Numerical model simulations of brown planthopper *Nilaparvata lugens* and white-backed planthopper *Sogatella furcifera* (Hemiptera: Delphacidae) migration

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Abstract

This paper reports on the performance of an atmospheric numerical model called BLAYER which has been adapted to forecast the movement of migrant brown planthopper *Nilaparvata lugens* (Stål) and white-backed planthopper *Sogatella furcifera* (Horvarth) populations from China to Korea. Comparison of model forecasts with trapping data for the 1987 and 1988 migration seasons indicated: (i) that the model is capable of successfully simulating the movement of planthoppers to Korea; (ii) that the model has sufficient detail to simulate insect movement into different regions of Korea; (iii) the source region for early season migrants is most likely to be south-eastern China (i.e. south of 25°N and east of 115°E); (iv) later season migrants may not necessarily always originate from an expanded northward region (south of 30°N); (v) the flight level of migrants may vary from about 500 to 2000 m altitude from one migration episode to another; and (vi) flight times ranging between 24 and 45 h are required to explain the migratory influxes. The results reported here have led to BLAYER forecasts of planthopper migration being produced on an operational basis within Korea.

Introduction

The brown planthopper *Nilaparvata lugens* (Stål) and white-backed planthopper *Sogatella furcifera* (Horvarth) (Hemiptera: Delphacidae) are serious insect pests of rice in Korea. *Nilaparvata lugens* and *S. furcifera* migrate from the warmer tropical regions of southern China to the Korean peninsula (as well as to Japan and middle China) in the early summer of each year since they are unable to sustain populations on the peninsula in the winter (Kisimoto & Sogawa, 1995). The distance these migratory pests must travel is over 1000 km and much of it is over the ocean. It has been shown that favourable meteorological conditions of sustained strong south-west winds in the lower atmosphere, which are often associated with the Bei-Yu Front, are necessary for the successful migration of planthoppers (Kisimoto & Sogawa, 1995; Sogawa, 1995). Irregular pests in Korea such as the Oriental armyworm *Mythimna separata* (Walker) (Lepidoptera: Noctuidae) also migrate on these strong south-westerly winds (Lee & Uhm, 1995).

Using meteorological analyses and forecasts of these conditions to predict accurately the location and timing of the arrival of these pests is an important part of any Integrated Pest Management (IPM) strategy devised to control them. Current forecasting methods for the migration of the *N. lugens* rely on the use of twice daily upper-air and surface weather data and charts to construct both subjective and objective (i.e. using a computer program, Watanabe, *et al*., 1990) trajectory analyses. Unfortunately, forecast

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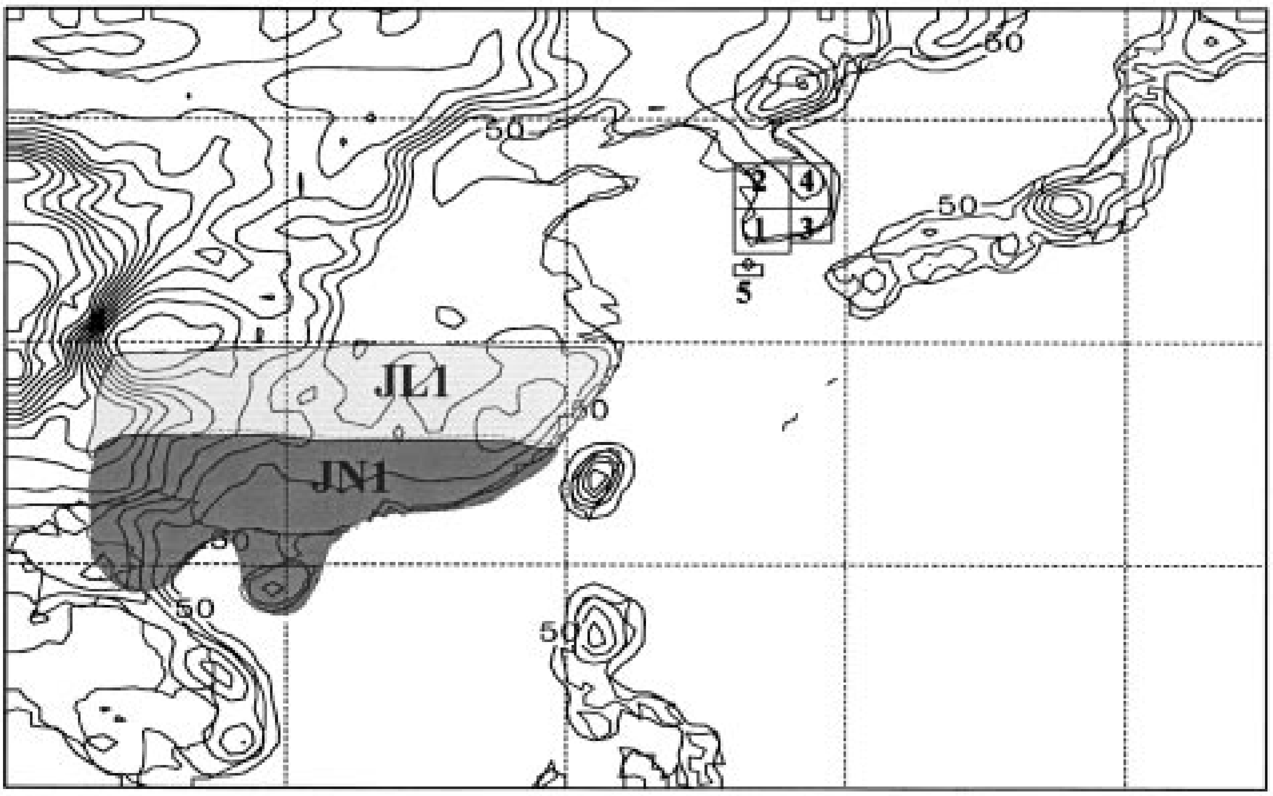

Fig. 1. The topography and domain of BLAYER model used for the simulations of planthopper migration. The contour interval for model topography is 250 m. The numbered boxes outline the five regions for which the comparisons between model predictions and trap data were done. The darkly shaded area is source region 'JN1' and the lightly shaded area is source region 'JL1'.

inaccuracies can arise since these analyses often do not use winds from the levels at which the insects are flying and they cannot capture the diurnal variations in the near-surface winds. This report describes the use of a more sophisticated atmospheric numerical model (BLAYER), which can account for these daily variations, as a detailed space–time interpolator to provide more accurate meteorological analyses at the altitude of insect transport.

The feasibility of using an atmospheric computer model to predict the wind-borne transport of migratory insect pests has been demonstrated at Iowa State University in the USA. A forecast model called BLAYER described in McCorcle (1988) and Turner (1993) has been successfully developed to forecast the springtime migration of the black cutworm moth *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae) into the US corn-belt for the purpose of optimizing crop-scouting efforts (McCorcle & Fast, 1989). *Agrotis ipsilon* migration is in many ways analogous to that of *N. lugens* and *M. separata* since strong low-level winds also assist their long-range movement. For *A. ipsilon*, the Great Plains low-level jet, a meteorological phenomenon unique to the US Midwest, aids their migration. For *N. lugens*, a low-level jet phenomenon, similar to the Great Plains low-level jet, except that is generally found at higher altitudes and is of a different dynamical origin (Chen *et al*., 1994; Hsu & Sun, 1994) aids their migration to Korea.

This paper first gives a brief description of BLAYER, as adapted to the problem of forecasting wind-borne *N. lugens* introduction to Korea. Following that, the results of simulations for two migration seasons in 1987 and 1988 are presented. Validation of the adapted version of BLAYER is achieved by comparison with *N. lugens* trapping data for 1987 and 1988 and with detailed meteorological analyses from early June 1987. The early June 1987 period was chosen due to the availability of observations from the TAMEX (Taiwan Area Mesoscale Experiment) weather experiment which was being held in the region at that time. A description of TAMEX can be found in Kuo & Chen (1990). Based on the results of the simulations and validation efforts, suggestions are made as to the importance of different regions in China as sources for *N. lugens* migration to Korea.

Methods

BLAYER is a numerical model capable of simulating atmospheric flows within the lower part of the troposphere. Its speciality is simulating boundary layer flows over sloping terrain. The atmospheric component of the model is governed by anelastic (i.e. sound waves are removed as possible solutions to the governing equations via an assumption of incompressibility), hydrostatic set of equations. The equations are expressed in a non-orthogonal, terrain-following, spherical set of co-ordinates. Additionally, a fine vertical structure is included in the lowest part of the atmospheric domain in order to resolve the strong vertical gradients in prognostic variables, such as temperature, that exist near the surface.

Prognostic (i.e. predictive) equations are of the form

$$\partial A/\partial t + V \bullet \nabla A = \partial(K\partial A/\partial z)/\partial z + F$$

where A is the prognostic variable of interest, it could be temperature, moisture, winds, turbulent energy or insects. F is a forcing term such as a source or pressure gradient. A specific example for an insect of such an equation is

$$\partial\chi/\partial t + V \bullet \nabla\chi = \partial(K_\chi\partial\chi/\partial z)/\partial z + S + \nabla\bullet(K_d\nabla\chi)$$

where χ is the insect concentration and the terms are in order from left to right, the local time rate of change, advection, vertical diffusion, source/sink, and horizontal diffusion. Unfortunately the system of equations is not closed, so assumptions about some of the unknowns have to be made. Namely, the coefficients of diffusion are assumed to have a functional dependence on turbulent energy. The equations are solved by a combination of finite difference and finite element techniques.

BLAYER was configured to have a time step of 5 min and a uniform horizontal grid spacing of 0.5 degrees for the *N. lugens* simulations. This latter measure was to make the output suitable for incorporation into a Geographic Information System (GIS). The domain used for BLAYER simulations was a 91 × 71 horizontal grid that extended from 100°E to 145°E, and from 10°N to 45°N and is shown in fig. 1 along with the model topography. There were 24 nodes in the vertical with a model top at about 2200 m. Upper boundary conditions were set by time-varying 850 hPa geopotential height fields. These fields were obtained from the USA's National Center for Environmental Prediction (NCEP) 40 year set of global meteorological analyses. See Kalnay *et al*. (1996) for a description of the NCEP analyses. (For operational forecasting using BLAYER within Korea, Korean Meteorological Agency analyses are currently being used.) Initially winds were geostrophic except in the lowest

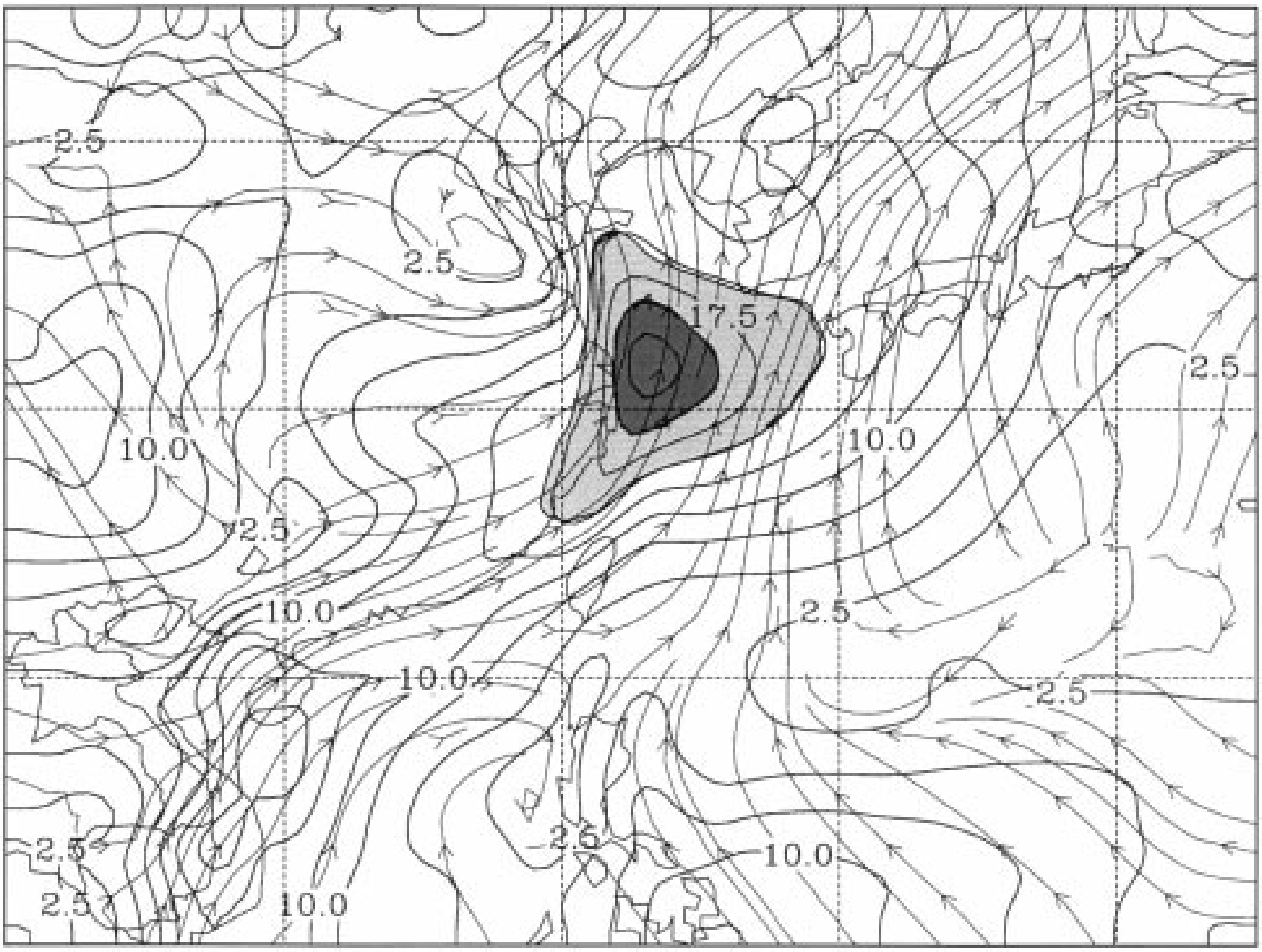

Fig. 2. BLAYER simulated wind speed (m s^{-1}) and streamlines at a height of 1350 m AGL valid at 00 UTC 2 June 1987. The contour interval is 2.5 m s^{-1}. The lightly and darkly shaded areas represent the regions where the simulated winds exceeded 15 and 20 m s^{-1} respectively.

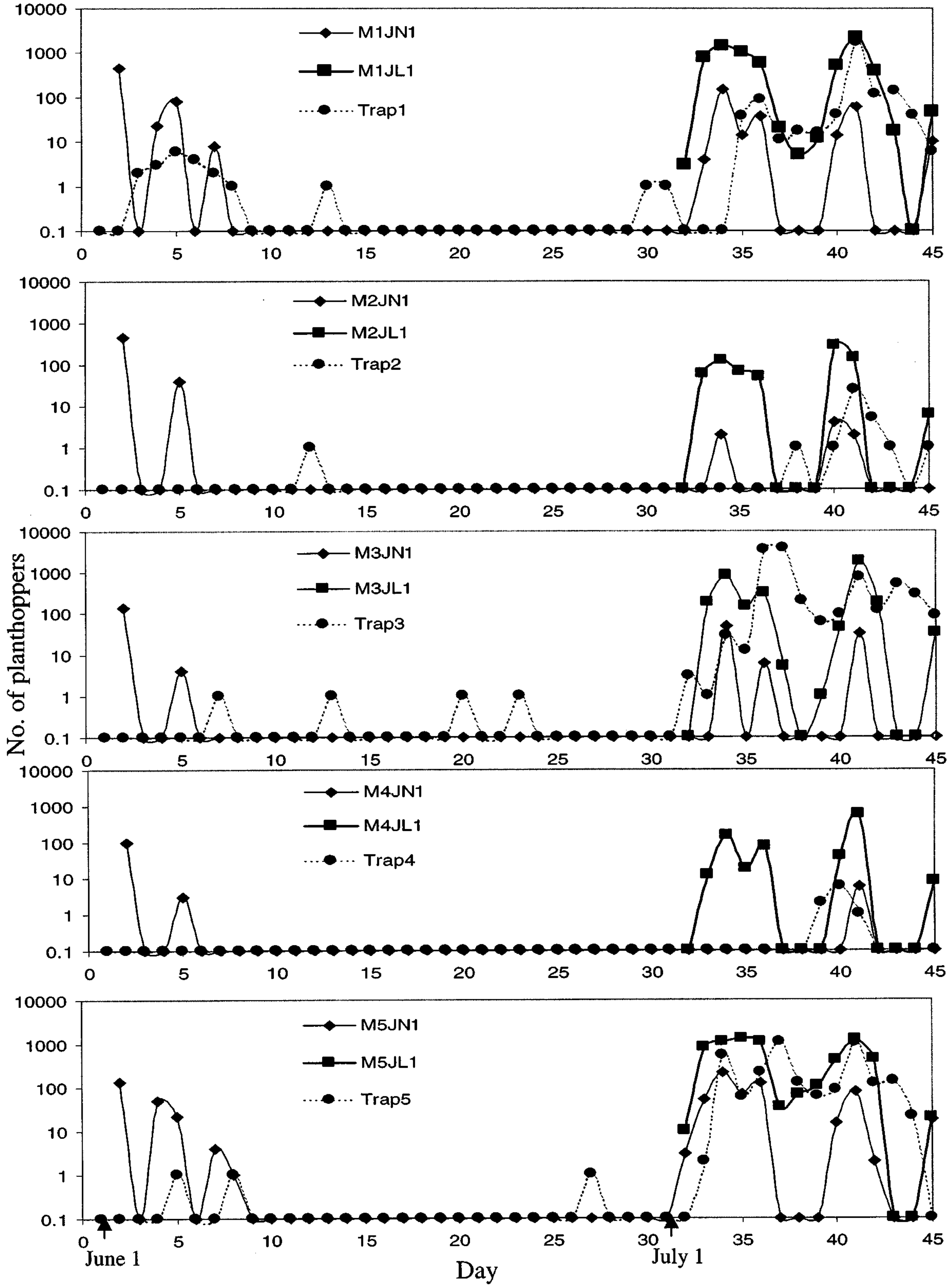

Fig. 3. Numbers of *Nilaparvata lugens* trapped or modelled within regions 1–5 for the period 1 June to 15 July 1987. The panels are ordered such that region 1 is at the top and region 5 is at the bottom. Note the vertical scale is a log scale and trap or model values of 0 have been rescaled to 0.1. Days are numbered consecutively from 1 beginning June 1. Note, within the key, abbreviation M refers to model forecasts, the next number refers to one of the five regions within Korea, and JN1 or JL1 refers to the source used.

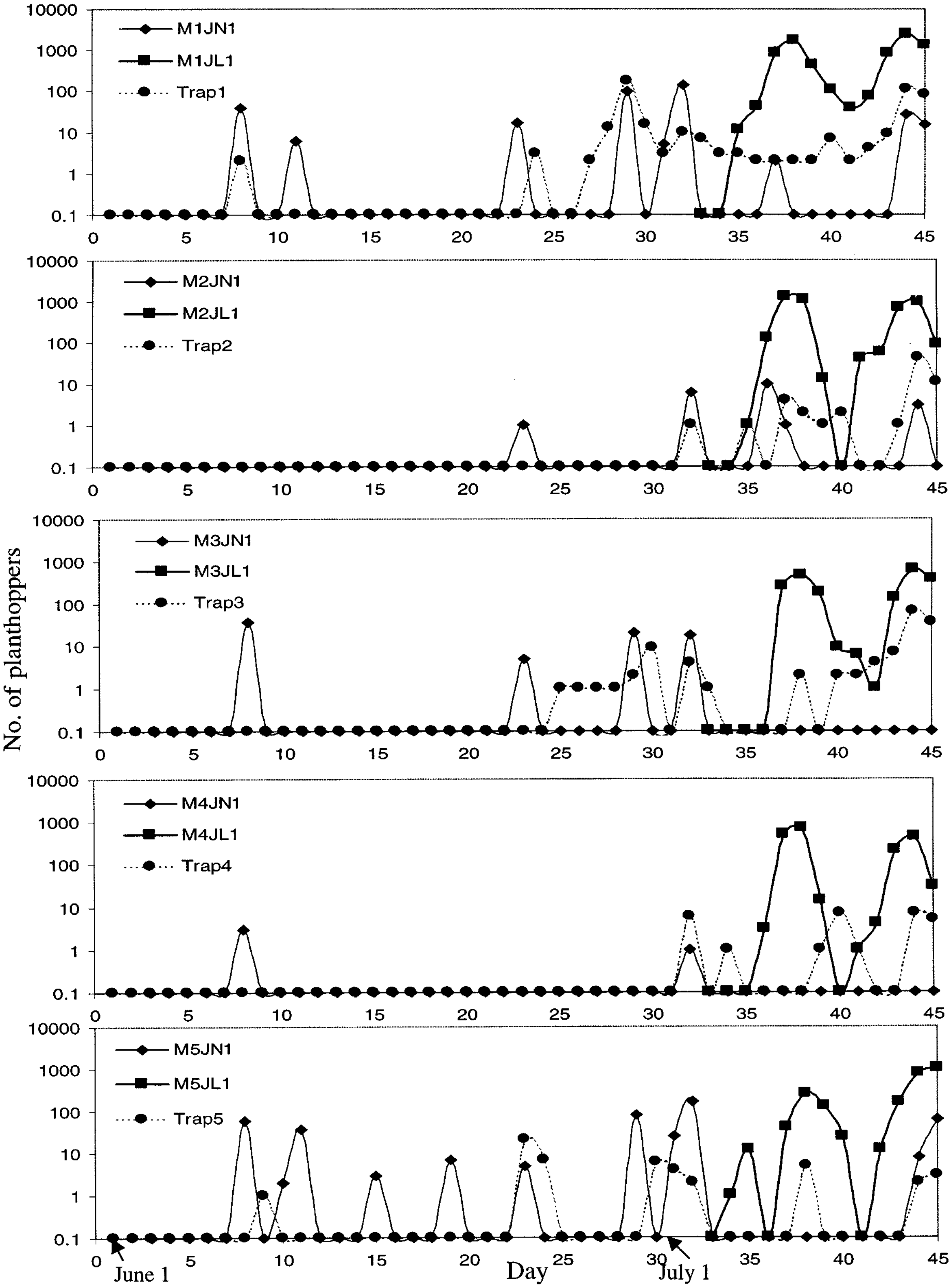

Fig. 4. Numbers of *Nilaparvata lugens* trapped or modelled within regions 1–5 for the period 1 June to 15 July 1988. The panels are ordered such that region 1 at the top and region 5 is at the bottom. Note the vertical scale is a log scale and trap or model values of 0 have been rescaled to 0.1. Days are numbered consecutively from 1 beginning June 1. Note, within the key, abbreviation M refers to model forecasts, the next number refers to one of the five regions within Korea, and JN1 or JL1 refers to the source used.

layers where they logarithmically decreased to zero near the surface. Note, a geostrophic wind is where the direction is parallel to the isobars and wind strength is inversely proportional to the spacing of the isobars.

A comparison with some meteorological observations at 00 UTC (Universal Time Coordinate) 2 June 1987 from the TAMEX Intense Observing Period (IOP) 5 case provided some meteorological validation for BLAYER. The period around 2 June 1987 was a time at which migration was thought to be highly probable so it was fortuitous to have the TAMEX dataset available. Comparison of the model streamlines shown in fig. 2 with the analysed winds of Chen *et al.* (1994) (fig. 5a) suggest the wind directions were simulated reasonably well. The magnitude of the maximum simulated wind speeds over the Yellow Sea of about 24 m s^{-1} was also quite close to the maximum analysed value of 23 m s^{-1}. The location of the maximum over the sea matched the analysis very well; however the maxima over the land area to the west in north-east China was missed by BLAYER.

Certain assumptions about *N. lugens* behaviour were made for the migration simulations reported in this paper and these are discussed now. It was assumed that the migrants can be transported continuously for the whole of the 48 h forecast period and that they had no forward flight

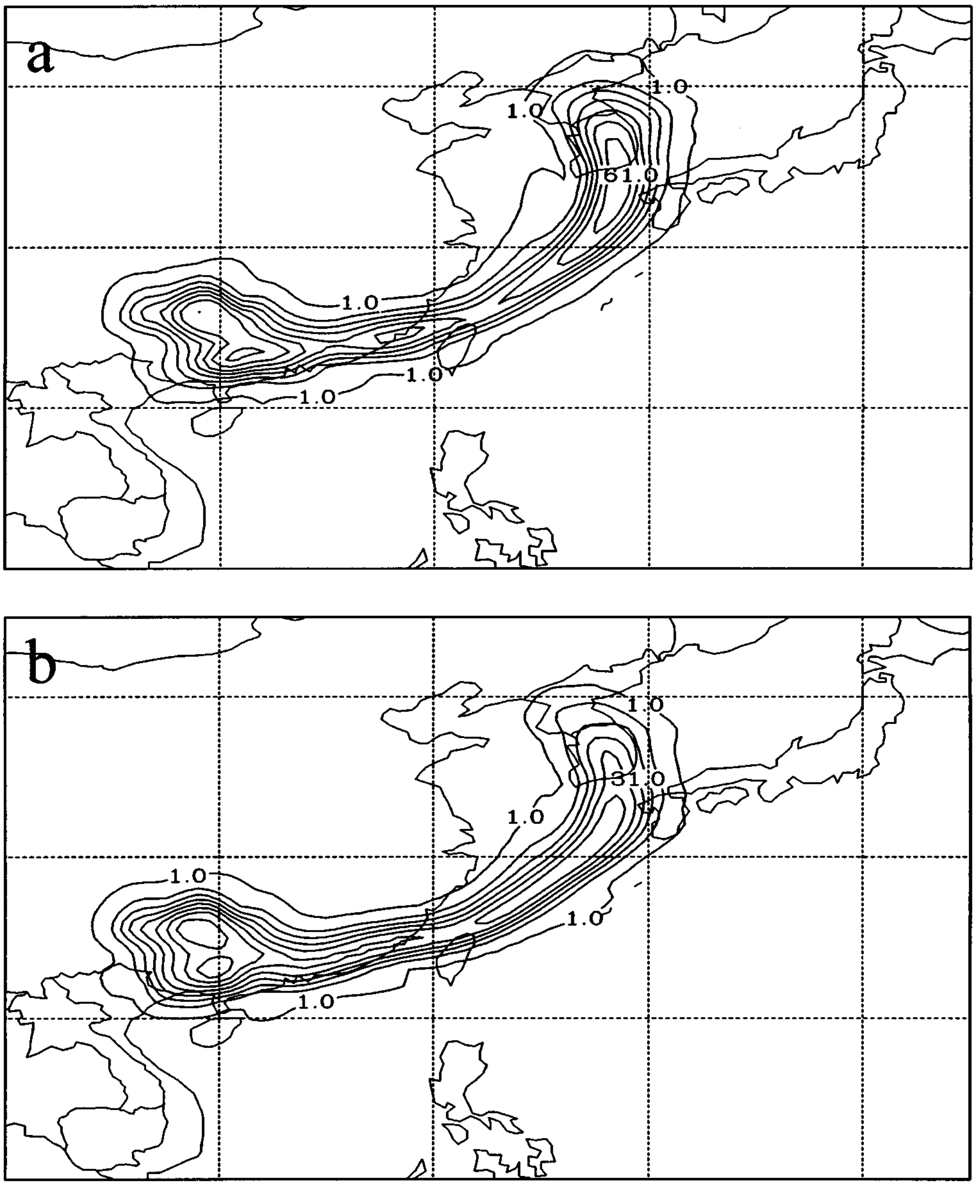

Fig. 5. Forty eight hour forecast of the relative concentration field of the *Nilaparvata lugens* 1143 m AGL valid at 00 UTC 3 June 1987 for a) an assumed take-off time of 0900 LST using source JN1, and b) an assumed take-off time of 1800 LST using source JN1.

speed of their own. A zero insect flight speed was assumed because tethered-flight experiments have shown that *N. lugens* stop active wing-beating when wind speeds exceed 5.5 m s^{-1} and it has been reported that biggest captures of planthoppers have occurred in south-westerly winds of 8–14 m s^{-1} (Kisimoto & Sogawa, 1995). Additionally, laboratory experiments have also shown that macropterous planthoppers can maintain active wing-beating for an average of only 9–12 h (Ohkubo, 1981). This is too short a time to cover the required 1000 km if wind speeds are 8–14 m s^{-1}. Therefore, it is assumed that the *N. lugens* cannot be wing-beating for the duration of the flight and so no limit, other than the 48 h length of the meteorological forecast, is imposed on the maximum flight time. Following Zhu *et al*. (1982) it was assumed that transport could occur at altitudes between 500 m and 2200 m (i.e. the model top) and that the insects are initially uniformly distributed vertically. Finally, it was assumed for most of the simulations that take-off occurs at 0900 Local Standard Time (LST). Turbulent wind gusts are thought to provide a take-off mechanism for the planthopper. The initial development of the daytime convective boundary layer occurs around 0900 LST and is often associated with the onset of turbulent wind gusts. *Nilaparvata lugens* have also been observed to take off at dusk under active wing-beating (Ohkubo & Kisimoto, 1971) in calm conditions so some simulations in which a take-off time of 1800 LST was specified were also performed.

For this paper, BLAYER simulations for all days between June 1 and July 15 1987 and 1988 were performed using the above assumptions about planthopper behaviour. The simulations started with a 12 h pre-forecast 'spin-up' period during which no insect movement was allowed. This was followed by a 48 h period beginning at 00 UTC (Universal Time Coordinate) (note 00 UTC corresponds to 0900 LST) for which insect transport was forecast. Two different source regions designated 'JN1' and 'JL1' which are shown in fig. 1 were used in the simulations. Source region JN1 covers most of south-east China south of 25°N plus parts of North Vietnam and Laos and is meant to encompass the 'B' and 'A' source regions of Kisimoto & Sogawa (1995). Source region JL1 is essentially a 5° northward expansion of region JN1 and is meant to represent the land area over China for which the Bei-Yu front has progressed past by late June. In other words the northern extent of JL1 coincides with the warm southern flank of Kisimoto & Sogawa's (1995) 'F2' region. Simulations using source JL1 were only done for dates after 1 July 1987 or 1 July 1988.

Variances in temperature, wind gustiness, land use and other factors have been reported to cause day to day and within region variations in the number of migrant planthoppers taking off (Kisimoto & Sogawa, 1995). However, due to a lack of accurate information about these factors over the source regions, the current simulations were performed assuming that the sources were the same strength each day and were spatially uniform.

Comparison of the model predictions of insect numbers were made with Korean light trap catch data. These data were gathered from a network of 60 sites throughout Korea operated by the Korean National Institute for Agricultural Science and Technology. The data were collected for the periods June 1 through July 15 for both 1987 and 1988. The trap data were then condensed by dividing Korea into five regions and simply summing the total of all *N. lugens* and *S. furcifera* caught at all sites within each region. These regions were numbered 1–5 and are shown in fig. 1. They correspond to south-west Korea, north-west Korea, south-east Korea, north-east Korea, and Cheju Island, respectively.

The combined regional trap data (see figs 3 and 4) indicated the earliest captures of *N. lugens* occurred in Korea for 1987 from 2 to 6 June and in 1988 on 8 June. A cursory examination of winds preceding these dates indicated that favourable migratory conditions may have occurred in the 48 h periods beginning 00 UTC 1 June, 00 UTC 4 June 1987, and 00 UTC 7 June 1988. Since, it can reasonably be assumed that migration occurred during these periods since no catches had been reported prior to these dates, the simulations of these periods provide good tests for BLAYER and are therefore examined in detail in this paper. Additionally, the 48 h period beginning at 00 UTC 1 June 1987 corresponded to TAMEX IOP 5 and allowed the direct comparison with BLAYER winds discussed above. Trap data from July 1987 suggest that a major influx started around the 4 July 1987, so simulations starting at 00 UTC 2 and 00 UTC 3 July 1987 are also examined in detail.

Results

Simulations performed of N. lugens *migration to Korea*

Simulation beginning 00 UTC 1 June and 00 UTC 4 June 1987

Figure 5a shows the 48 h BLAYER forecast of the '*N. lugens* cloud' valid at 00 UTC 3 June 1987 produced by the simulation beginning at 00 UTC 1 June with an assumed take-off time of 0900 LST. Note, unless otherwise stated, the take-off time for each simulation discussed is 0900 LST. Note also, that the contours represent the predicted relative concentrations of insects. Since no quantitative information about the numbers of planthoppers that took off from within the source was available we decided not to predict actual concentrations. The important thing to note from the contour plots is the pattern and spatial coverage of the simulated '*N. lugens* cloud'. The contour with value 1 can be interpreted as being the edge of the predicted cloud. It can be seen from fig. 5a that *N. lugens* could easily have reached Korea within the 48 h forecast period. In fact the simulation indicated that the distance between Korea and eastern China could have been covered within 27 h. For a simulation where everything was the same except that a take-off time 9 h later at 1800 LST was specified, the predicted pattern at 00 UTC 3 June was similar (fig. 5b) but less time (23 h) would have been required to cover the distance between Korea and eastern China. Comparison between 0900 and 1800 LST take-off simulations on three other dates showed no substantial differences in predicted relative concentration patterns so it was decided not to perform season long simulations with the later take-off time. However, the time required for the migrants to reach Korea was generally less in the 1800 LST simulations.

Trajectory analysis of the 0900 LST take-off simulation at 733 m AGL (Above Ground Level) (filled circles fig. 6) indicated that *N. lugens* originating in eastern China (filled oval) would have been carried to the north and west of the Korean peninsula (cross-hatched oval), but that *N. lugens* originating further west nearer the Vietnam border (filled octagon) could have made it to Korea (cross-hatched octagon) within 48 h. However, the trajectory analysis at 1350 m AGL (open circles fig. 6) indicated that *N. lugens*

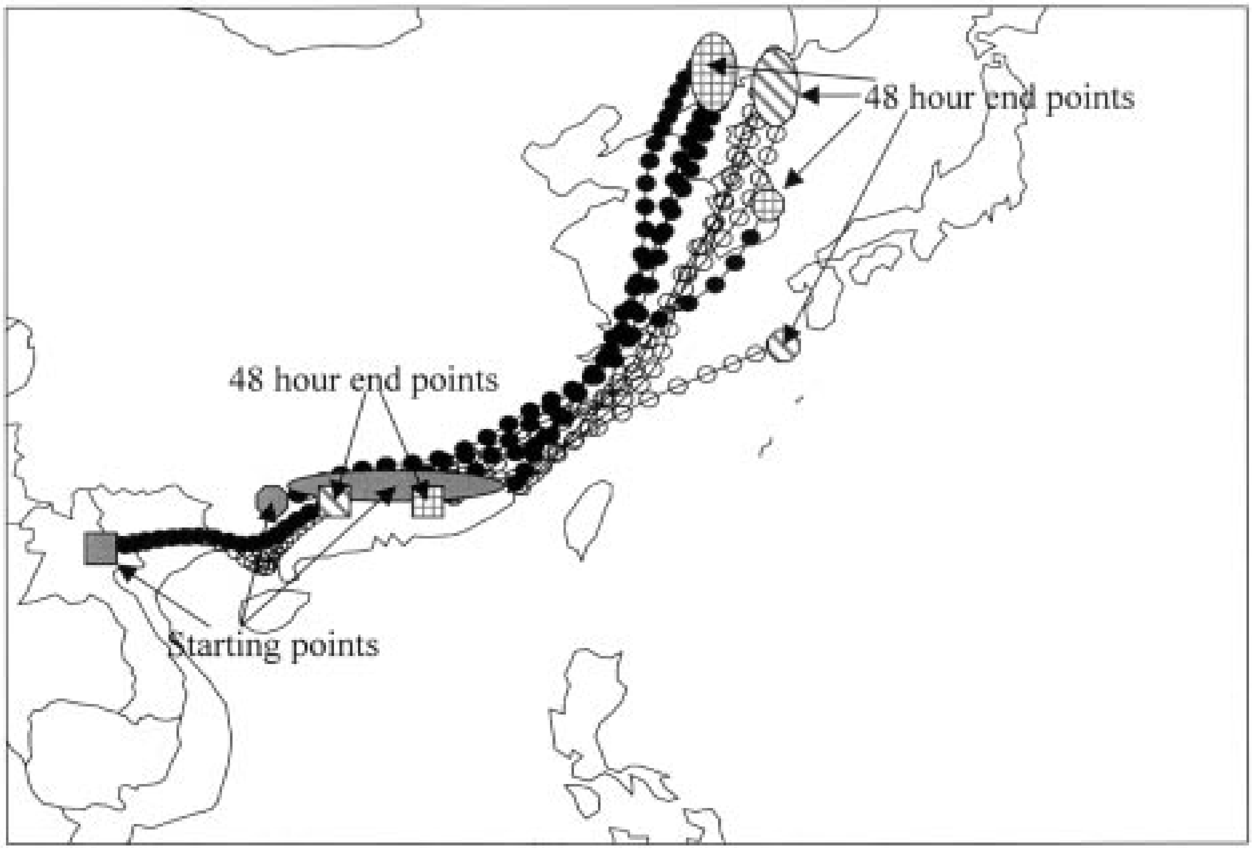

Fig. 6. Trajectories for the 1 June 1987 simulation at 733 m (closed circles) and 1350 m (open circles) AGL for various starting points within the source region JN1. The different starting regions are represented by the closed square, closed octagon, and closed oval and the corresponding end points are represented by the corresponding hatched shapes. The cross and diagonally hatched shapes are for the trajectories 733 and 1350 m AGL respectively.

originating in eastern China could have arrived in south-west Korea within 36 h. At this level, *N. lugens* originating further west (filled octagon) would have ended up further south to the west of Japan (diagonally hatched octagon). Simulated flights for higher altitudes indicated a path that would have taken the plant hoppers to the east of Korea. *Nilaparvata lugens* originating in Laos and western Vietnam (filled square) and flying at either 733 m or 1350 m altitude would only have made it to southern China (cross-hatched and diagonally hatched squares).

For the first influx of the 1987 season one other period of favourable winds that could have bought *N. lugens* to Korea began on 4 June. For 5, 6 and 7 June captures occurred in the three southern regions but tended to be light. Analysis of the predicted concentration fields (fig. 7a) and the trajectories from the simulation beginning at 00 UTC 4 June with a take-off time at 0900 LST indicated that the only possible source for migratory *N. lugens* was extreme eastern China. *Nilaparvata lugens* originating further west would have been transported in a northerly direction into northern China. Additionally, trajectories originating in eastern China below 1000 m AGL would have taken the *N. lugens* too far to the west of Korea. For the simulation assuming an 0900 LST take-off, 45 h would have been the minimum flight time for the eastern China migrants to reach Korea, while for the 1800 LST simulation the minimum time would have been 36 h. So, for this case, the model suggested that only those *N. lugens* originating in eastern China and flying at relatively high altitudes would have been able to reach Korea in a minimum of 36–45 h.

Simulation beginning 00 UTC 7 June 1988

Figure 4 shows that the first captures for 1988 occurred on 8 and 9 June and were confined to south-west Korea and Cheju Island. Results from the simulation beginning at 00 UTC 7 June 1988 suggested that like the 4 June 1987 simulation the source for the planthopper migrants captured in Korea was the extreme eastern edge of region JN1. Figure 7b shows that the leading edge of the insect cloud at 00 UTC 9 June at 530 m AGL lay over southern Korea and extended well to the east of the peninsula. Examining trajectories and concentration fields for altitudes above 1000 m (not shown) indicated that migrants flying at these levels would not have reached Korea. This leads us to conclude that for this case eastern China is the probable source for these *N. lugens* migrants and that flight levels below 1000 m were probably used. For the simulation assuming an 0900 LST take-off, 42 h would have been the minimum flight time for the eastern China migrants to reach Korea, while for the 1800 LST simulation the minimum time was 34 h.

Note that when analysing trajectory end-points after 48 h of simulation there may be considerable errors in the position. For example, a consistent under-prediction during a 48 h simulation in wind speed of 1 m s^{-1} could result in positional errors of about 170 km. However, by looking at several model simulations, and having gained confidence in the model predictions from comparison with the TAMEX analysis, it is strongly suggested that the early-season migrant planthoppers to Korea originate from south-eastern China, that their flights occur entirely over the ocean and last between 24 and 45 h. The altitude range at which the successful migrant *N. lugens* fly does not seem to be greatly restricted and could range from 500 to 2000 m.

Simulations beginning 00 UTC 2 and 00 UTC 3 July 1987

Trap reports for the period 3 to 6 July 1987 (fig. 3) indicated that there were probably two significant influxes into southern Korea during this period. One of these was into the region southeast of a line from about Cheju Island to Pusan on 3 to 4 July. The other influx into the South West Korea on 5 and 6 July where 3318 captures were reported at Jeju. Given the large numbers of captures reported at some sites and the

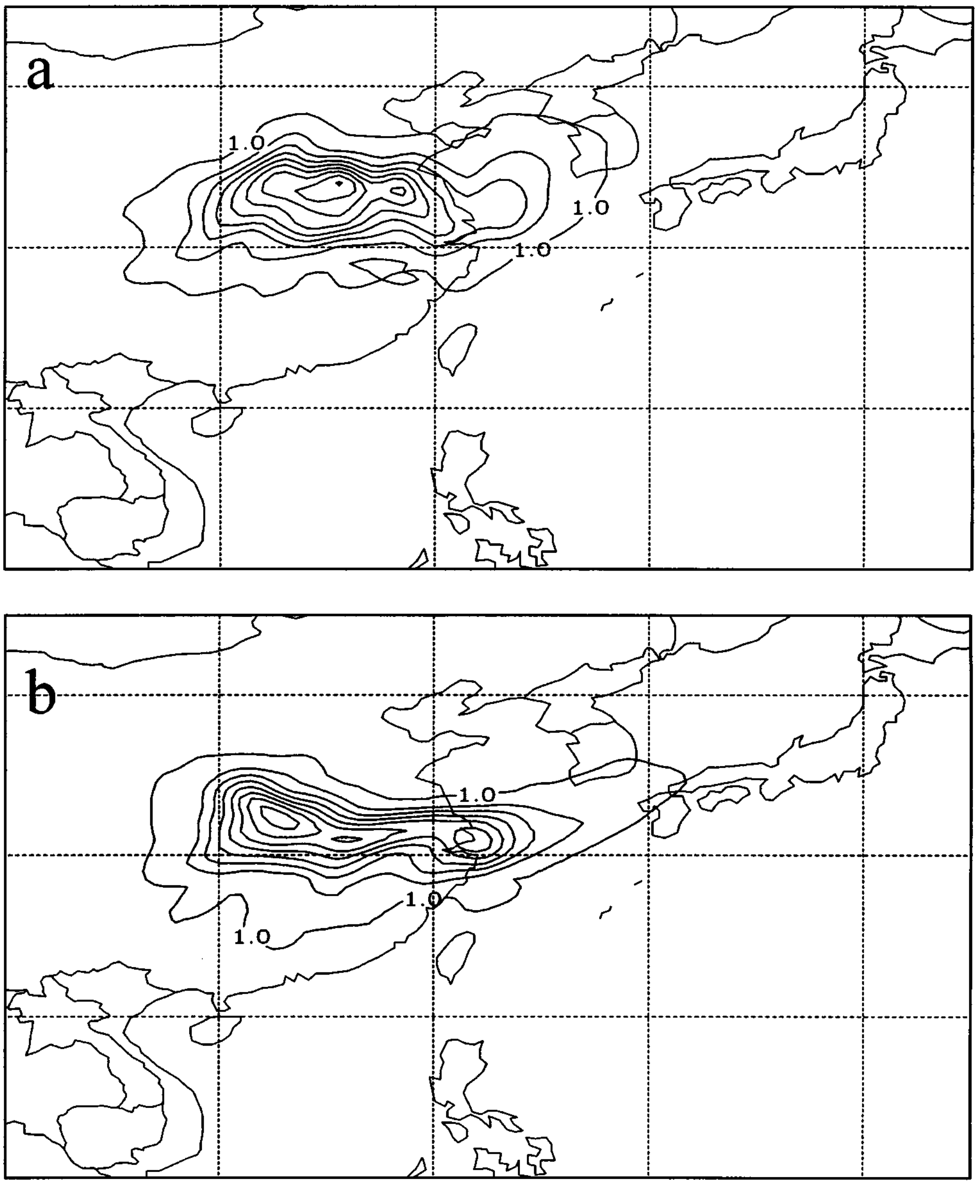

Fig. 7. Forty eight hour forecast of the relative concentration field of the *Nilaparvata lugens* valid at (a) 00 UTC 6 June 1987 1350 m AGL using source JN1, and (b) 00 UTC 9 June 1988 at 530 m AGL using source JN1.

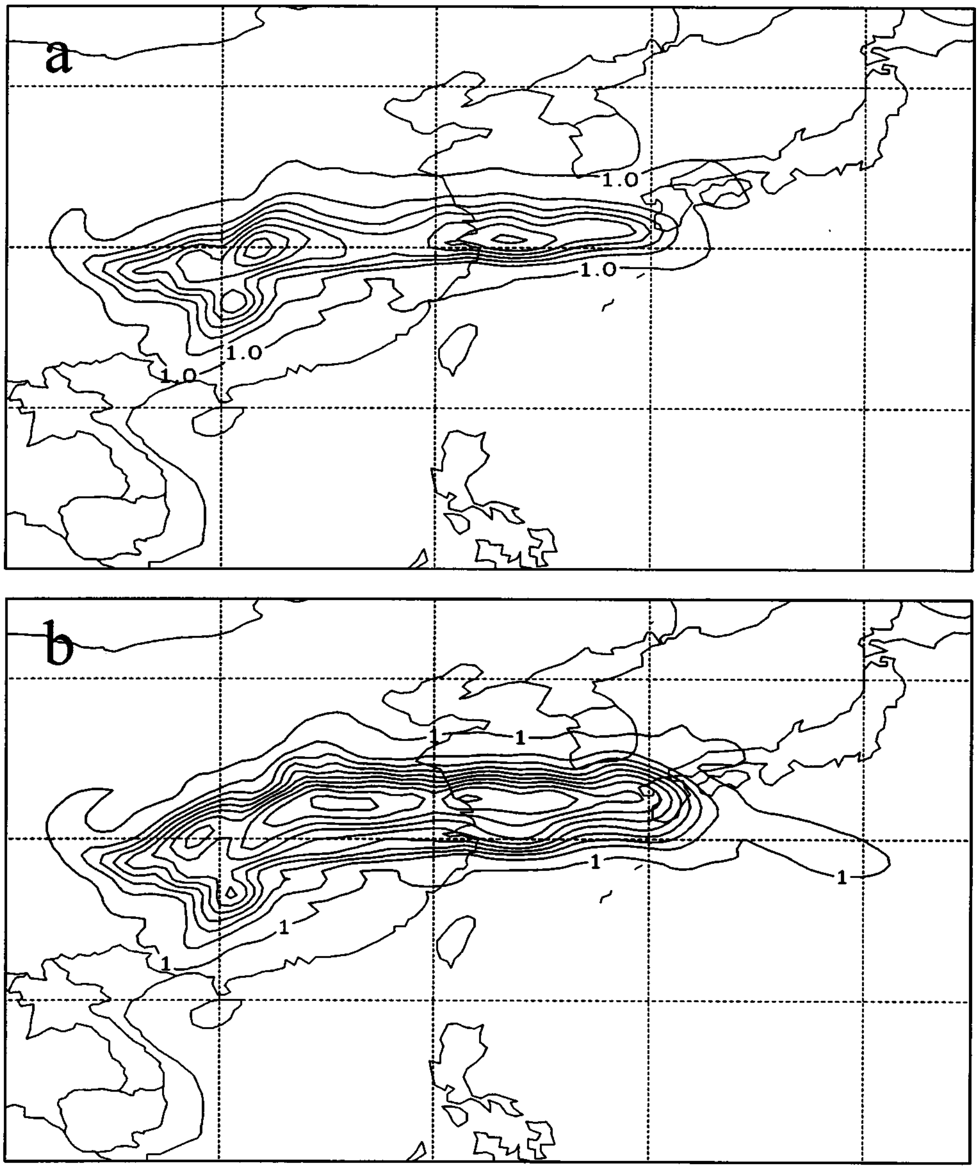

Fig. 8. Forty eight hour forecast of the relative concentration field of the *Nilaparvata lugens* valid at a) 00 UTC 5 July 1987 1143 m AGL using source JN1, and (b) 00 UTC 5 July 1987 at 1143 m AGL using source JL1.

fact that few captures were reported in the preceding week, it is likely that migration occurred during these periods.

The fact that there are differences in the distribution of trap captures for the early part and later part of this period provides another test for the model. Clearly if the model simulates the differences in distribution then confidence in its results is enhanced. For the simulation starting at 00 UTC 2 July 1987 the *N. lugens* cloud just reaches south-west Korea after 48 h (not shown). For the *N. lugens* to reach region 3 on 4 July either flight durations of longer than 48 h would have to be assumed or the model has under-predicted wind strength in this instance. For the simulation beginning 00 UTC 3 July, it is seen from fig. 8a (and fig. 3) that forecasts using source region JN1 suggest the movement of *N. lugens* into regions 1 and 5 on 5 July. Using source JL1 (figs 3 and 8b) allows for much larger numbers of *N. lugens* to move into these same regions in line with the large captures reported. However, forecasts assuming this source would have produced false alarms in the two northern regions. Examination of trajectories (not shown) indicate that the *N. lugens* that migrated to Korea during this period probably originated between 115 and 118°E, and between 25 and 30°N. Those east of 118°E would most likely have migrated to southern Japan. The points north of 25°N could have been a source since they lie on the paths of the trajectories that cross into Korea. The preferred heights for movement into Korea seemed to be lower than 1100 m for these two cases.

Seasonal simulations of N. lugens *movement for 1987 and 1988*

The results for the individual cases above are strongly suggestive of BLAYER's ability to simulate successfully *N. lugens* migration to Korea. However, to assess fully BLAYER's operational usefulness, quantitative analysis of forecasts for a much larger number of cases, including those for which trapping data indicate influxes did not occur, are necessary. In this section the results from simulations for 90 days in the 1987 and 1988 migration seasons are presented.

Similar to what was done for the observed trap data, the model predicted numbers have also been grouped into the same five regions as discussed earlier. These model predictions are also included in figs 3 and 4. The model predicted numbers that appear in these time series were generated simply by summing into a grand total the predicted 'relative' numbers at altitudes 733 m, 1143 m and 1350 m for all the grid points within each region. This procedure produced values that correlated well with the volume integrated model numbers and had the advantage that no re-scaling was required to produce comparable numbers to the regional light trap totals.

1987

Trap data indicated possible influxes from 2 to 8 June for regions 1, 3 and 5 with region 1 being the only area where captures of more than just one individual were reported. This may indicate that the migrants would only have reached south-west Korea in significant numbers. The model predicted influxes for regions 1 and 5 on four days (3, 4, 5 and 8 June), while for the other regions an influx was only predicted on 5 June. After that date there were only 'single individual' captures for only four other dates for all the regions, and there was only one date, 13 June (regions 3 and 5) where captures were reported in more than one region. BLAYER predictions indicated a zero influx of planthoppers into any of the regions for the remainder of the month. This, along with the trap data, suggests that no significant migratory opportunities occurred after 8 June. However, an analysis of the predictions for 13 June did show that if the simulation for that date had allowed for a flight duration of 60 h then some planthoppers could have reached Cheju Island and perhaps the south coast of Korea. Given the light numbers reported (only two) on 13 June, this suggests that if the captures on that date were of migrants, then very few migrants are able to remain airborne over 48 h.

Moving into July, there were major trap captures on most dates for 3 to 7 July for regions 1, 3 and 5. Generally BLAYER (using both source JL1 and JN1) captured the influxes into these regions well, but the light captures on 2 July for region 3 could not be explained, unless source JL1 had been assumed.

On 11 July there were major captures for regions 1, 2, 3 and 5, while region 4 had captures on 9 and 10 July. After 11 July there were large (but declining) numbers caught in regions 1, 3 and 5. Given that the major influx that occurred was predicted by BLAYER (using source JL1) to be on 11 July, the captures from 13 to 15 July may not reflect a migratory influx. In general, the predictions using source JL1 seemed to match the capture data better for regions 1, 3 and 5; however they did over-predict numbers for regions 2 and 4. Only two apparent influxes were not explained using source JN1.

1988

Trap data show captures on 8 June, for region 1 and 9 June for region 5, and influxes were predicted for regions 1, 3, 4 and 5 on the 8 June. The next period where all regions (except 4) had a predicted influx was the 23 June. Trap data showed no captures for the days from 9 to 22 June. This agreed very well with the model, although BLAYER did predict isolated light influxes for Cheju Island on three days during this period. This, along with the trap data, suggested that migratory opportunities were extremely limited during this period. On 23 June, the predicted influx for regions 1, 2, 3 and 5 preceded the generally light captures except for region 5 that occurred from 23 to 28 June. The next predicted influx on 29 June (regions 1, 3 and 5) matched well the larger trap captures that occurred in those same regions on 29 and 30 June. Interestingly, the model predicted no influx into regions 2 and 4 and no trap captures were reported. This is again highly encouraging in that it seems to indicate that the model has displayed a capability in predicting regional variation in planthopper influxes within Korea.

The first half of July 1988 had very few captures, with only significant but no large captures compared to the previous years numbers occurring about 2 and 14 July in all regions. Again simulations with source JL1 predicted extra-large numbers moving into all regions, while the simulations with source JN1 predicted the influxes into western regions 1, 2 and 5, but failed to predict the influx on 14 July for regions 3 and 4. It is suggested that in 1988 that the planthoppers may not have moved north of the region JN1 in China until after the first week of July.

Discussion

The results from the simulations conducted so far suggest that the source region for the early season planthopper migrants to Korea is south-eastern China (south of 25°N and east of 115°E), and that the planthoppers must have the ability to fly continuously for periods between 24 and 45 h, with much of the flight over the ocean and that the altitude of flight may vary from about 500 to 2000 m from one episode to another. If more remote source regions or circuitous migration routes are to be considered, much longer flight durations would be required in most cases. Simulations for which 1800 LST take-off times were assumed generally required flight times 4–9 h shorter than those for having 0900 LST take-off times. The physical reason for this is that during daylight hours wind speeds over land areas at flight level altitudes tend to be much weaker than at night or over the sea. This is because daytime heating over land creates a very turbulent boundary layer that acts as a brake on the flight level winds. Thus migrants which take-off at dusk would not spend the initial part of their journey in a relatively low wind-speed environment over the land areas of south-east China.

Most of the influxes into Korea in the early part of the migration season could have been explained using source JN1. However, for the later part of the season for most cases both JN1 and JL1 regions could have been sources for migrants. However, using JN1 led to the missing of two possible migratory influxes, while using JL1 resulted in the occasional prediction of influxes that probably did not occur.

The simulations presented here using the model indicated that BLAYER can reasonably accurately simulate the movement of a planthopper population from south-eastern China to Korea during periods of strong near-surface south-westerly flow. It is encouraging to note that *N. lugens* trap captures occurred in areas of Korea which were indicated to be the most likely by the model. Although the agreement with the trap captures is highly encouraging, it is somewhat surprising since the specific entomological assumptions about the *N. lugens* behaviour incorporated into BLAYER relating to the source region, take-off time, flight levels, and flight duration were not rigorously established. Confidence in BLAYER was also enhanced by the agreement between the modelled wind fields and the observed analysis fields from the TAMEX IOP 5 case on 1 and 2 June 1987.

Having established confidence in the model's capabilities, the entire BLAYER forecast system from meteorological data assimilation to forecast dissemination has commenced operations in Korea and its predictions are being incorporated into a GIS. On a cautionary note, it is important to understand that the computer model is a tool used to aid pest-management decision makers. Just because BLAYER predicts *N. lugens* have moved into Korea does not mean problems with hopper-burn which are caused by descendants of the migrants will develop. The model provides just one component in planning for pest management. Other important components relate to knowledge about *N. lugens* behaviour, trapping data, rice and insect phenologies, crop scouting, and pesticide options. Thus, care would have to be taken in ensuring how the model results are interpreted by people to whom the forecasts are distributed.

Finally, given the similarity between the migration to Korea of *N. lugens* and *M. separata* it is suggested that BLAYER could be applied to forecast the long-range transport of *M. separata* and the autumnal return migration of the *N. lugens* as described in Riley *et al*. (1991).

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