Analysis of atmospheric circulation situation and source areas for brown planthopper immigration to Korea: a case study

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Abstract. Rice planthoppers and related viral diseases have become one of the most important factors affecting rice production in Asian countries, and the resulting abuse of pesticides is laying a hidden danger for future food security. As the most economically devastating species, the brown planthopper, Nilaparvata lugens (Stål), moves from the tropical Indochina Peninsula to temperate regions where it cannot overwinter annually with the feature of long-range migration, and eventually appears in paddy fields of most East Asian countries. Compared with the overland migration that has been studied in more detail, there is relatively less understanding of N. lugens’ performance in transnational movement, especially in the representative overseas migration between China and Northeast Asia. Based on the light-trap data from China and Korea and the matched meteorological data of East Asia in 2016, a typical overseas migration event was basically analyzed. The results are as follows. First, the source area of the N. lugens population in this migration was in southeastern Jiangsu and eastern Shanghai. They took off at dusk on 1 August, flying at the altitude of 1700–2200 m, and landed in southwestern Korea at 02:00–11:00 UTC on 3 August. Second, a southerly airflow belt was the main weather factor for population’s overseas migration, and the confrontation between the western Pacific subtropical high and a northern high pressure in southern Korea was the main reason for population to land. Besides, we discussed the one-off feature of overseas migration compared to overland migration. These results show the close relation between weather systems and the migration dynamics of N. lugens and may extend the perception for N. lugens’ behavioral chain in the long-range migration between China and Northeast Asia, thus allowing a sufficient time for reasonable and effective control measures.

Key words: atmospheric circulation situation; Hybrid Single Particle Lagrangian Integrated Trajectory model; Nilaparvata lugens (Stål); overseas migration; weather system.

INTRODUCTION

The brown planthopper, Nilaparvata lugens (Stål), is a pest that has an extremely important impact on Asian rice, due to its destructive feeding pattern for rice and the widespread transmission of viruses in paddy fields (Bottrell and Schoenly 2012). According to statistics, the annual loss of rice production caused by N. lugens has exceeded $300 million in Asia (Min...
et al. 2014). The abuse of pesticides is one of the major hidden dangers for the future Asian rice production brought by *N. lugens*. Due to uncontrolled continuous pesticide use, *N. lugens* has shown high-level resistance to many of major-type insecticides (Zhang et al. 2016, Wu et al. 2018). Meanwhile, its natural enemies and competing species have been largely declining (Mattheson 2000, Bottrell and Schoenly 2012, Min et al. 2014). The breaking of restrictive relationship between *N. lugens* and its limiting factors (i.e., pesticides, natural enemies, and competing species) undermines the balance of farmland ecosystem, resulting in a low marginal benefit for using insecticides to reduce *N. lugens*-caused losses, and may even promote heavy outbreaks of pest (Way and Heong 1994, Bottrell and Schoenly 2012). The characteristic of long-range migration, relying on suitable atmospheric conditions, is one of the root causes for *N. lugens* to spread in Asian countries (Kishimoto 1976, Otuka 2013, Hu et al. 2018). From spring, planthopper populations migrate northward from the tropical Indochina Peninsula with summer monsoon to East Asia. After five expansion stages in eastern China (Cheng et al. 1979, Otuka 2013), they eventually reach North China or immigrate to Korea or Japan across the sea (Sogawa 1982, Zhu et al. 2000, Furuno et al. 2005, Otuka 2013, Min et al. 2014). The overseas migration phenomenon is a basic demonstration for the theory of rice planthopper long-range migration (Asahina and Turuoka 1968), but it may not be a field with a high research highlight compared to overland migration. Due to inconsistent observation methods and the lack of matching data, Asian countries more focus on the local overland migration, rather than the overseas migration that may involve different countries. This result has caused the separation of *N. lugens’* movement chain between upstream and downstream countries. However, it is clearly necessary to establish a reasonable and complete cognitive framework for the migration process of *N. lugens* in Asia under the deeper understanding of overseas migration. Ideally, this knowledge will be of great value when local agricultural officials formulate policies and farmers engage in the rice production.

The overseas migration mainly occurs from China to Northeast Asia (i.e., Japan and Korea) during the movement of *N. lugens* in Asia. Due to the less understanding of pest situation in other regions, the policymakers may fail to make a comprehensive consideration when deciding on local agricultural plans and policies annually. Possible outbreaks (for Japan and Korea) and backtrack (for China) of planthopper populations would cannot be actively dealt with in such scenarios. The research on this phenomenon (i.e., overseas migration) has been mainly based on the captured ways over the sea (Asahina and Turuoka 1969, 1970), analysis with meteorological backgrounds (Kishimoto 1976, Watanabe and Seino 1991), and the model simulation (Turner et al. 1999, Zhu et al. 2000, Otuka et al. 2010). However, because of few available cases (compared to overland migration) and the difficulty in obtaining capture data from upstream and downstream countries at the same time (Zhu et al. 2000, Otuka et al. 2005), the conclusion may be independent in general and lacks possibility verification. Using the Korean *N. lugens* catch data of 10-d scale in 2016, we try to determine an overseas migration process through an atmospheric transport and dispersion model and the Chinese light-trap data in upstream areas, and speculate the reasonable parameters of this case. This attempt may reduce the difficulty in determining a migration event from the long-interval observation, thereby extracting more available overseas processes from existing data for case studies and regular exploration. The meteorological conditions have impacts on *N. lugens* long-range movement, and they are directly resulted from the development and changes of some large-scale weather systems (Jiang et al. 1981, Bao et al. 2008, Lu et al. 2017). By analyzing atmospheric circulation fields and dynamic fields, we could have a clearer understanding of the migration case from its beginning to the end, which might increase our cognitive level on the overseas migration, or find some common patterns with others cases. Finally, we explore the major impacts of weather systems in overseas movements, and the similarities and differences between overland and overseas migrations. Through this study, we hope to contribute to the early warning of *N. lugens* immigration, especially when it is impossible to timely and effectively grasp the pest situation in the upstream region. It will enable plant protection agencies and
agricultural practitioners to use pesticides reasonably, thereby reducing the risk of losses in rice production due to increased pest resistance and reduced natural enemies.

**Materials and Methods**

*Pest catch data*

Insect catch data are the basis of studying long-range migration of insects. According to the change of the capture number, we can get a macroscopic process of a migration event. Observations and statistics of pest catches by investigation institutions (e.g., plant protection stations in China) are carried out every day, every five days, or every ten days in general. For some particular migration activities, the time interval of observation can be up to one hour. The data we used to research the situation of *N. lugens* immigration to Korea in 2016 came from Rural Development Administration, Korea. These light-trap catch data showed the average state of pest immigration every ten days in Korea during the major occurrence period of *N. lugens* in 2016 (Fig. 1). In addition, the spatial distribution visually showed main landing areas of the immigrant pest population (Fig. 2). However, the 10-d temporal interval is too long to research a migration case. Because of the combined effect of its own fat storage and the duration of weather system that facilitates long-range migration, most of the *N. lugens* populations only have a sustained flight capacity within 48 h (Rosenberg and Magor 1983, Chen et al. 1984). A 10-d migration is almost impossible. In order to achieve our research goals with limited data, we used a meteorology-based trajectory model to simulate possible moving routes within ten days. Combining results of Korean light-trap catches and trajectory model, we have identified the occurrence period of the migration case and obtained the pest source areas with high reliability. These results make our analysis and discussion more targeted and inspiring. In addition, *N. lugens* light-trap catch data from China would be used to assist in

Fig. 1. Each 10-d light-trap catch variation of *Nilaparvata lugens* immigrating to Korea during May–August 2016. The number of catches per ten days represents average state of entire country in the corresponding period. The average immigration number from July to August (immigration period) is 7 (per 10-d).

Fig. 2. Distribution map of paddy fields in Korea that suffered losses caused by *Nilaparvata lugens* in 2016. The areas marked green in this map are loss occurrence regions. It is obvious that the region near the coastline in southern Korea is the main immigration area and damage area for *N. lugens* in 2016. This diagram was drawn according to the information provided by Sung-Jun Hong of Rural Development Administration, Korea.
Fig. 3. (a) The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) backward trajectories based on the spatial distribution of *Nilaparvata lugens* in Korea, 2016. Nine HYSPLIT models (3 arrival locations [yellow stars] × 3 heights) with different parameters run every hour, from 15:00 UTC on 31 July to 14:00 UTC on 10 August. In order to highlight reasonable results (brown lines), unreasonable trajectories (e.g., those that take off at sea surface) were not drawn in the figure. These selected routes (subgraph) indicate that possible landing period is 02:00–11:00 UTC on 3 August, and the flight altitude is between 1700 and 2200 m. The reasonable takeoff locations (red points) were determined by local sunset time. (b) HYSPLIT forward trajectory results of 48 h, starting from 10 locations in possible insect area (yellow squares) and 1000/1500/2000 m altitudes (blue/green/red lines). It can be seen that the probability of pest being transported to Korea is greatest when the starting height is 2000 m.
verifying the analysis results of trajectory model. These pest data came from National Agro-Tech Extension and Service Center (NATESC) in China.

**Trajectory model**

Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model is a professional model of atmospheric transport and dispersion, jointly developed by the National Oceanic and Atmospheric Administration (NOAA), USA, and the Bureau of Meteorology, Australia (Stein et al. 2015). The model uses an air mass as the basic model object. It can be applied to simulate and speculate transportation and diffusion processes of air masses (e.g., atmospheric pollutant particles) based on the input data of meteorological initial fields and boundary conditions. *Nila parvata lugens* has a light weight, and its active flight speed is small (~0.3 m/s; Chen et al. 1984). When *N. lugens* is moving at a high altitude, its active flight capability can be assumed to be negligible, especially under the condition of high wind speed (Bao et al. 1999, Furuno et al. 2005). Under this assumption, *N. lugens* individual can be similar to a pollutant particle, and the HYSPLIT model can be used to simulate *N. lugens* migratory trajectory.

In order to obtain a reasonable simulation of pest migration (Fig. 3a), the parameters of HYSPLIT backward model were set according to the biological characteristics of *N. lugens*. First of all, 1000, 1500, and 2000 m above ground level (~mean sea level in eastern China and southern Korea) were selected as the model initial heights in August. That is because in warm seasons (e.g., summer), the altitude of about 1500 m is the main centralized height for flights of the *N. lugens* population (Deng 1981, Riley et al. 1991). Secondly, the running time length of model was set to 48 h since the continuous flight time of *N. lugens* is within 48 h in general in a long-range migration (Rosenberg and Magor 1983, Chen et al. 1984). Then, based on the occurrence range of pests on the spatial distribution map (Fig. 2), three locations (i.e., 34.44° N, 126.25° E; 34.82° N, 126.93° E; and 35.46° N, 128.48° E) in southern Korea were selected as starting locations. Finally, considering that there was no fixed law for landing time of *N. lugens*, the three initial locations would run backward trajectory model every hour between 15:00 UTC on 31 July and 14:00 UTC on 10 August (Seoul time: 00:00 on 1 August to 23:00 on 10 August), in order to estimate occurrence time, average migration trajectory, and insect source areas of the representative migration event (Fig. 1) as comprehensively as possible. The estimation was based on the HYSPLIT simulation results and the previous studies on biological characteristics of *N. lugens* takeoff (Chen and Cheng 1980, Crummay and Atkinson 1997). Besides, for interactively validating the backward result, we performed the forward trajectory simulation (Fig. 3b). In addition to initial heights and running time in the forward trajectory simulation consistent with that backward one, ten locations in the potential insect source areas were selected randomly to be the starting points of model, and the starting time was set as 11:00 UTC on 1 August (Beijing time: 19:00 on 1 August, which was the time of local sunset), because the time around sunset is the main period for *N. lugens* to emigrate (Chen and Cheng 1980, Crummay and Atkinson 1997).

**Meteorological data and analyzed variables**

Used to show and analyze atmospheric circulation and dynamic characteristics, the meteorological data were extracted from the FNL (Final) Operational Global Analysis dataset, with a spatial resolution of 1° × 1° and a temporal resolution of 6 h (00, 06, 12, and 18 UTC; FNL 2000). By assimilating many observational data, FNL data are able to provide a lot of global meteorological parameters with high reliability and utility since July 1999. Thus, it could satisfy our need to reflect the atmospheric situation during the occurrence period of the migration event.

For atmospheric circulation field, two isobaric heights (500 and 850 hPa) were chosen to analyze the impacts of atmospheric circulation on the movement and landing of *N. lugens* populations during the migration period. These two typical variables could show the role of atmospheric circulation in this migration on the high altitude and the prevailing migration altitude. Among various manifestations of atmospheric dynamic field, the wind and vertical velocity are the elementary factors that can directly affect insect migration (Bao et al. 2005, Hu et al. 2007, Wang et al. 2009). Considering the model results and *N. lugens*’ flight behavior, we focused on
analyzing wind at 850 hPa and vertical velocity from ground to prevailing height (850, 925, and 1000 hPa) in atmospheric dynamic field.

RESULTS

Brief pest situation in 2016 and model simulation results

In 2016, the area where N. lugens appeared in Korea was mainly concentrated in the coastal areas of southern Korea (Fig. 2). During this year, the area in Korea which suffered losses due to N. lugens was 2546 hm², and the occurrence rate (the ratio of occurrence area to total rice cultivation area) was 0.3%. These indicators mean that this year is a mild occurring year of N. lugens. At the same time, it could be seen from the 10-d average light-trap catch of N. lugens (Fig. 1) that the initial appearance of N. lugens in Korea was in early July, and the peak of immigration appeared in early August. For selecting a representative migration event, the ten days in early August were chosen as the simulation period, during which the maximum immigration number of N. lugens appeared.

As shown in Fig. 3a, the reasonable and selected simulation routes locate the possible insect source areas in southeastern Jiangsu and eastern Shanghai, speculating that the N. lugens population may complete this overseas migration in the altitude range of 1700–2200 m, and finally, landing in southwestern Korea between 02:00 and 11:00 UTC on 3 August (i.e., Seoul time: 11:00–20:00 on 3 August). The takeoff time was around dusk on 1 August, and there were many macropterous adults in the rice fields of candidate source areas during this period (Table 1). Obviously, the forward trajectory simulation results shown in Fig. 3b did not conflict with the backward one. It suggested that the N. lugens immigration from China to Korea within the predicted period was high confidence in this event.

Analyses of wind field and vertical velocity field

As shown in Fig. 3, the altitude of 1700–2200 m is the main migrant layer simulated by HYSPLIT in this case. However, a lower height range may be reasonable by considering the results of previous studies and the initiative of N. lugens. Thus, the wind field at 850 hPa was analyzed and used to infer the direct effects of wind on possible migration routes of insect. For the vertical velocity, its fields were displayed at 850, 925, and 1000 hPa. In this way, the effect of vertical velocity changes on rising of the N. lugens population to prevailing flight altitude from source areas, or descending to the ground in landing areas, could be analyzed more completely.

Seen from the change of wind field at 850 hPa from 12:00 UTC on 1 August to 12:00 UTC on 3 August (Fig. 4), there is a strong south airflow belt from the southeast coast of China to the Bohai Sea. Although there was not large-range

Table 1. Results of paddy field investigation for rice planthopper every five days, from 6 July to 5 August in 2016 at the Chongming Plant Protection Station in Shanghai, China.

| Time period | Total number of rice planthoppers | Percentage of macropterous rice planthoppers | Percentage of brachypterous rice planthoppers | Percentage of Nilaparvata lugens |
|-------------|----------------------------------|--------------------------------------------|-------------------------------------------|-------------------------------|
| 7.6–7.10    | 1096                             | 2.9                                        | 0.0                                       | 2.2                           |
| 7.11–7.15   | 1234                             | 10.8                                       | 0.0                                       | 6.8                           |
| 7.16–7.20   | 575                              | 15.0                                       | 0.0                                       | 21.8                          |
| 7.21–7.25   | 350                              | 23.1                                       | 0.0                                       | 14.3                          |
| 7.26–7.31   | 66                               | 3.0                                        | 6.1                                       | 25.0                          |
| 8.1–8.5     | 175                              | 2.9                                        | 0.0                                       | 37.9                          |
| Average     | 583                              | 9.6                                        | 1.0                                       | 18.0                          |

Notes: By comparing the percentage of adult rice planthoppers between the macropterous type and the brachypterous type in the observation area, it can be found that the average number of macropterous N. lugens may be much higher than that of brachypterous individuals. Such a result reflects that local living environment or meteorological conditions promoted transformation for N. lugens to macropterous type, and also, there might be a lot of macropterous adults of N. lugens suitable for long-range migration in possible insect source areas before the case happened. All data were obtained by randomly investigating 100 clumps of rice in the observation area of plant protection station. Except that the total number was rounded to integer, the other data were rounded to one decimal place.
low-level jet (wind speed ≥12 m/s), this airflow was still strong enough to transport pest population from East China to the Korean Peninsula before individual’s fats were completely consumed. At the same time, a north wind also moved southeastward from the Mongolian plateau. These north wind and south wind confronted between southern Northeast China and the southern part of the Korean Peninsula, especially over Korea, where the south airflow was prevented from expanding its influence areas further northward. A confrontation like this would promote the landing in the south of Korea for *N. lugens* populations carried by the south wind. After 12:00 UTC on 3 August, as the typhoon landed and gradually disappeared, the wind field between China and Korea became stable, and there was no airflow suitable for migration again. Therefore, considering this migration case from the perspective of 850-hPa wind field, the south airflow was undoubtedly the decisive factor contributing to this successful occurrence of migration. And, the north airflow prevented the northward step of south airflow, which was the direct cause of landing for pest populations.

As shown in Fig. 5, the evolutions of vertical velocity at three levels of 850, 925, and 1000 hPa are almost the same during the occurrence period. On the one hand, for the insect source area, East China was generally controlled by a weak downdraft starting from 12:00 UTC on 1 August. However, after 18:00 UTC on 1 August, the vertical airflow direction in some parts of this area reversed and became an updraft. This scenario occurred especially in the Lower Yangtze River Valley, which were mainly controlled by updrafts. Such vertical velocity condition was particularly advantageous for *N. lugens* populations to take off and emigrate from paddy fields in East China. With the change of wind direction again, the bottom atmosphere above the Lower Yangtze River Valley was gradually affected by downdraft after 00:00 UTC on 3 August. Since then, there had been no vertical airflow conditions that facilitated the takeoff of pests throughout early August. On the other hand, for the landing areas, most regions in Korea were mainly under the control of weak downdrafts after 00:00 UTC on 2 August, especially in southwestern Korea, where the airflow had maintained a vertical movement toward the ground. Such meteorological condition with a long-term downward airflow could help the pest population moving over southern Korea to reduce its flight altitude and eventually land on the paddy fields. The results of the vertical velocity field indicated that there was a suitable vertical airflow when the *N. lugens* population took off and landed.
Analyses of geopotential height field

Atmospheric circulation affects the appearance and change of weather factors. Therefore, by grasping the dynamics and situation of the atmospheric circulation, we can understand the cause of this *N. lugens* immigration event from a deeper level. First, the geopotential height field at 500 hPa that could describe large-scale situation was analyzed. As shown in Fig. 6a–c, four major weather systems can be clearly identified at this height. The first one is a high-pressure system in the westerly belt above the Mongolian plateau (MHP), and the second is a low-pressure system above the Yellow Sea and Bohai Sea (YBLP), which is located downstream of MHP. Then, there is a strong tropical low-pressure system in the northern part of the South China Sea, which is Typhoon Nida (No. 1604; Gao et al. 2019). The last one is the western Pacific subtropical high (WPSH), which is always present in the northwestern part of the Pacific Ocean. The four weather systems interacted and restricted each other, together determining the atmospheric circulation pattern on a large scale.

Fig. 5. Vertical velocity fields at 850/925/1000 hPa (a–d/e–h/i–l) in East Asia, during the period of migration case occurrence from 1 to 3 August 2016. The value greater/less than 0 means that the area is controlled by the downdraft/updraft. The data used in these images were extracted from the FNL data.
during this migration period. At 12:00 UTC on 1 August, the YBLP and WPSH mutually restricted and simultaneously extended westward into East China. The MHP and typhoon were developing very strongly. After that, the obvious changes in the synoptic situation were that the MHP moved to the southeast, and the typhoon system continued to expand influence scope and move northward. At the same time, the intensity of the YBLP and WPSH had weakened and their influence scope had narrowed. At 12:00 UTC on 3 August, the MHP continued to move southeastward and expand its control range gradually, and eventually confronted the WPSH in the southern part of the Korean Peninsula. For typhoon and YBLP, their intensity and influence range had been largely reduced, and disappeared finally. Since then, Korea had been alternately affected by the MHP and WPSH for most of the time until mid-August. Then, the geopotential height field at 850 hPa, which is the prevailing flight height of N. lugens in summer, was analyzed. As shown in Fig. 6d–f, there are three major weather systems: a typhoon near the coast of Guangdong Province (i.e., Typhoon Nida), a continental high-pressure system moving from the Mongolian plateau to southeast (i.e., MHP), and a high-pressure system in the northwestern Pacific Ocean (i.e., WPSH). During the migration period, the evolution of these three weather systems at 850 hPa was similar to that at 500 hPa. For typhoon, it moved

Fig. 6. Geopotential height fields at 500 hPa (a–c) and 850 hPa (d–f) in East Asia, during the period of migration case occurrence from 1 to 3 August 2016. The data used in these images were extracted from the FNL data.
northwestward from the southeast coast of China and eventually merged with a weak low-pressure system in Southwest China. For MHP, it moved to the southeast and gradually stabilized in the northeastern and northern parts of China. As its impact range expanded southeastward to the Korean Peninsula and southern part of the Japanese archipelago, this high pressure finally formed a confrontation with the WPSH. Finally, for the WPSH, it had been controlling the east side of area from eastern China to southern Korea through the whole migration period. With the gradual demise of the typhoon, the WPSH expanded to East China once again. But it was restricted by the MHP on its north side and failed to control the landing area over there.

**Important weather systems and weather factors**

Combining analysis results of the atmospheric circulation field and dynamic field, we could find the important effects of two combinations of weather systems and their related weather factors in this overseas migration event of *N. lugens*. The first combination was typhoon and WPSH. The confrontation between these two weather systems in eastern China brought two favorable conditions. Under the control of a typical low-pressure system (typhoon), the insect source area could maintain a continuous updraft during the migration period, which helped macropterous adults take off. More critically, the confrontation generated a southerly airflow belt from eastern China to southern Korea, and this stable and strong weather factor was one of the key reasons for achieving this migration event. For this airflow, the strong typhoon was its main source of power, and the relatively mild WPSH mainly played a role in guiding the wind direction. The second combination was WPSH and MHP. It was obvious that the confrontation between two weather systems in southern Korea largely prevented the southerly wind from flowing northward. The accumulated air mass flowed to the lower layer, generating a downdraft, which promoted the *N. lugens* populations to reduce their flying height and eventually land on the ground. In general, typhoon, WPSH, and MHP were important weather systems in this overseas migration event, and the southerly airflow belt was an important weather factor.

**DISCUSSION**

*Nilaparvata lugens* migrates regularly in East Asia every year (Cheng et al. 1979, Bottrell and Schoenly 2012, Otuka 2013). In general, the planthopper populations take the rice-growing areas in the Yangtze-Huaihe River Valley or North China as the northernmost destination of entire northward migration, instead of moving to the Japanese archipelago or the Korean Peninsula across the sea, unless there are favorable weather conditions (Zhu et al. 2000, Otuka et al. 2005, 2010, Zhai 2011). This shows that for overseas migration, the weather system plays an important role in its entire process, and there are some differences in characteristics between it and overland migration.

The impacts of weather systems on migrations of rice planthopper have been long concerned and researched. As a kind of long-range migratory small insect, it is obviously impossible for *N. lugens* to move tens of kilometers if *N. lugens* only relies on its own flight speed (Chen et al. 1984). Thus, the long-range migration is largely achieved with the help of weather systems. Previous researches have shown that weather systems, such as WPSH (Lu et al. 2017, Hu et al. 2018), continental low pressure and high pressure (Cheng et al. 1979, Jiang et al. 1981, 1982), thunderstorm (Greenbank et al. 1980), rainfall (Drake 1994, Tucker 1994), breeze (Drake 1982, Crummay and Atkinson 1997), and low-level jet (Watanabe and Seino 1991, Otuka et al. 2006, Bao et al. 2009), can affect migratory stages and ultimately determine the distance of migration and the landing location of insect populations. By summarizing the analysis results of this case, some features of weather systems acting on overseas migration may be able to be extracted. First, a lot of large-scale systems with strong intensity and long duration (e.g., typhoon and WPSH in this case) may be the key driving forces for the occurrence of overseas migration events. In previous studies, both large- and meso-scale systems are considered to have varying degrees of impact on the movement, concentration, and deposition of migratory insects (Jiang et al. 1981, 1982, Watanabe and Seino 1991, Drake 1994, Crummay and Atkinson 1997, Bao et al. 2009, Lu et al. 2017, Hu et al. 2018). However, the latter may not be able to satisfy the stringent
requirements of overseas migration, due to its short duration and small range of influence (e.g., the immigrants moving into Japan mainly rely on southwesterly low-level jet; Seino et al. 1987, Watanabe and Seino 1991, Otuka et al. 2006). Thus, more attention should be probably focused on large-scale weather systems in the study of overseas migration. Second, the interaction among various weather systems is particularly important for overseas migration. In this migration event, for example, the confrontation between the MHP and the WPSH over Korea eventually led to the landing of N. lugens in southern Korea. However, if the strength of systems, or the confrontation region, was different from that in this event, the landing location might be completely different. Therefore, overseas migration may be referred to as one-off migration for N. lugens. The coordinated cooperation between weather systems can make it immigrate to a land smoothly, but non-coordination among weather systems may let it land on the sea, leading to the death of the population.

As two typical migration patterns, overseas migration and overland migration have many of the same characteristics, but also some differences. The similarities are mainly manifested in two aspects. First of all, no matter what the type of underlying surface is, the landing region of pests will generally undergo a process of gradual immigration, the peak of immigration, and gradual emigration. This process is formed under the combined influence of physiological habits of N. lugens (e.g., reproductive cycle and feeding only on rice) and external conditions (e.g., the atmospheric circulation situation and meteorological element fields). The second similarity is that the pest number changes in the regions, through which N. lugens migrates every year, are mutually influential and interrelated. This feature occurs because that the total emigrated number of N. lugens in the upstream source area is often positively correlated with the initial pest situation in the downstream landing area under suitable external conditions (Cheng and Zhu 2006). The difference between the two types of migration is mainly reflected in performance results, even if they follow the similar migration pattern. For an overland migration event, it can be composed of multiple migration populations with multiple sources and times. In such situation, the stages of gradual immigration and the peak of immigration caused by one population may not be accurately distinguished, or even some of the weaker immigration peak signals may be masked by other stronger signals. In contrast, for the overseas migration, it is generally associated with a single N. lugens population. The variation curve of immigrant number is straightforward, and the characteristics at different stages are very clear. This difference is caused by different effects of various underlying surfaces on the two types of migrations. For overland migration, the eating and multiplication of pest population will not be affected when landing in an offtrack area due to sudden changes of weather systems at the landing stage (the premise is that there are wild rice plants or rice fields in the landing area). Their next generation can still achieve the goal of reaching the intended location with appropriate weather conditions. Therefore, a weather event may sometimes bring populations from different regions to the same location. However, for the population that moves across the sea, a perfect combination of the carrier airflow and landing conditions is essential if they want to successfully land at the destination across the sea. Otherwise, the different landing location will likely lead to sea surface landing and eventually cause death of the entire population (i.e., the one-off feature mentioned above). Obviously, it is uncommon for populations from different source areas to reach the same landing location for an overseas migration event.

**Conclusions**

After the trajectory simulation and the analyses of pest light-trap catches and atmospheric background, this immigration case from East China to southern Korea had been basically analyzed. In the attempt of using the HYSPLIT model to determine a migration example hidden in the long-interval data, the atmospheric transport and dispersion model demonstrated its ability to simulate the behaviors of migratory insects. Such a capability may create many possibilities in the study of long-range migration of N. lugens, together with other technical methods. However, compared to actual behaviors, a model that does not consider the active flight and biological characteristics of insects always has
errors. Thus, further exploration of the actual dynamics of migratory insects after leaving the ground would require high-temporal/spatial-resolution data based on advanced technology and systematic observation networks in the future. The combined analyses of atmospheric circulation and dynamic fields suggested that large-scale weather systems greatly affected the result of *N. lugens* overseas migration. In the discussion of the way that large-scale weather systems and their cooperation acted on overseas migrations, the concept of one-off in *N. lugens* overseas movement was proposed, and this concept further illustrated the importance of large-scale systems’ changes and coordination in overseas migration. Besides, using the pest catch data from upstream regions, the reliability of analyses about this case at present had been confirmed, and its migration chain of the *N. lugens* population from East China to Northeast Asia was basically clear. It indicates that early warning and management of pest risk are likely to be achieved in the future, through extensive and timely communication about *N. lugens* situation between different regions.

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