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Investigating vertical motion of small insects in atmospheric boundary layer using millimetre-wavelength radar and Doppler LIDAR

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Abstract: It is well known in the meteorological community that millimetre-wavelength cloud radars contain considerable contamination from aerial biota, and much of this comprises small weakly flying insects. Several methods have been explored for removing insect contamination from cloud radar data yet using this data to study the behaviour of insects remains a relatively unexplored area. Here, the authors describe the use of a collocated Ka-band cloud radar and Doppler LIDAR to study the vertical motion of small insects and investigate how this varies depending on the surrounding vertical air motion. We find that in the convective boundary layer, insects are largely concentrated in updrafts. During the daytime, small insects in downdrafts are found to descend at an average rate of 0.25 m s^{-1} , yet insects caught in updrafts showed a descent response that was dependent upon the strength of the updraft in which they were embedded. Although the downward motion of the insects increased with increasing updraft strength, it was insufficient to overcome the rising motion in the updraft, i.e. in updrafts the insects ascend but at a slower speed than the surrounding air. We also report an ongoing efforts to extend this research to the nocturnal stable boundary layer.

1 Introduction

The flight behaviour of small insects in the atmospheric boundary layer has long been a topic of investigation for entomologists [1], with the first studies using aerial netting to study the relative density of various taxa at different heights and try to relate this to atmospheric conditions [2]. The advancement of radar technology, both meteorological and entomological, has enabled considerable progress in studies of insects in flight in the boundary layer (e.g. [3–5]). However, the limitations of meteorological weather radar networks and specialised entomological radars are that they are only able to see insects above a certain size, particularly at higher elevations. The recent development of specialised meteorological cloud radars, which operate at millimetric wavelengths, has opened up new opportunities to study increasingly smaller insects even at high altitudes (e.g. [6, 7]). The study of insect behaviour with respect to the air motion in which they are embedded is of interest both to entomologists concerned with how the insects sense the atmospheric conditions around them [8], and also to meteorologists who need a robust method for removing insect clutter from the cloud radar returns and for removing biases introduced into radar-derived vertical velocities [9, 10].

In order to deduce the response of insects to the flow they are embedded in, independent measurements of the flow, uncontaminated by insect clutter, as well as the superimposed motion of the insects on top of the atmospheric motion are needed. A combination of an aircraft-mounted W-band cloud radar and an external gust probe were first used to investigate this issue by [7, 11]. This study, conducted on summertime fair-weather days in Kansas in the USA Great Plains, found that insects resist ascent when in updrafts. The strength of their resistance to the updraft was found to increase in proportion to the updraft strength. This suggested that the insects are somehow able to sense the vertical motion of the surrounding air, since their response is seen to be dependent on the updraft strength.

2 Methodology

We use a collocated Halo Photonics Streamline Doppler LIDAR and ProSensing Ka-band cloud radar in Lamont, Oklahoma, USA to investigate how the vertical motion of insects varies with respect to the updraft or downdraft in which they are embedded. Full details of the method can be found in [12] and so it is described only briefly herein. This method is based upon an extended version of the original methodology employed by [7, 11] but performed over longer time periods and using stationary rather than airborne instruments.

The Doppler LIDAR provides vertical profiles of atmospheric vertical velocity, uncontaminated by insect clutter, at temporal and spatial resolution of 3 s and 26 m. The Ka-band radar operates at 8.6-mm wavelength and provides vertical profiles of reflectivity, radial velocity, and spectrum width at 2.7 s temporal resolution and 30-m spatial resolution. The Ka-band radar operates in zenith-pointing mode and so the reported radial velocities represent vertical motion; however, unlike the Doppler LIDAR, the velocities measured by the radar contain contributions from both the true atmospheric motion and the superimposed velocities of any insects within the beam.

By comparing the radar-indicated vertical motion, w_r , to the true atmospheric vertical motion measured by the Doppler LIDAR, w_a , we are able to compute the vertical motion of insects within the beam, w_i , via simple subtraction: $w_i = w_r - w_a$. For this calculation, the vertical motion from the Doppler LIDAR was interpolated in time and height to match the resolution of the Ka-band radar data exactly.

Since the primary focus for this work was elucidating the behaviour of small insects with respect to the atmospheric motion in which they are flying, several filters were required to limit the data to clear-sky conditions and instances where only single insects were located in the beam. The Ka-band radar provides polarimetric reflectivity measurements, which enabled us to remove precipitation using a linear depolarisation ratio ($\text{LDR} = Z_c - Z_x$,

where Z_c is the co-polar reflectivity and Z_x is the cross-polar reflectivity) with a threshold of -15 dB [13]. To remove instances of multiple insects within the beam, we applied a co-polar spectrum width filter which removed data with a spectrum width value above 0.1 m s^{-1} . Times where no insects were present in the beam were discarded by removing data with a signal-to-noise ratio below zero.

The time period investigated was 1 July–31 August 2015. Data representing the convective boundary layer were selected as 14:00–18:00 local time, when the boundary layer is fully developed, and the mixed layer has reached its full extent. Data representing the nocturnal stable boundary layer were chosen as 23:00–04:00 local time. We note here that the location used for this study (north-central Oklahoma) is within the region that is commonly affected by the Great Plains nocturnal low-level jet during the summertime [14].

Due to the large number of single data points remaining after initial filtering, we follow the method of [7, 11] and separate the insect response w_i into bins based on atmospheric vertical motion w_a , with a bin size of 0.05 m s^{-1} . The data are split into 6-min bins based on the eddy turnover time in the convective boundary layer, and the same analysis period is kept for the stable boundary layer to enable direct comparison between the two cases. For each w_a bin containing more than five data points, the w_i values are averaged to give a mean value for that velocity and time interval. No separation based on height is performed. For strongly positive or negative w_a values, which occur at a much lower frequency, data falling into that bin will not occur during every time period.

3 Results

3.1 Concentration of insects in the convective boundary layer

The reflectivity measured by the Ka-band vertical radar can also be used as a proxy for aerial insect density in the atmosphere, allowing us to investigate the location of dense concentrations of insects with respect to the surrounding airflow. Fig. 1a shows the reflectivity recorded by the radar during 14:00–14:30 local time on 12 August 2015, a hot cloud-free summer day in this region. The panel in Fig. 1b shows the vertical motion recorded by the Doppler LIDAR for the corresponding time period. By comparing the two figures, we can easily identify plumes of increased reflectivity occurring at the same time as positive vertical motion (i.e. updrafts), which indicates that the insects are strongly concentrated in convective updrafts. The reflectivity is significantly reduced during time periods corresponding to downdrafts, so the aerial density of insects in downdrafts is much lower than that in updrafts.

3.2 Insect response to vertical motion in the convective boundary layer

Following the method outlined in Section 2, we processed radar and LIDAR data from 62 summertime days comprising 1 July–31 August 2015. After the filtering procedures to remove precipitation and multiple insects outlined in the previous section, we were left with over 1 million data points representing single insects in a range gate. After separating these data into bins based on 6-min intervals and the atmospheric vertical motion value, we were left with almost 30,000 values representing the average insect response to the surrounding vertical motion. The data are shown in Fig. 2 along with a quadratic best fit.

Fig. 2 illustrates that in downdrafts, i.e. the area to the left of the vertical line at $w_a = 0 \text{ m s}^{-1}$, the insects descend with respect to the flow. The average descent in downdrafts was calculated to be 0.25 m s^{-1} with a standard deviation of 0.3 m s^{-1} . The descent speed is relatively stable across the range of downdraft strengths. In contrast, when we consider the insect response to the surrounding flow when embedded in updrafts, we see that the strength of the insect response depends on the updraft strength. This mirrors the findings of [7, 11] but using data covering a much longer time period than the airborne campaign from which their data

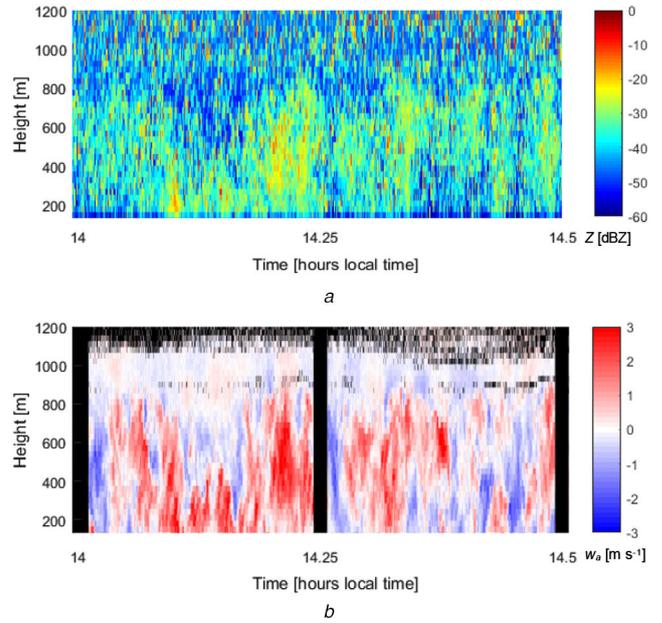


Fig. 1 Example of collocated reflectivity and vertical velocity data in the CBL

(a) Time-height reflectivity profile from the Ka-band radar for 14:00–14:30 local time on 12 August 2015, (b) Vertical motion recorded by the collocated Doppler LIDAR for the same time period. Positive values of vertical motion correspond to updrafts and negative values to downdrafts

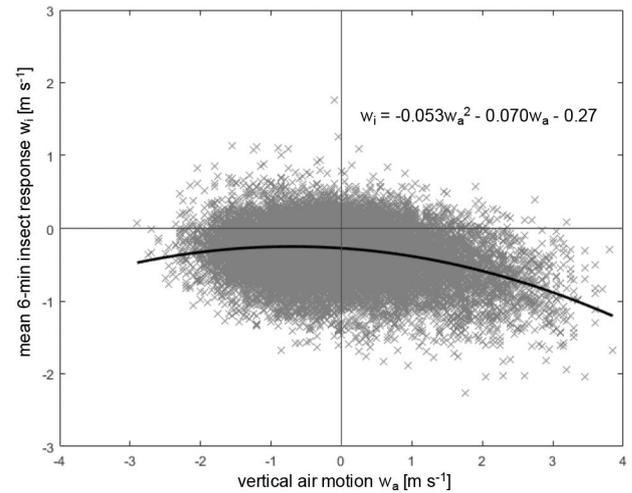


Fig. 2 Difference between the self-powered vertical velocity of small insects (w_i) and the surrounding vertical air motion (w_a) in which they are embedded. The solid black line represents a quadratic best fit to the data, performed using a quadratic linear regression. The root mean squared error corresponding to the fit is 0.31 m s^{-1} and $R^2 = 0.086$ (from [12])

originated, and without the additional complexity of needing to account for aircraft motion.

3.3 Concentration of insects in the stable boundary layer

We have also investigated how the cloud radar can be used to study the layering of insects within the nocturnal stable boundary layer as well as their nocturnal vertical motion. Fig. 3a illustrates a case of strong layering of insects into multiple distinct layers in the nocturnal stable boundary layer. This has been seen in many previous studies, and the insects have been theorised to collect in regions of stronger wind speed or temperature inversions. The region where the data were collected often has a strong nocturnal low-level jet during the summer [14], and we see in Fig. 3c that the night of 16 July 2015 shows a low-level jet developing over the course of the night, with peak wind speeds of $>20 \text{ m s}^{-1}$ at a height of around 400 m by sunrise. Once the wind speed reaches a peak of

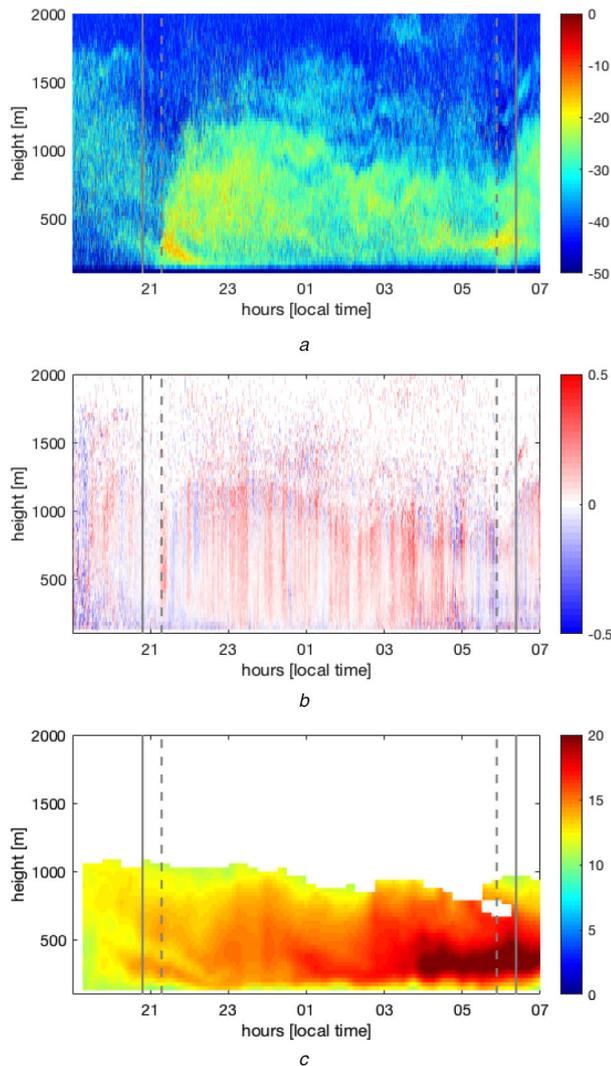


Fig. 3 Example of collocated data showing reflectivity, vertical velocity and horizontal wind speed in the SBL

(a) Time-height reflectivity profile from the Ka-band radar for the night of 16 July 2015. The reflectivity is shown in units of dBZ, (b) Vertical motion recorded by the collocated Doppler LIDAR for the same time period. Positive values of vertical motion correspond to rising motion and negative values to sinking motion. The vertical motion is shown in units of m s^{-1} , (c) The horizontal wind speed in units of m s^{-1} . The solid grey lines indicate sunrise and sunset and the dashed grey lines the start and end of civil twilight

over 20 m s^{-1} at 04:00, a band of stronger reflectivity develops at the height of the low-level jet maximum, suggesting that insects are preferentially collecting at altitudes with the strongest wind speed, as seen in several previous studies. Examination of several other cases with strong nocturnal low-level jets (not shown) indicates that insects are often most densely concentrated at the altitude of the jet maximum, although from the available data it is not possible to determine whether this is due to the higher wind speeds or a collocated temperature inversion.

The summertime nocturnal temperatures in this region indicate that a flight ceiling temperature of around 10°C would not be reached until heights of $\sim 3 \text{ km}$ and so the insect flight within the stable boundary layer shown in Fig. 3a is not constrained by temperature. Using the same method outlined for the convective boundary layer, we repeated this analysis for the nocturnal boundary layer case illustrated in Fig. 3, and the results are shown in Fig. 4.

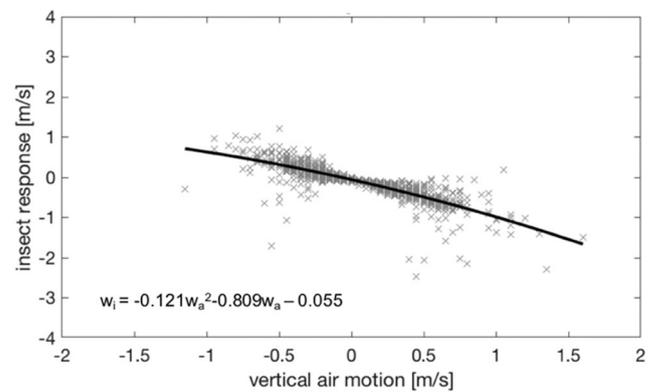


Fig. 4 Difference between the self-powered vertical velocity of small insects (w_i) and the surrounding vertical air motion (w_a) in which they are embedded for the night of 16 July 2015. The solid black line represents a quadratic best fit to the data, performed using quadratic linear regression

3.4 Insect response to vertical motion in the stable boundary layer

Examining Fig. 4, we see an almost inverse relationship between the insect response, w_i , and the vertical air motion, w_a . The insect response is to move upwards when in regions of sinking air and to move downwards in regions of rising air. The response is almost linearly proportional to the strength of the atmospheric vertical motion, which would seem to suggest that the insect response is such to try and remain at the same height, whether this is due to favourable temperatures or winds at that level. Other individual nights that have been examined have shown a similar relationship between the insect response and vertical air motion for other cases with strong insect layering with height (not shown), which often occurs on nights with a strong low-level jet. The cause and mechanism for this response are the subject of ongoing work.

4 Conclusion

Our findings suggest that in the daytime convective boundary layer small insects are travelling downwards in downdrafts at a constant rate of 0.25 m s^{-1} faster than the downdrafts in which they are embedded. In contrast, in updrafts, the insects are moving upwards, but at a slower rate than the surrounding airflow, and their ascent is slowed proportional to the speed of the updraft in which they are flying. It was suggested in [12] that this may be a consequence of the inability of small insects to fully counter gravity within turbulent updrafts, since the turbulence may act to impede lift generation at an airflow-dependent rate.

Similar analysis of a single nocturnal stable boundary layer case during a night with a strong low-level jet revealed an almost linear relation between the insect response and the vertical atmospheric motion. Initial examination of other cases with a similar wind profile, including low-level jets with pronounced maxima at altitudes between 300 and 1000 m, has suggested that this insect response may occur frequently for cases in which there is an incentive for insects to remain at a given height in the form of increased wind speeds or higher temperatures. Further investigation of insect responses in the stable boundary layer is a part of ongoing work on this subject.

This airflow-dependent response in both the convective and stable boundary layers would suggest that insects have some mechanism for sensing the vertical motion of the surrounding flow and responding accordingly. The method for this flow sensing is the subject of ongoing investigation.

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