Special edition paper

Research on the Use of Weather Radar in Train Operation Control


Wataru Kato* Yoshihiro Hono*

On December 25 2005, a derailment occurred near the Daini-Mogamigawa bridge between Sagoshi and Kita-Amarume stations on the Uetsu line. Experts pointed out in the investigation that a wind gust such as a tornado or downburst was a possible cause (Kobayashi et al, 2006)[1]. Based on those investigation results, we developed a gust prediction method using weather forecast charts and radar data of the Japan Meteorological Agency (JMA). At the same time, we started small Doppler radar and high-density ground-level weather observation with an aim of developing a gust prediction system using Doppler radar that could be able to detect gusts.

● Keywords: Tornado, Downburst, Doppler radar, Weather chart, Cold front

1 Introduction

On December 25 2005, a derailment occurred near the Daini-Mogamigawa bridge between Sagoshi and Kita-Amarume stations on the Uetsu line. The investigation report by Kobayashi et al (2006)[1] pointed out a wind gust such as a tornado or downburst as a possible cause of the derailment. Experts also considered that a tornado caused an accident on the Tozai line of Tokyo Metro (former Teito Rapid Transit Authority) in February 1978 and a derailment on the Nippo main line in September 2006.

Gust such as downbursts and tornadoes accompanying cumulonimbus clouds often occur across Japan, and some cause serious disasters. It is difficult, however, to detect those with anemometers that observe wind at discrete points because gusts are quite small-scale phenomena, both specially and temporally. Furthermore, even if we could detect a gust with an anemometer along the track, it would be too late to stop the train upon a gust warning.

Weather radars, which can make planar and continuous observation, are considered most appropriate for detecting such gusts. We thus started research on the following two themes using weather radar to detect gusts.

(1) Development of a gust prediction method using external high-level weather information such as weather charts and radar data

(2) Feasibility study of using small Doppler radars in train operation control

2 Improving Accuracy of Gust Prediction Methods

The overview of the gust prediction method is as follows.

(1) Determine from forecast charts whether or not a cold front that might form cumulonimbus clouds will pass the point to be checked.

(2) When there is a chance of a cold front passing, monitor using weather radar cumulonimbus clouds that are regarded as a cause of gusts.

(3) When the strength, area and height of the monitored cumulonimbus clouds exceeds the preset threshold.

(4) Determine that there is a potential for gusts.

Details are covered in the following sections.

2.1 What is a Weather Radar?

A weather radar is a device for weather observation. It emits electromagnetic waves from its antenna toward precipitation particles in the air and measures the distance to the target particles based on the time to receive the reflected waves, estimating the density of the particles based on the strength of the reflected waves. In this way, a weather radar estimates the amount of precipitation in the target area (Fig. 1).

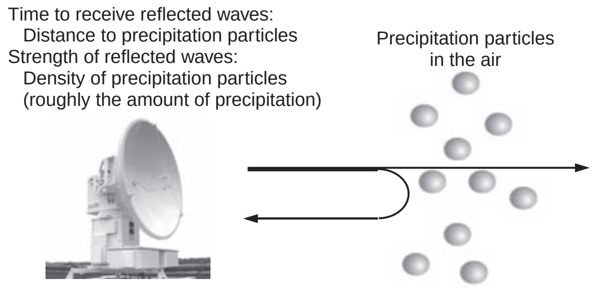


Fig. 1 Principles of a Weather Radar (Measurement of Distance and Precipitation)

2.2 Weather Conditions Where Gusts and Strong Winds Have Occurred

By checking the past weather conditions where gusts including tornados have actually occurred, we found that gusts in Japan often occurred in cold fronts and typhoons, with many in the areas along the coast. We further found by checking weather conditions at accidents that many of the past accidents by gusts or strong winds occurred in cold fronts in winter (November to March), with many of those in the areas along the Sea of Japan.

* Disaster Prevention Research Laboratory, Research and Development Center of JR East Group

Table 1. Gust Cases in Along the Sea of Japan and in Hokkaido in Winters from 2001 to 2006 (Source: JMA, 2008)[2)]

Date	Place	Phenomenon	Weather condition	Echo precipitation intensity level[1]	Echo cloud top height level[1]	Number of grids with 14 or stronger echo precipitation intensity[2]	Direction of cumulonimbus cloud movement	Speed of cumulonimbus cloud movement[3]
2002/10/15	Ota, Fukui	Downburst	Cold front	14	6	15	East-southeast	14
2002/11/4	Kaga, Ishikawa	Tornado	Cold advection	6	4	–	–	–
2003/12/18	Uchinada, Ishikawa	Other or unknown	Cold front	9	3	–	East-southeast	10
2004/2/5	Kashiwazaki, Niigata	Other or unknown	Other	8	4	–	–	–
2005/11/8	Ogata, Akita	Tornado or downburst	Cold front	14	4	10	Northeast	15
2005/12/25	Sakata, Yamagata	Other or unknown	Cold front	14	4	12	Northeast	17
2005/12/26	Minehama, Akita	Other or unknown	Low-pressure	14	5	24	–	–
2006/11/7	Saroma, Hokkaido	Tornado	Cold front	14	5	18	North-northeast	12
2006/11/9	Okushiri, Hokkaido	Tornado	Cold front	13	6	–	Northeast	10

*Shaded data is cases caused by a cold front.

1. Level of the radar echo data

2. Number of 1 × 1 km grid squares with 14 or stronger echo precipitation intensity observed within 20 minutes before the occurrence of the gust

3. Distance moved within 10 minutes before the occurrence of the gust (km/10 min.)

Table 2 Echo Precipitation Intensity and Echo Cloud Top Height Levels of JMA Radar Echo Data

Level	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Precipitation intensity (mm/hour)	Z<1	1≦Z<2	2≦Z<4	4≦Z<8	8≦Z<12	12≦Z<16	16≦Z<24	24≦Z<32	32≦Z<40	40≦Z<48	48≦Z<56	56≦Z<64	64≦Z<80	80≦Z

Level	1	2	3	4	5	6	7	8
Cloud top height (km)	H<2	2≦H<4	4≦H<6	6≦H<8	8≦H<10	10≦H<12	12≦H<14	14≦H

In the light of these findings, we decided to study gusts in the areas along the Sea of Japan. Specifically, we made case analyses of the sections between Niitsu and Sakata on the Uetsu line and between Niigata and Shibata on the Hakushin line.

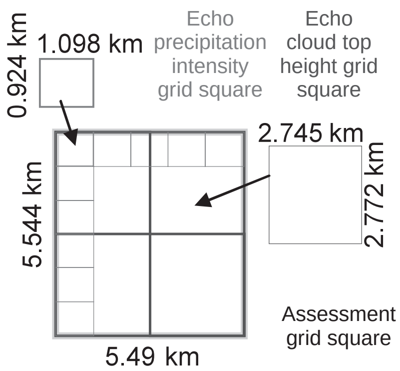
Table 1 shows the data of a total of nine cases. It includes seven cases of gusts in the areas along the Sea of Japan in the Hokuriku and Tohoku regions and the areas along the Sea of Okhotsk in Hokkaido in five winter seasons from November 2001 through March 2006. It also covers two cases in Hokkaido that caused serious damage after those seasons. As shown in Table 1, the cause of the gusts was cold fronts leading out of low-pressure zones in six cases. Other causes were involved in three cases. Severe damage tended to accompany the aforementioned six cases.

2.3 Primary Refinement of Gust Prediction Using Forecast Charts

In the areas along the Sea of Japan where JR East operates, a cold front passed an average of 25.4 days during the surveyed five winter seasons (151 days from Nov. 1 to Mar. 31 per season). We could thus narrow down the gust prediction to 25.4 of 151 days = approx. 17% in narrowing based on passing of cold fronts.

2.4 Secondary Refinement of Gust Prediction Using the Weather Radar Observation Data

For the secondary refinement of gust prediction, we decided to detect using the radar observation data powerful cumulonimbus clouds that are considered to be a cause of gusts. As explained in section 2.1, a weather radar is part of a system to observe the strength and height



	Latitude × Longitude	Actual distance
Precipitation intensity grid square	30 sec. × 45 sec.	0.924 km × 1.098 km
Cloud top height grid square	90 sec. × 112.5 sec.	2.772 km × 2.745 km
Alert grid square	180 sec. × 225 sec.	5.544 km × 5.49 km

Fig. 2 Grids Used in Radar Data Assessment

of cumulonimbus clouds by measuring the location and density cloud particles. The observation results are indicated as the strength indicator of cumulonimbus clouds (echo precipitation intensity) and in the height indicator (echo cloud top level), as shown in Table 2. The larger the number is, the more powerful the cumulonimbus cloud would be. The data is provided in approx. 1.1 × 1.1 km grid squares for the echo precipitation intensity and in approx. 2.7 × 2.7 km grid squares for the echo cloud top height. By combining that data, we are able to use the radar data of an approx. 5.5 × 5.5 km grid square—the least common multiple of the grid square sizes—to determine the threshold (Fig. 2).

To determine the specific threshold, we surveyed from past gust cases the echo precipitation intensity and the echo cloud top height. We also focused on the horizontal size of cumulonimbus clouds to see the area echo precipitation intensity is applied to. In this way, we further refined the gust prediction.

First, we studied what values of echo precipitation intensity and the echo cloud top height would be appropriate as the threshold. Table 1 shows that radar observed 9 to 14 for the echo precipitation intensity and 3 to 6 in the echo cloud top height level in the six gust cases associated with cold fronts. Of those cases, levels in both scales tended to be higher in cases where injury or more serious human suffering occurred. Perfect prediction of gusts is difficult with current technologies; still, we set as the threshold 14 for echo precipitation intensity and 4 for echo cloud top height levels to at least be able to detect cases that would involve human suffering.

Next, we surveyed the extent of the areas of 14 or stronger echo precipitation intensity in the past gust cases. The survey clarified that the area of 14 or stronger precipitation accompanying a cold front spread over a cluster of more than ten 1 km grids in the four cases.

Based on those findings, we suggested a gust prediction threshold where gusts will likely occur if the following two conditions are met when a cold front passes the areas along the Sea of Japan in winter.

(1) The area of 80 mm/hour or stronger echo precipitation intensity—indicator of the strength of cumulonimbus clouds—spreads over a cluster of more than 10 km^2, and

(2) The echo cloud top height—indicator of the height of cumulonimbus clouds—is higher than 6,000 m.

2.5 Setting an Alert Area

To optimize setting of the area to be under operation control when gusts are predicted, we examined how to set such an area.

From the radar echo data of the six cases of gusts accompanying cold fronts in the nine cases shown in Table 1, we surveyed the movement direction and speed of the cumulonimbus clouds that caused gusts every 10 minutes starting from 60 minutes before to the time of the gust occurrence. The purpose was to verify the alert area size required to detect cumulonimbus clouds before a gust reaches the railway track.

In the survey, we found that the movement direction was roughly north-northeast to southeast (Fig. 3).

As for the movement speed, cumulonimbus clouds moved up to 17 km in 10 minutes. We thus concluded that the radius of the alert area required to detect cumulonimbus clouds with an approx. 10 minute lead time to the gust occurrence is 34 km or larger (see Fig. 4).

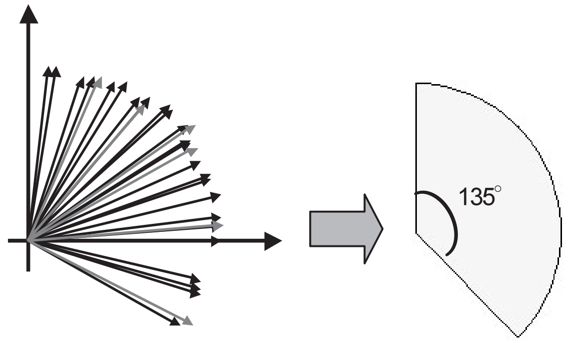


Fig. 3 Alert Direction Based on Movement Direction of Cumulonimbus Clouds

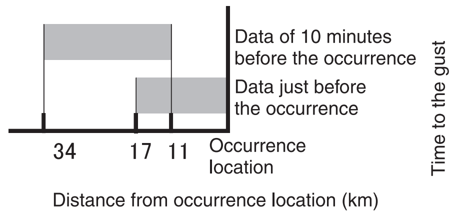


Fig. 4 Location of Cumulonimbus Clouds at Monitored Times Before Gust Occurrence

In light of those findings, we decided to set a fan-shaped alert area of approx. 38 km radius. That is equal to seven grid squares in the direction from north to southeast out of the grid squares where the echo data exceeds the threshold (Fig. 5).

By applying this method to the data of three winter seasons from 2004 to 2006 for verification, we found that the total time exceeded the threshold was approx. 150 minutes (2 hours 30 minutes) in a winter season.

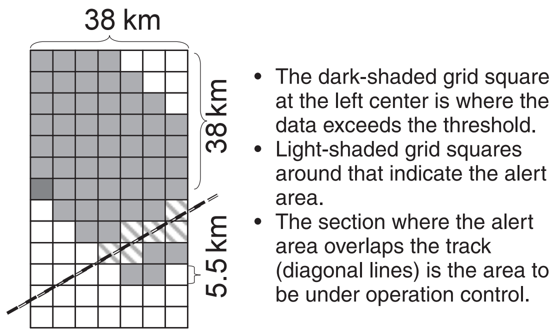


Fig. 5 Image of Radar Echo Data and the Alert Area Indication

2.6 Testing of Operation Control Rules

We tested operation control rules using the method in the sections between Niitsu and Sakata on the Uetsu line and between Niigata and Shibata on the Hakushin line from the end of January to the end of March 2007. But operation control was not actually ordered as no radar data exceeded the threshold in the check period.

3 Feasibility Study of the Use of Small Doppler Radars in Train Operation Control

As explained in Chapter 1, it is difficult to detect gust including tornados at point using anemometers because the horizontal scale of gusts is small. At present, it is said that gusts can only be detected by Doppler weather that can make planar observation.

A Doppler weather radar has a function of detecting the movement speed of the target based on the change of the frequency of the reflected electric waves. That is in addition to the standard weather radar function observing precipitation particles in the atmosphere such as rain and snow, as described in the section 2.1 (Fig. 6). It can thus acquire information about wind as well as precipitation. More specifically, it can observe the three-dimensional distribution of wind speed, which an anemometer set at a single point cannot.

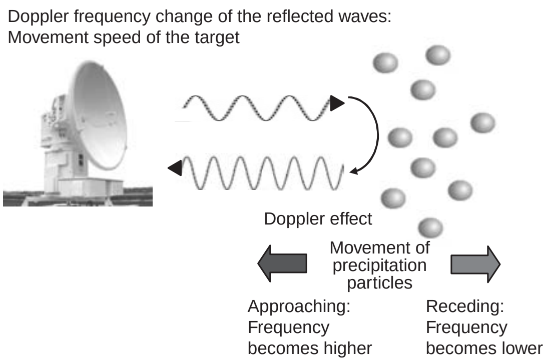


Fig. 6 Principals of a Weather Doppler Radar (Observation of Wind Speed)

Most conventional Doppler weather radars have been large-sized. They are used, for example, to monitor wind in wide areas around major airports to protect aircraft taking off and landing against phenomena such as downbursts and to measure wind direction and wind speed in the sky as data used in numerical analysis for weather forecasting. Larger radars can make efficient observation in a wider area, but they can observe only phenomena high in the sky at distances far away as electromagnetic waves of those proceed in a straight line over the curved earth. Larger radars are thus not appropriate to observe ground wind distribution that is important for railways.

Recently smaller-type Doppler radars for observation in a limited area have been developed. The possibility has thus emerged for using those for observation mainly near the ground along the track. We thus set a small Doppler weather radar on the roof of Amarume station on the Uetsu line, and started observation using that on March 1 2007. The purpose of that was to verify performance in detecting gusts such as tornados and downbursts based on on-site observation and case analysis and to evaluate the feasibility of using Doppler radar in train operation control.

3.1 Observation Using a Small Weather Doppler Radar

We set up the radar on the roof of Amarume station, approx. 2 km south of the Daini-Mogamigawa bridge on the Uetsu line where a derailment occurred (Fig. 7. Hereafter referred as the JR radar). The observation radius of the radar is approx. 30 km, meaning it can cover almost all of the Shonai plain except geographically shaded points (Fig. 8).

Fig.7 Weather Doppler Radar at Amarume Station (Balloon showing the antenna housed inside the dome)

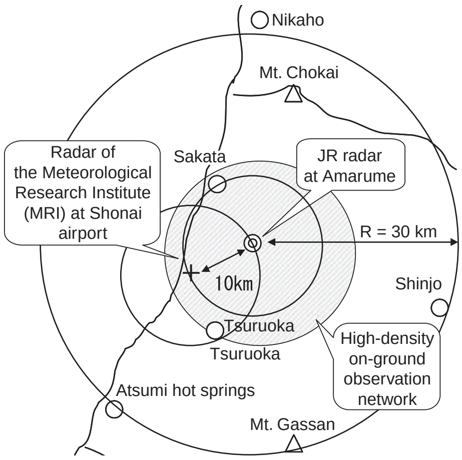


Fig. 8 Locations of Radars and Observation Areas

Fig. 9 shows an example of the observation results of southwest wind immediately before the passing of a cold front near the JR radar. The center of the image is the location of the radar. In the bottom left, southwest, direction is negative Doppler velocity approaching the radar; in the top right, northeast, direction is positive Doppler velocity receding from the radar. That means wind blew mainly from southwest to northeast at that time.

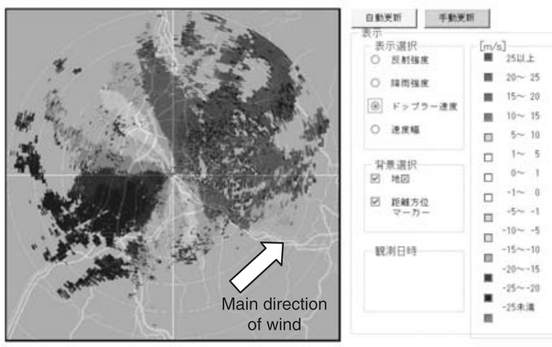


Fig. 9 Example of Observation Images of the JR Radar

3.2 Startup of the Weather Observation Project in the Shonai district

In July 2007, we started basic research for a gust detection system using small Doppler radars for safe railway operation (Fig. 10).

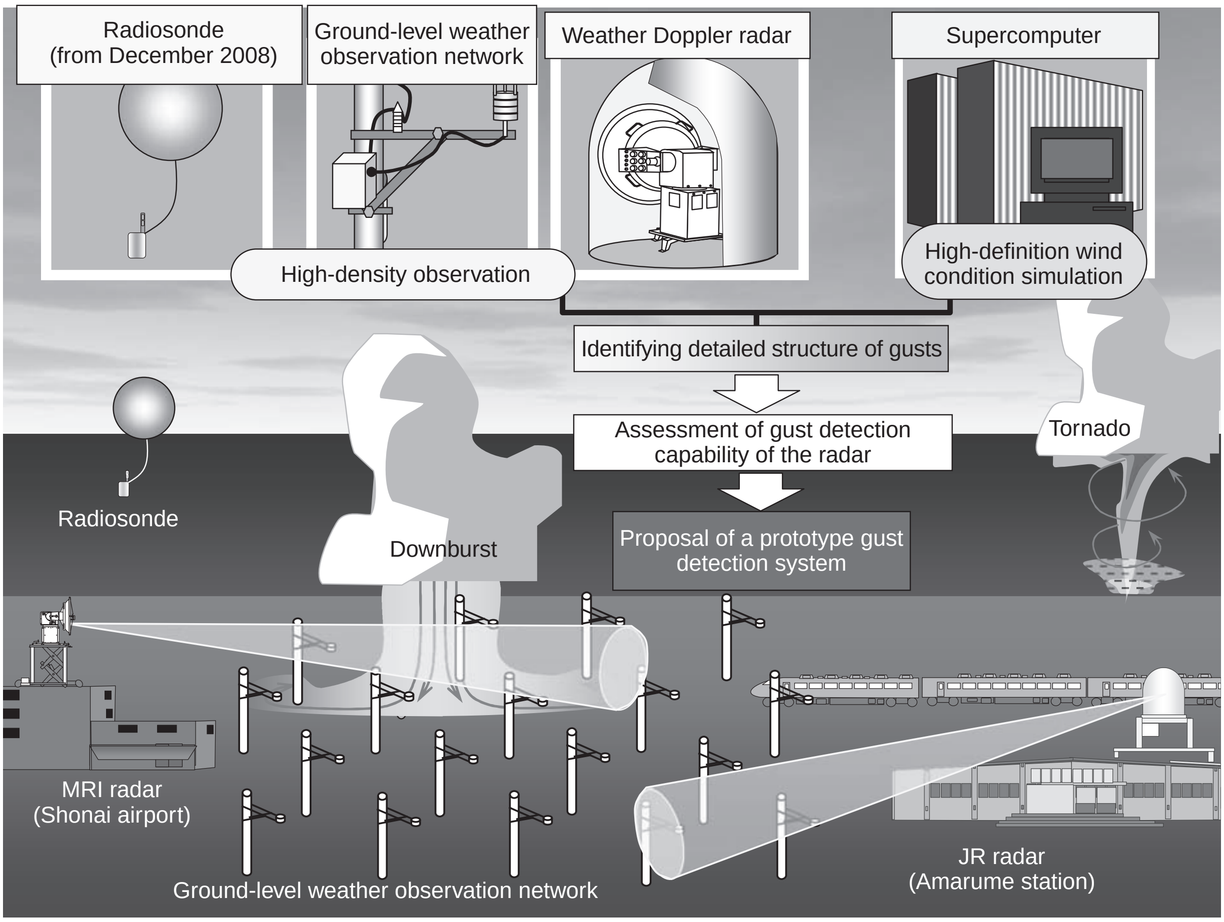


Fig. 10 Overview of the Basic Research for a Gust Detection System Using Small Doppler Radars for Safe Railway Operation

For that, we formed a research project team with the MRI of the JMA, the Railway Technical Research Institute (RTRI) and the Disaster Protection Research Institute of Kyoto University (DPRI), receiving support from the Japan Railway Construction, Transport and Technology Agency (JRTT).

In that project, we are able to identify meteorological phenomena in more detail both in the sky and at ground level. Observation of the sky is done with the JR radar, while ground-level observation is also made using 26 ground-level weather observers placed at a high density of approx. 4 km intervals (Fig. 11). In the period from the end of December 2007 to the middle of March 2008, the MRI set up a small Doppler radar at Shonai airport (Fig. 12. Hereafter referred to as the MRI radar) to identify the distribution of wind conditions in the sky in more detail by observing in conjunction with the JR radar.

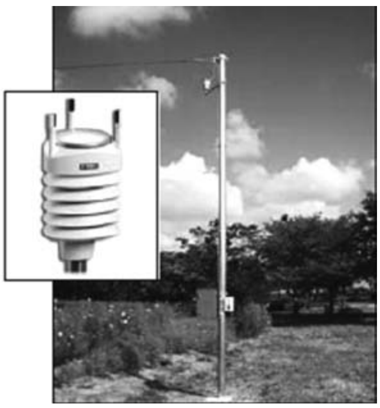


Fig. 11 High-Density Ground-Level Weather Observer (Able to Measure Direction and Speed of Wind, Temperature, Air Pressure, Precipitation and Humidity)

Fig. 12 MRI Radar Temporally Set Up at Shonai airport

3.3 Gust Observation Case and Results of Analysis by the Project

We were able to observe using the JR radar a case of gusts that occurred in Sakata on December 2, 2007. The following introduces the analysis results of that case.[3] We cannot see the image of the structure of the gust directly in the observation image (Fig. 13). However, the analysis results of the observation data of the Doppler

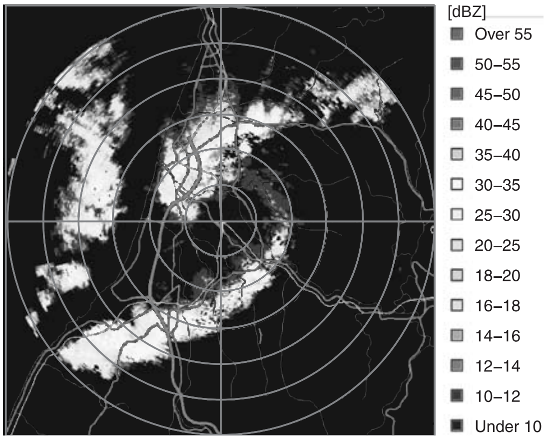


Fig. 13 Observation Image of the Gust Case in Sakata on December 2, 2007 (Reflection Strength)

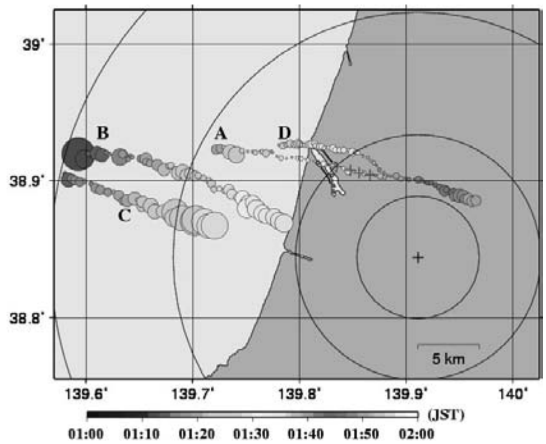


Fig. 14 Four Whirls Detected in the Analysis and Their Loci (+ Marks in the Figure are On-Ground Places Where Damage Occurred)

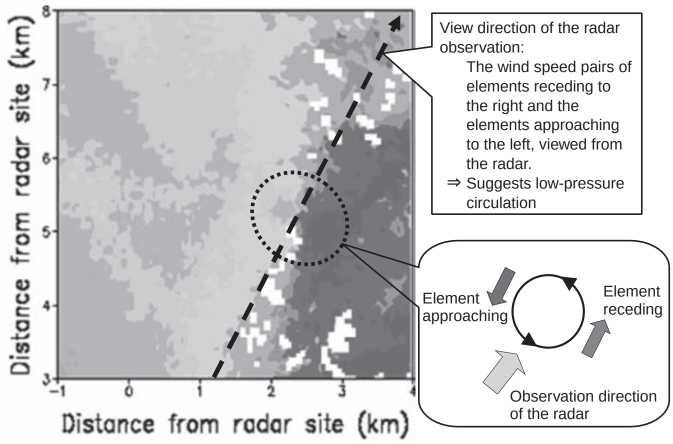


Fig. 15 Doppler Velocity Analysis Results for Whirl A

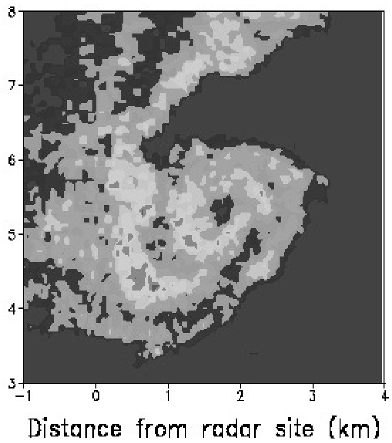


Fig. 16 Analysis Results of the Reflection Strength of Whirl A

velocity in the sky revealed four whirls, as shown in Fig. 14.

The locus of Whirl A was found to match relatively well with the on-ground damage area. In the more detailed analysis of Whirl A, we found that there were wind speed elements receding on the right side of the radar, and wind speed elements approaching on the left side. That suggests an anticlockwise cloud whirl such as is seen with low-pressure is present in the sky (Fig. 15). The reflection strength data supported that Whirl A had a spiral structure like the eye of a typhoon (Fig. 16).

We are planning to identify a more detailed 3-D structure of gusts using that observation data and simulation by a supercomputer to find out information necessary to develop a gust detection system.

4 Conclusion

We will further proceed with verification of the prediction accuracy of the gust prediction method through trials.

In the observation project using Doppler radar, we will analyze the winter observation data to March 2008 and conduct high-definition wind simulation that takes into account detailed geographic data. And at the same time, we will make observations again this winter. In the 2008 winter season, we started radiosonde observation on December 5 to acquire weather data at high elevations using a balloon with a weather observer. That is in addition to the observation system introduced in section 3.1.

We will make efforts to three-dimensionally identify the mechanism behind the occurrence of gusts, and we will continue research with a goal of proposing a gust prediction method using Doppler radar.

Acknowledgement

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Reference:

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