 26, 2011, which is a convective event. TMA is just east of an upper level trough that is amplified during the day (not shown), increasing the surface convergence. The lift index and precipitate estimated with the Tateno sounding (not shown) are \(-1.5^\circ C\) and 51 mm, respectively, indicating a less unstable and moist environment. Indeed, the convective cells yielded less precipitation over TMA as compared to that of the previous event. An almost zonal jet stream that was located further to the north of TMA with no undulation at 500 hPa was present on August 12, 2013 (Fig. 3C). The lift index of the Tateno sounding at 1200 UTC (not shown) was \(-2.0^\circ C\), and the total precipitable water was 63 mm. Thus, more water vapor was available than on July 23, 2013. Indeed, localized cells with higher intensity over TMA were likely due to the heat island effect. All three cases were simulated with and without the T-TEB scheme in the ARPS system to study its adequacy to reproduce the impacts of heat island and sea breeze on the spatiotemporal distribution of precipitation. Contingency tables and indices such as CSI, POD, FAR, and other error statistics are described in the next section for ARPS runs and JMA-precipitation analysis.

### 2.5 Analysis and verification statistics

The ARPS with GFS 2-km runs of hourly precipitation accumulation of nine summer months of July, August, and September of 2011, 2012, and 2013 were compared with 1,310 AMeDAS hourly precipitation accumulation data. So, hourly precipitation accumulation (mm) from 1310 AMeDAS were used to obtain the CSI, POD, and FAR (Donaldson et al. 1975). For each ARPS grid point, the precipitation forecast (Pf) was checked to verify whether it was greater (less) than a given precipitation threshold (Po) and whether the corresponding AMeDAS precipitation (Pa) was greater (or less) than Po. The contingency table below was used to compute the indexes as follows.

<table>
<thead>
<tr>
<th>AMeDAS Precipitation Pf &gt; Po</th>
<th>AMeDAS Analysis Pf &lt; Po</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARPS precipitation Pf &gt; Po</td>
<td>Number of Hits</td>
</tr>
<tr>
<td>ARPS precipitation Pf &lt; Po</td>
<td>Number of Misses</td>
</tr>
</tbody>
</table>

\[
\text{CSI} = \frac{\text{Number of Hits}}{\text{Number of Hits} + \text{Number of Misses} + \text{Number of False Alarms}}
\]

\[
\text{POD} = \frac{\text{Number of Hits}}{\text{Number of Hits} + \text{Number of Errors}}
\]

Only the ARPS grid point nearest to a corresponding AMeDAS station was used to estimate the CSI, POD, and FAR for hourly accumulation thresholds between 0 and 20 mm. Furthermore, the ARPS with GFS 12-km runs of temperature (T), dew point temperature (Td), and wind field at 850, 500, and 200 hPa and the precipitation difference fields of ARPS and AmeDAS were obtained to analyze the diurnal cycle of convection over Japan in the summer months of TOMACS.

The ARPS within 5-km of the JMA with and without the T-TEB runs of the three TMA convective episodes were verified with JMA hourly-precipitation analysis by means of the contingency tables to obtain the CSI, POD, and FAR. Additionally, for hourly precipitation, mean square errors (Takacs 1985), respective phase (dispersive), and amplitude (dissipative) were obtained to measure the ARPS performance within TOMACS.

### 3. Results

On August 26, 2011, severe convective event over Tokyo Bay area covered a large area with more than 50 mm precipitation accumulating in half an hour at 0630 UTC (not shown). It produced a major flood under weak synoptic forcing. The ARPS with T-TEB precipitation maximum occurred at 0900 UTC. Fig. 4 shows JMA 1-h precipitation field (A) and the ARPS with T-TEB precipitation (B), surface wind (C), air temperature differences (D), surface wind (E), and soil temperature (F) at 0900 UTC on August 26, 2011. JMA precipitation analysis indicates an area of stratiform rainfall with embedded convective cells westward in the east-west direction, while the ARPS with T-TEB placed the heaviest cells towards the east of TMA. It was a vigorous sea breeze circulation and heat island effects with a 2 h lag between the observed and simulated precipitation maxima. The ARPS/T-TEB simulated its thermodynamic and near surface dynamics features is not present in the control run especially in TMA. The displacement of the precipitation area is in agreement with the circulation at the medium and high levels at a wind intensity of approximately 35 km h\(^{-1}\) at 500 hPa, as indicated by the JMA analysis (Fig. 3A).

On July 23, 2013, convective event over TMA depicted a maximum precipitation of more than 50 mm in half an hour at 0700 UTC (1600 LT) between Shinjuku and Kawasaki Prefectures as seen in the JMA precipitation analysis fields (Fig. 5A). Figure 5 also
Fig. 4. JMA 1-hour rainfall accumulation field (A), ARPS simulated rainfall field (B) and surface winds (C), difference between control and T-TEB runs for air temperature (D), for surface winds (E) and for soil temperature (F) in the 1-km grid region centered in Tokyo Bay at 0900 UTC 26 AUG 2011. Geographic contours, longitude, latitude, and color scales are indicated.
Fig. 5. Similar to Fig. 4 but for the rainfall event at 0700 UTC 23 JUL 2013.
shows the ARPS control and T-TEB simulated fields of precipitation, surface wind and soil temperature, and surface wind and air temperature differences (B-F). There was a 1-h delay between the JMA and ARPS rainfall fields (Not shown). Soil temperature in TMA was 3–5°C higher for the T-TEB simulation at 0400 UTC, which was sufficient to induce and reinforce the southeast winds (not shown) and Tokyo Bay moisture advection to trigger the supercell thunderstorm, as seen in Fig. 5A. A long westward sea breeze front along the coast from the Ibaraki Prefecture to the south in the Chiba Prefecture started at about 0200 UTC and propagated to produce a northwest-southeast line of thunderstorms with an intense precipitation two hours later, at 0700 UTC. Later, both JMA and ARPS/T-TEB simulations indicated less intense rainfall areas propagating from the northwest to the southeast. In spite of a time lag and amplitude and phase differences between JMA and ARPS, the use of T-TEB produced a more intense heat island over TMA than otherwise (Figs. 5D–F).

On August 21, 2013, convective episode had two-precipitation maxima of 30 mm according to the JMA half-hour analysis both over Tokyo Bay at 0630 UTC and 1330 UTC. Figure 6 shows the JMA (a) and ARPS/T-TEB (B) precipitation fields and differences of air temperature (C), surface wind (D), and soil temperature (F) in relation to the control run and the surface wind fields (E) at 1330 UTC on August 21, 2013. In this weaker convective case, the east sea breeze is more significant later in the simulation than in the two previous cases shown above. The simulated precipitation field is much smaller than the observed one; however, it is greater around the 0630 UTC maximum (not shown). The surface wind and the air temperature difference fields indicate that the heat island and the south sea breeze are the dominant features. The precipitation accumulation is less without the injection of moisture from the west sea breeze in this case.

The total precipitation accumulation fields for JMA analysis and ARPS/T-TEB simulation are shown in Fig. 7. ARPS precipitation patterns tend to agree with the JMA analysis fairly well, especially in terms of the overall direction of displacement associated with the steering level, but less so in terms of the amount of precipitation on August 26, 2011, and July 23, 2013. Further, it is even less when evaluated for August 21, 2013.

A comparison of the control and T-TEB runs obtain precipitation accumulation differences for the cases of overestimation (Fig. 8) shows that the T-TEB resulted in greater precipitation over TMA by 80 mm; howev-er, random anomalies are present almost everywhere in the domain.

Figure 9 shows the time evolution of CSI for five precipitation thresholds between 0.0 to 4 mm from JMA and ARPS with and without T-TEB precipitation fields at 1-km spatial resolution over the smaller domain shown in Fig. 1. The simulations of the events on August 26, 2011, and July 23, 2013, indicate greater improvement of the overall control runs for the 2011 to 2013 summer months (not shown), with scores above 0.3. The ARPS depicted little activity except very weak rains in the case of the weak convection of August 21, 2013. The optimal performance was for August 26, 2011, but after 6 h of integration, the performance tended to decrease with the convective time scale as the meteorological signal advanced through the domain. This indicates the need for new observations or data assimilation to innovate the boundary conditions.

Finally, Fig. 10 presents the time evolution of phase (dispersion) and amplitude (dissipation) errors of ARPS with and without T-TEB compared to the JMA hourly-precipitation analysis at 1-km resolution. The RMSE increases with time in all the three cases and is dominated by phase errors. Later into the simulation integration, the RMSE tends to decrease as the diurnal cycle of convection dies out.

Thus, the inclusion of the urban boundary scheme T-TEB had a positive but limited impact because other observational and modeling issues need to be included. Nevertheless, it is an important step forward in analyzing the ARPS/T-TEB system where higher density and better quality datasets such as the ones provided by TOMACS are essential so that it can be used where limited data are a major constraint.

4. Conclusion

Organized summer convection over Japan between 2011 and 2013 followed the westerlies with average spans of 550 km, lasting 10 h, and achieving phase speeds of 17 m s⁻¹. Deep convection over TMA was induced by the heat island and sea breezes during weak synoptics forcing. It was well simulated with the ARPS/T-TEB system with the boundary and initial conditions from the JMA global model. The three episodes of convection during TOMACS indicate significant heat island effect that corroborates with previous observations except that of the ARPS/T-TEB modeling system. The dynamics at high levels is determinant to trigger the convective storms over a broad or localized area, but if one of these two conditions are satisfied, the probability of thunderstorms over TMA
Fig. 6. Similar to Fig. 4 but for the rainfall event occurred at 1330 UTC on 21 AUG 2013.
Fig. 7. Total precipitation accumulation field of JMA analysis and ARPS with T-TEB simulation for 26 AUG 2011 (top), 23 JUL 2013 (middle), and 12 AUG 2013 (bottom). Geographic contours, longitude, latitude, and color scales are indicated.
Fig. 8. Total precipitation accumulation field between ARPS control and with T-TEB simulations for episodes of 26 AUG 2011 (A), and 23 JUL 2013 (B). Geographic contours, longitude, latitude, and color scales are indicated.

Fig. 9. Time evolution of CSI for precipitation thresholds between 0.0 and 4.0 mm at 1-km resolution of JMA and ARPS with T-TEB simulation of convective cases over TMA in 26 AUG 2011 (A), 23 JUL 2013 (B), and 21 AUG 2013 (C). Dashed lines denote control run results.
area will be considerably high due to the lower lift index, and CIN and higher CAPE are induced by the heat island effect. Dissipation (phase) errors on hourly precipitation forecasts tend to dominate, though CSI scores improved between 50% and 300% of the advective time scale with JMA, rather than with the GFS and the boundary and initial conditions. The goal of the study was to test the T-TEB scheme, which was recently implemented in the ARPS system. Thus, the statistical indexes indicate the reliability of the ARPS precipitation forecast for the three events analyzed in this work. The T-TEB includes momentum transfer by buildings and constructions. Similar simulations for the Metropolitan Area of São Paulo include the wind acceleration by buildings and structures. Perhaps, the homogeneity assumption used in the simulation is the main constraint, and it may intensify the acceleration when the urban area mainly comprises buildings. Future work will include assimilation runs of all available datasets, but also the use of the ARPS/T-TEB system for MASP and other places with limited data sets.

Acknowledgments

This work was partially supported by FLAGSHIP 2020, MEXT, within the priority study area #4 (Advancement of meteorological and global environmental predictions utilizing observational “Big Data”). The research was developed at Laboratory of Hydrometeorology of the Institute of Astronomy, Geophysics and Atmospheric Sciences of the University of São Paulo, São Paulo, Brazil, in cooperation with the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA). The authors are grateful to MRI, JMA, for providing the datasets for the initial and boundary conditions and rainfall analysis files for verification. Appreciation is also extended to the National Research Institute for Earth Science and Disaster Prevention for its support with regard to TOMACS. The authors are also very grateful to the two anonymous reviewers for their assistance in improving this manuscript. The first author is partially supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grant 301149/2017-8.

References


