

SURF: understanding and predicting urban convection and haze

Article

Liang, X., Miao, S., Li, J., Bornstein, R., Zhang, X., Gao, Y., Cao, X., Chen, F., Cheng, Z., Clements, C., Dabberdt, W., Ding, A., Ding, D., Dou, J. J., Dou, J. X., Dou, Y., Grimmond, C. S. B. ORCID: <https://orcid.org/0000-0002-3166-9415>, Gonzalez-Cruz, J., He, J., Huang, M., Huang, X., Ju, S., Li, Q., Niyogi, D., Quan, J., Sun, J., Sun, J. Z., Yu, M., Zhang, J., Zhang, Y., Zhao, X., Zheng, Z. and Zhou, M. (2018) SURF: understanding and predicting urban convection and haze. *Bulletin of the American Meteorological Society*, 99 (7). pp. 1391-1413. ISSN 0003-0007 doi: 10.1175/BAMS-D-16-0178.1 Available at <https://centaur.reading.ac.uk/75601/>

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Comprehensive multi-scale observations and modeling are enabling an international team of scientists to understand and better predict urban effects on heavy summertime convective precipitation and wintertime fine particle pollutant episodes in the Greater Beijing Metro Area.

Abstract Urbanization modifies atmospheric energy and moisture balances, forming distinct features, e.g., urban heat islands (UHIs) and enhanced or decreased precipitation. These produce significant challenges to science and society, including rapid and intense flooding, heat waves strengthened by UHIs, and air pollutant haze. The Study of Urban-Impacts on Rainfall and Fog/Haze (SURF) has brought together international expertise on observations and modeling, meteorology and atmospheric chemistry, and research and operational forecasting. The SURF overall science objective is a better understanding of urban, terrain, convection, and aerosol interactions for improved forecast accuracy. Specific objectives include: a) promoting cooperative international research to improve understanding of urban summer convective precipitation and winter particulate episodes via extensive field studies; b) improving high-resolution urban weather and air quality forecast-models; and c) enhancing urban weather forecasts for societal applications, e.g., health, energy, hydrologic, climate change, air quality, planning, and emergency-response management. Preliminary SURF observational and modeling results are shown, i.e., turbulent PBL structure, bifurcating thunderstorms, haze events, urban canopy model development, and model forecast evaluation.

PROGRAM SYNOPSIS

The Study of Urban-Impacts on Rainfall and Fog/Haze (SURF) Project investigates urban, terrain, convection, and aerosol interactions for improved weather and air quality forecast accuracy achieved by the combination of expertise from an international group of multidisciplinary scientists and by the employment of complementary research methodologies. Principal Chinese participants were from the Institute of Urban Meteorology (IUM), Environmental Meteorology Forecast Center (EMFC), Chengdu University of Information Technology (CUIT), Beijing Weather Modification Office (BJWMO), and National Marine Environment Forecast Center (NMERC). Principle international groups include San Jose State University (SJSU), National Center for Atmospheric Research (NCAR), Vaisala Group (VG), University of Reading (UR), City College of New York (CCNY), and Purdue University (PU).

SURF consists of four symbiotic components:

- Observations with research-level boundary layer (BL) instrumentation to augment extensive operational surface, boundary layer, and upper air networks during SURF summer thunderstorm and winter haze field study periods. Resulting data are archived, quality controlled, and available to Chinese and international partners.
- Numerical model development and verification activities, which involved use of SURF observations to develop and test advanced modules to improve urban parameterizations in the operational and research-grade urbanized Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) and in air quality models. New parameterizations are available for inclusion in publically available versions of the WRF model.
- Modeling of case studies that involves use of the newly upgraded research grade weather and air quality numerical models to simulate SURF “golden-case” thunderstorms and haze events, whose model input and output data are available to interested modelers.
- Applications with the newly upgraded operational numerical models for improved IUM urban weather and air quality forecasts and for use by health, energy, hydrologic, climate change, air quality, planning, and emergency response managers.

*The order is rapidly fadin’
And the first one now will later be last
For the times they are a-changin’
– Bob Dylan¹*

Global urbanization has accelerated over the past 65 years, in 1950, 30% (746 million people) of the global population resided in cities, but by 2014 that number had increased to 54% (3.9 billion), and the United Nations projects a value of 66% (6.4 billion) by 2050 (UN 2014). Half of all urbanites currently live in small cities, while 28 mega-cities (> 10 million) already have 13% of the global population; and by 2030, 41 mega-cities will exist. Urbanization challenges society and science, overcrowding, infrastructure, and economic activities make cities vulnerable to disasters like flooding and haze, according to an UN-Habitat (2016) report.

The High Impact Weather Program of the World Meteorological Organization (WMO 2013) lists urban-induced floods as well as heat waves and air pollution as two of its five major foci. US urban heat waves produce more weather-related deaths than any other weather phenomenon (NRC 2010). More than 700 deaths occurred from a 1995 five-day Chicago heat wave, while a 2015 event in India resulted in nearly 2 500 deaths (Di Liberto 2015). The 14-day European August 2003 heat wave claimed 40 000 lives (Robine et al. 2007), with a large number in cities (Vandentorren et al. 2004). Heavy rainfall caused flooding in July 2012, killing 79 people in Beijing and with losses of US \$1.7B.

¹ From “The Times They Are A-Changin” copyright © 1963, 1964 by Warner Bros. Inc.; renewed 1991, 1992 by Special Rider Music

Urban areas also enhance the severity of gaseous and (solid and liquid) aerosol pollution, producing photochemical haze, smog, and acid rain episodes (Cao et al. 2013). One billion people experience excessive outdoor pollution, and during 2012 air pollution was linked to one of eight deaths globally (UNICEP 2016). Urban air pollution costs approximately 2% of GDP in developed countries and 5% in developing countries.

Anthropogenic aerosols penetrate deep into human organs (Li et al. 2011), and cause severe health consequences, e.g., asthma, heart attacks, nervous system damage, and lung cancer (Tie et al. 2009). Aerosol impacts on weather and climate include alterations of: radiation fluxes (Andreae et al. 2005), horizontal visibility (Quan et al. 2015), atmospheric stability (Zhao et al. 2006), planetary boundary layer (PBL) development (Quan et al. 2013), cloud formation (Andreae et al. 2004), and convective precipitation (Rosenfeld et al. 2008). While significant knowledge concerning aerosol impacts on some aspects of weather systems has been obtained, their impacts on radiation (Ao et al. 2016; Wang et al. 2016), clouds, and rainfall is far from complete, especially in urban areas (Stevens 2008).

Observation and numerical modeling are two important methods used in urban weather studies. Concurrent observations of processes in adjacent urban and rural atmospheres are fundamental to understanding interactions between underlying surfaces, aerosols, and the atmosphere. Numerical models for urban weather and air quality provide valuable information to decision makers and the public for many applications. The WMO has proposed that National Meteorological and Hydrological Services produce impact-based forecasts for environmental, energy, transportation, and health effects (Tan et al. 2015). Urban forecast model skill should increase as better a understanding of urban atmospheric processes emerges from large field measurement programs (Shepherd 2005).

URBAN THUNDERSTORMS. Urban impacts on precipitation were the focus of the now-classic 1970s Metropolitan Meteorological Experiment (METROMEX) field study, which investigated modification of summer convective rainfall by the St. Louis urban area. Observations showed that the urban area increased precipitation, both within the city and 50–75 km downwind of it, by 5–25% over upwind values (Huff and Vogel 1978; Changnon, 1979; Changnon et al. 1981; Braham et al. 1981; Changnon et al. 1991). Similar results were found by Shepherd et al. (2002) around Atlanta and four other large US cities (Burian and Shepherd 2005).

Radar images of 91 summer thunderstorms during 2000–9 over Indianapolis by Niyogi et al. (2011), however, showed 60% of them with a variety of alterations (i.e., they initiated, intensified, split, or dissipated) over the city. These results agreed with the older observations by Bornstein and LeRoy (1990) for New York City (NYC) and Bornstein and Lin (2000) for Atlanta, as both studies also showed both urban initiated and bifurcated (i.e., splitting and going around the city, respectively) thunderstorms.

Numerical modeling enables controlled experiments to characterize physical processes producing urban-precipitation modification. MM5 simulations by Craig and Bornstein (2002) showed an Atlanta thunderstorm arising from urban heat island (UHI)-induced convergence over the city. Simulations of two thunderstorms over Atlanta with WRF by Shem and Shepherd (2009) also showed the convergence effect, with rainfall increases downwind of the city. A case simulation with WRF and its Single Level Urban Canopy Module (SLUCM) option by Miao et al. (2011) showed that early (prior to 1980) Beijing urbanization decreased (as compared with a no-urban simulation) maximum rainfall over Beijing due to increased urban surface dryness. Further urbanization decreased rainfall, however, as storms bifurcated around the city.

A case-study WRF simulation, coupled with its multi-level Building Environment Parameterization (BEP) urbanization option, by Yu and Liu (2015) showed that Beijing produced upstream and downstream precipitation increases. Yu et al. (2016) used SLUCM to simulate a heavy August Beijing storm, and results showed suburban increases of sensible heat flux, temperature, and wind speed, which facilitated storm merging and enhanced precipitation. Zhang et al. (2017b) simulated two Beijing summer thunderstorms with SLUCM, and showed contrasting urban effects on precipitation under strong and weak UHIs, i.e., initiation vs. bifurcation, respectively.

Recent reviews have summarized the processes producing urban impacts on precipitation, e.g., Shepherd (2005) reviewed publications from 1990–2005, covering observations and simulations, and stressing both thermodynamic and microphysical impacts. Shepherd (2013) reviewed post-METROMEX lightning and winter precipitation studies, focusing on fluxes, aerosols, and bifurcation. Han et al. (2014) stressed a range of urban precipitation enhancers, from UHIs to surface roughness to aerosols, while Mitra and Shepherd (2016) focused on resulting storm modifications (e.g., bifurcation, merging).

To address the above “apparently conflicting” urban precipitation impacts in the literature, a synthesis–hypothesis was proposed by Bornstein (2011), in which strong UHIs initiate convective activity (and thus produce a city-center precipitation maximum) during periods with near calm regional flows. During strong wind, weak UHI conditions, however, moving thunderstorms bifurcate and move around cities because of building-barrier effects. This latter effect thus produces a precipitation minimum over and downwind of cities, and maximum around the city in lateral boundary convergence zones and in the downwind re-convergence area.

Dou et al. (2015) for the first time showed UHI magnitude as key to determine urban effects on summer thunderstorms. Based on 2008–12 Beijing hourly precipitation observations, they showed that strong (greater than average) UHIs induced or enhanced thunderstorm formation. With weak UHI conditions, however, thunderstorms bifurcated and bypassed the city due to building-barrier effects. This study was thus the first validation of the Bornstein (2011) hypothesis concerning how UHI-magnitude impacts summer convective precipitation, but an analysis of simulation results to understand bifurcation dynamics is still lacking.

Numerical modeling of urban thunderstorms relies heavily on numerical weather prediction simulation results to provide background conditions. Such models, however, still have significant uncertainties in the estimation of the timing and amount of precipitation. Uncertainties in the numerical simulation of urbanization impacts on heavy rainfall, in particular, thus still require further investigation (Yu et al. 2018).

URBAN AEROSOLS AND HAZE. Atmospheric aerosols, also called particulate matter (PM), directly influence radiation transfer processes and cause direct climate effects because of their optical scattering and absorption properties (Charlson et al. 1992). As cloud condensation nuclei (CCN), they indirectly influence climate by changing cloud formation, precipitation, and radiation transfer processes (Rosenfeld et al. 1997; Liu and Daum 2002). Atmospheric aerosols have a variety of sources, as well as complex chemical compositions and physical properties, with anthropogenic fossil fuel combustion as their largest source (Andreae and Crutzen 1997). Biomass burning, wind-blown dust, sea salt, and volcanos are other important global sources. Chemical composition affects radiative transfer and cloud formation processes, e.g., black carbon (also called soot) and dust are the two most important absorption aerosols (Bond et al. 2013), while important scattering aerosols include sulfates, nitrates, and ammonium.

Aerosol impacts on cloud microphysical processes, (e.g., evaporation, condensation, collision and coalescence, and droplet breakup) are better understood on larger scales than for city scales (van den Heever and Cotton 2007). Generalization of natural aerosol impacts is difficult, however, as they range from precipitation enhancement to suppression, e.g., high concentrations in winter orographic clouds yield more cloud water, but less rainwater (Rosenfeld et al. 2008). Too many CCN reduce autoconversion rates, since droplets coalesce less efficiently than giant CCN (GCCN), such as sea salts (Grabowski 1999). When droplets ascend above the freezing level, precipitation enhancement results, however, by dynamic invigoration from frozen droplets (Carrió et al. 2010), forming hail and graupel. An excellent review of all aspects of these processes appears in Fan et al. (2016). Biomass smoke also significantly alters synoptic weather (Robock 1991), and fossil fuel aerosols alter regional (or even global) climates (Jacobson 2001).

Urban environments, with abundant pollutant CCN and GCCN, thus also modify cloud microphysical processes (after dynamical effects initiate it, as discussed above). Pollution aerosols have resulted in annual precipitation losses of 15–25% over topographic barriers downwind of major coastal urban areas in California and Israel (Givati and Rosenfeld 2004). Aerosol particle size distribution (PSD) also affects microphysical processes, e.g., RAMS idealized-simulations by Comarazamy et al. (2006) for Puerto Rico showed that cloud droplet production is significantly larger in polluted air than in clear skies, and that rainwater in polluted air is less than that in unpolluted air. Building from this study, Hosannah and González (2014) simulated impacts on a local NYC thunderstorm event by ingestion of observed AEROSOL RObotic NETwork (AERONET) PSDs (<https://aeronet.gsfc.nasa.gov/>). Results showed impacted precipitation totals, rates, and spatial patterns, while month-long simulations showed smaller prediction errors with observed PSDs than with assumed model distributions.

As one of the most densely populated countries, China has high aerosol loadings, because of intense anthropogenic and natural emissions. Its complex aerosol sources and geographical distribution, together with the large scale circulations of the East Asian monsoons, cause a complex transport and mixing of air masses, producing strong chemical and physical interactions (Ding et al. 2016). Long-term multi-satellite observations of rainfall, clouds, and aerosols indicate that they influence cloud properties, particularly cloud droplet size (Jin et al. 2008).

Beijing is one of the largest cities in China, with a population over 20 million, and it suffers from high aerosol concentrations, and with its nearby complex terrain, is an excellent region to study aerosol-cloud-precipitation interactions. Many observational and numerical studies have investigated the role of aerosol on its radiation balance and precipitation processes. Surface radiation observations by Wang et al. (2016) at four Beijing sites showed polluted days having both attenuated direct and downwardscattered shortwave radiation fluxes. Modeling by Chen et al. (2015) found that while aerosols decreased Beijing urban-area rainfall, they increased domain-averaged values. Zhong et al. (2015) compared impacts from UHIs and aerosols on a summer precipitation event over Beijing with a WRF-Chem/UCM ensemble. Results showed aerosol impacts dominant, with enhanced downstream convection and precipitation.

Direct observational evidence on the relationship between aerosols and cloud/precipitation in Beijing is still limited, however, thus requiring time-resolving measurements of both aerosols and weather processes. The SURF project, which includes radiometer, lidar, radar, tower, and aircraft measurements, was thus initialized in 2015 to study aerosol effects on Beijing haze and precipitation processes.

CRITICAL SCIENCE NEEDS. The Beijing-Tianjin-Hebei (BTH) area (Fig. 1a) includes the megacities of Beijing, Tianjin, Shijia-zhuang, Tangshan, with 90 million people, with 40 million just in the Beijing-Langfang-Tianjin belt. The BTH area includes complex topography with mountains, plains, and coastal areas (Fig. 1a), and seven of the 10 most polluted Chinese cities, with 40% of days during 2013 (mostly in winter) having “very hazardous” air quality (CMEP 2014).

Severe spring pollution frequently impacts Beijing and Northern China, with hourly PM_{10} concentrations as high as $1000 \mu g m^{-3}$. Regional transport by summer monsoons subjects Beijing and surrounding cities to high concentrations of secondary aerosols from the North China Plain and southern China (Wang et al. 2010). Severe autumn and winter haze events also occur in Beijing e.g., $PM_{2.5}$ concentration were $> 800 \mu g m^{-3}$ in January 2013 (Guo et al., 2014). Such episodes occur under stagnant, weak synoptic conditions, especially one or two days before a cold front passage. During haze episodes, the sky is colored light yellow or orange gray, and has a pungent smell.

Given the human and environmental tolls from Beijing haze and floods (resulting from the precipitation processes discussed above), the Chinese Ministry of Science and Technology provided supports to the Institute of Urban Meteorology (IUM) for extensive field measurement and modeling campaigns to study both Beijing summer convective thunderstorm and winter haze events. A preliminary workshop (March 2014) defined study goals and methodologies. Additional planning workshops were held before the first summer thunderstorm (March 2015), first winter haze (November 2015), and second summer (May 2016) studies.

All workshops were held at the IUM Beijing headquarters, with more than 40 invited Chinese experts from government agencies, laboratories, academia, and industry. An International Advisory Committee (IAC) was constituted with 10 representatives from the WMO, US, UK, Finland, and Israel. The entire group defined research needs and barriers, and workshop reports are available from the corresponding author. This paper thus summarizes the SURF effort, carried out to better understand atmospheric interactions between urban areas and aerosols that effect summer convective processes and winter haze episodes.

From the first Workshop, the overall SURF goal was identified as: A better understanding of urban, terrain, convection, and aerosol interactions on both summer thunderstorm precipitation and winter haze episodes. The SURF project period is 2014 to 2019, and has the following specific goals:

- Conduct international collaborative field studies to improve understanding of urban impacts on convective weather systems and haze episodes.
- Improve high-resolution (1 km) urban numerical weather and air quality forecast models for research and operational applications.
- Increase use and effectiveness of urban forecasts for social, economic, and environmental applications, e.g., for health, energy, climate change mitigation and adaptation, air quality, planning, and emergency-response management.

The critical science needed to achieve these goals was identified as increased understandings of:

- urban (i.e., UHI circulation, surface roughness, and building-barrier) and complex terrain impacts on 4-D PBL structures (i.e., height, turbulence, and inversions) by analysis of mountain-valley and urban produced wind and thermal patterns
- urban model parameterizations of PBL, building canopy, and water balance processes, as well as multi-scale data assimilation for observation-rich cities
- complex terrain, urban, and aerosol impacts and interactions on summer convective rainfall distribution, intensity, and timing, e.g., UHI-initiated vs. bifurcated thunderstorms
- long-range transport vs. local (urban and complex terrain) processes and pollutant emission impacts on horizontal, PBL, and diurnal structures of aerosol concentration patterns and on the duration of regional winter haze and fog episodes
- urban and complex-terrain 4-D meteorological and chemistry impacts on regional winter haze and fog episodes, including radiation and thermodynamic aerosol effects on PBL structures
- how to improve the performance of high-resolution urban-model produced weather and air quality forecasts of summer precipitation and winter haze/fog episodes.
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SURF FIELD STUDIES. To gain a greater understanding and improved predictions of urban summer convective precipitation and winter haze, the greater BTH region is ideal for observational studies, as it is the largest metroplex in North China and experiences both summer flooding and winter haze. SURF summer field studies thus focused on urban impacts on rainfall initialization, movement, and intensity, while winter field studies focused on aerosol (regional and local) sources, transport, and transformation processes. Three field programs were conducted, two of which focused on thunderstorms (July - August 2015, July-September 2016) and one on haze (November 2015–January 2016).

Field sites and instrumentation. Operational meteorological data are collected every 5 min at 1992 surface BTH-area Automatic Weather Stations (AWSs), 348 of which are in Beijing. Twice daily radiosondes are launched at 0800 and 2000 LST (where LST = GMT+8 h), at NAN (Fig. 1b; all site and agency acronyms are defined in Supplement A), with additional 1400 LST soundings during flood seasons (June-August). Surface energy-balance fluxes have been observed operationally since 2012 by eddy-covariance techniques at one urban (IAP), three suburban (MIY, SHU, WUQ), and one rural (SDZ) tower (all PBL observational sites are shown in Fig. 1). Other operational PBL sensors (Table 1) include four S-band weather radars and six X-band radars, nine wind profilers, and a GPS/MET network, all supported by BMS, TMS, or HMS.

During field study periods, existing operational PBL networks were augmented, e.g., the summer 2016 study (Table 1) added five wind profilers; one scanning Doppler lidar; a PBL aerosol Micro Pulse lidar (MPLs) each at the IAP tower and DAX sites; and 10 Vaisala CL51 ceilometers for cloud height and aerosol backscatter profiles. Continuous 10 Hz turbulent flux and mean meteorological data were also collected at multiple levels at two sites (the 325 m Beijing “super site” tower and the 38 m Tianjin tower).

A van-mounted MPL aerosol lidar at DAX drove from the IAP fixed MPL site to IUM (Figs. 1b) on several days, while it circled the 4th Ring Road on one hazy day. During Intensive Operational Periods (IOPs), five additional radiosondes were launched daily at NAN, and eight small-balloon soundings were taken daily at each of three sites (IUM, CHA, DAX) from 28 August to 2 September 2016 under all conditions. Photos of a selection of these instruments and sites are shown in Fig. 2.

About 250 BTH-area Environmental Protection Bureau (EPB) stations (35 in Beijing), in addition to 14 BMS stations, operationally measure hourly concentrations of surface: PM_{2.5}, PM₁₀, SO₂, NO₂, NO, NO_x, CO, and O₃. Special mobile lidar observations were also carried out during three 2016 winter IOPs. During fair weather winter-2015 and -2016 IOPs (15 and 19, respectively) King Air aircraft flights were flown over pre-approved flight paths (Fig. 1) at altitudes from 600 to 3 600 m (at 300 m intervals). The aircraft is equipped with atmospheric gas and aerosol instrumentation, including cloud images (resolution of 2.3 μ m), cloud drop spectra (2 to 19 200 μ m), aerosol spectra (0.11 to 3 μ m), and meteorology probes (1 Hz sampling frequency) for temperature (T), relative humidity (RH), and horizontal wind speed (V) and direction.

Data sets. The Urban Meteorological Data Sharing Platform (UMDSP) archives the 2015 and 2016 SURF datasets, includes site and instrument metadata, manufacturer-provided software, and quality controlled (QCed) observations from the wind profilers, MPLs, Doppler lidar, flux towers, microwave radiometers, and radiosondes. Additional observation data (e.g., weather radar, aircraft, and lightning) will be added. Golden case SURF datasets (defined as well documented, clear signal events) are available to research partners. The status of SURF PBL observational data are summarized in Supplement B, and all SURF instrumentation sources, accuracies, sampling periods, data, etc. can be viewed and downloaded by the international research community through granted access to the UMDSP website: <http://www.ium.cn/dataCenter/>.

IOP forecasts. A daily procedure was followed by the SURF Forecast Group (SFG) to decide whether or not to call for summer 12 h IOP, with its additional rawinsonde soundings and/or mobile observations. Each day at 0830 LST during a field study period, SFG forecasters received the BMS 72 h operational synoptic forecast. They focused on evolving synoptic patterns to determine if thunderstorms were likely on the next day; if so, a tentative “go” (for the IOP) was issued. At 1500 LST, BMS updated its 48 h forecast, and if thunderstorms still seemed likely on the next morning, SFG forecasters evaluated the latest synoptic maps and NWP forecasts. The models considered included the European Centre for Medium Range Weather Forecast (ECMWF) system and IUM Urban (described below). Based on this evaluation, a final “go” or “no-go” decision was made. The process resulted in a five-part daily forecast summary: previous-day weather situation; current (500 and 850 hPa) upper level and surface charts; 36 h European Center forecast; 36 h IUM 3 km forecast; 24 h IUM 1-km urban forecast; and SFG IOP conclusions.

The forecast accuracy for summer-2015 and 2016 thunderstorm events (Table 2) shows that correct forecasts increased (due to the year of additional experience) from 67% for IOP days in 2015 to 74% for days in 2016. Correct forecasts predicted thunderstorm activity (or not) anywhere in the Beijing study area anytime on the given IOP day. The forecast procedure for haze IOPs is simpler, as winter haze mostly occurs under stable weather condition and as severe episodes can last more than three days. The IUM operational WRF-Chem model provides 96 h forecasts, and if a haze event is forecast to occur within four days and to last for at least three days, a haze IOP (with BJWMO aircraft observations) was carried out until the event ends.

SURF MODELING. IUM operational weather and air quality forecast system. A modified version of the WRF model (ARW versions 3.5.1; Skamarock et al. 2008) is used as the IUM weather model in both operational and research modes. Its operational Rapid-refresh Multi-scale Analysis and Prediction System (RMAPS) includes five off-line, one-way nested components, each with its own horizontal grid spacing (Δx). The system starts with ECMWF Global forecasts (at 3 h intervals) and terminates with hourly weather and air quality forecasts. Relationships between these internal operational components, as well as the observational data used by each, are shown in the flow chart of Fig. 3 and described below:

- Nowcasting (NOW) Model (Δx of 5 and 2.5 km): uses input from the Variational Doppler Radar Analysis System (VDRAS) for 6 h real time forecasts, with ingested data from seven S-band weather radar and all AWS sites.
- Short Term (ST) Model ($\Delta x = 9$ and 3 km): uses WRF Data Assimilation (WRFDA), and either the WRF Noah (for rural grid points) or SLUCM (for urban grid points) land-surface modules for operational 72 h forecasts, for which regional and local data are assimilated.
- Urban Model ($\Delta x = 1$ km): for urban weather forecasts with the multi-level BEP + Building Energy Model (BEM) urban PBL modules for 24 h real time (but not yet operational) forecasts and research studies, where BEM, BEP, and their urban LU/LC input data are described below and where its AWS assimilated input weather-data were described above.
- Integration (IN) Model: combines observations into the NOW, ST, and Urban model forecasts for objective 12 h forecasts, where its input (QPE) are radar data and are calibrated by AWS rain-gauge observations.
- CHEM Model ($\Delta x = 9$ km and 3 km): for 96 h chemical forecasts from the WRFChem model, where its input emission (Q*) and concentration (χ) data are discussed below.

In the operational mode, the 1-km Domain-3 of the Urban model (459 by 402 grid cells) is driven by its 3-km Domain-2 (549 by 423 grid cells) output. The 3-km domain encompasses most of North China, while the 1-km domain covers most of the BTH area centered on Beijing (a somewhat larger area than in Fig. 1a).

Initial conditions (ICs) for the 3-km operational ST model are obtained through the WRF preprocessor NDOWN option and a 3-D VAR approach, which uses 9-km ST model outputs, with its IC and boundary conditions (BCs) from ECMWF, the National Centers for Environmental Prediction Global Forecast System (NCEP GFS), or CMA Global and Regional Assimilation and Prediction System (GRAPES), and with the preferred order of usage of: ECMWF (if available), GFS, and GRAPES (if necessary). The 3-km 72-h operational simulations have their ICs adjusted by WRFDA-ingested of: S/C band weather radar, Global Navigation Satellite System-Zenith Total Delay (GNSS-ZTD), radiosonde, Aircraft Meteorological Data Relay

(AMDAR), and AWS surface observations. NDOW then provides BCs for the 1-km Domain-3 Urban model from its 3-km output, and VDRAS output is assimilated into the 1 km domain via FDDA.

Additional details on all of these steps are provided by Zhang et al. (2017a). RMAPS analysis and forecast products are operationally provided to BMS for weather warning and many forecasting applications, e.g., urban flooding, air pollution, weather modification, energy consumption, and emergency-response management.

Application of this system for modeling SURF UHI, thunderstorm, and haze case study events are discussed below. Parameterization options for each application are also given.

Urban weather-model. The 1-km WRF-Urban cooling-tower and 3 km thunderstorm simulations used the sophisticated multilayer urban canopy model option in WRF-Urban (Chen et al. 2011), comprising advanced versions of BEP of Martilli et al. (2002) and (in the cooling tower study) of BEM of Salamanca et al. (2010) to estimate anthropogenic heat fluxes (Q_A).

The single NASA 30-m Landsat urban land-use class is scaled up to 1 or 3 -km (as appropriate) and then resampled into three new urban building (i.e., low, medium, and high) classes according to gridded urban-fraction values. Required gridded urban parameters (e.g., building-plan area fraction, mean building height) are derived from remotely-sensed building morphological data maintained by the Beijing Institute of Surveying and Mapping and scaled up according to building-plan-area-weighted average; details provided in Zhang et al. (2013).

Other WRF parameterization options selected for the two urban weather studies are listed in Table 3, where the Noah land-surface module has four soil moisture and temperature layers, and where the BouLac PBL scheme uses TKE prediction. The 9km domain also uses Kain-Fritsch cumulus parameterization, not needed in the finer resolution domains (Fan et al. 2013). *Chemical model.* The operational IUM 3 km WRF-Chem model simulates formation, transformation, and transport processes of both primary and secondary atmospheric pollutants, including gases and PM species. It used two nested grids (Table 3), with 38 vertical layers. Physical parameterizations include: SLUCM; Carbon Bond Mechanism-Z (CBM-Z) chemical mechanism, which include comprehensive reactions and alterable scenarios (Zaveri et al. 1999); Model for Simulating Aerosol Interactions; MOSAIC chemistry-aerosol mechanism, with its four bin sizes (Zaveri et al. 2008); and the fast photolysis computation code of Fast-J, Wild et al. (2000).

Anthropogenic emission- data for 2012, with a resolution of $0.1 \times 0.1^\circ$, was developed by Multi-resolution Emission Inventory for China (MEIC) group (<http://www.meicmodel.org>) and were interpolated to the 3 and 9 km model grids via a bi-linear method. Meteorological ICs for the 9 km and 3km WRF-Chem model, and BCs for the 9 km grid, were obtained through the WRF Preprocessing System (WPS), via output from the 9 km operational ST model. An idealized vertical profile for each chemical species, based upon northern hemispheric, mid-latitude, clean environment conditions, is used to provide chemical ICs and BCs (WRF-Chem User Guide 2017). Meteorological and chemical BCs for the 3 km model are directly obtained from the outer 9 km domain.

PRELIMINARY FINDINGS. The following preliminary results are presented only to highlight the range of SURF research activities, with additional details available in cited references and on the UMDSP website: <http://www.iu.cn/dataCenter/>.

Urban HOST. Nighttime relationships between turbulence intensity and wind speed over urban canopies were investigated to verify the HOckey-Stick Transition (HOST) hypothesis of Sun et al. (2012, 2016), previously developed from observations over a grass field. The hypothesis describes the roles of non-local large coherent turbulence eddies during turbulent mixing via the linear relationship between turbulence intensity and mean wind speed V under near neutral conditions, i.e., $u_* = \sqrt{\tau/\rho}$, where τ is turbulent momentum stress, ρ is air density, and u_* is friction velocity. Turbulent flux measurements at the 47 m level (near the urban canopy top) of the 325 IAP tower (Fig. 1) were used to show that the dominant linear relationship between u_* and V also exists over urban canopies. The strong wind shear from the rough urban surfaces produces turbulence in near neutral urban stability conditions, shown by Bornstein 1968 to exist over NYC, as stable boundary layers over urban canopies are thus hard to maintain. The role of surface roughness on turbulent mixing is also reflected in the increasing slope (Fig. 4) of the u_* - V relationship with increasing surface roughness (sorted by wind direction) over the heterogeneous Beijing surface, consistent with the observations by Mahrt et al. (2013).

Urban surface energy balance. The exchange of energy between urban surfaces and the overlying atmosphere involves five important processes: absorption and emission of radiation by urban surfaces, turbulent transfer of heat energy to or away from the surface, evaporation of water stored in its surfaces and/or condensation of atmosphere water vapor onto the surface, thermal conduction of heat within the ground, and anthropogenic heat fluxes.

Table 4a shows the average midday (1000-1400 LST) radiative and energy fluxes from both the 140-m level of the urban IAP tower and the 36-m suburban MIY tower (sites are about 50 km apart, Fig. 1) for June to August 2015. The IAP site shows slightly lower incoming shortwave radiation, due to its higher atmospheric $PM_{2.5}$ concentrations (discussed below). Reflected shortwave radiation is lower at IAP, with an albedo of only 0.10, as compared to the 0.13 suburban-value. Both sites have similar incoming longwave radiation fluxes, as its dominant control is cloudiness and its values are similar at both sites, i.e., 14 clear, 20 cloudy, and 31 rain days; the cloudiness classification procedure is described in Miao et al. (2012).

Although MIY has higher outgoing longwave radiation, the net all-wave radiations are nearly equal. Significant differences existed, however, in the surface energy partitions, as IAP has smaller turbulent sensible and latent heat fluxes, and thus a larger

(estimated) residual heat storage. Another contributing factor to urban heat storage is its anthropogenic heat flux source (discussed below).

Daily mean Bowen ratios (ratio of turbulent sensible to latent-heat flux; Table 4b) of 0.56 and 0.49 for IAP and MIY, respectively, are lower than previous urban and suburban estimates from sites with similar or larger fractional vegetated cover. For example, Tokyo has a ratio of 1.77 in July with a urban vegetation percentage of 29% (Moriwaki and Kanda 2004), while the values for IAP and MIY are 21.7 and 37.0, respectively (Miao et al. 2012). The high Beijing urban latent heat flux Q_E is likely due to roadway greenbelt-watering, air conditioning, and roadway sprinkling for dust control, while at suburban MIY, it is from crop irrigation (Miao and Chen 2014).

Urban PBL depth. PBL depth is important for many applications, including weather and air-quality forecasts. Data from the Leosphere WindCube Doppler lidar (located near the IAP tower) were used to study PBL evolution on six days during the 2015 summer SURF campaign. A Doppler Beam Swinging (DBS) scan-mode was used, which takes 4-5 or 2-3 s per beam scan with elevation angles of 75 or 90°, respectively.

Daytime convective boundary layer (CBL) depth was estimated by a vertical velocity variance threshold ($1 \text{ m}^2 \text{ s}^{-2}$, Barlow et al. 2011), as lidar wind profiles have shown this method as more accurate than maximum wind-shear methods (Huang et al. 2016). This method, however, has limitations with nocturnal boundary layers (NBLs), so their tops are herein defined as where the variance decreases to 10% of its nearsurface maximum (minus a background variance), following LeMone et al. (2014). These two methods have thus herein been combined to determine diurnal variations of SURF urban PBL depths. Results (Fig. 5) show clear diurnal patterns, with depths ranging from 270-1500 m. They also show good agreement with the elevated inversion in the 1315 LST radiosonde potential-temperature profile at the NAN site.

Normalized relative backscatter (NRB) data from two MPL lidar (in a vertical to zenith scan mode) were also used to concurrently estimate midday PBL heights on 11 August 2015 from 1250-1402 LST, both alone a mobile route (Fig. 1b) and at a fixed site (adjacent to the urban IAP tower). As MPL instruments cannot be absolutely calibrated, small differences exist in CRB values when both were co-located (at start time of Fig. 6). Results show a fairly uniform urban CBL depth (about 1.2 km), with well mixed conditions near the tower (Fig. 6a). While the mobile rural-heights (about 0.8 km, Fig. 6b) were generally lower than the concurrent IAP urban values (s expected), they increased when the instrument passed through the urban areas. In addition, both sections show some PBL-top gravity wave activity and the mobile results also show two large 10-min rural convective periods. *Urban weather-model development.* RMPAS-Urban forecasts suffer from overpredicted (especially nocturnal) 2-m temperatures and 10-m wind speeds. Use of the BEP scheme (also with default look-up table input parameters), did improve Beijing operational 2-m temperature and 10-m wind speed absolute-biases by 4°C and 1 m s^{-1} , respectively (Barlage et al. 2016). Despite the use of BEP, urban models still consistently overestimate 2-m temperatures because of incorrect predicted surface energy-balance terms. Beijing anthropogenic heat emissions are comparable to other major cities, e.g. NYC (Gutiérrez et al. 2015a), and mega-city anthropogenic heat is partly due to air conditioning (A/C) systems. These systems release a mixture of sensible and latent heat to the environment, and in summer, 50–80% of the heat released by evaporativecooled A/C systems is latent energy (Sailor et al. 2007). Air conditioning heat releases in BEM, however, are assumed as 100% sensible heat (Salamanca et al. 2011), an important reason for the over-predicted 2-m urban temperatures.

To improve RMAPS-Urban performance, SURF simulations used the new Evaporative Cooling (EC) scheme of Gutiérrez et al. (2015a, b), developed for NYC and incorporated into the BEM urbanization option. Model evaluation of predicted temperatures and humidities used both data from eight urban AWS sites across Beijing and fluxes from the 140-m level of the IAP tower (Fig. 1b). The modeling period was 4-11 July 2015, which included dry (6^{th} - 11^{th}) and wet (4^{th} - 5^{th}) days.

Results show major improvement for daytime “total” sensible plus latent heat flux values (Fig. 7a and b), although the timing of its peak was about 2 h too late. The increased latent heat flux during the EC simulation (accurately) slightly increased moisture-values throughout the diurnal cycle (Fig. 7d). While the corresponding decreased nighttime latent heat flux also improved the too high temperature peak (Fig. 7c), it remained 2-h too early. The model is also much drier than the observations in the initial period, presumably due to the specified initial land surface soil moisture.

These impacts from the EC parameterization on simulated urban temperature and humidity are, however, significant (Table 5). The largest RMSE improvement for temperature is for the wet days, with the reverse true for the dry days; smaller differences are seen between dry and wet days for the corresponding humidity values. The largest bias improvements with the EC formulation for both temperature and humidity, however, are on the dry days. Improvements were also seen in the PBL height and inversion-structure (not shown), also consistent with the NYC results of Gutiérrez et al. (2015b). Future efforts to obtain improved urban thermal-response data will be carried out via in-situ or satellite infrared observations.

Thunderstorm-bifurcation modeling. Two simulations with the 3 km IUM Urban model (Table 3) were carried out for the 22 July 2015 SURF IOP thunderstorm, an: (a) Urban case with 2010 land use data and (b) No-Urban case, which converted all urban Beijing-area grid points to cropland, the dominant surface surrounding the city.

Results reproduced the weak observed UHI before the storm bifurcated around Beijing, but its magnitude was underestimated by 0.5°C (not shown). While the Urban case somewhat overestimated peak precipitation and total accumulation around the city, it correctly simulated its timing, location, and bifurcation pattern (Figs. 8a vs. 8c); the No-Urban results (Fig. 8b) showed no bifurcation. Results were used to gain insights (not shown) into urban dynamic

mechanisms leading to bifurcation, i.e., a deep (blocking) high-pressure perturbation upwind of Beijing and deep downward urban vertical velocities; additional details can be found in Dou et al. (2018) and Bornstein et al. (2018).

Haze event. A regional PM_{2.5} haze episode occurred in the North China Plain (NCP, Fig. 1a) from 26 November to 1 December 2015, when observed hourly concentrations at many Beijing sites abruptly increased and decreased several times in 24-h. Average concentrations at 35 Beijing sites (red line, Fig. 9) experienced PM_{2.5} decreases at 1700 LST on 29 November and 0600 LT on the next day, followed 13 h later by an increase to 500 $\mu\text{g m}^{-3}$. This value is 15 times the annual standard of 35 $\mu\text{g m}^{-3}$ (no hourly standard exists in China). To understand the dynamic, physical, and chemical processes responsible for these high concentrations and rapid changes, a WRF-Chem simulation was carried out (Table 3).

The observations show that northward-moving near-surface polluted air met southward-moving clear air and thus formed a surface convergence zone. This zone first passed northward over Beijing by 2000 LST on 29 November (Fig. 10a), producing high PM_{2.5} values (up to 500 $\mu\text{g m}^{-3}$) over southern urban Beijing. When the cold air strengthened and pushed the boundary southward 12 h later, concentrations over the city fell abruptly to 100 $\mu\text{g m}^{-3}$ (Fig. 10b). A re-strengthened southerly flow then pushed the boundary northward over Beijing for a second time at 1400 LST on the 30th (Fig. 10c), and concentration in the southern part of the city thus rose to 700 $\mu\text{g m}^{-3}$. These high concentrations continued to move northward, so that 6 h later, an UHI-induced convergence (Fig. 10d) drew maximum concentrations into central Beijing from the south.

Data from the IUM Doppler lidar at the 325-m IAP tower and from the mini-MPL lidar at HAI (7 km NW of the tower) were also used in the analysis of PM_{2.5} concentrations on the 30th. The HAI data (Fig. 11a) show increasing surface PM_{2.5} starting at 0900 LST, peaking at 600 $\mu\text{g m}^{-3}$ by 1700 LST. The near-surface flow from the northeast at IAP (up to 370 m) until about 0500 LST corresponds to decreasing PM_{2.5} at HAI and to the low Carrier-to-Noise Ratio (CNR) values at IAP (Fig. 11b). As the PM_{2.5} front pushed into Beijing, concentrations (as reflected in the larger CNR values) steadily rose throughout the lowest 600 m of the IAP PBL. The shape of the IAP (fixed point) internal boundary layer is consistent with urban-barrier-induced surface frontal-retardation of a moving cold-front. As the IAP tower was always north of the concentration front (Fig. 10), winds in its lowest 200 m remained northerly, although above 300 m they were consistently southerly.

Chemical modeling (Table 3) correctly simulated the maximum PM_{2.5} south of Beijing at 2000 LST on 29 November (Figs. 12a vs. 10a), but incorrectly had the max southeast of the city (and not to its east) at 0800 LST on the 30th (Figs. 12c vs. 10c). It did, however, correctly place a narrow maximum over Beijing 12 h later (Figs. 12d vs. 10d). All simulated maximum concentrations are, however, underestimated by a factor of two. Possible reasons for this include underestimated heating-season pollutant emissions, failure to correctly simulate the complex urban meteorology conditions, and missing modeled heterologous reactions during high humidity conditions.

Li et al. (2017) also showed that shifting wind directions (from northerly to southwesterly) above the stable boundary layer was the key process that transported the heavily polluted air over Beijing. Morning convective turbulent mixing then transported upper polluted air downward, leading to the observed dramatic increases of PM_{2.5} on November 30. Such local scale processes (e.g., dilution due to northwesterly downslope winds from the mountains around Beijing, and the rapid increases of pollutants due to shifting wind directions and vertical mixing) are difficult to model and can lead to serious underestimation of PM_{2.5} peak concentrations.

SUMMARY. SURF is truly a multidiscipline effort, in which scientists (i.e. observationalists, modelers, meteorologists, engineers, and chemists) and forecasters collaborate across disciplines to create knowledge and to develop modeling tools to improve urban weather and air quality predictions. SURF has four components: experimental (field) studies, numerical model development, modeled case studies of thunderstorms and haze events, and applications (improved forecasts). The structure of its lead agency (IUM), which comprises both urban PBL researchers and operational weather and air quality urban numerical-forecasters, facilitates active collaboration with stakeholders, who provided useful insights for hypothesis testing and field study planning.

New scientific insights from SURF include use of flux data from a 325 m urban tower to confirm the HOckey-Stick Transition (HOST) turbulence-wind relationships over urban canopies, and a new composite diagnostic-method of Doppler lidar turbulence intensities to produce more accurate estimates of diurnal variations of urban PBL-depth. These new findings will be applied to reduce systemic differences between simultaneous fixed and mobile lidar observations. They will also be incorporated into IUM operational WRF models to evaluate their roles in forecast improvement, as the IUM urbanization schemes require additional development to reduce predicted urban temperature and wind biases. A new anthropogenic cooling tower latent-energy module was added to the BEM urban weather model; while it reduced model biases, additional development is also needed. Analyses of energy balance fluxes from the 325 m Beijing tower and at a nearby suburban tower showed reasonable urban-induced differences, which will also be useful in this effort.

A SURF “golden case” bifurcating summer convective thunderstorm event was analyzed and correctly simulated with the IUM urbanized WRF model. Simulated outputs were useful in gaining insight into the bifurcation mechanisms (i.e. from deep blocking high-pressure perturbations and intense downward vertical velocities); other SURF storms will be analyzed for additional insights. Regional and urban aspects of a SURF haze episode were analyzed and correctly simulated with the IUM chemical model to better understand 4-D transport mechanisms. Urban land surface, anthropogenic heat, and emission impacts on such events will be further investigated.

Many challenges still need investigation within the scope of SURF, including development of advanced data assimilation methods for the dense and diverse observations at the urban scale, (e.g., aerosol PSDs). While the BEP and BEM urban parameterizations represent current state-of-the-art for high resolution urban forecast models, problems still exist in the partition between their latent and sensible anthropogenic-heat components and in their vertical distributions. The comprehensive SURF data set thus presents unique opportunities to test, calibrate, and develop improvements for such models, as they allow for model performance assessment, parameterization development, and golden-case analyses. An example of this is the evaporative cooling (cooling tower) SURF study, as its large errors in sensible heat flux need further investigation. Comparative studies of modeled and observational energy and radiation budgets should be carried out via model sensitivity experiments (e.g., for PBL height values.) SURF looks to explore new boundaries for high-resolution urban modeling (to subkilometer scales) for a variety of summer and winter conditions. Urban precipitation processes involve large-scale and urban forcings, as well as cloud microphysics modifications from natural and urban CCN, but aerosol impacts on urban precipitation are still largely unknown. SURF may answer some of these questions by its planned urbanization of WRF-Chem and by application of the new model to its golden case data sets.

SURF has now entered an intensive data processing and modeling phase. These theoretical, numerical, and operational developments, as well as the massive datasets and planned journal publications, will aid future research in a wide variety of cities into the remaining unknowns of urban meteorology, climate, climate change, and air quality.

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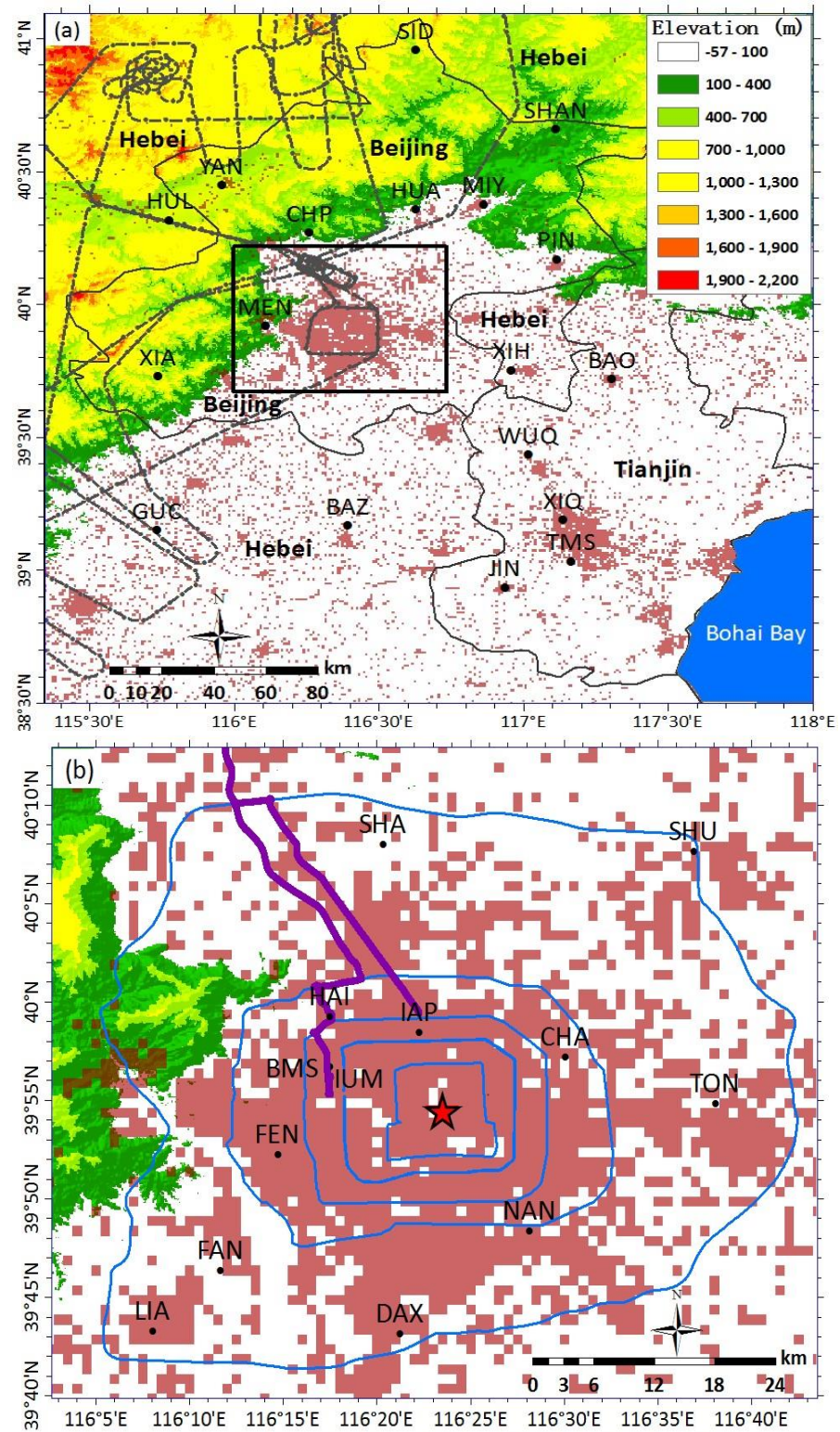


Fig. 1. Study area (a) full and (b) Beijing zoom-in (area of black box in a); with topography (m, color bar); urban areas (pink); province names (full words); Tian'an Square (red star); PBL instrument sites (dots; three letter abbreviations defined in Supplement A); King Air flight tracks (dashes); mobile lidar route (purple), which starts from IAP ends at IUM; and Beijing Ring Roads 2 to 6 (light blue circles).



Fig. 2. Photographs of some SURF instrumentation (a) 325-m tower at IAP, (b) small balloon radiosonde at IUM, (c) GPS radiosonde at NAN, (d) X-band radar at SHU, (e) ceilometer at LIA, (f) Mini-MPL at DAX, (g) wind profiler at SID, (h) mobile wind profiler at CHA, (i) wind profiler at SHA, (j) wind profiler at YAN, (k) wind profiler at GUC, (l) King Air airplane, (m) Doppler lidar and Mini-MPL at IAP, and (n) mobile MPL, where three letter abbreviations are defined in Supplement A.

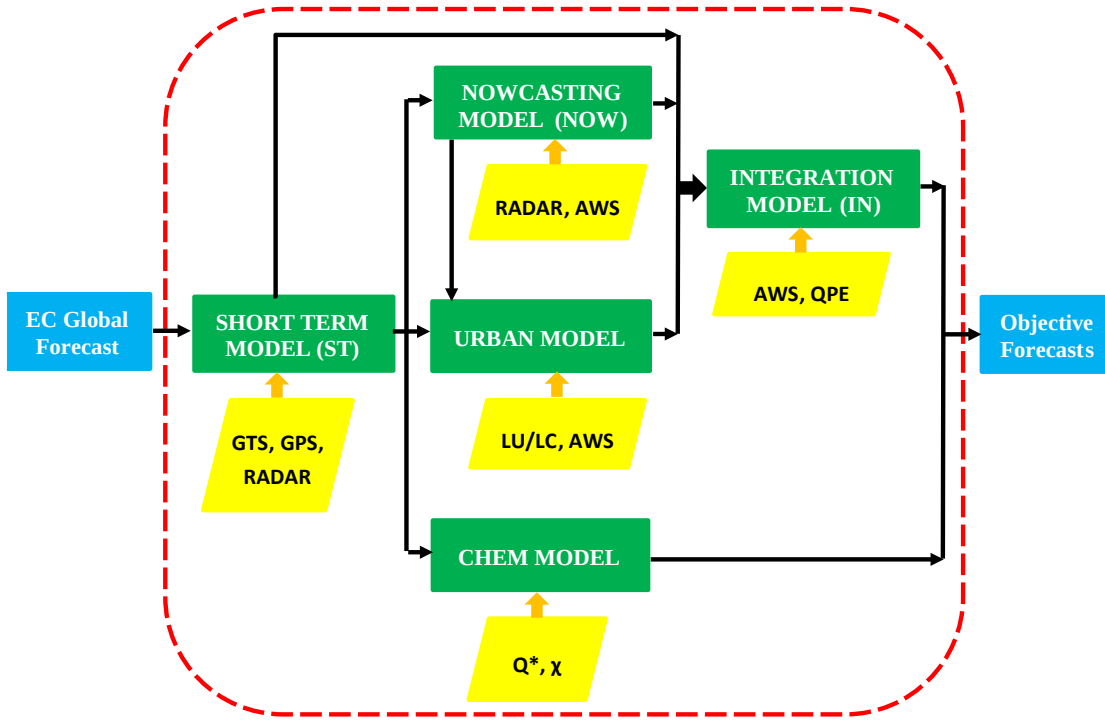


Fig. 3. IUM RMAPS modeling system flow-chart, where input and outputs (blue boxes), component models (green boxes), and input data (yellow boxes) are discussed in the text, and where EC is the ECMWF model, Q^* emission inventory, and χ concentration.

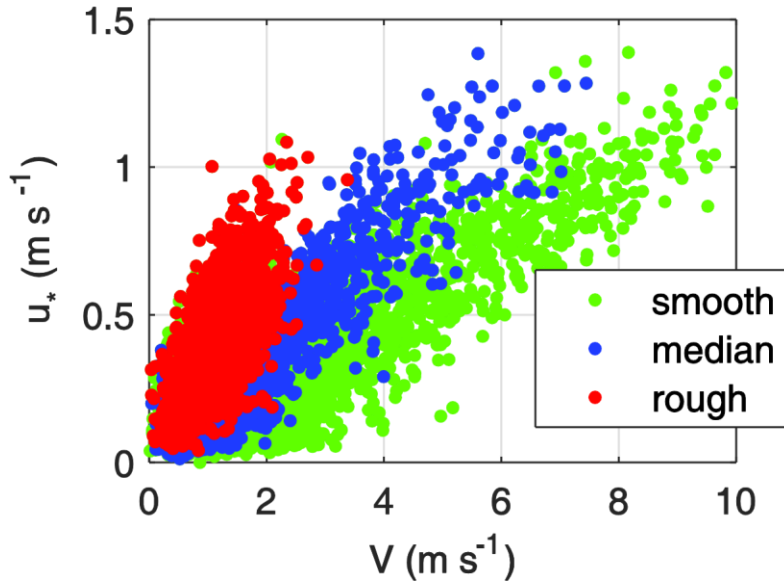


Fig. 4. Wind speed V vs. friction velocity u_* (each dot represents 30-min average value) at 47-m Beijing IAP tower level on nights following sunny days in 2015 for rough, medium, and smooth surfaces, i.e., wind direction ranges of: 160-240, 300-360, and 360-160°, respectively.

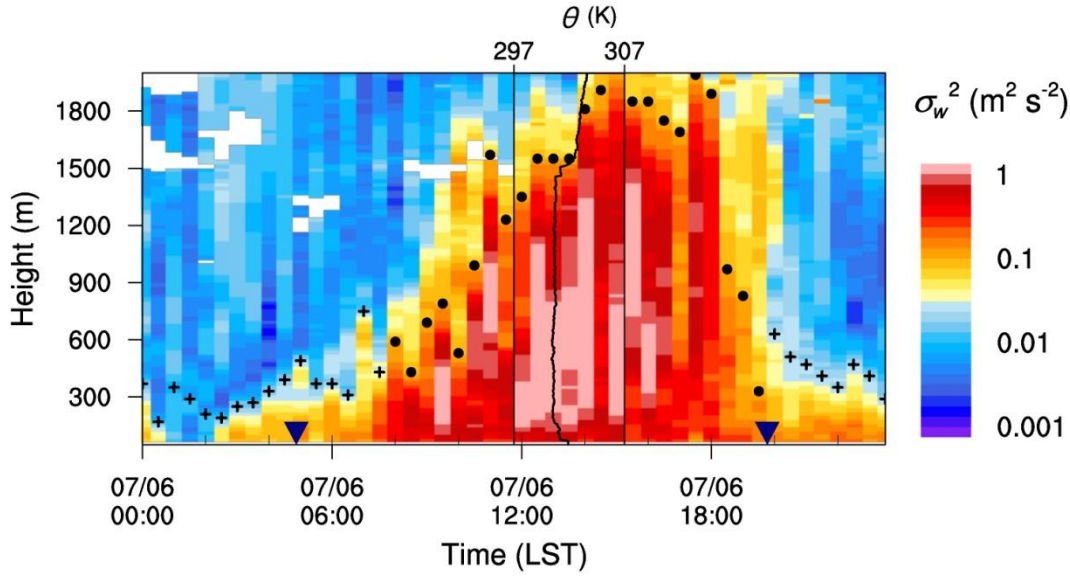


Fig. 5. Doppler lidar Beam Swinging (DBS) scans of 30-min mean vertical-velocity variances (colors, $\text{m}^2 \text{s}^{-2}$) on 6 July 2015, with CBL (●) and NBL (+) depths from threshold and fractional methods, respectively (described in text); potential temperature (K) profile (solid line) from the 1315 LST NAN radiosonde; and sunrise and sunset (triangles); from Huang et al. (2016).

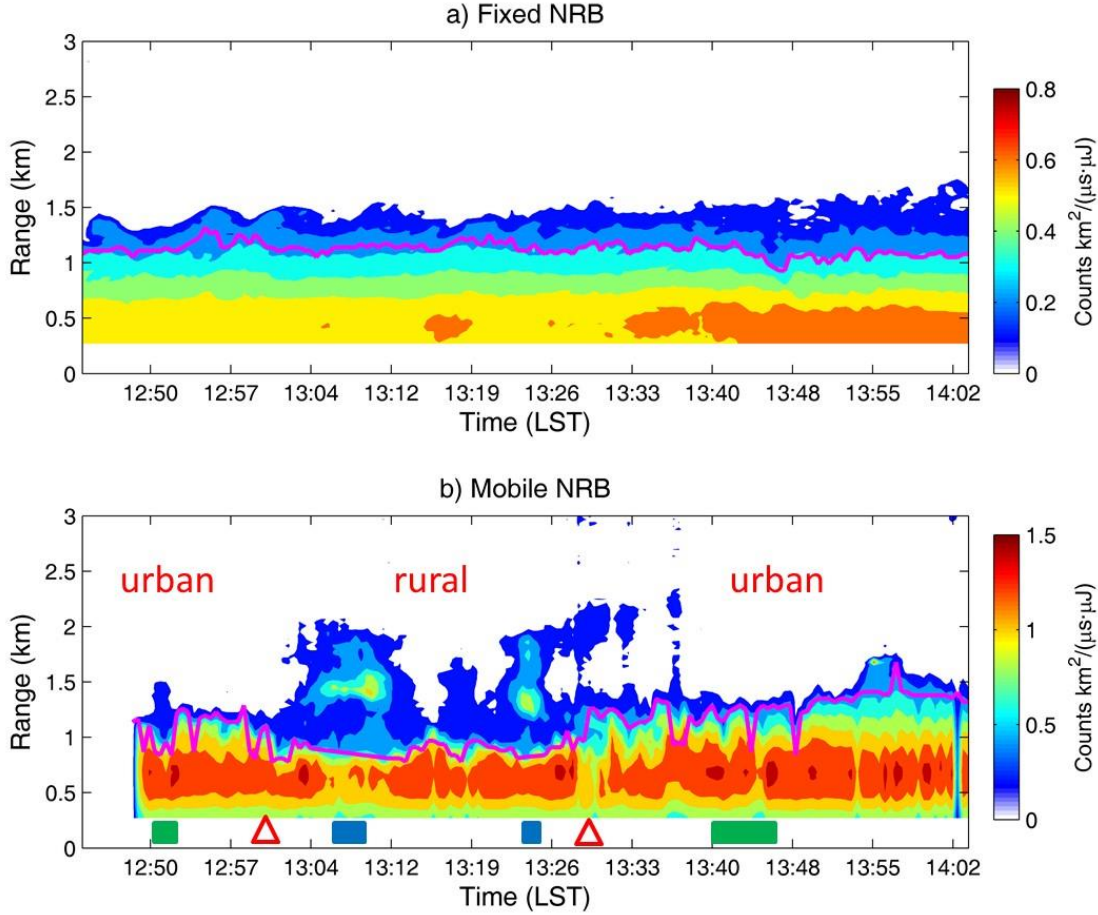


Fig. 6. Concurrent cross sections of MPL normalized relative backscatter (NRB, colors; note different scales) and PBL height (magenta lines) from wavelet covariance transforms on 11 August 2015: (a) at IAP and (b) on the mobile route of Fig. 1b, where the red triangles delineate period in rural areas and rectangular bars indicate periods on Ring Roads 5 (green) and 6 (blue).

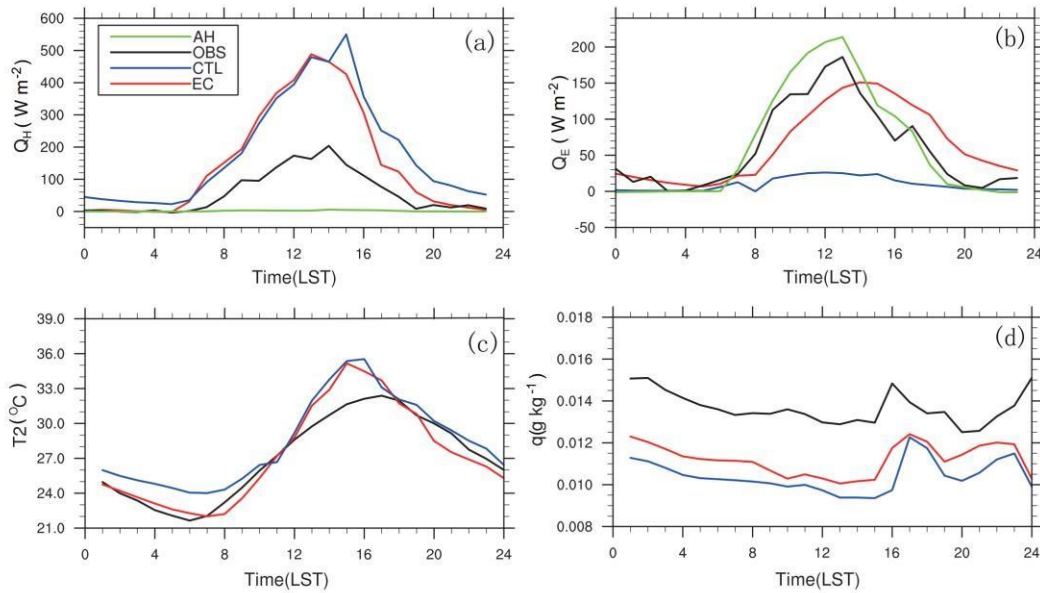


Fig. 7. Diurnal variations of average-summer observed 140-m level IAP-tower observed (OBS, black); and WRF Control (CTL, blue) and Cooling Tower (EC, red) simulated (a) sensible and (b) latent heat-fluxes, as well as EC anthropogenic heat-flux component (AH, green); and 2-m average (for eight urban stations): (c) temperature and, (d) specific humidity.

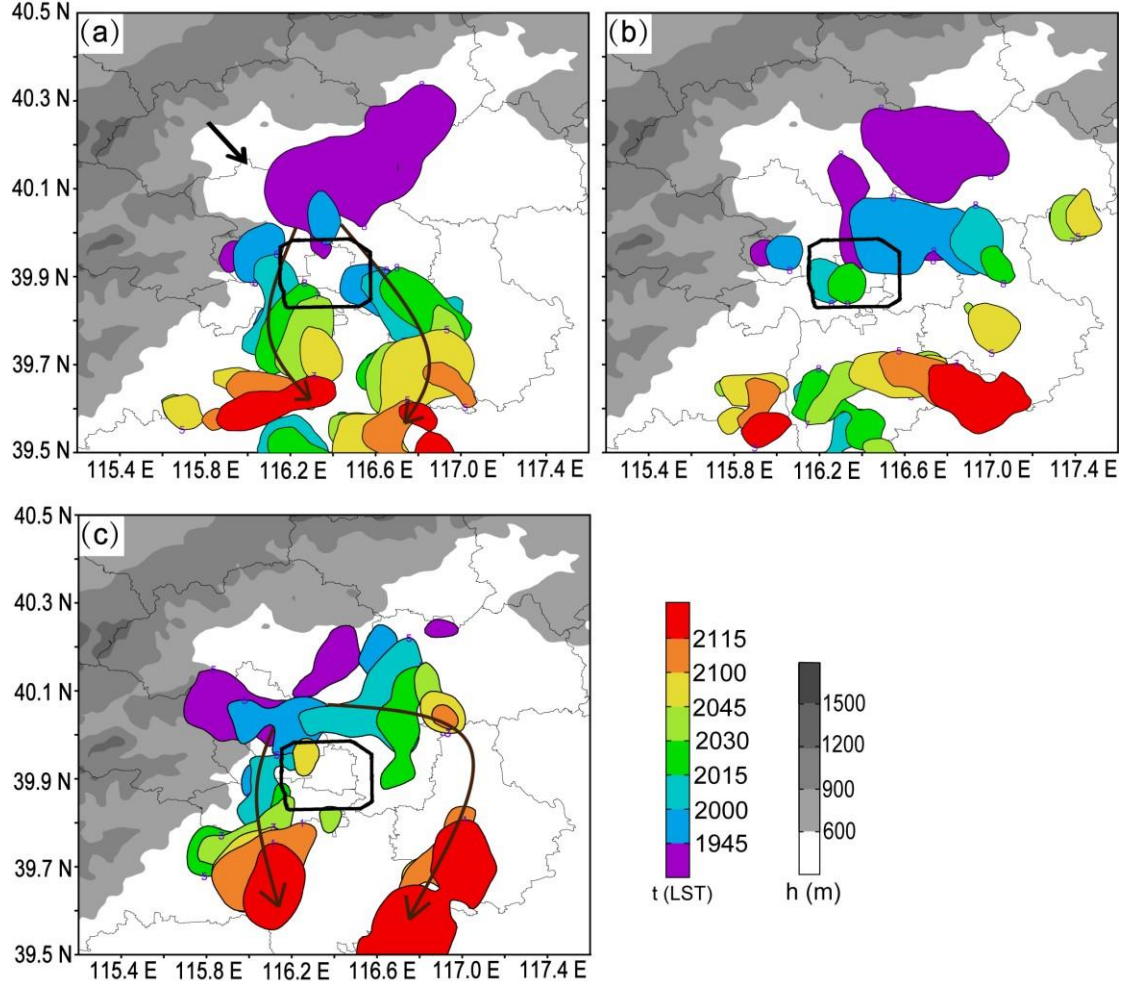


Fig. 8. Precipitation centers on 22 July 2015 every 15 min (colors) for the: (a) Urban and (b) No Urban simulations (min outline values 3-8 mm) and (c) observations (min outline values 1-5 mm), where grays are topographic height (m), black rectangle is Ring Road 4, short arrow is storm-movement direction, and long arrows are storm-center trajectories.

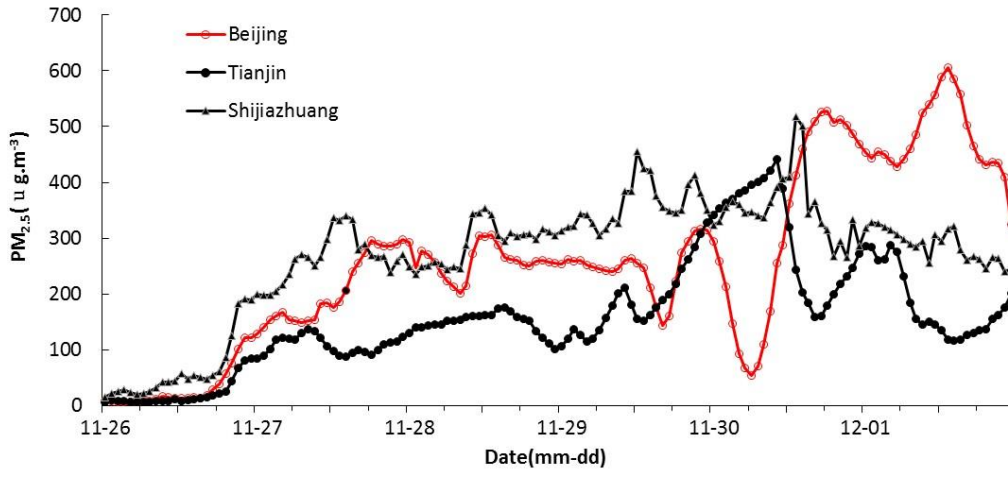


Fig. 9. Average hourly observed $\text{PM}_{2.5}$ concentration ($\mu\text{g m}^{-3}$) from 26 November to 1 December 2015 from 35 Beijing, 28 Tianjin, and 27 Shijiazhuang urban sites.

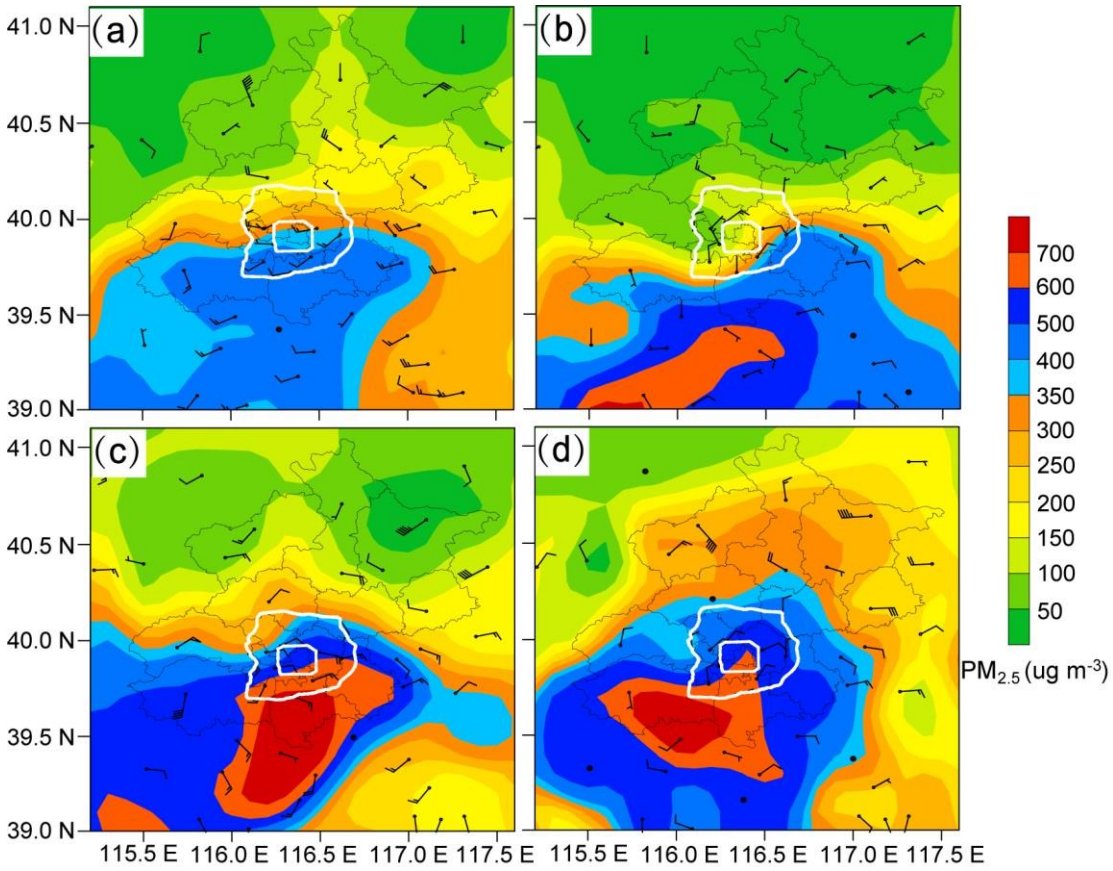


Fig. 10. Observed Beijing-area 10-m surface wind (1 full barb is 1 m s^{-1}) and $\text{PM}_{2.5}$ concentration (colors, $\mu\text{g m}^{-3}$) during November 2015 at: (a) 20 LST on the 29th; and at (b) 08, (c) 14, and (d) 20 LST on the 30th, with Ring Roads 4 and 6 (white circles).

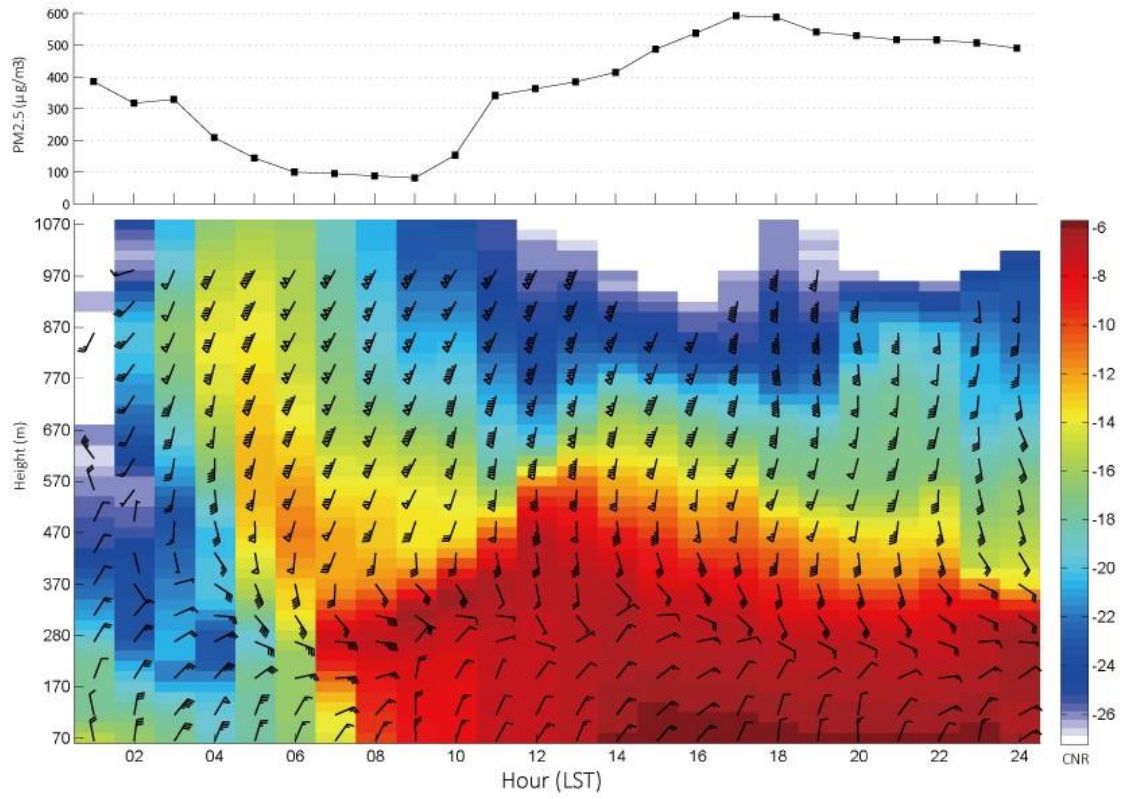


Fig. 11. Hourly observations on 30 November 2015 of: (a) $\text{PM}_{2.5}$ concentration ($\mu\text{g m}^{-3}$) at HAI, and (b) PBL horizontal wind vectors (1 full barb is 2 m s^{-1}) and dB Carrier-to-Noise Ratios (CNR, colors, dB) from IAP Doppler lidar. The db-units version of CNR used herein is $\text{CNR}(\text{db}) = 10 \cdot \log_{10}(\text{CNR})$, and as $\text{CNR}(\text{db})$ is less than unity, the values in the figure are negative powers of 10.

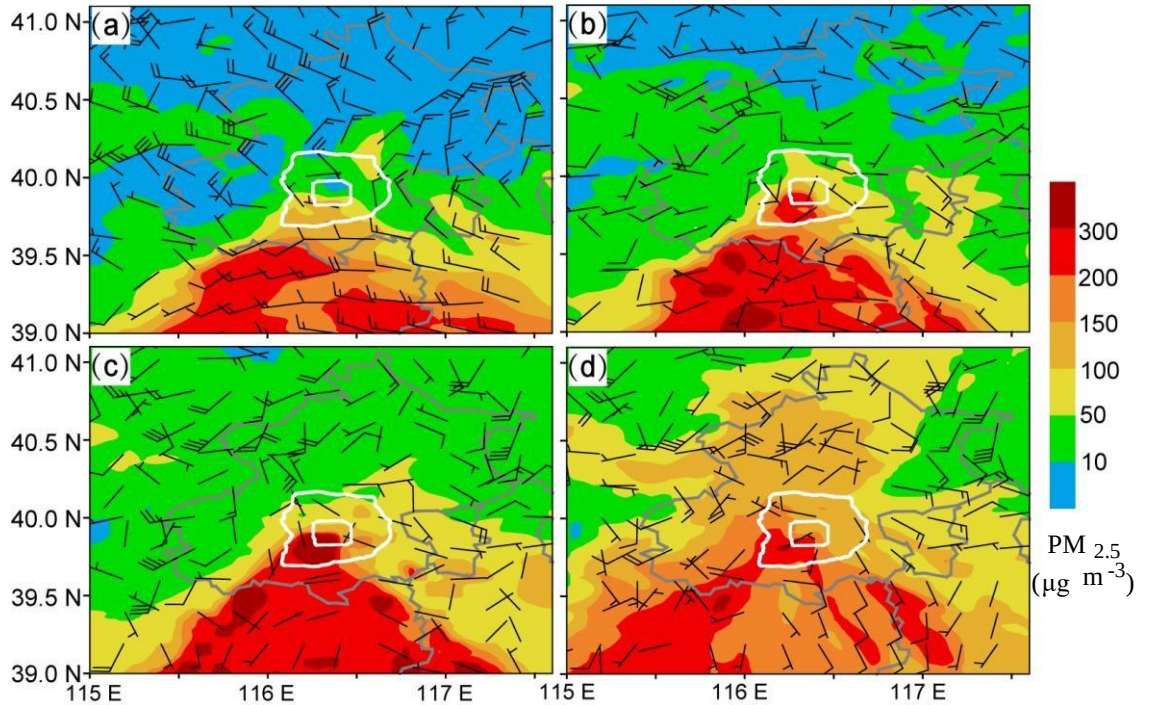


Fig. 12. Simulated Beijing-area 10-m wind (1 full barb is 2 m s^{-1}) and $\text{PM}_{2.5}$ concentration (shades, $\mu\text{g m}^{-3}$) during November 2015 at: (a) 20 LST on the 29th, and (b) 02, (c) 08, and (d) 20 LST on the 30th; with Ring Roads 4 and 6 (white circles).

Table 1. Number of 2016 summer SURF PBL observational sites during: normal operations (NO), plus additions during field study (FS) and IOP periods; AWS, GPS MET, and soil moisture “surface” sites not included.

Instrument/Period	NO	FS	IOP	Total
Wind profiler	9	5	0	14
Radiometer	3	0	0	3
Aerosol lidar	0	2	0	2
Doppler lidar	0	1	0	1
Flux tower	5	0	0	5
Ceilometer	10	0	0	10
Weather radar	4	0	0	4
X-band radar	6	0	0	6
GPS sounding	1	0	3	4
Mobile lidar	0	0	1	1

Table 2. Thunderstorm-occurrence forecast accuracy (in days) during 2015 and 2016 summer IOPs, with good/correct (unscored) and bad/incorrect (no underscore) forecasts (defined in text).

Forecast \ Observed	2015		2016	
	Yes	No	Yes	No
Yes	<u>7</u>	8	<u>20</u>	9
No	4	<u>17</u>	7	<u>26</u>

Table 3. Models (described in text) and options (reference for each given only once) for three modeling studies reported herein, where Δx is horizontal grid spacing, LW is long wave, SW is short wave, M-O is Monin-Obukhov, M-O-J is Monin-ObukhovJanjic, BEP is described in Martilli et al. (2002), and BEM is described in Salamanca et al. (2010).

	Thunderstorm-bifurcation study		Urban cooling tower study	Haze study	
	D 1	D 2	Domain 3	Domain 1	Domain 2
Models and versions	WRFDA v3.5.1 + WRF-Urban v3.5.1		WRF-Urban v3.5.1	WRF-Urban v3.3.1 + WRF-Chem v3.3.1	
Horizontal grid points	649*400	550*424	460*403	223*202	232*253
Δx (km)	9	3	1	9	3
Vertical layers	50			38	
Cumulus physics	Kain-Fritsch (Kain 2004)	None	None	Grell (Grell and Devenyi 2002)	None
Microphysics	Thompson (Thompson et al. 2004)				
LW Radiation	RRTM (Mlawer et al. 1997)				
SW Radiation	Dudhia (1989)		RRTM	Goddard (Chou and Suarez 1994)	
PBL Physics	ACM2 (Pleim 2007)	BouLac (Bougeault and Lacarrere 1989)		YSU (Hong et al. 2006)	
Rural surface	Noah (Chen and Dudhia 2001)				
Urban Physics	SLUCM	BEP	BEP + BEM	SLUCM (Kusaka et al. 2001)	
Surface layer	M-O	M-O-J (Janjic 2002)		M-O (Beljaars 1994)	
Aerosols	None			MOSAIC (Zaveri et al. 2008)	
Chemistry	None			CBMZ (Zaveri et al. 1999)	
Photolysis	None			Fast-J scheme (Wild et al. 2000)	

Table 4. Midday (1000-1400 LST) average June-August 2015 mean SURF values at the 140-m level of the urban IAP and 36-m suburban MIY towers of: (a) radiative and energy fluxes and (b) ratios of radiative and energy fluxes normalized by net or incoming radiation.

(a) Mean values ($W m^{-2}$)

Site	K↓	K↑	L↓	L↑	Q↓	Q*	Q _H	Q _E	Q _F	ΔQ_s
IAP	581.3	60.8	408.7	474.2	990.0	455.0	94.3	96.4	70.5	334.8
MIY	605.2	75.7	418.2	490.7	1023.4	457.1	147.2	177.5	—	132.3

(b) Ratios

Site	Albedo	$\square$	Q_H/Q_E	Q_H/Q^*	Q_E/Q^*	$\Delta Q_s/Q^*$	$Q_H/Q\downarrow$	$Q_E/Q\downarrow$	$\Delta Q_s/Q\downarrow$
IAP	0.10	0.49	0.98	0.21	0.21	0.74	0.10	0.10	0.34
MIY	0.13	0.51	0.83	0.32	0.39	0.29	0.14	0.17	0.13

Note: K is shortwave radiation; $(\downarrow)$ and $(\uparrow)$ are incoming and outgoing, respectively; L is longwave radiation; $Q\downarrow$ is $K\downarrow + L\downarrow$; Q^* is net all-wave radiation; Q_H and Q_E are turbulent sensible- and latent-heat fluxes, respectively; Q_F is IAP urban anthropogenic heat flux, calculated following Demuzere et al. (2008) and Zheng et al. (2015); heat storage ΔQ_s is $Q^* + Q_F - (Q_H + Q_E)$; Bowen ratio is Q_H/Q_E ; Albedo is $K\uparrow/K\downarrow$; and transmissivity $\square$ is $K\downarrow/\text{Zenith-radiation}$.

Table 5. Period-average (over eight urban stations) Root Mean Square Error (RMSE) and Mean Bias (Bias) values for hourly WRF simulated vs. observed AWS 2-m temperature (T, °C) and specific humidity (q, g kg⁻¹) for dry and wet days, and for the control (CTR) and cooling tower (EC) simulations.

Simulation	RMSE		Bias	
	CTL	EC	CTL	EC
T, dry days	1.29	1.00	1.25	0.41
T, wet days	1.34	0.43	1.13	0.68
q, dry days	0.026	0.017	-0.051	0.031
q, wet days	0.035	0.024	-0.053	0.042