# **Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient Cities (TOMACS)**

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#### 1. Introduction

It is recognized that large cities with populations of several million people are inherently vulnerable to torrential rainfall. A typical example of the damage caused by torrential rain is inland flood damage which occurs when the drainage system cannot cope with the rainfall amount. The frequency of inland floods tends to be higher in large cities because of the large area of asphalt pavement and closely spaced concrete buildings. In 29 June 1999, a torrential rainfall (hourly rainfall of 77mm) was occurred in Fukuoka City, Japan and caused floods in underground space such as subways and underground shopping complexes. In 21 July 1999, the floods occurred in Nerima, Tokyo, which was caused by a localized heavy rainfall (hourly rainfall of 131mm). In each case, one people was drowned in the flooded basement. Localized heavy rainfall that occurred in Zoshigaya, Tokyo, on 5 August 2008 made 5 workers drawn in the sewage pipe and caused the flooding of 34 houses above floor level (Kato et al., 2009a). One week before the flooding in Tokyo, a flash flood occurred in the Toga River in Kobe City on 28 July 2008 and five people were drowned by the sudden increase of the water level: 134cm in ten minutes (Fujita and Kunita, 2010). According to statistics of Japan Meteorological Agency (JMA), the number of occurrence of torrential rainfall tends to increase in these thirty years (JMA, 2010). An increase in the occurrence of torrential rainfall, which may be due to global warming, can cause extensive damages to large cities.

In 2010, Japan Science and Technology Agency (JST) launched the new research program "Social System Reformation Program for Adaption to Climate Change" under the "Special Coordination Funds for Promoting Science and Technology" of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). "Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient Cities (TOMACS)" is one of the research projects selected for the JST research program. TOMACS has been started since July 2010 by three core research institutes: National Research Institute for Earth Science and Disaster Prevention (NIED), Meteorological Research Institute (MRI), and Toyo University. The present paper describes mission, structure, and research topics of TOMACS.

#### 2. Mission and Structure of TOMACS

# 2.1 Mission

TOMACS aims to understand the processes and mechanisms of extreme weather, using dense meteorological observation networks designed in the Tokyo metropolitan district, to develop a monitoring and predicting system of extreme phenomena (MPSEP), and to implement social experiments on extreme weather resilient cities in collaboration with related government institutions, local governments, private companies, and residents.

#### 2.2 Project Structure

TOMACS consists of three research themes (Fig.1): "Studies on extreme weather with dense meteorological observations", "Development of the extreme weather early detection and prediction system", and "Social experiments on extreme weather resilient cities". More than 25 organizations and over 100 people participate in the project. The National Research Institute for Earth Science and Disaster Prevention (NIED) acts as the core research organization for the whole



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project, with responsibility for its planning and accomplishment. The Meteorological Research Institute (MRI) is responsible for the first research topic, in which a total of 12 research institutes and universities are involved. NIED is responsible for the second research topic, involving a total of 10 research institutes and universities. Toyo University is responsible for the third research topic, where a total of 11 research institutes, universities, and local government organizations participate.

The steering committee for the project is set up under the president of NIED. The committee, which consists of prominent figures in various fields related to the present project, advises participants on the planning and accomplishment of observational and numerical studies of extreme weather, development of the early detection and prediction system, and the execution of social experiments. The committee also discusses the results of social experiments and summarizes a proposal for the establishment of extreme weather resilient cities, which proposal will be submitted to the Social Experiments Strategy Committee of the Cabinet Office. Because the project covers many different fields, such as remote sensing, meteorology, hydrology, and sociology, and involves a large number of participants, the liaison council is setup under the principal investigator of the project. The council, which consists of delegates of each participating organization, discusses the research plans and research results of each topic, and share information so as to achieve the project purpose efficiently and in a coordinated manner. The relevant working groups for dense meteorological observations, extreme weather early detection and prediction, and social experiments holds discussions on each research topic, and create appropriate and detailed research plans.



Fig. 1 Project structure and organization

## . Research Themes

#### 3.1 Studies on extreme weather with dense meteorological observations

To understand the initiation, development, and dissipation processes of convective precipitation, and to clarify the mechanism of localized heavy rainfall, which are potential causes of natural disasters such as flooding and landslides, a variety of cumulus activities are studied by dense research and operational meteorological observation networks in the Tokyo Metropolitan Area, numerical experiments, and statistical analysis of environmental conditions preferable for extreme weather. The Meteorological Research Institute (MRI) is the core research institute to accomplish the research mission. Following organizations are participating in this research theme. X-NET group (NIED, Chuo Univ., National Defense Academy, Univ. of Yamanashi, Central Research Institute of Electric Power Industry, Japan Weather Association), Toshiba Corporation, Hokkaido Univ., National Institute of Information and Communications Technology (NICT), Osaka Univ.

One of unique features of TOMACS is utilization of dense meteorological instruments in the Tokyo Metropolitan area (Fig.1, Table 1). The field campaign using research instruments and operational meteorological networks are carried out by fourteen research organizations in the summers of 2011-2013 targetting the environment conditions for thunderstorms, initiation of convections and life cycle of thunderstorms.

# a. Environment Observations

Radio sonde soundings will be carried out at several sites in the Tokyo metropolitan area to capture the atmospheric environment for heavy rainfall. Because the observations are planned in a highly urbanized area, risk is assessed utilizing

sonde trajectory simulation before sonde launch. UHF wind profilers are operated by JMA to measure wind profiles every 10 minutes. GPS Meteorology is fully adapted for the experiment to obtain information on atmospheric water vapor which is a primary source of convections. JMA analyzes the GPS earth observation network (GEONET) data of the Geospatial Information Authority of Japan to obtain measurements of precipitable water vapor (PWV) and assimilates GPS derived PWV to the meso-scale model. In the experiment, to increase the resolution of GPS, 5 receiver sets have been installed in the eastern area of the Tokyo Metropolitan area.



Fig. 2 Dense meteorological observation network in Tokyo Metropolitan Area

Target	Meteorological parameter	Research Instruments	<b>Operational Instruments</b>
Environment	<u>Troposphere</u> Temp., water vapor, wind	Radiosonde Microwave radiometers	Radiosonde. UHF Wind profilers GPS network (GEONET)
	Boundary layer Temp., water vapor, wind	UAV, Doppler Lidar	Radiosonde, UHF wind profiler AMeDAS
	<u>Surface</u> Temp., wind, rain, Td, P	High spatiotemporal surface meteorological network	AMeDAS AEROS
Thunderstorm	Non-precipitation Cumulus (VIS, IR)	Web cameras	JMA MTSAT (rapid scan imager)
	<u>3D, High spatiotemporal</u> Precipitation distribution	Ku-band fast scan radar	-
	<u>3D field</u> Precipitation and wind Polarimetric parameters	X-NET (X-band polarimetric) C-band polarimetric radar	MLIT X-band polarimetric radar JMA C-band Doppler radar
	Vertical profile Drop size distribution	Micro rain radar	-
	<u>Surface</u> Drop size distribution Rainfall amount	Disdrometer (2DVD, optical) AWS	Raingauge network (AMeDAS, MLIT, local gov)
	Lightning	-	JMA LIDEN

Table 1 List of meteorological instruments in used in TOMACS

One of the keys to the experiment is measurement of the atmospheric boundary layer. Observations with an Unmanned Air Vehicle (UAV) are planned in selected areas in the Tokyo Metropolitan Area to measure environmental conditions prior to convection initiation. The relationship between sensible/latent heat flux from the surface and the height of the boundary layer/initiation of cumulus clouds are studied using scintillometer, radio sonde soundings, temperature profilers, wind

profilers and rapid-scan satellite images. Numerical models, which can simulate the effect of urban areas on the atmospheric boundary structure, is also used. Network of twelve Automated Weather Stations (AWS) with high spatiotemporal resolution was set up in the western part of radar observation area. Six laser-based optical disdrometers were mounted on each six stations to measure drop size distribution and rainfall intensity during the interval of 10seconds. These surface data are used to study a detailed structure of extreme weather and to validate radar QPE and QPF algorithms.

## b. Thunderstorm Observations -

A variety of advanced remote sensing techniques are employed to detect the initiation of convections and to observe the whole life cycle of thunderstorms. In the experiment, two research Doppler lidars (NICT and Hokkaido University), as well as two operational Doppler radars (JMA) at Narita and Haneda airports, are operated to make observations of the behavior

of sea breeze fronts and air flow in the atmospheric boundary layer prior to initiation of convection. Frequent observations from the JMA Geostationary Satellite MTSTAT which has begun since the summer of 2010, performed every 5 minutes, are used to provide information on the initiation of thunderstorms. The convective cloud information observed by MTSAT and information on precipitable water distribution given by GEONET are used to study the initiation of convections and the ensuing processes that develop.

A Ku-band FM-Chirp fast scan radar, which was developed by Osaka University and Sumitomo Electric Industries, is used in the field experiment. This radar makes full volume scans in 1 minute, and observes reflectivity, Doppler velocity and polarimetric parameters at approximately 10 m-interval. It is expected that thunderstorm structure will be illustrated in very high temporal-spatial resolutions. Other radars in the Tokyo Metropolitan Area are X-NET (Maki et al., 2008), two MLIT (Ministry of Land, Infrastructure, Transport and Tourism) X-band polarimetric radars (Maesaka et al. 2011), an MRI C-band solid state polarimetric radar and three JMA C-band operational Doppler radars (Fig. 3).



Fig. 3 Radar network of TOMACS.

#### 3.2 Development of Early Warning and Prediction System

The aim of the second research topic is to establish a "Monitoring and Prediction System of Extreme Phenomena (MPSEP)" which can process real-time data from X-band research radar network (X-NET), C-band radar, MTSAT, surface meteorological observation network, etc. and predict the occurrence of localized heavy rainfalls and strong winds. Information from the MPSEP is utilized in the social experiments described in the third research topic. The research theme also aims to establish an extreme weather database, which will be useful for case studies of extreme weather and planning disaster countermeasures. The core research institute to accomplish the research mission is NIED. Following organizations are participating in this research theme: Meteorological Research Institute (MRI), National Institute for Land and Infrastructure Management (NILIM), Kyoto Univ., Central Research Institute of Electric Power Industry (CRIEPI), Japan Weather Association (JWA), Electronic Navigation Research Institute (ENRI). Japan Meteorological Agency (JMA)

## a. X-NET products

X-NET data is classified from level 0 to 4 according to the level of processing managed (Table 2). Level 0 data is raw radar data, which is usually recorded in the original format used by each radar manufacturer. Level 1 data is raw data after format conversion to NetCDF which is a set of software libraries and machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data. Level 1.5 data refers to radar data after fundamental corrections such as attenuation correction and unfolding of Doppler velocity data. The accuracy of the correction scheme of this level has a large impact on higher level data, such as those for rainfall rate and wind speed. The data format used for levels 1 to 4 is NetCDF. The coordinate system for levels 1.5 to 4 is geographic coordinates, which is a more convenient system for applying data. Level 2 data is essentially real-time data which refers to "basic" meteorological products calculated from Level 1.5 data. Examples of Level 2 data are distributions of rainfall (R), composite rainfall map (Maki et al. 2012), rain water content (M), wind vector (u,v,w). Level 3 data are "advanced" meteorological data calculated from Level 2 or Level 1.5 data, examples being distributions of the area of rainfall (AR) within a drainage area, cumulative rainfall (CR), effective rainfall (ER), and vertically integrated liquid water content (VIL). Other examples are microphysical parameters such as hydrometeor type (HT), and drop size distributions (DSD). To retrievals of microphysical parameters from X-band polarization radar, rainfall attenuation corrections of  $Z_{\rm H}$  and  $Z_{\rm DR}$  are essential and the method proposed by Kim et al. (2010) is employed. Objectively analyzed wind field adjusted with a numerical model is also categorized into the Level 3 products. Additional examples include echo top height, kinematic parameters, and wind gust data. Level 4 data are "forecasted" products. Graphical examples of products of each level are shown in the next chapter of this paper.

Data level		Description	Format (Coordinate)	Example
LEVEL 0		Raw radar data	system dependent (usually polar)	T, Z, V, W (for conv. radar) $Z_{DR}$ , $\rho_{hv}$ , $\Phi_{DP}$ , $K_{DP}$ (for pol. Radar)
LEVEL 1		Raw radar data	NetCDF (polar)	ditto
LEVEL 1.5		Raw radar data after quality control	NetCDF (geographic)	ditto
LEVEL 2	2p	2D "basic" precip. parameters	ditto	R, M, (u, v, w)
	2v	3D "basic" precip. parameters	ditto	ditto
LEVEL 3	3p	2D "analysis" precip. parameters	ditto	AR, CR, ER, VIL, HT, DSD, (u, v) <sub>a</sub>
	3v	3D "analysis" precip. parameters	ditto	HT, DSD, (u, v, w) <sub>a</sub>
LEVEL 4	4p	2D "nowcast" precip. parameters	ditto	R, M, AR, CR, ER, VIL, SW
	4v	3D "nowcast" of precip. paramaeters	ditto	R, M, (u, v, w),
SUPLLIM ENTAL	CReSS	Outputs from cloud Resolving model	ditto	Meteorological parameters
	JMA	Operational weather information	ditto	Radar, Objective Analysis, MSN

## Table 2 List of X-NET products

# b. Quantitative Precipitation Forecast (QPF)

Three types of forecasting method are employed; early detection of torrential rainfall based on three-dimensional precipitation structure, 1-hour precipitation forecasts (nowcasting) based on the extrapolation method, and 4-hour forecasts based on a numerical model with 3-DVAR data assimilation. The early detection method utilizes information on precipitation development in the upper atmosphere for 5-10 minute forecasts. Hirano and Maki (2010) found that the increase of vertical integrated liquid water content (VIL) precedes surface rainfall by 5-10 minute in the case of Zoshigaya torrential rainfall. Kim et al. (2012) found in the same rainfall event that the precipitation core was formed at about 4 km height and fell to the ground at 5–25 minutes after its first appearance. These results suggest the possibility early detection of torrential rainfall using radar data. The extrapolation method used in nowcasting predicts future locations of precipitation areas with the use of motion vectors, which are obtained by the correlation analysis of consecutive radar images. The accuracy of this method depends on the accuracy of the input rainfall information. Kato et al. (2009b) showed the MP radar QPE improves the nowcasting accuracy. The other nowcasting error source is assumption of steady states of precipitation systems; thus, the accuracy of nowcasting is not high for rapidly developing or decaying systems. Four-hour QPF are based on the cloud-resolving numerical model with the data assimilation technique. We are developing a real-time 3DVAR analysis as the data assimilation technique. The calculation time for 3 hour QPF is around 10 minutes. The forecasting area is over the Kanto Plane, with a horizontal resolution of 1km and 45 vertical layers.

# 3.3 Social Experiments on Extreme Weather Resilient Cities

The aim of the third research project is to validate the effects of MPSEP on the prevention of disasters, and the reduction of damage in those situations, through field tests of the MPSEP in four different disciplines; emergency deployments, river management, infrastructure, and education. To make MPSEP suitable for practical use, and before implementing any social experiments, surveys will be conducted for each experimental field on what information is appropriate and on the effective means of transmitting such information. Toyo Univ. is the core university to accomplish the research mission. Following organizations are participating in this research theme. NIED, Tokyo Metropolitan Research Institute for Environmental Protection (TMRIER), Nihon Univ., Tokyo Fire Department (TFD), Edogawa Ward of Tokyo, Yokohama City, Fujisawa City, and Minami-Ashigara City of Kanagawa Prefecture, East Japan Railway Company (JR East), Central Japan Railway Company (JR Tokai), Obayashi Corporation.

## a. Test bed

The project test-bed is the Tokyo Metropolitan Area, which is defined in the present study as the 50km area surrounding the headquarters of the Tokyo Metropolitan Government. The Tokyo Metropolitan Area is the world's most populous metropolitan area: the total population in these cities is approximately 30 million, which corresponds to the entire population of Canada. About 10 million people use some kind of public transportation every morning to commute to their schools and offices. The area contains most of Tokyo, Kanagawa, and Saitama prefectures and a part of Chiba prefecture. Five mega-cities are within the area; the 23 wards of Tokyo (8.5 million), Yokohama City (3.6 million), Kawasaki City (1.3 million), Saitama City (1.2 million), and Chiba City (0.9 million). The networked radar setup in the Tokyo Metropolitan Area is one of the unique features of the present study.

Social experiments on the application of X-NET products to predictions of natural disasters and risk managements are currently underway in four different disciplines: emergency deployments, river managements, infrastructures, and educations.

Since 2008, the TFD has been experimentally using the NIED X-band polarization radar for fact-finding to identify typhoons, localized heavy rains or others most clearly. The radar has been in use mainly for the earlier preparation for flood protection/control and the better, more specific monitoring of weather conditions. Starting in 2011, the X-band polarization radar-provided information can be viewed on the TFD's "Disaster Information System (web-GIS)". The X-band polarization radar web site (Fig. 5) activates its alert sound system when precipitation reaches a warning level, showing the fire stations in the "areas of danger" so that they can quickly prepare for an upcoming rainstorm. The TFD's Disaster Information System demonstrates both the X-NET information and the detailed area data (i.e., past inundation damage, river water levels, landslide hazard area, etc.) simultaneously on its map. This duality conveniently helps firefighters quickly decide on the action to take for flood protection.

One of characteristics of urban rivers is its short response time to rainfall: the water level of an urban river rises rapidly after localized heavy rainfall. Yokohama City one of participants of examining QPE and QPF as information for improving flash flood warning systems in urban water parks. The train traffic is controlled by rainfall information collected by company's own rain gauge networks located at train stations. The East Japan Railway Company and the Central Japan Railway Company are examining X-NET QPE and QPF information for their computer-assisted traffic control systems. Monitoring and nowcasting of severe storms are required for construction managements: they will help worker's safety and

a company to keep a construction schedule. Obayashi Corporation is examining X-NET wind information for safety management at tall construction sites. In 2011, information on strong wind and rainfall information of X-NET were sent to the construction site of the "Tokyo Sky Tree" (634 m) to examine its usefulness. The Tokyo Metropolitan Research Institute for Environmental plans Protection to set up surface meteorological instruments and X-NET monitor displays in several high schools in the metropolitan area to be used for science education and students safety management.



## Fig. 5 Social Experiments in Tokyo Fire Department

#### 4. Summary

After setting up the dense meteorological instruments in the Tokyo Metropolitan Area, full scale campaign observations have started since 2011. Some interesting results were obtained from observations: detection of precipitation core by Ku-band rapid scanning radar, detection see breeze by Doppler lidar and C-band Doppler radar, the role of see breeze for initiation of thunderstorms. These results suggest early detection of thunderstorms, which is useful for warning of urban flashfloods. Social experiments have started since 2012 at several local governments and private companies. Tornado damages and lightning injury in Tsukuba on 7th May will accelerate the research on prediction of damaging winds and lightning which is a challenge of the present research projects. The dense meteorological observations in the Tokyo metropolitan area is being considered as an international test-bed for deep convection study.

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