Fundamental observation to clarify the mechanism of urban heat environment and the heavy rainfall in urban areas

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Abstract

The growing need for knowledge about the dynamic behavior of sudden localized heavy rains, however, it is very difficult to observe and predict the behavior of such extreme events. We have been researching to find the reason of the growth and development of locally heavy rains to improve the weather forecast accuracy. This paper covers the following results of researches: Monitoring, experimentation and numerical simulation, this paper presents: an analysis of guerilla rainfalls cases observed with X-band Doppler radar.

Keywords: Locally Heavy rain, Doppler radar, MP radar

Introduction

The Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report (AR4) states that the entire globe is warming based on observations of increases in global average air and ocean temperatures and a rising global average sea level. A look at the linear warming trend over the past 100 years reveals an increase of 0.74℃, which is consistent with increases in the sea level. The urban heat island (UHI) phenomenon has combined with global warming to produce a 3.0°C rise in Tokyo's temperature over the past 100 years, and a dire situation where the 'thermal environment is virtually palpable.

The thermal environment issue has even been identified as a contributing factor in the locally heavy rains which have occurred in Japan in recent years. These recent deluges have been remarkable for their substantial rainfall, but even more so for their sudden and localized nature. Typically lasting for one to two hours, the occurrence of these deluges has been impossible to predict, leading to the death of 10 people in 2008 and prompting the media to dub them ‘guerilla downpours’. This term ranked among the top 10 'Buzzwords of the Year' (*Ryūkōgo Taishō*) for 2008, reflecting the extent to which they garnered national attention. Japan's urban areas are unprotected against such heavy rains for example and the only option for inhabitants is to evacuate. In Japan the Japan Meteorological Agency defined extreme down pore as the rainfall intensity is 80mm/hour or more. We also defined that heavy downpour as the 100mm/houre or more and the rainfall event ends within one or two hours. However, their sudden occurrence makes this difficult. In response to a death which occurred on 5 August, 2008 in Tokyo's Toyoshima Ward when rains flooded a sewerage worksite, Tokyo's District Public Prosecutor's Office commented on the difficulty in predicting sudden flooding caused by natural phenomena, prompting heads of disaster prevention organizations to recognize the need to accurately monitor and predict sudden downpours.

In order to closely monitor these guerilla downpours in Tokyo and the rest of the Kanto region, we constructed 'X-NET', a joint observation network of multiple X-band Doppler radars which accurately tracked the intensive downpours which occurred in 2008 . X-NET's good observation results prompted the Ministry of Land, Infrastructure, Transport and Tourism to set up multiple X-band Doppler radars from 2009 in the Kanto, Chubu, Kinki and Hokuriku regions of Japan to monitor downpours. The Ministry is also investigating the launch of the ‘Central Flood Forecast Support Center’ (provisional name) to bolster existing flood forecasting systems. The X-NET system was built using the existing radar system in Kanto Region. For example the radar system in Chuo University was install in 1995 and the initial cost for installing the system was about 100million yen.

In 2009 Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has built a new radar network using MP radar system covering Kanto, Chubu, Kinki, and Hokuriku regions. This year MLIT spent about 3billion yen to install total number of 11 radars. This system has just started operating and the rainfall information is updated every two minutes.

X-band multi parameter radar (MP radar) can monitor cross polarization phase difference has now in practical use and this is the reason many projects are now using X-band radar system throughout the world. Followings are the MP radar projects outside of Japan.

In France Flood forecast by radar in the Mediterranean Alps (FRAMEA) called field experiment has carried out to evaluate the MP radar system to forecast flood（Testud et al. 2007）. In United Stated University of Oklahoma and National Severe Storms Laboratory (NSSL) build new mobile X-band dual-polarimetric radar called NO-XP (Biggerstaff, 2007). In Athens, Greece the MP radar was installed to validate its data with distrometers and rain gauges（Kalogiros et al.,2007）

Even with the ability to observe locally heavy rains in real time, however, the task of forecasting sudden, localized guerilla downpours remains extremely difficult. To that end, we have been researching locally heavy rains from a number of aspects to assist in their forecast. Based on our X-band Doppler radar observations of rainfall movement in the Kanto region, we identified four patterns which we then compared to the wind fields at the time.

Based on the above-mentioned monitoring, experimentation this paper presents an analysis of guerilla downpour cases observed with Doppler radar.

Guerilla downpours

Outline of observations

Weather radar

In 1995, we set up an X-band Doppler radar in Tokyo's Bunkyo ward to monitor rainfall with the aim of understanding the mechanism behind locally heavy rain (**Fig. 1**). In addition to monitoring rainfall intensity, Doppler radar is capable of tracking wind movements within the precipitation area. We can also measure the vertical profile of raindrops by changing the radar antenna's angle of elevation without changing its direction. An outline of Chuo University's Doppler radar system is provided in **Table 1**.The Doppler radar has an observational radius of 128 km, frequency of 9445 MHz, wavelength of 3.2 cm, an observational resolution of 250 m in the range direction and 0.7° in the angular direction, and radar conversion constant of B=200 and β=1.6. The Doppler radar is set up in central Tokyo, where it monitors intense downpours occurring in the Kanto region with a high level of accuracy and precision.

Effectiveness of Doppler radar observation

We will now describe a case of locally heavy rain which occurred on 26 April, 2005. **Fig. 2** shows two radar images taken at 14:00 and 14:30 on 26 April, 2005. Meanwhile, **Fig. 3** indicates the relationship between rainfall intensity and horizontal distance of A-A´cross section. The figure shows that the torrential downpour delivered instantaneous rainfall intensity of 50 mm or more within a range of less than 1 km, and that these sites of peak rainfall intensity experienced a subsequent decline in said intensity to 20 mm or less over a period of 20-30 min. Our Doppler radar has a high observational resolution of 250 m in the range direction and 0.7° in the angular direction and can perform real-time observations, thus allowing us to monitor a series of events from the appearance of such locally heavy rains to their development and eventual dissipation.

Characteristics of Kanto region rainfall

Upon analyzing the past 15 years of collected data, we found that there are four patterns of rainfall which bring locally heavy rains. Guerilla downpours, which have occurred frequently in Japan in recent years and are characterized by locally heavy rain phenomena over a range of a few to a dozen kilometers which then dissipate after about an hour, manifest in one the following three patterns: (1) the front formation type rainfall; (2) the cells advection type rainfall; and (3) the isolated cell type rainfall. These three patterns occur on a rainfall scale of 20-200 km and deliver increased rainfall intensity in a short period within the local rainfall area. Meanwhile, locally heavy rains which deliver significant rainfall over a wide area for an extended period appear in the form of (4) line-shaped convection system. This fourth pattern occurs as rainfall phenomena with a scale of 200-2000 km similar to that of a front or low pressure system. We will next describe the features of each rainfall pattern .

Features of front formation type rainfall

This type of rainfall travels from the northern area of the Kanto Plain (northern Gunma & Ibaragi) and the western mountain ranges to Tokyo Bay while forming a front. **Fig. 4** is an initial radar image of frontal rainfall taken at 18:00 on 15 July, 1996 which shows areas of precipitation occurring along the mountain ranges. On this particular day, there was a macroscale northwesterly sea breeze which is typical in summer, with rain areas visible in the mountain ranges of Ibaragi and southern Gunma. In this figure depicting front formation type rainfall on the Kanto Plain in summer, upflows are generated by sea breezes blowing into the boundary layer and occur between Gunma's mountains, or are generated by the collision of sea and mountain breezes. The rain areas which formed the front then move in a southeasterly direction and, one hour later, the frontal rain area indicated as point 'a' in **Fig. 5** advances. The shape of the surface wind vectors allow us to discern cold outflows radiated from the rain area and a southwesterly sea breeze close to the coast. **Fig. 6** shows the time series vertical profile of the rain area using the radar's 350° azimuth angle. In this figure, the sea breeze is blowing from the southeast to the northwest, while the rain area is moving in the opposite direction. Pushed by the Westerlies, the rain area located at an altitude of more than 6 km is shifting to the southeast. Furthermore, the center of Cell I's echo appearing in **Fig. 6(a)** has moved approximately 5km to the southeast just 10 min later, as shown in **Fig. 6(b)**. However, we can assume from this time-series image that upflows are generated in newly-formed Cell II due to a collision of the rain area's cold outflows with sea breezes, which then pushes the front. The time from a single cell's appearance to its dissipation is about 20 to 30 min, while the time taken to replace a cell is about half that at 15 min, during which time the center of the rain cell travels about 5 km. The cell's rate of travel is determined by this cell replacement, and it continues in a southerly direction until reaching Tokyo Bay.

Features of cells advection type rainfall

Fig. 7 is a radar image of cells advection type rainfall. This type of rainfall extends its rain area in a band-like formation in the same direction in which the precipitation cell is traveling, bringing rain to a wide expanse of the Kanto Plain. **Fig. 8** shows the surface wind distribution at the time the rainfall occurred as captured by the Automated Meteorological Data Acquisition System (AMEDAS). This system was set up in every about 17 km^2 from the Meteorological Agency in Japan to observe precipitation. This type of wind system differs from that of the front formation type because it does not form an organized surface wind system and the position where the rainfall will occur is unpredictable, with potential falls either on the plain or in the mountains. **Fig. 9** shows the upper-level wind speed distribution on this particular day. The rain area is being pushed by strong winds at an altitude of more than 4 km and speed of 20 m/s, and its wind field is consistent with the cell's direction and speed. **Fig. 10** contains continuous radar images of a vertical profile taken on 3 August, 1997. At 17:30, the rain area is traveling at a higher altitude than the 8-km-high developed cell and appears to have triggered rainfall via the subsequent precipitation cell. This rainfall pattern is capable of bringing a very intense amount of rain over a narrow area for an extended period. This is caused by a band-shaped rain area moving in a longitudinal direction, thus resulting in prolonged rainfall directly below.

Features of isolated cell type rainfall

In the radar image in **Fig. 11**, the rainfall forms a precipitation area of between 5 and 15 km, bringing high instantaneous rainfall intensity of more than 32 mm/h. Referred to as isolated cell type rainfall, this pattern has a small time scale and spatial scale compared to those of the previous two rainfall patterns. It occurs in three types: (a) a so-called 'heat thunderstorm' which lasts around 20-30 min from its appearance to dissipation; (b) a precipitation cell which occurs suddenly in the Tokyo metropolitan area either before or after the occurrence of front formation type rainfall; and (c) convective rainfall accompanying the passage of a low pressure system or cold front. Of the 19 isolated cell type rainfall events captured over this particular radar observation period, these three types occurred with a frequency of 10, 5 and 4 times, respectively. The positions where rainfall occurred are distributed over a wide area and are successive. **Fig. 12** shows the upper-level wind speed distribution at the onset of a heat thunderstorm using sonde observation. The isolated cell type rainfall appears when the wind speed is low and no wind shear is present. Heat thunderstorms with a wind speed of less than 15 m/s up to an altitude of 7 km occurred 8 times out of 11 rainfall events, while those with a wind shear of less than 90°at an altitude of more than 1 km occurred 10 times during the same number of rainfall events. Extrapolating either the initial or subsequent isolated-cell's point of origin or their direction currently remains a difficult task. As such, the only aspect of isolated cell type rainfall which is easy to predict is the date on which it will occur based on the atmospheric stability and vertical wind speed profiles.

Line-shaped convection system

In this type of locally heavy rain, cumulonimbus clouds align in a linear formation and maintain a linear rain area while absorbing other newly formed cumulonimbus clouds and remaining stationary for an extended period. **Fig. 13** is a radar image of a locally heavy rain caused by a line-shaped convection system. The linear rainband had a width of 15 km and length of 100 km and remained stationary for 3 h while delivering a locally heavy rain. **Fig. 14** is a similar radar image of a deluge which occurred in Niigata and Fukushima in 2004 as a result of a linear rainband spanning 400 km. Meanwhile, **Fig. 15** illustrates two rain areas within the intense rainband of the a-a' cross section of **Fig. 14** with an instantaneous rainfall intensity exceeding 40 mm and each more than 60 km in length. These results suggest that linear rainbands bring intense rainfall over a wide area and are therefore likely to cause considerable damage. Previous research tells us that these rainbands occur close to the center of low pressure systems, on cold and stationery fronts, and in areas of moist air influenced by typhoons.

Joint observation using a network of multiple Doppler radars (X-NET)

In order to better understand the processes behind the occurrence of locally heavy rain and further develop observational techniques, Japan's Chuo University, the National Research Institute for Earth Science & Disaster Prevention (NIED), the National Defense Academy of Japan and the Japan Weather Association (JWA) have established a network of X-band Doppler radars in the Tokyo metropolitan area to conduct joint observations and collect the results in real time. This radar network is called 'X-NET'. Doppler radar measures wind speed by using the Doppler effect of radio waves to determine the speed (Doppler velocity) in the direction of precipitation particles moving away from and towards the radar. Combining the observed data of multiple Doppler radars makes it possible to ascertain the three-dimensional distribution of wind direction and wind speed. X-band radar also has the advantage of being able to closely measure rainfall intensity because it uses radio waves with a wavelength of 3 cm, which are shorter than the 6.5-cm radio waves used by the Japan Meteorological Agency (JMA) and the Ministry of Land, Infrastructure, Transport and Tourism's C-band radar systems. This allows X-NET to achieve a high observational resolution of 500 m compared to 1000 m for weather radar. One disadvantage of X-band radar is the considerable effect of attenuation caused by rainfall; however, this can be rectified through the use of multiple X-band radars. The X-NET network was established in 2006 and commenced full-scale joint observations from 2007. X-NET performed continuous 24-h observations between June and November of 2008 when a spate of locally heavy rains occurred all over Japan, and obtained outstanding observation results. **Fig. 16** shows the observation results of a locally heavy rain which suddenly struck Toyoshima ward in Tokyo on 5 August and claimed 5 lives. In contrast to the 10-min measurement intervals and 1-km resolution of JMA's radar, X-NET performed measurements every 5 min at a resolution of 500 m, thus enabling it to capture heavy rainfall areas not visible to the JMA radar. It also achieved largely positive results relative to Toyoshima ward's ground-based rain gauges. X-NET's 5-min observation intervals also enable accurate monitoring of the rain areas which are responsible for locally heavy rains. Efforts are currently underway to identify ways of reducing the risks that disasters pose to citizens by making the information obtained by these technologies available to the public.

Conclusion

We have conducted surveys on torrential rainfall and the microphysical processes of clouds as well as researching thermal environments and the effects of their mitigation with the aim of understanding the mechanisms behind locally heavy rains which accompany the exacerbation of thermal environments. The results of our research are summarized below.

Rainfall in Japan's Kanto region can be classified into four patterns, namely, front formation type rainfall cells advection type rainfall, isolated cell type rainfall and Line-shaped convection system. isolated cell type rainfall is a potential cause of Japan's sudden, locally heavy rains known as 'guerilla downpours', while the linear rainband pattern has the potential to cause wide-scale damage due to the prolonged rain which it delivers over an area of some 100 km. We have been observing torrential downpours with a network of X-band Doppler radars called 'X-NET' and have achieved positive results.

Acknowledgement

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References

Eito,H., Yoshizaki M., Fukuda M., Fujiyoshi Y., Inokami A., Igarashi T. and members of X-BAIU-99 observation (1999) Case study on the structures of two line-shaped convective systems observed around Nagashima on 2 July 1999(in Japanese). Proc. of the Autumn Conference of Japan Meteor, Soc., 75, 100

Intergovernmental Panel on Climate Change(IPCC)(2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment, Report of the Intergovernmental Panel on Climate Change

Maki Masayuki, Maesaka T,., Iwanami K.., Misumi R., Kato A., Suzuki S,. Shimizu S., Kieda K., Yamada T., Hirano H., Kato T., Kobayashi F., Hiraguchi H., Kusunoki K., Masuda A., Suzuki Y., Moriya T., Kim D-S. Lee D.-In (2008) X-band Polarimetric Radar Network in the Tokyo Metropolitan Area, International Workshop on the Hazardous Winds Associated with Severe Storms

Mikami Takehiko (2008) Climatic variations in Japan reconstructed from historical documents., Weather, Vol.36, 190-193

Mikami Takehiko (2006) Recent progress in urban heat island studies: Focusing on the case studies in Tokyo, E-journal GEO, Vol.1, 79-88

Misumi R., Divjak M., Tanahashi S. and Takeda T. (1994) A numerical study on the formation of organized convective storms: Part I. Formation patterns of long-lasting cells, Journal of the Meteorological Society of Japan, 72, 235-253

Misumi R., Divjak M., Tanahashi S. and Takeda T. (1994) A numerical study on the formation of organized convective storms: Part II. Dependence of "broken-line formation" of squall-line on its line direction, Journal of the Meteorological Society of Japan, 72, 873-884

National Research Institute for Earth Science and Disaster Prevention (2007) Proceedings, International Sympojium on X-band Weather Radar Network –Challenge the Severe Storm-, Tukuba, Ibaraki 1-83

Shimizu S., Uyeda H., Moteki Q., Maesaka T., Takaya Y., Akaeda K., Kato T., Yosizaki M. (2008) Structure and Formation Mechanism of a 24 May 2000 Supercell-like Storm Developing in a Moist Environment over Kanto Plain, Japan. Monthly. Weather. Review. 2008, vol.7, 2389-2407

Yamada Tadashi (2008) Integrated Analysis for the Water Cycle Simulation Based on Hydro-Meteorology, EWRI Congress 2008

Table1

Table 1 Performance of Doppler radar

	Intenxity Mode	Doppler Mode
Transmitted Frequency	9445MHz	9445MHz
Pulse Width	0.9 μ s	0.45 μ s
Repetition Frequency	1000MHz	2000MHz
Detection Range	128km	64km
Resolution	250m	125m

Figure1

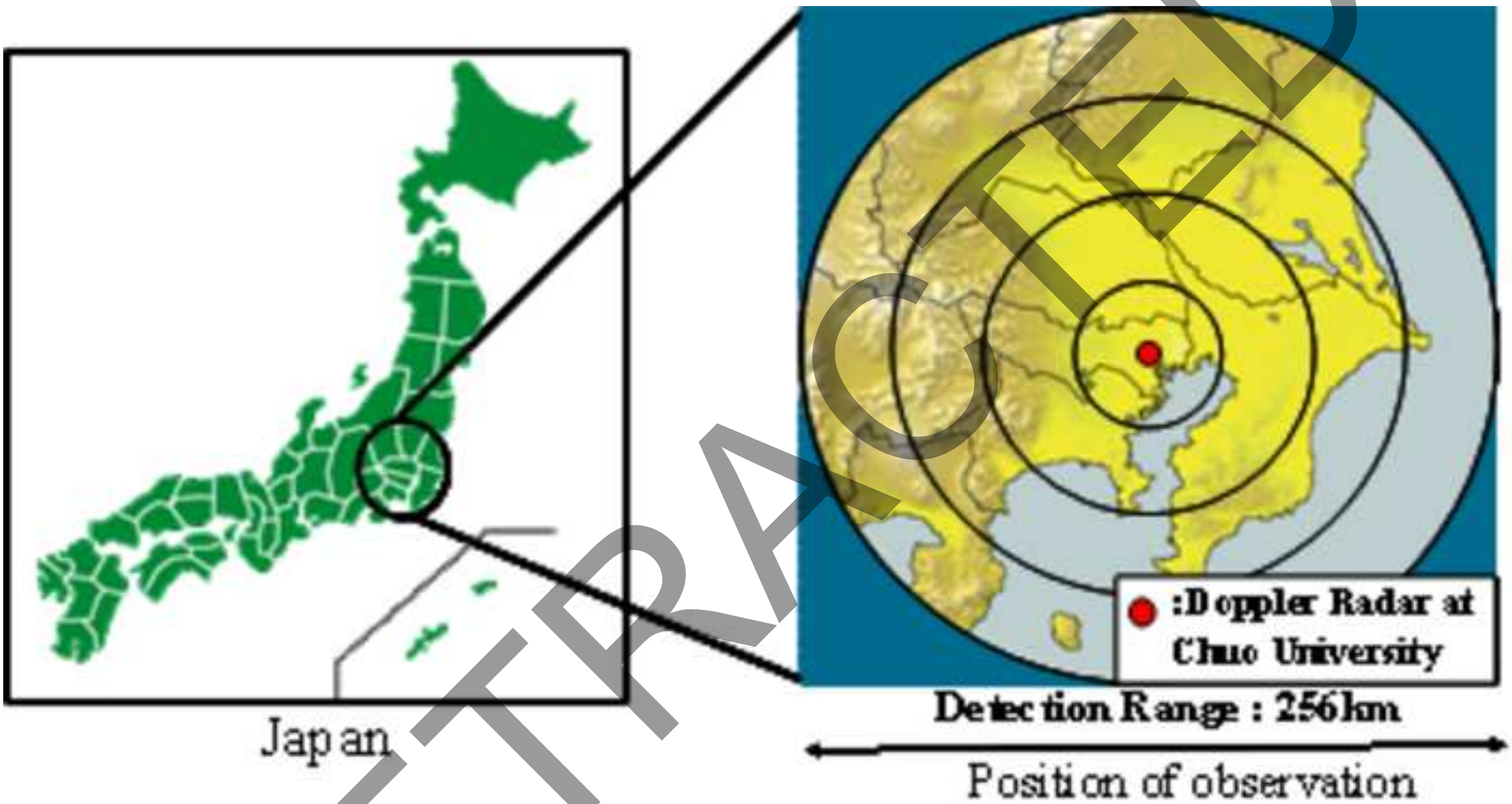


Fig. 1 Observation area

Figure2

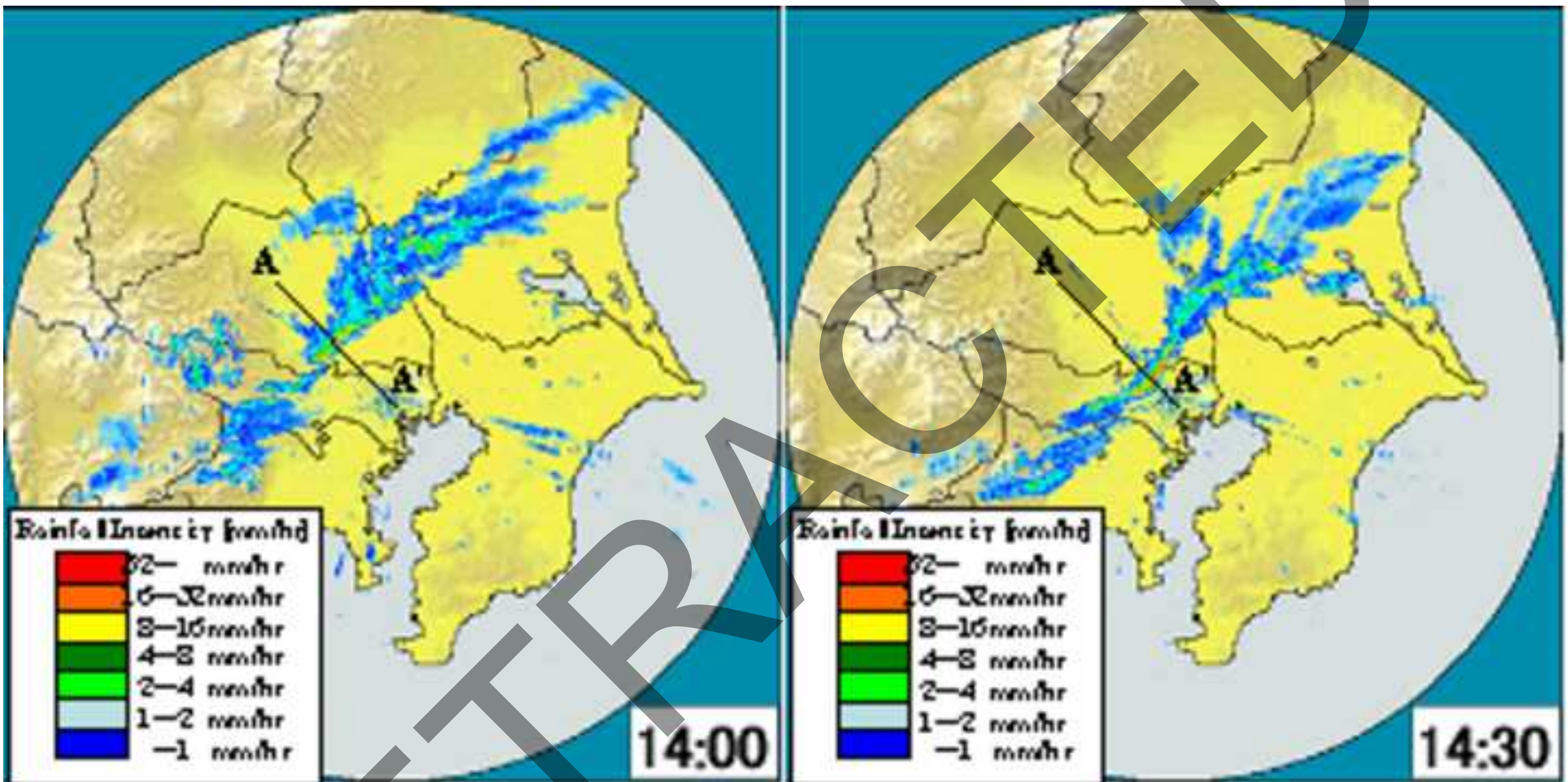


Fig. 2 Radar image taken at 14:00 and 14:30(April 26, 2005)

Figure3

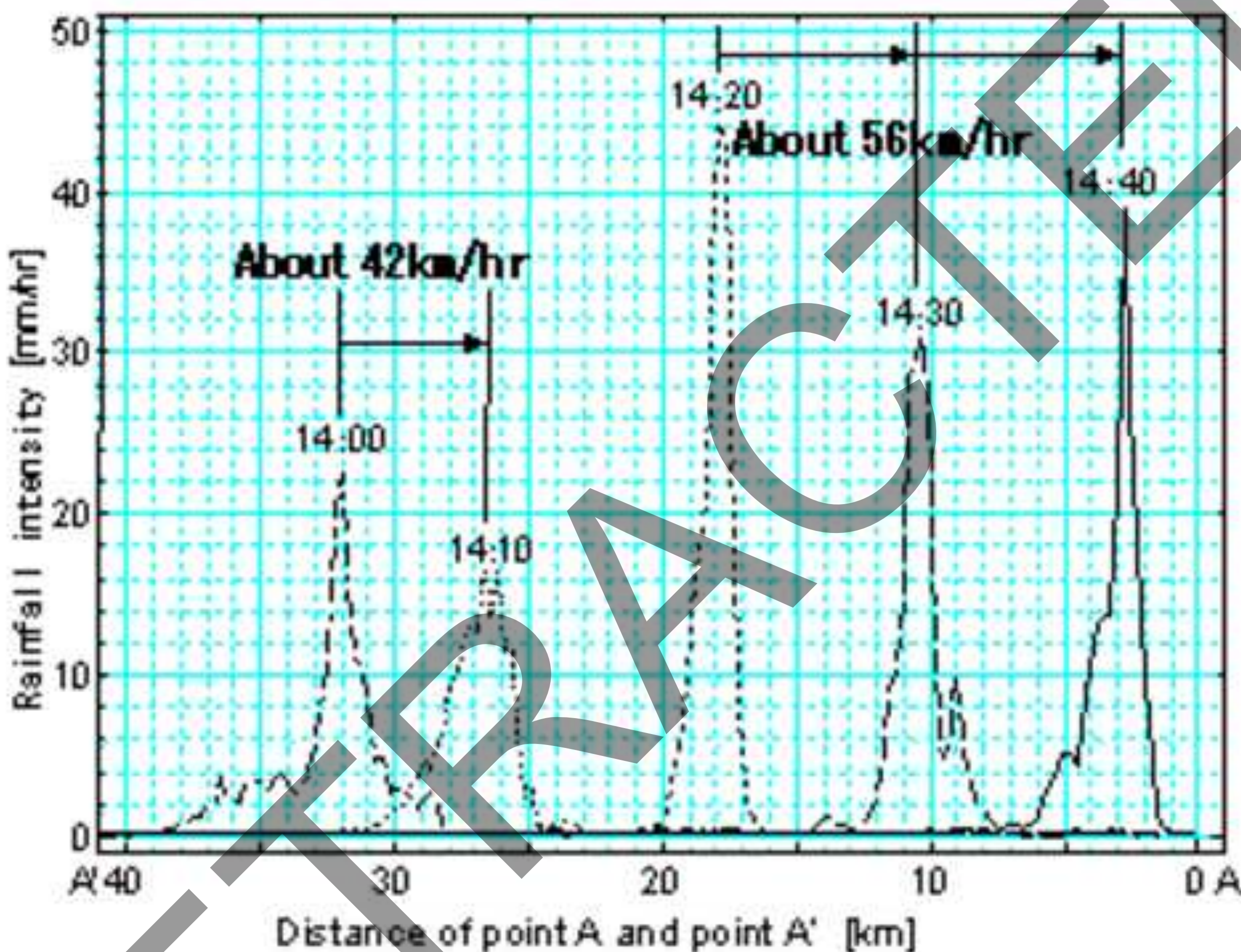


Fig. 3 Relationship between rainfall intensity and horizontal distance of A-A' cross section (April 26, 2005)

Figure4

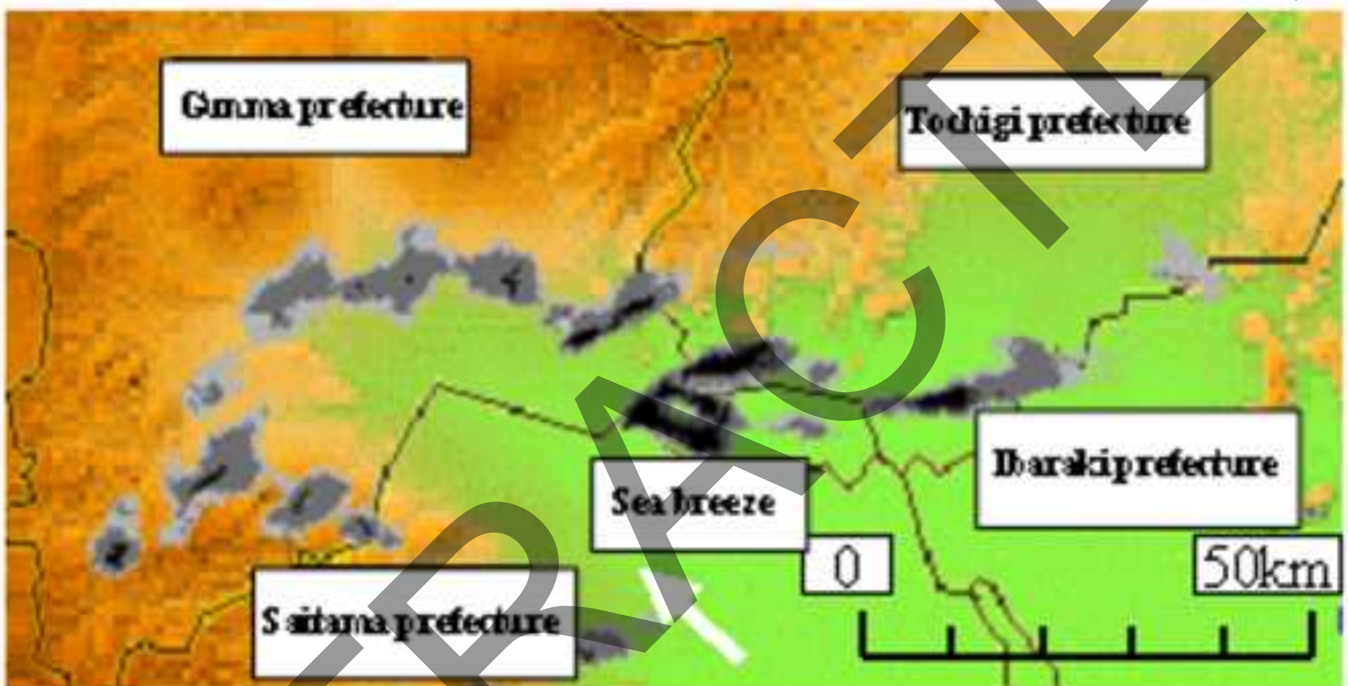


Fig. 4 Radar image of rain band generating along the mountain: Black area shows that rainfall generates along the mountain.

Figure5

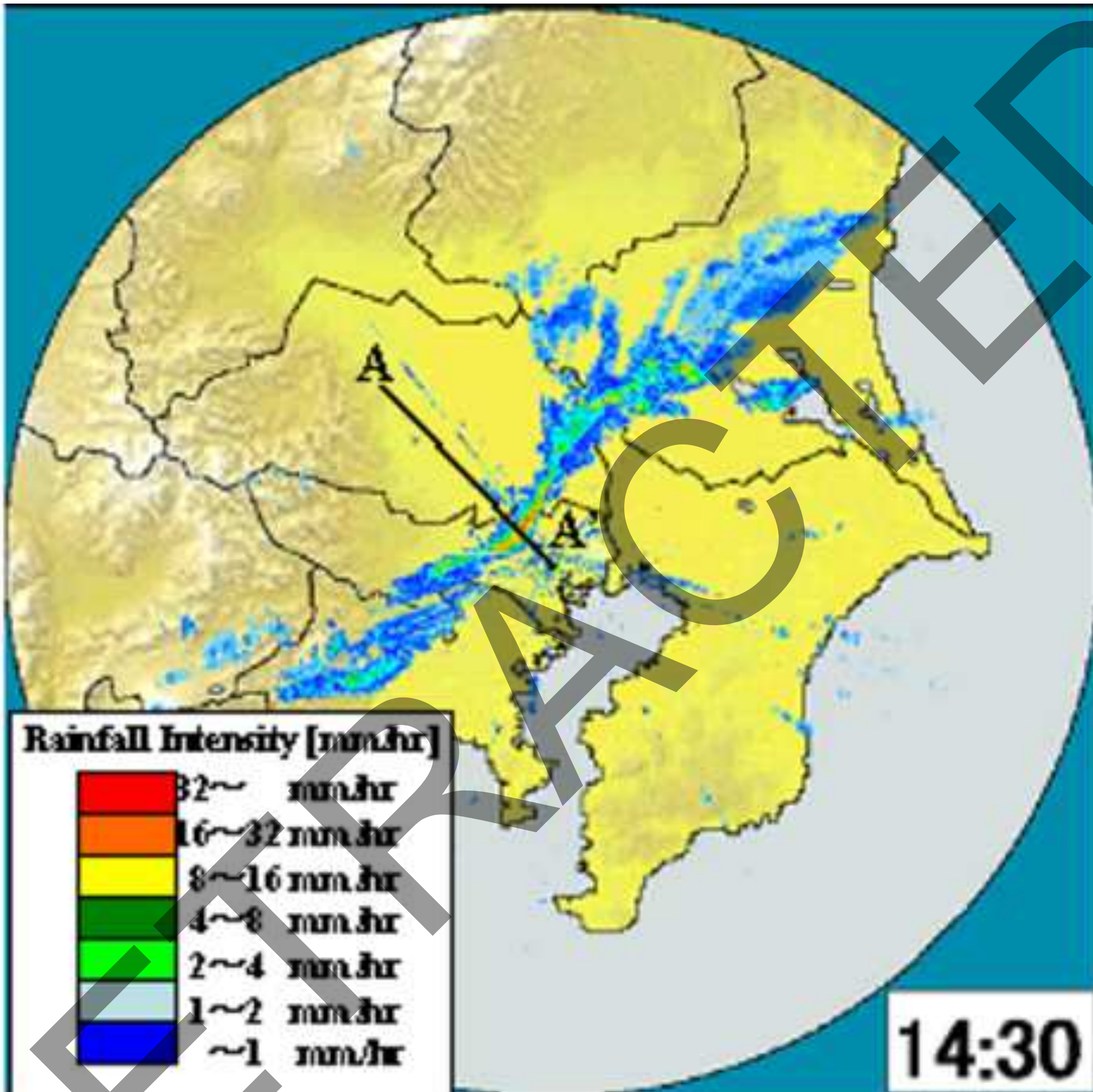


Fig. 5 Radar image of front formation type rainfall at mature stage and wind vectors at surface: Wind vectors indicate cold outflow blowing radially from rain band.

Figure6

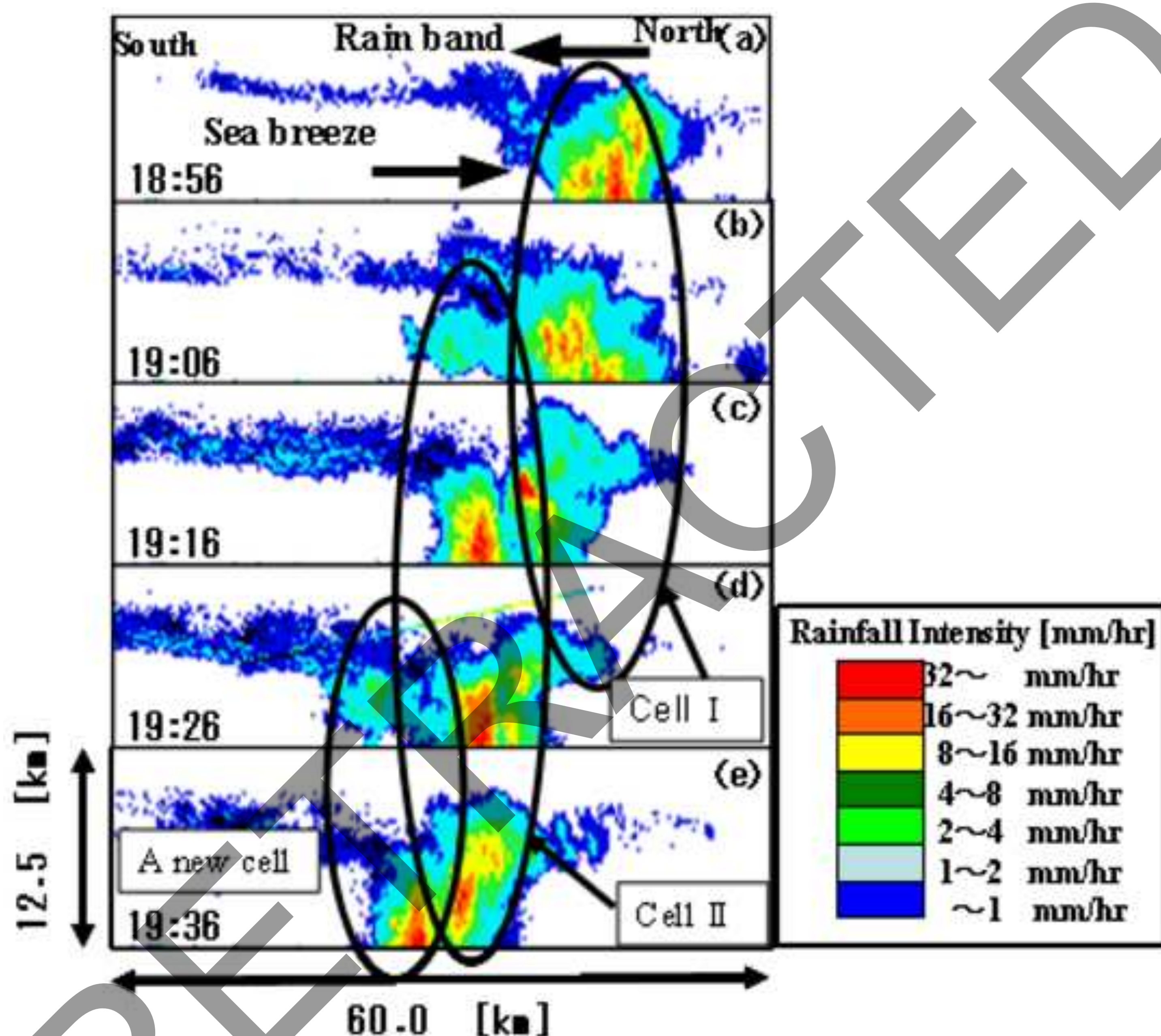


Fig. 6 The radar images of precipitation cells with vertical section from cumulus stage to dissipating stage

Figure7

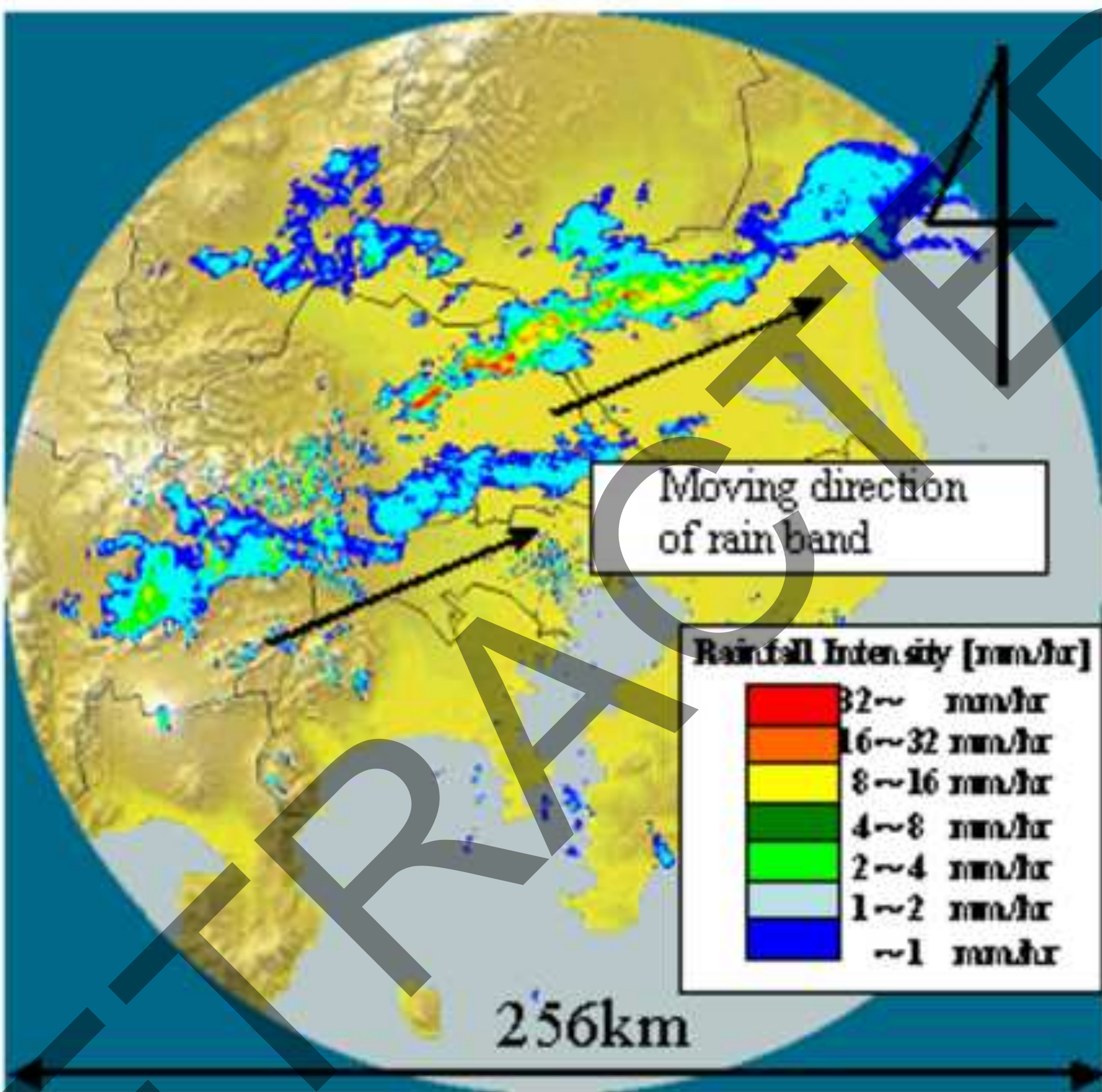


Fig. 7 Front formation-type rainfall: An advected direction of rain band corresponds to a expanding direction of the rain band

Figure8

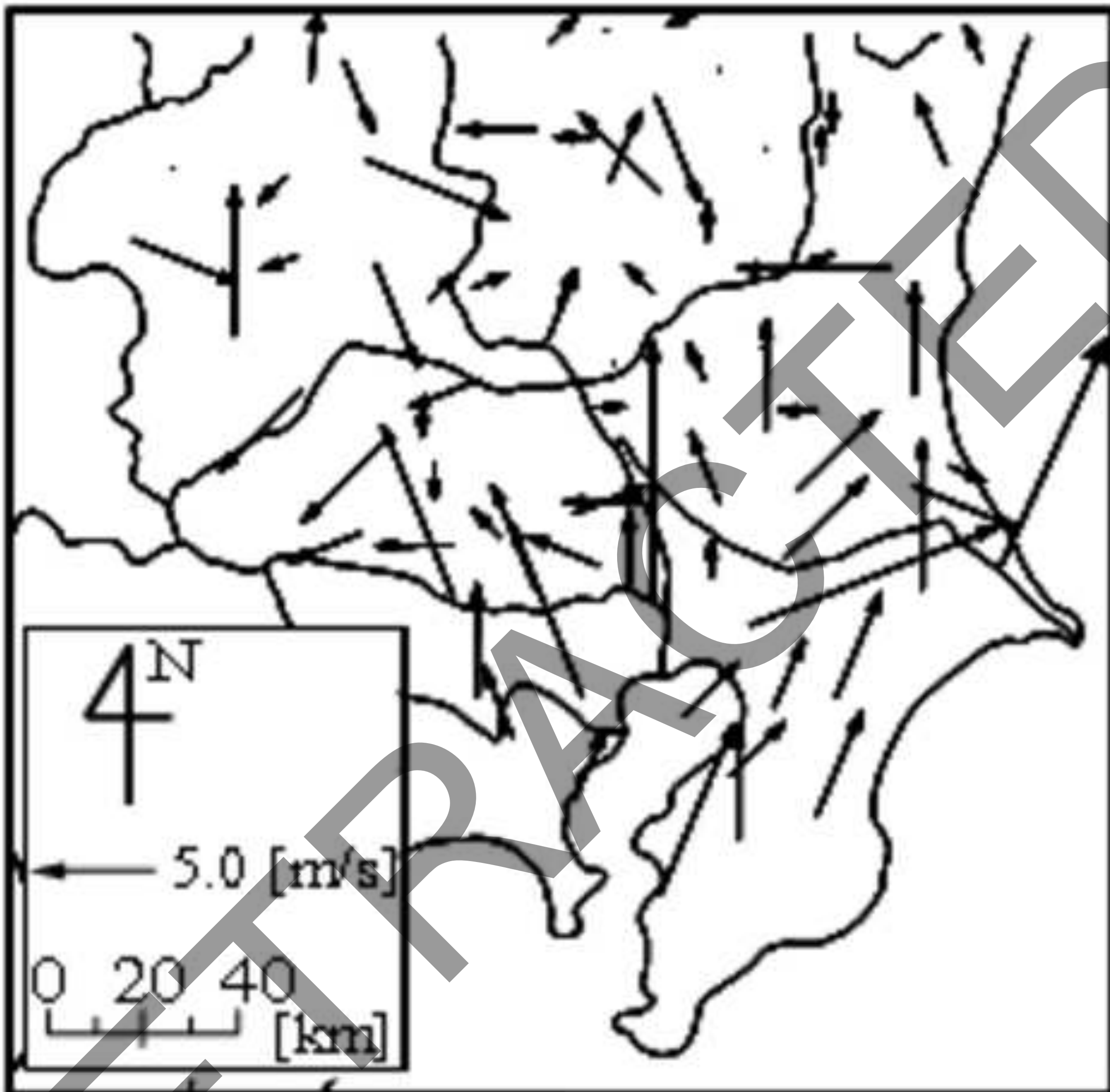


Fig. 8 A distribution of surface wind caught by AMeDAS, in giving rise to this rainfall

Figure9

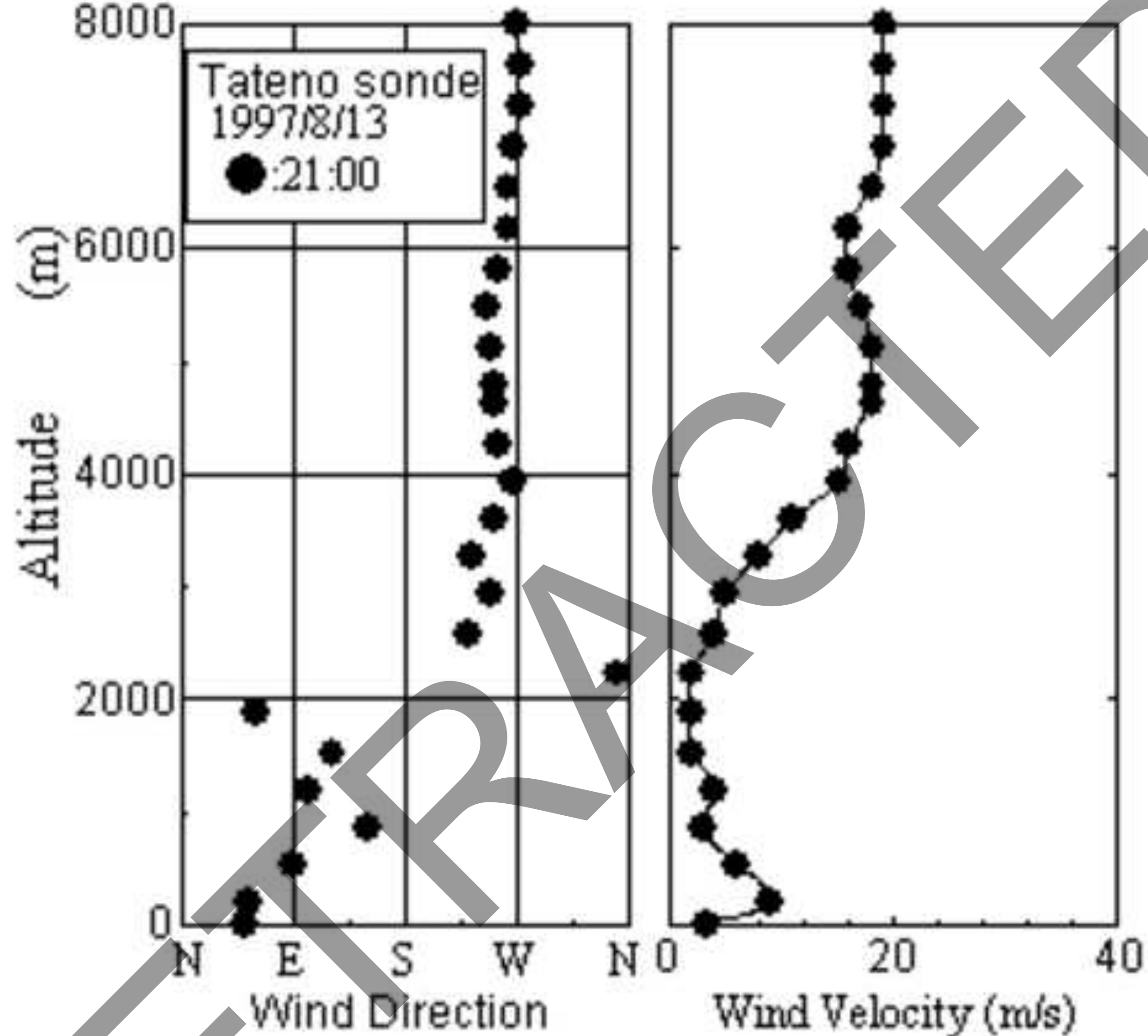


Fig. 9 Wind profile by rawinsonde: Wind with more than 20 m/s advected precipitation cells over 4km altitude

Figure10

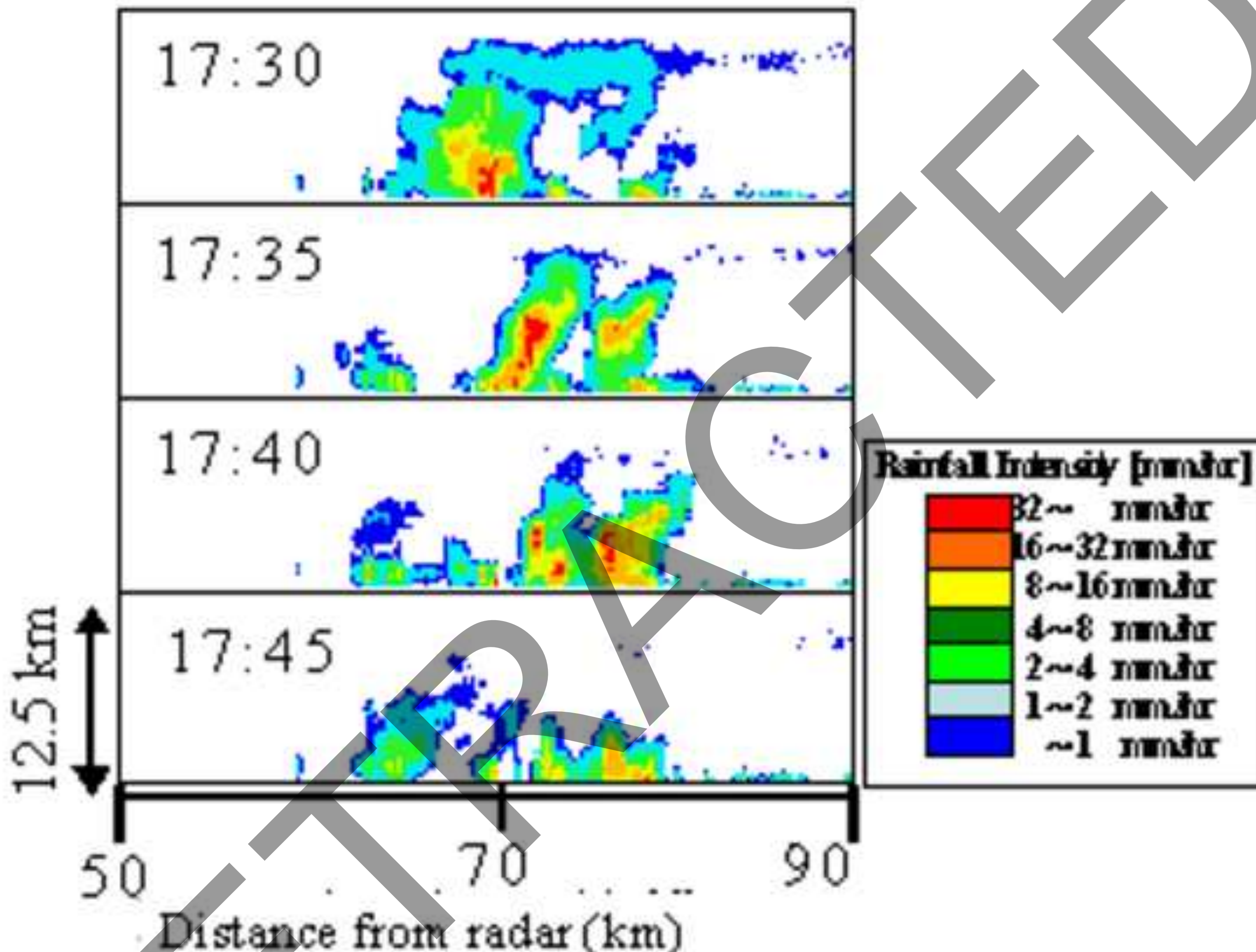


Fig. 10 Radar images with vertical section on cells advection type rainfall: An upper rain band advecting at 17:30 caused next precipitation cell

Figure11

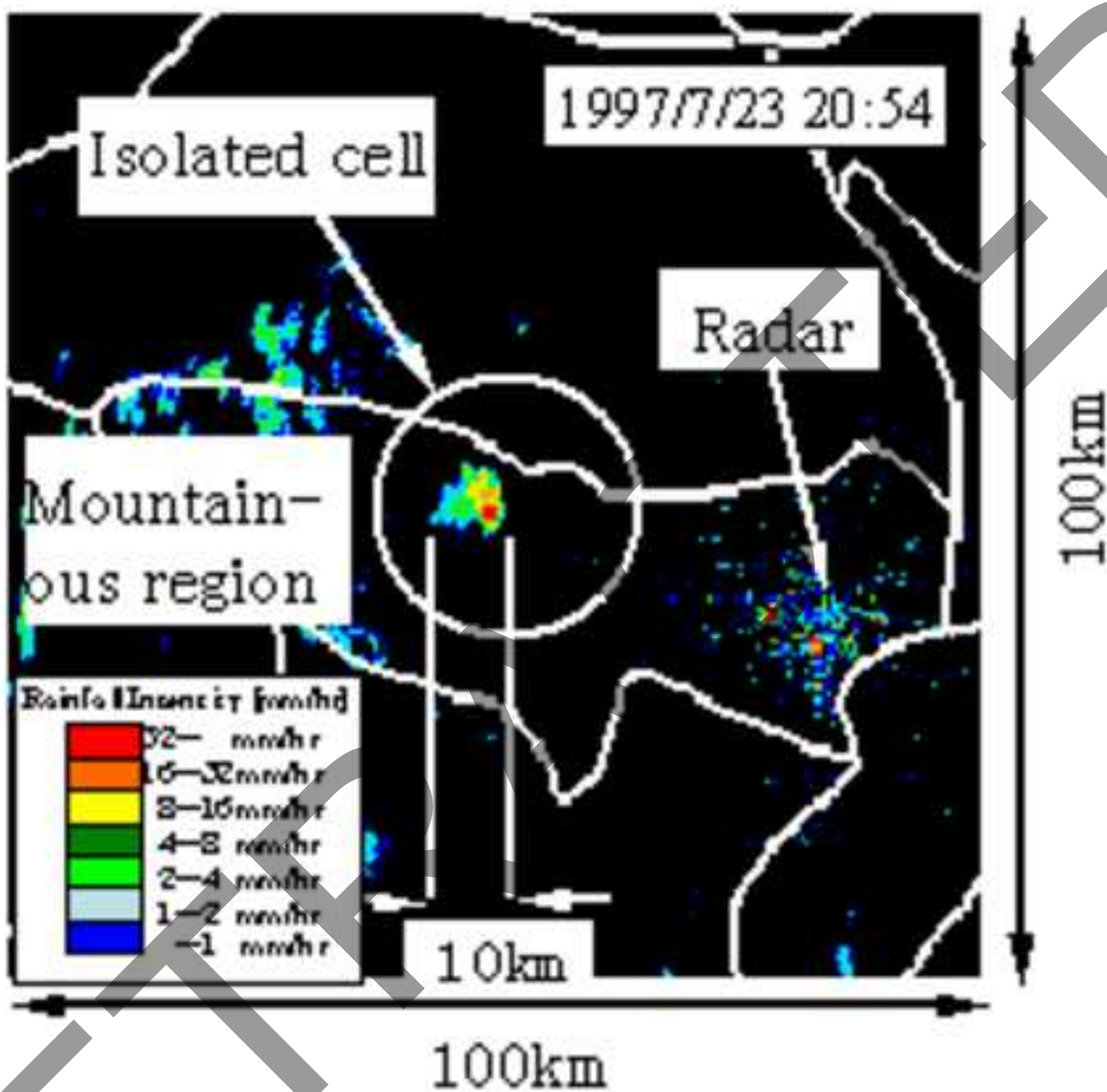


Fig. 11 Radar image of isolated cell type rainfall: A scale of this rain band is about 10km around, and there is a rain band with more than 64mm/hr

Figure12

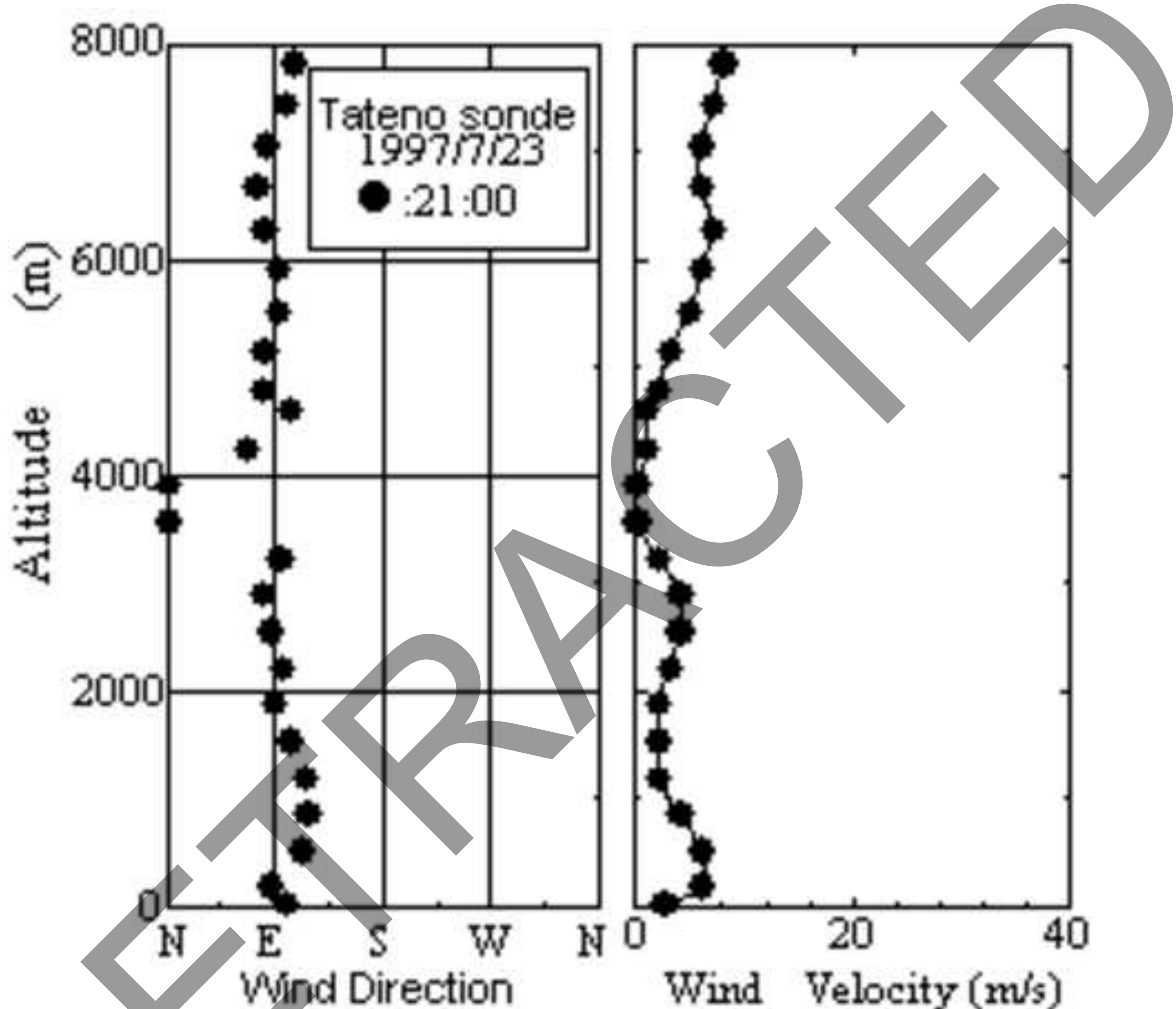


Fig. 12 Wind profile by rawinsonde: No shear exists on wind direction, and wind velocity is under 10 m/s.

Figure13

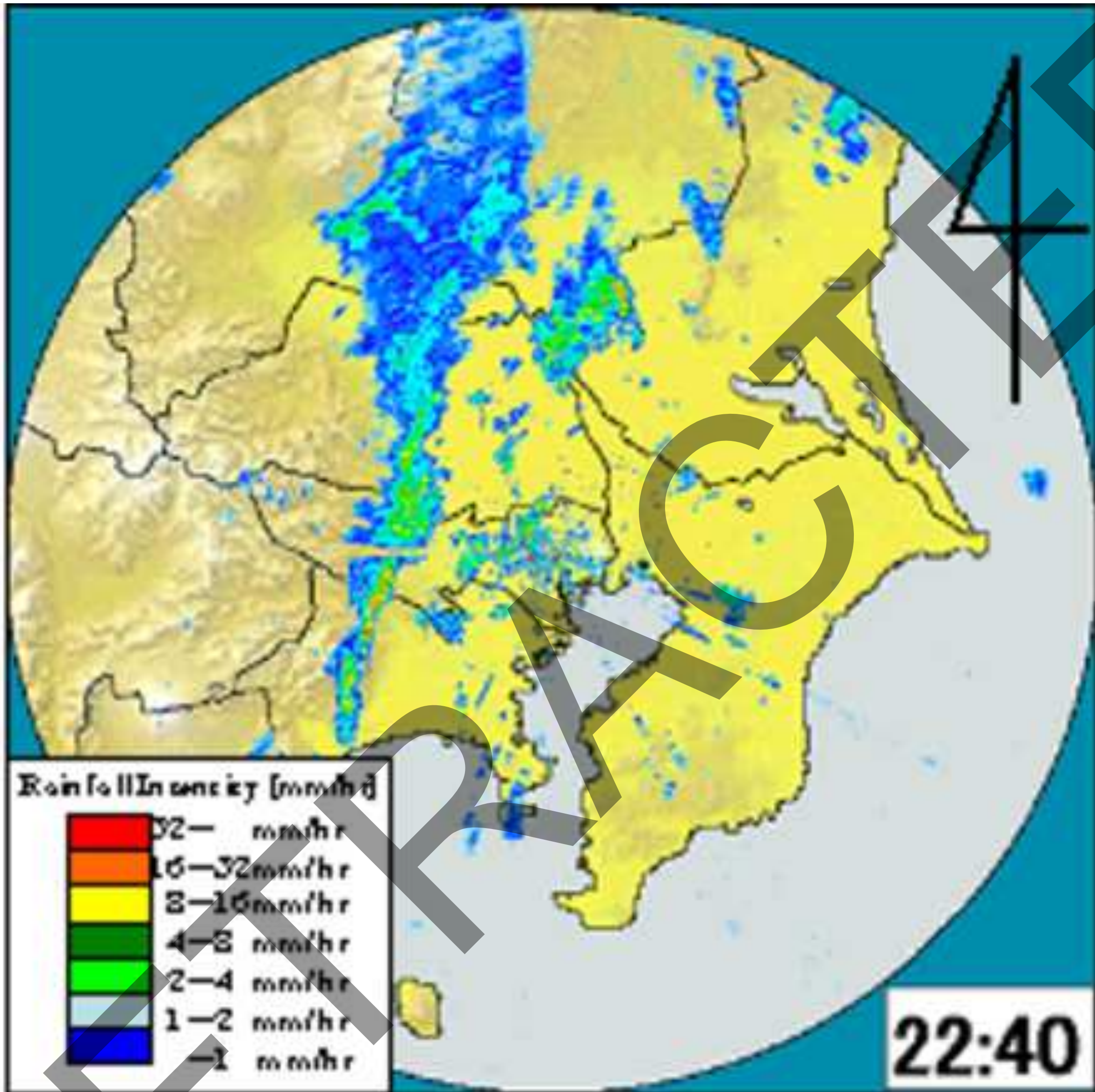
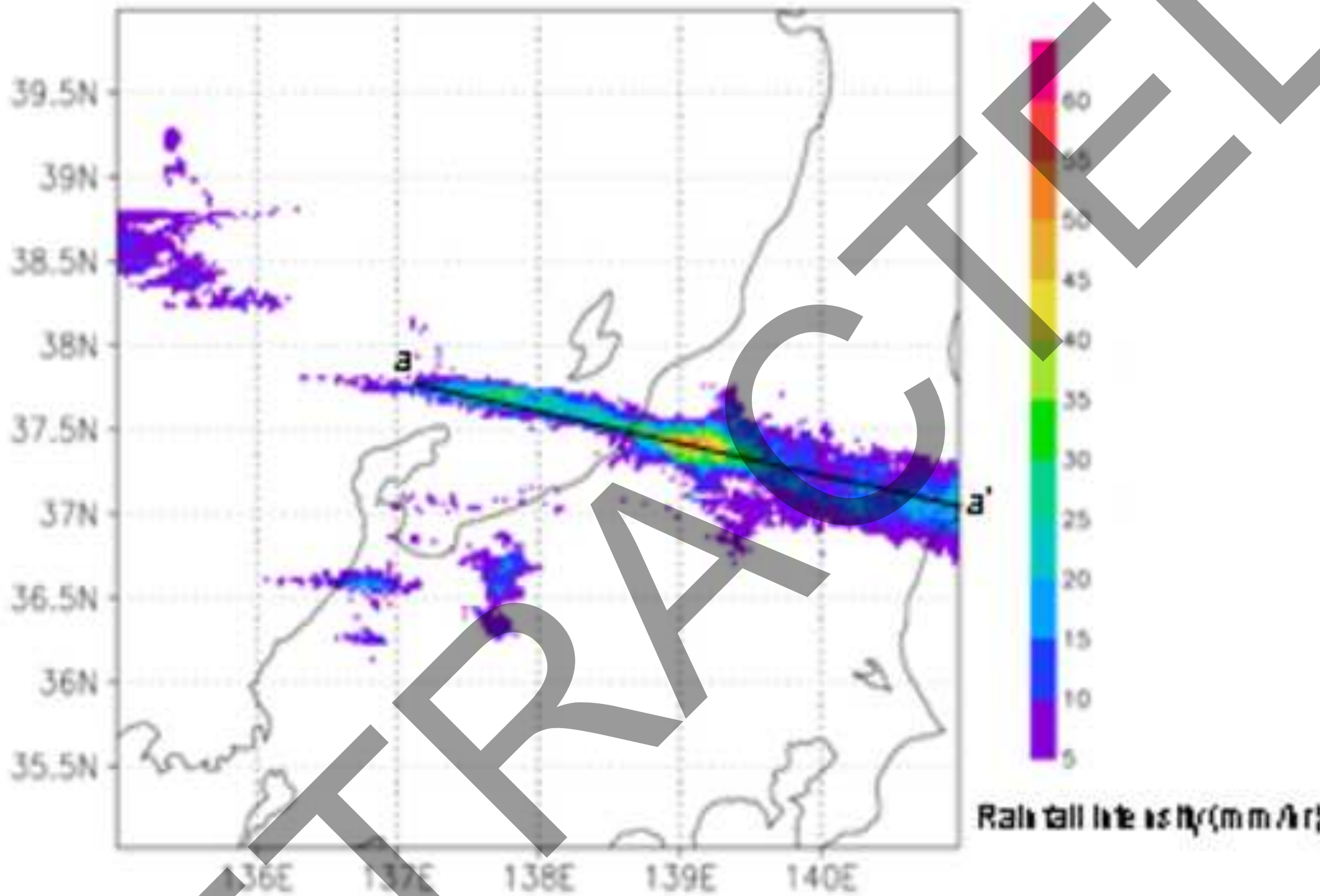


Fig. 13 Radar image of locally heavy rain caused by line-shaped convection system (Aug. 28, 2008)

Figure14



RETRACTED

Fig. 14 Radar image of the Niigata-Fukushima heavy rainfall in 2004 observed by Japan Meteorological Agency radar composites (10AM July 13, 2004)

Figure15

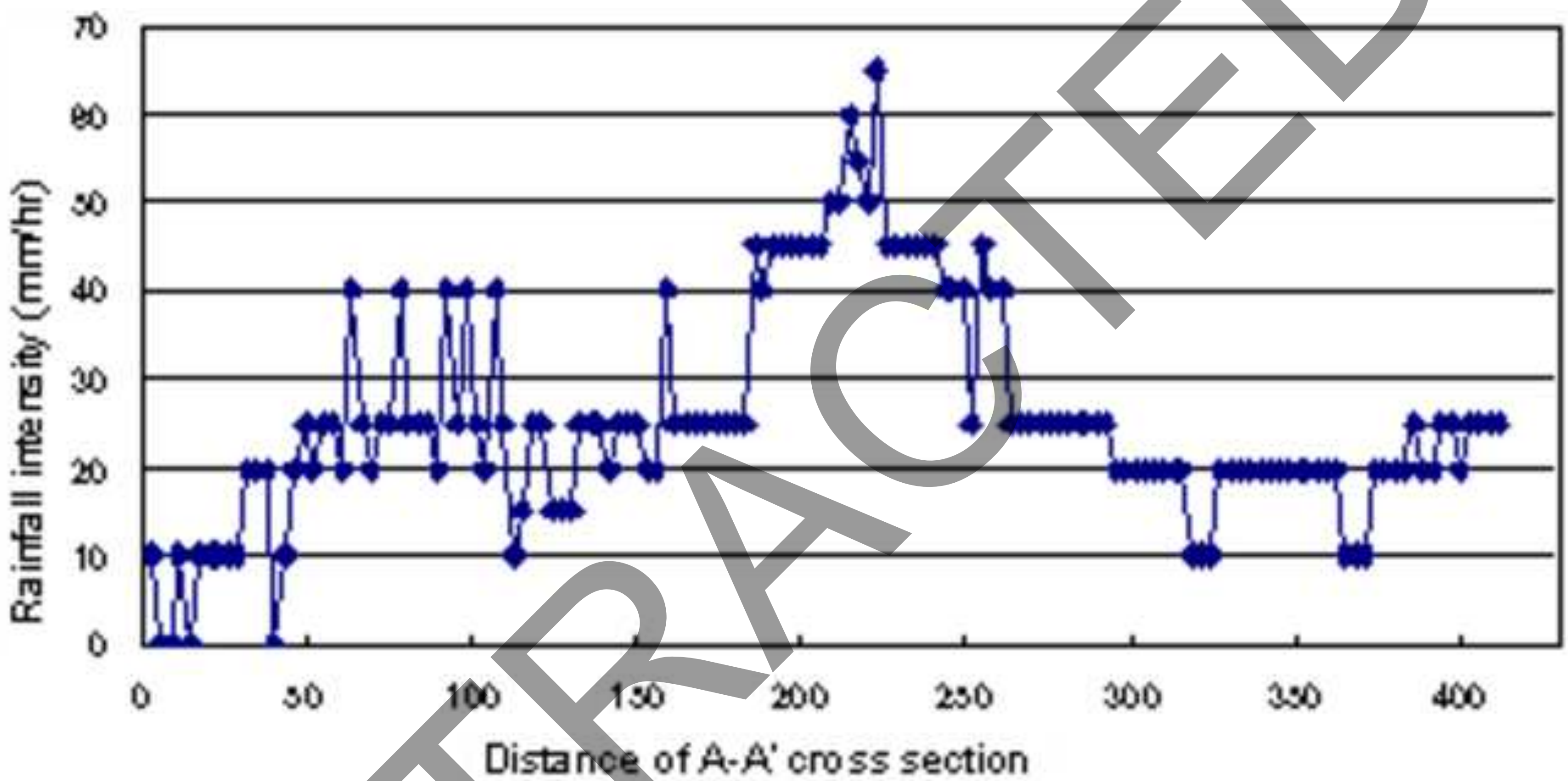


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Fig. 15 Relationship between rainfall intensity and horizontal distance of A-A' cross section of fig-14

Figure16

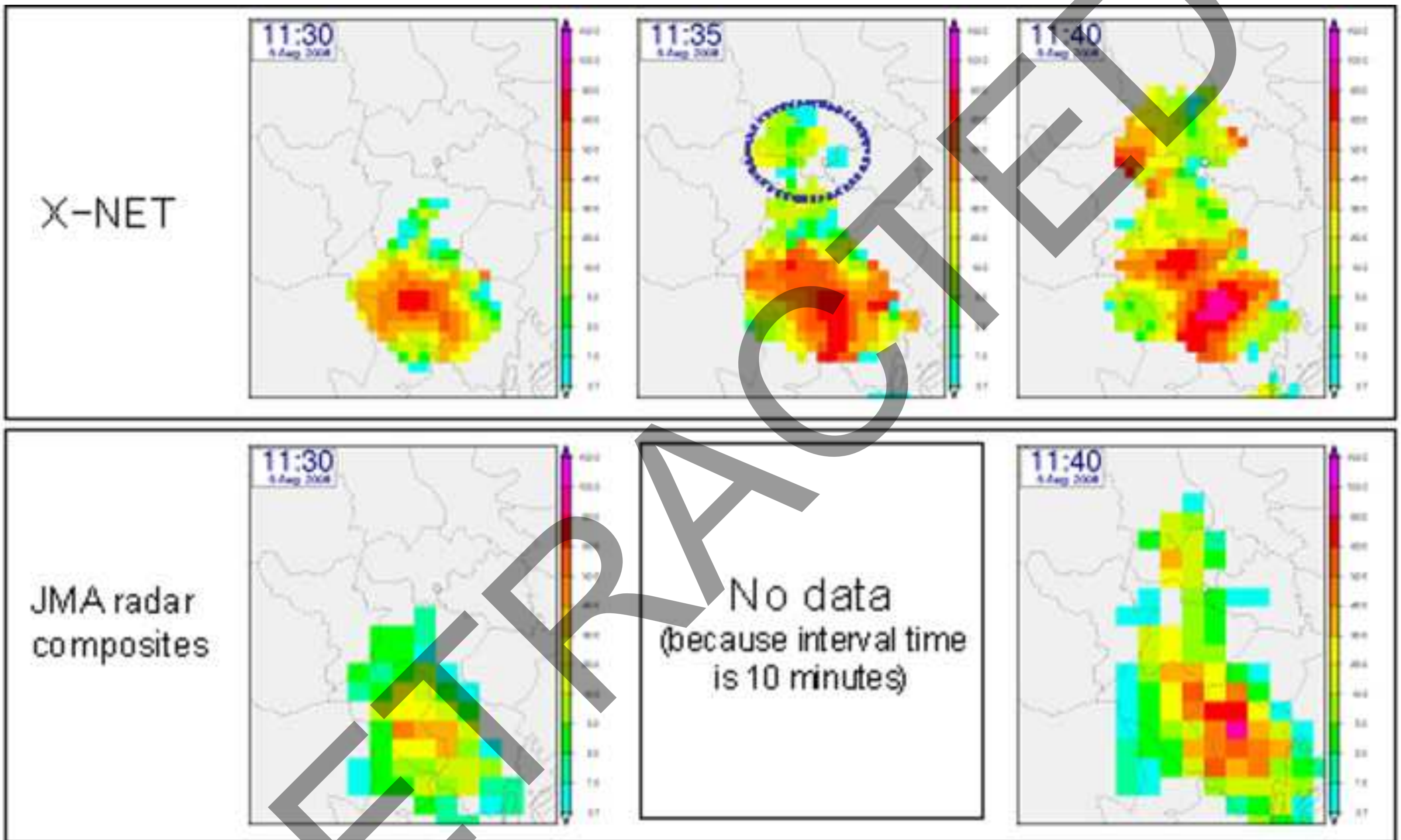

Fig. 16 The radar image of locally heavy rain observed by X-NET and JMA radar composites (Reference: National Research Institute for Earth Science and Disaster Prevention)