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Migration of rice planthoppers and simulation techniques

Akira Otuka

To analyze and predict long-distance migration of rice planthoppers, a variety of simulation models have been developed in the past. Initially, synoptic weather charts were used to find the relationship between immigrations and weather conditions. Subsequently, many two-dimensional computer simulation models have been proposed to predict migrations. Although these models were successful in migration prediction, there is room for improving prediction quality. A first three-dimensional simulation model was developed in the late 1990s, and it showed considerable advancement in prediction technologies. Recently, a migration prediction system was developed using a new Lagrandian type of three-dimensional model, and it presents real-time information on timing and areas of migration in eastern Asia. This chapter summarizes a history of state-of-the-art simulation models and presents recent migration analyses using these simulation techniques.

The brown planthopper *Nilaparvata lugens* (Stål) and the whitebacked planthopper *Sogatella furcifera* (Horváth) are major pests of rice in Asia. Many studies on the migration of these species, especially in East Asia, have been intensively conducted with a variety of methods, such as catches on ships and airplanes as well as in rice fields and on the tops of mountains (e.g., Kisimoto 1971, Ohkubo and Kisimoto 1971, Kisimoto 1976, Cheng et al 1979, Dung 1981, National Cooperative Research Group of Brown Planthopper 1981a,b). Meteorological analyses, radar observations, and mark and recapture field experiments have also been conducted (e.g., Kisimoto 1976, Nanjing Agricultural College et al 1981, Rosenberg and Magor 1983, Seino et al 1987, Watanabe and Seino 1991, Riley et al 1991, Sogawa 1995, Turner et al 1999). Based on these studies, it is now believed that the species migrate for long distances ranging from northern Vietnam to China, Korea, and Japan in a few generations.

The temporal change of the biotypes of various *N. lugens* populations indicated that the populations in Asia are grouped into three: the East Asian, Southeast Asian, and South Asian (Sogawa 1992). These populations have been shown to have different properties of insecticide susceptibility (Nagata 2002, Nagata et al 2002) and wing-form response (Nagata and Masuda 1980, Iwanaga et al 1987), as well as feeding

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on resistant rice varieties (Sogawa 1992, Tanaka and Matsumura 2000). *N. lugens* occurring in the region ranging from northern Vietnam, China, and Korea to Japan belongs to the East Asian population (Sogawa 1992).

To analyze and predict the migration of the East Asian population, several two-dimensional methods have been proposed. For example, to find the migration source, backward trajectories in the wind fields obtained from upper-air data every 6 h have been calculated by using a streamline-isotach method (Rosenberg and Magor 1983). A similar two-dimensional model has been used for migration prediction in China (Zhou et al 1995). A prediction model that uses low-level jet development over the East China Sea was proposed (Seino et al 1987). Based on this model, a software application to predict migrations was developed (Watanabe et al 1990, 1991). To estimate migration sources for immigrants into western Japan, Sogawa (1995) used a backward trajectory analysis of migrations from 1987 to 1990 with 12-hourly data. However, since these methods used only weather data at a particular pressure level (mainly at 850 hPa) at long time intervals such as 6 or 12 hours, their analytical and prediction qualities were limited spatially and temporally. Moreover, a previous study by means of airplane collection indicated that the flight height of rice planthoppers flying over southern China in July over three years ranged from 300 to 2,500 m, with a peak of the aerial density at 1,500 to 2,000 m (Dung 1981). In late September and October, the flight height decreased to 500 to 1,000 m. The aerial density at lower levels dynamically changed to show an increase due to the drop in air temperature during weather changes (Dung 1981). Additionally, a radar observation in September in China revealed that the layers of these insects often had well-defined ceilings corresponding to an air temperature of 16 °C (Ohkubo 1973, Riley et al 1991). Since the insects dynamically fly at various altitudes depending on the air temperature, a migration simulation in three dimensions that can calculate aerial densities and trajectories at different levels has been needed.

Recently, three-dimensional migration models have been developed to improve analytical and prediction qualities. There are two types of migration models: one is a temporally forward model and the other is a backward one. The forward model calculates temporal evolution of the aerial density of rice planthoppers. The backward model tracks planthoppers' trajectories backward from an immigrated area to the source. This chapter reviews these recent models and their migration analyses.

Analyses by three-dimensional models

BLAYER model

Features of the model. A three-dimensional atmospheric numerical model for planthopper migration, BLAYER, was developed for the first time by an international team with researchers from New Zealand and South Korea (Turner et al 1999, Zhu et al 2000). This model simulates atmospheric flows in the boundary layer less than 2,200 m above the ground. It is a hydrostatic model. The relative aerial density of planthoppers in each grid cell of 0.5 degrees (about 50 km at mid-latitudes) is calculated by directly solving an advection-diffusion equation. This is a so-called an

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Eulerian representation, in which the grid points are fixed, and parcels of flowing air with planthoppers are convected across the grid from one cell to another. Because of the lack of knowledge on the migration process, the following assumptions are made for the modeling of major immigrations into Korea in June and July: the source of rice planthoppers is assumed to be two regions depending on month—one a region south of 25°N and east of 105°E for analyses in June (mainly Guangdong and Guangxi in China and northern Vietnam), and the other a Chinese region north of 25°N, south of 30°N, and east of 105°E for analyses in July. The source moves with time because rice planthoppers invade northern regions in southern China in later seasons (Cheng et al 1979). Rice planthoppers are presumed to take off at 0900 local time, or 0100 UTC (Universal Time Coordinate), and to keep flying during the prediction duration of 48 h without landing along the way. It is also assumed that they fly at altitudes from 500 to 2,200 m (the model top).

Analytical results. The simulation results showed that the model could explain the large migrations captured by daily light traps in South Korea (Turner et al 1999). The model could reproduce the first migration of the season in early June and major migrations from late June to early July (Turner et al 1999).

The study importantly pointed out that the wind direction in the lower troposphere changes at different levels. When a geostrophic southwest wind blows parallel to isobars at a high level of 850 hPa, which is often the case in the *Bai-u* rainy season in East Asia, a southerly wind blows at the surface level. This is due to the surface friction of the rotating Earth, and this phenomenon is called the Ekman Spiral (Stull 1988, Ogura 1971). Therefore, the flight heights of migrants may affect their arriving areas. Inversely, immigrants arriving at different heights over the monitoring site may have come from different source regions.

BLAYER was successful for the planthopper migration simulation. However, there seems to be some room for improvement: (1) the top level of the model is limited (2,200 m), whereas the atmospheric dynamics above this layer are also important to simulate an accurate state of the whole atmosphere; (2) the takeoff time was mainly set to 0100 UTC, but observed takeoff events of rice planthoppers occur at dusk and dawn, or at about 1000 and 2100 UTC in summer (Ohkubo and Kisimoto 1971, Lai 1982, Riley et al 1991).

Backward trajectory analysis model (BTA model)

Features of the model. To estimate possible migration sources, models to calculate the backward trajectories of planthoppers from monitoring trap sites have been used. The first three-dimensional model is one developed by Otuka et al (2005a). The method employs both an advanced weather forecast model and a BTA model. The weather forecast model, MM5, calculates three-dimensional wind fields with temporally and spatially high resolutions and the BTA model calculates three-dimensional backward trajectories using simulated winds.

MM5 is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation (Anthes and Warner 1978, Grell et al 1994, NCAR 2003). The model has

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many sophisticated features such as choices of physical parameterization, multiple nesting capability, simulation output of high temporal and special resolutions, and global relocatability of calculation domains (NCAR 2003). This last feature enables researchers to simulate the atmosphere anywhere on Earth if global initial data are available. For analyses of past migration events, the initial data used in the simulation are NCEP/NCAR reanalysis data, which are 6-hourly global data with a 2.5-degree horizontal resolution (Kistler et al 2001). The horizontal resolution of the calculation domain is set at 33 km. The model's top level is usually 100 hPa (about 16 km in the standard atmosphere), and therefore the model simulates atmospheric flows in the troposphere as well as a lower part of the stratosphere. In the vertical direction, there were 24 levels from the surface to the top. The model outputs simulated data at 1-hour intervals.

In the BTA model, it is assumed that planthoppers travel at the same velocity as the wind during flight. Therefore, backward trajectories are calculated simply by the following equations:

$$\begin{aligned} x(t-1) &= x(t) - Udt \\ y(t-1) &= y(t) - Vdt \\ z(t-1) &= z(t) - Wdt \end{aligned} \tag{1}$$

where (x, y, z) denote insect position, (U, V, W) spatially and temporally interpolated values of wind velocity output by MM5, and t the calculation time step. One time step (dt) is set to 50 sec. The equations apparently do not consider air temperature in any way. Trajectories start over the trap site on a catch date and are terminated at dawn or dusk, when *N. lugens* and *S. furcifera* are known to take off (Ohkubo and Kisimoto 1971, Lai 1982). The distribution of terminal points over the land indicates possible migration sources.

Estimated sources. Kyushu, in the western part of Japan, is the front of immigration in the *Bai-u* rainy season (Fig. 1). Using catch data in both net traps in June from 1988 to 2001 in northern Kyushu and a suction trap in southern Kyushu, backward trajectories were calculated and possible sources were estimated (Otuka et al 2005d). The results indicated that the source was Fujian, eastern Guangdong, southern Jiangxi Province in China and Taiwan (Fig. 2). However, since harvesting of the first rice crop in Taiwan is usually completed by mid-June, only southern China is the possible source for migrations from late June to early July. The results also indicated that the possible source estimated by two-dimensional analysis tended to be the southwestern part of the source region estimated by the three-dimensional analysis. This was due to the difference in wind speed and direction at each level. The wind at 850 hPa, which is used in the two-dimensional analysis, shows higher speed and a more westerly component than the wind at lower levels.

*Cross-boundary migration***.** In the introduction, it was mentioned that the populations in Asia have been grouped into three (Sogawa 1992). The boundary between the East Asian and Southeast Asian populations lies between the Philippines and Taiwan. Migrations across this boundary have been investigated (Otuka et al 2005c). Three

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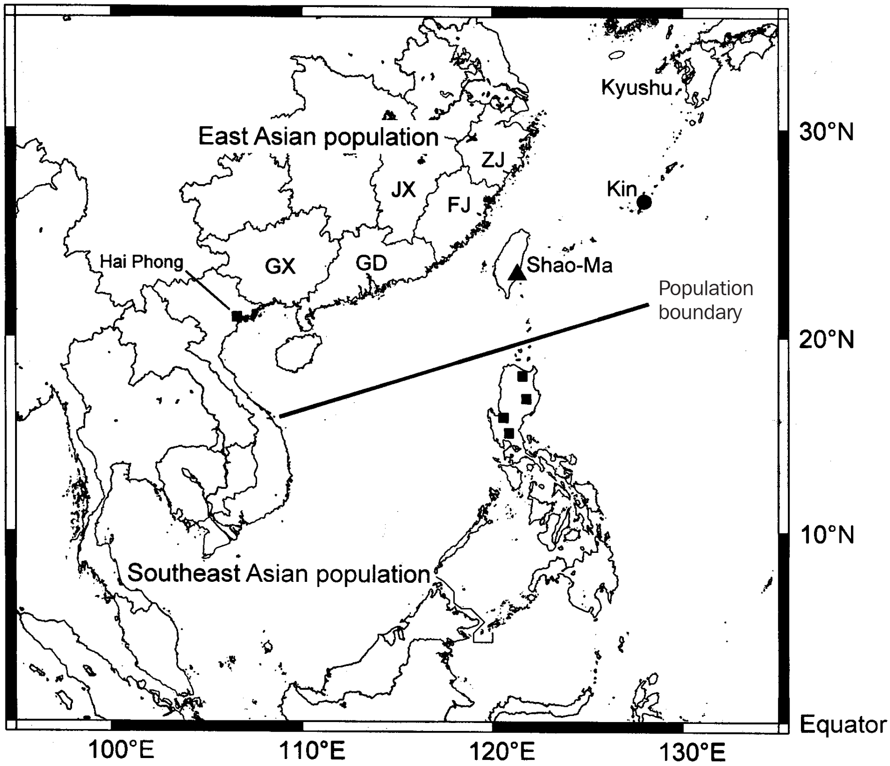

Fig. 1. Area of interest for this chapter. The boundary between the East Asian population and the Southeast Asian population lies between Taiwan and the Philippines. Solid squares in northern Vietnam and Luzon indicated takeoff areas for migration simulation by GEARN.

migration events have been found to be such a cross-boundary migration (CBM). Table 1 shows three peaks of *N. lugens* captured in eastern Taiwan and Okinawa Island of southwestern Japan. Figure 3 shows the distribution of terminal points of BTA for the three peaks. In all cases, the trajectories reached over the Philippines, where its population of *N. lugens* belongs to the Southeast Asian population, having different properties important for pest management such as insecticide susceptibility and wing-form response. It is still unknown how often CBM happens and how much impact on the East Asian population the gene mixing has. Continuous careful monitoring is necessary.

GEARN

Model description. A migration simulation model, GEARN, was developed under cooperation between atomic energy researchers and entomologists in Japan (Nature 2004, Furuno et al 2005). GEARN was originally a simulation model for predicting the dispersion of radioactive particles released in a future potential accident in an atomic

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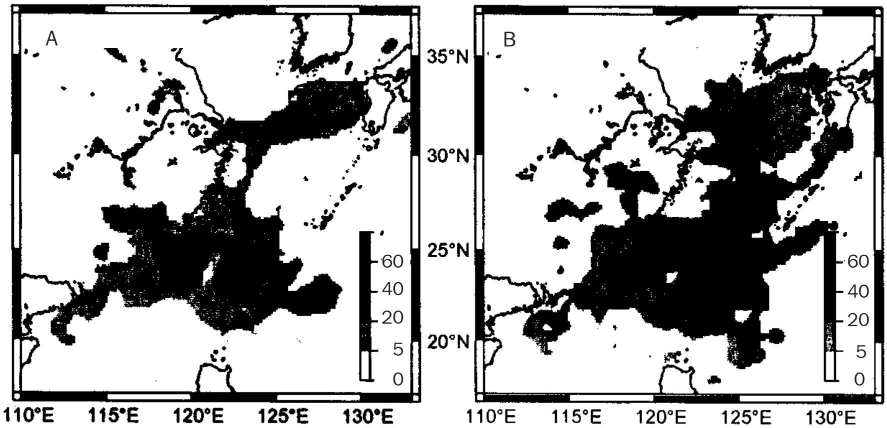

Fig. 2. Distribution of terminal points of backward trajectories that started over northern and southern Kyushu, western Japan. Terminal time was set at dusk or dawn in the source regions. (A) Trajectories started over northern Kyushu on dates with a catch peak in June from 1988 to 2001. (B) Trajectories started over southern Kyushu in June from 1988 to 2001. The number indicates the frequency of terminal points in the mesh of 0.5 degree in latitude and longitude. Gray areas of the land, such as Fujian, Guangdong, and Jiangxi provinces in China and Taiwan, indicate the possible migration source. (Modified from Otuka et al 2005c.)

Table 1. Catch number of *N. lugens* in western Japan and eastern Taiwan.[a]

Date	Site	Net/light trap	Number of *N. lugens*	Symbol in Figure 3
15 June 2000	Kin, Japan	Light	0	
16 June 2000	Kin, Japan	Light	3	
17 June 2000	Kin, Japan	Light	109	Circle
18 June 2000	Kin, Japan	Light	49	
17 June 1999	Kin, Japan	Light	0	
18 June 1999	Kin, Japan	Light	0	
19 June 1999	Kin, Japan	Light	23	Star
20 June 1999	Kin, Japan	Light	2	
26 August 1978	Shao-Ma, Taiwan	Net	36	Triangle

[a] Data from the Japan Plan Protection Network and Liu (1985). No catch of *S. furcifera* was recorded in the Japanese cases.

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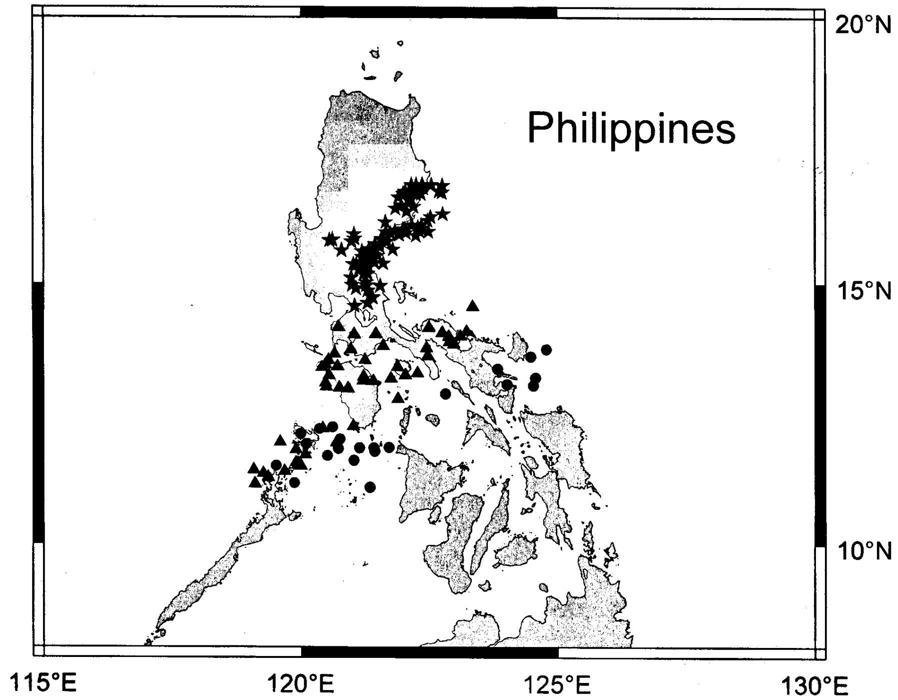

Fig. 3. Distributions of terminal points of backward trajectories that started over Kin and Shao-Ma on the dates of the catch peaks in Table 1. Solid circle indicates terminal point of the trajectories that started over Kin on 17 June 2000. Solid star and triangle indicate terminal points for Kin in 1999 and Shao-Ma in 1978. All the terminal points reached over Luzon. This result suggests cross-boundary migrations from the Philippines to the East Asian population. (Modified from Otuka et al 2005c.)

energy power plant. The model does not calculate the aerial density of planthoppers directly like BLAYER (an Eulerian representation), but traces step by step the three-dimensional positions of many planthoppers during migratory flight, and converts the number of planthoppers in a calculation cell into the aerial density. This is a so-called Lagrangian representation, in which each planthopper moves with flowing air, and the density is calculated as the number of planthoppers in each cell. For planthopper migration study, their various behaviors are mathematically modeled as in Figure 4. First, the model lets planthoppers take off at dawn or dusk in the source. This is based on the observations that *N. lugens* and *S. furcifera* take off during twilight periods of about 100 lx and have two peaks per day (Ohkubo and Kisimoto 1971, Lai 1982). As many as 34,000 insects take off at constant time intervals in 1 hour from random horizontal positions in a takeoff area of 50 km^2. Second, after the takeoff, the planthoppers actively climb upward for 1 hour at a vertical rate of 0.2 m s^{-1}. This rate has been estimated in a radar observation by Riley et al (1991). Third, air currents advect and diffuse the insects, but they won't go beyond the temperature ceiling of 16.5 °C,

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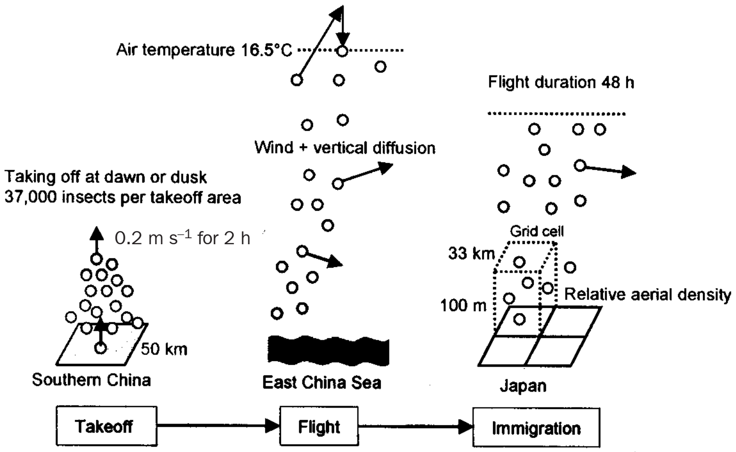

Fig. 4. Schematic diagram of the migration simulation model GEARN. Open circle indicates a planthopper. The insects fly upward for 1 hour after takeoff, and move at the same velocity as the wind, taking vertical diffusion into account. The dotted line indicates an air temperature of 16.5 °C. Planthoppers do not cross this level. Finally, the relative aerial density of the planthoppers over the destination is calculated based upon the number of insects in a grid cell in the lowest layer less than 100 m. (Modified from Otuka et al 2006.)

at which half of *N. lugens* have been found to stop wing-beating in a tethered flight experiment (Ohkubo 1973). Atmospheric data such as wind, temperature, and diffusion coefficients are outputs from the MM5 simulation. During flight, the insects keep flying and do not land on Earth's surface, which is the same as in the BLAYER model. This assumption is made because the landing rate of oversea migrants is unknown at present. The flight duration is set to 48 h. The relative aerial density is computed as insect number per a calculation grid cell at any time step of the simulation.

CBM analysis. By using GEARN, migrations in various regions, such as migrations from China to Japan (Otuka et al 2006), from the Philippines to China and Taiwan (Otuka et al 2005c), and from northern Vietnam to southern China (Otuka et al 2008), have been analyzed. The last two cases are introduced here. As described in the previous section, the backward trajectory analysis revealed that CBMs from the Philippines to East Asia were found to be feasible. If migrations from the Philippines to southern China occurred in the early season, April to June, the next generation of those immigrants in southern China could migrate to farther northern regions in East Asia about one or more months later. Since the insect's properties in the two populations are different from each other, this possible gene mixing could be important for pest management. For this reason, the forward simulation model GEARN estimated possible migrations from the Philippines from April to June under several weather patterns over the South China Sea favorable for such migrations (Otuka et al 2005c). The result showed that 21 migrations at dusk or dawn in 14 days over 10 years from

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1995 to 2004 reached southern China. The typical weather patterns were low-pressure systems or typhoons located in the South China Sea, with winds blowing from the Philippines to China. The destination regions were mainly Guangdong, Fujian, and Hainan provinces, which are the source regions of migrations in the *Bai-u* rainy season. Although this result is circumstantial evidence for CBM, continuous careful attention must be paid to the possible change of the insect's properties due to future gene mixing.

Early migration. Simulation from northern Vietnam to southern China has been conducted with light trap data in northern Vietnam (Otuka at al 2008). Although the general pattern of northeastward migrations of *N. lugens* was proposed in previous studies (e.g., Cheng et al 1979), concrete survey data such as daily light trap data have not been reported. Recently, after an outbreak of *N. lugens* in China in 2005, China's provincial plant protection institutions began to release occurrence information with specific light trap data when large immigration peaks were recorded in their provinces. Migration simulations from northern Vietnam were evaluated with these Chinese light trap data. First, the light trap data at Hai Phong in northern Vietnam indicated that emigration peaks of *N. lugens* and *S. furcifera*, which multiplied on winter-spring rice, appeared in late April to early May (Otuka at al 2008) (Fig. 5A). Setting the dates of these peaks as starting dates, migration simulations were conducted. Figure 5B shows an example of a migration simulation that started over Hai Phong from 1100 to 1200 UTC on 28 April 2005. The destination regions of the area of nonzero aerial density at 24 h after takeoff were found to be distributed over southern Chinese provinces: Guangxi, southern Hunan, Jiangxi, northern Guangdong, and northwestern Fujian (Fig. 5C). The region formed a diagonal belt stretching northeast. In fact, according to the Chinese data, immigration catch peaks appeared in light traps along the diagonal belt region, which supported the simulation results.

Migration prediction

The migration simulation model GEARN is used for migration prediction when the weather model forecasts future atmospheric flows (Otuka et al 2005b). First, a 72-hour weather forecast over the East Asia region from Vietnam, the Philippines, China, and Korea to Japan was made with both mesh data output by a global model, the Global Spectral Model of the Japan Meteorological Agency (JMA), and a sea surface temperature data RTG SST of the U.S. National Oceanic and Atmospheric Administration. The temporal and horizontal resolution of the prediction data is 1 h and 33 km, respectively. Second, two sets of migration prediction of 48 h starting at dusk and dawn per 1 day were used. Hence, predictions for 2 days from today were obtained. The prediction results are available at http://agri.narc.affrc.go.jp/.

An example of the prediction performed on 1 July 2007 is shown in Figure 6, which provides information on the timing and area of migration. The hitting ratio of the migration prediction in 2004 to 2006 ranged from 74% to 85%. This value corresponded to the hitting ratio of the weather forecast by the JMA.

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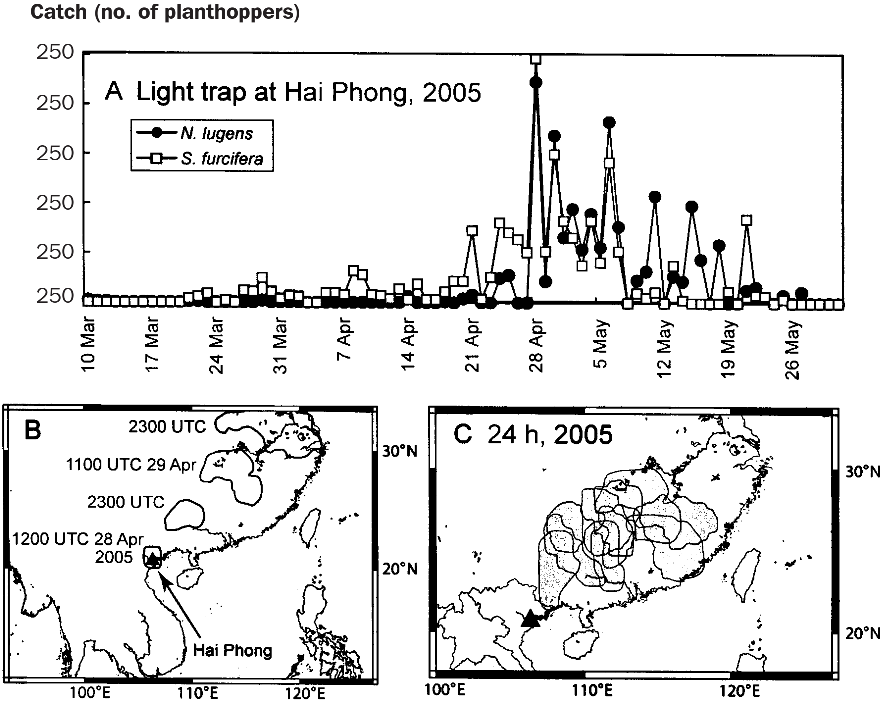

Fig. 5. The daily catch of rice planthoppers in the light trap at Hai Phong, northern Vietnam, in 2005 (A), and simulation results (B, C). (B) A migration cloud, nonzero density region, started over Hai Phong at 1100 UTC on 28 April 2005 and moved northeastward to southern China. (C) The migration simulations for clear catch peaks in Figure 5A were repeated and the migration clouds at 24 h after takeoff were superimposed on the map. This result shows major destination regions in the early migration. (Modified from Otuka et al 2008.)

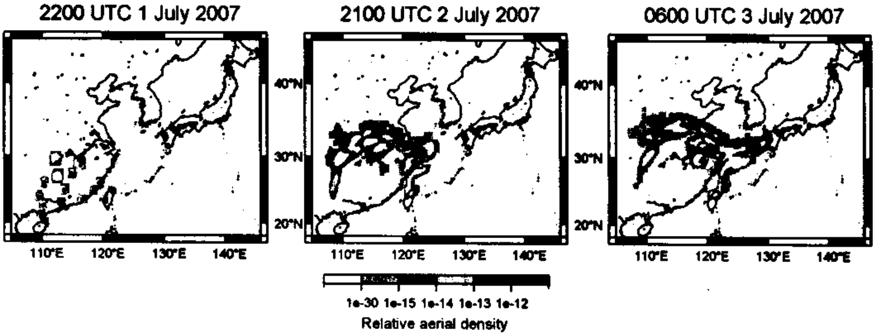

Fig. 6. An example of migration prediction from 1 to 3 July 2007. The migration clouds (regions in gray) from 16 takeoff areas started at 2100 UTC on 1 July 2007. At 0600 UTC on 3 July, the migration clouds reached over Kyushu (see Fig. 1). This prediction was successful, and in fact large catches were recorded mainly in southern Kyushu.

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Summary

Since rice planthoppers fly at lower levels warmer than an air temperature of 16.5 °C during migratory flight, three-dimensional models are essential to simulating migrations at such levels. The models enable analyses and predictions with high temporal and spatial resolution. They have therefore become a standard method of migration analysis.

From the BTA and forward simulation results, it was suggested that CBMs are invading the East Asian population, which is a matter of concern and must be monitored. Sufficient information on migrations on the Indochina peninsula is not yet available. The occurrence of planthoppers on the peninsula seems quite different from that in the East Asian population. For example, outbreaks of serious virus diseases transmitted by *N. lugens*, rice grassy stunt and ragged stunt diseases, occurred in 2006 in the Mekong Delta in southern Vietnam, and these diseases remain serious threats. The dispersion of these viruses on the Indochina peninsula and possible CBMs into the neighboring populations should be carefully monitored. A future study on these migrations on the Indochina peninsula is being planned.

The small brown planthopper, *Laodelphax striatellus* (Fallén), is one of the rice planthoppers, and a vector of rice stripe virus (RSV) that causes rice stripe, a serious virus disease of rice. In western Japan, the proportion of viruliferous adults of *L. striatellus* has recently shown a gradual increase to 6–16% according to information released by local plant protection offices. At the same time, it has been reported that, in Jiangsu Province, China, which is located about 900 km west of Japan, an outbreak of *L. striatellus* on the two-crop system of wheat and rice occurred in 2004 and 2005 (Zhu 2006). Fifteen to 50% of the species carried RSV. Recent rice stripe virus epidemics in Zhejiang Province have also been reported (Wang et al 2008). The feasibility of overseas migration from China to Japan and its consequent impact on the local population are a subject of future investigation. Since wheat is harvested from mid-May to mid-June in Jiangsu Province and the dispersion of the insects could occur then, the first target of migration analysis would be possible migrations during that period of time.

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Notes

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