Methods to Estimate Spatial Distribution of Local Meteorological Conditions along Railway Line

Takaaki FUKUHARA  Saki TANIMOTO  Keiji ARAKI
Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division

In order to estimate meteorological conditions on a time-scale and spatial-scale sufficient to prevent meteorological disasters on the railway system by interpolating data collected from anemometers or rain gauges, meteorological conditions were estimated using numerical simulations. Numerical simulation results were compared with recorded data for strong winds, heavy rainfall, and heavy snowfall. As a result, although there were cases where meteorological conditions were underestimated in the numerical simulations, it was possible to reproduce meteorological phenomena qualitatively.

Keywords: numerical simulation, countermeasure for meteorological disasters

1. Introduction

To prevent meteorological damage to railways caused by strong winds, heavy rain and heavy snowfall, weather monitoring equipment such as anemometers and rain gauges are installed along railway lines. Meteorological data obtained from such equipment is called “point data” because the weather monitoring devices are installed every few kilometers and up to ten kilometers apart. Meteorological phenomena which cause damage to a railway are brought about by thunderclouds, typhoons or low pressure. These meteorological phenomena have particular time and spatial scales as shown in Fig. 1. Damage to railways due to these phenomena may not occur at data points or within their vicinity because wind, rain, and snow have spatial distribution. Meteorological phenomena such as localized heavy rain showers, occurring on a spatial scale which is smaller than the intervals at which weather monitoring equipment are placed along railway lines, may not be observable by these devices. Further, there could be damage such as the rise of a river caused by heavy rain beyond the perimeter of these equipment as well as damage caused by heavy rain alongside the railway track. Meteorological phenomena which cause damage to railways can be captured more accurately by obtaining spatial meteorological data in addition to that collected at the “data point”, and obtained from weather monitoring equipment such as anemometers and rain gauges.

Meteorological data with spatial distribution are obtained by meteorological radar data, analysis rainfall (Ministry of Land, Infrastructure and Transport), XRAIN (the Ministry of Land, Infrastructure and Transport X-band MP radar network), GPV data (grid point value: The value of each grid when covering the earth with grids which are regular and equal), and so on. With XRAIN data it is possible to obtain distribution of rainfall with a 250m spatial resolution (interval in the horizontal direction of data), but it does not cover the whole of Japan. Moreover, the smallest resolution of rainfall data which can be obtained across Japan is 1 km and that of wind velocity data is 5 km.

A train operation control section along a line is usually about several km long, up to approximately several tens of kilometers, and train control occurs when wind velocity or rainfall reaches a given threshold. Therefore, it is thought that using only the data currently available in Japan would not allow the collection of spatial weather information at a resolution which can be utilized for disaster prevention purposes. It is in the past few years that obtaining meteorological data has become possible in shorter time and spatial resolution, as mentioned above.

In order to set a threshold for train operation control, it is necessary to consider disasters which have occurred in the past. However, it is not possible to know what the weather conditions were at the time of the accidents, nor the spatial resolutions. Therefore, it is difficult to estimate wind velocity, rainfall, and snow depth for those events as well. One of the other ways to obtain spatial meteorological conditions is through numerical simulation using a meteorological model.

This is a method to obtain finer weather conditions for the target area by dividing it into small grids (grid point) and then solving equations on air and heat at each grid point by using computers. Today, numerical simulations are used for making weather forecasts. It is possible to obtain the spatial distribution of weather conditions at the time of accidents because it is possible to calculate the meteorological phenomena of strong winds, heavy rain, and heavy snow by using meteorological numerical simulation.

Methods for extracting strong wind spots have been developed by using numerical simulation techniques such as meteorological models and fluid models, and a topographi-
cal factor analysis in order to estimate areas where strong winds are prone to occur along railway lines [2, 3]. However, that project focused only on strong winds. Therefore, in the present study, in addition to strong winds, heavy rain and heavy snow were also included, and numerical simulations were made to reproduce these meteorological conditions which led to weather related disasters on the railways. Then, an evaluation was made to check the reproducibility of meteorological conditions by comparing the results of calculation with observations.

2. Numerical calculation of spatial meteorological conditions using numerical simulation

In meteorological numerical simulation, various kinds of meteorological models suitable for reproducing meteorological phenomena have been developed. These meteorological models are used where appropriate. Therefore, when conducting a numerical simulation of the weather, the meteorological phenomena to be reproduced and the spatial resolution to be employed are determined, and then a model suitable for the simulation is selected. Next, initial conditions that are the state of the atmosphere in the model at the beginning of the calculation along with boundary conditions: that is the weather condition at the boundary of area for calculation are set respectively, and then numerical simulations are performed. The model and the settings used for this calculation are described below.

2.1 Numerical simulation model

To estimate the meteorological conditions (strong winds, heavy rain, and heavy snow) that cause damage along railway lines, a horizontal grid point interval was set at 250 m in consideration of the spatial extent of the meteorological disaster to the railway. A WRF (Weather Research and Forecasting [4]) model was used on this occasion. This model is widely used for research and weather forecasting, and can be used for calculations using a horizontal resolution of 250 m.

2.2 Settings on the numerical calculation

As mentioned above, the settings for the calculation target area and the time step, the creation of initial-boundary conditions, the setting of several physical processes (such as cumulus, short wave and long wave radiation, microphysics, the exchange of heat and that of water vapor) are carried out. Then a numerical simulation is performed. The conditions that were set in this calculation are shown below. A calculation domain was set measuring 35 km from the east to the west and 27 km from the south to the north, on the Ishikari-Plane, Hokkaido. This area is prone to strong winds, heavy rain and heavy snow. The calculation area with observation points is shown in Fig. 2.

The horizontal grid interval was set at 250 m in this simulation. Therefore the number of horizontal grids was 141 from east to west, and 109 from south to north. The number of lateral grids was set to 35.

The horizontal grid interval of 250 m in this numerical value calculation is small compared to the meteorological data used for making initial conditions and boundary conditions. Therefore, even if numerical simulations were performed with this grid point interval from the beginning of the calculation, the result of the calculation would not be correct because the initial conditions and the boundary conditions would not have been set appropriately. So the calculations were performed with a 250 m grid resolution using a method called ‘nesting’. In this method, coarser areas were calculated at coarser grid resolution first, and then finer areas were calculated at finer grid resolution, in which case the ratio of the resolution between coarser grid and the finer grid was 3 to 5.

4 domains were set with horizontal resolutions of 9 km, 3 km, 1 km and 250 m. The location of each calculation area is shown in Fig. 3. The period in the numerical calculation was set at 36 hours to 48 hours so that the period of the development and subsidence of the meteorological phenomena causing strong winds, heavy rain, and heavy snow might be included. The time step was set to the different values by which we can perform calculations at the grid point interval in each domain (45 seconds in D1 and 0.5 seconds in D4). The size of the calculation area, the horizontal grid interval and the time interval are shown in Table 1. Then, it is necessary to set initial conditions and boundary conditions. The atmospheric conditions that contain the temperature, the wind, and the humidity at each level, and that of the ground (and sea level) are set in the WRF model. When establishing initial and the boundary conditions, the above-mentioned GPV data provided by Japanese and foreign weather organizations are widely used. In this study, GSM objective analysis data was used, provided by the Japan Meteorological Agency (JMA).
These data sets include temperature, wind, relative humidity at the several altitudes, and have a horizontal resolution of 20 km. However, several data such as the humidity of the ground and surface temperatures necessary for making initial and boundary conditions are not recorded. Therefore, in addition to GSM objective analysis data, final analysis data provided by NCEP (NCEP - fnl) was also used. Even though this data is recorded at intervals of 1 degree in the latitudinal and longitudinal directions (about 110 km), the humidity of the ground and the surface temperature are recorded. Physical processes are based on the schema used for calculating at high resolution with the WRF model (about 300 m of horizontal grid interval). Moreover, in the case of strong winds, physical processes of the boundary layer (near the ground) were based on the scheme which can reproduce strong wind conditions as well.

### 3. Results of the numerical simulation and comparison with the results of the observation

#### 3.1 Strong wind case

Strong wind disasters are caused by typhoons, developing low pressure, a distribution of atmospheric pressure in which the high pressure area lies to the west and the low pressure area to the east, and the passing of a cold front and small low pressure area. The area which we select for numerical simulation is the one where strong winds are caused by a distribution of such atmospheric pressure, when the high pressure area lies to the west, and the low pressure area to the east, which is called a winter pressure pattern. This paper presents the results of numerical simulations of sudden increases in wind speed caused by winter pressure patterns.

At first, a comparison was made of the time series of horizontal wind velocity observed at the point located east of the area (hereafter, we call point A), and the simulation results on the calculation grid nearest to the point A. These timings are shown in Fig. 4. In this figure, the maximum values of wind speed obtained from observations and through calculation respectively, are nearly equal to each other; however, the time when the wind speeds reach their maximum values are different, whereby calculated time is 1 or 2 hours later than observed results. As for the wind directions, those calculated by numerical simulation are different from observed results for only 1 ~ 2 directions out of 16 wind directions; so it can be said that the tendency of the change of the wind direction from the south to the west can be reproduced by calculation. Then, with regards to distribution of the wind speeds obtained by simulation: anemometers that observe only wind speed are widely used in Japan; scalar values of wind velocity are shown therefore, not considering wind direction. The distribution of wind speed at 12:30 when a sudden increase of wind speed occurred is shown in Fig. 5 and at 13:00 (30 minutes later) are shown in Fig. 6, respectively. In these figures, the area of wind speed exceeding 10 m/s is shown in the western part of the calculation domain at 12:30 and shown in most of the calculation domain. Therefore, it means that the strong winds begin to blow near the coastline and then blow in the eastern area of the calculation domain.

In addition, in the north of the area (black ellipse in Fig. 6), wind velocity exceeds 25 m/s near the hilltop, but

### Table 1  Horizontal grid interval, area, and time step of each simulation domain

| Domain  | Domain 1 | Domain 2 | Domain 3 | Domain 4 |
|---------|----------|----------|----------|----------|
| Horizontal grid interval | 9 km | 3 km | 1 km | 250 m |
| Area    | 900 km × 720 km | 390 km × 300 km | 120 km × 108 km | 35 km × 27 km |
| Time step | 45 sec | 15 sec | 3 sec | 0.5 sec |

![Fig. 4](https://via.placeholder.com/150)

Comparison of calculated and observed time series for wind velocity and wind direction in strong wind case  
(At point A)

![Fig. 5](https://via.placeholder.com/150)

Spatial distribution of wind velocity obtained by simulation at 12:30, 23rd. Dec.
is less than 10 m/s across the swamp that lies between the hills and on the plain, east of the hill.

From this, there is a tendency for the wind to weaken at a point close to the foothills on the leeward side of the hill in this case. Such a tendency is not necessarily adequately recorded in the same way by anemometers that are located on the ground if the arrangement interval of anemometers is coarse.

3.2 Heavy rain case

Meteorological phenomena which bring heavy rain can include typhoons and seasonal rain fronts. In the calculation domain set out above, heavy rain, considered to be due to these meteorological phenomena, was also observed. This paper shows the calculation results for cases where hourly rainfall exceeded 30 mm in this area in summer. An hourly rainfall of this magnitude is such rainfall as will be announced heavy rain advisories in this area.

In the first instance, the time series of hourly rainfall was observed at 2 observation points, point A and point B near the center of the domain. These observations were then compared with the simulation results on the calculation grid nearest to point A and point B. These time series are shown in Fig. 7. In this figure, rainfall obtained by calculation on the grid nearest to point B is lower than the rainfall observed at point B; however, on the grid nearest to observation point A, it is almost possible to reproduce the time variation and the peak value of hourly rainfall observed at point A through calculation. However, the observed peak rainfall occurs at 7:00 whereas through calculation it happens at 9:00 at both points, showing 2 hour difference.

Next, spatial distribution of hourly rainfall was obtained through calculation. Figures 8 and 9 show hourly rainfall obtained through calculation at 7:00 when the maximum hourly rainfall was calculated and at 9:00 when the maximum rainfall was observed, respectively. In these figures, hourly rainfall exceeding 20 mm was calculated for the eastside of the areas at 7:00, however, little precipitation was obtained at 9:00 in most of the area.

Then, the spatial distribution of hourly rainfall obtained by calculation was compared with results obtained through rainfall analysis conducted by the JMA. Here, calculated rainfall distribution at 7:00 (Fig. 8) was compared with measured rainfall at 9:00 (Fig. 10).
The calculated volume of rainfall was underestimated for the whole while the calculated domain affected by precipitation was smaller than the area identified through field observations. However, the tendency that the amount of rainfall becomes larger on the east side could be reproduced by numerical calculation in this domain.

3.3 Heavy snow case

Heavy snowfalls are often caused by winter pressure patterns with strong cold air mass. Heavy snowfalls had been observed in the area under observation in such weather conditions. This section presents the results of calculations for similar heavy snow, as a heavy snow warning had been announced in this area (Heavy snow advisories will be announced when snowfall is more than 30 cm for 12 hours in this area).

At first, the time series of hourly change in snow depth at intervals of 1 hour observed at the point A and the calculation results at the grid nearest to the point A are shown in Fig. 11. The increase in snow depth in 1 hour was 4 cm-7 cm according to field observations, but it was about 2 cm at most, on the grid nearest to point A through numerical calculation. This means that change in snow depth was not accurately reproduced. Areas subject to snowfalls may be different from observation, as mentioned in heavy rain case in section 3.2. Therefore calculated results of distribution of change in snow depth over 12 hours, from 12:00 to 24:00, are shown in Fig. 12. In this figure, the changes in snow depth over 12 hours were less than 10 cm for this domain, therefore changes in snow depth in more than 30 cm obtained through observation were not reproduced in calculation.

In the case of heavy snow caused by severe winter pressure patterns, the distance between high pressure over the continent and low pressure over the sea is large and water vapor is supplied by the wind as is blows in off the Sea of Japan. Heavy snowfall is not reproduced by calculation in this case because the above meteorological conditions are not taken into consideration.

Moreover, changes in depth of snow were caused by snow blown by the wind in addition to actual snowfall. In addition, this effect is also due to finer airflow and terrain than the grid point set in this model. These effects may therefore explain why large change in snow depth found through observation could not be accurately reproduced in numerical calculations. This means that it is necessary to take into consideration wind flow and a topography on a finer scale than the grid interval used, which cannot be reproduced by a WRF model. Therefore, it is one of the coming subjects that these effects are to be taken into consideration in the numerical calculation by applying fluid model that can perform calculation at the grid points of smaller intervals.

According to the results described in section 3.1 and later, among the meteorological phenomena targeted in this study, heavy snow could not be reproduced. Strong winds and heavy rain however could be reproduced qualitatively through meteorological numerical calculations using spatial grid points set at 250 m intervals, though the place and time of occurrence of these phenomena were different from those found through observation. Therefore, the spatial distribution of the wind speed and precipitation which are the meteorological phenomena of interest, are considered more or less equivalent to the values obtained through numerical simulation. Accordingly, it is possible to estimate the structure of weather phenomena that lead to strong winds and heavy rain, and evaluate weather conditions before the onset of strong wind and heavy rain. Based on these results, it will be possible in future to estimate in future whether there is a possibility that such strong wind and heavy rain occur when the same weather conditions become similar to the evaluated conditions.

4. Investigation into accuracy improvement

Numerical simulations were conducted in this study with respect to strong winds, heavy rain and heavy snow. However, heavy snow phenomena could not be reproduced. As a way to improve this reproducibility, it is possible to add observational data by inputting ground surface observation data into the model.

Such methods have been studied before, to improve the accuracy of numerical calculations. It is indicated that the reproducibility was improved by including various observational data of the ground and upper air to initial and boundary conditions of a model. However, there are only a few upper air data sets which have been published officially. However, ground data such as rainfall and wind speed are easily available because it is observed by railway companies themselves and by other agencies through their weather observation points, and is widely published.

Therefore, in order to estimate the degree by which
accuracy can be improved by incorporating only ground observation data, numerical simulations were carried out in which temperature and wind speed obtained from ground meteorological observation points in the calculation domain were incorporated into the initial conditions. The two simulation cases were then compared: one with incorporated observation data, and the other without.

The WRFDA was applied with the incorporated data, which is an optimized tool for the WRF model. The heavy snow cases described in Section 3.3 were selected to carry out the comparison of calculated results with or without incorporating observation data. Observed meteorological data, such as air temperature, wind speed and direction, snow accumulation at the 5 local observation points, was employed, including data from observation points A and B in the calculation domain. The Japan Meteorological Agency AMeDAS had two additional observation points in the calculation domain, therefore temperature, wind speed and direction data from these seven points were incorporated into the model for calculation.

After incorporating the observation data into the initial and boundary conditions, calculations were made under the same conditions, and the time change of snow depth was examined. The results of the calculations are shown in Fig. 13. Comparing Fig. 12 and Fig. 13, snow depth changes increased slightly in the entire area by incorporating ground surface observation data into the model, but even if the ground surface observation data was incorporated, the increased value was less than 10 cm and still there was a large difference between the calculation result and the observation result. Therefore, it was found that the calculation accuracy is not significantly improved by incorporating only ground surface observation data such as wind and air temperature at the various observation points in the model.

This study shows the results of calculations incorporating ground surface observation data which railway companies observe or obtain easily. The result of calculations revealed certain significant deviations from the observed data. It is thought that because the atmospheric conditions from the ground to the upper air are set in the model, incorporating only the ground surface data obtained by several observation points into the model is not sufficient to representing the reality of atmospheric conditions in the model. This means that the result of calculation has a large difference from that of observations. Therefore, by incorporating the spatial observation data of winds and water vapor at given altitudes, available from devices such as weather radars, into the initial and boundary conditions of the model, attempts will be made to improve the reproduction accuracy of the simulations so that they can be used for preventing meteorological disasters affecting railways.

5. Conclusion

Data obtained from the anemometers and the rain gauges installed along the railway track is called “point data.” It has now become possible to obtain “spatial data” information using observation technology, such as radars, which have been developed over recent years. However, spatial datasets are not available at the required resolution, which means that in their present state they cannot necessarily be utilized to prevent train disasters.

Therefore, in order to interpolate the appropriate values at the points where the anemometers and the rain gauges are not installed, and to obtain the ground surface meteorological information at the required time-spatial intervals for railways, numerical simulations widely used for weather forecasting and weather research in recent years were performed to strong winds, heavy rain and heavy snow related weather conditions. Then the simulation results were compared with the field observations.

From the simulation results, it was found out that strong winds and heavy rain could be reproduced qualitatively using meteorological numerical calculation with spatial grid points at 250 m intervals, though the places and times of occurrence of these phenomena differed from field observations. Therefore, the actual spatial distribution of the meteorological phenomena of interest such as wind speed and precipitation are considered relatively close to the values obtained through numerical simulation. As such, it is possible to estimate the structure of weather phenomena which bring about strong winds and heavy rain, and to evaluate the weather conditions before the occurrence of strong winds and heavy rain. As a result, even though there were discrepancies in the time and places where strong winds and heavy rain occurred between simulated and actual data and there was not absolute consistency between observed results and calculations, it was found that wind velocity and precipitation could be reproduced qualitatively through simulation. Therefore, it is possible to estimate the spatial structure of meteorological phenomena causing strong winds and heavy rain.

In addition, to improve accuracy of calculation, a simulation was performed by incorporating observed data obtained at several points on the ground into the model; however, the accuracy of simulation was hardly improved. As a reason for that, it is considered that the atmospheric conditions in the model cannot be represented by only incorporating the ground data at several points into the model. Therefore, it was found out that other data needs to be incorporated, such as wind speed at altitude, into the model to enhance the accuracy of the simulation.

If the weather conditions can be sufficiently reproduced by the numerical calculations, it is possible to estimate where such meteorological phenomena, as caused the disaster in the past, are likely to occur by numerical calcu-
lation. Therefore, it is conceivable that spatial distribution of meteorological conditions obtained by numerical simulation can be very useful in preventing railway disasters. It is expected that future accuracy of reproduction through numerical calculation will be obtained by properly reproducing the exchange of water vapor between the atmosphere and the sea, and by incorporating atmospheric wind and water vapor, in addition to ground-based observation data into the model.

References

[1] Japan Meteorological Agency : Various Meteorological Phenomena http://www.jma.go.jp/jma/kishou/know/whitep/1-1-2.html (In Japanese).

[2] Araki, K., Fukuhara, T., Shimamura, T., Imai, T., “A Method to Detect Strong Wind Sections Along Railway Lines by Using Numerical Simulations,” RTRI Report, Vol.24, No.5, pp.29-34, 2010 (in Japanese).

[3] Fukuhara, T., Araki, K., Tanimoto, S., “Method to Pinpoint Locations along Railway That Are Subject to Strong Winds with Due Consideration on Local Winds,” RTRI Report, Vol.27, No.11, pp.23-26, 2013 (in Japanese).

[4] W. C. Skamarock, J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X.-Y. Huang, W. Wang, J. G. Powers, “A Description of the Advanced Research WRF Version 3,” NCAR Technical Note, 113pp, 2008.

Authors

Takaaki FUKUHARA  
Assistant Senior Researcher, Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division  
Research Areas: Strong Wind Countermeasure

Keiji ARAKI  
Senior Researcher, Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division  
Research Areas: Strong Wind Countermeasure

Saki TANIMOTO  
Researcher, Meteorological Disaster Prevention Laboratory, Disaster Prevention Technology Division  
Research Areas: Strong Wind Countermeasure