Reconstruction of the origin of *Antigastra catalaunalis*, a new moth for the Dutch fauna (Lepidoptera: Crambidae)

Joop Schaffers

KEYWORDS
Threshold temperature, backtracking, forward tracking, trajectory, lifespan

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In September 2006 six specimens of *Antigastra catalaunalis* (Duponchel) were recorded in various places in The Netherlands. This migrant was also seen in five other countries in northern Europe in considerable numbers. In searching for the origin of the migrants, the trajectory model TRAJKS of the Royal Netherlands Meteorological Institute (KNMI) is used. Seven assumptions were made about the behaviour of the moth. The trajectories made by the computer are used to calculate the most likely journeys. Five cases are presented, corresponding to recordings of the moth at various places in northern Europe. The long-distance movement varies from three to fourteen nights. Problems were met due to rainfall, calm weather, and the low resolution of the trajectory model. Two depressions in the west of Ireland and an accumulation of favourable weather conditions over continental Europe made it possible for the migrants to travel over 1,000 km or more. The likely source of the moths appears to be two estuaries, of the Rhône and the Aude, in the south of France. The moths take advantage of the two gates in the mountain chain in southern Europe, west and east of the Massif Central in France. The threshold temperature of the species might be 17°C and the longevity of the females two weeks, although there are many uncertainties due to the poor resolution of the wind data used and the poor knowledge of the behaviour of the moth. Unfortunately (and surprisingly) there are no records of the moth in France, which could have been very helpful in this investigation.

Introduction

The sesamum shoot and leaf webber, *Antigastra catalaunalis* (Duponchel), a pest on sesame (*Sesamum indicum*) in the tropics, is present in all continents, except Antarctica (figure 1). In Europe it occurs throughout the Mediterranean region: Portugal, Spain, France, Italy, Greece, Cyprus and Malta (CAB International 2007). The caterpillar is known to feed on *Linaria* sp. and *Antirrhinum* sp. in the subtropical region of South-Europe (Slamka 1995), round-leaved fluellen (*Kickxia spuria*) and common snapdragon (*Antirrhinum majus*) in France, and sharp-leaved fluellen (*Kickxia elatine*) in Spain (Dr. Antonio Vives, pers. comm.).

The lifespan of male and female individuals differs and depends on ambient temperature: with temperatures increasing from 16 to 30°C, longevity increases from 6.2 to 8.3 (males) and from 7.0 to 10.7 days (females) (Singh *et al.* 1992). The preoviposition period also depended on temperature and varied from 2.0 days (at 30.6 ± 5.1°C) up to 6.5 days (at 15.8 ± 7.5°C). The oviposition period ranged from 5.3 days (at 29.1 ± 3.5°C) to 4.2 days (at 15.8 ± 7.5°C).

In the temperate zone of Europe, *A. catalaunalis* is repeatedly found as a migrant. The species has been recorded in the past twelve years intermittently in England (Mark Parsons, pers. comm.). In Denmark the first record was in 1984 (Bjarne Skule, pers. comm.), in Sweden in September 2004 (Nils Ryrholm, pers. comm.) and in Ireland in October 2005 (Ken Bond, pers. comm.).

In various articles about this species no information was found on the number of generations in the tropics, but like many moths in the tropics it probably breeds continuously. No information was found either on the number of generations in the south of France. The moths fly in the south of Europe from the end of August until October, which suggests a single generation (Antonio Vives, pers. comm.), but there may also be two: one generation before August and one between August and October.

The immigrations in 2006

In September and October 2006, *A. catalaunalis* moths were repeatedly captured in Belgium, England, Guernsey, The Netherlands, Ireland, Denmark and Sweden (table 1), indicating extraordinary northward migration. For Belgium and The Netherlands the species was new to the fauna. In The Netherlands it was first captured on 16 September in St. Kruis (Henk Bondewel and Pieter Simpelaar, pers. comm.), and then on 18 September in Retranchement (Anna Almekinders and Hans van Kuijk, pers. comm.), on 25 September in Bathmen (Harrie Groenink, pers.

comm.) and in Doorwerth, on 27 September in Kruiningen (Floor Lamoen, pers. comm.), and on 28 September again in Retranchement (Anna Almekinders and Hans van Kuijk, pers. comm.).

In England, 72 specimens were recorded in 2006 (table 1) (Anonymous 2006), but there may have been more than 100 (Mark Parsons, pers. comm.). The remarkable number of 19 specimens on 23 September coincides with the National Moth Night. Most of the records in Denmark were made with light-traps in which the catches were collected and identified over a period of several days (Bjarne Skule, pers. comm.). The record in Sweden is also made with a light-trap during the period of 30 September to 11 October 2006 (Nils Ryrholm, pers. comm.). Inquiry in Germany indicated there were no records (Willy Biesenbaum, pers. comm.).

Chances that a moth comes to light during migration are very low (Jason *et al.* 2002, Feng *et al.* 2004). It only comes to light-traps after it has stopped migrating and flies around to locate mates and plants to deposit eggs. So records can only be noted at least one day (say 12 hours) after arrival. Note that in the world of lepidopterists the date of the record generally is the date of the evening they start with the trapping with light.

It is one thing to simply register the presence of a particular moth species, it is quite another to reconstruct its origin. In this article I try to reconstruct the source of the moths found in several places in northern Europe, which I present as five 'cases', based on a trajectory model used in meteorology, plus a handful of explicit assumptions.

1. *Antigastra catalaunalis* of 18.09.2006 in Retranchement (province of Zeeland, The Netherlands). Photo: A. Almekinders
1. *Antigastra catalaunalis* van 18.09.2006 in Retanchemant (Nederland).

Table 1. Records of *Antigastra catalaunalis* in countries north of France in September 2006.
Tabel 1. Waarnemingen van *Antigastra catalaunalis* in landen ten noorden van Frankrijk in september 2006.

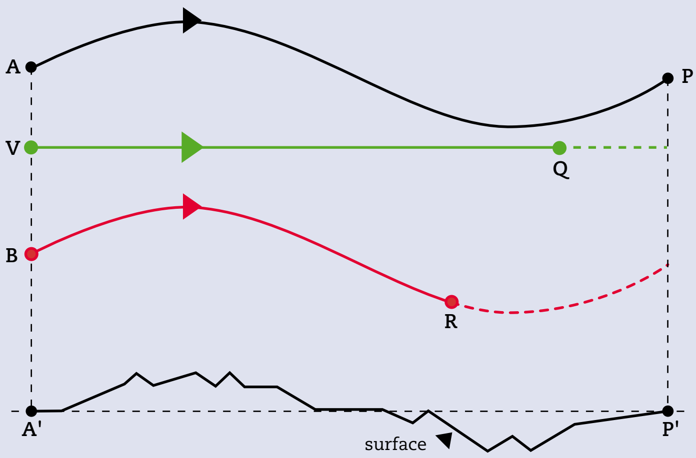
Date	Belgium	England	Guernsey	Netherlands	Ireland	Denmark[1]	Sweden
5 September	2						
7	1						
12		3	2				
13	1	6					
14		9					
15		2					
16	1	5	1	1			
17		1					
18				1			
19		1					
21		6					
22	1	1					
23	1	19					
24	1	5			3		
25		3		2			
26		1					
27		3		1		1	
28		2		1			
29	1	1					
30						4	1
1 October						1	
2		1					
4						2*	
11		1					
18		1					
25		1					
Total	9	72	3	6	3	23	1

[1] Catches based on periods of more than four days are not attributed to a particular date (but they are included in the total).
[1] Vangsten gebaseerd op periodes van meer dan vier dagen (dat wil zeggen, bij meer dan vier dagen tussen opzetten en leeghalen van de val) werden niet toegekend aan een specifieke datum (maar ze werden wel meegeteld bij het totaal).
* Number of specimens caught in light-traps during 3-5 and 2-6 October 2006, attributed to the median date.
* Aantal vlinders gevangen in lichtvallen van 3-5 en 2-6 oktober 2006, toegekend aan de tussenliggende datum.

Box 1

Trajectories

The path of a moving air particle through the atmosphere (trajectory) can be calculated with the model TRAJKS of the Royal Netherlands Meteorological Institute (KNMI). The term 'air particle' is often used in meteorology; think, for example, of 1 m^3 air. In the present calculation, the model uses data from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a horizontal resolution of 1 × 1 degree and a time step of 6 hours. At each grid point in a 1 × 1 degree grid cell on the globe values are assigned to weather variables. Vertically this occurs on 9 levels, from the surface up to 780 m elevation.



1-1 Trajectories of air particles A and B and the path of moth V, all departing on the same moment. Note that the vertical scale is much larger than the horizontal scale.
1-1 Trajectoriën van luchtdeeltjes A en B en de baan van vlinder V, die tegelijkertijd vertrekken. Let op: de vertikale schaal is veel groter dan de horizontale.

The meteorological variables important for this study and the desired output of the model

Forward tracking

Suppose an air particle departs in the air at A, vertically above place A' (see figure 1-1). In reality the distance AB is, for example, 200 m and the distance A'P' 200 km. In the following example the data are related to the trajectories from Sens in France. The input data for a departure from Sens are the date (13 Sept 2006), the moment of departure in whole hours (18:00 h), the pressure at the start (950 hPa), the coordinates of the place of departure in tenth of degrees (3.0° E, 48.2° N) and the duration of the trip (11 hours). TRAJKS calculates the movement of the air, in figure 1-1 this is the trajectory AP. Nota bene: the trajectory has three dimensions, whereas in figure 1-1 only the path in the vertical plane is visible. At the same time TRAJKS calculates pressure, ambient temperature, speed and relative humidity of the air particles during the trip.

As desired output, the model produces a map with the projection A'P' of the trajectory AP, and graphs in which the various variables are depicted against time. During one run of the model several trajectories can be calculated at the same time, for example with several starting pressures (= heights).

Figure 4 shows an example of three trajectories used in Case 1, from Sens in France to the east of England. The air starts at three different levels, as indicated by three air pressures. For instance, 960 hPa pressure at the start in this case corresponds with 230 m above the surface in Sens. This particular air particle arrives 11 hours later at 967 hPa, which is 170 m above surface in England. At lower altitudes moving air experiences more friction, thus velocity is lower. A lower velocity means a shorter trajectory and the direction tends more toward the lower pressure (depression). This implies that moths starting at various heights end up in different places.

Backward tracking

Suppose an air particle arrives in P, vertically above place P'. The input data are the date (14 Sept 2006), the moment of arrival (05:00 h), the pressure (= height) at arrival, the coordinates of the place of arrival and the duration of the trip (11 hours). The model then calculates where the air particle had moved for the previous 11 hours, thus assessing its starting point A, and the trajectory AP is drawn.

The source of the moths

The source of windborne migrants trapped at a particular place can be estimated by so-called 'backward trajectory analysis', i.e., by tracing back the origin of the air which arrives at the same place and at the same time (Box 1). Two main factors are important for this type of historical analysis: behaviour of the migrant (i.e., the moth), and weather conditions. It is absolutely necessary to make (simplifying) assumptions, to make the model tractable.

Moth behaviour

Since knowledge of the flight behaviour of *A. catalaunalis* is lacking completely, the following assumptions were made, partially based on the behaviour of similar species, *Plutella xylostella* (L.) (Plutellidae) (Chapman *et al.* 2002) and *Loxostege sticticalis* L. (Pyralidae) (Feng *et al.* 2004). The relation between (assumed) characteristics of the moths and the physical quantities used in backtracking is explained in Box 2.

1. The moths fly only during the night. They take off at dusk (Feng *et al.* 2004) and land at dawn. The precise moments were chosen at civil twilight, i.e., about half an hour after sunset and half an hour before sunrise.
2. The moths take off and fly during the night only if temperature exceeds a threshold. For *L. sticticalis* this is about 20°C (Feng *et al.* 2004). For the current trajectory analysis at first 18°C was picked for *A. catalaunalis* (after personal communication with H. Feng), but several trajectories suggested an even lower flight threshold. Therefore, a final threshold of 17°C was assumed.
3. In articles about migrating moths, accumulation of the migrants in well-defined layers is mentioned, typically at heights of 200-400 m (Chapman *et al.* 2003, Feng *et al.* 2004, Wood *et al.* 2006). This led to the assumption that the moths start at a height of 300 m above the place where they take off. This height corresponds with an air pressure at the start of 35 hPa lower than at surface level (see formulas in Box 3).

Box 2

How assumptions about moth behaviour relate to the model

In order to add the data into the model, a number of assumptions must be made.

1 The moth takes off at civil twilight. If on 13 September the sunset in A' (see figure 1-1, Box 1) is at 18:05 h, the moth departs half an hour later at 18:35 h ('halfway' the twilight). If on 14 September the sunrise in P' is at 05:28 h, the moth lands half an hour earlier at 04:58 h. Because only input in whole hours is possible, two runs are made at 18:00 and 19:00 h. The desired trajectory is then found by interpolation.

2 The moth does not fly below the threshold temperature, T_d. For *A. catalaunalis* T_d = 17°C is chosen. One possible output of a model run is a temperature-time graph. If temperature during the night drops below T_d, the moth descends to air with a temperature that is high enough and a new run is made. If this air cannot be found, the flight stops.

3 The starting height for *A. catalaunalis* is chosen at 300 m above surface level. The pressure at 300 m height is 35 hPa less than at surface level (see Box 3). The pressure at surface level is calculated by TRAJKS. The pressure at the start can now be added.

4 It is assumed that the moth, after the start at 300 m, flies horizontally during the whole trip. This is indicated in figure 1-1 by the green line through the points V and Q. The model has to calculate for example five trajectories with starting heights (pressures) around 300 m, in figure 1-1 five air particles between A and B. The air particles and the moth depart at the same moment. Because at higher altitudes an air particle experiences less friction, its speed is greater. In a time span Δt air particle 'A' will have covered a larger distance (the length of the curve AP) than particle 'B' (BR). The moth departs in V with the same speed as that of the air particle in V, but in a different direction (see Box 3).
The distance the moth covers in time span Δt can be calculated from the output data of the five trajectories. Box 3 shows how the pressure-time graphs correspond with the speed-time graphs and how to calculate the distance VQ.
Figures 5 and 6 show projections of trajectories from air particles that travel on fluctuating heights (A'P' in figure 1-1). To make the journey of the moth at constant height visible in these two figures, those trajectories from the model output are used that fit the best with the journey VQ of the moth.
The starts from both the Aude estuary and the Rhône estuary cause the most difficulties in the trajectory investigation, due to the sudden transition from sea level to the mountains and due to the mountains themselves. Small changes in starting coordinates or in starting height cause big differences in length and direction of the displacement. In case 1 it was necessary to cut the first night in six parts, due to the large differences in wind velocity between adjacent trajectories. In each part the procedure as mentioned above was followed.

5 The moths only migrate if it is not raining. Among the output data is a relative humidity graph. If the relative humidity is high (90-100%) at a particular place it could indicate that it is raining, or has recently rained in that place. In that case, data on rainfall from that place are necessary. Rainfall data from several stations of Meteo France, the French Meteorological Institute, were being used.

Box 3

Formulas used in model calculations

1 If a body moves with an average speed $\bar{v}$ in a straight line, the covered distance in a time interval can be calculated with $\Delta x = \bar{v}\,\Delta t$.
For a linearly moving body with variable speed, this corresponds with determination of the area under the curve in a velocity-time graph.

2 The change in pressure (Δp) in the atmosphere associated with a small change in height (Δh) can be calculated with

$$\frac{\Delta p}{\Delta h} = -\frac{gpM}{RT},$$

where g is the local gravitational acceleration, p the air pressure, M the molar mass of the air, R the universal gas constant and T the absolute temperature of the air; p and T are constant along Δh.
For surface pressure p = 1.00 × 10^5 Pa, T = 293 K, g = 9.81 m/s^2 (in The Netherlands), M = 28.8 g/mol and R = 8.314 J/molK,

$$\frac{\Delta p}{\Delta h} = -\ 0.116\ hPa/m$$

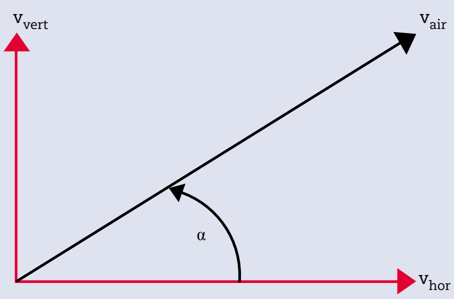
3 For parallel and straight isobars on a weather map the constant airspeed between the isobars can be calculated with

$$v = \frac{1}{\rho f}\,\frac{\Delta p}{\Delta x},$$

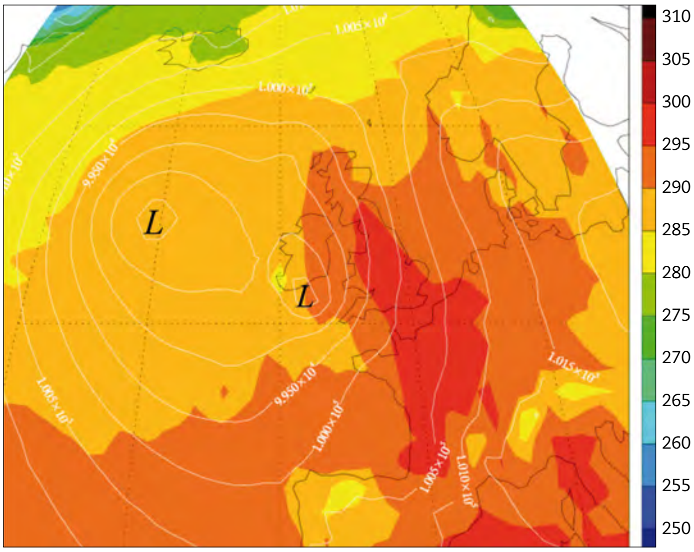
where $f = 2\Omega \sin \varphi$ (the so-called geostrophic wind); ρ is the density of the air (= 1.3 kg/m^3), Ω the angular velocity of the earth (= 7.29 × 10^5 s^{-1}) and φ the latitude. In figure 2 the horizontal pressure gradient can be determined from the weathermap around England:

$$\frac{\Delta p}{\Delta x} \approx 3.0\ \text{Pa/km}.$$

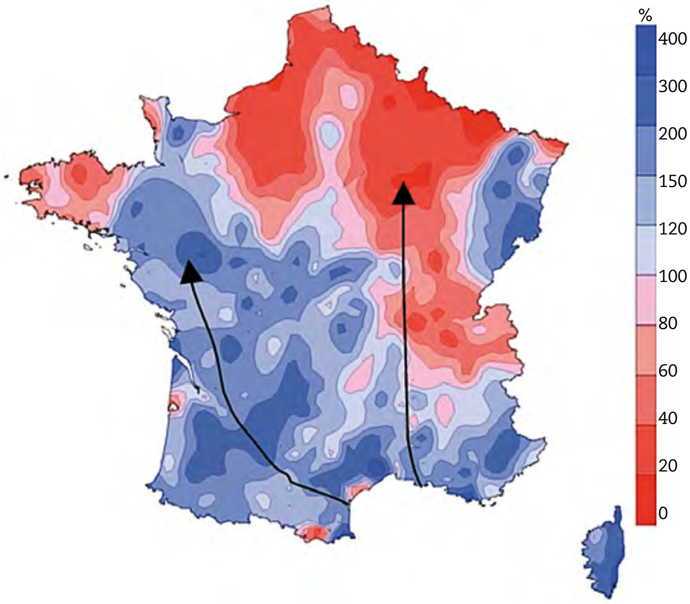
The geostrophic wind becomes v = 20 m/s.

4


v_{hor} (i.e., the horizontal component of v_{air}) = $v_{air} \cdot \cos \alpha$. For small angles α, $v_{air} \approx v_{hor}$ (= v_{moth}) because cos α ≈ 1. For instance, on 23 Sept 2006 an air particle mounts in 2 hours from 300 m to 360 m and covers a horizontal distance of 43 km. Then α = 0.0801° and cos α = 0.999.



2. Surface map from the depression west of Ireland on 21.09.2006, 18:00 h. The white lines are lines of constant pressure (isobars). The corresponding pressures are presented in Pascal (Pa), for example 1.000x105 Pa (=1000 mbar). The temperatures (the colours in the vertical scale) are in Kelvin (K). Source: KNMI
2. Grondkaart van het lagedrukgebied ten westen van Ierland op 21.09.2006, 18:00 uur. De witte lijnen zijn lijnen van constante druk (isobaren). De bijbehorende druk is weergegeven in Pascal (Pa), bijvoorbeeld 1.000x105 Pa (=1000 mbar). De temperaturen (de kleuren in de vertikale balk) zijn in Kelvin (K). Bron: KNMI



3. Rainfall in September 2006 in France, expressed in the normal rainfall in that period (below 1000 m). The arrows indicate the valley routes west and east of the Massif Central. Source: Météo-France
3. Neerslag in september 2006 in Frankrijk, uitgedrukt in the normale neerslag in die periode (onder 1000 m). De pijlen geven de valleiroutes aan, ten westen en ten oosten van het Massif Central. Bron: Météo-France

4 After the start at 300 m high, the moths fly horizontally (= at constant pressure) during the whole night. They need to flap their wings constantly not to lose height.
5 When flying downwind at a constant pressure, the moths take the horizontal value of the wind speed. They do not add an extra flight speed, nor do they influence flight direction.
6 The moths take off at every wind direction, there is no favourite direction.
7 The moths only migrate if it is not raining (Feng *et al.* 2004).

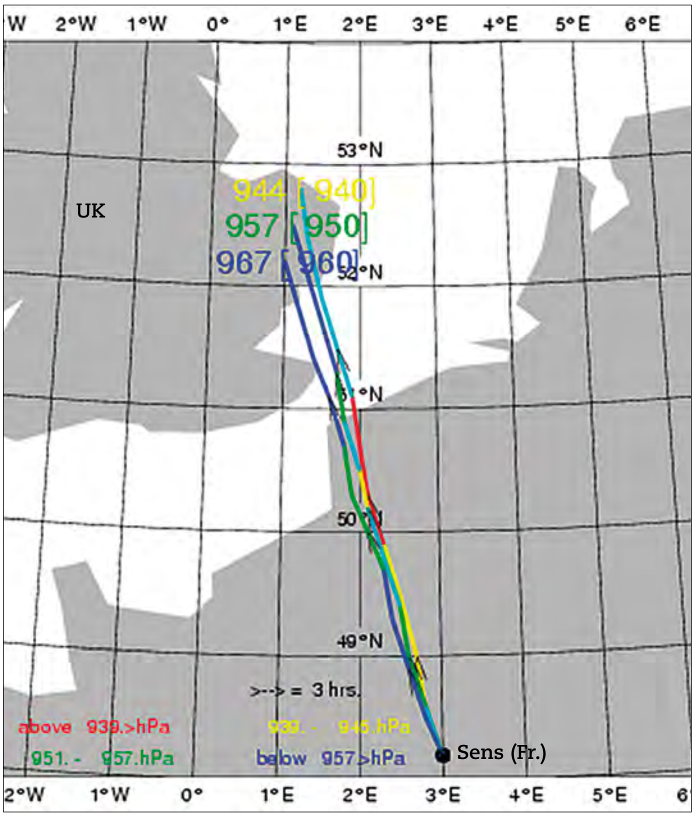
Weather

Apart from behaviour, the second main influence on a migrant's path is the weather. The combined action in September of depressions west of Ireland and anticyclones on the continent causes winds from the south over France. Most powerful were those on 13-14 and on 20-21 September (figure 2). The deep depression on 21 September caused in the east of England isobars at sea level, with a difference in pressure of 5 hPa over a distance of 170 km. Calculation of the wind velocity (assuming no friction) gave 20 m/s (= 72 km/h) (see formulas in Box 3). Only this sequence of such favourable weather conditions enabled all the records in countries north of France. The heavy rainfall in September in the west of France (figure 3) complicates the trajectory investigation. The moths don't fly if it is neither raining, nor just after rain. Rainfall reports of different weather stations in the west of France were taken into account.

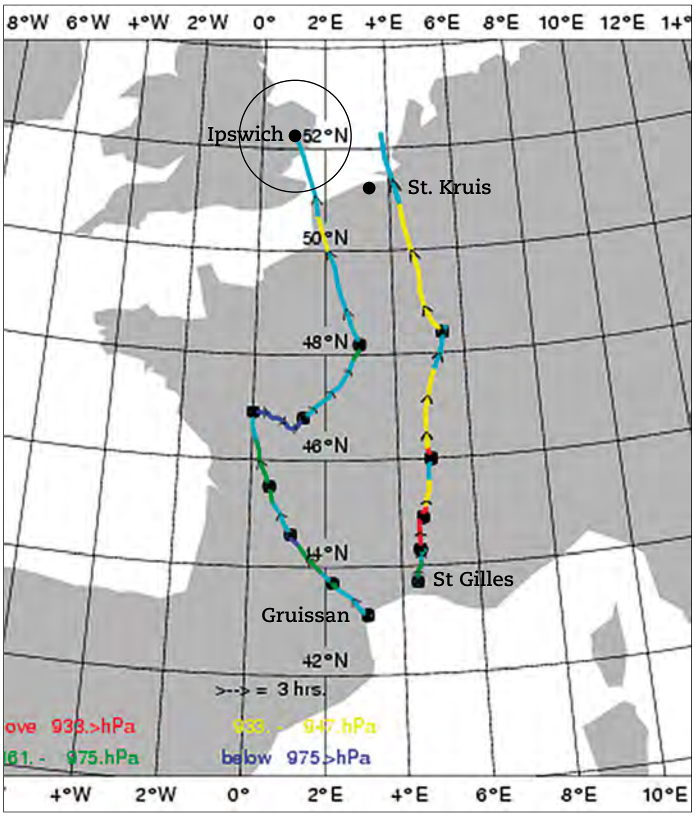
Mountains form a barrier for *A. catalaunalis*, because they force the air to go up, and thus the temperature of the air drops, possibly below the flight threshold. Therefore it is not

Table 2. Wind direction (Dir) and force (Bft) in Arles (Rhône delta) and Narbonne (Aude delta) in September 2006 at dawn at 300 m above surface level. Favourable situations for migration northward are in red, but if temperature is too low and/or rain prevents moths from taking off, favourable winds are in black.
Tabel 2. Windrichting (Dir) en -kracht (Bft) in Arles (Rhône delta) in september 2006 in the schemering op 300 m boven de grond. De windrichting is rood wanneer de omstandigheden gunstig zijn voor noordwaartse migratie (maar gunstige windrichting blijft zwart wanneer lage temperatuur en/of regen het vertrek van de motten verhinderen).

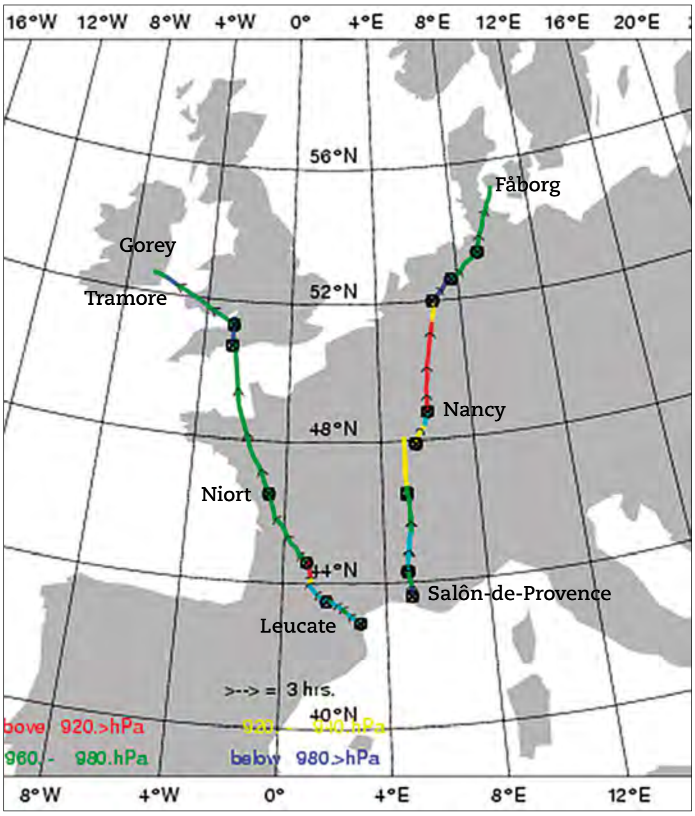
	Arles		Narbonne			Arles		Narbonne	
Date	**Dir**	**Bft**	**Dir**	**Bft**	**Date**	**Dir**	**Bft**	**Dir**	**Bft**
1	S	3	SE	2	16	NW	4	W	7
2	NW	2	W	3	17	NW	6	NW	7
3	N	1	W	3	18	NW	7	NW	7
4	N	1	SE	2	19	N	5	NW	5
5	S	2	SE	2	20	S	3	SE	4
6	S	2	E	3	21	S	5	SE	6
7	W	2	NW	1	22	SE	5	SE	6
8	NE	3	E	2	23	SE	6	SE	6
9	S	2	SE	4	24	SE	7	SE	4
10	S	3	SE	4	25	NW	7	NW	7
11	S	4	SE	3	26	N	7	NW	7
12	S	4	SE	5	27	N	3	S	1
13	SE	7	SE	7	28	SW	2	S	2
14	S	4	W	5	29	S	3	SE	2
15	NW	5	NW	7	30	S	5	SE	4



4. An example of trajectories from Sens (France) to East Anglia on the night of 13-14 September 2006. The air starts at three different levels, indicated by the three air pressures (in brackets at the end of the trajectories). The colours show the different heights at which the air particle travels.
4. Een voorbeeld van routes (trajectoriën) van Sens (Frankrijk) naar East Anglia in de nacht van 13 op 14 september 2006. De lucht vertrekt op drie verschillende hoogtes, corresponderend met drie niveaus van luchtdruk (de getallen tussen haakjes aan het eind van de routes). De kleuren geven de hoogtes aan waarop de lucht verplaatst wordt.

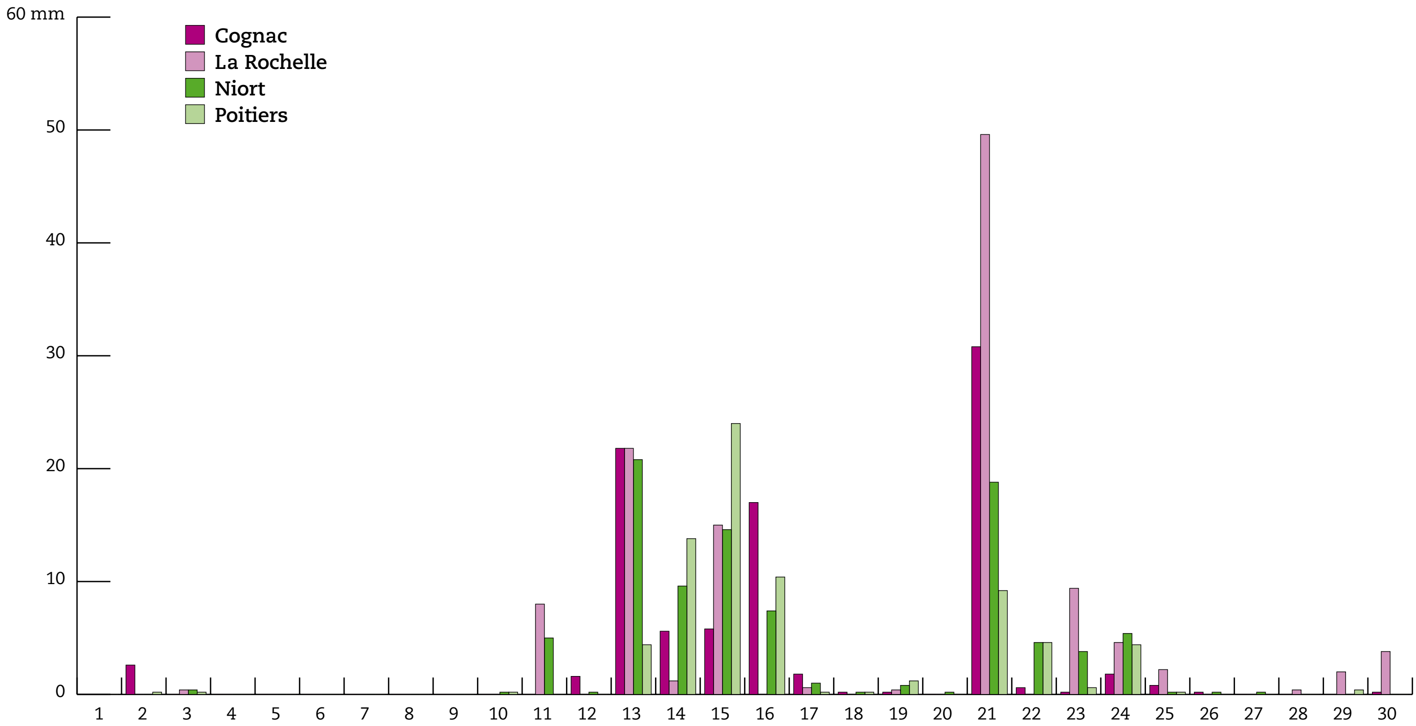


5. The journey from Gruissan (Aude delta) to the southeast of England (left) (Case 1) and the journey from Saint Gillis (Rhône delta) to Sint Kruis (The Netherlands) (right). The circle around Ipswich indicates the model's 10% uncertainty in prediction of the journey length (radius: 129 km). Note that one trip from the south of France to Northern Europe takes several nights. The trajectories from each night are connected to show the whole trip.
5. De tocht van Gruissan (Aude delta) naar het zuidoosten van Engeland (links) (Case 1 in de tekst) en de reis van Saint Gillis naar Sint Kruis (Nederland) (rechts). De cirkel rond Ipswich geeft de onzekerheid van het model aan, van 10% in de totale lengte van de gereconstrueerde route (straal: 129 km). Let op: de reis van het zuiden van Frankrijk naar noordelijk Europa duurt verscheidene nachten. De routes (trajectoriën) van de aparte nachten zijn hier verbonden om de hele reis te tonen.



6. The journey from Leucata (Aude delta) to Gorey and Tramore (Ireland), and from Salon-de-Provence (Rhône delta) to Fåborg (Denmark). Note that one trip from the south of France to Northern Europe takes several nights. The trajectories from each night are connected to show the whole trip.
6. De reis van Leacate (Aude delta) naar Gorey en Tramore (Ierland) en van Salon-de-Provence naar Fåborg (Denemarken). Let op: de reis van het zuiden van Frankrijk naar noordelijk Europa duurt verscheidene nachten. De routes (trajectoriën) van de aparte nachten zijn hier verbonden om de hele reis te tonen.

surprising that the moths only succeed in migrating northward if they are taken along with the wind through two gates in the mountainous chain of the Pyrenees, Massif Central, and the Alpes: the valley formed by the Aude, Canal du Midi and the Garonne west of the Massif Central, and the Rhône valley in the east. In figure 3 the valley routes are outlined with arrows. For Arles in the Rhône estuary and Narbonne in the Aude estuary the wind direction and force, are given at 300 m above the ground in table 2. Only the days in September are investigated in this study. Here too the influence of the powerful pressure systems around 13 and 21 September is visible.



7. Rainfall in September in four weather stations in the region Poitou-Charentes in West-France. Source: Météo-France
7. Neerslag in september in vier weerstations in de regio Poitou-Charentes in West-Frankrijk. Bron: Météo-France

Trajectories

A trajectory is the path of a moving air particle (Box 1). The trajectories were calculated with the TRAJKS model (Stohl *et al.* 2001) from the Royal Netherlands Meteorological Institute (KNMI). Choosing the date, time, height and place as starting coordinates, the model predicts the path of the air in the hours following departure (forward tracking), or it reconstructs the path in the hours preceding arrival (backward tracking). In this study, first crude backtracking is applied to find the origin of the moths. Then more precise forward tracking provides a more realistic scenario for the moths' journey.

Moths found throughout northern Europe: Five cases

Five cases are presented, i.e., recordings in different places. All times mentioned are in Greenwich Mean Time (= Coordinated Universal Time, or UTC). So 19:00 h means 7 o'clock in the evening in Greenwich (UK). After one run, the trajectory model produces information about four variables for the travelling air particle in one night: air pressure (p), ambient temperature (T), velocity (v) and relative humidity (RH). The time needed to ascend to 300 m and to descend to the ground is assumed to be negligible.

Case 1: Southeast England, 14-15 September

In the night of 14-15 September several specimens of *A. catalaunalis* were recorded in the southeast of England. They probably came from the Aude delta (figure 4, 5). On 9 September, the moth took off at 18:38 h at Gruissan in the Aude delta, where T = 21.9°C and v = 2.0 m/s. It ascended to 300 m, where T = 20.5°C and v = 6.5 m/s. Temperature during the whole flight that night was between 20 and 21°C. Wind speed increased from 6.5 to 10.5 m/s at 02:00 h and ended at 7.4 m/s. Relative humidity went from 73 to 64%. The moth arrived in Fumel at 05:00 h on 10 September.

In the second night, the flight occurred under very favourable conditions. At the surface, T = 26.4°C and v = 2.4 m/s. At 300 m, T = 25.8°C and v = 7.1 m/s. At the arrival in the morning above Loudun, T is still 23.1°C and v = 7.0 m/s. RH increased from 38 to 52%. In the third night, T dropped from 23.7°C at the start at 300 m to 20.0°C in the morning above Châteauroux, v was relative low (4.5-3.1 m/s) and RH went from 63 to 74%. During the night from 12 to 13 September, the moth travelled over 195 km to Sens during 10 h and 10 min, with T between 23.2 and 20.3°C, v between 4.7 and 7.9 m/s and RH between 50 and 69%.

During the last night of the journey to England the moth exploited the formerly mentioned powerful weather systems on 13 and 14 September. Starting at surface level with 24.2°C and 4.4 m/s, they ascended to 300 m where T = 23.4°C and v = 11.1 m/s. During the night, wind speed fluctuated between 11.1 and 13.4 m/s. They arrived after a flight of 460 km in the vicinity of Ipswich.

The uncertainty that follows from the trajectory model is 10% of the total length of the track (circle with 129 km radius in figure 5). This reconstruction may explain the records on 14 September in Peacehaven (East Sussex), New Romney (Kent), Bradwell-on-Sea (Essex) and Dunwich Heath (Suffolk). The records on 15, 16 and 17 September probably have the same origin.

Case 2: Southwest of The Netherlands, 15-16 September

In the night of 15-16 September there was a record in Sint Kruis (province of Zeeland, The Netherlands). In this case, the moth took off on 10 September in Saint Gillis, near the Camargue in the Rhône delta (figure 5). It is interesting to note how it could take advantage of the shape of the country in the next days. Taking off at about sea level it ascended to 300 m and descended the next morning to the surface at 190 m above sea level. In the evening it climbed again to 300 m above surface level and reached now 490 m above sea level. During the jump on 13 September to The Netherlands the flight altitude had become 550 m above sea level. This means that the moth met stronger winds and could travel a longer distance than in a flat terrain, where it would not have exceeded 300 m. The highest wind speed it met that night was 15 m/s (= 54 km/h). On 14 September it arrived off the North Sea coast in the vicinity of The Hague. During the whole flight period the temperature was above the 18°C. This reconstruction could explain the arrival in Zeeland on 14 September, where it stopped migrating. It came in the light-trap two nights later, when it was flying around in Zeeland.

Case 3: Southern Ireland, 24-25 September

In the night of 24-25 September three specimens were recorded in the South of Ireland, two in Gorey and one in Tramore. Reconstructing the origin of the moths found in Ireland only succeeded by means of backtracking (as motivated below), hence the reverse presentation of this case: i.e. in the sequence 24-10 September. Figure 6 shows the journey from Leucate in the Aude delta to Ireland.

Gorey and Tramore are ca. 84 km apart. Backtracking in the morning of 24 September from a place with coordinates between the two places indicated that the moths took off in the evening of 23 September in the vicinity of Weston-super-Mare in Sommerset, England. Temperature during that trip was quite low, varying between 17.2 and 18°C, and wind velocity started at 12.3 m/s and reached a maximum of 14.8 m/s. Because the temperature was near the threshold (17°C), this phase was critical – the flight lasted only 6 hours and the Irish coast could just be reached.

On 22 September the moths were already present in Weston-super-Mare but could not take off, because T at all levels was <16°C. In the night of 21-22 September the south wind was very strong, but temperature declined rapidly, which made a solution with a passage from France impossible. Starting in the south of England near the coast in Bridport (there is one record on 21 September in Walditch in the Bridport area!) at 300 m above surface, the moths met a stormy wind with a speed of 20 m/s (compare the speed as calculated from the isobars in figure 2). With a threshold temperature of 17°C they could fly twice the distance needed for reaching Weston-super-Mare – why didn't they? A glance at the map of England gives a possible explanation. If the moths started at about 225 m instead of the usual 300 m, they could pass the hills in Dorset, but not the Mendip Hills in Sommerset. These have an average height of 260 m with a ridge of 325 m, the Beacon Batch. After 68 km and 1.1 hour flying they were already caught by the vegetation at 19:50 h and with a speed of 15 m/s. There may be several reasons why they did not take off again, for instance the heavy blowing wind at surface level, the lack of a dawn stimulus, or the dullness caused by the landing. Even with a start at 300 m the ridge in Sommerset may have stopped them. The number of individuals recorded in Ireland (3) however requires a large number of moths to take off in Weston-super-Mare. The question then is whether that ridge is big enough to stop this many moths.

The flight in the night of 20-21 September from Niort (France) to Bridport is a normal 11 hours flight with temperature decreasing from 23.2 to 18.3°C. After 4 hours flight, above the department Pays-de-la-Loire, the wind speed increased due to an interesting phenomenon called inversion. Normally, temperature decreases with increasing height in about the first 700 m of the atmosphere. However, in department Pays-de-la-Loire at ground level T = 19.9°C and at 435 m above the ground T = 21.5°C. The consequence of inversion is that wind velocity can be higher in the layer just above the inversion because the wind experiences less friction. Every meteorological phenomenon that leads to a higher wind speed enhances the possibility to find a moth further northward.

In the night of 19-20 September there was a possible displacement from Fontenay-le-Comte to Niort. It is only 29 km at low level (170 m), with near-threshold T of 17.3-17°C. Even if there was no flight that night it has no influence on the outcome of the total trip (not included in figure 6). From 13-18 September there was no displacement of the moths in Fontenay-le-Comte (Niort) because weather conditions were disadvantageous: T was too low, wind was mainly west-northwest, and it rained much – as can be told from data from a weather station in Niort (figure 7).

The moths flew in the night of 12-13 September from Villeneuve-sur-Lot to Fontenay-le-Comte (Niort) under normal conditions: T > 18°C during the whole night and v had moderate values between 4 to 8 m/s. During the flight from Toulouse to Villeneuve-sur-Lot T exceeded 18°C except for the last 2 hours (end T = 17.3°C). To enable the trip on 10 September from Leucate (Aude delta) to Toulouse, the moths had to start at 375 m above the ground.

The whole journey from Leucate in France to Gorey/Tramore in Ireland is 1409 km long and has taken fourteen nights: six (seven) nights with flight activity and eight (seven) nights without.

Case 4: East Denmark, 30 September - 1 October

In the night of 30 Sept-1 Oct four specimens were recorded on the isles in the east of Denmark, in Langeland, Røsnæs, St. Torøje and Aarsdale, The moths possibly came from the Rhône delta (figure 6). On 20 September the moths departed northward from Salon-de-Provence in the Rhône delta. They flew only part of the first night, due to the threshold T of 17°C. After 2 hours flying in the second night considerable differences in wind velocity occured between heights. At surface level v = 5.2 m/s, but at 150 m above surface level v = 11.4 m/s. Only dividing the rest of the night in four periods, the calculation of the displacement is acceptable (see Box 2). The trip this night ended near Langres (5.0° E, 47.9° N), ca. 150 km southwest of Nancy.

On 23 September in Nancy the normal starting height of 300 m above surface level explains the records on 25 September in Doorwerth and Bathmen in the east of The Netherlands (province of Gelderland). For a starting height of 425 m the trajectories ended more eastward, on the track towards Denmark. The next night there was almost no wind: v at 300 m asl dropped from 1.2 m/s at dawn to 0.3 m/s after 5 hours. It was assumed that the moths would not take off, and the same starting place was chosen on 25 September. During this night a 3.5 hours flight at low T (17.3°C) brought the moths further to the northeast. There was no flight activity on the following two nights because T was too low. In the night of 28-29 September, a 6 hours flight at constant temperature of 17.5°C occurred. Finally, after flying for 8 h the following night the moths arrived on 30 September in Denmark, at Fåborg on the island Fyn, i.e., 50 km distant from Langeland.

The whole journey from Salon-de-Provence to Langeland was 1400 km long and took seven nights with flight activity and three nights without flying. Langeland is at 270 km from the isle Bornholm (Denmark) and 325 km from Utlängan, an island southwest of the Baltic island Öland (Sweden). The record on 4 October in Lille Torøje on the island Sjælland (Denmark) probably also originates from the Rhône delta.

Case 5: Southeast England, 23-24 September

In the night of 23-24 September six specimens were recorded in southeastern England (Kent and Sussex). This journey took only three nights from Narbonne (Aude delta) to Kent/Sussex. On the evening of 20 September the favourable wind direction in the left gate in southern France (table 2) coincided with a strong southern wind over western Europe (figure 2). During the night T increased from 18.9 to 22.0°C and v from 6.0 to 16 m/s. The displacement that night was 500 km. Two nights flying later they arrived at Kent/Sussex in the morning of 23 September.

Discussion and conclusions

The answer to the main question is clear: the migrant *A. catalaunalis* recorded in northern Europe likely has its origin in the south of France. Two periods with favourable wind directions for migration from southern France to northern Europe occur, one for the Rhône delta (10-20 September) and the other for the Aude delta (9-20 September) (table 2). However, probably only the moths that took off on day 1 or 2 of these periods could have made it to northern Europe. This is because after each northward step (= night), the wind must be from the south again at the starting place for the next evening. The development of the two depressions west of Ireland made this possible.

With the tools used in this investigation it is simply impossible to reconstruct the journeys of the moths in full detail. The main reasons are (1) the resolution of the model is limited, and (2) the biology and behaviour of the species is poorly known. More specifically, the following uncertainties are relevant:

The model's predictions come with an uncertainty of about 10% in the length (or end position) of the travelled path. Going from France to Denmark this is about 140 km.

The method is sensitive to exact starting places. A difference at the beginning of 25 km within one delta in southern France may lead to a difference of 100 km or more at the end.

The model is sensitive to the choice of height at the start. For example, going from southern France to the Netherlands in case 2, a shift of height at the start from 256 to 300 m leads to a total distance of 878 km instead of 990 km, a difference of nearly 15%.

Illuminance at dawn can vary tenfold between a cloudy and a clear sky. Therefore, the timing of take-off at dusk will depend on the covering of the sky.

It is unclear how migrating moths behave during nights with little or no wind.

Once a moth stops migrating, it is not known how much time it takes to arrive at a light-trap after it has started flying around in the next evening. If trapped later at night the moths may have covered tens of kilometres extra. So there is an uncertainty in the coordinates of the place where the moth is recorded. If one specific record was chosen for this study, the day of arrival was certain. The model was used to verify the possible arrival days, and in the cases presented there where no multiple solutions for day of arrival.

Another choice of values of the variables, like starting height and threshold temperature, does not lead to another origin than the south of France. However, it is possible that, in some special cases, it leads to a different duration of the whole trip to northern Europe. Varying the assumptions about moth behaviour and investigating their consequences for the model outcomes would have been so complex and time-consuming that it fell beyond the scope of this work.

The duration of the journey from France to Ireland (case 3) implies that the longevity of the (female?) moth is at least fourteen days. Also the track to Denmark points in this direction. The 4 October record in Lille Torøje may indicate a lifespan of fourteen days. This value is higher than the values found by Singh *et al.* (1992). Perhaps this difference may be attributed to the relatively low temperatures during part of the journey. It is not clear whether females stop migrating as soon as they deposit their first egg or migrate further. In the journey of case 1 night temperatures exceeded 20°C in 90% of the time, in one night they even were between 23 and 26°C. Day temperatures must have been higher than night temperatures. So it is feasible that the preoviposition period in this case was shorter (i.e., 5 days), presuming that the moths start migrating on the day they emerge from the pupa.

The threshold temperature was set at 17°C, where at first it was presumed to be 18°C. There are several arguments for lowering it to 17°C. Some tracks or part of tracks can only be made with temperatures below 18°C. The temperatures at ground level at dawn in Gorey and Tramore on 24 September were 16.2°C and 15.6°C, respectively (ECMWF model). Still, that night moths came into the light-trap. Although temperature at ground level is influenced by details of the surroundings (such as sandy soil, vegetation, sheltered places), it does indicate that the threshold temperature might be below 18°C.

Not every attempt with backtracking was a success. The arrival in Guernsey and Portland (England) on 12 September could not be explained. In addition, many questions remain. Some of these relating to the biology of the moths are: do the moths feed during the migration or do they utilize their fat reserves? When do they mate? Singh *et al.* (1992) found in their laboratory study that a female deposits eggs just after copulation – does this mean that they mate during migration? Which variables determine the migration period of the males? Unfortunately the sex of the recorded moths is unknown.

It is not easy to estimate how many moths must have taken off in southern France to make so many records possible in the Northern Europe, but it must have been a very large number. It is a great deficiency – and ever so much surprising – that there are no observations whatsoever of the species in France.

Is it not amazing to see such a tiny (sub)tropical moth, after a journey of ten days, covering a distance of 1725 km, arrive on a very small island in southern Sweden?

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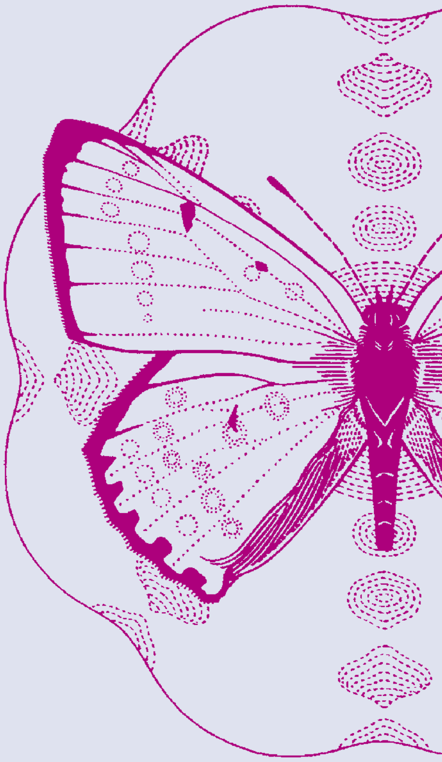
Samenvatting

Reconstructie van de herkomst van *Antigastra catalaunalis*, een nieuwe soort voor de Nederlandse fauna (Lepidoptera: Crambidae)

In september 2006 zijn in Nederland zes waarnemingen gedaan van *Antigastra catalaunalis*. Ook in andere landen ten noorden van Frankrijk is deze migrant waargenomen, opvallend meer dan in de voorgaande jaren, in Engeland zelfs meer dan 100. De soort kent een tropische en subtropische verspreiding over bijna alle continenten met als noordelijkste leefgebied Zuid-Frankrijk. Over de biologie van de soort is weinig bekend. De bekendste voedselplant in de tropen is sesam (*Sesamum indicum*). Voor Zuid-Europa worden soorten genoemd uit enkele geslachten van de helmkruidfamilie (Scrophulariaceae). Bij het zoeken naar de herkomst van de migranten in noordelijk Europa is gebruikgemaakt van het trajectoriemodel TRAJKS van het KNMI. Dit model berekent de route die een luchtdeeltje beschrijft in de loop van de tijd (trajectorie), hetzij in het verleden (backward tracking), hetzij in de toekomst (forward tracking). Met behulp van zeven expliciete aannamen wordt getracht op een zo consistent mogelijke wijze de tochten van de kleine vlinders te achterhalen. Door te kiezen voor een constante vlieghoogte ten opzichte van zeeniveau tijdens één nacht, zijn de trajectoriën niet rechtstreeks te gebruiken. Interpoleren en rekenen met de computergegevens is nodig. Er worden vijf mogelijke 'reizen' besproken van plaats van vertrek tot plaats van aankomst. De reisduur varieert van drie tot veertien nachten. Belangrijke grootheden hierbij zijn de drempeltemperatuur waarbij de vlinder nog actief is en de hoogte waarop hij vliegt. Problemen doen zich voor bij regendagen, windstille dagen en met de betrekkelijk lage resolutie van het model. Twee depressies ten westen van Ierland in de maand september speelden een hoofdrol bij de gunstige weersomstandigheden in opeenvolgende dagen. Alleen hierdoor konden de vlinders zo ver noordelijk verschijnen. De grootste verplaatsing in een nacht is 500 km. De dieren zijn waarschijnlijk afkomstig uit de riviermondingen van de Rhône en de Aude in Zuid-Frankrijk. Opvallend is het gebruik van twee poorten in de hindernis die gevormd wordt door de bergketen in Zuid-Europa. Uit het onderzoek volgt een waarschijnlijke drempeltemperatuur van 17°C. De levensduur van de vrouwtjes zou langer kunnen zijn dan de ruim tien dagen die een Indische publicatie geeft. Er zijn via deze weg aanwijzingen voor een levensduur van twee weken. De onzekerheid in de gevonden verklaringen worden vergroot door de lage resolutie van het trajectoriemodel en de geringe kennis van de biologie van de vlinder. Opvallend is het ontbreken van waarnemingen in heel Frankrijk, waar in september grote aantallen vlinders op vele dagen zichtbaar moeten zijn geweest.



Joop Schaffers
Dalweg 88
6865 CV Doorwerth
joopschaffers@planet.nl