temperate populations of *N. lugens* and *S. furcifera*. These variations have also been found in immigrant populations in Japan sampled at different locations in different years (Iwanaga et al., 1986; Matsumura, 2002). Annual changes in the insecticide susceptibility have been reported since the 1970s (Nagata and Masuda, 1980; Nagata, 2002). The degree of virulence that *N. lugens* immigrating into Japan shows for resistant rice varieties has changed since the late 1980s (Sogawa, 1992; Tanaka and Matsumura, 2000). These genetic variations and the resulting phenotypic changes in the planthoppers may reflect the changes in the cultural practice and varieties in the migration source area. Therefore, the estimation of the emigrant release area is essential to improve the management strategies against planthoppers.

Migration of planthopper was related to the synoptic weather conditions; airflow associated with the passage of depressions along the front (Kisimoto, 1976; Jiang et al., 1981). Seino et al. (1987) proposed that the low-level jet stream which progresses along with a seasonal rain front largely affects the long-range migration of planthoppers into Japan. Watanabe et al. (1988) developed a computer software package to analyze the state of the low-level jet stream using wind speed and direction at 850 hPa. They showed that the development of the low-level jet stream was highly correlated with the timing and location of the immigration of the planthoppers (Watanabe and Seino, 1991; Watanabe et al., 1991; Watanabe, 1995). Rosenberg and Magor (1983) applied a trajectory analysis to identify possible source of the *N. lugens* migration into Japan. Sogawa et al. (1997) also applied a back-trajectory analysis and revealed that the southwesterly winds associated with the “Bai-u” front and frontal depressions brought planthoppers from southern China to central China as well as to Japan. Both analyses were based on only a single atmospheric pressure level (850 hPa) of weather chart and/or meteorological grid data whose time interval was considerably long (6–12 h). These factors limited accuracy of their estimation.

Turner et al. (1999) applied an atmospheric numerical model to simulate the migration of planthoppers from southern China to Korea. While their model can simulate three-dimensional meteorological fields, no after-take-off vertical movement process from the ground was included and the vertical distribution of their initial value was uniform. The take-off time, which was set 9:00 h LST (local standard time), differs from the widely observed East Asia take-off times of dawn and dusk (Ohkubo and Kisimoto, 1971; Riley and Reynolds, 1987; Riley et al., 1991).

This paper aims at precise simulation of the planthopper migration processes through the modification of a high performance 3D atmospheric dispersion model by adding several parameters determined from the flight behavior. The model consists of an atmospheric dynamic model MM5 (Grell et al., 1994) for calculating meteorological fields and a particle random-walk model GEARN (Ishikawa and Chino, 1991) for atmospheric dispersion. This model configuration can simulate detailed movement of planthoppers, especially in vertical motions, comparing with conventional models as mentioned above.

The concept of these models is used in the latest version of a computer-based emergency response system, WSPEEDI (Worldwide Version of the System for Prediction of Environmental Emergency Dose Information) to forecast long-range atmospheric dispersions of radionuclides accidentally discharged into the atmosphere (Terada et al., 2004). The performance of MM5/GEARN was previously evaluated by data sets from a field tracer experiment (Furuno et al., 2004).

MM5/GEARN also has a function to find the source in neighboring countries when radiation monitoring data show widespread high levels over Japan. Whereas conventional source estimation methods employ back-trajectory models, this function simulates atmospheric dispersions based on input parameter sets that are formed by a combination of possible release points, release starting times and take-off periods, and compares the simulation results with observations to find the best-fitting set of source terms.

In this paper, the modifications made to GEARN in order to simulate the migration of planthoppers are described first. Then a simulation is performed to find the release areas by using the source term estimation function for the migration of planthoppers to western Japan, and the results are compared with the actual observations from a case study in June 1998.

2. Model description

2.1. MM5

Fig. 1 shows the computational flow for the simulation of planthopper migration by the combination of two models, MM5 (Grell et al., 1994) and the modified GEARN. MM5 is a non-hydrostatic atmospheric dynamic model developed by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR). An outline of the model is provided here, and the model is described in detail in Grell et al. (1994). MM5 calculates

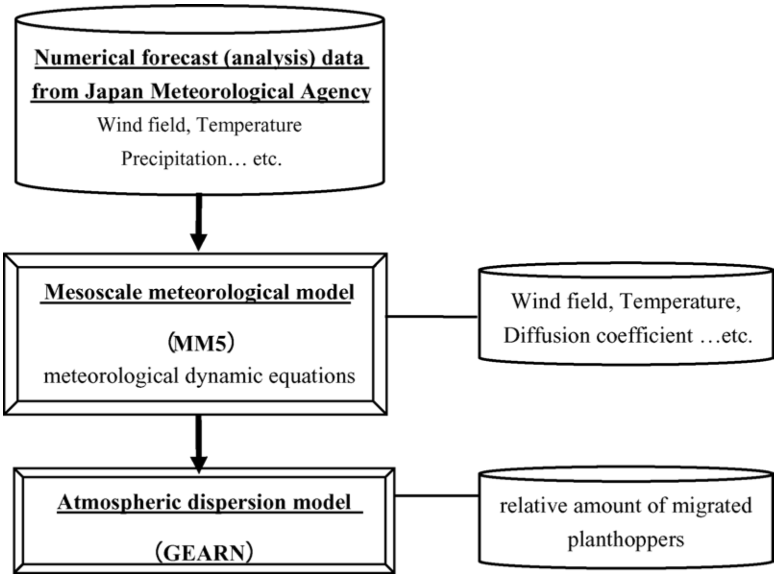

Fig. 1. Calculation flow of the simulation system.

meteorological fields based on atmospheric dynamic equations. It accommodates four-dimensional data assimilation, multi-nested domains, and various physical parameterizations. Meteorological fields are initialized by using numerical forecasts and/or analysis data from Japan Meteorological Agency (1998), National Center for Environmental Prediction (USA), European Center for Medium-range Weather Forecasts, etc.

The detailed description of our model setting is given in Section 3.2.

2.2. GEARN

The detailed description of GEARN is provided in Ishikawa and Chino (1991) and Terada et al. (2004), and an outline is shown here. GEARN was originally developed to calculate the atmospheric dispersion of radionuclides by tracing the trajectories of a large number of marker particles discharged from a source. It is already evaluated by some dataset from field experiments and nuclear accidents (e.g. Furuno et al., 2004). The model is a Lagrangian-type, thus it is easy to introduce flight behavior of planthoppers, such as flight duration and critical temperature for hovering, into the model.

In the application to the migration of planthoppers, the following assumptions were made: (1) planthoppers follow the airflow and turbulence mixing; (2) planthoppers cannot fly in an atmosphere of below 16.5 °C; (3) planthoppers take-off during a 1 h period at dawn and dusk; (4) the takeoffs in the 2 days before the sampling day are considered; (5) the arrival of planthoppers is determined by the number of net-trap catches.

The first assumption is based on the experimental results that planthoppers cannot fly against the winds but can hover in the airflow (Ohkubo, 1981). This means that the movements of marker particles in the model follow the airflow. Since this movement of planthoppers is similar to the movement of radioactive gases, GEARN is not modified for this assumption. It is clear that this assumption would not be applicable to other migratory insects that have strong flight ability, e.g., grasshoppers.

The second assumption is from the study by Ohkubo (1981) showing that 50% of planthoppers are no longer active below the critical temperature of 16.5 °C. Thus, planthoppers cannot exist in air below 16.5 °C in the model domain. The horizontal distribution of the height of the 16.5 °C level is defined from the vertical profile of model temperature at the horizontal grid points in the computational area. Since temperature gradually decreases from the earth surface to the tropopause, the search for a temperature of 16.5 °C is started from the earth surface. The height at which 16.5 °C first appears is defined as the 16.5 °C level. When the temperature of the earth surface is lower than 16.5 °C, the first layer altitude of the model is defined as the 16.5 °C level. If a particle moves into a position higher than the 16.5 °C level, the marker particle is immediately dropped at the 16.5 °C level in this simulation.

The third assumption is also from Ohkubo (1981), who reported that planthoppers tend to fly up at an illumination level of around 100 lx. We determined the two take-off periods, 21:00–22:00 h UTC and 10:00–11:00 h UTC, from this result. The initial position of planthoppers is assumed to be a height of 1 m above the ground. The initial rising velocity is set as 0.2 m s^{-1} based on the results of radar observation (Riley et al., 1991). The rising up continues 2 h or until the 16.5 °C level is reached in the model. If the 16.5 °C level is sufficiently high in the warm regions, planthoppers can reach at the height about 1400 m above the ground in 2 h. The low-level jet generally appears around 925–700 hPa levels (about 700–3000 m above the ground), thus such planthoppers reach the low-level jet within 2 h and have possibility to reach Japan in about 1 day. On the other hand, planthoppers in the cold domain hardly reach the low-level jet since the 16.5 °C level is comparably low.

The fourth assumption is based on a preliminary numerical analysis showing that the mass transport from the south-end of China to Japan required 1.5–2 days. Thus, the releases of planthoppers occurring 2 days before the start of sampling are considered in the simulations. Although the maximum duration of continuous wing-beating observed in laboratory experiments is about 1 day (Ohkubo, 1981), there are no data on the possible flight time of planthoppers in nature. The dependency of estimated release areas on flight time is discussed in Section 5.1.

For the fifth assumption, the amount of planthoppers comparable to the net-trap data can be calculated by the following equation:

$$n_p = V_p S_{\text{trap}} t_{\text{int}} C_p|_{z=1}, \tag{1}$$

where V_p is the wind speed at the net-trap point, S_{trap} the area of the mouth of the trap, t_{int} the integration time (24 h in this simulation; see Section 3.2), and $C_p|_{z=1}$ is the calculated surface air concentration by GEARN at the net-trap point integrated in time interval equal to the sampling interval.

The movement of a marker particle that represents the planthoppers at each time step is described by two basic processes: transport by the three-dimensional mean wind, and turbulence diffusion. Mean wind fields are provided from MM5 at intervals of 1 h.

The location of a particle for sequential time steps with the time interval of Δt is determined from

$$x_{i+1} = x_i + u_m\Delta t + R_{x,m}, \qquad y_{i+1} = y_i + v_m\Delta t + R_{y,m},$$

$$z^*_{i+1} = z^*_i + w^*\Delta t + \frac{\partial K^*_z}{\partial z^*}\Delta t + R_{z^*} \tag{2}$$

where $(x, y, z^*)_i$ and $(x, y, z^*)_{i+1}$ are the positions of a particle at the start and end of the time step, (u_m, v_m, w^*) the wind velocity and m is the map scale factor. $R_{x,m}$ and $R_{y,m}$ are the horizontal diffusion terms and R_{z^*} is the vertical diffusion term. The horizontal diffusion terms are defined as

$$R_{x,m} = \sqrt{24K_{x,m}\Delta t}\,R_n, \qquad R_{y,m} = \sqrt{24K_{y,m}\Delta t}\,R_n, \tag{3}$$

where $K_{x,m}$ and $K_{y,m}$ are the horizontal diffusion coefficients ($K_{x,m} = K_{y,m} = K_{\text{hor}}$ is assumed in this model). R_n is a uniform random number between 0 and 1. The horizontal diffusion coefficient K_{hor} is derived from the mean-square displacement of horizontal diffusion σ^2_{hor} as follows:

$$K_{\text{hor}} = \frac{1}{2}\frac{d\sigma^2_{\text{hor}}}{dt}. \tag{4}$$

The formulation of σ^2_{hor} is given by Gifford (1982):

$$\sigma^2_{\text{hor}} = 2K_L t + \frac{V_0^2}{\beta^2}(1 - e^{-\beta t}) + \frac{K_L}{\beta}(-3 + 4e^{-\beta t} + e^{-2\beta t}), \tag{5}$$

where t is the travel time of each particle. According to Gifford, the values of the large-scale eddy diffusivity K_L, the initial speed of a particle V_0 and the inverse of time scale β are 5×10^4 m^2 s^{-1}, 0.15 m s^{-1} and 10^{-4} s^{-1}, respectively. The vertical diffusion coefficient K_z is calculated by MM5.

The air concentration at each Eulerian grid cell C_p is computed by summing up the number of marker particles in the each grid cell as

$$C_p = \frac{1}{V}\sum b_n q_n, \tag{6}$$

where V is the volume of the grid cell, q_n the attribute of quantity of planthoppers given to each particle, and b_n is the contribution ratio of n-particle to the grid cell. The parameter b_n is defined as the overlap ratio of a Lagrangian cell whose center is a particle position to the Eulerian model cell. The unit of C_p is n m^{-3}, where n is the number of particles. C_p at the first layer is provided for Eq. (1).

3. Source term estimation

3.1. Concept of the source term estimation

A case study to find the release area was carried out by the source term estimation function included in WSPEEDI. The following four parameters were estimated in the original function for nuclear emergency: the release point, release rate, release starting time and release periods. Three of these parameters—i.e., all but the release rate—are determined by the following procedure: (1) making a matrix of possible release points, release starting times, and release durations; (2) carrying out the atmospheric dispersion simulations for the possible conditions using parallel processors; (3) comparing the results with the monitoring data by statistical analysis of the normalized mean square error (NMSE); (4) choosing the release condition best-fitted to the monitoring data as the source term. Finally, the release rate is determined by the ratio of the relative concentration calculated under the assumption of 'unit release', 1 Bq h^{-1} for radionuclides, to the monitoring data.

The release areas of planthoppers are estimated by applying this function, since the release starting time and period are already assumed based on field observations, as mentioned in Section 2.2. The difference between applying the model to a nuclear emergency and using it to find the release area of planthoppers is that the migration to Japan may be the result of several release areas, whereas a single release point is derived as a solution for nuclear emergency. The candidates of sources are points for nuclear accident and rectangular areas for planthoppers. Source strength is Bq h^{-1} for nuclear accident and 1 planthopper h^{-1} m^{-2} for planthoppers. Moreover, the method for finding a release area by the NMSE between observations and calculations cannot be used, since there is no clear temporal and spatial representation of the observed data (a detailed description of this phenomenon is given in Section 5).

The correlation between the simulated and observed numbers of immigrating planthoppers is evaluated by using the Spearman's coefficient of rank correlation (Sokal and Rohlf, 1995). When the ranking of each simulation and observation value is represented as (ξ_i, η_i), the correlation coefficient r_s is defined by

$$r_s = 1 - \frac{6}{n(n^2-1)} \sum_{i=1}^{n} (\xi_i - \eta_i)^2, \qquad (7)$$

where n is the number of net-trap points. The highly correlated areas and release start times are picked up as release information. Spearman's coefficient of rank correlation is obtained by using the statistical discovery software JMP® (SAS Institute Inc., 2002).

The release rate of planthoppers is not estimated in this case study since the reliability and the spatial resolution of observation data is insufficient. This is one of the future plans.

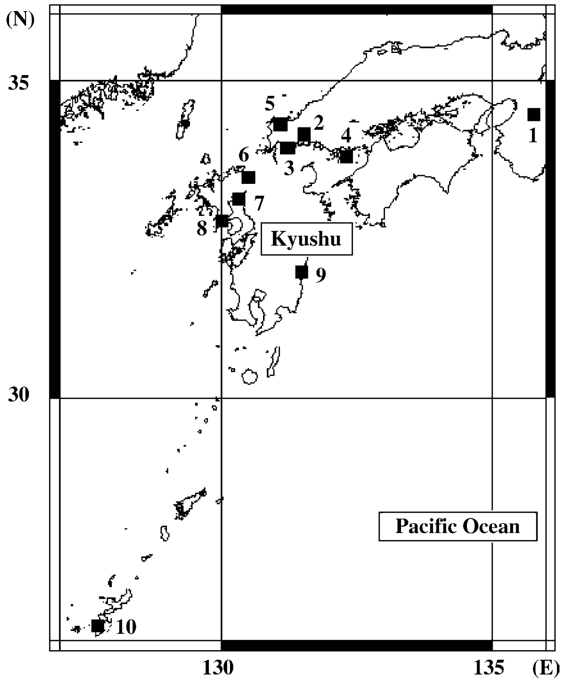

Fig. 2. Ten net-trap observation points in western Japan. The numbers in the figure are corresponding to the point number of Table 1.

3.2. Case study

A case study was carried out to simulate the migration and the source term estimation for the first arrival of planthoppers to western Japan on 13 June 1998. The catch data of *S. furcifera* taken from 10 observation points in western Japan were used (Fig. 2 and Table 1). In these observation points, two net traps, 1 m in diameter, mounted at 10 m above the ground were employed for monitoring the planthopper immigration. A 13 June net-trap catch means a catch made from 00 UTC 13 June to 00 UTC 14 June.

Table 1
The number of planthoppers caught at each observation point on 13 June 1998

	13 June
Nara (Pt. 1)	0
Yamaguchi 1 (Pt. 2)	1
Yamaguchi 2 (Pt. 3)	0
Yamaguchi 3 (Pt. 4)	5
Yamaguchi 4 (Pt. 5)	25
Chikushino (Pt. 6)	0
Kawazoe (Pt. 7)	302
Isahaya (Pt. 8)	22
Sadohara (Pt. 9)	0
Naha (Pt. 10)	0

The calculation domain is a 4200 km × 4200 km area including East Asia. The area is divided into computational grids of 140 × 140 with a resolution of 30 km. The vertical dimension of the computational area is up to 150 hPa and divided into 23 grids.

Concerning the meteorological calculations by MM5, meteorological fields are initialized by numerical analysis data from Japan Meteorological Agency (1998), whose horizontal and temporal resolutions are 1.25° and 6 h, and they have 17 vertical layers. The Schultz (1995) scheme including the ice-graupel processes is used here for the explicit microphysical parameterization, the Grell scheme (Grell, 1993) for the cumulus model, and the MRF scheme (Hong and Pan, 1996) for atmospheric boundary layer and ground surface temperature. MM5 outputs meteorological fields every hour.

For the source term estimation, 56 areas with a width of 2° of latitude and longitude, as shown in Fig. 3, are assumed to be possible release areas. The southwest and northeast corners of the domain including 56 areas are (107°E, 17°N) and (123°E, 31°N), respectively. The release amount from all possible release areas is uniform as 1 planthopper h^{-1} m^{-2}. In the model, 10^5 particles h^{-1} and per an area are released. Such assumption is adopted since there is no data of the take-off quantity of planthoppers. As long as correlation is used for statistical evaluation, their absolute take-off quantity is not required. The release height is set as 1 m above the ground. The contribution from areas over the sea surface is zero even if the migration of planthoppers from these areas to Japan is meteorologically possible.

Four possible release starting times at 10 and 21 UTC on 11 June and 12 June for the sampling of 13 June are assumed for migration to western Japan. Fig. 4 shows the conceptual diagram of the release start time and integration time.

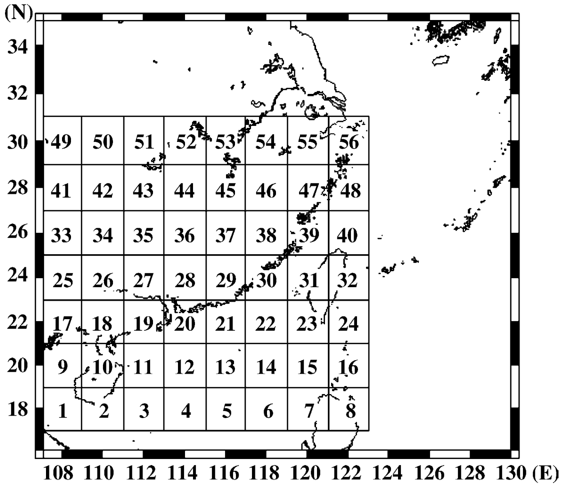

Fig. 3. The 56 possible release areas with a width of 2° of latitude and longitude width. Taiwan is mainly located in the areas of nos. 31 and 32, and Fujian is located around the areas nos. 29, 30, 37 and 38.

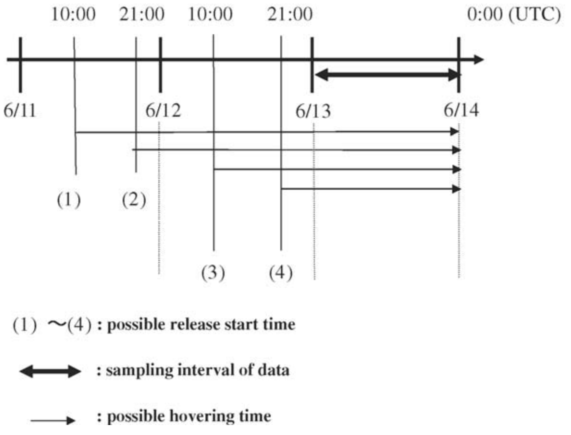

Fig. 4. The conceptual diagram of the release start time and integration time.

In order to calculate the Spearman's coefficient of rank correlation between calculation and observation, the integral period of calculation is set to 24 h, which is equal to the sampling interval. The movements of all planthoppers are treated until the end of 13 June in this simulation. Because of the condition for take-off times, the calculation duration time is only discontinuously determined as shown in Fig. 4 (27, 38, 51, and 62 h).

4. Results

4.1. Meteorological fields

Fig. 5 shows the wind field at 850 hPa calculated by MM5 at 00 UTC, 10–14 June 1998. The low-level jet began to progress on 11 June, and the wind direction of the low-level jet around the East China Sea changed from the southeast to the west–southwest through 12 June and 13 June. According to weather charts, the Bai-u front existed far from southern coast of Japan before 11 June, and it began moving to Japan with a depression generated in China from 13 to 14 June. The report of JMA described that active convections existed in southern China and cold high pressure existed in the northeast region of Japan. The calculation results therefore agreed well with these weather reports. Fig. 6 shows the horizontal distribution of the 16.5 °C level from MM5 at 00 UTC, 11 June. The 16.5 °C level in China was at a high altitude, e.g., 2000 m above sea level, while that in Japan was at a low altitude.

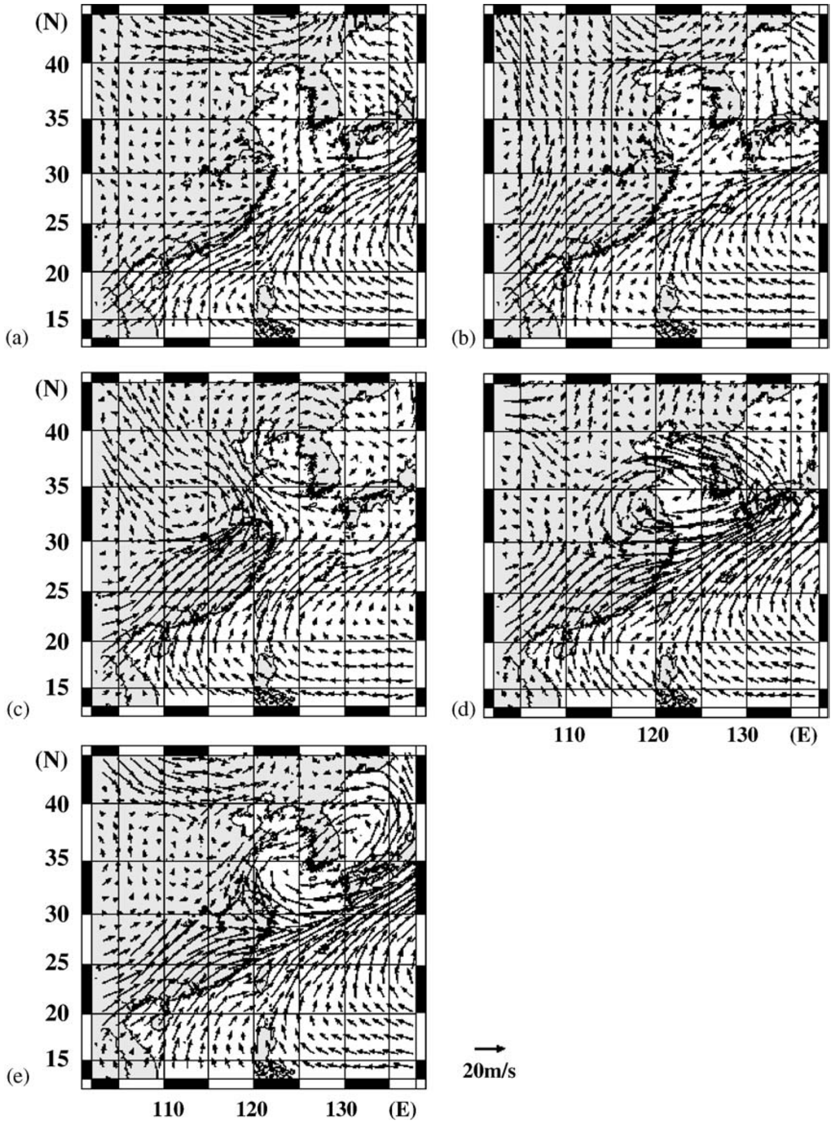

Fig. 5. The wind field at 850 hPa calculated by MM5 at 00 UTC, 10 June 1998 (a), 11 June 1998 (b), 12 June 1998 (c), 13 June 1998 (d), 14 June 1998 (e).

4.2. Release area estimation

Fig. 2 shows the distribution of 10 net-trap points in western Japan, and Table 1 shows the number of white-backed planthoppers, *S. furcifera* caught on 13 June 1998. There were more than 300 planthoppers at Kawazoe, 25 or fewer planthoppers at Yamaguchi 1, 3, 4 and Isahaya, and no planthoppers at Nara, Yamaguchi 2, Chikushino, Sadohara and Naha.

Fig. 7 is the vertical and horizontal distributions of planthoppers released from the area no. 38 at 11 June, 21 UTC. According to the effect of the initial rising velocity explained in Section 2.2, planthoppers were distributed over the height of 1500 m from the ground surface at 2 h from the release starting time (Fig. 7a). After that, they moved northeastward by southwest winds (Fig. 7b and c). Since the low-level jet existed around the areas, the moving velocity at higher altitude is larger than that at lower altitude. Planthoppers had already arrived in Japan after 27 h, and its vertical distribution had shifted to lower altitude since they moved into the colder domain than the release area (Fig. 7d).

The Spearman's coefficients of rank correlation between calculated concentrations from 56 release areas and sampling data are estimated for the following four cases: (a) calculated concentrations at sampling points from each release area are the sum of them due to four releases [(1) + (2) + (3) + (4)] in Fig. 4, (b) due to

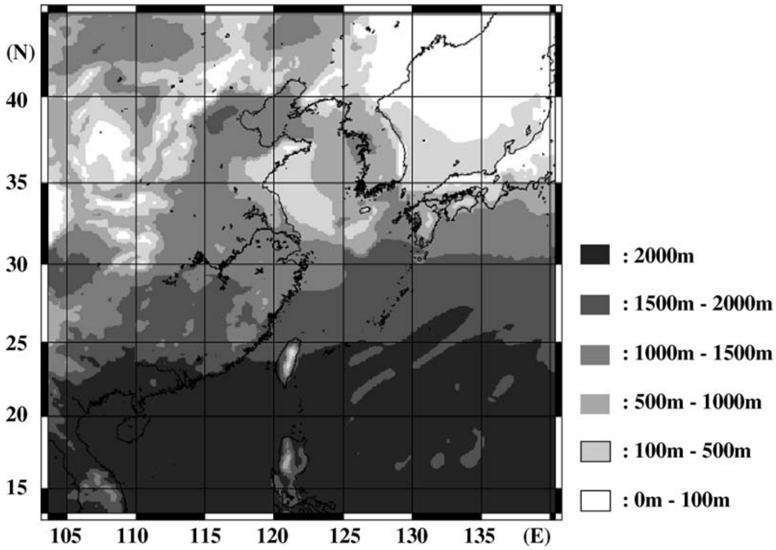

Fig. 6. The horizontal distribution of the 16.5 °C level from MM5 at 00 UTC, 11 June 1998.

three releases [(2) + (3) + (4)], (c) due to two releases [(3) + (4)], and (d) due to [(4)].

Table 2 shows the results of the estimated release areas by using the Spearman's coefficient of rank correlation. We set the significance level is 0.15. There are some reasons of the low significance level; limited number of net-trap points, observation frequency (once a day), and possibility that more than two release points contribute single observation.

No areas are below 0.15 in the cases of (c) and (d). This means that the releases (3) and (4), i.e., 10 UTC and 21 UTC 12 June, do not contribute to the migration of planthoppers to these areas on 13 June, whereas the release starting times (1) and (2) on 11 June made a large contribution.

The result of (a) contains a wide region ranging from the comparatively near (northern) areas to Japan, such as nos. 45 and 53, to the far (western) areas, such as nos. 27 and 20. The area no. 32 includes Taiwan, which is seldom considered as a source but is estimated as one in this simulation.

On the other hand, only five estimated areas whose probability is below 0.15 appeared in the result of (b). The limited areas around Fujian, southeastern China, and the comparatively near (northern) areas are estimated in this condition.

5. Discussion

5.1. Dependency of the estimated release area on flying time

Since the simulation has the capability to output results with finer temporal resolution, we will first discuss

Table 2

The results of the estimated release areas by using the Spearman's coefficient of rank correlation

	(1) + (2) + (3) + (4)			(2) + (3) + (4)		
	Area	Correlation	Probability	Area	Correlation	Probability
1st	45	0.726	0.014	45	0.619	0.038
2nd	27	0.644	0.031	38	0.496	0.087
3rd	32	0.559	0.059	37	0.444	0.116
4th	38	0.496	0.087	53	0.413	0.135
5th	53	0.490	0.091	46	0.393	0.148
6th	35	0.470	0.101			
7th	31	0.468	0.102			
8th	20	0.444	0.116			
9th	37	0.444	0.116			

Areas whose probability is below 0.15 are shown.

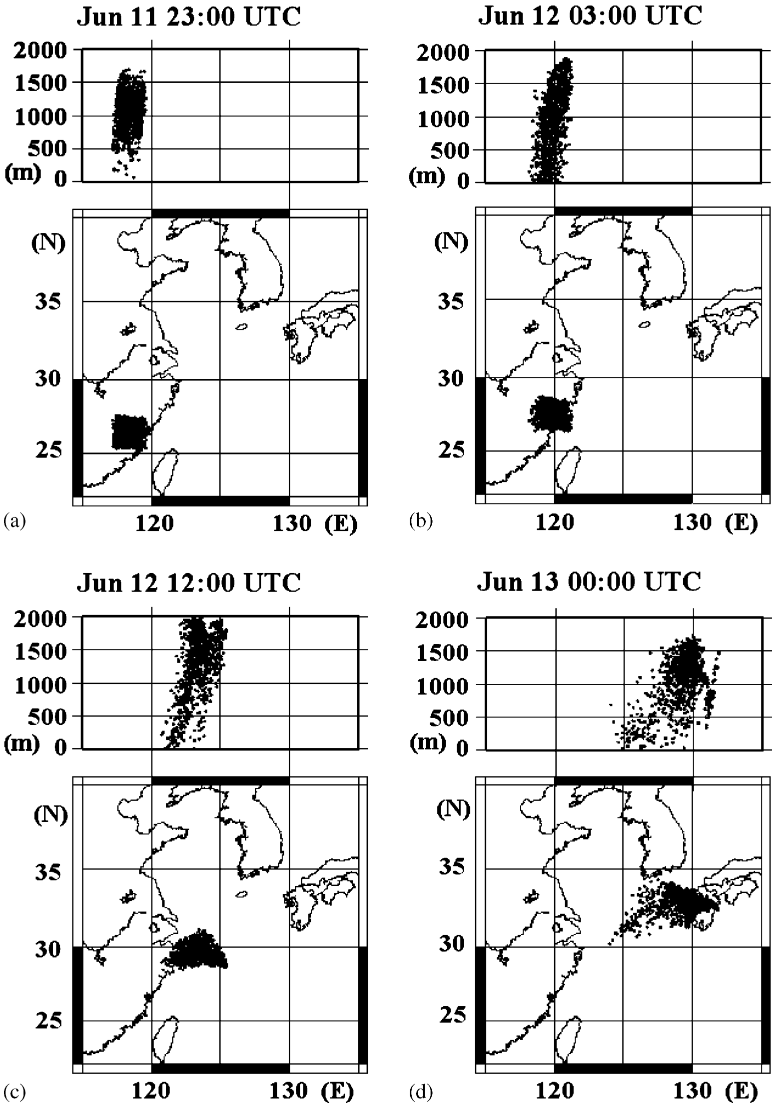

Fig. 7. The vertical (upper) and horizontal (lower) distributions of planthoppers at: (a) 11 June, 23 UTC (2 h after the release starts), (b) 12 June, 03 UTC (6 h), (c) 12 June, 12 UTC (15 h), and (d) 13 June, 00 UTC (27 h). The release area is no. 38, and the release start time is 11 June, 21 UTC.

the influence of the length of possible flying times on the estimated results by using finer calculated results.

Fig. 8 shows the time series of the calculated concentrations of planthoppers over each hour at the ground level at Isahaya. The top figure shows the results of release from the northern area no. 45 at 10 UTC 11 June (hereafter 10 UTC-45), the second, 10 UTC-20, shows the results of release from the south coastal areas, the third, 10 UTC-32, shows the results of release from areas including Taiwan, and the last, 21 UTC-38, shows the results of release from areas including Fujian. These figures show, for example, that planthoppers released from area no. 45 at 10 UTC 11 June reached Isahaya with a flying time of 54 h, planthoppers released from area no. 20 reached Isahaya with a flying time of 38 h, etc.

The difference of the appearance time of the peaks can be explained by the passage of the depression or the rain front (see Fig. 5). Planthoppers released from the eastern areas nos. 32 and 38 easily reach the strong low-level jet stream that existed over the East China Sea, and can arrive at western Kyushu in a short period. The sharp peak in the third and fourth figures appearing from the end of 12 June to the beginning of the 13 June is due to this condition. On the other hand, the planthoppers released from the northern areas such as nos. 45 and 53 did not advance to the

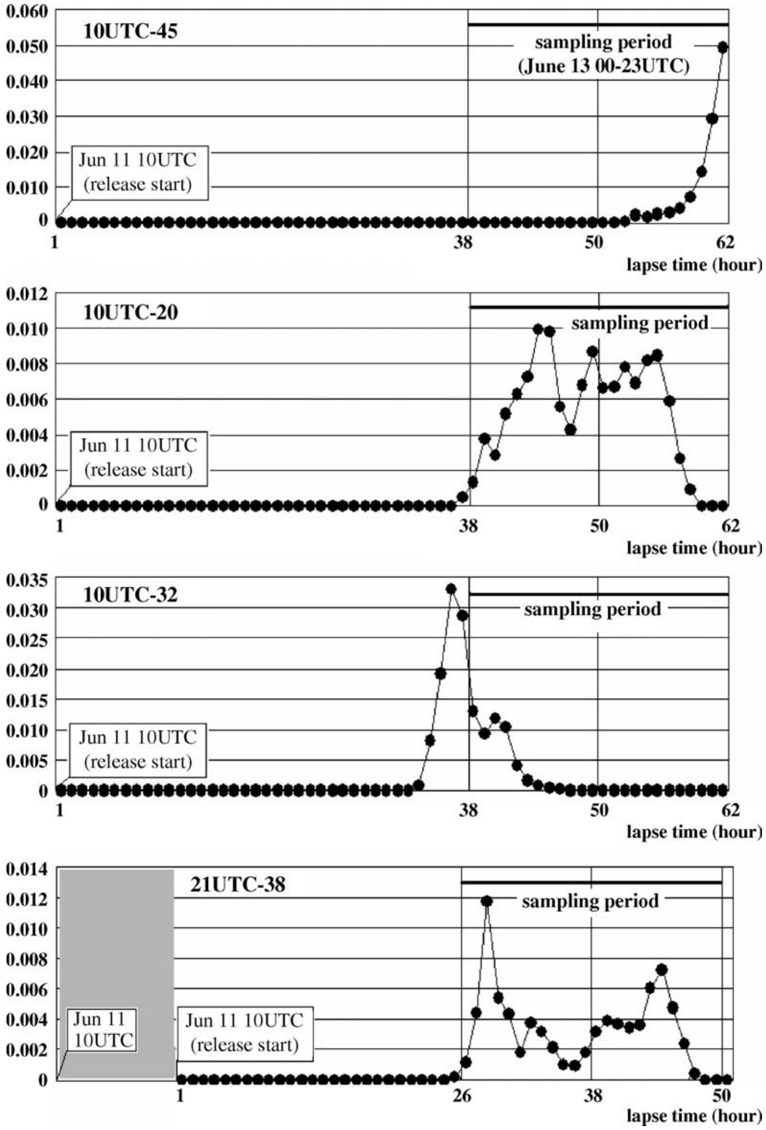

Fig. 8. The time series of the calculated concentrations of planthoppers over each hour at the ground level at Isahaya. The caption 10 UTC-45 means the results of release from the area no. 45 at 10 UTC 11 June.

region of the strong westerly winds, since the 16.5 °C level of these areas is generally lower than the height of the low-level jet, and since the low-level jet stream did not appear above these areas until the passing of the depression on 13 June.

Table 3 classifies the peak appearance times of concentrations of planthoppers at Isahaya by results (a) and (b) from the release areas listed in Table 2. Assuming that the maximum flying time is about 60 h, all the results of Table 2 may be possible as the source. If the maximum flying time is shorter, however, some conditions can be eliminated. For example, if it is less than 50 h, release conditions that include northern release areas such as 10 UTC-45 and 10 UTC-53, are eliminated, since the appearance time of the peak is over 50 h from the release starting time.

Similarly, the conditions of the release starting time of 10 UTC 11 June, except 10 UTC-32 and 10 UTC-31, which include Taiwan, and the conditions including northern area 21 UTC-53 are eliminated if the maximum flying time is about 38 h. Only the conditions 21 UTC-38 and 21 UTC-37 remain as possible conditions when the possible flying time is within 30 h.

Since the maximum flying time is about 1 day (Ohkubo, 1981), the area nos. 37 and 38 around Fujian and the release starting time at 21 UTC 11 June have the

Table 3
Classification of the peak appearance times of concentrations of planthoppers at Isahaya by results (a) and (b) from the release areas listed in Table 2

62 h		50 h		38 h	
Time-area	Appearance time of peaks	Time-area	Appearance time of peaks	Time-area	Appearance time of peaks
10 UTC-45	54–62	10 UTC-27	41–46	10 UTC-32	33–44
10 UTC-27	41–46, 47–60	10 UTC-32	33–44	10 UTC-31	34–47
10 UTC-32	33–44	10 UTC-35	43–62	21 UTC-45	31–36
10 UTC-38	57–62	10 UTC-31	34–47	21 UTC-38	26–36
10 UTC-53	53–62	10 UTC-20	38–59	21 UTC-37	29–48
10 UTC-35	43–62	21 UTC-45	31–36, 38–50	21 UTC-46	33–34
10 UTC-31	34–47	21 UTC-38	26–36, 37–48		
10 UTC-20	38–59	21 UTC-37	29–48		
10 UTC-37	54–62	21 UTC-53	39–51		
21 UTC-45	31–36, 38–50	21 UTC-46	33–34, 39–50		
21 UTC-38	26–36, 37–48				
21 UTC-37	29–48				
21 UTC-53	39–51				
21 UTC-46	33–34, 39–50				

Appearance times of peaks are expressed as the lapsed time (h) from the release starting time.

highest possibility of the source conditions. If a slightly longer flying time is also possible, Taiwan and the northern area of Fujian are also identified as release sources.

Table 2 indicates that the estimated release area becomes wider with increasing flying time of planthoppers. Because immigrant planthoppers are treated only as the sum over 24 h, there is no way to judge the appearance time and duration time of immigration peaks in this period. Thus, the accuracy of the estimation result of Table 2 is the limit at the present sampling interval.

If the sampling interval becomes shorter, however, detailed estimations like those shown in this section become possible. The temporal resolution of the sampling interval is one of the most important parameters affecting the calculation accuracy.

5.2. The critical temperature to determine the activity of planthoppers

According to the normal temperature of weather station data from Japan Meteorological Agency (1998), the 16.5 °C contour traverses from southwest to northeast Japan from May to July. Thus the critical temperature for hovering is serious for this season of Japan. For example, Fig. 9 shows the 15.5, 16.5, and 17.5 °C contours at the 850 hPa level on 00 UTC 13 June drawn from the Global Analysis Data of Japan Meteorological Agency. The width of contours per 1 °C at this altitude is several 10 km. This means that the assumption to restrict the activity of planthoppers in the atmosphere below 16.5 °C considerably affects the simulation results. If the experimental result to derive the critical temperature of 16.5 °C has an error of 1 °C,

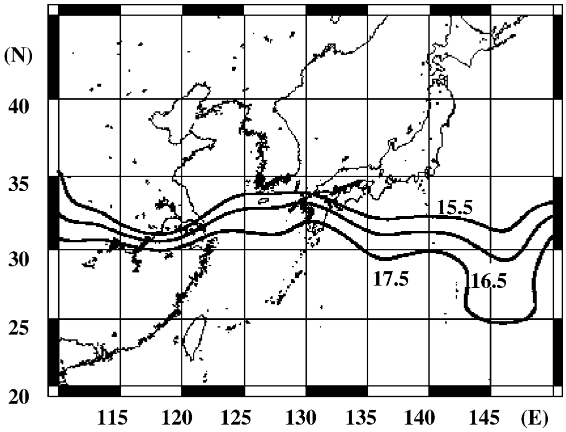

Fig. 9. The 15.5, 16.5, and 17.5 °C contours at 850 hPa level on 00 UTC 13 June drawn from the Global Analysis Data of Japan Meteorological Agency.

this results in a difference of several tens of kilometers north or south in the distribution of planthoppers. Thus, the choice of 16.5 °C as the critical temperature should improve the reliability from an entomological viewpoint.

5.3. Spatial representation of observed data

The difference in the number of planthoppers caught at the three net-trap points, Chikushino, Kawazoe, and Isahaya, in northern Kyushu could not be well reproduced by these calculations. There was a comparatively large difference in the number of captured planthoppers between Chikushino and Kawazoe, although the distance between the two net-trap points was only 40 km. If this difference was due to entomological phenomena, some modification of the model would be needed for more significant comparison between the calculated and observed results. Otherwise, if it is due to the local terrestrial effect near the net-trap points, the uncertainty of the spatial representation of observed data should be evaluated. For this purpose, it is necessary to make observations at higher spatial resolution.

5.4. Generality of the estimated release area

We also calculated the migration from Taiwan, which has never previously been considered. The results suggested that Taiwan is also a possible source of planthoppers in Japan, depending on the wind direction. Such migration would be considerably influenced by the structure of the low-level jet, which is affected by the summer monsoon. Although the active seasonal rain front and the strong southwestward low-level jet appearing in this case study are typical for June, the state of the summer monsoon varies interannually. Therefore, further case studies on planthopper migrations in other years will be needed to generalize the source term information of planthoppers.

6. Concluding remarks

A new numerical simulation model for long-range migration of rice planthoppers was developed. The model was applied to a case study for the estimation of release areas of planthoppers migrating to Japan by comparing calculation results with observations. The results showed that not only the areas around Fujian, where a lot of paddy fields exist, but also unexpected areas, including Taiwan, are possible source areas for this case.

These results are obtained when the probability was set to 15%. However, it is difficult to apply the higher probability for more accurate estimation, since it is hard to gain the observation data of take-off amount in South Asia, and since the temporal resolution and accuracy of net-trap catch data are insufficient. Thus, we need to apply this estimation method to other several cases to increase the accuracy of the results. The increase of observation points and their reliability for calculating the Spearman's coefficient of rank correlation is also one of the future subjects.

It was also shown that the calculation results were affected by the following parameters: the critical temperature of 16.5 °C used to determine the activity of planthoppers and the possible flying time. It is important to increase the accuracy of these related parameters in order to improve the accuracy of the simulation.

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