

The accuracy of Doppler radar wind retrievals using insects as targets

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ABSTRACT: Insect returns from the UK's Doppler weather radars were collected in the summers of 2007 and 2008, to ascertain their usefulness in providing information about boundary layer winds. Such observations could be assimilated into numerical weather prediction models to improve forecasts of convective showers before precipitation begins. Significant numbers of insect returns were observed during daylight hours on a number of days through this period, when they were detected at up to 30 km range from the radars, and up to 2 km above sea level. The range of detectable insect returns was found to vary with time of year and temperature. There was also a very weak correlation with wind speed and direction. Use of a dual-polarized radar revealed that the insects did not orient themselves at random, but showed distinct evidence of common orientation on several days, sometimes at an angle to their direction of travel. Observation minus model background residuals of wind profiles showed greater bias and standard deviation than that of other wind measurement types, which may be due to the insects' headings/airspeeds and to imperfect data extraction. The method used here, similar to the Met Office's procedure for extracting precipitation returns, requires further development as clutter contamination remained one of the largest error contributors. Wind observations derived from the insect returns would then be useful for data assimilation applications. Copyright © 2010 Royal Meteorological Society and Crown Copyright

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1. Introduction

During summer, insects are a common source of non-precipitation echoes for C-band rain radars (Wilson *et al.*, 1994; Meischner *et al.*, 1997; Lothon *et al.*, 2002). In the UK operational system, these returns are usually discarded because of their low reflectivity: the radars and their associated data processing systems are designed to target precipitation returns. In some circumstances, insect returns from Doppler radars can be used to provide information about the wind field. The purpose of this paper is to assess Doppler radar insect returns in the United Kingdom and determine how suitable these are as wind observations for assimilation in numerical weather prediction (NWP) (Sun, 2005). As insect returns appear in fine weather, they would provide wind measurements for times and locations that otherwise would have no such observations.

Insects detected by weather radars are normally undertaking long-distance migration (Drake and Farrow, 1988). Insect migration at high altitudes is quite well observed and understood (Drake and Farrow, 1988; Gatehouse,

1997). High altitude migration allows insects to be carried at much faster speeds than can be achieved close to ground level with independent flight, allowing the insects to reach suitable new habitats. Seasonal migrations occur as some insects winter at lower latitudes and migrate polewards for summer, thus reaching new feeding and breeding areas. Meteorological conditions affect the occurrence of insect migration: insects are poikilothermic, so will fly only when and where the air is sufficiently warm. The upper limit to which an insect will ascend (and be able to maintain flight) is related to a temperature tolerance, which varies considerably among different species of insects (Drake and Farrow, 1988). In a UK study, Wood *et al.* (2009a) observed that daily maximum temperature could account for 70% of the variation in returned insect reflectivity, which indicated greater insect numbers on warmer days.

During the daytime, ground heating and convection tend to result in a well mixed planetary boundary layer. Insects make use of convection for vertical transport during the day, particularly micro-insects that weigh a few mg or less, because they may have a very small self-propelled ascent rate, e.g. 0.2 m s^{-1} (though the descent rate can be a fall speed of $>1 \text{ m s}^{-1}$ Thomas *et al.*, 1977). The upper limit of transport by convection is marked by the top of the convective boundary layer. Observations with a cloud radar in the United Kingdom (Wood *et al.*, 2009a) observed insects up to 800 m above

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the convective boundary layer, usually in the morning, which indicated that some day-flying insects were also ascending under their own power. Smaller insects are more prevalent during the day, which may be due to the presence of convection, to a lower temperature tolerance, or because they are less visible to predators than larger insects (Drake and Farrow, 1988). Insect trapping at 200 m during daytime in July 2002 (in the United Kingdom) indicated a peak insect size around 1 mg (Wood *et al.*, 2009a).

At night, ground cooling results in a temperature inversion that makes the planetary boundary layer much more stable. Nocturnal insects are usually larger, stronger, flyers (Drake and Farrow, 1988; Wood *et al.*, 2009b) that do not rely on convection to become airborne. Insects detected during dusk or night migrations (Reynolds *et al.*, 2009; Wood *et al.*, 2009b) consist of a higher percentage of larger (>40 mg) and more strongly flying species, which in the United Kingdom are often noctuid moths (Wood *et al.*, 2009b). For this reason the observed velocity at night is less likely to correspond accurately to the true wind velocity.

While insect returns can give a coherent velocity signal which may be used to observe the wind, this presupposes that insects act as passive tracers carried by the wind. In fact there are many examples where insects seem to direct their flight, which would reduce the accuracy of 'wind' velocities from insect targets. Insects often migrate at levels associated with temperature or velocity features – or the boundaries of such features (Drake and Farrow, 1988; Reynolds *et al.*, 2009). For example, insects that make use of the nocturnal jet that results from the temperature inversion are able to migrate much faster and farther. Large insects such as grasshoppers have been noted in the United States to fly at speeds of 3–6 m s⁻¹ and to control their ascent and descent to stay at an appropriate temperature (Achtmeier, 1991), though micro-insects only fly at <1 m s⁻¹ (Dudley, 2002; p. 78). Micro-insects may also congregate less intentionally as a result of turbulence at the small scale associated with the feature (Reynolds *et al.*, 2009). A study by Wilson *et al.* (2004) in various parts of the United States found that most clear air returns during the day were small insects and that observed winds were fairly representative. Furthermore, no preferred orientation was observed from dual-polarization returns (Wilson *et al.*, 2004). Insect migration against the wind is rare and usually only occurs close to the ground where the wind is weak. It is assumed here that the day-flying insects observed by the radar were small and weak flyers, their migration should be with the wind, and their own airspeeds unlikely to make a significant difference to the velocity measured by the radar.

The objective of this study is to examine the meteorological factors that affect the incidence of insect returns to the UK Doppler rain radars, and evaluate the accuracy of using these for wind observations. All days during 2007 and 2008 with sufficient insect returns (see Section 2.2) were examined to determine if insects targeted

particular weather conditions. The focus here is on day-time insect returns, as it is assumed that these would be mostly micro-insects, expected to fly at less than 1 m s⁻¹, unlike during the night. The study focuses on using VADs (Velocity Azimuth Displays) (Browning and Wexler, 1968) for wind observations, which assume a linear wind field and so average out variations: the bias of radial wind measurements (e.g. Salonen *et al.*, 2007) is more complicated to determine. The intent here is to determine how useful insect returns would be for wind profile measurements without reference to the exact meteorological conditions that could affect their flight, with a view to how the data could be handled in routine data assimilation.

The paper is organized as follows. Section 2 describes data collection and the various methods that were used to analyse the data. Section 3 contains results with three foci, the assessment of insect observations in relation to meteorological conditions, investigation of common orientation using a dual-polarization radar, and comparison of the observed wind and model wind to evaluate error and bias. Section 4 summarizes the findings. Throughout, the passive target assumption is tested by searching for indication that insects direct their migration by their own exertions or preferentially selecting certain wind directions.

2. Data collection, processing and analysis methods

The period used for data collection was the summers of 2007 and 2008. During 2007 data were collected from two radars, one a single-polarization C-band Doppler radar (Chenies) in the UK rain radar network, and the other a dual-polarized C-band Doppler radar (Thurnham) that was under development. During 2008 data were collected *via* the Met Office and BADC (British Atmospheric Data Centre) from the four operational Doppler radars (Chenies, Clee Hill, Dean Hill and Cobbacombe) (Figure 1). The radars yield a PPI (Plan Position Indicator) scan around 360° at low elevation angles, which displays as a conical 2D map of returns. Table I contains the details for each radar. The sample volume of 1° by 1° by 600 m, which broadens with increasing range, would contain many insect targets. The operational radars scanned five elevations every 5 min, and Thurnham scanned a full cycle every 10 min. All radars scanned with both short pulse (Doppler) and long pulse (for reflectivity/precipitation) during every cycle. However, only short pulse data were used here. All data were collected during standard radar operation with no changes made to facilitate insect detection.

Data were collected for every day between late May and mid September, which was the entire insect 'season', that there were sufficient insect returns (see Section 2.2) to acquire a velocity observation. In this study the velocity observations are wind profiles derived as described in Section 2.3. Unfortunately the summers of 2007 and 2008 were particularly wet for England, with above average rainfall and more rain days than average for several

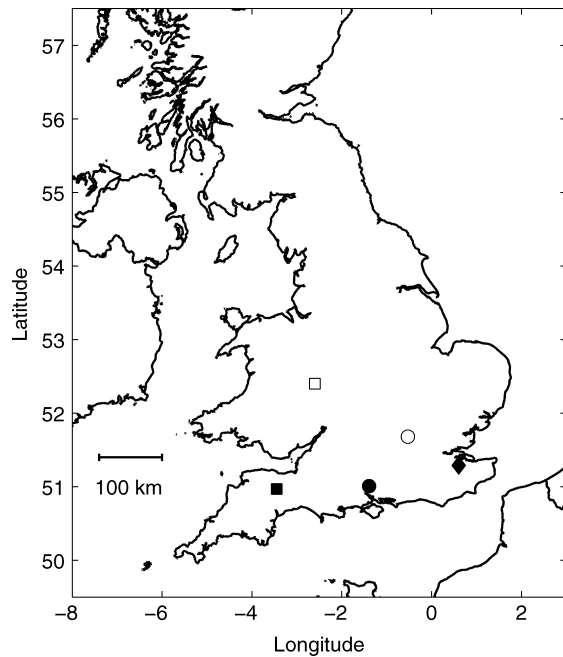


Figure 1. Location of Doppler radars in United Kingdom. ○ Chenies
□ Clee Hill ■ Cobbacombe ● Dean Hill ◆ Thurnham.

summer months (Met Office online Climate Summary at <http://www.metoffice.gov.uk/climate/uk/index.html>), so the number of days with insect returns was limited. In the southern half of England, for 2008 summer (June–August) precipitation anomalies were 100–180% of the 1970–2000 average, and for 2007 summer precipitation was 150–225% of the average. Few days were identified as having strong convection, despite a previous study (Hand *et al.*, 2004) noting that a majority of UK rainfall cases between June and August are convective. Table II indicates the days for which data were collected, and from which radar(s). Note that the Thurnham radar was unavailable for much of summer 2007 and all of 2008.

2.1. Insect visibility/occurrence

In this study only daytime insect returns were examined. This was for two reasons: (1) the smaller daytime insects are considered more likely to be essentially passively carried by the wind, therefore any self-propulsion should contribute a relatively small error in the observed velocity field; and (2) the Doppler data from the radars at night usually yielded a poorer velocity field with a limited

Table II. Dates of data acquired and source radar.

Year	Month	Day	Radar	
2007	June	19	Chenies, Thurnham	
		July	7	Chenies
	19		Chenies, Thurnham	
	30		Chenies	
	August	1, 5, 11	25	Chenies, Thurnham
			26, 27	Chenies
		28		Chenies, Thurnham
			September	4, 7, 10
		2008		May
	June		8	Chenies
			10	Clee Hill, Dean Hill, Cobbacombe
			17	Chenies
July	24			Chenies, Clee Hill, Dean Hill, Cobbacombe
			30	Chenies, Clee Hill, Cobbacombe
	21, 22, 23	4	Chenies	
		14	Chenies	
		25	Chenies, Clee Hill, Dean Hill, Cobbacombe	
26, 27, 28		Chenies, Clee Hill, Dean Hill, Cobbacombe		
	August	7,15, 30	Chenies, Chenies, Dean Hill, Chenies	
September		10	Chenies, Dean Hill, Cobbacombe	
		13	Chenies	

Most days gave at least several hours, and up to 12 h of insect returns.

Table I. Operational short pulse parameters for the Doppler radars.

Radar	Pulse length (μs)	Pulse repetition frequency (pps)	Range gate (m)	Doppler scan elevations	Beam width
Chenies	0.5	900/1200	600 (averaged)	1°, 2°, 4°, 5°, 5.5°	1°
Clee Hill	0.5	900/1200	600 (averaged)	1°, 2°, 4°, 6°, 9°	1°
Cobbacombe	0.5	900/1200	600 (averaged)	1°, 2°, 4°, 6°, 9°	1°
Dean Hill	0.5	900/1200	600 (averaged)	1°, 2°, 4°, 6°, 8°	1°
Thurnham	0.4	885/1180	250	1°, 3°, 6°, 9°	1°

range, such that it was difficult to extract a useful observation.

For every day listed in Table II, statistics were collated for the range to which insect returns were detected at the lowest elevation, the height to which insects were detected, the prevailing wind direction, and approximate insect velocity. Both the range to which an observer could detect directionally coherent movement of targets and the range to which wind observations would be of sufficient quality and signal strength for use in applications such as data assimilation were noted by analysing raw radar scans. Often, insects were apparent to 500 m or more above the practical vertical limit (using a procedure similar to that in Section 2.2) for retrieving a quality velocity measurement. Height and range limits are used in this study as a proxy to indicate airborne insect population size.

Height and range limits are correlated because the beam elevation means height increases with range through the insect layer. However, the detection range is also limited by the system sensitivity because beam spread weakens the returned signal. The vertical profile of insect density and the beam angle will determine if the range limit is at an altitude lower than or corresponding to the height limit. Very sparse insects will give a weak signal that is difficult to extract, as the return is close to the signal limit of the system. Generally, for elevations above 2.5°, the height limit (often at the convective boundary layer) is visible: for lower elevations the detection limit is reached first.

The range data were estimated to the nearest kilometre below 10 km, and to the nearest 2–5 km above 10 km. The height data were rounded to the nearest 100 m. Non-uniformity in the insect distribution meant that range/height varied with azimuth in some cases, so an upper limit was used. The direction was either an average or else the direction at the height of densest insects, and rounded to the nearest of sixteen compass points.

2.2. Extraction of insect velocity observations

A method to extract insect returns from the raw radar scans is extremely important to enable the use of the Doppler velocity observations. The processing described here is developmental and the results of the analyses performed below are used to indicate the efficacy of these methods to extract useful observations. It is impossible to create a method that identifies insect returns with 100% accuracy because all parameters will overlap for different target types. It is also probable that any birds whose velocity and reflectivity signals were not distinguishable could not be excluded. Certainly, processing for insects may require more levels of filtering than for precipitation, because precipitation gives a comparatively strong and clear signal (with the exception of very light drizzle, which has a reflectivity comparable to that of strong insect echoes). Ground clutter is a much greater problem in insect extraction because clutter returns are stronger than insect returns.

The method used here for identifying clutter is based on the constancy of ground clutter returns between scans, creating a map of regions with a high probability of clutter. A standard probability of detection (POD) map is normally formed from accumulating counts of each gate (radar's sample volume) with any real signal, i.e. returns above a reflectivity threshold denoting the detection limit, using many days' data. Ground clutter should have a high POD, near 100%. However, close to the radar, omnipresent insects made this method unsuitable to distinguish clutter. Instead, the clutter was located by its low standard deviation of velocity at a gate over time and from this a pseudo-POD was created to identify clutter close to the radar. The most effective clutter removal was achieved by applying the pseudo-POD close to the radar and the standard POD far from the radar. For operational purposes, a similar method must be developed. Alternatively, a Clutter Index (Sugier *et al.*, 2002) that evaluates the constancy of pulse-to-pulse reflectivity of clutter returns could be used. Such a Clutter Index will soon be available on all UK Doppler radars. No other spectral-analysis-based clutter detection methods (e.g. Luke *et al.*, 2008; Hubbert *et al.*, 2009) were available, or are anticipated to be in use by the Met Office in the near future.

Extraction of the velocity measurement for the single polarization radars followed a procedure that adapted techniques used in the Met Office's operational method, and applied extra filtering steps. First, a noise threshold was applied, which removed the lowest reflectivity (dBZ) values and was a function of range. Next, clutter was removed using several combinations of pseudo-POD, velocity and reflectivity thresholds: for example, $\text{POD} > x\%$ and $\text{velocity} < y \text{ m s}^{-1}$ and $\text{reflectivity} > z \text{ dBZ}$. The remainder were then cleaned to remove spurious values that did not conform to the observed velocity field, using a spatial Laplacian filter (Joe and May, 2003) for both velocity and reflectivity, and also a five-by-five spatial filter. The five-by-five filter compared the 'good' velocity values in a five-by-five array of adjacent gates and discarded the central value if it differed greatly ($> 3.5 \text{ m s}^{-1}$) from the median, or if the variance of all 'good' values was very large ($> 20 \text{ m s}^{-1}$).

For Thurnham, the dual polarization provides a range of parameters (Illingworth, 2004) that were used to identify insect returns, in conjunction with the thresholds and filtering described for single polarization data. Extra 'texture' parameters were created by the root-mean-square difference of a gate to its eight adjacent gates. The additional parameters were used for a probabilistic identification of targets, as described in Rennie *et al.* (2008). Parameters used for probabilistic identification included reflectivity, differential reflectivity, Doppler width and the spatial texture of differential phase shift. For each target type (insects, clutter, precipitation), a probability density function was created for each parameter. Parameter thresholds were applied for velocity, differential phase shift, reflectivity, Laplacian of velocity and texture of differential phase shift. The dual polarization method was

more accurate than using single polarization parameters alone (Rennie *et al.*, 2008).

2.3. Comparison with model wind

The assumption that diurnal insects can be treated as passive tracers of the wind may be tested by comparison with an independent velocity measurement. This method can also detect other sources of bias. The model background of the Met Office UK 4 km model was chosen for this, because no independent wind observations exist with suitable temporal and spatial coverage. The model background is the state description for the forecast at 3 h after the previous analysis time, and is used for assimilating observations within a 3 h window. The velocity comparison was made between a VAD (Velocity Azimuth Display) with velocity at the radar location interpolated to model height levels, and a corresponding velocity profile extracted from the model background at the radar location. The whole procedure is analogous to standard precipitation VAD processing and wind profile observation monitoring used by the Met Office.

The VAD was calculated by fitting a sine curve to the radial velocity at each range, for all elevations, assuming a linear wind field. The VAD calculation was based on the method used for BALTEX (BALTic sea EXperiment) (Andersson, 1992; Michelson *et al.*, 2000), and used the following equations, derived from optimizing the least squares fit of observations to an idealized radial wind field (V_r) where for each azimuth θ_n :

$$V_m = a \cos \theta_n + b \sin \theta_n \quad (1)$$

Solving the least squares optimization equation yields a and b , the orthogonal vector components of velocity, and rearranging, giving (Michelson *et al.*, 2000):

$$a = \frac{\sum (v - U_m) \cos \theta - \frac{\sum \sin \theta \cos \theta \sum (v - U_m) \sin \theta}{\sum \sin^2 \theta}}{\frac{\sum \cos^2 \theta - \left(\frac{\sum \sin \theta \cos \theta}{\sum \sin^2 \theta} \right)^2}{\sum \sin^2 \theta}} \quad (2)$$

and

$$b = \frac{\sum (v - U_m) \sin \theta - a \sum \sin \theta \cos \theta}{\sum \sin^2 \theta} \quad (3)$$

where v_n is the observed radial velocity, U_m is the mean of all v_n , θ_n is the azimuth and the sum is over all n azimuthal observations. From these the speed and direction may be calculated conventionally, with

$$Speed = \frac{\sqrt{a^2 + b^2}}{\cos \phi_e} \quad (4)$$

adjusting for scan elevation ϕ_e , and,

$$f = \text{atan}(a/b) \quad (5)$$

where f is the wind source direction. Only data in diametrically opposite pairs are used, in order to balance the representation of azimuths in calculating the mean velocity (which can result in loss of often 20–50% of values, and at extremely cluttered ranges the minimum number (eight) of pairs may be absent). A range limit of 30 km was applied to maintain the validity of the linear approximation. Any cases for which the root-mean-square of residuals to the sine curve fit was greater than twice the calculated speed were excluded. VADs with residual RMS greater than 6 m s^{-1} were also excluded, as were VADs with error greater than twice the speed. The velocity from all ranges and elevations was then averaged into 200 m height bins. For all radars VADs were calculated every third scan cycle, resulting in 15 min intervals, except for Thurnham which had 30 min intervals because of its longer scan cycle. VADs were manually quality checked to remove very erroneous results (which would be discarded in typical, pre-assimilation quality-control procedures anyway) and VADs from precipitation.

In order to calculate the errors in a and b in Equations (2) and (3), the estimated variance of the residual mean square (with $n - 2$ degrees of freedom for the two parameters calculated) is required, given by:

$$s^2 = \frac{\sum (v - V_r)^2}{n - 2} \quad (6)$$

Rewriting Equation (1) in vector notation as $\mathbf{V}_r = \mathbf{X} \cdot \mathbf{p}$, where $\mathbf{p} = [a \ b]^T$ and the n th row of \mathbf{X} is $[\cos \theta_n \ \sin \theta_n]$, the variance of a and b was then derived from the coefficient \mathbf{X} , using $\text{Var}(p_{jj}) = s^2([\mathbf{X}^T \mathbf{X}]^{-1})_{jj}$. The errors in direction and speed are not linearly related to the variances of a and b . The error in direction was calculated by propagating the error through the direction calculation, a function of two variables whose covariance would be strictly positive. Writing the variances of each variable as σ^2 with an appropriate subscript, the error variance in the wind source direction may be given by (Berthouex and Brown, 1994):

$$\sigma_f^2 = \left(\frac{\partial f}{\partial a} \right)^2 \sigma_a^2 + \left(\frac{\partial f}{\partial b} \right)^2 \sigma_b^2 + \left(\frac{\partial^2 f}{\partial a \partial b} \right) COV_{ab} \quad (7)$$

Using Equation (5) this gives:

$$\sigma_f^2 = \frac{1}{(a^2 + b^2)^2} (b^2 \sigma_a^2 + a^2 \sigma_b^2 + (a^2 - b^2) COV_{ab}) \quad (8)$$

The error in angle is inversely proportional to the fourth power of the speed (since speed is $\sqrt{a^2 + b^2}$).

In calculations with the real data, the true covariances were replaced by the covariances estimated using s^2 . This direction error calculation was also applied to the

model background, with the standard deviation of u and v taken from model statistics (pers. comm. R. Renshaw, 2009). For data assimilation purposes, the background error is defined for u and v and assumed Gaussian and independent ($COV_{uv} = 0$).

2.4. Calculation of insect orientation

The dual polarization data from Thurnham were used to determine which way the insects were oriented, hence whether they were aligned with the wind. The differential reflectivity, Z_{DR} , describes the difference in returns for horizontally and vertically polarized beams. Thurnham's Z_{DR} limit was ± 8 dB. Since insects are approximately oblong targets (and assumed horizontally oriented), the vertical polarization would give an isotropic scan, whereas the horizontal polarization would produce a stronger signal when the insects are side-on to the beam. When insects have a common orientation this results in a two-peak sinusoidal variation with azimuth. It should be noted that the Z_{DR} had an asymmetric distribution and large spread, which would be due in part to random insect orientation and varying insect dimensions, and partly due to the noisiness of the Z_{DR} radar estimate. The Z_{DR} mode was around 3.5 dB, the mean was 2.5 dB and the standard deviation was 2.8 dB.

The insect orientation was determined by analogous application of the VAD calculation to a permutation of the raw Z_{DR} data, after applying a Laplacian filter to Z_{DR} to improve the signal. Further details are provided in the Appendix 1. Note that there is a 180° ambiguity in orientation as the head and tail of insects can't be distinguished, but it is assumed insects are facing close to the direction of travel, and the calculated orientation was adjusted to fit this assumption.

The calculation of uncertainty in direction in Section 2.3 was not reproduced for the insect orientation calculation, since the accuracy of the orientation appeared to be generally better than the low precision indicated by the least squares fit, probably due to the larger spread in Z_{DR} values. The orientation was fairly consistent over time, which lent a greater confidence to the calculation. Instead, a different approach to assess the uncertainty was taken, whereby subsampled data (a random selection of approximately half) were used for 50 calculations, and the standard deviation of the results was used to estimate the orientation precision. As the insects were assumed to face within 90° of the wind heading, a standard deviation of greater than $\pm 90^\circ$ would be considered a complete uncertainty in direction. As the data are sub-sampled, from what may be a small data set initially, the derived standard deviations must represent an overestimate of the true uncertainty. There was generally a strong directional signal at middle heights, but larger errors at low and high levels, which may indicate insects were not showing a common orientation, or the signal was too noisy (sparse data). Typically, directional estimates above 1400 m that were possible with the full data set were not possible with

a sub-sampled data set, hence errors above 1400 m are undefined but to be assumed large.

3. Results

3.1. Meteorological conditions

The authors made a qualitative general observation that more insects were detected when the weather was warm, and possibly there was a greater likelihood of observing significant numbers of insect returns if the preceding day was fine. Strong insect returns were noted on several warm days with lots of convection, which would have assisted insects to ascend. Comparison of Central England Temperature mean and maximum (from the Met Office Hadley Centre at <http://hadobs.metoffice.com/hadcet/>) indicated that days with insects were not the warmest days by this estimation, implying that local temperatures and rainfall were probably important. In optimal conditions the insect signal was clear to 25 km, though visible at ranges up to 40 km, and insect heights ranged up to 2000 m but were sometimes visible a few hundred metres higher. Ranges and heights (Figure 2) are correlated as described in Section 2.1, with the spread due to variation in the vertical distribution of insects on different days. Comparison of the insect range limit with model temperature at 250 and 500 m at the radars' locations revealed a weak positive correlation with $R^2 = 0.13$. Correlation with the temperature at greater heights was weaker. Note that the model temperatures for fine days with no insects (range near zero) are absent from this analysis.

It is hypothesized insect numbers would increase when wind strength and direction were favourable for migration. Nocturnal moths have been shown to select seasonally-favourable wind directions and compensate for cross-wind drift (Chapman *et al.*, 2008). Whether diurnal micro-insects in the United Kingdom also select wind by direction has not been shown. Examination

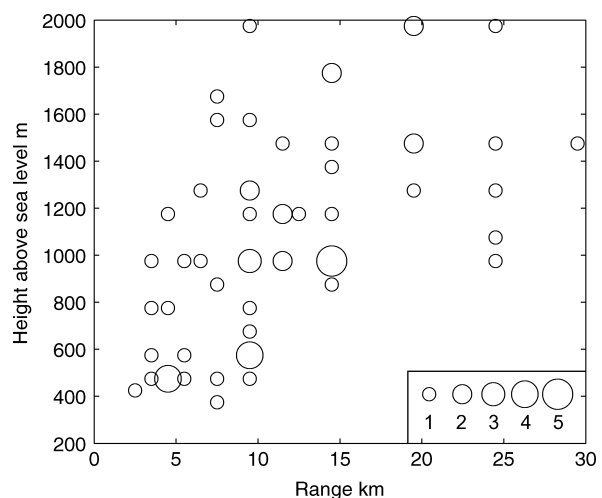


Figure 2. The ranges and heights to which strong insect echoes were observed, for each day and radar. The circle size indicates the number of instances with that range and height.

of the range/height to which insects were observed, and the wind speed (from the model at several heights between 500 and 1200 m) showed negligible correlation ($R^2 \approx 0.03$). There was a correlation ($R^2 \approx 0.3$) between insect range/height and insect velocity, suggesting that insects travel faster on days when conditions are more favourable. This correlation may result from several factors:

- for actual wind speed increasing with height, insects at greater altitudes allow a higher wind speed to be measured, and,
- larger insects can travel higher and fly faster, which could positively bias wind speed.

It must also be considered that for such a small sample size, the impact of other factors (e.g. due to poor model representativeness or other meteorological factors affecting insect numbers) could hide correlations. Overall, the best conclusion that can be made is that very low *positive* correlations exist between insect numbers, temperature and wind speed.

Finally it was investigated whether insects were more likely to be aloft on occasions with particular wind directions. Figure 3 indicates the wind direction *versus* time of year, with the range denoted by size of marker. The most insects seen early in summer (i.e. June) were associated with southeasterly winds. Moderate insect returns were also seen in early summer on warm days with northerly winds. Later in July, easterly through northwesterly winds were favoured, and temperature also affected insect numbers (not shown). Towards September, winds closer to northerly were preferred. With only 2 years' data, bias due to prevalent winds is possible, though most wind directions appear represented in each month. Obviously if any wind directions were associated with precipitation during the study period, these would have fewer insects also. The conclusion is that wind direction may have affected insect numbers, along with temperature and wind speed. A comprehensive analysis of weather data and airborne insect population over more years would be required to demonstrate any significant correlation.

3.2. Direction of insects using Z_{DR}

The direction that insects were facing was estimated using the dual-polarization radar at Thurnham. There were 7 days with data from Thurnham (Table II) for which the insect orientation was calculated. Of these, only three gave results with sufficient agreement that ambiguity could be resolved. The others had too high an uncertainty due to sparseness of insect returns to determine if a common orientation existed.

For the three cases, the radar wind direction (i.e. from insect velocity), model wind direction and insect orientation (that insects are facing away from, to match wind source convention) are shown in Figure 4, and described below.

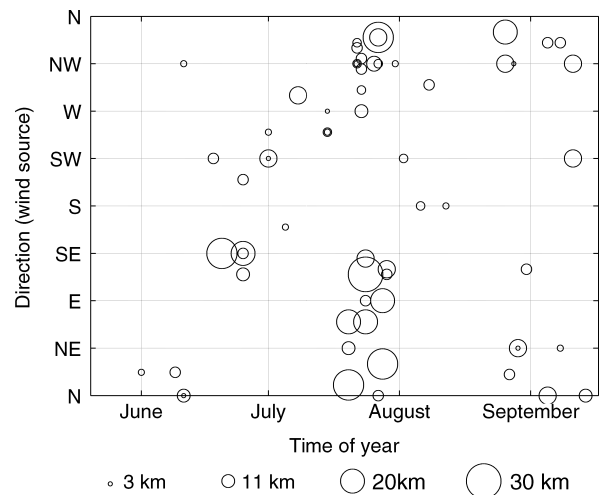


Figure 3. Insect range and insect direction (origin, analogous to wind source) by time of year. The range to which insects were seen is indicated by the circle size.

19 June 2007: (Figure 4(a)) Data spanned from 0700 h (UTC) to 1430 h with no data between 0800 and 1130 h. Radar and model winds were typically $10\text{--}13\text{ m s}^{-1}$ between 500 and 1500 m altitude, and southsoutheast to southeast. Radar wind, model wind and insect orientation were closely aligned for much of the time. After 1330 h the model wind turned more easterly. Generally the insects faced consistently more northerly than their direction of travel (about 10° on average), but this is within measurement uncertainty. Radar direction errors were very small, in the order of $5\text{--}10^\circ$. Model errors were similar, except for two profiles when the wind was slower, with error up to 15° at 200 m. The insect orientation estimate at 200 m was poor: orientation errors at 400–1000 m were $<5^\circ$ and at 1200–1400 m were $<10^\circ$, and above this the error was large, with sparse data.

19 July 2007: (Figure 4(b)) All data pertain to the period between 0830 and 1000 h when radar data were available. Model winds at the surface were northeast, tending south at 800–1000 m and then southeast at 1400 m. Model wind speeds were $1\text{--}3.5\text{ m s}^{-1}$. Radar winds were northeast at surface, tending east–east northeast at 800–1000 m then northnortheast at 1400 m. Radar wind speeds were $1\text{--}2.5\text{ m s}^{-1}$. Maximum wind speed was at 400–800 m. Insect orientation was east-northeast near the surface, eastsoutheast at 800–1000 m and northnortheast at 1400 m. The directions of travel (the converse of the direction given above) and speeds at three levels are shown in Table III, for ease of comparison. Only close to the ground (based on average velocity at 200 m) do insects appear to travel at a distinctly different angle to the radar wind. The radar direction error was $\sim 10^\circ$ up to 1000 m then increased to 30° . Model error was $<30^\circ$ between 400 and 600 m, up to 70° at 200 and 1500 m. These errors are small enough that the model and radar directions must be considered different. Insect orientation error (95% CI) at 200 m was $<10^\circ$; at 400–800 m was $<4^\circ$, and 1000–1200 m was $<10^\circ$ and

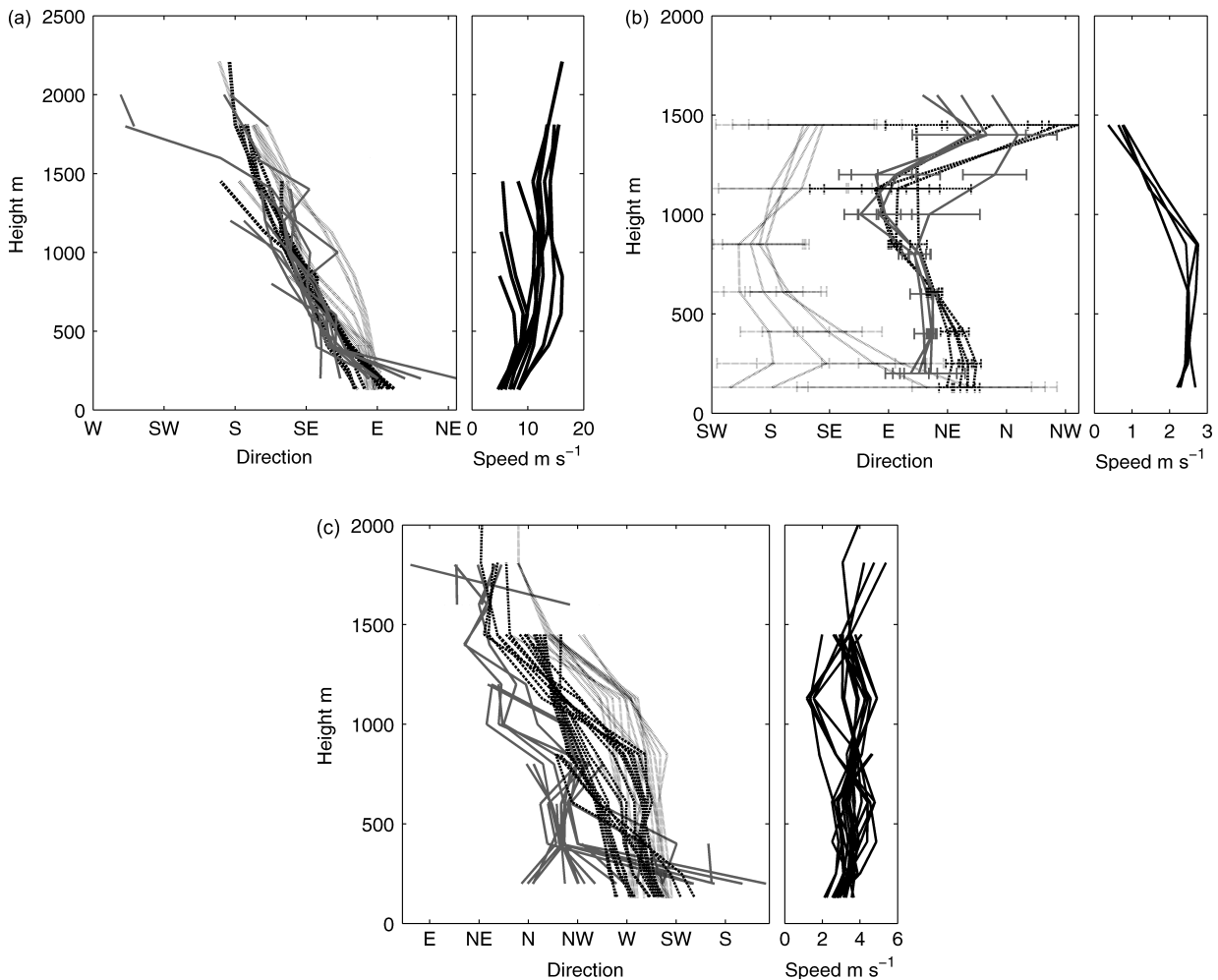


Figure 4. Direction of model wind, observed radar wind, and insect orientation from Z_{DR} for (a) 19 June 2007, ——— Insect Z_{DR} ——— Observed ——— Model (b) 19 July 2007 and (c) 25 August 2007. The panel on the right shows observed insect speed. The error bars are indicated for (b) July 19, so that the disagreement between observations and model are clear. On the other days, the error bars are not plotted as this would be difficult to visualize.

Table III. Direction of travel from model, observed velocity, and the orientation (heading) of insects.

Height (m)	Model	Radar	Insect
300	SW ($<45^\circ$) (1 m s^{-1})	SW ($\sim 10^\circ$) (2.5 m s^{-1})	WSW ($4\text{--}10^\circ$)
800–1000	N ($30\text{--}60^\circ$) (2.5 m s^{-1})	W–WSW ($\sim 10^\circ$) (2.5 m s^{-1})	W–WNW ($4\text{--}10^\circ$)
1400	NW ($40\text{--}70^\circ$) (1.5 m s^{-1})	SSW (30°) (1 m s^{-1})	SSW (large)

In brackets are directional uncertainty or distribution, and speeds.

above the error was large due to sparse data. The error bars are shown in Figure 4(b).

The insect velocities were more southerly (i.e. clockwise), which may have been due to insect flight. However, the discrepancy between radar velocity and model background could not result from only insect flight. To investigate its cause, comparison was made with radiosondes at 0900 h (33 km northnortheast of

Thurnham) and 1200 h (50 km southsoutheast of Thurnham), a wind profiler between 0830 and 1000 h (94 km northnortheast of Thurnham) and aircraft-measured winds within 50 km. All showed wind directions more easterly than the model background, though at the wind profiler's location the model wind was more easterly and so there was better agreement. Inspection of the model background and analysis at 0900 and 1200 h indicated that the wind in southeast England was southerly (in disagreement with observations) until the 1200 h analysis (once the observations had been assimilated) when winds in southeast England became easterly, in agreement with observation. It is, therefore, concluded that in this region of England, during this period and in the height range examined (up to 1500 m), the model background had diverged from truth, and the assimilation of wind observations corrected this in the 1200 h assimilation cycle. The wind observations from the Thurnham radar would have been of assistance in this case. The low wind speeds imply a higher uncertainty in direction, as at the large scale small changes in the model pressure field may strongly alter the wind direction.

25 August 2007: (Figure 4(c)) The model wind was west–southwest to 1000 m, turning north above this. The observed wind was westsouthwest tending through west and north to northnortheast above 1400 m. Model and radar wind direction varied by $\sim 45^\circ$ during the day, and in a similar fashion (southwest to west to southwest). Model wind direction agreed well with the nearest wind profiler (94 km northnortheast), although the wind profiler measured a speed greater than both the model and insects. The insects' orientation varied from southeast through south to southwest between 400 and 1600 m. The insect orientation was generally 45° further clockwise compared to the radar wind. In this case the radar wind direction was between that of the model and that of insect orientation. Therefore, given wind speeds were $3\text{--}4\text{ m s}^{-1}$, if insects were travelling at 2 m s^{-1} , it is possible that the insect travel affected the radar wind velocity. However, the observed wind speed was slower than the model, which may have been due to clutter affecting the speed, or the model may have overestimated speed. It cannot be definitely concluded that insects altered the radar wind direction by up to 45° , but in this case it appears possible, though only if strong-flying insects were present. Radar direction error was typically $<20^\circ$. Model direction error was typically $<30^\circ$, so radar and model directions could agree at some heights, though the difference in direction was almost consistently positive (model–observation). Insect orientation error was greater on this day, as the signal was weaker; the standard deviation was $<45^\circ$ with the majority having a standard deviation $<20^\circ$.

So out of three cases:

- in the first the wind was too strong for insect flight to noticeably affect the wind speed;
- in the second insect direction alone could not have accounted for the disparity with the model (probably due to poor model representation of truth for a short period), and,
- the third had the potential for insects to account for the direction change.

Interestingly, the insect direction was more northward in June, and more southward in August, which correlates with the hypothesized seasonal preferred direction of migration, but these two incidences cannot prove the trend.

3.3. Analysis of bias and error in the observed wind

The error of the VADs calculated as *per* Section 2.3 gives an indication of the uncertainty of the VAD by the fit of the least squares. The uncertainty in speed and direction were derived from the standard deviations of a and b . Generally, the uncertainty was low. The values for which 90% of all VADs had lower uncertainty are indicated in Table IV. The difference in error between Chenies, Thurnham and the other radars could be the result of several factors, including

different instrument sensitivity and insect population. Thurnham has horizontal polarization, which yields a stronger signal from oblate targets, dual polarization to assist with processing, and higher resolution: all of which can reduce the resultant error. However, the factor likely causing the most difference among the single-polarization radars is the amount of clutter around the radars. The large amounts of clutter around Clee Hill, Cobbacombe and Dean Hill reduce the amount of available data and increase the likelihood of clutter contaminating the processed data. Greater spatial variability in the wind field above radars situated in hilly areas may contribute to the spread in radial velocity, although this cannot be tested.

The bias of the insect wind was examined by comparison with wind profiles derived from the Met Office UK 4 km resolution model. This analysis was to determine if any biases exist, and to examine sources of error and bias. Furthermore, this information can be used to indicate areas where processing should be more stringent, or to indicate the size of error to be associated with the wind measurement. The potential types of bias include that from insects with non-zero air velocity (resulting in higher speed, or different direction) and errors due to the presence of clutter or other spurious returns. Discrepancies due to poor model representativeness cannot be accounted for in this way, although this will have some impact. For example, in one case (19 July 2007, see Section 3.2) the model wind below 1000 m was from more than 90° different to the observed wind direction for two forecast periods (6 h).

The model and observed wind speeds are compared in Figure 5, which shows for each radar the observed wind speed *versus* the model speed. A 2D histogram is used so that every point is represented; the maximum coincident values number between 3 and 14. For low model speeds (less than 2 m s^{-1}), the observed wind was often faster, which could result if the model underestimated the wind or insect flight contributed to the speed (which is possible for cases when the speed difference was within range of insect flight, e.g. less than 2 m s^{-1}). Note also that very low speed VADs were likely excluded as the RMS residual error could easily exceed the speed. For high model wind speeds (greater than 5 m s^{-1}), the observed wind speed was typically lower in comparison. In those cases it is possible that the model overestimated the speed

Table IV. Ninety percent of VADs (velocity azimuth display wind profile) had uncertainties lower than the limits shown.

Radar	Ninety percent of speed uncertainty (m s^{-1})	Ninety percent of direction uncertainty ($^\circ$)
Chenies	0.7	10
Clee Hill	2.0	37
Cobbacombe	1.3	38
Dean Hill	1.4	46
Thurnham	0.7	13

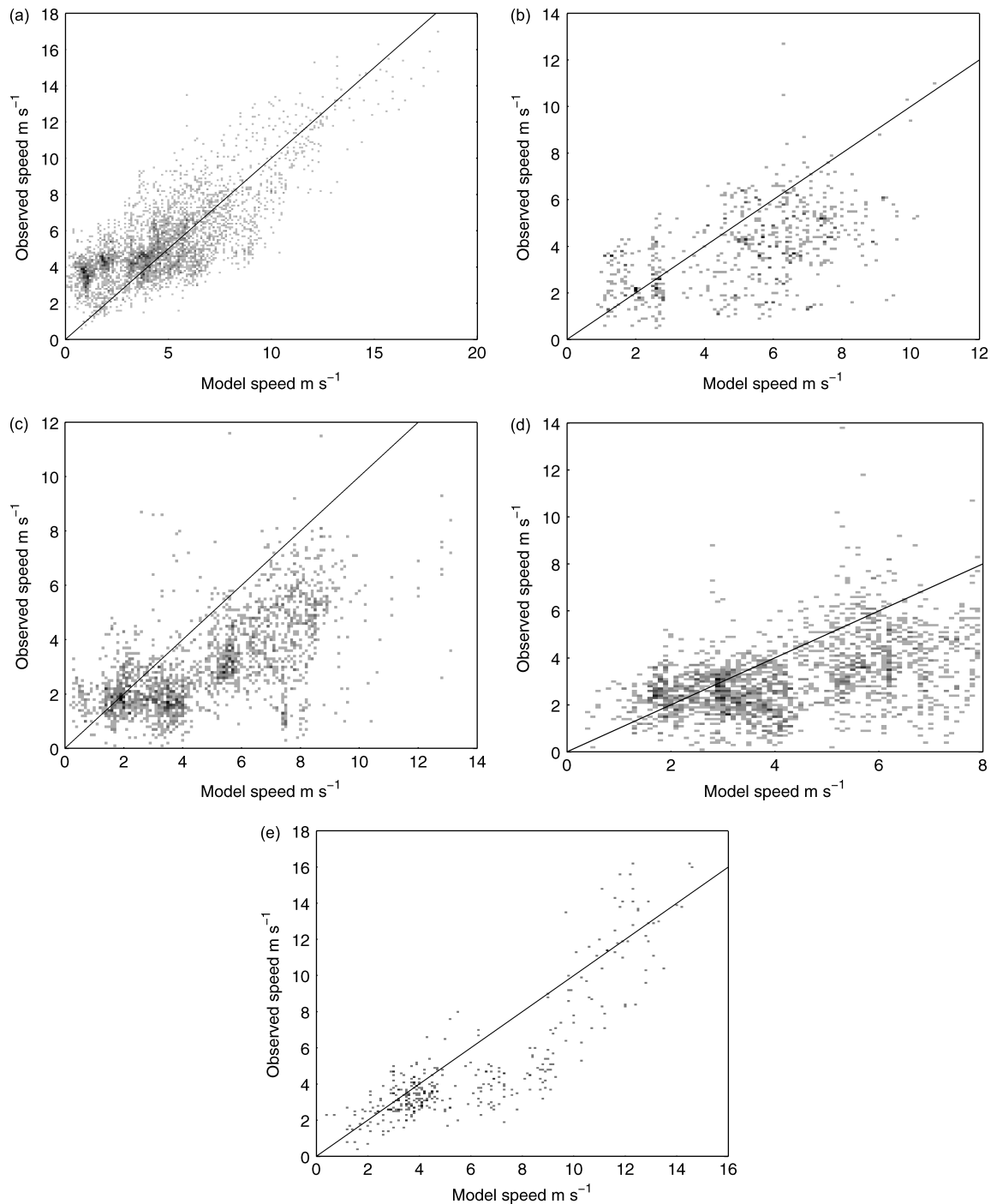


Figure 5. 2D histograms of observed speed *versus* model speed for (a) Chenies, (b) Cleve Hill, (c) Cobbacombe, (d) Dean Hill and (e) Thurnham. Darker shades indicate multiple incident values, so that every time and height level is represented. The line where model speed equals observed speed is indicated.

or that the data contained excessive clutter or noise. Notably, Chenies, which has the least ground clutter, had a more positive speed bias than the other radars in this analysis, implying clutter contamination is a contributor. The prevalent bias does not prove insect flight increasing the observed wind speed is a principal source of error, unless the wind speed is low.

Analysis of the difference in direction (observation minus model) *versus* model wind speed (Figure 6) indicated that directional agreement depended upon wind

speed. For high model speeds (greater than 10 m s^{-1}), the observed direction shows good agreement (within 40°) with the model. However, the majority of model wind speeds were less than 10 m s^{-1} , and for this range the difference in direction occupies an increasing range with decreasing model speed. For model speeds less than 2 m s^{-1} the directional difference ranged from 0 to 180° . There are three most likely reasons for this. Firstly, the mesoscale features likely to force strong winds are unlikely to be grossly wrong in direction, whereas it is

possible that smaller scale features with low wind speeds will not be modelled as accurately. Secondly, the impact that insect flight could have on observed wind speed must decrease as wind speed increases. Thirdly, for low wind speeds, clutter discrimination is more difficult and the effect of clutter contamination will more strongly impact VAD estimates of low speeds. The examples in Section 3.2 indicate that the model sometimes deviates strongly from the 'truth' and also that insect-biased direction can be different to the true wind direction. This result supports the exclusion during processing of low-speed, insect-based VADs (e.g. less than 2 m s^{-1}) as they are likely to be less accurate.

The average radar speed and direction bias (observation minus background) for all days, and for each radar, is shown in Figure 7. This indicates the sort of uncertainty that might be applied to these wind measurements. The number of observations contributing to these data decreases with height, with maximum values in the order of several hundred. A horizontal dotted line indicates the height above which there were less than 20 observations available during the study period. The mean bias did not differ for VADs with higher and lower uncertainties (derived from residual root mean squares as described in Section 2.3, not shown). However, the few VADs with high uncertainties (e.g. speed uncertainty $>3 \text{ m s}^{-1}$) tended to differ more from the model wind.

The speed bias for four radars increased with height by $2\text{--}3 \text{ m s}^{-1}$ (except Clee Hill which decreased with height). All radars had a speed bias of -1 to -2 m s^{-1} close to the ground (except Chenies which had a bias of 0 m s^{-1} near ground level). The bias above 1000 m was mostly positive, indicating that the observed wind was faster. This pattern implies that clutter contamination may have caused negative bias (stronger closer to ground level), and also that at altitude insect flight may have contributed a positive bias. Chenies, with least ground clutter, had the most positive speed bias. Another possible cause

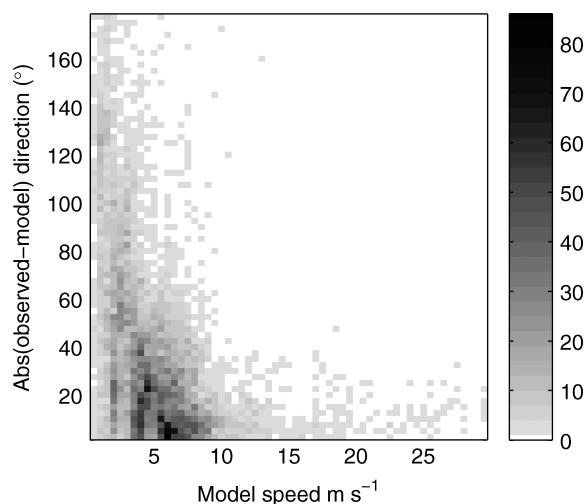


Figure 6. 2D histogram of direction bias (observed minus model background) *versus* model wind speed. The greyscale represents the count of values with the specified speed and direction bias. Zero values are white.

of bias near the ground would be if the model poorly represented the boundary layer wind, for example if small-scale spatial variations such as shear were displaced. Bias due to insects may have resulted from strong-flying insects being present at these greater heights. The standard deviation of speed bias is $1.5\text{--}2.5 \text{ m s}^{-1}$ for all radars, with no obvious trend with height.

The direction bias in Figure 7 is typically between -20° and 20° for all radars, and tended to be further from zero at higher altitudes (or with less observations). The standard deviation of the direction bias was between 40° and 60° for most radars (lower for Thurnham).

A comparison of the VAD biases with radiosonde and wind profiler biases (model-observation) was made to determine if another instrument with similar sample size would have different errors. The radiosonde and wind profiler observations were taken over the same days in order to have comparable representativeness. Results indicated that these had a lower speed bias than radars. The absolute biases are summarized in Table V. For the wind profilers, with a large sample (tens of profiles), typical absolute values were a mean speed bias of less than 1 m s^{-1} with standard deviation (s.d.) less than 2 m s^{-1} , and directional bias of less than 10° with s.d. less than 35° . For radiosondes, with small sample sizes (less than 10 profiles), the mean and standard deviation for speed bias were only slightly larger, while the directional bias was up to 20° with standard deviation of $20\text{--}50^\circ$. In summary, other wind-profiling instruments had a lower bias than insect-derived VADs, and small sample sizes gave larger biases and standard deviations. Typical biases for precipitation VADs, based on all VADs over three-monthly periods in 2007 and 2008 (statistics of comparison with the Met Office Global NWP model, pers. comm. Colin Parrett, 2009), were substantially lower for a large number of VADs (say 1500–2000), as indicated in Table IV. It was also noted that there was a small low-level negative speed bias, largest at Cobacombe, which was similar in direction (though smaller in magnitude) to the negative low-level bias noted for insect VADs. The vector RMS errors for insect and precipitation VADs are of a similar magnitude, which suggests that insect VADs can be as reliable as precipitation VADs. It may be concluded that insect winds can have a similar representativeness to precipitation winds, but that insect winds will have a larger error term.

4. Summary

Data were collected from five Doppler radars in the United Kingdom during the summers of 2007 and 2008, for daytime periods when insect returns were sufficiently strong. The spatial availability of a clear velocity signal was examined. On 'good' days insect returns were apparent at up to $10\text{--}30 \text{ km}$ from the radar, and often $1000\text{--}2000 \text{ m}$ above sea level. The airborne insect population size showed a very small positive correlation with air temperature and speed, which may be negligible.

There may be a seasonal direction preference for insects to be aloft in winds that carry them northward at the start of summer and southward at the end of summer; this has been neither proven nor disproven due to insufficient data.

The question of whether insects affect the radar-derived wind velocity through their own flight to a degree which impedes use of the observations has not been fully

resolved. Examination of insect orientation reveals that insects will orient themselves in a common direction at a presumed acute angle to the direction of travel. However, the difference between observed wind velocity and model wind velocity was not accounted for by this alone. From only three examples, few conclusions can be made. However, it is apparent that other factors must also be important in affecting the observation error.

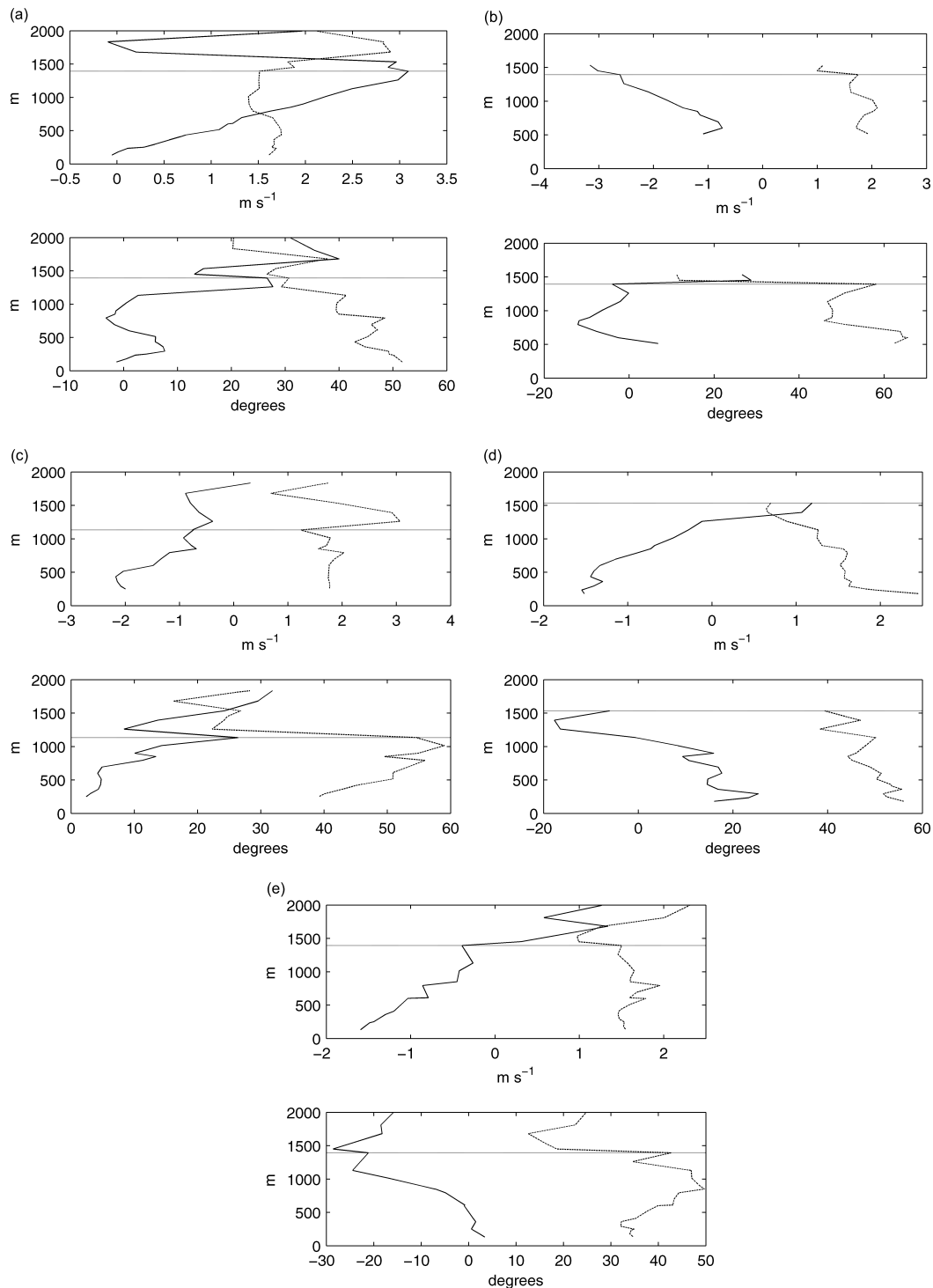


Figure 7. Speed and direction bias (observation minus model) for (a) Chenies, (b) Clee Hill, (c) Cobbacombe, (d) Dean Hill and (e) Thurnham, using all days. Below the horizontal dotted line the number of samples is greater than 20. Top images ((a)–(e)): Speed Mean (–) & St. Dev. (– –). Bottom images ((a)–(e)): Angle Mean (–) & St. Dev. (– –).

Table V. Limits of absolute bias in speed and direction, and vector RMS bias, for wind profiles using insect VADs (taken from Figure 7), windprofilers ($n \sim 550$), radiosondes ($n \sim 25$), and precipitation ($n = 1000$).

Max(abs(bias))	Insect	(s.d.)	Windprofiler	(s.d.)	Radiosonde	(s.d.)	Precipitation
Speed (m s^{-1})	<3	(<3)	<1	(<2)	<2	(<2)	<1
Direction (degrees)	<40	(60)	<5	(<35)	20	(20–50)	<5
Vector RMS error (m s^{-1})	1.5–4.5	–	–	–	–	–	~ 3

The mean bias of the observations compared to the model, from the vector RMS error and the observation-minus-model mean, was typically several metres per second, and about 20° . Due to the small sample size over a long period, this may not be a very useful estimate of the bias, as sources of error contributing to this cannot all be identified. However, some of this bias appears to be due to clutter contamination or processing issues. Identification or quantification of bias due to insect flight was hampered by a shortage of data; however further collection of dual-polarization data to analyse insect orientation would be beneficial. Compared to the bias calculated for other wind observations, the insect-derived VADs had a higher uncertainty. However, the uncertainty is small enough that the observations should be of some use. Observations that disagree strongly with the model background are normally discarded for data assimilation purposes.

Improving clutter removal with more stringent processing would reduce the number of available VADs, but the remaining observations should have a smaller speed bias. The directional bias may be also reduced through improved processing. Exclusion of low velocity VADs should also limit the inclusion of erroneous observations from excessive clutter or insects' non-zero airspeed. New methods of removing clutter will be investigated in the future. It is expected that changes in 2009 by the Met Office to how the raw data are processed and stored may allow improvements in insect identification to be developed, for example by inclusion of Clutter Index and Signal Quality Index parameters.

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Appendix 1.

The calculation of insect orientation was achieved by manipulating the Z_{DR} data so that the VAD calculation could be applied. This was mainly for the convenience of using existing code to fit a sinusoid to the data. The method is indicated in Figure A.1. First the data were split into 180° segments (Figure A.1(a)) and interleaved to give an averaged single-peak sinusoid. The mode was subtracted from all data (Figure A.1(b)) so that the sinusoid is centred on $Z_{DR} = 0$. The VAD calculation was then applied to find the direction as *per* Equation (5) (Figure A.1(c)), and this value was divided by two to reproduce the 'direction' of the double-peaked sinusoid (Figure A.1(d)) of the original data. As the VAD calculation finds the angle of maximum velocity, this angle had 90° added to indicate insect 'head on' (minima) not 'side on' (maxima) direction (Figure A.1(d)). Then $n \times 180^\circ$ was manually added to correct the orientation to within 90° of the observed wind direction.

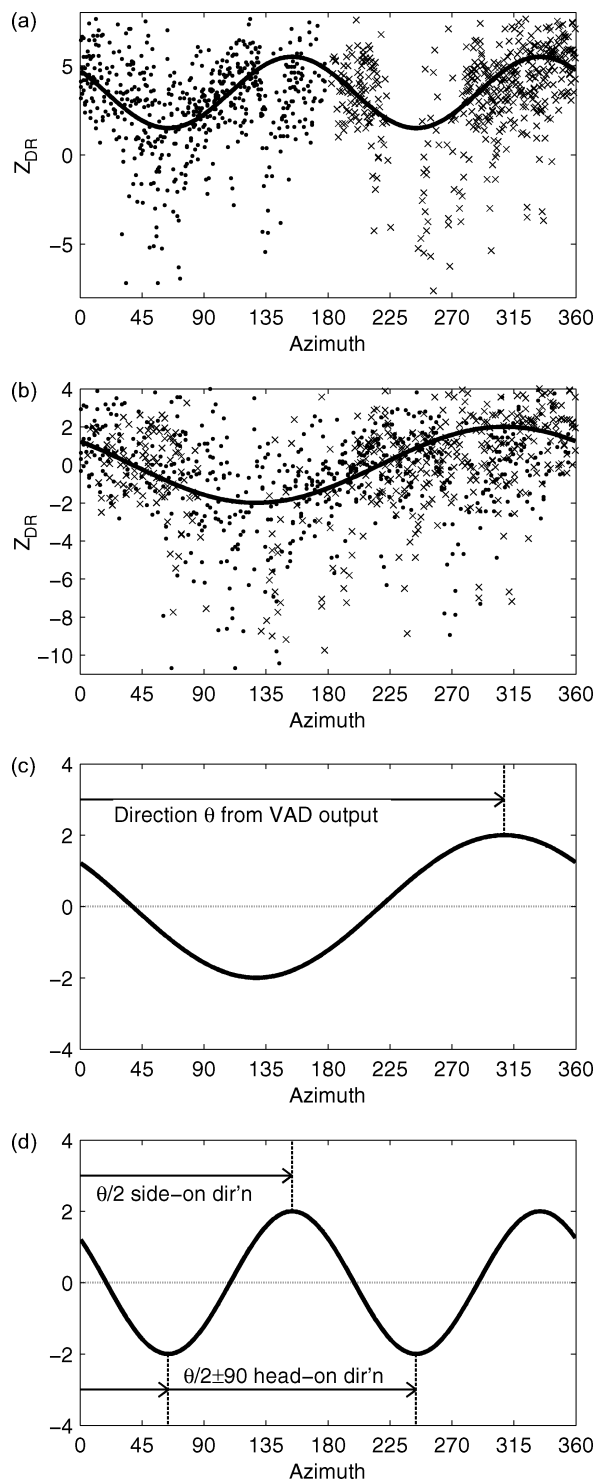


Figure A.1. Method to find insect direction. (a) Raw Z_{DR} data from three consecutive ranges shows a $\sin(2\theta)$ curve. (b) The data from azimuth $< 180^\circ$ (●) and azimuth $> 180^\circ$ (×) are interleaved and the mode is subtracted. (c) The direction is calculated. Y units are arbitrary. (d) The direction is halved to give a side-on direction, and shifted by 90° to give insect orientation with 180° ambiguity.