Urban integrated meteorological observations: practice and experience in Shanghai, China

Article

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Capsule Summary of Article

The Shanghai urban integrated meteorological observation network (SUIMON) is introduced with examples of intended applications in this megacity

Abstract

Observations of atmospheric conditions and processes in citiesare fundamental to understanding the interactions between the urban surface and weather/climate, improving the performance of urban weather, air quality and climate models, and providing key information for city end-users (e.g. decision-makers, stakeholders, public).In this paper, Shanghai’s urban integrated meteorological observation network (SUIMON)and some examples of intended applications are introduced. Its characteristics include being: multi-purpose (e.g. forecast, research, service), multi-function (high impact weather, city climate, special end-users), multi-scale (e.g. macro/meso-, urban-, neighborhood, street canyon), multi-variable (e.g. thermal, dynamic, chemical, bio-meteorological, ecological), and multi-platform (e.g. radar, wind profiler, ground-based, satellite based, in-situ observation/ sampling). Underlying SUIMON is a data management system to facilitate exchange of data and information. The overall aim of the network is to improve coordination strategies and instruments; to identify data gaps based on science and user driven requirements; and to intelligently combine observations from a variety of platforms by using a data assimilation system that is tuned to produce the best estimate of the current state of the urban atmosphere.

Key words: urban observations; urban meteorology; urban boundary layer; urban environment, Shanghai.

1 Introduction

The world's population exceeds 7 billion, with half living in urban areas(UN 2013).Current projections suggest that the global population will reach 8 billion in 2025, with nearly 5 billion living in urban areas. This increase has formed, and will inevitably produce, hundreds of large cities (> 1million population), megacities (> 10 million population) and conurbations (or mega-regions) most of which are coastal in developing countries. Urbanization brings not only people to cities but also capital, services, convenience and benefits to economic production. At the same time, however, natural hazards and huge environmental pressures, including extreme weather (e.g. urban floods, heat waves) and environmental episodes (e.g. haze, photochemical pollution) can pose significant challenges for the crisis and risk management of these areas, the effects of which are often exacerbated by the decreased resilience and increased vulnerability associated with dense urban populations and infrastructure and intensive economic activities plus climate change(Tang 2008).

Observations of atmospheric conditions and processes in urban areas are fundamental to understanding the interactions between the underlying surface and the weather/climate, and improving the performance of urban weather, air quality and climate models. Such observations also provide key information for end-users (e.g. decision-makers, stakeholders, public) for a myriad of applications (see, for example, the range described by Dabberdt, 2012).

A number of major field campaigns in urban areas have been conducted in various parts of the world for different purposes (Table 1). These include short term campaigns such as in the USA (e.g. URBAN 2000(Allwine et al.2002), Joint Urban 2003(Allwine et al. 2004), Pentagon Shield(Warner et al. 2007),Madison Square Garden(Hanna et al. 2006))and Europe (e.g. ESCOMPTE(Cros et al.2004), CAPITOUL(Masson et al.2008),BUBBLE(Rotach et al. 2005), DAPPLE(Arnold et al.2004), and REPARTEE(Harrison et al.2012)). These studies have had many objectives, including a focus on near-surface turbulence characteristics, vertical structure of the entire urban boundary layer(UBL), and air pollution.

In addition, observational networks have been established to focus on urban weather research. One notable example is the Helsinki Testbed concerned with mesoscale weather forecasting and dispersion, involving model development and verification; demonstration of integration of modern technologies with complete weather observation systems; end-user product development; and data distribution for the public and research community (Dabberdt et al. 2005, Koskinen et al.2011). Other examples include the Houston Environmental Aerosol Thunderstorm Project(HEAT)(Orville et al. 2004), which aimed to determine the sources and causes for the enhanced cloud-to-ground lightning over Houston, Texas, and the Tokyo Metropolitan Area Convection Study (TOMACS), designed to better understand various meso-scale processes over Tokyo Metropolitan Area(Maki et al. 2012).Most of the urban observation studies to date have been for short-periods, for a relatively limited set of atmospheric and environmental conditions, rather than the full range that need to be understood for ongoing urban operations.

In 1872 Shanghai established a multi-function observatory, Xujiahui (“Zikawei” in Shanghai dialect), one of a small group of urban stations with long(>100 years) continuous records(Gherzi,1950). In 1958, weather stations were installed in the 10 rural counties of the province of Shanghai, extending the spatial dimension to about 30 km. The first dedicated urban meteorological observations in China were established in the downtown area of Shanghai in the 1970s - early 1980s. The >10 monitoring sites located over urban surfaces were used to investigate a wide range of urban effects (Zhou and Chow 1990)such as the warmer air temperatures (urban heat island, UHI),humidity characteristics (wet or dry island), precipitation characteristics and the spatial variability of air quality notably the turbidity island (Zhou and Zheng, 1991).

Today in Shanghai, there are a series of networks of different instrument types (e.g. automatic weather station (AWS), weather radar, Met-towers, wind profilers, lightning mapping systems, remote sensing systems) that provide dense observations through a network of networks, referred to here as SUIMON (**S**hanghai's **U**rban **I**ntegrated **M**eteorological **O**bservation **N**etwork). SUIMON covers the whole of the Shanghai metroplex and nearby seashores, which includes major transportation facilities, notably the Shanghai container port, the largest in the world, and Pudong International Airport. The objective of this paper is to introduce the characteristics, functions, and current state of SUIMON, and to provide examples of intended applications and future plans for its development. This multi-faceted network has the capability to cover all applications identified in Table 1, while also providing opportunities for intensive campaigns with a rich spatial and temporal database to provide context. SUIMON already provides important data to support the economic activities within Shanghai and the East China region.For example, the world's largest seaport (Yangshan seaport, Fig 1) is located on the coast here at the end of a chain of islands. A large amount of traffic travels along exposed roads to this destination. With a weather station located right at the container-port, forecasts for both shipping and road traffic are supported. This allows both efficient loading of cargo and safer travel on both land and sea, under the wide range of meteorological conditions experienced in this region.

2. The multi-function of **S**hanghai's **U**rban **I**ntegrated **M**eteorological **O**bservation **N**etwork (SUIMON)

2.1 Features of SUIMON

The coastal city of Shanghai, a direct-controlled municipality that is administratively equivalent to a province, is located at the middle of China's coastline (Fig. 1a), had a population greater than 23 million in 2010 (Zou, 2011), with more than 2.6 million automobiles, more than 32,000 tall buildings(>30 m tall) and over 1200 skyscrapers(>100 m tall) in2012(Table 2)(Shanghai Statistics Bureau, 2013). The city, given its subtropical monsoon-setting, with water on two of its three sides, frequently experiences typhoons, severe rain, heat waves, thunder and lightning, fog, storm surges and other meteorological hazards.

In order to understand the interactions between the urban surface and atmospheric processes, improve the performance of urban weather, air quality and climate models, and to provide key information for city end-users (e.g. decision-makers, stakeholders, public) SUIMON has been established (see Box 1 for design features). The initial foci for SUIMON relate to high impact weather; urban environmental and micro-meteorological conditions; special needs for end-users; along with data acquisition, integration and assimilation systems. Of particular interest are rapidly changing atmospheric conditions associated with low pressure systems (e.g., severe convective weather) and more stagnant periods (e.g., fog and haze).

Today Shanghai's urban observations extend over an area (6340 km^2) that is roughly 120km by 120km (Fig. 1). SUIMON, a network of networks, has been established from different systems and instrumentation deployment types (Table 3). The ultimate goal of SUIMON is to provide measurements of all the processes that influence Shanghai's regional environment and the city itself, including both physical and chemical characteristics of the boundary layer and the free atmosphere, so linkages can be better understood.

Box 1: **SUIMON design features**

SUIMON is designed to satisfy the following features:

- Multi-purpose: forecasts, research, service
- Multi-function: high impact weather, urban environment, special end user needs
- Multi-scale: macro/mesoscale, urban scale, neighborhood scale, street canyons, buildings
- Multi-variable: thermal, dynamic, chemical, bio-meteorological, ecological
- Multi-platform: radar, wind profiler, ground-based, airborne, satellite based, in-situ observation, sampling
- Multi-linked: linkages between all platforms

With:

- Management to facilitate exchange of data and information
- Ability to improve coordination of strategies and instruments and to identify gaps in observations based on science and user driven requirements
- Capability to intelligently combine observations from a variety of platforms using a data assimilation system that is tuned to produce the best estimate of the current state of the urban atmosphere.

Mega cities and conurbations have vast infrastructure, for example transport networks, transmission lines, drainage networks, and underground spaces (e.g. metro-lines, parking garages). These are all vulnerable to weather and can benefit from focused observations (Tang 2008) (see Box 2). User-driven observations can provide the tailored, information-rich products and services that decision makers can use effectively. Box 2 provides examples presented delivered by SUIMON.

Box 2: Examples of urban weather sensitive applications in Shanghai

In Shanghai, urban weather-sensitive applications include:

- **Urban Flood control:** Flood control agencies need data on precipitation (rain, snow) distribution and runoff, as well as the water storage capability of urban pervious surfaces, drainage systems, and water-logged ground.
- **Electric power:** Power plants, grid operators, and local utilities need high-resolution air temperature for assessing energy demand and resulting loads on the electric grid. Wind and solar radiation are also needed for renewable energy assessments.
- **Urban Design:** Urban planners and design departments need information on the UHI, vegetation stress index, urban air quality, wind
- **Public Health:** Pollutant emissions and concentration, solar radiation, wind, humidity and air temperature are needed at appropriate scales for street level, air quality, pollen, predictions of heat stress.
- **Transport management:** Transport agencies need data on strong winds (especially channeling wind), precipitation and its forms (i.e. rain, freezing rain, sheet or snow), surface state (dry, wet, ice covered), and high-resolution spatial forecasts (e.g. roadway scale) for metros, highways, and seaports.
- **Security & Emergency response:** Urban emergency response agencies need timely and accurate information on extreme weather, such as detailed street-level flood information, and high spatial and temporal resolution wind, temperature, and moisture data in and above the urban canopy.

Some of the pressing air quality related scientific questions that are being addressed drawing on SUIMON relate to the temporal and spatial extent of the pollution plume from the Shanghai megapolis; how the photochemical processes function under very high aerosol loadings; the impact of the synoptic and local scale weather on pollutants; and the influence of atmospheric composition, especially ozone (O_3) and fine particles, on human health, agriculture, eco-hydrology and other systems.

With the development of SUIMON, and public environmental awareness of the data and observational capability, the range of end-users is increasing. These now include urban managers concerned with air pollution control and regulation and the public wanting information related to air quality. There is interest in real-time conditions and the forecast for the next few hours to days, tied to concerns about environmental exposure and its health effects. Other end users include those who need to aid decision making in an emergency response to nuclear, biological or chemical (NBC) releases.

2.2Observation Networks within SUIMON

The locations of the stations within the networks of SUIMON were selected to provide spatial coverage across the Shanghai province, while also considering siting requirements of the instruments used to undertake the observations. The finer details of exact locations are often constrained by logistics, such as access to sites or availability of land. As Shanghai is also rapidly changing, notably in terms of the rapid increase in tall buildings (Table 2), site characteristics also are rapidly changing. This impacts both the representativeness of individual sensors/sites and also end user needs, reflecting the increased density of people in certain areas. Thus network design is an on-going consideration. This is also tied closely to the quality assurance/quality control (QA/QC) that is undertaken within the data management system (DMS) which is central to SUMION (section 2.3).

A hierarchy of surface level weather stations has been developed, that include the WMO official first order station (located at Baoshan) and nine weather stations (second order) across the province of Shanghai (Fig. 1a, Table 3). These 10 state-level weather stations meet standard WMO specifications (WMO,1996) and are maintained and supervised by SMS personnel. Each monitors meteorological elements automatically using an automatic weather station (AWS). In addition, 65 automatic rain gauges and 200+ AWS stations monitor, at a minimum, temperature, humidity, precipitation, wind speed and wind direction, sometimes with additional variables (e.g. air pressure, visibility), distributed across Shanghai at a range of different heights above ground level. These are used to characterize and validate thermodynamic and kinematic structures of various meso-scale features near the surface. Wind direction and wind speed, temperature, humidity, rain and pressure are archived at the central database every 1 minute. The overall density of surface based temperature sensors across the 6340.5 km^2 area is about 1 per 30 km^2. The surface based raingauge networks is approximately 1 per 20 km^2.

A key characteristic of SUIMON is that the surface based network is complemented with the capacity to observe the vertical characteristics of the atmosphere. This provides a 4-dimensional data set of the Shanghai area and the surrounding region (fulfilling a goal proposed for many urban areas (Grimmond et al.2010, NRC 2010, 2012)). At the WMO official first order station (Baoshan, Fig. 1) upper air soundings provide vertical data (1 s temporal resolution) of temperature, humidity wind speed and direction every 6 h. On the east coast and west Shanghai there are S-band Doppler Weather Surveillance Radar(WSR) systems (Table 3). These are supplemented by a moveable radar (X-band dual–polarization Doppler weather radar) to help identify severe weather and estimate precipitation rates. Single- and dual-Doppler wind field retrieval technologies are used to identify boundary convergence lines (Liang, 2007). The routine S-band radars provide total coverage of Shanghai municipality and neighboring Jiangsu and Zhejiang provinces with a temporal resolution of 6 min.

The lightning mapping system including three LS7000 sensors and one LS8000 sensor(Table 3)covering the whole Shanghai and neighboring areas, provides continuous monitoring of intra-(and inter-) cloud and cloud-to-ground lightning density. Water vapor contentis observed with a dense network of GPS/Met stations that consist of 31 receiving stations within Shanghai with a spatial resolution of 10 - 15 km. Beyond the radio-soundings, two microwave radiometers (Table 3), one operational and one movable, monitor the profile of temperature, humidity, water vapor density and liquid water content to about 10 km, with a vertical resolution of 100m from 250 m to 2km, and 250m above(Table 3).

A network of 13 instrumented broadcasting masts (Fig.1), with wind sensors at 10,30,50,70, and 100m above ground level (agl), plus temperature and humidity sensors at 10 and 70m agl, provide vertical information close to the surface (lower boundary layer) (Fig. 2a).Ground based remote sensing includes 10 wind profilers(Table 3) that provide detailed information about boundary layer wind fields and mixing layer height (Fig. 2b). These provide information from 60 m to 3000 m with gates of 60m or about 100 m resolution which vary with model and operating mode (high or low) across the network.

Local scale flux measurements (Table 3) are conducted within the densely built-up area of Xujiahui (Fig. 1). Within the footprint of the flux tower is the site where routine weather data have been collected for more than 140 years. The micrometeorological instrumentation, mounted at 80m, includes eddy covariance measurement (Aubinet et al. 2012) of turbulent sensible and latent (water vapor) heat plus carbon dioxide fluxes. Simultaneously the four components of net all-wave radiation (long-wave and short-wave incoming and outgoing/reflected radiation) with slow response air temperature and relative humidity sensors are measured. With the flux measurements, the surface energy balance and carbon fluxes are being investigated (Ao et al. 2014). These measurements will be used to verify and modify urban land surface models used in weather and the climate prediction model. Within Shanghai, radiation measurements are also undertaken in Baoshan (Table 3).

In addition to the physical characteristics of the atmosphere, observations related to atmospheric composition (e.g. ozone (O_3) and its precursors, aerosols)are measured at 10 sites(Fig.1) across the region. As ground-level O_3 is formed as a result of complex photochemical reactions of nitrogen oxides, carbon monoxide(CO) and various volatile organic compounds(VOCs), the concentration of O_3 and its precursors are measured nearly 10 m above the surface (Table 3). VOCs concentrations sampled for 24 h are analyzed with a lab-based gas chromatography system coupled with mass-selective detection(Geng,2008). Other surface based *in situ* observations include particulate matter(PM_1,$PM_{2.5}$,PM_{10}) and black carbon(BC) (Table 3).

The vertical O_3 concentration profile is observed by O_3-GPS soundings, to understand the exchange between the upper and lower parts of the boundary layer. Other ground-based remote-sensing includes lidars (e.g. ceilometers, micro-pulse (MPL)) and a sun photometer. These provide continuous, real-time measurements of the boundary layer depth and coherent structures by sensing aerosol backscatter (Table 3).MPL data, available from 1 July 2008, allow aerosol extinction coefficients and boundary layer height to be measured with vertical resolution of 30m from 250 m to 20 km. Column aerosol optical properties and solar extinction, observed with an 8 channel Sun photometer during the daytime (Table 3), are used to derive aerosol optical depth(He 2012a).The light scattering coefficient due to particles is measured with an integrating nephelometer.

These data are complemented with those from satellite based remote sensing(e.g.

derived from MODIS, FY-3, Table 3)to study the aerosol distribution across Shanghai and East China(He 2012b).Three satellite data receiving systems provide data from 8 polar-orbiting(NOAA 15/16/17/18, FY-3A,FY-3B,EOS/TERRA,EOS/AQUA) and 4 geostationary satellites(FY-2D,FY-2E,FY-2F,MTSAT-2). The satellite derived data are used to monitor a wide range of variables (e.g. cloud location and extent, surface temperature, fog, haze) (Cui and Shi 2010, 2012, Cui et al. 2014).

2.3 Data acquisition, integration and assimilation in SUIMON

Critical to SUIMON is the integrated data management system (DMS) that has been built and operated by the Shanghai Meteorological Service(SMS) (Fig. 3). This acquires and stores the multi-scale, multi-source meteorological observations (e.g. AWS, weather radars, wind profilers, met-tower observations, Table 3) with their metadata (e.g. Table 4). All the information collected at this stage is termed Level0 data.

The data undergo initial processing (e.g. decoding, extracting, format checking)and are loaded into raw databases (MYSQL/SQL SEVER/File Databases) to create Level1 data. These are stored in a series of different databases(e.g. surface observations, vertical profiler, atmospheric composition).

The quality control (QC) sub-system includes an information feedback mechanism to improve the completeness, validity and accuracy of the meteorological data. The metadata related to the regular instrument calibrations and format are utilized to assess data quality along with monitoring transmission, meteorologically based QC and comprehensive manual QC. Currently, the QA/QC is performed on the AWS, wind profiler and met-tower data streams automatically by using the approach of both climatic and regional history extremes, a time consistency check, a logical consistency check between variables, and a spatial consistency check. These metrics are used to generate QC flags, which are incorporated into secondary databases with the Level2 data, while the raw databases are kept intact.

The Local Analysis and Prediction System (LAPS)(Liu et al. 2012) and ARPS (Advanced Regional Prediction System) Data Analysis System(ADAS) are used with, and within, SUIMON for integrated data analysis and data assimilation using for example, the sounding data, AWS, radar reflectivity, wind profiler, GPS/Metto support meso-scale numerical weather prediction models (NWP). The meso-scale models used include weather and research forecasting (WRF) versionv3.0. Urban focused observations are used as input or to evaluate sub-models for other models such as urban boundary, urban canopy, and air quality models. Different urban land surface schemes such as SUEWS (Järvi et al. 2011), plus other options with WRF (Chen et al. 2011) and available more generally (e.g. those included in Grimmondet al. 2011) will be evaluated with SUIMON. The different models are key to the integration of the multi-resource nature of the observational data within SUIMON.

For climate modeling, a nested regional climate model developed by the China National Climate Center (RegCM_NCC) (Ding et al.2006) is used and run operationally in the East China region(green area in Fig.1 inset). To date, the model performance, evaluated using SUIMON data, has focused on temperature and precipitation (Chen et al. 2008, Dong et al. 2008, Yang et al. 2008). Currently, performance of cWRF[1] is also being evaluated using SUIMON data for the East China region.

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[1]http://cwrf.umd.edu/ (last accessed 6 April 2014)

Depending on the requirements, personalized data sharing and services are established for different departments and users. The weather forecasters, researchers, end-users and others, receive their required data by means of FTP (file transfer protocol), API (application programming interface), web services and data push through Intranet/Internet plus other approaches. Given weather forecasters and researchers within SMS currently are the main users of these observations, their data is available via intranet or internet. The specialized end users in Shanghai (e.g. transportation sector) get their products (e.g. road weather information) through internet or point-to-point connection. Different users have different permissions, related to the timeliness, data frequency and data type that they can access under the regulation on sharing the meteorological observation data to maintain the data securely. International collaborations are encouraged under the framework of bilateral co-operation in meteorological science and technology.

Continuous regular assessment reports are prepared to evaluate the equipment (e.g. AWS, Met-towers, weather radars) using indices such as fault time, data acquisition rate and data errors rate etc. The data collected regularly to describe the setting for each site are extensive (Table 4), reflecting WMO guidance (WMO,2004) and Muller et al.(2013). These data allow users to assess the characteristics of both individual sensors and the network in terms of applicability for a particular use. The design of individual networks and across networks is reviewed regularly. In addition, as demand from a broader range of sectors for applications has developed, SUIMON as a whole is reviewed to identify how these requests can best be met both with the current configuration plus additional data needs, or personnel with specific skills to support the better use of the data streams.

3 Application Case Studies

3.1 Heat island, sea breeze and convective weather

Large cities are inherently vulnerable to severe weather such as torrential rain, lightning and wind gusts. A typical example of the damage caused by torrential rain is inland flooding exacerbated by the large area of impervious surfaces (e.g. asphalt, concrete) and closely spaced buildings of cities. Li et al.(2003) developed a fine-mesh regional meteorological model that has been applied in Shanghai and neighboring areas to simulate small-scale weather features, such as the land and sea breeze, land and lake breezes and UHI effect in this area and to study the characteristics and the formation mechanism of the surface shear line in the region. The results suggest that the interaction between the sea breeze and the lake breeze is the main factor for the formation and maintenance of the surface shear line which related to the short-term convective weather. Based on the dense meteorological observation network in SUIMON, the distribution of occurrence of the severe convective precipitation events (daily rainfall > 50mm) derived from the dense surface AWS monitoring records (Fig. 4a) shows a high frequency over the urban area and the mouth of the Yangtze river, that matches well with the spatial distribution of cloud-to-ground flash density (Fig. 4b). This may be due to the presence of the urban heat island and the sea breeze circulation. For example, on 15 August2012 (Fig. 5) there was a short period of convective precipitation which fell on the north-western part of Shanghai area. Prior to this there was both an UHI (2 m air temperatures) and a sea breeze. These combined to create two areas of convergence and areas of surface wind shear (Fig. 5).

SUIMON has, and is being, used to investigate UHI effects on thermodynamic instability; UHI convergence in association with intensification and/or initiation of electrically active thunderstorms in the metropolitan area; and UHI enhancement of convective updraft strength in relation to the frequency of lightning, to characterize and evaluate thermodynamic and kinematic structures of thunderstorms, in the context of a better knowledge of the physical process of rain formation maintenance, and evolution. For example, a large hail-producing supercell developed ahead of a severe squall line around Shanghai on 5 June 2009. The supercell and its interaction and relations with the squall line over the urban environment were analyzed using a number of SUIMON data sources including the AWS network, Doppler radar data and wind profiler data(Dai et al. 2012).The data analysis revealed that the storm intensified while passing through a surface convergence zone induced jointly by the UHI and a sea breeze front. Techniques such as quantitative precipitation estimation(QPE) and quantitative precipitation forecasting (QPF) have been developed, improved and employed in operational applications to assess the urban water logging risk under rainfall condition in Shanghai(Zou et al.2012). Knowledge that the most vulnerable areas are in the urban center and mouth of the Yangtze River can now be correlated with exposure (e.g. socio-economic, construction, industrial activities) in these areas to develop risk maps for improving emergency preparedness.

3.2 Photochemical and Urban aerosol pollution

Cities are a major source of air pollution emissions due to the burning of fossil fuels for heating and cooling, industrial processing, and transport of people and goods. Cities also modify their ambient weather (especially winds, turbulence, radiation, mixing height and temperature) in ways that often negatively affect the dispersion, transformation and concentration of those pollutants. Air quality forecasts and warnings are needed at multiple scales of the region, city, and street. Information about the atmospheric circulation are combined with the higher temporal, vertical, and horizontal spatial resolution data (e.g. urban boundary layer structure and mixing layer heights, vertical profiles of winds, turbulence, temperature inversion).The city, with its characteristic roughness height and temperature evolution, has a strong impact on the structure of the urban boundary layer and hence on the pollutant dispersion near the surface.

Within SUIMON O_3 concentration and photochemical precursors have been systemically measured and their relations investigated (Geng et al. 2006; Liang et al. 2009). For example, the ozone "weekend effect" (Tang et al. 2008) and the impacts of the precursors on ozone formation (Geng et al. 2008) have been revealed.

Ground-based remote sensing (e.g. sun photometer, MPL 4 Lidar, ceilometer) have been used to investigate urban aerosol and fog/haze events(Huang et al. 2010; He et al. 2012a,2012b).The observations have been used to evaluate the performance of the WRF-Chem model. This is now used routinely as a chemical weather forecast for the Yangtze River Delta Region(Zhou et al. 2012). Furthermore, SUIMON is being used to improve the chemical weather forecast by providing improved data for a reaction scheme of photo-oxidants and particle interactions. This has been taken further to investigate the relation between air pollution and human health(Cao et al. 2009;Huang et al. 2009;Chen et al.2010).

3.3 End User applications supported by SUIMON

The SUIMON data are provided in close to real–time to weather forecasters. The publically accessible website (http://www.soweather.com/index.html) provides weather forecast/warnings, plus more specialized forecasts, such as for road and health. With the aid of a geographic information system (GIS) interface the public can access the real-time met-records and forecasts for the area of the city of interest to them. New specialized products are being developed in conjunction with end-users, for example, urban inundation warnings, meteorological condition forecasts to aid safe driving, energy demand and related loads on the electric grid (Table 5).

One impetus for enhancing the density of data collection near the city centre was the

World Exposition (Expo) held in Shanghai during the summer of 2010. During that time an even denser network of sensors (area 5.28km^2) was embedded in SUIMON. These provided real-time support for improved high risk weather prediction for the region, down to detailed knowledge across the Expo park for heat exposure (Tang et al. 2012).

New specialized forecasts are being developed for different sectors. For example, with the building of the Shanghai Tower(632m, one of the tallest buildings in the world) and other large construction projects, the ability to forecast winds at more than 100m above the surface becomes critical both for those involved in construction and those working/living in the vicinity(Fang et al. 2013). This has taken advantage of SUIMON wind profiler data and the met –towers more directly, but also other data feeds have been used to enhance the data assimilation into the NWP model generally.

Given the high frequency of intense storms, the design of billboards that are permitted in the city has become one area of focus given the damage caused when intense gusts cause them to become unattached. Combining Fluent CFD modelling(Fang et al.2013), with the extensive wind data available across the area, has resulted in new designs to reduce damage(Fig.6)

4 Future considerations in urban meteorological observations in Shanghai

In the next five years, to meet emerging science-and-user driven needs and requirements, the Shanghai Meteorological Service (SMS)expects to enhance the multi-functions of **S**hanghai's **U**rban **I**ntegrated **M**eteorological **O**bservation **N**etwork (SUIMON). The emphasis will be on the acquisition of information associated with physical processes of the urban boundary layer and the effects of the underlying surface (Box 3). It is expected that SUIMON will continue to evolve because of new user requests and new technologies, as it repeatedly has done over the last 140 years. Many of the developments in the near future are expected to involve better use of the combined database. One key challenge is how to monitor the spaces between buildings given the rapid increase in tall buildings (Table 2) in Shanghai and the many other rapidly growing cities of Asia and South America. Applications from response to fires to management of energy use to near-surface air quality would benefit from improved understanding of this very large urban canopy layer. SUIMON, with measurements to end-user support provides a prototype for Integrated Urban Weather, Environment and Climate Services (Grimmond and WMO Secretariat 2014)

Box 3: Future enhancements to SUIMON

- Meso-and micro-scale processes over urban surfaces (such as cloud microphysics, precipitation processes)
- Height (and structure) of the PBL and vertical profiles of wind, temperature, water vapor and atmospheric composition
- Field studies to validate satellite observations and modeling simulations of urban precipitation processes and to extend basic understanding of the processes involved
- Enhancing existing observing systems to focus on city-atmosphere interactions, especially to monitor and track land-cover/land-use changes, atmospheric composition, cloud microphysics, and precipitation processes
- Modeling systems that explicitly resolve multi-scale (e.g. urban canopy, street, building) processes, aerosols and cloud microphysics, complex land surfaces, to enable a more complete understanding of the feedbacks and interactions

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Table 1: Examples of comprehensive urban studies conducted since 2000, with the following aspects included: T – tracer, D- dispersion, AQ-air quality, M – meteorology, PBL-planetary boundary layer, UEB-urban energy balance, CP – convective processes, MP-meso-scale processes.

Table 2: Height distribution of Shanghai's buildings over eight storeys in 2012 and 2000 (Shanghai Statistics Bureau, 2013)

Table 3: Instrument types in SUIMON. Upper table provides codes used in the main table

Table 4: Metadata about the site and its surrounding are collected at each site. These data are kept in a digital record (Excel spreadsheet)which allows for consistent and rapid retrieval of data for all sites (automated and manual). The example shown, of 10 pages from the metadata file, is for the Baoshan WMO first order station for Shanghai (in the supplementary material larger versions of each of the pages are provided). On the left hand side are images of the individual pages. Top right hand side provides a key number for the LHS whichgives an overview of what is covered in each page shown.

Table 5:Examples of urban weather/climate and environmental services in Shanghai

Fig. 1:Shanghai's location within China(inset), observation sites within the Shanghai urban integrated meteorological observation network (SUIMON) in 2013. The 10 counties that make up the province of Shanghai andthe land cover derived from Landsat Thermal Mapper imagery (image date:25 May2010).

Fig. 2:Information about wind direction and speed with height(a)instrumented meteorological-towers at five levels (Baoshsan tower shown) (b) wind profilers. Spatial variations on atypicalsummerday shown.Color indicates height (0-6000 m), barbs indicate wind speed. Shown on Google Earth base image. See Fig. 1b for locations of both types of sites.

Figure 3:Data management and data service of SUIMON

Fig. 4:(a) Number of severe convective precipitation events (1994-2008) and (b) spatial distribution of cloud-to-ground flash density($fl{\cdot}yr^{-1}{\cdot}km^{-2}$)(2008-2012).

Fig. 5:Short-term convective precipitation associated with urban heat island and seabreeze convergence lines on 15 August 2012(a) accumulated rainfall distribution between 13:00-17:00 measured by AWS and rain gauges(b) radar OHP(one hour total rainfall before 15:59 LST)(c)air temperature distribution at 2 mmeasured by AWSon 12:00 LST, and (d)wind speed and direction at 10 m at 12:00 LST and the two surface wind shear lines(red ones),blue lines indicate the surface convergence zone.

Fig.6 Typhoon Haikuion 7August2012 (a) track and intensity wasmonitored, forecasted and warnings delivered to public. The storm caused damage in the area. (b) One type of damage that occurs frequently is the collapse of billboards. Example shown from a highway in Shanghai duringTyphoon Haikui. (c) The maximum windspeed (m s^{-1}) duringTyphoon Haikui across the whole Shanghai area ismonitored (10 m height). (d) Detailed analysis is being undertaken on billboard design and siting to enhance public safety so the area is better prepared for future tyhphoons. Analysis has been conducted using the Fluent CFD model to estimate the canopy wind distribution (m s^{-1}), (e) wind load on billboard (N m^{-2}) and (f) to determine different risk levels caused by the gusts on billboards along major roads.

Table 1: Examples of comprehensive urban studies conducted since 2000, with the following aspects included: T – tracer, D- dispersion, AQ-air quality, M – meteorology, PBL-planetary boundary layer, UEB-urban energy balance, CP – convective processes, MP-meso-scale processes.

Name	Where	When	T	D	AQ	M	PBL	UEB	CP	MP	Reference
(a) Short term campaigns											
Urban 2000	Salt Lake City,USA	Oct 2000	Y								Allwine et al.2002
Joint Urban	Oklahoma City, USA	Jul 2003	Y	Y		Y	Y	Y			Allwine et al.2004
Pentagon Shield	Washington, DC, USA	2004	Y	Y							Warner et al. 2007
Madison Square Garden	Manhattan, NYC, USA	2004, 2005	Y	Y							Hanna et al. 2006
ESCOMPTE	Marseilles-Berre, France	June – July 2001		Y	Y	Y	Y	Y			Cros et al.2003
BUBBLE	Basel,Switzerland	1 year 2002	Y	Y		Y	Y	Y			Rotach et al.2005
DAPPLE	London, UK	May 2002 to July 2006	Y	Y	Y	Y					Arnold et al.2004
REPARTEE	London,UK	Oct 2006, Oct/Nov 2007	Y	Y	Y	Y	Y				Harrison et al. 2012
CAPITOUL	Toulouse, France	Feb 2004 to Mar 2005	Y	Y	Y	Y	Y	Y			Masson et al. 2008
HEAT	Houston, Texas, USA	Jul-Sep 2005			Y	Y			Y	Y	Orville et al. 2004
TOMACS	Tokyo Metropolitan Area, Japan	Summers 2011-2013					Y		Y	Y	Maki et al. 2012
ClearfLo	London, UK	Jan – Dec 2012			Y	Y	Y	Y		Y	Bohnenstengel et al. 2014
(b) Long term (> 1 year continuous observations)											
METROS	Tokyo, Japan	2002-2005					Y		Y	Y	Takahashi et al.2009
NYC Mesonet	New Yok City, USA	2003 to present				Y			Y	Y	Reynolds 2003
DCNet	Washington DC,USA	2003 to present	Y	Y							Hicks et al.2012
Helsinki Testbed	Helsinki, Finland	Jan 2005 to present		Y		Y	Y		Y	Y	Dabberdt et al. 2005 Koskinen et al.2011
SUIMON	Shanghai, China	2000 to present			Y	Y	Y	Y	Y	Y	This paper

Table 2: Height distribution of Shanghai's buildings over eight storeys in 2012 and 2000 (Shanghai Statistics Bureau, 2013)

Type of Building(storeys)	8 -10	11-15	16 -19	20 -29	>30	Total
Number of Buildings 2012	4,367	15,125	7,484	3,839	1,207	32,022
2000	536	684	831	1,266	212	3,529
Construction area(10^6m^2) 2012	29.11	103.90	66.90	69.96	35.63	305.50
2000	4.51	8.75	11.00	26.95	10.59	61.80

Table 3: Instrument types in SUIMON. Upper table provides codes used in the main table

* : On-site personnel state-level weather station	F_{CO2}: CO2 flux	MS: Mean separation	SR: spatial resolution
@ Baoshan 31.40 °N, 121.45°E	Freq. Frequency data are archived	N: number of stations providing data	ST: soil temperature
@ Dongtan 31.52°N, 121.96°E	GRS: Ground based RS	NSMC: National Satellite Meteorological Centre	T: Temperature
@ Expo park 31.23°N, 121.5°E	GS: Geostationary Satellite	P: pressure	u, v, w: 3-dimensional wind velocities
@ Pudong 31.22°N, 121.55°E	Ht: Height(s) sampled above the ground	PBL: planetary boundary layer	V: vertical
@ Qingpu 31.13°N,121.12°E	IBT: Instrumented broadcast tower	POS: Polar-orbiting Satellite	VP: Vertical Profile
@ Xujiahui 31.19°N, 121.43°E	IT: instrument tower	Q*:net all wave radiation	VT: Virtual temperature
AEC: aerosol extinction coefficient	K↑: outgoing or reflected short-wave radiation	Q_E: latent heat flux	WD: Wind direction
AOD: aerosol optical depth	K↓:incoming short-wave or solar radiation	Q_H: sensible heat flux	WS: wind speed
ASC: Aerosol scattering coefficient	K↓:incoming direct solar radiation	R: Resolution	WSR: Weather Surveillance Radar
AWS: Automatic weather station	KDP: Specific Differential Phase Shift	RH: relative humidity	ZDR: Differential Reflectivity
BC: Black Carbon	L↑:long-wave outgoing radiation	RS: remote sensing	λ: wavelength
CR: cover range	L↓:long-wave incoming radiation	SO: surface observation	ϕDP: Differential Phase Shift

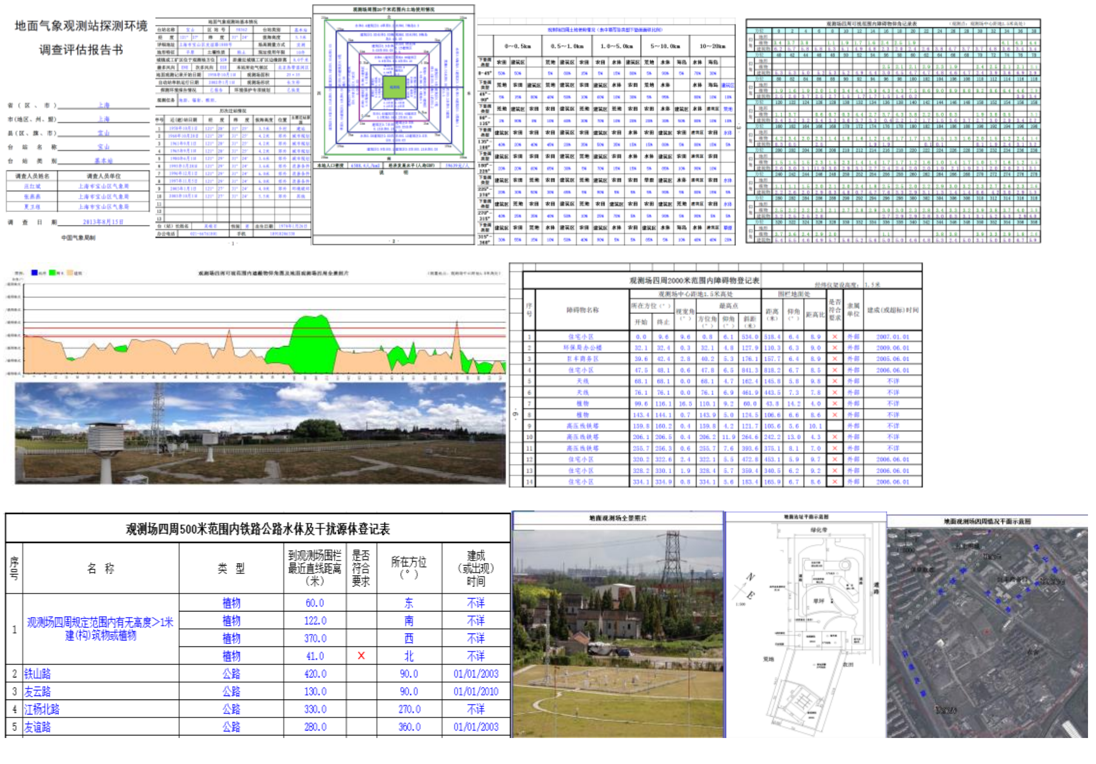
Type	N	Coverage	Freq.	Variables	Model Manufacturer (Country)
SO*	10	MS：25 km	1 min	T, P, RH, WS, WD, Rain, Visibility, ST	4:MILOS500 Vaisala (Finland) 6: ZQZ-CII Jiangsu Radio Scientific Institute Ltd. (China)
SO	1	@ Baoshan	1 min	K↓, K↑, $K↓_{dir}$, Q*	FS-S6, FS-T1, FS-D1, Jiangsu Radio Scientific Institute (China)
SO, AWS^	200+	MS：5.6 km	1 min	T, P, RH, WS, WD, Rain, Visibility (have 4 or more variables	Vaisala MAWS301, MiILOS500(Finland) SAWA-1(B),Jiangsu Radio Scientific Institute (China)
SO	65	MS：4.8 km(Plus AWS)	1 min	Rain	SR-IIShanghai Institute of Meteorological Science(China)
VP/IBT	13	MS: 22 km Ht: 10^T, 30, 50, 70^T,100 m agl	1 min	WS, WD, [$^{T:}$ T, RH]	ZQZ_TFJiangsu Radio Scientific Institute(China) HMP45D Vaisala (Finland)
VP/RS Wind	3	VR: 60 m (low mode), 60 m & 102 m (high mode) to 3000 m	30 min	Wind profiler: vertical and horizontal of WS, WD RASS：VT @ Qingpu	Vaisala LAP 3000 (Finland)

	7	VR: 60 m MS: 25 km(plus LAP 3000)	30 min	Wind profiler:WS, WD	TWP3 Beijing METSTAR Radar CO. Ltd.(China)
VP/RS,upper air sounding	1	@ Baoshan VR: per second Action distance: max. 200km; min: ≤100m	6 h	Latitude, longitude,T,P,RH,WS,WD	L band sounding system is composed of L band secondary windfinding radar; type GTS digital electronic radiosonde and ground check set. GFE(L)-1NanJing DaQiao Machine CO., Ltd.(China)
WSR	2	λ: S-band Fixed, CR: 230/460 km, E: east coast, W: western Shanghai	6 min	Radar reflectivity, radial velocity, spectrum width	WSR-88D (USA) [E] CINRAD WSR-98D (China) [W]
	1	λ: X-band, Mobile CR: 120 km	6 min	Dual polarization products (Z_{DR}, K_{DP}, ϕ_{DP})	DWSR-2001X-SDP1M(USA)
GRS, Lightning mapping	3	Locational accuracy: ~500 m CR: 200 km	1s	Cloud-to-ground (CG) flashes and strokes survey-level cloud	Vaisala LS7000 (Finland)
	1	Locational accuracy: ~500 m CR:200 km	1s	Total cloud discharges, cloud-to-ground (CG) flashes and strokes	VaisalaLS8000 (Finland)
VP/RS	2	V: 10 km, R: 100/250 m 1 operational, 1 movable	1 min	Verticalprofile of temperature, humidity, water vapor density, liquid water content	TP/WVP- Microwave radiometer 3000, Radiometrics (USA)
GPS/Met	31 (19+12)	MS: 14 km	30 min	Precipitable Water Vapor(PWV)	19 Trimble NetRs(USA) 12 Ashtech Z-12 (USA)
IT/Flux	1	@ Xujiahui Ht: 80 m (building + tower height: 55 + 25 m)	10 Hz, 30 min	Q_H, Q_E,F_{CO2},u,v,w, TV K↓,K↑, L↓,L↑,Q* T,RH WS,WD	Irgason Campbell Scientific (USA) CNR4 Kipp and Zonen (Netherlands) HMP155A Vaisala (Finland) ZQZ_TFJiangsu Radio Scientific Institute (China)
SO/O3	10	MS：25 km Ht：Xujiahui 55m, others <15 m	1 min	Ozone analyzer: O3	EC9810,Ecotech, Inc.(Australia)
SO/NOx	10	MS：25 km Ht：Xujiahui 35m, others <15 m	1 min	NO/NO2/NOx analyzer: NO,NO2,NOX	EC9841B,Ecotech, Inc.(Australia)
SO/SO2	2	Ht: Expo park4m,Dongtan5m	1 min	SO2 analyzer:SO2	EC9850,Ecotech, Inc.(Australia)
SO/CO	3	Ht: Xujiahui55m,Pudong14m,	1 min	CO analyzer: CO	EC9830,Ecotech, Inc.(Australia)

		Dongtan5m			
SO/VOCs	10	Ht: 2 m Campaigns on typical day at 10 stations	1 – day	VOCs concentrations	Sample canister: 6 L silonite canister with silonite coated valve, 29-10622Entech Instruments Inc.(USA) Lab Analysis: 7100 VOC preconcentrator Entech Instruments Inc.(USA) Agilent GC6890 gas chromatography coupled to Agilent MSD5975 N mass-selective detection (length: 60 m, diameter: 0.32 mm, film thickness: 1.0 µm)
SO/PM	3	Ht: Expopark,Pudong, Dongtan<10m	1 min	PM_{10}, $PM_{2.5}$, PM_1	GRIMM180, GRIMM Technologies, Inc.(Germany)
SO/ASC	3	Ht: Expo park 4m,Pudong14m, Dongtan5m	1 min	Nephelometer: ASC	M9003, Ecotech Inc.(Australia)
SO/BC	2	Ht: Pudong14m,Dongtan5m λ:370, 470, 520, 590, 660, 880 and 950 nm	2 min	Aethalometer: BC light absorption by suspended aerosol particles	AE 31 Magee Scientific(USA)
GRS/AOD	3	Ht: Expo park 4m,Pudong 14m, Dongtan 5m λ: 1020, 936, 870, 670, 500, 440, 380, 340 nm	1 min	AOD, Angstrom index	CE318 Sun photometer CIMEL (France)
VP/O3	1	Baoshan VR:per second	typical day	O3 concentration profile	O3-GPS sounding(China)
VP/GRS	3	2-fixed:Expo park,Baoshan; 1-movable VR: 5 or10 m, from 90 m to 7 km	16s	Ceilometer: PBL height, Vertical distribution of aerosols, Cloud base, AEC	CL31/CL51,Vaisala(Finland)
VP/GRS	2	Expo park, Pudong VR: 15,30,60,75 m From: 100m to 20 km	30s	Vertical distribution of aerosols, PBL height	Micro-pulse Lidar MPL-4B-IDS, SigmaSpace (USA)

POS/RS	-	Overpass:2 times a day λ:5 bands S:1 km		cloud, surface temperature,soil moisture fog, haze	NOAA 15/16/17/18 (USA)
POS/RS	-	Overpass:9:00-10:00,13:00-14:00		AOD, profile of T, humidity, $K\uparrow$& total radiance, Total ozone	NSMC FY-3A,FY-3B (China) Sensor: VIRR, IRAS, MWTS, MWHS, MERSI, MWRI, TOU, SBUS, SIM, ERM
POS/RS	-	Overpass: 10:30 (T) 13:30 (A) every 8 days λ: 0.4 to 14.4 µm (36 bands) SR: 2 bands @ 250 m, 5 @ 500 m, 29 @1 km		Surface temperature, Cloud temperature, Water vapour, Ozone Emissivity, surface reflectance, albedo, vegetation indices, Land cover type	NASA MODIS EOS TERRA and AQUA (USA)
GS/RS	-	SR 1.25 km λ:5 bands(1 VIS,1 vapor,3 IR)		cloud, surface temperature, fog, haze	NSMC FY-2D, FY-2E,FY-2F (China)
GS/RS	-	λ:0.55 to 4.0 µm(5 bands) SR: VIS band @1 km, IR1-IR4 4 Bands: @4 km		cloud, surface temperature,rain, fog,haze	MTSAT-2(Japan)

Table 4: Metadata about the site and its surrounding are collected at each site. These data are kept in a digital record (Excel spreadsheet)which allows for consistent and rapid retrieval of data for all sites (automated and manual). The example shown, of 10 pages from the metadata file, is for the Baoshan WMO first order station for Shanghai (in the supplementary material larger versions of each of the pages are provided). On the left hand side are images of the individual pages. Top right hand side provides a key number for the LHS whichgives an overview of what is covered in each page shown.



C	Covers sheet, Location: Provinces , County, station name, type, Who and when the survey undertaken
1	Site name, location, history, major changes, Contact details
2a	Land cover by distance (5 rings) to the station and direction (8 sectors)
2b	Table of percentage cover (three dominate of 14 classes) for the 40 areas (5 * 8) around the site of the station; Classes: farmland, buildings, wasteland, water, construction, health facilities, island,mines, forest, prairie, mountains, desert; Population density, GDP
3	What is visible every 2◦ from the centre of the site (at 1.5 m above ground) the height (m)of the terrain , vegetation and building
4	Graph &360◦ photo (half shown) of data p3
5,6	Obstacles taller than 1.5 m within 2 km of site
7	Panoramic photo of the site
8	Schematic plan view of a ground station site
9	Aerial photo of the site

C	1	2a	2b	3
4	5			
6	7	8	9	

Table 5:Examples of urban weather/climate and environmental services in Shanghai

Sectors	Examples of urban weather/climate and environmental services	End Users (examples)
Water	River catchment precipitation Urban inundation Coastal storm surges.	Water Authority, Emergency Response center, drainage company.
Urban infrastructure	Urban wind, heavy rainfall, heatwave, lightning forecast	Urban Planning Bureau, Urban Green Bureau, public.
Energy	Wind and solar resource assessment Wind power forecast for wind mill energy consumption estimation(electric, gas)	Development and Reform Commission,power companies, wind power plants.
Health	UV index Pollen concentration Heat/health warnings, Weather/climatic based Disease prediction(asthma, COPDChronic Obstructive Pulmonary Disease)	Public Health Authority, Public
Environment	Air Quality Index(AQI)forecast Haze, O_3 forecast NBC release	Environment Protection Bureau, Hospitals, Schools, Public

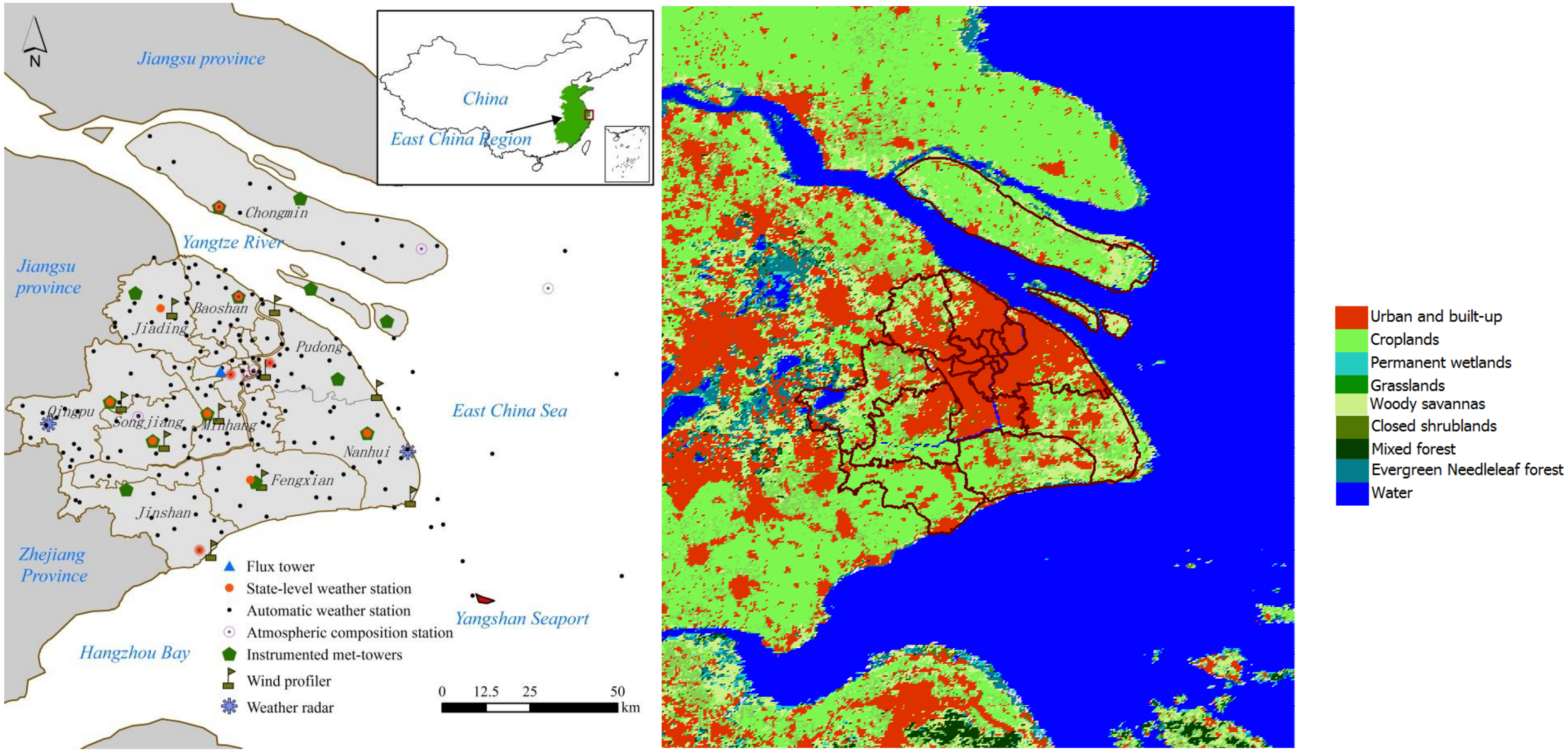
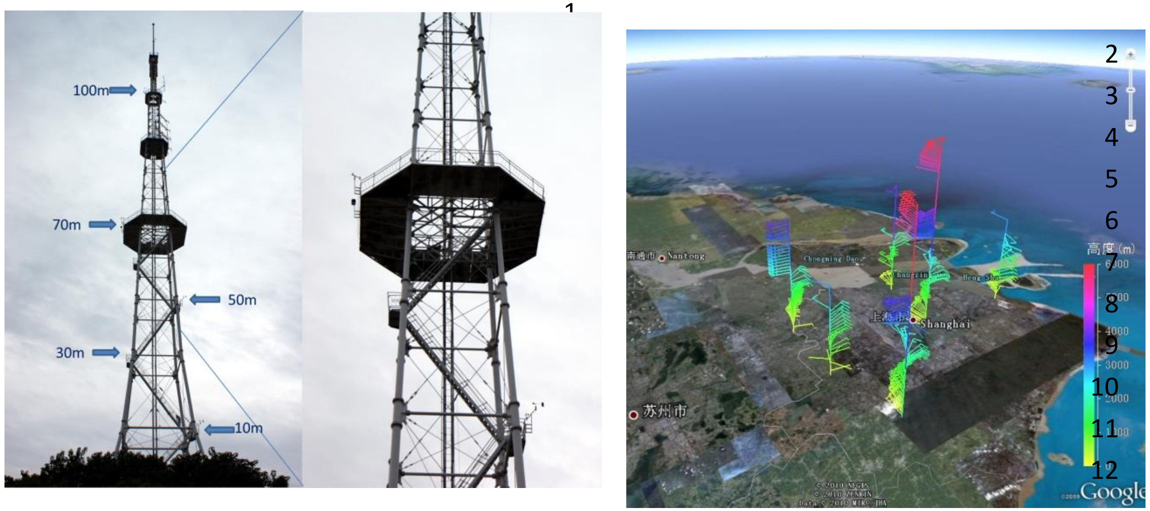


Fig. 1:Shanghai's location within China(inset), observation sites within the Shanghai urban integrated meteorological observation network (SUIMON) in 2013. The 10 counties that make up the province of Shanghai andthe land cover derived from Landsat Thermal Mapper imagery (image date:25 May2010).



(a) (b)

Fig. 2:Information about wind direction and speed with height(a)instrumented meteorological-towers at five levels (Baoshsan tower shown) (b) wind profilers. Spatial variations on atypicalsummerday shown.Color indicates height (0-6000 m), barbs indicate wind speed. Shown on Google Earth base image. See Fig. 1b for locations of both types of sites.

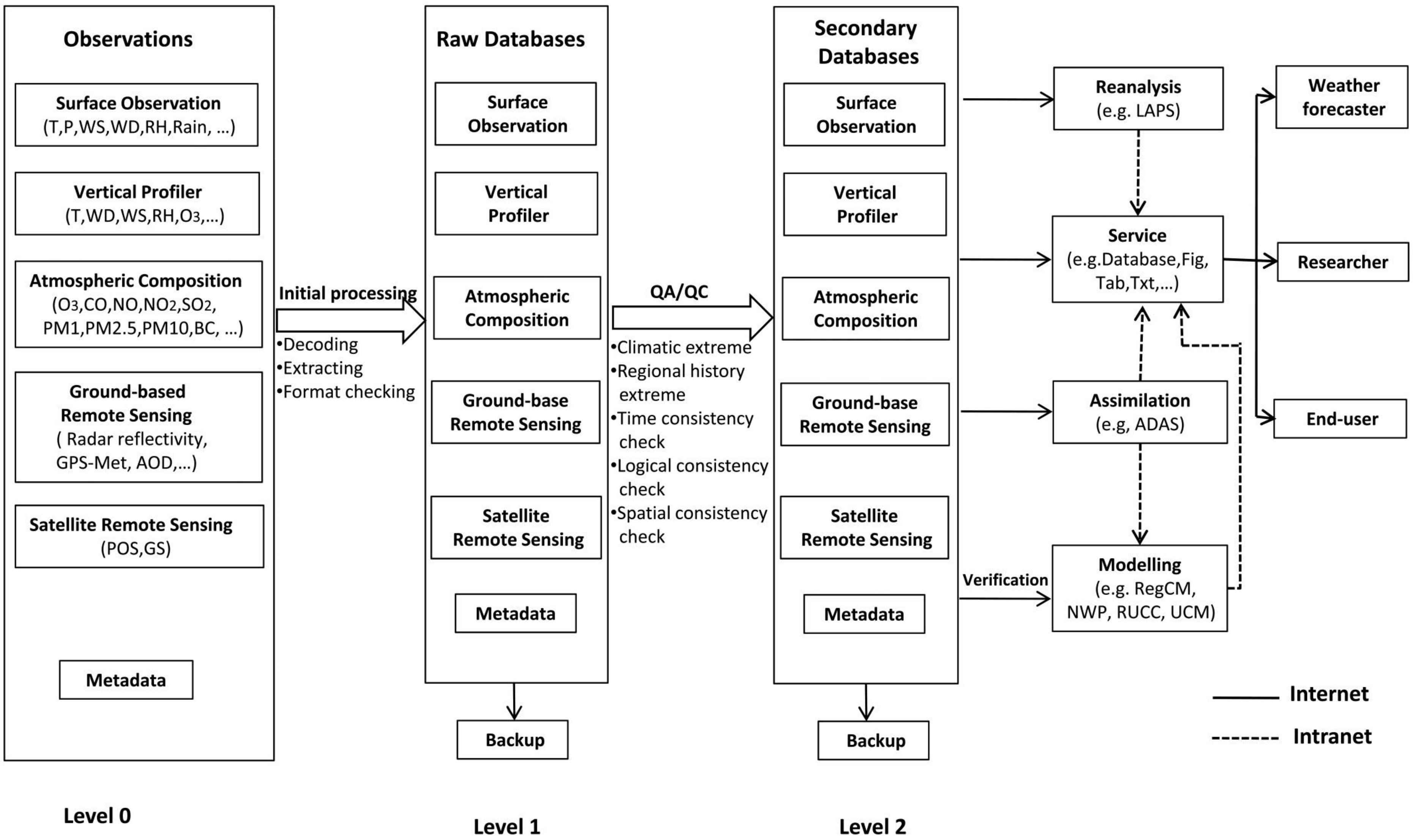


Figure 3:Data management and data service of SUIMON

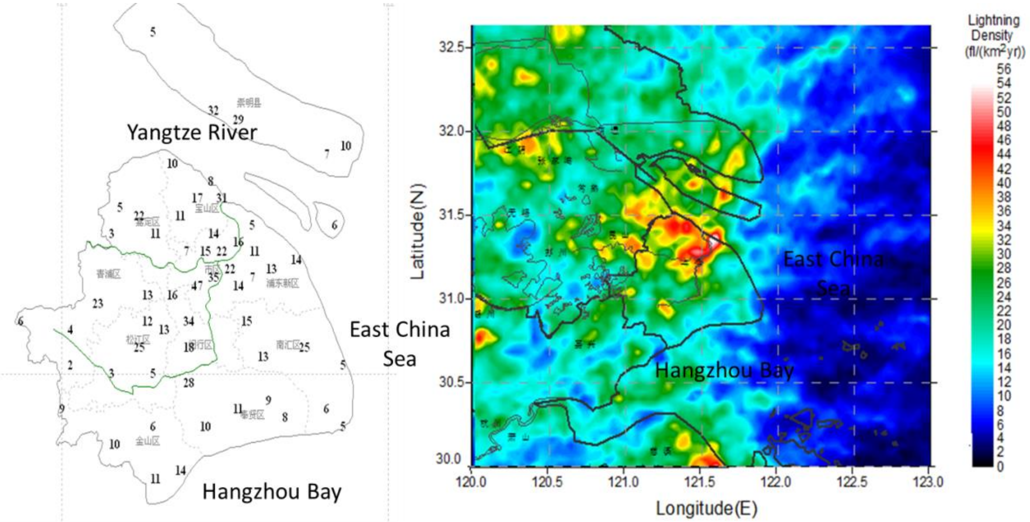


Fig. 4:(a) Number of severe convective precipitation events (1994-2008) and (b) spatial distribution of cloud-to-ground flash density(*fl*·yr^{-1}·km^{-2})(2008-2012).

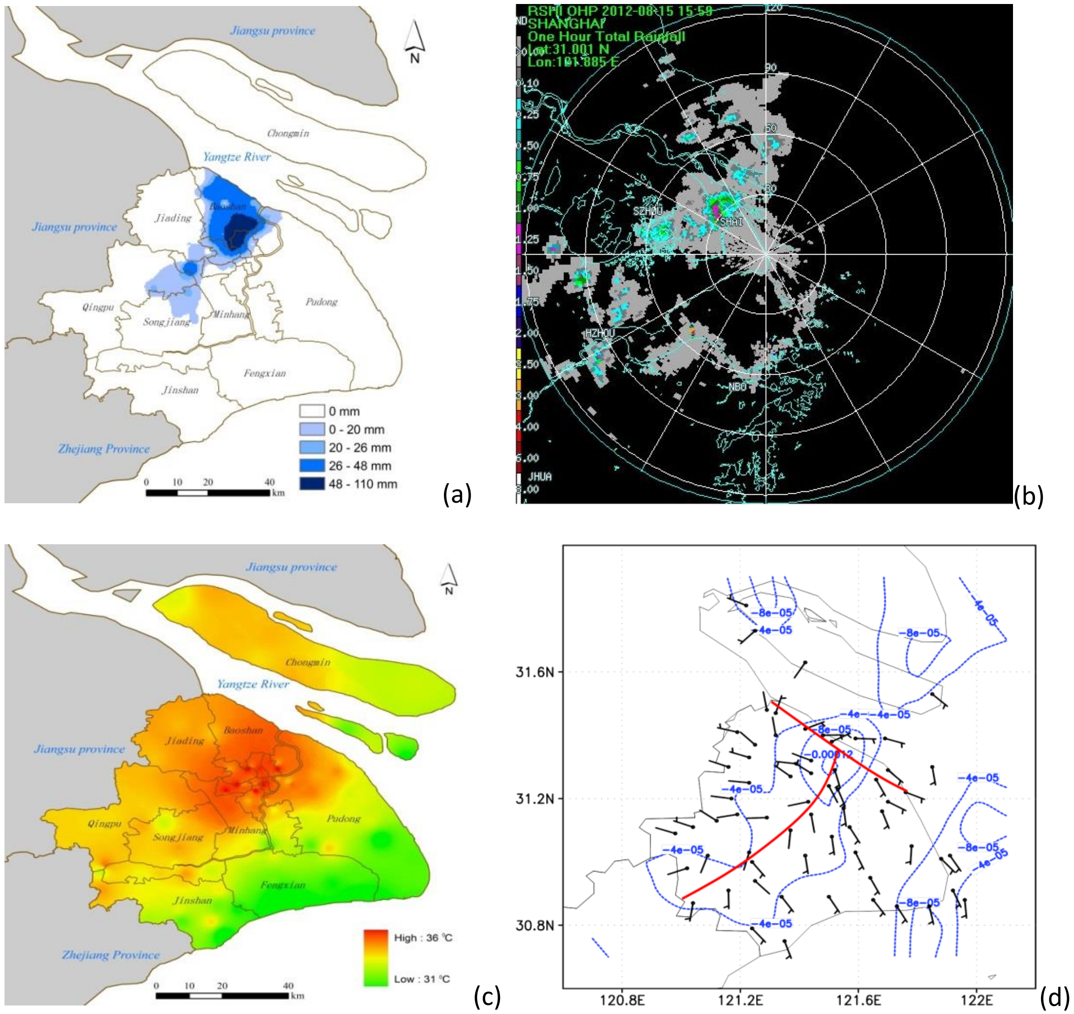


Fig. 5:Short-term convective precipitation associated with urban heat island and seabreeze convergence lines on 15 August 2012(a) accumulated rainfall distribution between 13:00-17:00 measured by AWS and rain gauges(b) radar OHP(one hour total rainfall before 15:59 LST)(c)air temperature distribution at 2 mmeasured by AWSon 12:00 LST, and (d)wind speed and direction at 10 m at 12:00 LST and the two surface wind shear lines(red ones),blue lines indicate the surface convergence zone.

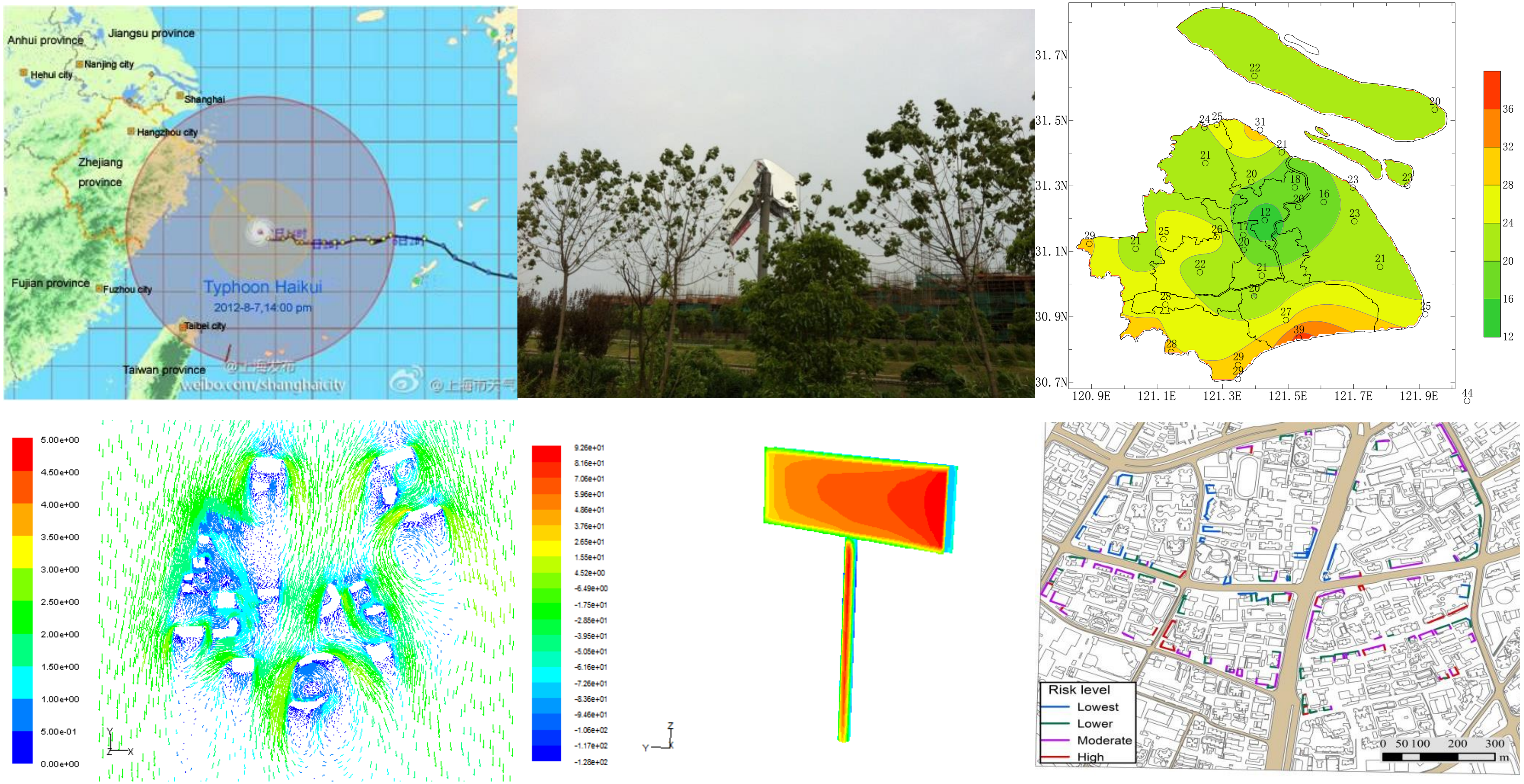


Fig.6 Typhoon Haikuion 7August2012 (a) track and intensity wasmonitored, forecasted and warnings delivered to public. The storm caused damage in the area. (b) One type of damage that occurs frequently is the collapse of billboards. Example shown from a highway in Shanghai duringTyphoon Haikui. (c) The maximum windspeed (m s^{-1}) duringTyphoon Haikui across the whole Shanghai area ismonitored (10 m height). (d) Detailed analysis is being undertaken on billboard design and siting to enhance public safety so the area is better prepared for future tyhphoons. Analysis has been conducted using the Fluent CFD model to estimate the canopy wind distribution (m s^{-1}), (e) wind load on billboard (N m^{-2}) and (f) to determine different risk levels caused by the gusts on billboards along major roads.