



Cloud-radar observations of insects in the UK convective boundary layer

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ABSTRACT: Radar has been applied to the study of insect migration for almost 40 years, but most entomological radars operate at X-band (9.4 GHz, 3.2 cm wavelength), and can only detect individuals of relatively large species, such as migratory grasshoppers and noctuid moths, over all of their flight altitudes. Many insects (including economically important species) are much smaller than this, but development of the requisite higher power and/or higher frequency radar systems to detect these species is often prohibitively expensive. In this paper, attention is focussed upon the uses of some recently-deployed meteorological sensing devices to investigate insect migratory flight behaviour, and especially its interactions with boundary layer processes. Records were examined from the vertically-pointing 35 GHz 'Copernicus' and 94 GHz 'Galileo' cloud radars at Chilbolton (Hampshire, England) for 12 cloudless and convective occasions in summer 2003, and one of these occasions (13 July) is presented in detail. Insects were frequently found at heights above aerosol particles, which represent passive tracers, indicating active insect movement. It was found that insect flight above the convective boundary layer occurs most often during the morning. The maximum radar-reflectivity (an indicator of aerial insect biomass) was found to be positively correlated with maximum screen temperature. Copyright © 0000 Royal Meteorological Society

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1 Introduction

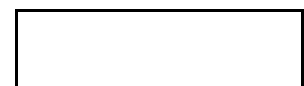
Many insect species are adapted to undertake long-distance migrations on the wind (Johnson, 1969; Drake and Gatehouse, 1995; Gatehouse, 1997). Some of these species are economically-important pests or disease vectors (Pedgley, 1993; Drake and Gatehouse, 1995; Reynolds *et al.*, 2006), while others are beneficial (Chapman *et al.*, 2004a) or their conservation may be desirable for aesthetic reasons (e.g. the Monarch butterfly; Malcolm and Zalucki, 1993). In each case, an understanding of the role of migration in the species' ecology is crucial for the optimization of management strategies.

It is extremely difficult to observe and quantify high-altitude insect movements using traditional entomological techniques. Thus, the deployment of special-purpose entomological radars in the late 1960s (Schaefer, 1976) has greatly added to our knowledge of insect flight behaviour at high altitudes (see references on *The Radar Entomology Website*, <http://www.pems.adfa.edu.au/~s9104004/trews/>). However, entomological radars, whether of the older azimuthally-scanning types (Drake, 1981a, 1981b) or the newer vertical-looking nutating systems (Chapman *et al.*, 2003) are nearly always based on X-band (3.2 cm wavelength) ex-marine technology, and they are only able to

detect individuals of relatively large species. The vertical-looking entomological radars, for example, can detect insects weighing > 2 mg at short range (150 m), but only individuals above about 15 mg are detectable at 1 km (Smith *et al.*, 2000). Many migrant insects are much smaller than this, and require high power and/or high-frequency radars for satisfactory detection over all the likely heights of flight. The development and construction of such systems is generally well beyond the means of entomological research budgets (but note Riley *et al.*, 1991; Riley, 1992). One way of surmounting this problem is the opportunistic use of radars designed for other (most notably meteorological) purposes (Hardy *et al.*, 1966; Richter *et al.*, 1973; Irwin and Thresh, 1988; Achtemeier, 1991). The recent development of vertically-pointing Ka and W-band cloud radars (35 and 94 GHz respectively, see later) which, on warm cloudless days, will be detecting almost exclusively insect targets (Clothiaux *et al.*, 2000; Khandwalla *et al.*, 2002) potentially provides the scientific community with another tool with which to investigate the effects of atmospheric processes on insect migration.

Entomological radar observation programmes have, up until now, been strongly focused on large insects (moths, migratory grasshoppers) flying under stable boundary layer conditions at night (Drake and Farrow, 1994; Reynolds and Riley, 1997; Reynolds *et al.*, 2005; Wood *et al.*, 2006; Wood, 2007). Much less is known about the interrelations between the atmosphere and small

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day-flying insects, although atmospheric influences are certainly present as shown by the insect-delineated cellular patterns occasionally seen on radar displays under conditions of thermal convection (Hardy and Ottersten, 1969; Schaefer, 1976). This paper presents observations made with 35 and 94 GHz cloud radars (*Copernicus* and *Galileo*), combined with data from a 905 nm lidar, entomological radars and aerial netting. These collectively have the potential to reveal facets of insect migratory patterns which have hitherto been very difficult to study and are consequently little understood.

In Section 2 a brief description is given of the cloud radar and lidar instrumentation, and an outline of the theory needed to apply cloud radar capabilities to observations of insects. Cloud radar reflectivity gives an indication of the total biomass of insects and this paper shows how it is possible to estimate insect mass under certain conditions (Section 3). One cloudless (and convective) day in July 2003 was selected for a case study presented in Section 4, and insect observations from several other cloudless days with anti-cyclonic synoptic-scale flow during the summer of 2003 are then discussed in Section 5.

2 Methods

2.1 Cloud radar and lidar instrumentation

The cloud radars used in this study were the zenith-pointing 94 GHz (W-band, 3.2 mm wavelength) *Galileo* and the 35 GHz (K_a-band, 8.6 mm wavelength) *Copernicus* radars located at Chilbolton in Southern England (51.1445°N, 1.4370°W). *Galileo* is of the conventional pulsed type with a pulse width of 0.5 μs, a beamwidth of 0.5° and is operated with a range resolution of 60 m and a PRF of 6250 Hz, yielding a folding velocity of ±5 m s⁻¹. The first three moments of the Doppler spectrum are calculated from the average of 30 FFTs (fast fourier transforms; 256-point) which gives a temporal resolution of 1.25 s. Incoherent averaging over 30 s is then performed to improve the sensitivity which is estimated at -36 dBZ at 1 km. The sensitivity of the radar falls off as the distance from the radar squared, which equates to approximately 6 dB for every doubling of range. It has been calibrated to within 1.5 dB by comparison with the 3 GHz (S-band, 10 cm wavelength) radar, *CAMRa*, at Chilbolton which itself has been calibrated to better than 0.5 dB using the redundancy of its polarimetric parameters in rain (Goddard *et al.*, 1994). Coincident profiles of high ice cloud are chosen as the calibration target. Care is taken to ensure that no liquid water is present in the profiles, and that the 94 GHz signal is not experiencing Mie-scattering.

In Section 3, data are shown from the 35 GHz *Copernicus* radar, which is located within a few metres of the 94 GHz *Galileo* radar. *Copernicus* is of the conventional pulsed type with a pulse width of 0.4 μs, a beamwidth of 0.25° and is operated with a range resolution of 30 m and a PRF of 5 kHz, yielding a folding velocity of ±10.7 m s⁻¹. The first three moments of the Doppler spectrum are calculated from the average of 4 FFTs (512-point) which

gives a temporal resolution of 0.75 s. Incoherent averaging of 40 moments over 30 s is then performed to improve the sensitivity which is estimated at -36 dBZ at 1 km. *Copernicus* has been calibrated to within 1.5 dB by comparison with the 3 GHz radar at Chilbolton in a similar manner to the *Galileo* radar.

Situated close to the cloud radars was a zenith-pointing Vaisala CT75K ceilometer (lidar) consisting of an InGaAs diode laser operating at 905 nm with a divergence of 0.75 mrad and a field of view of 0.66 mrad (both half angle). It is a fully automated system which produces averaged profiles every 30 s with a range resolution of 30 m. Calibration of the lidar to within 5% is achieved using the technique described by O'Connor *et al.* (2004).

2.2 Remote sensing: cloud radar and lidar

A Doppler cloud radar commonly measures the first three moments of the Doppler spectrum. The first moment, or radar reflectivity factor, Z , is related to the number of targets and their size within a certain pulse volume at a given range. Assuming spherical liquid drops,

$$Z \propto \int_0^{\infty} n(D) D^6 \gamma_f(D) dD, \quad (1)$$

where $n(D) dD$ is the number concentration of water droplets with diameters between D and $D + dD$, and $\gamma_f(D)$ is the Mie/Rayleigh backscatter ratio. If all drops are small compared to the wavelength, then $\gamma_f(D) = 1$. Because Z has such a large dynamic range it is often expressed as 'dBZ', where $\text{dBZ} = 10 \log_{10}(Z [\text{in mm}])$, so a concentration of a single mm diameter drop per cubic metre, which is Rayleigh scattering, has a Z of $1 \text{ mm}^6 \text{ m}^{-3}$, or 0 dBZ. Since Z depends on both number and size there is an ambiguity; an observed radar reflectivity of 0 dBZ could correspond to a single mm drop in a cubic metre or 1 million 100-micron drops in a cubic metre. Flying insects have relatively large effective diameters and are, potentially, good radar targets, but their number concentration is rather low so that the range of insect reflectivities coincides with that of clouds.

The mean Doppler velocity and Doppler spectral width (second and third moments) may have significant contributions from the air motion as well. The mean Doppler velocity measured by a zenith-pointing Doppler radar is the sum of the vertical air motion and the mean Z -weighted velocity of the targets within the beam. In this paper we adopt the convention that velocity is positive away from the radar. The Doppler spectral width is a measure of the variation of the radial velocities of the targets within the pulse volume.

To aid the discrimination between insects and clouds information is included from the co-located lidar. The geometric optics approximation can be applied because the lidar wavelength is small compared to cloud droplet and insect sizes. In this case the lidar backscatter coefficient, $\beta \propto ND^2$, expressed in units of $\text{m}^{-1} \text{ sr}^{-1}$, so that, compared to the radar return, the lidar signal has a relatively high sensitivity to number concentration. Due

to their low number density, insects are not normally detected by the lidar, whereas the high number density of smaller (typically $10\mu\text{m}$) liquid water droplets encountered in liquid water clouds results in a very strong signal, $\beta > 5 \times 10^{-5} \text{ m}^{-1} \text{ sr}^{-1}$ (and subsequent attenuation). A moderate lidar return arises from aerosol particles which, although numerous, are at least an order of magnitude smaller than cloud droplets and are not detected by the radar. Thus, the combination of radar and lidar provides an unambiguous means of identifying targets as insects.

The reflectivity due to rain is several orders of magnitude larger than the reflectivity from insects, making the latter undetectable when rain is falling. However, insects generally do not migrate at altitude in large numbers under rainy conditions (D.R. Reynolds, personal observations). Consequently, cloudless days were chosen for study by examination of the daily cloud radar and lidar images.

2.3 Entomological radar and aerial netting

In order to assess the types of insect target potentially detectable to the cloud radars, information was obtained on the aerial populations for daytime (06:00–19:00 hrs) on 13 July 2003 (the date used for the principal case-study). The aerial densities of the larger species were derived from the data archive of the continuously-operating vertical-looking X-band (9.4 GHz, 3.2 cm wavelength) radars (VLRs) which monitor insects in 15 height bands between 150 and 1188 m above ground (Chapman *et al.*, 2002, 2003; Reynolds *et al.*, 2008). For targets which are well described by the underlying analysis model (Smith *et al.*, 1993), it is practicable to estimate the mass of individual insects and thus to convert the numbers detected by the radar into aerial densities in various mass categories (Chapman *et al.*, 2002). Small insects ($< 1 - 2 \text{ mg}$) are not detected by the entomological radars, so the density data for this component of the aerial fauna was derived from aerial sampling with a kytoon-suspended net (Chapman *et al.*, 2004b) at Cardington, Bedfordshire (52.1040°N , 0.4227°W ; which is c. 167 km NE of Chilbolton), on several warm days in mid July 2002. Aerial netting data were unfortunately not available for July 2003, but experience shows (Chapman *et al.*, 2004a, and unpublished data), that the dominance of the major taxa of small insects (aphids, small Diptera, Ichneumonoidea, Chalcidoida, etc) are consistent enough between years to make no significant difference to the general shape of the aerial density versus mass category curve. Mass values for all the groups of tiny insects sampled by the net were obtained from measurements of specimens caught or, in a few cases, estimated from the literature. The air-flow through the net was estimated by a wind-run meter hung below the kytoon.

2.4 Models for meteorological data

Meteorological variables were analysed to assess the impact of boundary layer conditions on insect activity. Output from operational numerical weather prediction

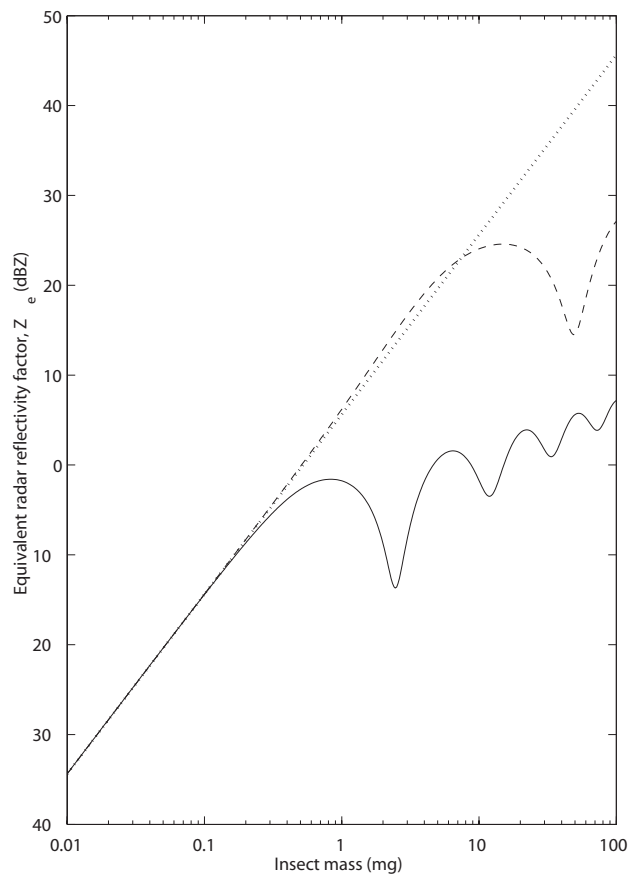


Figure 1. Theoretical radar reflectivity factor versus insect mass at three radar frequencies (94 GHz (—), 35 GHz (- - -), 3 GHz (· · ·)), assuming 1 insect per m^3 .

models were archived every hour for the grid box over Chilbolton as part of the Cloudnet project. Model data from the mesoscale version of the Met Office Unified Model (Cullen *et al.*, 1997) provided the meteorological variables given in this paper.

3 Estimating insect mass from radar reflectivity

3.1 Theory

Following Riley (1985, 1992) it is assumed that the backscattering properties of an insect can be adequately represented by a spherical water droplet of the same mass. The radar reflectivities at 3 wavelengths are given in Figure 1 for a range of water droplet masses. Rayleigh scattering applies at 3 GHz so the picture is simple: 1 insect, of diameter 1 mm, per m^3 will have a mass of 0.5 mg and a reflectivity of 0 dBZ; with the reflectivity being proportional to the square of the mass of the insect, a 15 mg insect per m^3 will correspond to about 30 dBZ. At higher frequencies (35 and 94 GHz), the wavelength of the transmitted radiation is of similar size to that of the droplet diameter and therefore full Mie theory was used to calculate the theoretical radar reflectivity (assuming a spherical target). The departure is significant at 35 GHz once the insects are above 10 mg, with one 15 mg insect per cubic metre reduced to about 25 dBZ rather than

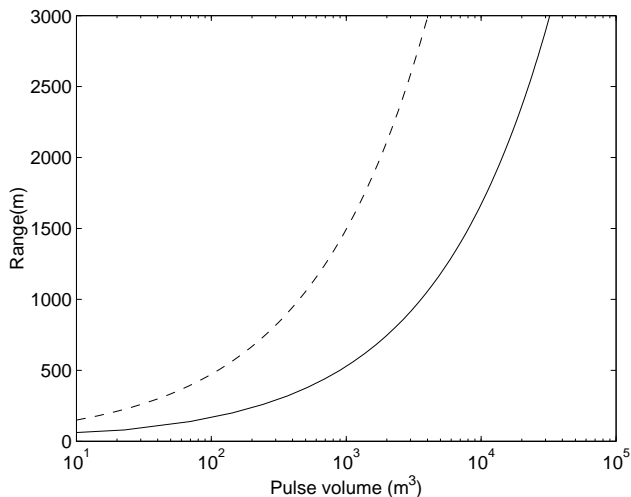


Figure 2. Variation of the radar pulse volume with height for the 94 GHz *Galileo* radar (—), and for the 35 GHz *Copernicus* radar (---).

30 dBZ. At 94 GHz Mie scattering becomes significant for 0.5 mg insects with the reflectivity reduced to about -3 dBZ rather than 0 dBZ. Note that, at 94 GHz, Mie scattering limits the reflectivities of insects larger than 0.5 mg to be close to 0 dBZ. Rayleigh scattering at 10 GHz still holds for droplets up to 0.2 g, as shown by Riley (1985), and larger still for 3 GHz (shown here in Figure 1).

Figure 1 assumes that there is 1 insect per cubic metre. To relate the observed radar reflectivity to insect mass we need to know their concentration but this cannot be deduced directly from the reflectivity. However, it is possible to detect whether there is one or many insects within a given pulse volume by utilising the Doppler spectral width, σ_v . It is assumed that in most cases all insects will not be flying with exactly the same velocity. Therefore, if σ_v is very small, then it can be concluded that there is only one target within the pulse volume responsible for the observed reflectivity. If the pulse volume can be estimated then the observed reflectivity (single target) per pulse volume measurement can be transformed into a reflectivity per cubic metre measurement for comparison with Figure 1, and so estimate the mass of the observed insect can be estimated.

The variation of pulse volume with height is given in Figure 2 for the two cloud radars present at Chilbolton. The pulse volume can be calculated approximately as $V_{pulse} = \pi 4r^2\theta^2z$, where r is the range from the radar to the pulse, θ is the beam width (a function of wavelength and antenna size) in radians, and z is the radar range resolution (radial length of an individual gate). The 35 GHz *Copernicus* radar has a smaller beamwidth (larger antenna) and improved range resolution, relative to the 94 GHz *Galileo* radar. However, it should be noted that the beam pattern is Gaussian, not top-hat, and therefore estimated reflectivity arising from a single insect at beam centre will be greater than that from the same insect at the

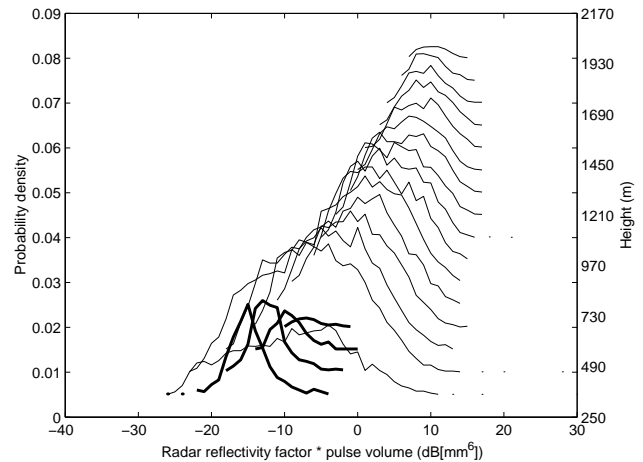


Figure 3. Distribution of effective single insect reflectivities (measured reflectivity multiplied by pulse volume) at various heights for single targets at Chilbolton on 7 July 2007. Distributions at 94 GHz *Galileo* shown in thick lines, 35 GHz *Copernicus* in thin lines. An incremental offset has been added to each distribution to show the variability with height.

edge of the beam. The reflectivities given in Figure 1 are the maximum expected for any given insect mass.

3.2 Cloud radar observations

An estimation is now made of the range of mass of the insects that the radar detects for those occasions when the Doppler spectral width is less than 0.1 m s^{-1} and it can safely be assumed that there is a single insect within the beam. To do this a new variable is defined, 'effective single insect reflectivity', which is the product of the radar reflectivity of a single insect per cubic meter (displayed in Figure 1) and the pulse volume at that range (as displayed in Figure 2). This new variable is in units of $\text{dB}[\text{mm}^6]$ and, for Rayleigh scattering, is the size of the single insect in the beam in mm^6 relative to a 1 mm insect, which would have a mass of 0.5 mg. In Figure 3, the values of this 'effective single insect reflectivity' are derived for the 24 hours of data on 7 July 2007 observed with 30 second resolution and plotted as a series of probability distribution functions (pdfs). A histogram is constructed from the time sequence of measured effective single insect reflectivities in each height bin, which is then normalised by the total number of observations at that height (including all observations, not just those where insects were detected). The total number of observations at each height is of the order 5000–10000 depending on the radar. Height bins of 120 m were chosen, starting above the blind zone of each radar (the first bin is at 310 m for the 94 GHz *Galileo* radar and 430 m for the 35 GHz *Copernicus* radar) and the effective single insect reflectivities are then binned by height.

The decrease in sensitivity with height of each radar is clearly noticeable in Figure 3 as the slope with range of the left-hand-side cut-off for the pdfs. Remembering that the radar sensitivity is -36 dBZ at a range of 1 km, then at this range the 35 GHz pulse volume (Figure 2) is about

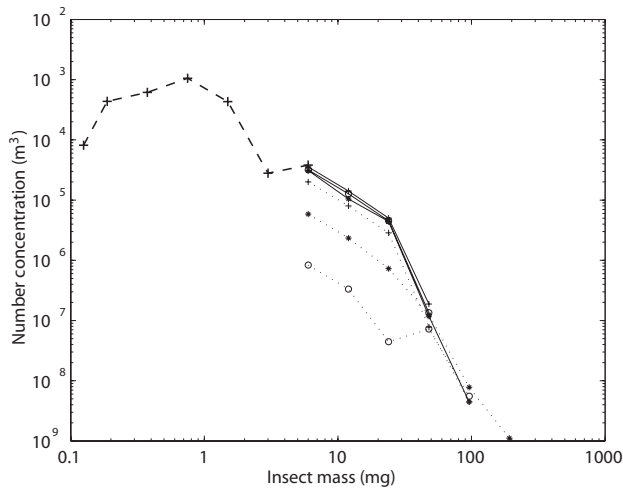


Figure 4. Observed distributions of average density against mass from aerial netting (at 200 m above ground) (dashed line) and from vertical-looking entomological radar at various heights above ground: 208(—+—), 350(—*—), 492(—o—), 634(· · + · · ·), 776(· · * · · ·) and 918 m(· · o · · ·).

400 m^3 , so the minimum effective single insect reflectivity detectable at this range would be $-10 \text{ dB}[\text{mm}^6]$. At 2 km range the sensitivity would be -30 dBZ , the pulse volume is about 1000 m^3 , and the minimum detectable value would be $0 \text{ dB}[\text{mm}^6]$. These values correspond to the left-hand-side cut-off of the pdfs in Figure 3.

At 35 GHz, the maximum effective single insect reflectivity is close to $10 \text{ dB}[\text{mm}^6]$ at all heights, or an insect mass of about 2 mg, which—from Figure 1—is still in the Rayleigh region; thus at 35 GHz the pdfs can be interpreted as reflecting the true distribution of insect size and mass, apart from the sensitivity truncation for insects $< 0.1 \text{ mg}$ above 1 km. The peak concentrations of effective single insect reflectivity at 35 GHz relate to insect masses in the range 0.3–1 mg. Note that the X-band entomological radar has a sensitivity limit of 15 mg at 1 km range and would fail to detect any of these insects. The influence of Mie scattering at 94 GHz (Figure 1) explains why the 94 GHz pdfs are truncated at values near to $-5 \text{ dB}[\text{mm}^6]$ and interpretation of the pdfs in terms of distribution of size is more difficult.

3.3 Comparison of cloud radar with entomological observations

Figure 4 shows typical distributions of insect mass from aerial netting studies, carried out at Cardington in mid July 2002, and from the X-band vertical-looking entomological radar at Chilbolton during 13 July 2003. The aerial netting studies were carried out at a nominal height of 200 m and show a peak in the size distribution at about 1 mg. The number concentrations of insects $> 10 \text{ mg}$ are at least two orders of magnitude lower.

Data from the entomological radar, which is not very sensitive to insects $< 15 \text{ mg}$ at 1 km, has a similar number concentration of insects at 10 mg to the aerial netting studies; and for insects 100 mg or larger, typical

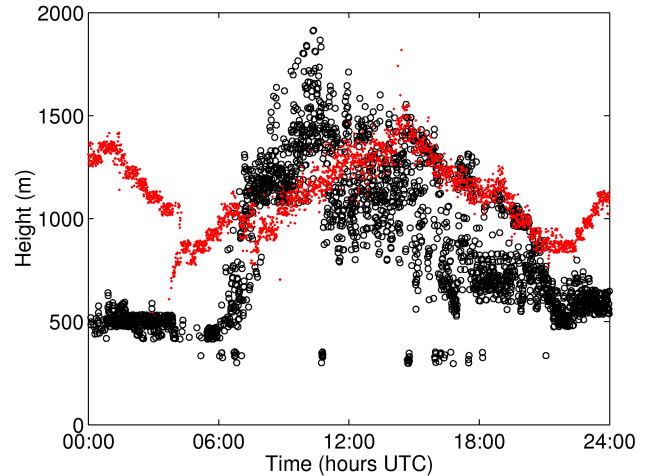


Figure 5. Maximum insect (black circles) and aerosol (small red dots) heights for 13 July 2003; 30-second data.

concentrations are down five orders of magnitude from those in the 1 mg range.

Thus, the mass at peak concentrations from the aerial netting study agree remarkably well with the size range detected by the 35 GHz *Copernicus* cloud radar.

4 Case study (13 July 2003)

Cloud radar and lidar data for 13 July 2003, a day with anti-cyclonic flow conditions, no cloud and a maximum screen temperature of 28.5° C , was chosen for detailed analysis here. In addition, results from a selection of cloudless summer days in 2003 will be summarized in Section 5.

Both the maximum aerosol height and the lifting condensation level (LCL) were investigated as a means to determine the depth of the convective boundary-layer (CBL). On the cloudless days examined by us, maximum aerosol height appeared to be the most consistent indicator of CBL depth, and this variable is therefore used throughout this paper as a proxy for daytime CBL depth.

4.1 Insect and aerosol height

Figure 5 shows maxima in insect and aerosol height. The insects can be seen to rise above the maximum aerosols (hence the CBL) between 07:00–11:00 hours UTC on this day. The greatest observed insect rise above the CBL was c. 800 m, where the maximum insect target was 1885 m above the ground. However, for this time period, the majority of the maximum insect heights (5-minute average) were not more than 400 m above the CBL, and after 12:00 very few maximum insect heights were above the CBL.

In Figure 6 the mean reflectivity factor Z (in $\text{mm}^6 \text{ m}^{-3}$) is shown for insects at all observable heights. The mean Z of insects is likely to be underestimated within the CBL because the cloud radars cannot make observations close to the surface (because much of the bottom c. 400 m of the atmosphere can be obscured due

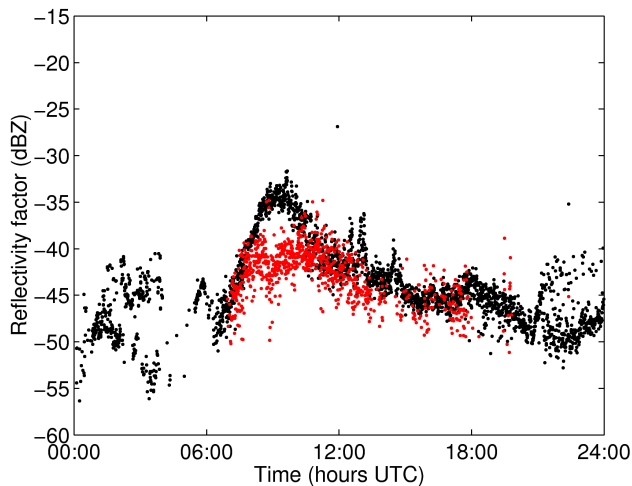


Figure 6. Mean reflectivity factor (Z) of insects above (red) and below (black) the convective boundary layer (CBL) on the 13 July 2003, where it is assumed that the maximum aerosol height corresponds to the top of the CBL.

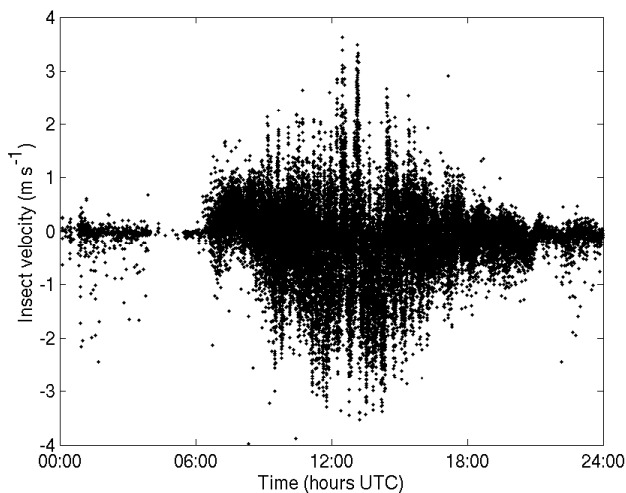


Figure 7. Doppler velocity of insects on the 13 July 2003. This measurement includes the contribution from the vertical air motion; 30-second data.

to ground clutter). The reflectivity factor is measured on a log scale, so it is still apparent from Figure 6 that there are often many more insects within the CBL than above it. It can be seen that the phenomenon wherein insects go above the boundary layer occurs most in the later morning hours.

4.2 Insect vertical Doppler velocity

Figure 7 shows upwards (positive) and downward (negative) vertical velocities of insects relative to the ground (i.e. including vertical motion of the air itself). It was clear that the insects reached much higher speeds during the daytime, and this is consistent with transport by updraughts within the CBL. Most small insects (aphids, planthoppers) cannot fly upwards at more than 0.2 m s^{-1} by their own powered flight (Riley *et al.*, 1991; David and Hardie, 1998), and even large insects (grasshoppers and

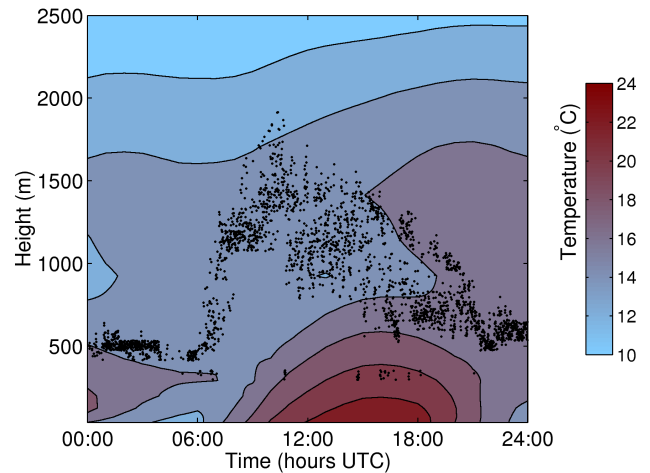


Figure 8. Temperature for 13 July 2003 from the Met Office UM data, with maximum insect height superimposed (black dots).

noctuid moths) only ascend at rates of $0.4 - 0.5 \text{ m s}^{-1}$ (Schaefer, 1976; Riley and Reynolds, 1979; Riley *et al.*, 1983), so the resulting speeds of up to 4 m s^{-1} must be a combination of the insects' flight power and updraughts. Most downward atmospheric motions in the CBL are slower than updraughts. However, even small insects like aphids are able to reach high fall-speeds (up to 1.8 m s^{-1}) by folding their wings (Thomas *et al.*, 1977). High downward insect speeds may hence be attributed a combination of the two effects. It is worth noting that normal meteorological targets tend to move more steadily as one body, whereas each insect target can move around independently, leading to a larger spread in velocities.

Vertical winds are very small (e.g. not more than 0.1 m s^{-1}) in the more stable boundary layers at night, and therefore target velocities would be expected to be similar to known insect climb rates. This seems to be borne out in Figure 7 with recorded maximum velocities at night $< 0.5 \text{ m s}^{-1}$.

4.3 Location of insects with respect to meteorological conditions

Figure 8 shows the evolution of temperature with height and time on 13 July, with maximum insect heights superimposed. The highest insects were evidently flying at altitudes with temperatures of about 14° C . Observing a number of these occasions may give an indication of flight temperature thresholds, and hence the temperature restraints on insect flight heights in northern temperate regions. Horizontal wind speeds were also examined (not shown). Wind speeds of up to 10 m s^{-1} occurred at heights where insects were present at night-time, particularly in the evening after 20:00, probably due to the development of a nocturnal jet. During the morning, the wind speed reached 9 m s^{-1} between 250 and 750 m; at higher altitudes—and at all altitudes in the afternoon—the speeds were typically 5 m s^{-1} .

From the case study analysis thus presented, it is apparent that insects reach their maximum heights of

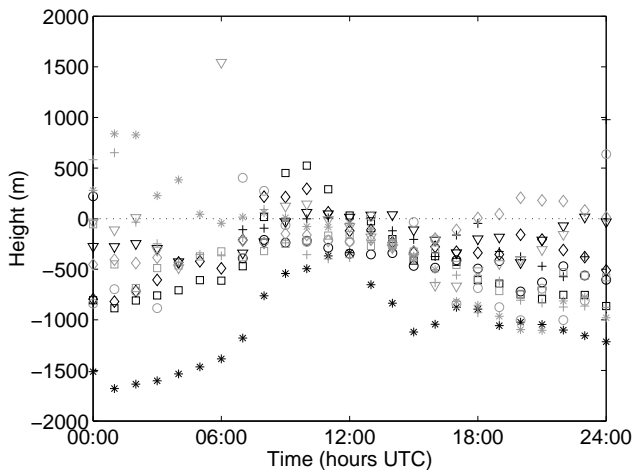


Figure 9. Maximum insect height minus aerosol height (averaged over 60 minutes) for each of the 12 cloudless days of study in 2003 at Chilbolton. Each symbol represents one of the days given in Table I. Points are labelled in order + * o square diamond inverted triangle, where cases 1–6 are in black and 7–12 are in grey.

flight during the daytime. Therefore, investigation focused on daytime maximum insect heights, and whether or not these were above the CBL on other days in summer 2003.

5 Results from cloudless days in summer 2003

The days chosen were in the summer months of 2003 because there was a preponderance of anti-cyclonic conditions associated with the heat-waves in that year. There were 12 days with very little or no cloud for which there were reliable data from the 94 GHz *Galileo* radar. A full data analysis was performed (similar to that in Section 4) and a summary is presented below.

5.1 Maximum insect height and vertical velocity

On 6 of the 12 chosen days, the insects rose above the maximum aerosol height (representing the CBL; see Table I). Figure 9 shows the time at which the maximum insect heights were above the maximum aerosol heights and by what distance. In particular note that on 12 July, 13 July, 14 August and 15 August there were numerous insects recorded well above the CBL, whilst on 13 June and 3 August, the groups were only slightly above the CBL. It is worth noting that since there is no CBL at night, the aerosol is not an indicator of boundary-layer depth (sunrise varied from 3:50–5:42 hours UTC and sunset from 20:24–18:19).

When the maximum insect height was above the maximum aerosol height, it was most frequently in the morning, between about 08:00 and 12:30. Insects ascended the largest distance above the convective activity on 12 July 2003, and this was also the day on which the summer's maximum insect height was recorded, 2365 m. However, it should be noted that there were only 7 of the 5-minute averaging periods when maximum insect height was above 2000 m, so flight at these heights in the UK is rare.

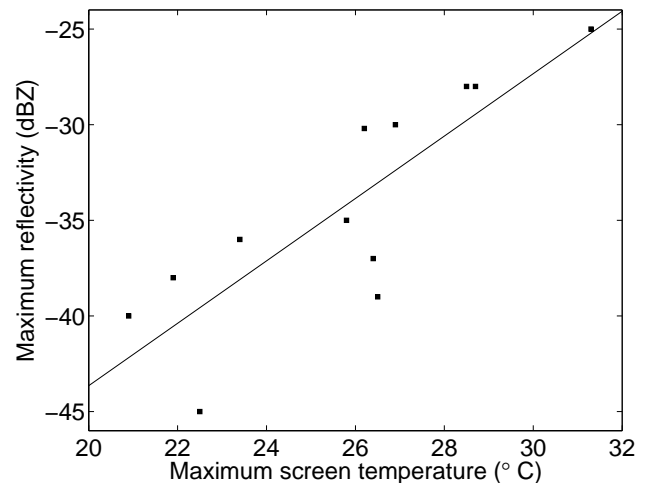


Figure 10. Maximum radar reflectivity (5-minute average), plotted against the maximum screen temperature for the 12 cloudless days, with a regression line superimposed.

5.2 Influence of environmental factors

Using the regression line in Figure 10, the maximum radar reflectivity (from the 5-minute average) was found to be significantly (p -value < 0.001) related to screen temperature and 70% of the variation in reflectivity was explained by the maximum screen temperature.

This result indicates that on days with higher temperatures there were more insects flying, because the flight temperature threshold would have been reached for more species and also because a higher temperature would have led to more insects developing to the 'flight ready' state in a shorter time period (Johnson, 1969). Entomological radar studies in the UK (Smith *et al.*, 2000; Chapman *et al.*, 2002) and meteorological radar studies in the USA (Wilson *et al.*, 1994) have also found a significant positive relationship between surface temperature and insect aerial density. In a preliminary cloud radar study, Khandwalla *et al.* (2002) found that "significant insect echoes only exist when the daily mean surface temperature is above a threshold of approximately 10° C."

There appeared to be no relationship between wind speed on the study days and either the maximum height reached by the insects, or whether they occurred above the CBL (not shown). The number of range-gates in which insects were found, indicating their vertical spread, was not related to wind speed either.

Rather surprisingly, temperature at the maximum insect height affected neither the maximum insect height itself nor whether insects rose above the CBL. The main mass of insects occurred below 2000 m, and this would have represented ceilings in the range 13 – 14° C.

6 Conclusions

The main finding of this study was that although day-flying insects can, and usually do, take advantage of thermals, significant numbers of insects appear to engage in flight above the CBL. The maximum insect heights

Table I. Maximum individual insect heights for the 12 cloudless days studied (times in hours UTC).

Case ^a	Date (all 2003)	Maximum insect height above ground (m)	Time of maximum insect height	Time above the CBL	Maximum height ^b above the CBL (m)	Sunrise	Sunset
1	13 June	1525	11:00	09:00–11:00	250	03:50	20:21
2	15 June	1525	11:30	-	-	03:50	20:22
3	20 June	1400	17:30	-	-	03:50	20:24
4	12 July	2365	10:00	08:00–12:30	800	04:04	20:18
5	13 July	1885	10:00	07:00–14:00	400	04:05	20:17
6	3 August	1645	15:00	09:00–15:00	175	04:33	19:50
7	7 August	1705	15:00	-	-	04:39	19:43
8	14 August	1705	14:30	08:00–13:00	400	04:50	19:30
9	15 August	1825	14:00	12:00–14:00	400	04:51	19:28
10	12 September	1285	16:00	-	-	05:35	18:28
11	13 September	985	14:30	-	-	05:37	18:26
12	16 September	1285	15:30	-	-	05:42	18:19

^aAll data from the Chilbolton Observatory.

^bHeight above the boundary layer represents the distance above the 5-minute average of maximum aerosol height. The maximum heights during the study period are shown in bold.

recorded in the summer of 2003 at Chilbolton, approached 2000 m, and on one occasion (09:00–10:00 on 12 July) exceeded this height. Active flight well above the CBL usually occurs in the morning (08:00–12:30 hours UTC), and the peak numbers above the CBL occurred at approximately 10:00. The insects themselves were not necessarily descending after 10:00, but the CBL was growing. On eight of the 12 days, the maximum insect height was observed at 14:00 or later, hence on those days many insects were still rising in the afternoon, though usually within the CBL.

Flight of insects above the CBL needs some explanation, because aerial density profiles of aphids (c. 0.5 mg mass) seem to require that these insects produce enough lift to become neutrally buoyant when they are in updrafts but stop producing lift when they are in downdrafts (Reynolds and Reynolds, 2008). It is possible that the insects observed above the CBL had ascended on thermals that subsequently dissipated, but the insects then continued at these heights by their own flight power. However, this might indicate that the species involved were larger than aphids, and more strongly flying. Reynolds *et al.* (2008) found that dawn emigrants (predominantly in the 16–32 mg range) sometimes formed layer concentrations in inversions; these layers persisted through the early morning but eventually merged into the insect activity which built up later in the morning (from 06.00–08.00 hrs onwards) in conjunction with the development of daytime convection. The disruption of stratiform layers of insects by the upward progression of convective plumes has also been noted by Campistron (1975) and Farrow (1986). In any event, the presence of insects above the CBL is yet more evidence that insect migrants are active fliers and not passively dependent on convective up-currents.

The minimum ambient temperature at which numbers of insects were recorded in flight was 13–14° C. The temperature near the surface appears to be important

in predicting the mass of insects in the CBL. A significant relationship was found between the reflectivity and the maximum screen temperature during the day. This is probably due to (a) hotter days are associated with more aerial migration, and (b) hotter days are associated with more frequent, longer-lasting and deep convective plumes allowing more insects to be spread through the depth of the CBL and maintained at high altitudes for longer.

Finally, it is worth stating that these millimetric cloud radar observations on cloudless days provided information on migrating insects that could not be acquired with currently deployed or envisaged entomological radar systems. The present paper has outlined the capabilities of radars operating at 94 and 35 GHz for micro-insect observation and has developed theory needed for this purpose.

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References

- Achtemeier GL. 1991. The use of insects as tracers for “clear-air” boundary-layer studies by Doppler radar. *Journal of Atmospheric and Oceanic Technology* **8**: 746–765.

- Campistron B. 1975. Characteristic distributions of angel echoes in the lower atmosphere and their meteorological implications. *Boundary-Layer Meteorology* **9**: 411–426.
- Chapman JW, Reynolds DR, Smith AD. 2003. Vertical-looking radar: A new tool for monitoring high-altitude insect migration. *Bioscience* **53**: 503–511.
- Chapman JW, Reynolds DR, Smith AD. 2004a. Migratory and foraging movements in beneficial insects: a review of radar monitoring and tracking methods. *International Journal of Pest Management* **50**: 225–232.
- Chapman JW, Reynolds DR, Smith AD, Smith ET, Woiwod IP. 2004b. An aerial netting study of insects migrating at high-altitude over England. *Bulletin of Entomological Research* **94**: 123–136.
- Chapman JW, Smith AD, Woiwod IP, Reynolds DR, Riley JR. 2002. Development of vertical-looking radar technology for monitoring insect migration. *Computing and Electronics for Agriculture* **35**: 95–110.
- Clothiaux EE, Ackerman TP, Mace GG, Moran KP, Marchand RT, Miller MA, Martner BE. 2000. Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites. *Journal of Applied Meteorology* **39**(5): 645–665.
- Cullen MJP, Davies T, Mawson MH, James JA, Coulter SC, Malcolm A. 1997. *Numerical methods in atmospheric and ocean modelling: The Andre J. Robert memorial volume.*, ch. An overview of numerical methods for the next generation UK NWP and climate model. Canadian Meteorological and Oceanographic Society, Ottawa, Canada, pp. 425–444.
- David CT, Hardie J. 1998. The visual responses of free-flying summer and autumn forms of the black bean aphid, *Aphis fabae*, in an automated flight chamber. *Physiological Entomology* **13**: 277–284.
- Drake VA. 1981a. Quantitative observation and analysis procedures for a manually operated entomological radar. Technical Paper 19, CSIRO Australia Division of Entomology.
- Drake VA. 1981b. Target density estimation in radar biology. *Journal of Theoretical Biology* **90**: 545–571.
- Drake VA, Farrow R. 1994. The influence of atmospheric structure and motions on insect migration. *Annual Review of Entomology* **33**: 183–210.
- Drake VA, Gatehouse AG (eds). 1995. *Insect migration: tracking resources through space and time*. Cambridge University Press.
- Farrow R. 1986. Interactions between synoptic scale and boundary-layer meteorology on micro-insect migration. In: *Insect Flight: Dispersal and Migration*, Dantharayanan W (ed), Springer-Verlag, Berlin/Heidelberg, pp. 185–195.
- Gatehouse AG. 1997. Behaviour and ecological genetics of wind-borne migration by insects. *Annual Review of Entomology* **42**: 475–502.
- Goddard JWF, Tan J, Thurai M. 1994. Technique for calibration of meteorological radars using differential phase. *Electronics Letters* **30**: 166–167.
- Hardy KH, Atlas D, Glover KM. 1966. Multiwavelength backscatter from the clear atmosphere. *Journal of Geophysical Research* **71**: 1537–1552.
- Hardy KR, Ottersten H. 1969. Radar investigations of convective patterns in the clear atmosphere. *Journal of Atmospheric Sciences* **26**: 666–672.
- Irwin ME, Thresh JM. 1988. Long-range dispersal of cereal aphids as virus vectors in North America. *Philosophical Transactions of the Royal Society, London, B* **321**: 421–446.
- Johnson CG. 1969. *Migration and dispersal of insects by flight*. Methuen and Co, London.
- Khandwalla A, Majurec N, Sekelsky SM, Williams CR, Gage KS. 2002. Characterization of radar boundary layer data collected during the 2001 multi-frequency radar IOP. In: *Twelfth ARM Science Team Meeting Proceedings*. ARM meeting: St Petersburg, Florida, pp. 1–5.
- Malcolm SB, Zalucki MP (eds). 1993. *Biology and conservation of the monarch butterfly*. Natural History Museum of Los Angeles County, Science Series 38.
- O'Connor EJ, Illingworth AJ, Hogan RJ. 2004. A technique for autocalibration of cloud lidar and for inferring the lidar ratio for ice and mixed phase clouds. *Journal of Atmospheric and Oceanic Technology* **21**(5): 777–786.
- Pedgley DE. 1993. Managing migratory insect pests—a review. *International Journal of Pest Management* **39**: 3–12.
- Reynolds AM, Reynolds DR. 2008. Aphid aerial density profiles are consistent with turbulent advection amplifying flight behaviours: abandoning the epithet 'passive'. *Proceedings of the Royal Society, London, B* **275**: In Press.
- Reynolds DR, Chapman JW, Edwards AS, Smith AS, Wood CR, Barlow JF, Woiwod IP. 2005. Radar studies of the vertical distribution of insects migrating over southern Britain: the influence of temperature inversions on nocturnal layer concentrations. *Bulletin of Entomological Research* **95**: 259–274.
- Reynolds DR, Chapman JW, Harrington R. 2006. The migration of insect vectors of plant and animal viruses. *Advances in Virus Research* **67**: 453–517.
- Reynolds DR, Riley JR. 1997. The flight behaviour and migration of insect pests: radar studies in developing countries. NRI Bulletin 71, Natural Resources Institute, Chatham UK.

- Reynolds DR, Smith AD, Chapman JW. 2008. A radar study of emigratory flight and layer formation by insects at dawn over southern Britain. *Bulletin of Entomological Research* **98**: 35–52.
- Richter JH, Jensen DR, Noonkester VR, Kreasky JB, Stimmann MW, Wolf WW. 1973. Remote radar sensing: atmospheric structure and insects. *Science* **180**: 1176–1178.
- Riley JR. 1985. Radar cross section of insects. *Proceedings of the IEEE* **73**(2): 228–232.
- Riley JR. 1992. A millimetric radar to study the flight of small insects. *Electronics and Communication Engineering Journal* **4**(1): 43–48.
- Riley JR, Cheung X, Zhang X, Reynolds DR, Xu G, Smith AD, Cheng J, Bao A, Zhai B. 1991. The long-distance migration of *Nilaparvata lugens* (Stål) (Delphacidae) in China: radar observations of mass return flight in the autumn. *Ecological Entomology* **16**: 471–489.
- Riley JR, Reynolds DR. 1979. Radar-based studies of the migratory flight of grasshoppers in the middle Niger area of Mali. *Proceedings of the Royal Society, London, B* **204**: 67–82.
- Riley JR, Reynolds DR, Farmery MJ. 1983. Observations of the flight behaviour of the armyworm moth, *Spodoptera exempta*, at an emergence site using radar and infra-red optical techniques. *Ecological Entomology* **8**: 395–418.
- Schaefer GW. 1976. Radar observations of insect flight. *Symposium of the Royal Entomology Society, London* **7**: 157–197.
- Smith AD, Reynolds DR, Riley JR. 2000. The use of vertical-looking radar to continuously monitor the insect fauna flying at altitude over southern England. *Bulletin of Entomological Research* **90**: 265–277.
- Smith AD, Riley JR, Gregory RD. 1993. A method for routine monitoring of the aerial migration of insects by using a vertical-looking radar. *Philosophical Transactions of the Royal Society, London, B* **340**: 393–404.
- Thomas AAG, Ludlow AR, Kennedy JS. 1977. Sinking speeds of falling and flying *Aphis fabae scopoli*. *Ecological Entomology* **2**: 315–326.
- Wilson JW, Weckworth TM, Vivekanandan J, Wakimoto RM, Russell RW. 1994. Boundary layer clear-air radar echoes: origin of echoes and accuracy of derived winds. *Journal of Atmospheric and Oceanic Technology* **11**: 1184–1206.
- Wood CR. 2007. The biometeorology of high-altitude insect layers. PhD thesis, University of Reading, UK.
- Wood CR, Chapman JW, Reynolds DR, Barlow JF, Smith AD, Woiwod IP. 2006. The influence of the atmospheric boundary layer on nocturnal layers of noctuids and other moths migrating over southern Britain. *International Journal of Biometeorology* **50**: 193–204.