Recent Airborne Radar Observations of Migrant Pests in the United States [and Discussion]

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Recent airborne radar observations of migrant pests in the United States

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An airborne radar was used to detect insets dispersing from an area of about 200000 hectares of maize infested with *Heliothis zea* (Boddie) and *Spodoptera frugiperda* (J. E. Smith), in the lower Rio Grande River Valley (LRGRV) of northeast Mexico. During the night of 20 June 1989, a ground-based radar, located at the downwind edge of the maize production area, detected early evening take-off and departure of flying insects. Simultaneously, an airborne radar detected low numbers of airborne insects 50 km downwind. Large numbers of flying insects were detected 200–700 m above ground as the aircraft approached the source. The edge of the emigrating cloud of insects was clearly marked by a rapid change in numbers of airborne insects; the cloud was subsequently intercepted at various locations downwind of the source area. The downwind edge of the insect cloud appeared to travel northward at least 400 km in 7.7 h. Maximum *H. zea* moth emergence occurred on 18 June from maize in the LRGRV. Three days later, maximum oviposition occurred in cotton near Uvalde, 370 km from the LRGRV and downwind on the night of the mass migration observed.

1. Introduction

Zea mays (L.) is an important cereal crop in many countries and often serves as a host to lepidopteran insect pests that ultimately disperse to other high value crops (Sparks *et al.* 1986). Maize may produce large populations of insects imagoes, if the economic value of the maize crop does not warrant chemical control of larval stages. Raulston *et al.* (1986*a*) described a maize-growing area in the Lower Rio Grande River Valley (LRGRV) of northern Mexico that acts as an insectary capable of producing billions of corn earworm, *Heliothis zea* (Boddie) moths. Circumstantial evidence indicates that *H. zea* moths can migrate long distances (Hartstack *et al.* 1982). An understanding of insect movement from source areas is needed to improve pest management in high value crops that are vulnerable to pest migration.

A ground-based radar (GBR), previously operated at the northwestern edge of the LRGRV maize-growing area, documented the emigration of a large number of moths from the Mexican side of the LRGRV (Wolf *et al.* 1986). The quantity of moths leaving the maize measured by the GBR agreed with the estimated number of imagoes produced on the maize. Earlier estimation of the dispersal of these emigrating moths relied on estimated dispersion parameters and extrapolated meterological data (Wolf *et al.* 1986). However, incorrect dispersion parameters may result in large errors in estimated dispersion. Also, interpolations of National Weather Service (NWS) data often differ from local nocturnal field measurements. Therefore, on-site measurements of flight duration, dispersion rates and meteorological parameters are needed to improve and validate insect dispersion models.

Schaefer (1979) reported an airborne radar (ABR) technique for investigating the vertical distribution of insects along a flight path. He obtained height-density and height-orientation profiles for various locations while studying moths of spruce budworm *Choristoneura fumiferana* (Clem.) in New Brunswick, Canada. We used an improved airborne radar system to detect insects flying downwind of the LRGRV source area during June of 1989.

2. Methods

(*a*) *Site description*

The LRGRV in northern Tamaulipas, Mexico and southern Texas, U.S.A. lies in a region described by Correll & Johnston (1970) as the Tamaulipan brush lands. The climate is semi-arid subtropical. About 200000 ha† of maize (85% of the maize in the LRGRV) is grown annually on irrigated land south of the Rio Grande River (centred at 25° 30′ N 98° 00′ W. Cotton, sorghum and sugar cane are the major irrigated crops north of the river. Insignificant numbers of host plants for *H. zea* occur on non-irrigated land during June. Land use outside the valley is mostly dryland sorghum production or cattle ranching (Raulston & Houghtaling 1986). Earlier ecological investigations of insect and crop phenology show that the LRGRV is a major source area of dispersing insects (Raulston *et al.* 1986*b*).

A site near Uvalde, Texas (370 km northwest of the LRGRV), was selected for sampling emergence of local moths and monitoring potential fallout of immigrating moths. The area around Uvalde, Texas, is also Tamaulipan brush land, with the major crops being irrigated cotton and maize (about 16200 ha of maize).

(*b*) *Entomology*

Soil samples were dug from 100 maize fields in the LRGRV and 40 maize fields near Uvalde. The sampling period spanned the corn earworm pupation cycle in fruiting corn during June 1989. Two soil samples (1 m^2 × 10 cm deep per sample) per field were screened for pre-pupae and pupae. Species composition, sex, and mortality factors were determined. Each live field-collected pupa was re-buried inside a small emergence cage with a plastic tube leading to a screened collection cage on the soil surface. Re-burial sites had soil and vegetation similar to the respective collection site. Cages were examined daily for emergence to determine emergence profiles for the two areas.

(*c*) *Airborne radar*

Hobbs & Wolf (1989) describe the ABR principles and signal processor used in these studies. Our ABR transceiver had a 25 kW peak power, a 3.2 cm wavelength, a 100 ns pulse length and a 2560 Hz pulse repetition rate. The transceiver could be electronically switched between a dummy load or circular parabolic reflector antenna. The dummy load position of the waveguide switch prevented any target echoes from reaching the receiver so that radar-noise levels could be recorded. A 0.61 m diameter antenna was mounted inside the aircraft's camera port so a radome was not used. The resulting conical beam pointed downward below the aircraft and had a 2.5° half-power width. A rotating feed caused the beam polarization to rotate at 10 Hz around the beam centreline.

The ABR system was installed in a twin-engine Aero Commander‡ airplane. This airplane

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† 1 hectare = 10^4 m^2.

‡ Mention of company names or products does not imply endorsement by the U.S. Department of Agriculture.

has a true airspeed of 268 km h^{-1} at normal power settings. The crew consisted of a pilot, copilot and radar operator. Position coordinates were obtained from a Morrow Inc. Model 604 Loran receiver. A Model 100 Radio Shack computer automatically recorded position coordinates and plotted a map of aircraft track on the computer screen each minute. Position information was additionally obtained from the aircraft's direction and distance measuring receivers. Indicated airspeed, altitude, and heading were manually noted in the radar log.

A signal processor obtained target samples from 48 ranges (distances) spaced at 15 m intervals starting 146 m below the aircraft. These samples were multiplexed onto three channels of a frequency-modulated analogue tape recorder. Sample altitude was the difference between airplane altitude and radar range. The fourth channel of the tape recorder contained synchronizing signals for decoding the data.

During analysis of data, voltages from two channels of the tape recorder were passed through an analogue adder, a low-pass filter and recorded on a strip chart recorder. These voltages represented the sum of insects (area density) flying above 250 m; so, the vertical axis of each strip chart recording was scaled and labelled insects per hectare. The scale factor was empirically determined during high insect density and when the airborne radar was within two miles of the GBR.

Tape recorder voltages were digitally sampled at times corresponding to strip chart maxima, minima, and inflection points. Each digital sample consisted of nine seconds of data from each of 48 radar ranges. The mean voltage and standard deviation for each range were calculated. The difference between mean voltage and mean radar-noise was equal to mean target amplitude for each of the 48 ranges. A graph of mean target amplitude (representing insect numbers) versus altitude showed the vertical distribution of insects (insect profile).

(*d*) *Ground-based radar*

The GBR was located within 100 m of the Rio Grande River, and within 20 km of the northwest corner of the source area. Data from the GBR were used to calculate profiles of insect density versus altitude. Profiles were measured at 15 min. intervals during the first two hours of insect flight and thereafter at 30 min. intervals until the overhead density of flying insects decreased by two orders of magnitude from the peak. Operating and analysis procedures were similar to those described earlier by Wolf *et al.* (1986). Insect density profiles were integrated to obtain area density values.

(*e*) *Meteorology*

Meteorological observations at the GBR site included visual cloud cover assessment, upper-air soundings, and automated temperature, humidity, wind vector, and pressure measurements at the surface. An instrument package (radiosonde) attached to an ascending helium-filled balloon transmitted wet and dry bulb temperature and barometric pressure to a ground-based radio receiver. The balloon azimuth and elevation angles were measured with an optical balloon-tracking theodolite. An Apple II computer automatically logged theodolite and radiosonde values at five-second intervals. Uninstrumented helium-filled balloons were tracked hourly to provide additional upper wind information.

(*f*) *ABR missions*

Four ABR missions were flown during the night of 20 June 1989. Intervals between missions allowed for insect displacement, refuelling, and planning for subsequent missions. The objectives of these missions were: (*a*) to measure insect density near the GBR while the most dense portion of the insect cloud was passing the GBR; (*b*) to determine positions of the downwind and crosswind edges of the insect cloud; (*c*) to measure density and vertical distribution of insects ahead of, and within, the dispersing insect cloud; (*d*) to determine duration of insect fight. A fifth mission (while returning to Weslaco, Texas after sunrise) provided data during low insect density.

3. Results

Peak emergence of adult *H. zea* from maize in the LRGRV occurred 15 days before peak emergence at Uvalde (figure 1). At Uvalde, maximum oviposition by *H. zea* on cotton preceded maximum emergence by 12 days. An estimate of the total number of reproductive females produced on maize and the potential number of hectares that they could infest (table 1) was based on: (*a*) 10% survival of pupae to reproductive status; (*b*) 1000 viable eggs per female; (*c*) an economic infestation level of 25000 eggs ha^{-1}; (*d*) a uniform distribution of

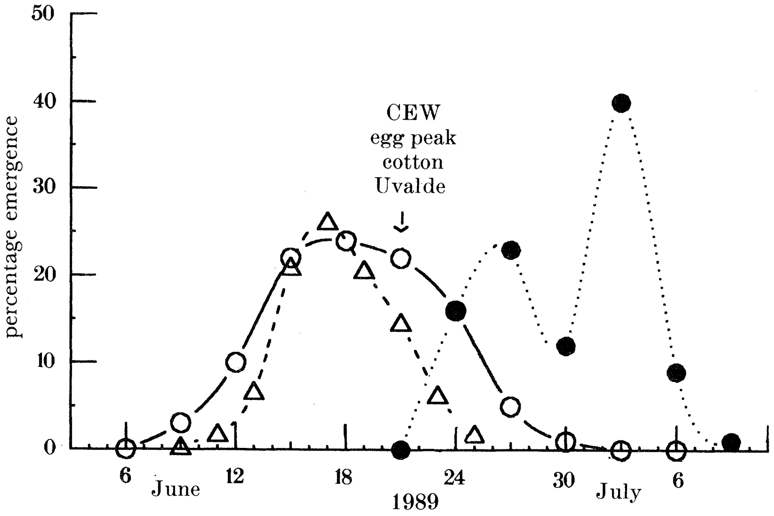

FIGURE 1. Emergence of fall armyworm (FAW) and corn earworm (CEW) from maize fields in the Lower Rio Grande River Valley and near Uvalde. (Open triangles, LRGRV FAW; open circles, LRGRV CEW; closed circles, Uvalde CEW.)

TABLE 1. TOTAL *HELIOTHIS ZEA* PUPAE PRODUCED IN THE LOWER RIO GRANDE RIVER VALLEY AND UVALDE AREAS, AND ESTIMATED AREA OF POTENTIAL INFESTATION BY REPRODUCTIVE FEMALES DURING JUNE, 1989

location	maize area	number of soil samples	number of pupae produced[a]	number of adult females[b]	area of potential infestation[c]
	(ha)		($\times 10^9$)	($\times 10^8$)	(ha)
LRGRV	200000	200	6.70	3.35	13400000
Uvalde	16200	80	0.72	0.36	1440000

[a] Based on pupae recovered per square meter per soil sample.
[b] Assumed 10% survival between pupa and reproductive stage.
[c] Assumed each reproductive female lays 1000 eggs, and an economic infestation level of 25000 eggs per ha.

females. An estimated 7.9×10^9 fall armyworm, *Spodoptera frugiperda* (J. E. Smith), emerged from maize fields in the LRGRV with peak emergence on 17 June 1989.

Meteorological soundings during the night of 20–21 June 1989 showed a low-level jet wind from 142° at 21h30 Central Daylight Savings Time and 161° at (GMT-5) 00h40 (figure 2). Upper-air temperature profiles showed the bottom of the atmospheric inversion layer to be near the top of the jet wind.

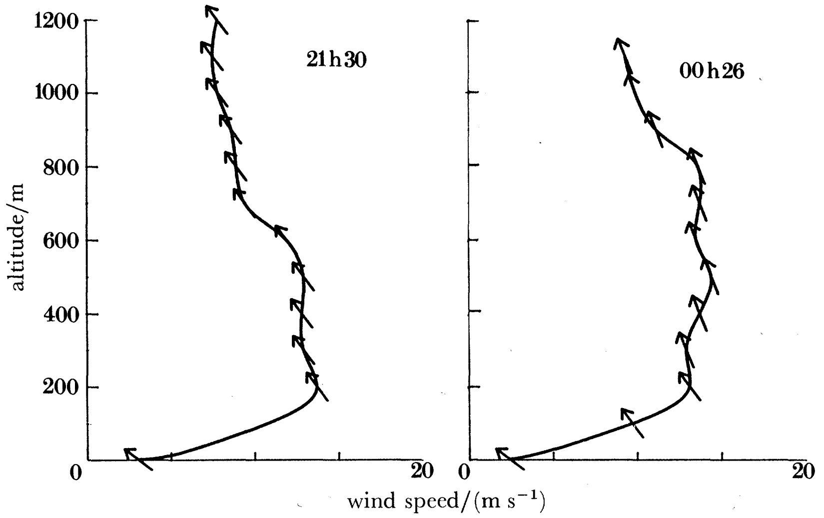

FIGURE 2. Wind speed profiles measured at the ground based radar during night of 20–21 June 1989.

NWS upper wind data (19h00 and 07h00) were spatially and temporally interpolated to estimate wind vectors. These interpolated wind vectors were then used to calculate the path or track of passive particles at 600 m altitude. Three tracks during the night of 20–21 June 1989 had north-northwestward displacements (350°).

The GBR detected numerous insects passing overhead from 21h00 to 23h00 during the night of 20 June 1989 (figure 3). Insect density peaked at 21h33. Species composition of insects detected by the GBR and ABR was unknown; however, peak radar voltages from individual targets were similar to voltages from corn earworm or fall armyworm moths. From the GBR data, the edge of the insect cloud passing overhead was defined as the occurrence of 50% of the night's maximum density (i.e. at 21h16 and 22h04 for the leading and trailing edges, respectively, figure 3). Insect cloud edge no. 0 (table 2) was located at the GBR at the time 21h16. From the ABR data, cloud edge was defined as the location where insect density changed by 50%.

The first ABR mission started at 21h30 when insect density above the GBR was near maximum. The aircraft flew downwind beyond the insect cloud (21h39) and then turned upwind toward the McAllen, Texas airport (figure 4). ABR missions could not be flown into Mexico so the aircraft turned eastward at McAllen and passed the GBR at 21h53. At this time, the ABR display indicated numerous insects as high as 750 m above ground. After passing the GBR, the aircraft descended briefly to 600 m altitude for visual monitoring of insect flight activity. One insect per second could be seen in the aircraft's landing lights. The time at this altitude was about one minute. Five minutes later the aircraft landed at the McAllen airport; the remains of twelve insects were on the windscreen and wings and thorax of two *H. zea* moths were recovered from the engine cooling fins.

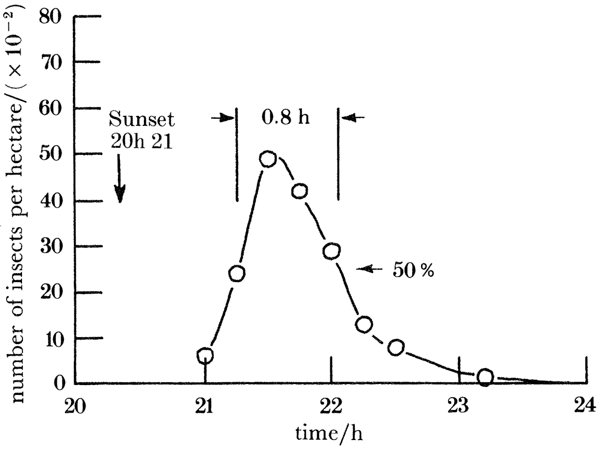

FIGURE 3. Density of insects passing the ground-based radar located near the northern edge of maize production area in the LRGRV during the night of 20 June 1989. (Cloud width $(0.8 \text{ h} \times 54 \text{ km h}^{-1}) = 43$ km.)

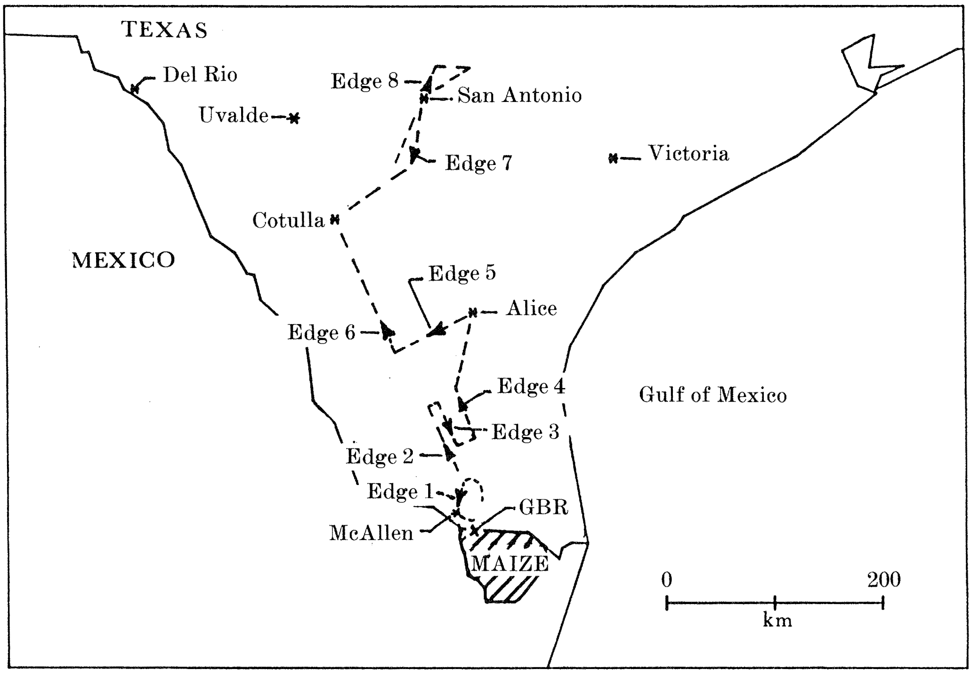

FIGURE 4. Track (dashed lines) of aircraft during four airborne radar missions during the night of 20–21 June 1989. A solid arrow indicates direction of aircraft displacement and location of insect cloud edge (50% change in insect density along aircraft track). GBR is location of ground-based radar.

The strip chart recording of insect density[†] showed that the edge of the insect cloud was encountered at 21h46 while flying upwind toward McAllen at location number 1,26 km from the GBR (figures 4 and 5*b*). The leading edge of the insect cloud was thus moving at 13.9 m s^{-1} (table 2). During three successive missions the insect cloud was detected seven times (figures 4, 6, 7, 8 and 9). Edge locations 2, 3, 6, 7 and 8 were interpreted as sequential locations of some

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[†] The conversion of radar mean volts to insect density was an approximation so strip chart recordings showed relative insect density fluctuations.

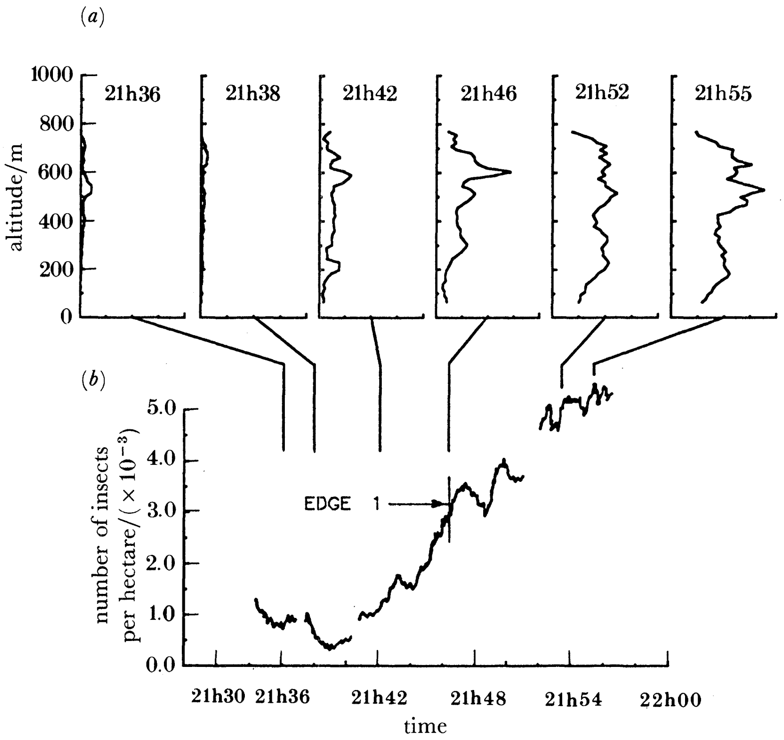

FIGURE 5. (*a*) Insect profiles. (*b*) Numbers of insects per hectare near the source area during mission 1 (between Weslaco and McAllen) 20 June 1989. A 50% change in density was designated as a cloud edge.

TABLE 2. GROUND SPEED OF LEADING EDGE[a] OF INSECT CLOUD DETECTED BY GROUND AND AIRBORNE RADARS DURING NIGHT OF 20–21 JUNE 1989

cloud edge location number	time of night	distance from source	cloud edge displacement distance	duration	speed
	(h)	(km)	(km)	(h)	($m s^{-1}$)
0[b]	21h16	0	—	—	—
1	21h47	26	26	0.52	13.9
2	23h08	85	59	1.36	12.1
6	01h21	204	119	2.21	14.9
7	04h04	343	139	2.72	14.2
8	04h56	421	78	0.87	24.9

[a] Cloud edge defined as location where insect density changed by 50%.
[b] Location no. 0 was at edge of maize production area in LRGRV.

portion of the northern edge of the cloud. These interpretations were based on a clockwise wind shift of 40° during the night, for locations downwind from the LRGRV, derived from wind measurements at the GBR, interpolated NWS data, and differences between aircraft heading and displacement vectors. Edge locations 4 and 5 (figures 4 and 7) were interpreted as the eastern or northeastern of the cloud.

The last evidence of an insect cloud occurred at 04h56 at location 8 which was about 420 km from the source area (figure 9). Insect density fluctuations and low average densities prevented an accurate measurement of this cloud edge location. The error in measuring the location of edge no. 8 probably accounts for the apparent increased displacement velocity listed in table 2.

The vertical distribution of insects within the dispersing insect cloud extended from the surface to *ca.* 800 m altitude near the LRGRV (figure 5*a*). An insect layer had formed by 23h00 with the maximum density 500 m above the ground (figure 6*a*). This insect layer gradually descended to 450 m at 01h12 and 400 m at 04h18 (figures 7*a* and 8*a*). The insect

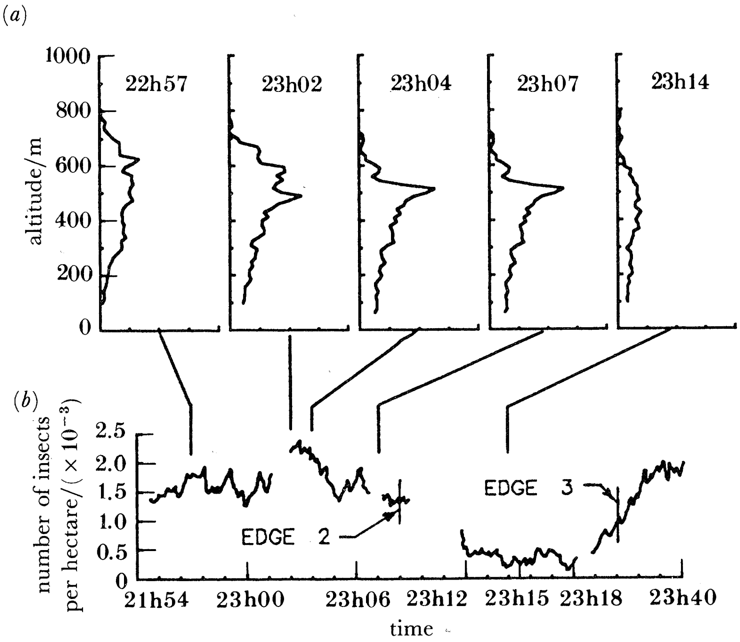

FIGURE 6. (*a*) Insect profiles. (*b*) Numbers of insects per hectare for first portion of mission 2 (between McAllen and Alice, 20 June 1989). A 50% change in density was designated as a cloud edge.

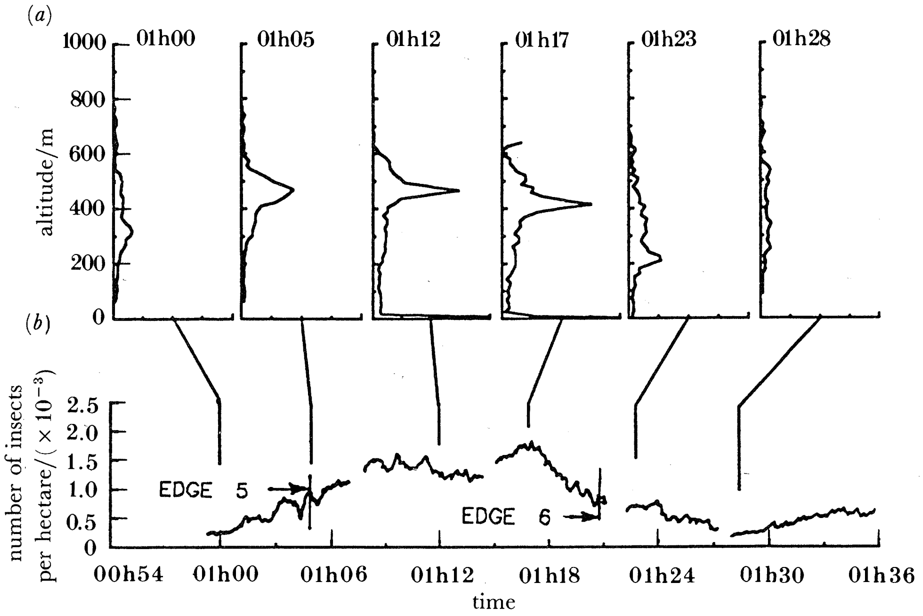

FIGURE 7. (*a*) Insect profiles. (*b*) Numbers of insects per hectare for mission 3 (between Alice and Cotulla, 21 June 1989). A 50% change in density was designated as a cloud edge.

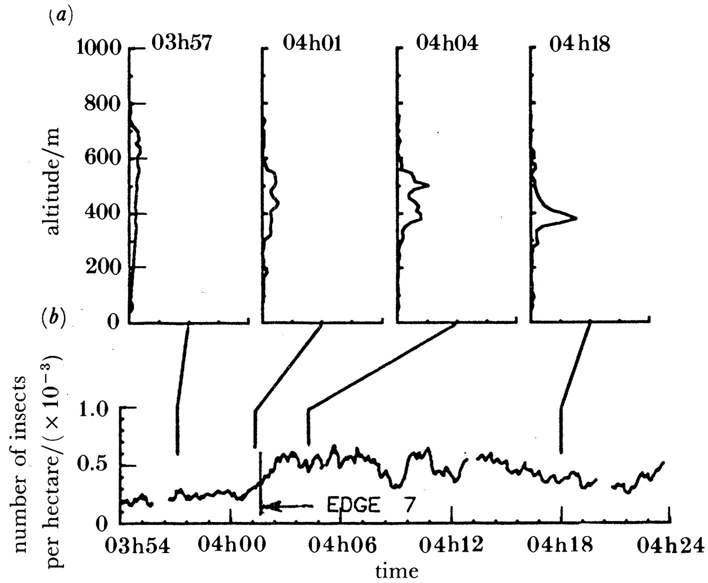

FIGURE 8. (*a*) Insect profiles. (*b*) Numbers of insects per hectare for first part of mission 4 (between San Antonio and Cotulla, 21 June 1989). A 50% change in density was designated as a cloud edge.

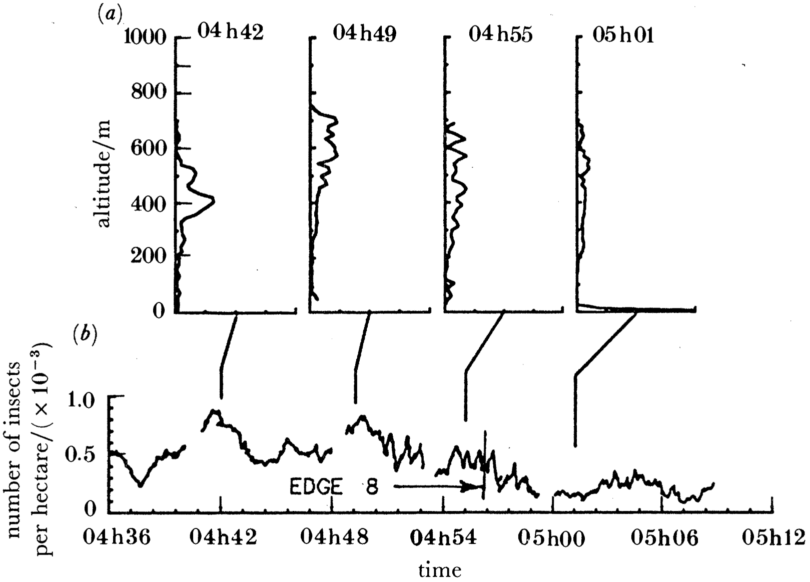

FIGURE 9. (*a*) Insect profiles. (*b*) numbers of insects per hectare for last part of mission 4 (between Cotulla and San Antonio). A 50% change in density was designated as a cloud edge.

layer extended from 400 m to 700 m altitude (04h49) and from 300 to 600 m altitude (04h55) as the aircraft passed over the northern and southern limits of the city of San Antonio, respectively (figures 4 and 9*a*). We interpreted the increase of insect altitude over the city to be an urban thermal effect.

The shape of the insect profiles changed when the aircraft encountered mild turbulence. Between San Antonio and Cotulla, Texas mild turbulence occurred from 03h54 to 04h09 (previous flights had been smooth even during ascent and descent). During turbulence at

04h04, insects were flying between 300–600 m altitude. In smooth air at 04h18 the insects were concentrated in a layer at 400 m altitude (figure 8). The next turbulence occurred from 04h42 to 04h49 while flying over the city of San Antonio. This turbulence was also accompanied by an increased vertical insect distribution (figure 9). If the turbulence also occurred at the insect flight altitude, the concentrating mechanism or behaviour which produced a thin layer in smooth air may have been disrupted.

The combined effects of physical dispersion processes, insect flight behaviour, and flight termination caused insect density within the cloud to decrease with distance downwind from the LRGRV (figure 10). Insect density within and downwind of the insect cloud was obtained from the strip chart recordings. The rate of insect density decrease was greatest between 0 and 100 km and again between 250 and 350 km downwind of the LRGRV. This bimodal rate of change in insect density was interpreted as an insect behaviour effect and/or an artefact of the aircraft's locations within the insect cloud.

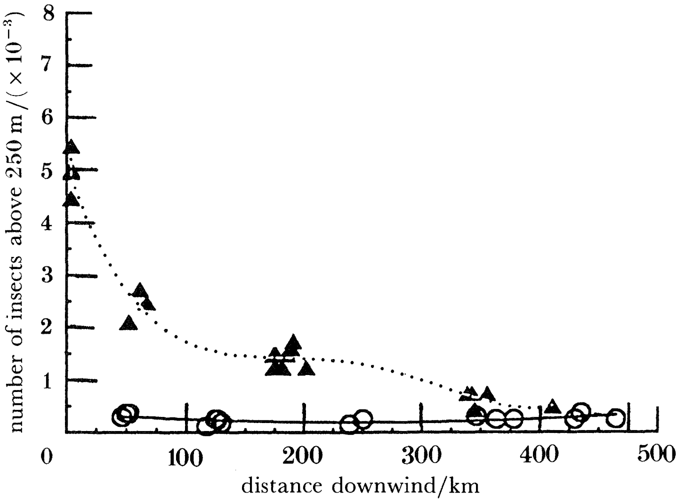

Figure 10. Density of insects flying higher than 250 m altitude inside and outside a cloud of insects which emigrated from a maize production area in the LRGRV during the night of 20–21 June 1989. (Closed triangles, inside insect cloud; open circles, outside insect cloud.)

The ABR detected an occasional target during daylight on the morning of 21 June, but averaged radar signals were not statistically different from radar noise.

The progression of the cloud edge for about 400 km (figure 4) and significant numbers of insects within the cloud for 7 h 40 min (figure 10) are evidence for long distance dispersal during a single night. Several nights of such long distance dispersal could have resulted in maximum corn earworm oviposition at Uvalde two weeks prior to local emergence (figure 1).

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Discussion

J. R. Riley (*ODNRI, Malvern, U.K.*). Mr Wolf was kind enough to acknowledge the ways in which he has benefitted from radar entomology in the U.K., and I would like to say in return, that his own dedicated and enthusiastic contributions to the subject have also been of considerable benefit here. The airborne radar study of long-range moth migration described in Mr Wolf's paper is unique in that he was able to maintain contact with the moths for at least 400 km. Many of the data have still to be analysed, but the results presented here demonstrate again the great power of airborne radar systems when used in migration studies. I would like to ask if any evidence has been found for the maintainance of orientation during the flight, and also if there is any suggestion that moths take off in winds from particular directions?

W. W. Wolf. Regarding orientation, Dr Riley was there operating my ground-based radar on a previous occasion and saw crosswind orientation during the night, very frequently. On the particular night I've described here the ground-based radar did not show much orientation, except at very low altitudes. I have not yet extracted the orientation information from the full data set, but I hope to do so and I think the results will be very interesting. If the airborne radar shows consistent crosswind orientation downwind it will definitely affect dispersion parameters.

On the subject of take-off, we've always seen take-off at the same time of night, about 30–45 minutes after sunset. The only indication that I have of preferred winds comes from when we were operating the radar in northwest Texas during the fall. When the wind was from the south it seemed that the flight was at a much lower altitude than when the wind was from the north.

P. J. Mason (*Meteorological Office, Bracknell, U.K.*). It is of some interest to compare Mr Wolf's observations with our knowledge of the dispersion of passive materials under similar nocturnal conditions. Under nocturnal conditions, dispersion due to small-scale three dimensional eddies is limited and the main effects are movements in various directions at separate heights. It is common to see an initially well-mixed region of material split in different layers, each moving in the direction appropriate to its height.

R. J. V. Joyce (*Cranfield Institute of Technology, Bedfordshire, U.K.*). Mr Wolf, with characteristic generosity, has paid tribute to the pioneer work done in radar entomology by the late Dr Glen Schaefer and by Dr J. Riley. I simply wish to add that my own programme on the flight activity of the noctuid moth *Heliothis armigera* (Hübner) in Sudan, in which Dr. Schaefer conducted the investigations which inspired Mr Wolf, was undertaken because of the evidence collected by him, A. N. Sparks and others, of long distance flights of *Heliothis spp.* over the Gulf of Mexico. These included catches of moths in specially designed black-light traps mounted over 300 m above ground and on oil-platforms 100 miles offshore.

In the Sudan Gezira, *H. armigera* was disappointing as a long-distance flyer, only a small fraction of the population climbed much above the crop boundary layer and the majority of moths engaged in intermittent flight in the lower 10 m of air-space. Displacement was invariably downwind, and massive redistribution of populations (and subsequent oviposition on cotton) occurred when strong but short-lived cold-fronts, resulting from out-flows from the convective storms which can sweep across the Gezira characteristically at the time of the maximum flight activity of *H. armigera* moths, were found by Schaefer (1976) to concentrate airborne insects 60-fold in a single hour.

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J. R. Riley (*ODNRI, Malvern, U.K.*). Regarding Professor Joyce's comment, we found exactly the same effect with *H. armigera* in central India. The moths persisted in flying below radar cover, but by using an infra-red video system we could look at the flight above the crop. It was quite clear that the reason we were not finding them on the radar was that they were flying low, as Professor Joyce had previously found.