Special edition paper

Research on a Gust Detection System Using Doppler Radar


Chusei Fujiwara* Hiroto Suzuki*

JR East set up a Doppler weather radar on the roof of Amarume Station in March 2007 with the aim of developing a gust detection and prediction method and assessing applicability of that to train operation decisions. Utilizing observation data of the radar, we are developing an automatic gust detection system. In this project, we studied the validity of characteristics of vortices assumed in the algorithm of that gust detection system based on observation data of the weather observation network across the Shonai Plain. The assessment results proved that the ground-level wind velocity predicted and the vortex model assumed by the gust detection system are valid.

●Keywords: Doppler radar, Gust, Tornado, Gust detection, Weather observation

1 Introduction

Gusts sometimes bring about railway accidents and transport disruption with their destructive force. There is thus great need for gust warning information, and establishing a gust warning method is an important issue in terms of railway accident prevention.

On December 25 2005, a derailment occurred near the Daini-Mogamigawa Bridge between Kita-Amarume and Sagoshi stations on the Uetsu Line. Regarding the cause of the accident, the investigation results report of the Aircraft and Railway Accidents Investigation Commission (current Japan Transport Safety Board) pointed out that the accident occurred because the train received localized gusts exceeding the critical wind velocity of overturning while it was running[1]. In order to prevent such gust accidents in the field of railways, development of a method whereby gusts can be detected and train operation suspended before passing that section of track is needed.

However, gusts such as tornados and downbursts (strong downdrafts from cumulonimbus clouds) form in a small space in a short span of time, making it difficult to detect those with existing anemometers placed at discrete points. Even if we could detect a gust with anemometers along the track, it would be too late to issue a gust warning and stop the train. Thus, for effective prevention of railway accidents by gusts, Doppler radars that can observe wind movement in a wide area continuously at a short interval are considered most appropriate.[2]

We set up a Doppler weather radar on the roof of Amarume Station and started observation on March 1, 2007 with an aim of developing a gust detection and prediction method and assessing applicability of that to train operation decision (Fig. 1).

This report covers an overview of gust observation at the Shonai Plain in Yamagata Prefecture, a gust detection algorithm using Doppler radars, and the results of a study on the validity of characteristics of vortices assumed in that algorithm.

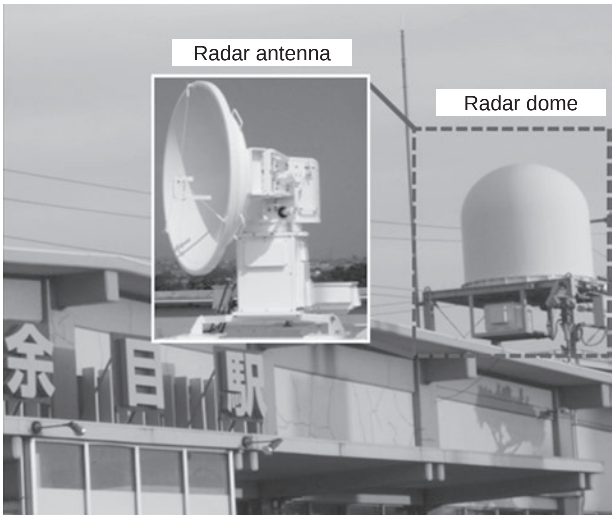

Fig. 1 Doppler Radar Set up on the Roof of Amarume Station on the Uetsu Line

2 Overview of Gust Observation at the Shonai Plain

2.1 Gust Observation at the Shonai Plain

In order to develop a system of detecting, predicting, and tracking gusts, it is important to identify actual gusts we have known little about. Observation of gusts such as tornados and downbursts and the weather phenomena that cause them has the following problems as those occur in a small scale in a short span of time.

(1) Gust observation by usual weather observation is difficult.
(2) Information is not necessarily accumulated in an organized manner because the small number of cases resulting in damage have to be studied in individually isolated gust damage surveys and the like.

From July 2007 to March 2010, we carried out basic research on a gust detection system using small Doppler radars for safe railway operation. That research using the weather observation network deployed at the Shonai Plain shown if Fig. 2 was conducted with the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA), the Railway Technical Research Institute (RTRI) and the Disaster Prevention Research Institute of Kyoto University (DPRI), receiving support from the

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

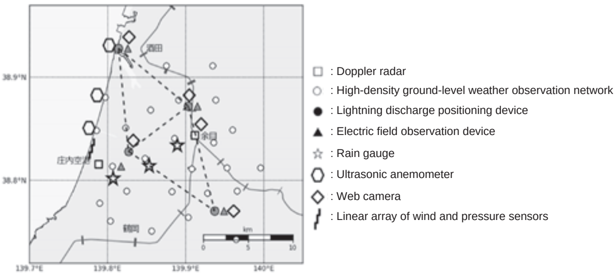

Fig. 2 Weather Observation Network at the Shonai Plain

Japan Railway Construction, Transport and Technology Agency (JRTT).[2] Furthermore, we started a joint research project with MRI on the gust detection system using Doppler radars in April 2009.

The observation area of the Doppler radar installed on the roof of Amarume Station on the Uetsu Line (hereinafter, "JR radar") is a 30 km radius around Amarume Station, covering the whole Shonai Plain (Fig. 2). The JR radar is fixed at an angle of elevation of 3.0º, the smallest angle of elevation at which surrounding buildings do not block radar beams, and it carries out observation at the frequency of one rotation every approx. 30 seconds. This means that the JR radar has higher time and space resolution than that of usual weather radars, allowing detection of gust phenomena that are small in size and short in time.

As the JR radar can observe at a limited height even though it has high time resolution, we set up a Doppler radar of MRI at Shonai Airport in winter to continue observation of the characteristics and three-dimensional structure of vortices.

In addition to the JR radar, we set up 26 weather observation devices in a dense and geometric arrangement so as to measure wind direction and velocity, temperature, humidity, and air pressure, thus forming a high-density ground-level weather observation network at the Shonai Plain. We used this to look at the relation of those measurements to gust phenomena at ground level.

We also set up 12 anemometers at 100 m intervals and 25 barometers at 50 m intervals to form a new linear array of wind and pressure sensors that allows observation at high time resolution (100 ms). With this system set up linearly along the cost northwest of Shonai Airport over a total length of 1.2 km, we are investigating the detailed structure of gusts at ground level (see 4.2.1 below).

2.2 Knowledge on Gusts at the Shonai Plain Gained through Past Observation

As a result of joint research with MRI, the following regarding to gusts on the Shonai Plain was clarified.[2]

(1) Many vortices occur in winter at the Shonai Plain, and many of them move in the direction of seasonal winds (from the Japan Sea inland).

(2) At the Shonai Plain in winter, multiple vortices are often observed at the same time.

(3) Gusts accompany rainfall (snowfall), making them observable by radars.

(4) Most remarkable gusts at ground level accompany atmospheric vortices of which horizontal size is small at less than a few kilometers.

Taking into account those research results, we have started development of a gust detection system based on technology for detecting, predicting, and tracking atmospheric vortices by Doppler radars.

3 Principles and Problems of the Gust Detection System

We made a prototype gust detection system using data of the JR radar, which can indicate the location and intensity of vortices that might bring about gusts.[2]

The composition of the prototype gust detection system is as follows.

(1) Automatically detect the pattern of the vortex (pair of winds approaching and receding) from observation values of the Doppler radar and calculate the tangential velocity of that vortex.

(2) Track the detected vortex. Calculate the velocity and direction of the moving vortex from that locational information to figure out the center position of the forecast vortex route after a few minutes.

(3) Calculate the wind velocity of the vortex by combining the tangential velocity and movement velocity of that vortex.

(4) If the center position of the forecast route of an atmospheric vortex involving gusts with wind velocity greater than the standard comes near or passes the track, issue a warning for that section (Fig. 3).

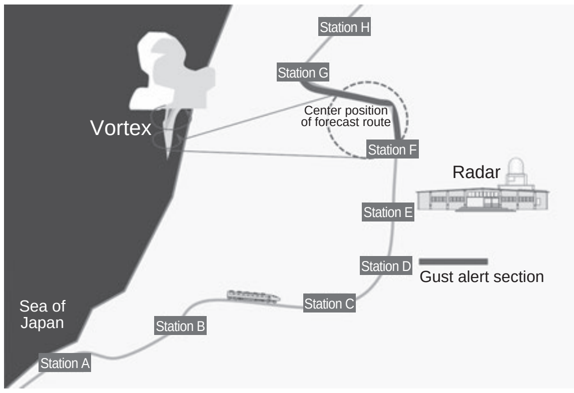

Fig. 3 Overview of Gust Detection System

In the core of the gust detection system, the part for detecting vortices improved on and developed based on the mesocyclone detection algorithm[3] developed by the MRI.

The algorithm of the prototype gust detection system includes the following assumptions due to limitations of radar observation and the fact that characteristics of vortices that occur at the Shonai Plain are not-yet clarified.

(1) The JR radar performs observations at an angle of elevation of 3º to prevent beams from being blocked by surrounding buildings. The observation altitude is therefore 0.5 km at 10 km from the radar, meaning atmospheric vortices are observed. In the gust detection system, we assume that the

wind velocity at ground level and of the atmospheric vortex agree with each other.

(2) It is assumed that vortices are of the structure of the Rankine combined vortex (virtual vortex model that has distribution where the tangent component of the velocity accompanying the vortex is in proportion to the distance from the vortex center inside the vortex and in inverse proportion to that distance outside the vortex).

(3) It is assumed that vortices bringing about ground-level gusts have no vertical inclination.

In order to verify the validity of those characteristics of vortices assumed in the gust detection system and study the applicability of the system to judgment on train operation based on knowledge gained, we carried out analysis using a database of long-term observations obtained by the weather observation network deployed at the Shonai Plain as explained in the next chapter.

4 Study of Validity of Assumptions on Characteristics of Vortices Used in the Gust Detection System

4.1 Relation between Wind Velocities of Atmospheric and Ground-level Vortices

The relationship between the atmospheric wind observed by a Doppler radar and the wind observed at ground level is an essential issue in putting a gust detection system in place because a Doppler radar cannot directly observe ground-level gusts. There is however few past observation research on the inside of vortices including at ground level, with only an exceptional attempt in the USA where measurement devices were temporally set up on the forecast route of a tornado.[4] In our research, we carried out statistic analysis of the relation between gusts that occur at ground level and atmospheric vortices observed by a Doppler radar. This was done using long-term observation data of vane anemometers of the high-density ground-level weather observation network devices.[5]

The data used, analysis method, and analyzed cases are introduced as follows.

(1) Data used: Wind data of ground-level weather observation points (one-second values of WXT520 and WS425 ultrasonic anemometers) and Doppler velocity data of the JR radar were used.

(2) Analysis method: After converting wind data of ground-level observation points to Doppler velocity acquired by the radar, we compared the converted data with the Doppler velocity in the atmosphere above those ground-level observation points observed by the JR radar.

(3) Analyzed cases: 18 remarkable vortex gusts extracted in winter from 2007 to 2012 were investigated.

Fig. 4 shows an example of comparison of Doppler velocity in the atmosphere and at ground level. While the ground-level absolute value was larger when a gust occurred, the Doppler velocity in the atmosphere and at ground level generally agreed well with each other.

Fig. 5 is a scatter diagram of the Doppler velocity in the atmosphere and at ground level related to the 18 remarkable vortex gust cases. We applied 32 data values of the JR radar when a vortex was passing in the atmosphere above the observation point out of data of before and after the case gust occurred. For example, in the case shown in Fig. 4, we applied three data values of the times marked with bold crosses.

The time when the radar beam scanned over the ground observation points is recognized as 1 sec. accuracy, and we used the data of that time (not necessarily the time of the gust) for comparison. As shown by the difference of +/-5 ms^{-1}, Doppler velocity in the atmosphere and at ground level agreed well with each other. The correlation coefficient is 0.88. Cases where the velocities greatly differed were those when the area near the vortex center where the air condition changes greatly passed over the observation point. We presume that the difference was caused by factors such as vertical inclination of the vortex.

In summary, the comparison of Doppler velocity in the atmosphere and at ground level using the data of 18 cases where gusts were observed at ground level statistically demonstrated good correlation. This result supports the validity of the method of estimating ground-level wind velocity by the gust detection system that relies on atmospheric vortices.

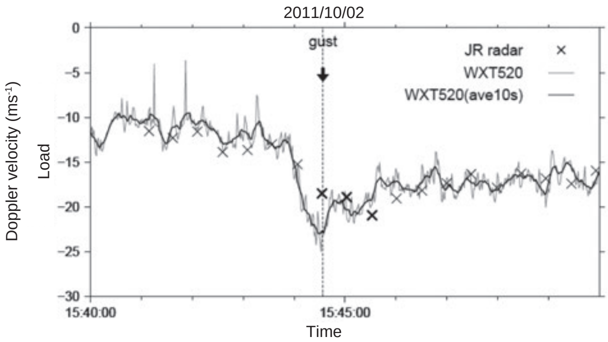

Fig. 4 Doppler Velocity Observed by JR Radar at and above Ground-level Observation Points (WXT520 ground-level anemometer height: 7.6 m, radar beam height: 375 m)

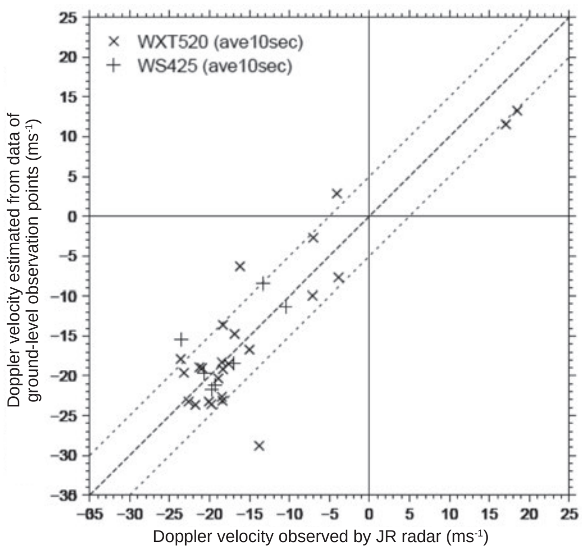

Fig. 5 Scatter Diagram of Ground-level Data and Atmospheric Doppler Velocity Data of 18 Gust Cases

4.2 Horizontal Structure of Vortices near Ground Level

4.2.1 Linear Array of Wind and Pressure Sensors

Comparison of the atmospheric vortices detected by the JR radar and weather data of the high-density ground-level weather network revealed characteristics of ground-level gusts of the Shonai Region such as that they are accompanied by atmospheric vortices. But, vortices observed by a Doppler radar are smaller than the intervals of the devices of that network, so it is difficult to estimate the horizontal structure, intensity, and spatial scale of ground-level vortices. This prevents clarification of ground-level gust phenomena accompanying those vortices.

We thus newly developed a linear array of wind and pressure sensors.[6] This is an ultrahigh-density observation system for wind velocity and air pressure with high time resolution sampling (100 ms) consisting of 12 anemometers at 100 m intervals and 25 barometers at 50 m intervals. The system was set up linearly on the cost northwest of Shonai Airport over a total length of 1.2 km (Fig. 6). By deploying this system at a right angle to the direction of movement of vortices reaching the Shonai Plain from the Sea od Japan, we can gain observation data (wind direction, wind velocity, air pressure) of a vortex at multiple points when a vortex passes over the system. That allows us to identify the detailed horizontal structure of a ground-level vortex such as its spatial scale and intensity. As the horizontal size of a vortex occurring at the Shonai Plain in winter is a few hundred meters to 2 km, data of a vortex passing the system can be obtained. Furthermore, winter observation by the Doppler radar installed at Shonai Airport by MRI on the three-dimensional structure of cumulonimbus clouds that bring about gusts may allow us to identify the detailed three-dimensional structure atmospheric vortices and accompanying ground-level gusts (Fig. 7).

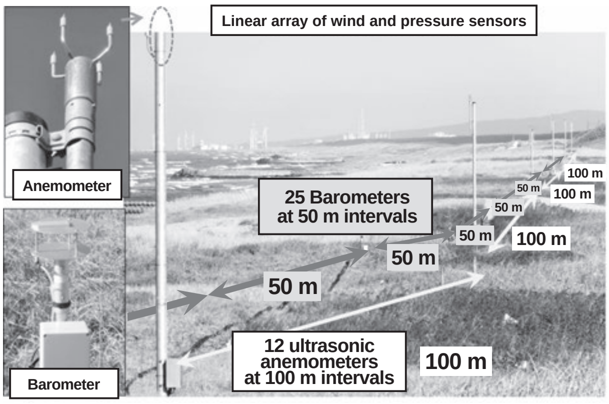

Fig. 6 Linear Array of Wind and Pressure Sensors on Coastal Area of Shonai Plain

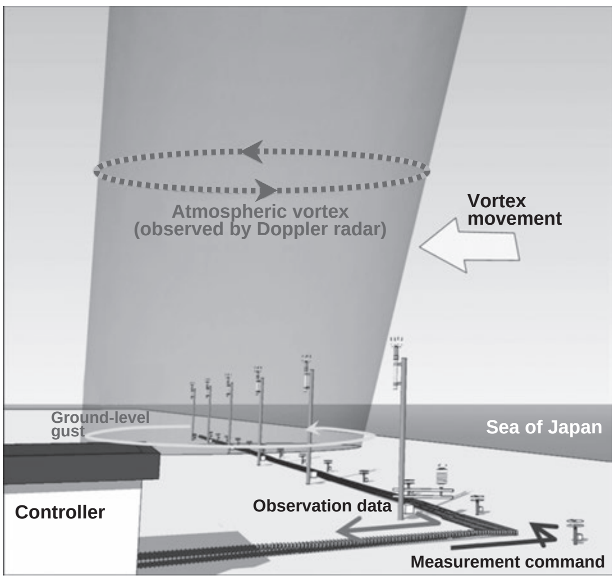

Fig. 7 Conceptual Image of Identifying Detailed Three-dimension Structure of Atmospheric Vortex and Ground-level Gust Using Linear Array of Wind and Pressure Sensors

4.2.2 Case of Detection of Tornado-type Airflow

We analyzed a case where the center of a vortex coming from the Sea of Japan to the Shonai Plain passed the southwest side of the linear array of wind and pressure sensors at 10:24 am on January 29, 2012.[7] From the temporal change of the tangential velocity of that vortex (Fig. 8 (a)) obtained from data of Anemometer E of the system (see Fig. 9 for placement of anemometers) and the movement velocity of that vortex tracked by two Doppler radars

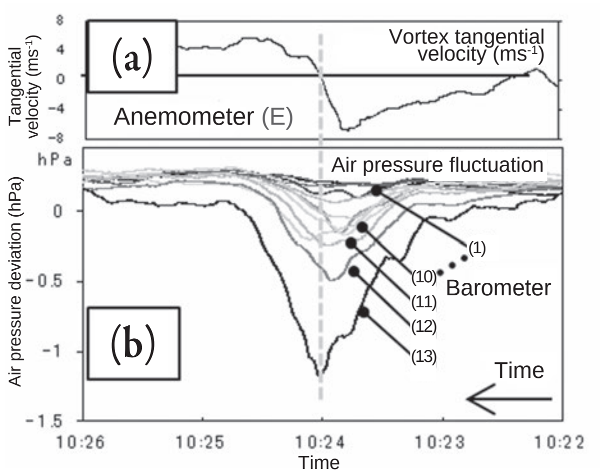

Fig. 8 (a) Distribution of Vortex Tangential Velocity Measured by Anemometer (E)
(b) Time History of Air Pressure Fluctuation Data Measured by Barometers
(Numbered from (1) to (13) from northeast, see Fig. 9)

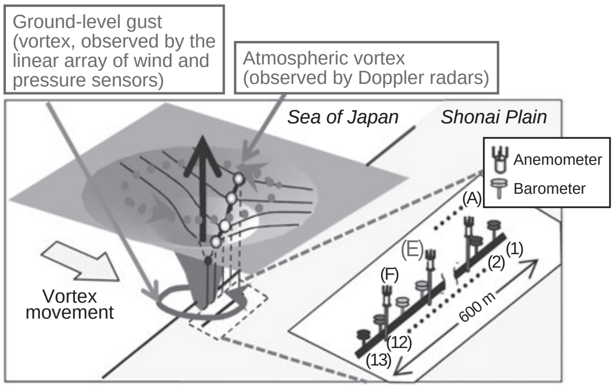

Fig. 9 Model Diagram of Tornado-type Airflow Based on Observation Data of Fig. 8

(moving 13 ms^{-1} east-southeast), we estimated the diameter of maximum tangential velocity of that vortex as approx. 500 m and the maximum tangential velocity as 5 ms^{-1}. The total 18 ms^{-1} of the maximum tangential velocity and the vortex movement velocity agreed with the 17.7 ms^{-1} measured by Anemometer E. The time history data of the barometers (Fig. 8 (b)) shows that barometers on the southwest side nearer to the vortex center measured a larger drop of air pressure. For those reasons, we presumed that the vortex of this case had a tornado-type airflow structure, and the linear array of wind and pressure sensors could detect its characteristics in detail (Fig. 9).

4.2.3 Verification of the Rankine Combined Vortex

When detecting a vortex with the gust detection system, the model that best fits measurements is selected assuming the Rankine combined vortex model. So, if the actual structure of the vortex largely differs from that model, the system cannot detect the vortex, likely overlooking the gust too. Detailed investigation of actual vortices is thus needed to check the appropriateness of assuming the Rankine combined vortex. In light of that, we examined whether the ground-level vortex fit the pattern of the Rankine combined vortex in the case on December 10, 2012.[8] That is the case where the largest drop in air pressure was seen in observation data during the observation period.

At 12:09 pm on December 10, 2012, a vortex with a clear hook echo (pattern of rainfall echo accompanying a vortex) and pattern passed over the north end of the multi-system ground-level observation system. The vortex moved east-northeast (at around 45º to the system), and the movement velocity of the vortex was estimated as approx. 16 ms^{-1} based on the Doppler velocity pattern of the radar with the lowest angle of elevation (approx. 90 m height). As the vortex passed, anemometers detected an increase in wind velocity and barometers a drop in air pressure. The maximum wind velocity was 35.3 ms^{-1} observed by an anemometer at 50 m from the north end of the system, and the maximum drop of air pressure was 4.0 hPa observed by a barometer at the same point. Looking at the positional relation between those in detail, we estimated that the vortex center passed a point 0 to 150 m from the north end of the system and that the diameter of maximum tangential velocity was less than 150 m.

The solid line in Fig. 10 (a) is the tangential velocity spatio-temporally transformed using the vortex movement velocity and the data of the anemometer that observed the maximum wind velocity, and the dotted line is the tangential velocity of the Rankine combined vortex with assumed cyclostrophic wind balance (balance between centrifugal force and barometric gradient force). The solid line in Fig. 10 (b) is the drop of air pressure obtained in the above-mentioned manner from the data of the barometer that measured the largest drop of air pressure, and the dotted line is the drop of air pressure of the Rankine combined vortex. Assuming the maximum tangential velocity of the Rankine combined vortex to be 21 ms^{-1} and the diameter of maximum tangential velocity to be 60 m, the overall distribution of the observed fluctuation agreed well with the distribution of the Rankine combined vortex in terms of both of wind velocity and air pressure.

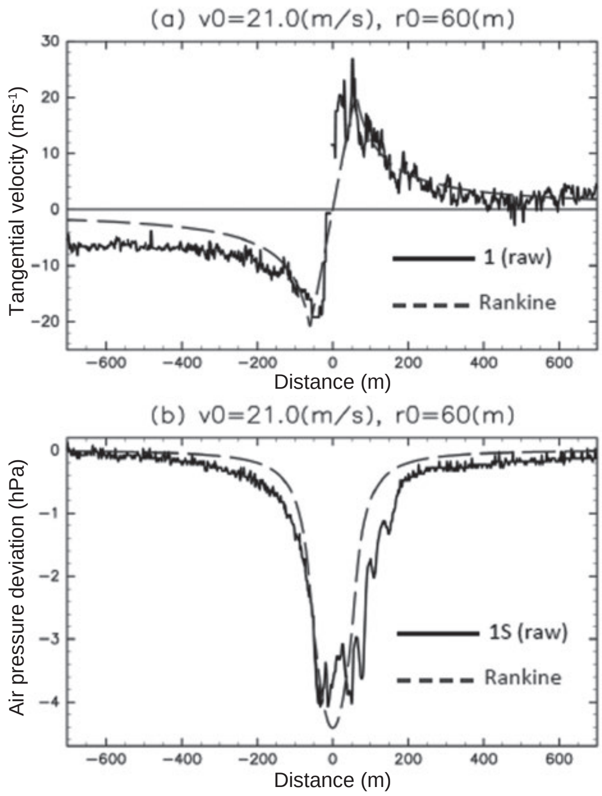

Fig. 10 (a) Tangential Velocity Measured by Anemometer Recording Maximum Wind Velocity
(b) Air Pressure Measured by Barometer Recording Maximum Drop of Air Pressure
Solid Lines: Spatio-temporally Transformed Distribution
Dotted Lines: Distribution of the Rankine Vortex Assuming Cyclostrophic Wind Balance

We found that the linear array of wind and pressure sensors observed gusts greater than 25 ms^{-1} and accompanied by a vortex at least in 22 cases in winter in 2011 and 2012. We plan to analyze more cases in the future with an aim of proving the universality of the phenomenon.

4.3 Vertical Structure of a Vortex

The gust detection system detects atmospheric vortices. It predicts the direction of movement and destination of vortices on the assumption that vortices do not have inclination because there is little data on inclination of vortices. Therefore, when a vortex is inclined forward in the direction of movement in relation to the atmospheric vortex, the ground-level vortex goes ahead and the system is late in issuing a warning. That means it is difficult to secure warning lead time for the system. In contrast, when the ground-level vortex is located behind the atmospheric vortex in terms of the direction of movement, warning lead time can be secured. It is thus important to identify the actual three-dimensional structure of vortices that cause gusts.

Analysis of data from the radars of MRI at Shonai Airport that observe three-dimensional structure of vortices revealed the three-dimensional structure of vortices that occur at the Shonai Plain (Fig. 11).[9] It was shown in all of the seven cases where

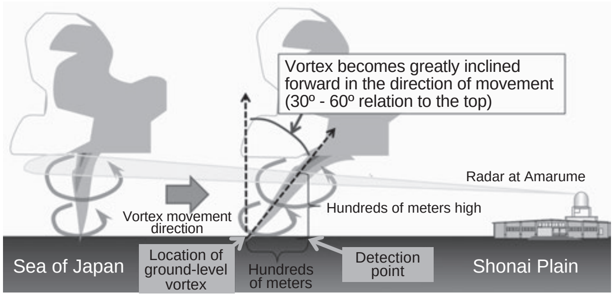

Fig. 11 Relation between Inclination of Vortex Occurring at Shonai Plain and Detection System

three-dimensional structure of vortices was analyzed that vortices that occurred at sea became largely inclined forward in the direction of movement (30º to 60º in relation to the top) after making landfall in the Shonai Plain. This means that the ground-level vortex is situated seaward a few hundred meters behind the atmospheric vortex observed by the gust detection system. In other words, at the Shonai Plain, ground-level vortices are located further from the track than atmospheric vortices observed by the system. We thus confirmed that the gust detection system could issue sufficiently early warnings.

5 Conclusion

We have developed a prototype gust detection system that uses Doppler radars and analyzed the validity of the characteristics of the vortex assumed in the algorithm of the system based on observation data of a weather observation network set up on the Shonai Plain. The analysis results clarified the following items.

(1) Wind velocity of atmospheric vortices observed by radars and that of vortices observed at ground level agree with each other with a margin of +/-5 ms^{-1}. Thus, it is fairly reasonable to consider wind velocity of atmospheric vortices estimated by the gust detection system as wind velocity at ground level.

(2) The horizontal structure of vortices observed at ground level largely agrees with that of the Rankine combined vortex model. Thus, the vortex model applied in the gust detection system is appropriate.

(3) As vortices are inclined forward in the direction of movement after making landfall, the gust detection system can issue early warnings.

It is known that misdetection and overlooking of vortices by the gust detection system causes excessive or insufficient operation control.[10] In order to overcome those issues, we will continue working on improving the algorithm and detection accuracy of the gust detection system. And also, in view of putting the gust system into practical use, we are planning to establish criteria (threshold values) of wind velocity of vortices for use in train operation control and develop a method of forecasting the route of gusts.

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