Real-time prediction system for migration of rice planthoppers *Sogatella furcifera* (Horváth) and *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae)

Akira OTUKA, Tomonari WATANABE, Yoshito SUZUKI, Masaya MATSUMURA, Akiko FURUNO and Masamichi CHINO

1 Department of Information Science and Technology, National Agricultural Research Center; Tsukuba 306–8666, Japan
2 Department of Plant Protection, National Agricultural Research Center for Kyushu Okinawa Region; Nishigoshi, Kumamoto 861–1192, Japan
3 Department of Environmental Science, Tokai Research Establishment, Japan Atomic Energy Research Institute; Tokai, Ibaraki, 319–1195, Japan

(Received 12 May 2004; Accepted 30 November 2004)

Abstract

The white-backed planthopper, *Sogatella furcifera*, and the brown planthopper, *Nilaparvata lugens*, are pests of rice and migrate from south China to Japan in the rainy season of early summer. In order to achieve high-precision migration prediction, a real-time prediction system was developed. In this system, the latest meteorological data are supplied online to an advanced numerical weather prediction model, MM5. The model forecasts three-dimensional atmospheric fields at one-hour intervals. In these fields, a planthopper migration simulation model, GEARN, calculates movement of a number of modeled planthoppers and predicts their relative aerial density at three-hour intervals. The results are converted to maps and become available on the Internet. The maps of relative aerial density provide information about the timing and area of migrations over the next two days. During the main migration season in June and July 2003, the system achieved a prediction quality that was comparable to that of rainfall forecasts by the Japanese Meteorological Agency.

Key words: *Sogatella furcifera*; *Nilaparvata lugens*; long-distance migration; real-time prediction; numerical simulation

INTRODUCTION

Every year, rice fields in eastern Asia are invaded by rice planthoppers, mainly the white-backed planthopper, *Sogatella furcifera* (Horváth) and the brown planthopper, *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae). These planthoppers mainly immigrate into Japan from southern China by being carried by southwesterly winds during the Bai-u early-summer rainy season (e.g. Kisimoto, 1976; Seino et al., 1987).

It is important for the management of migrating planthoppers to be able to predict the occurrence of migrations: i.e., when, whence and whither planthoppers will migrate. Networks that monitor migration events have been established in East Asian countries (Zhou et al., 1995; Watanabe, 1997; Kim et al., 2001); at the same time, much research on predicting migrations have been conducted. Previously, the relationship between an observation site and the position of seasonal rain fronts over the East China Sea were regarded as key factors for prediction (Kisimoto, 1976). More objectively, a numerical trajectory analysis method was employed to find migration sources (Rosenberg and Magor, 1983). Since this model can trace an air parcel backwards or forwards using wind fields, the forward method was applied for migration prediction in China (Zhou et al., 1995). In late 1980s, strong wind streams that develop to the south of low pressure systems and are called low-level jets, were proposed to be the carriers for immigrants to Japan (Seino et al., 1987; Watanabe and Seino, 1991). Currently, upper-level weather charts that highlight low-level jets are operationally provided to and utilized by plant protection offices in Japan.
(Watanabe et al., 1990). However, since all these methods utilize a two-dimensional wind field at a particular pressure level at long time intervals such as 6 or 12 h, the quality of their predictions have been limited.

In recent years, numerical methods have been improved from two-dimensional to three-dimensional ones. First, a three-dimensional simulation method using a boundary layer model was developed (Turner et al., 1999). This Eulerian approach calculates planthopper concentration in each calculation grid cell by prognostic equations, and has been able to simulate large migrations observed by daily trap data in Korea. However, a prediction system based on this model has not yet been developed.

A simulation method that consists of a particle dispersion model and a numerical weather prediction model was applied to the planthopper migration study by the authors. It is a Lagrangian approach that traces planthoppers in the model space, taking into account various planthoppers’ behaviors. The method estimated possible migration sources by simulating a number of migrations from meshed takeoff areas over China and Taiwan.

In this paper, this simulation model is employed to improve prediction quality. A real-time prediction system was developed based on the model, which automatically calculates the future atmospheric fields and possible migrations using online atmospheric analysis data. The prediction was evaluated by operational daily catch data in the 2003 season. This paper presents the evaluation result and technical descriptions of the prediction system including system structure, data flow and prediction data provided.

**MATERIALS AND METHODS**

**Planthopper behavior related to long-distance migration.** *S. furcifera* and *N. lugens* are tiny insects about 3–4 mm in size and 1–3 mg in weight (Ohkubo, 1973). Many field observations have shown that the planthoppers take off at either dusk or dawn (e.g. Ohkubo and Kisimoto, 1971). A radar observation showed that *S. furcifera* and *N. lugens* fly to an altitude of several hundred to 1,000 m above the ground at an estimated upward speed of 0.2 m/s (Riley et al., 1991). The species fly at about 1 m/s, whereas the wind speed of low-level jets when migration occurs is typically more than 10 m/s (Seino et al., 1987). Laboratory experiments of tethered *N. lugens* adults indicated that they have the ability to fly for up to 23 hours in air of high humidity (Ohkubo, 1973). *Nilaparvata lugens* ceases flying at cooler temperatures; half of them stop beating their wings when the air temperature is below 16.5°C (Ohkubo, 1973). Their post-migration landing process is not yet fully understood.

**System structure.** A schematic diagram of the system structure is shown in Fig. 1. Ellipses and squares show data and processing components, respectively. Arrows show data flow. There were two main models used: MM5 and GEARN. MM5 is a numerical weather prediction model (Anthes and Warner, 1978; Grell et al., 1994). This model is one of the most popular models in the meteorological community, and its source code is available. MM5 can be used for a wide range of studies in-

![Fig. 1. Schematic diagram of system structure.](image-url)
volving monsoons and typhoons on a larger scale, and fronts and urban heat islands on a smaller scale (NCAR, 2003). If an initial field is available, the simulation can be performed for any place on the globe.

GEARN is a particle dispersion model that was used to calculate the movement of migrating planthoppers. From the position of the insects, the relative aerial density for each grid was estimated. This model was originally developed for dispersion studies of radioactive particles by the Japan Atomic Energy Research Institute (Ishikawa and Chino, 1991). Some modifications made for the migration study are summarized in the next section.

The prediction process started when the system acquired meteorological data from the databases. The initial data for weather forecasts in this study were output data of the Global Spectrum Model (GSM) of the Japan Meteorological Agency (JMA) (JMA, 2002). Real-time global sea surface temperature (RTG_SST) data analyzed by National Ocean and Atmosphere Administration (NOAA) of USA were also utilized (Thiebaux et al., 2001). The GSM data were acquired through a weather service company, and RTG_SST data are available to the public on the Internet. The analysis data were preprocessed to produce initial data for MM5. A weather forecast was performed and atmospheric fields were predicted at one-hour intervals. These atmospheric fields were supplied to GEARN, which then calculated relative aerial density of immigrants. The results were transferred to electric figures of PDF format. There were four types of figures: sea level pressure; horizontal wind fields at three pressure levels of 850, 900 and 950 hPa; relative aerial density of planthoppers; and animation of the time series of relative aerial density. After the figures were created, they were sent automatically to the project’s web page with the address of http://agri.narc.affrc.go.jp. This web page is open to the public.

Migration model. Detailed descriptions of a GEARN simulation of planthopper migration can be found partly in Furuno et al. (1999). In the model, no distinction was made between *S. furcifera* and *N. lugens*. Based on their behaviors, the positions of flying planthoppers were calculated to meet certain conditions. The calculation domain shown in Fig. 2 was used for the prediction, where as many as 17 takeoff areas (solid squares) were defined in China and Taiwan, based on the Chinese light trap distribution (solid triangles in Fig. 2) (Wang, 2001), paddy field distribution (Huke and Huke, 1982) and preliminary simulation analyses. A takeoff area is defined as an area where simulated planthoppers take off, and they are located in major rice cultivation regions. As the light traps are generally situated in major rice cultivation regions, the takeoff areas near traps were selected. According to the preliminary experiments, coastal regions in Fujian and Taiwan were found to be source regions in many cases. Therefore three takeoff areas were firstly placed in Fujian and Taiwan. Dense distribution of takeoff areas may be more accurate since the actual paddy field distribution is continuous. However, from the simulation point of view, a larger distance between (or smaller number of) takeoff areas is preferred to reduce computational time. Moreover, in preliminary experiments, calculated migrations from very close adjacent takeoff areas overlapped over Japan because of their diffusion patterns. Therefore, it is not necessary to compute migrations from very close takeoff areas. The
distance between the takeoff areas was determined to be about 200 to 300 km, which was equal to the horizontal size of a typical simulated migration from one takeoff area over western Japan (see Fig. 4). Therefore, the other 14 takeoff areas were placed in major paddy regions, keeping such a distance from each other. They were not situated in mountainous regions. All the takeoff areas were distributed almost uniformly in southern China and Taiwan. 

For each takeoff area, 1,852 planthoppers were assumed to begin migration at dusk (10 Coordinated Universal Time, UTC) or dawn (21 UTC), with their take-off randomly distributed within the takeoff area. The number of planthoppers was determined to be one of the minimum values that could reproduce reasonable simulation results. The planthoppers took off at constant time intervals for one hour. Since no information on planthoppers’ density in source regions was available, it was presumed that planthoppers took off from all the takeoff areas at every takeoff time during a prediction period. This was one of the assumptions applied to the prediction system. Planthoppers that had taken off were assumed to rise vertically at a speed of 0.2 m/s (Riley et al., 1991). While they flew in winds, planthoppers were assumed to move at the same velocity as wind, with vertical diffusion taken into consideration by random walk. Horizontal diffusion was not taken into account because it was simply too great in preliminary simulations. The equations of motion are given in the appendix. However, they did not move beyond the temperature ceiling of 16.5°C. Finally, relative aerial density for each grid was estimated based on their positions. The density was calculated for every takeoff area. The density at the lowest vertical level (less than 100 m above ground level) was used to predict whether the planthoppers would immigrate into Japan. No landing processes were modeled. The grid size of the model domain was 118×118×20. Horizontal resolution of the model grid was 33 km×33 km. The vertical coordinate was a terrain-following $z^*$ coordinate (Furuno et al., 1999).

**Prediction procedure.** A 72-hour weather forecast initialized at 00UTC was conducted by MM5. Then two 48-hour runs were conducted by GEARN with different takeoff times: 10 UTC and 21 UTC. The simulation time of 48 h was determined based on preliminary results, which showed the migration duration from China to Kyushu typically ranged about 24 to 36 h. This procedure was performed once a day during the main migration season from June to July. If any non-zero relative density area in the lowest vertical level covered an observation site for more than one hour in a 24-hour period, the system predicted a migration at that site on that day. This non-zero relative density area is referred to as a migration cloud (see Figs. 3 and 4).

**Evaluation method.** Figure 3 presents an example of relative aerial density at 21 UTC June 27, 2003, showing combined migration clouds that started from all the takeoff areas at 21 UTC June 26. The clouds were predicted to cover the whole Kyushu region. Migration clouds from each takeoff area can be obtained from the web site as well, e.g. a migration from Fujian province that started at 21 UTC June 26 is shown in Fig. 4. Information on both the timing and area of migration can be obtained from these figures.

The prediction quality was evaluated as follows: if the model predicted a migration from any takeoff area during a 24-hour period of interest and there was any catch of planthoppers at the same site during the same period, the prediction was regarded as correct. The prediction was also regarded as cor-
rect if the model predicted no migration and there was no catch. In other cases the prediction was regarded as incorrect. The daily predictions were evaluated by a hitting ratio defined by:

\[
\text{Hitting ratio (\%)} = \frac{\text{Number of days when the migration event was correctly predicted}}{\text{Total number of days}} \times 100
\]

The catch data used were operational daily catches acquired at three sites, Saga (33.17N, 130.33E), Kumamoto (32.95N, 130.78E) and Kagoshima (31.52N, 130.50E) (Fig. 2). Tow net traps mounted at 10 m above the ground were used at Saga and Kumamoto, whereas a suction trap (3.8 m in height) of the Johnson-Taylor type installed on the roof of a 2-floor building (8.5 m) was used at Kagoshima. The aperture of the suction trap was 70 cm, and the power of the fan was 650 Watts. The evaluation period was from June 1 to July 16, 2003. Planthoppers in the trap were collected at 00 UTC every day and the number of catches counted. These data were obtained from the Japan Plant Protection Network System (JPP-Net) (Watanabe, 1997). Because of very small catches of *N. lugens* in the period, only the catch of *S. furcifera* was used for the evaluation.

**RESULTS**

The results of the daily evaluation are presented in Table 1. From the table, the hitting ratio for Saga was 82% (=36/44). In the same way, the ratios for Kumamoto and Kagoshima were calculated to be 83 and 72%. The average was 79%.

The first migration of the *Bai-u* rainy season on 12 June was correctly predicted. On the other hand, an outstanding prediction failure was recorded at Saga on July 2, 2003. Since the migration calculation is sensitive to the wind field, the prediction error was mainly caused by forecast error.

The prediction system automatically worked as required during the evaluation period, except for 2 days, July 10 and 14, 2003, when GSM data were not available because the data were not delivered from the weather service company for unspecified reasons. The loss of GSM data occurred three times in 2003.

**DISCUSSION**

The results showed that the system automatically operated without difficulty. This is the first real-time prediction system to use 3-dimensional wind fields given numerically by the weather forecast. The system enabled migration prediction that predicted the timing and area of migrations. Nonetheless, there are several issues to be discussed, including assumptions made about takeoff, evaluation period, determination of migration events based on catch data, estimation of migration sources, and system improvements.

The most powerful assumption made for the prediction was that planthoppers were supposed to take off from every predefined takeoff area at every takeoff time (takeoff assumption). The regions where planthopper density is high in June and July are located in southern China at latitudes less than 25 degrees N (Zhou et al., 1995). The takeoff areas in Fujian, Guangdong, Guangxi and Hainan provinces qualify as such regions (Fig. 2). In some years, however, northern regions around 30 degrees N have been invaded by the beginning of June. Therefore, the other northern takeoff areas were included. Since the theoretically designated takeoff areas widely cover possible source region, it is thought that the takeoff assumption is reasonable.

The evaluation period was limited to June to
mid-July. There were several reasons for this limitation. The first one was that the evaluation period must match the takeoff assumption. Conditions in source regions in earlier months, such as in April and May, would not match the assumption very well since the density of planthoppers would still be low (Zhou et al., 1995). Therefore, if the evaluation period included the earlier months, the evaluation would result in too many false positives, and hence, an underestimation of the hitting ratio. The second reason is that most of migrations from overseas are concentrated in the Bai-u rainy season, making it the period of greatest concern. Third, from an evaluation point of view, since preceding migrations in earlier months were limited in number, the contamination of locally reproduced planthoppers in the trap data in June and July was expected to be low, which was an important condition in conducting an accurate evaluation. After mid-July, evaluation becomes rather difficult because of the contamination of locally reproduced planthoppers. Therefore the limited evaluation period of June to mid-July was selected.

In the evaluation, a migration was considered to have occurred when any catch greater than one was recorded. This seems controversial since there remains the possibility of capturing locally reproduced planthoppers or locally hopping planthoppers among the daily catches. A locally hopping planthopper is defined as a planthopper captured by the trap because it has taken off again shortly after landing of long-distance migration. Especially, some of the small catches after obvious, large catches could be due to locally hopping planthoppers. At the same time, the possibility that a catch of only one indicated a migration event cannot be denied entirely. In general, because there is no apparent difference between migrated and locally reproduced or locally hopping planthoppers, determination of a migration event should be performed carefully using various information including meteorological conditions, date, number of catches.

Table 1. Daily prediction result of the 2003 season

<table>
<thead>
<tr>
<th>Date</th>
<th>Saga P</th>
<th>Saga Net</th>
<th>Saga Suction</th>
<th>Kumamoto P</th>
<th>Kumamoto Net</th>
<th>Kumamoto Suction</th>
<th>Kagoshima P</th>
<th>Kagoshima Net</th>
<th>Kagoshima Suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/01</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>1</td>
<td>06/24</td>
<td>Y</td>
<td>28</td>
</tr>
<tr>
<td>06/02</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>06/25</td>
<td>Y</td>
<td>15</td>
</tr>
<tr>
<td>06/03</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>06/26</td>
<td>Y</td>
<td>10</td>
</tr>
<tr>
<td>06/04</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>06/27</td>
<td>Y</td>
<td>57</td>
</tr>
<tr>
<td>06/05</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>06/28</td>
<td>Y</td>
<td>5</td>
</tr>
<tr>
<td>06/06</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>06/29</td>
<td>Y</td>
<td>0</td>
</tr>
<tr>
<td>06/07</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>06/30</td>
<td>Y</td>
<td>39</td>
</tr>
<tr>
<td>06/08</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>07/01</td>
<td>Y</td>
<td>7</td>
</tr>
<tr>
<td>06/09</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>07/02</td>
<td>N</td>
<td>239</td>
</tr>
<tr>
<td>06/10</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>07/03</td>
<td>Y</td>
<td>159</td>
</tr>
<tr>
<td>06/11</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>07/04</td>
<td>Y</td>
<td>73</td>
</tr>
<tr>
<td>06/12</td>
<td>Y</td>
<td>21</td>
<td>Y</td>
<td>0</td>
<td>Y</td>
<td>24</td>
<td>07/05</td>
<td>Y</td>
<td>12</td>
</tr>
<tr>
<td>06/13</td>
<td>N</td>
<td>5</td>
<td>Y</td>
<td>3</td>
<td>Y</td>
<td>11</td>
<td>07/06</td>
<td>Y</td>
<td>95</td>
</tr>
<tr>
<td>06/14</td>
<td>N</td>
<td>6</td>
<td>Y</td>
<td>—</td>
<td>Y</td>
<td>38</td>
<td>07/07</td>
<td>Y</td>
<td>12</td>
</tr>
<tr>
<td>06/15</td>
<td>N</td>
<td>2</td>
<td>N</td>
<td>—</td>
<td>N</td>
<td>9</td>
<td>07/08</td>
<td>Y</td>
<td>16</td>
</tr>
<tr>
<td>06/16</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>22</td>
<td>07/09</td>
<td>N</td>
<td>2</td>
</tr>
<tr>
<td>06/17</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>1</td>
<td>N</td>
<td>13</td>
<td>07/10</td>
<td>×</td>
<td>1</td>
</tr>
<tr>
<td>06/18</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>6</td>
<td>07/11</td>
<td>N</td>
<td>0</td>
</tr>
<tr>
<td>06/19</td>
<td>N</td>
<td>0</td>
<td>Y</td>
<td>1</td>
<td>Y</td>
<td>8</td>
<td>07/12</td>
<td>Y</td>
<td>5</td>
</tr>
<tr>
<td>06/20</td>
<td>Y</td>
<td>2</td>
<td>Y</td>
<td>0</td>
<td>N</td>
<td>8</td>
<td>07/13</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>06/21</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>0</td>
<td>N</td>
<td>7</td>
<td>07/14</td>
<td>×</td>
<td>0</td>
</tr>
<tr>
<td>06/22</td>
<td>Y</td>
<td>1</td>
<td>N</td>
<td>0</td>
<td>Y</td>
<td>26</td>
<td>07/15</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>06/23</td>
<td>Y</td>
<td>123</td>
<td>Y</td>
<td>65</td>
<td>Y</td>
<td>91</td>
<td>07/16</td>
<td>N</td>
<td>1</td>
</tr>
</tbody>
</table>

The evaluation was conducted at Saga, Kumamoto and Kagoshima site. The letter Y or N in P column indicates that some or no migration was predicted, respectively. The catch in Net or Suction column shows the number of S. furcifera. Letter ‘×’ indicates no prediction was conducted because of no incoming GSM data. Letter ‘—’ indicates no catch data was available.
and trap type. If meteorological conditions are taken into consideration in estimating migration events, a backward trajectory analysis, for example, may be used. However, conventional two-dimensional methods could introduce estimation errors because of their limited precision. There seems to be no reliable meteorological analytical method that can be used. Therefore, this study did not use any meteorological information in determining authentic migration events. When the small catches of less than 3, for example, were not used, the new estimation resulted in a hitting ratio of 84% (90/107). As described so far, the hitting ratio is sensitive to the criterion of immigration. However, it shows approximate prediction accuracy.

The hitting ratio of the daily prediction for the evaluation period was 79%. The system predicts migrations over the following two days. To consider the prediction quality, this hitting ratio was compared with the hitting ratio of weather forecasts in Japan. The Japan Meteorological Agency evaluated its weather forecast quality by a hitting ratio of rainfall prediction (Appendix). The result shows that the hitting ratio of rainfall in the Kyushu region over the subsequent day and the day after in June 2003 was 80 and 75 percent, respectively. These values are almost same as the hitting ratio for the daily prediction of the planthopper migration.

This system has the potential ability to estimate migration sources, as well. To find possible migration sources, each migration cloud has to be traced backwards. For example, the migrations in Kyushu on 23 June 2003 were estimated to derive from coastal regions in Fujian and Guangdong provinces, and Taiwan. However, this estimation has a margin of error mainly caused by errors in forecasted wind fields; a re-analysis of weather simulation using final analytical weather data could simulate wind fields more accurately. Therefore, possible migration sources given by the prediction system should be treated as a “rapid” estimation. Precise “final” estimation of migration sources for Japan using the simulation model is to be discussed in a future study.

There are other limitations and possibilities of the prediction system. Since catches of *N. lugens* were small during the evaluation period, catches of *S. furcifera* were used for the evaluation. In other words, migration intensities of the species were different under the same weather conditions. This phenomenon suggests that the population density of *N. lugens* in the source regions was lower than that of *S. furcifera*, if the flying behaviors of the species do not differ much. At the same time, it was indicated that the prediction system was unable to make separate predictions for each species.

Another limitation is that the system predicts only relative aerial density, not absolute density. This is because the population density of the insects that were ready for takeoff in source regions was unknown. If the population density were known, the system could predict absolute aerial density although a further intensive evaluation study would be necessary.

It is believed that the East Asian population of the planthopper is sustained by migrating within the region from northern Vietnam and China to Korea and Japan (Sogawa, 1992). Although the present system is designed for migrations in western Japan, immigrations into Korea could also be predicted because the prediction domain includes the Korean Peninsula. Korea is a rice cultivation country invaded by planthoppers during the *Bai-u* rainy season. Furthermore, migrations within China, or between Vietnam and China may be seen if appropriate takeoff areas are established. To construct a prediction system for the entire East Asian region is a challenging task, and international collaborations are desired.

**ACKNOWLEDGEMENTS**

The authors thank Mesoscale and Microscale Meteorology Division of National Center for Atmospheric Research for their enormous help in developing the system, especially Dr. Jimmy Dudhia, Dr. Wei Wang, Dr. Kevin Manning, Dr. David Gill, and Dr. Hiroyuki Kusaka. Real-time GSM data and the parallel computer were supplied by the Computer Center for Agriculture, Forestry, and Fisheries Research.

**REFERENCES**


Grell, G., J. Dudhia and D. Stauffer (1994) *A Description of*


**APPENDIX**

**Basic equations.** In GEARN, the position of a planthopper was calculated by the following equations of motion (Furuno et al., 1999):

\[
x_{t+1} = x_t + u \Delta t
\]

\[
y_{t+1} = y_t + v \Delta t
\]

\[
z_{t+1}^* = z_t^* + \Delta t + \frac{\partial K^*}{\partial z^*} \Delta t + \sqrt{24 K^* \Delta t R}
\]

where

\((x, y, z^*)\): particle position (m). The vertical coordinate is the terrain-following \(z^*\) coordinate defined by equations: \(z^*=(z-z_g)/h\), \(h=(z_i-z_g)/z_i\), where \(z, z_g, z_i\) are vertical coordinates in a Cartesian coordinate system, ground height and top height of the calculation domain, respectively.

\((u, v, w^*)\): wind (m/s). The vertical component is in the \(z^*\) coordinate.

\(K^*\): vertical diffusion coefficient (m^2/s) in the \(z^*\) coordinate.

\(\Delta t\): time step (s).

\(R\): random number from \(-0.5\) to 0.5.

The second terms on the right side of the equations
indicate advection by wind. The third and forth term in the vertical equation are diffusion by vertical dependence of $K_z^*$ and random diffusion, respectively. These terms represent displacements by turbulence. Only the vertical diffusion coefficient was taken into account and horizontal diffusion was not taken into account for simplicity. This simplicity is verified in the evaluation. It was assumed that planthoppers were transported by the horizontal wind regardless of their flying speed. Since the planthoppers were assumed to beat their wings during the flight to balance the gravity, there was no gravity term in the vertical equation.

**Hitting ratio for rainfall forecast.** The method to calculate the hitting ratio of rainfall used by JMA is described. A weather forecast released at 17:00 Japan Standard Time was used for the evaluation. The forecast predicts some or no rainfall for each forecast area over the next two days. If the forecast predicts some/no rainfall in a forecast area and it actually rains/doesn’t rain at all, respectively, then the forecast is correct. There are several rainfall observation stations in each forecast area. The hitting ratio was calculated by the ratio of the number of correct stations to the total number of the stations in the forecast area. The hitting ratios cited in the paper were values for the 24-hour period of the next day and the second day, which were averaged over the whole forecast areas.