FIELD OBSERVATIONS AND SIMULATIONS OF ATMOSPHERIC TRANSPORT OF NOCTUIDS FROM NORTHEASTERN MEXICO AND THE SOUTH-CENTRAL U.S.

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ABSTRACT

Nocturnal measurements documented the vertical profile of the atmospheric environment during May and June from 1984 to 1990. This time corresponded to peak emergence of *Helicoverpa zea* (Boddie) and *Spodoptera frugiperda* (J.E. Smith) from $2x10^5$ ha of mature corn in the Lower Rio Grande Valley (LRGV) of Texas and Mexico. The atmospheric data revealed a maximum average relative humidity of about 85% between 400 m and 600 m altitude. Average cloud cover ranged annually from 26 to 58%. Average air temperature of 22.5°C at 500 m Above Ground Level (AGL) was significantly cooler in 1987 than in any year except 1990. Maximum average wind speed ranged from 9.3 m/s to 15.2 m/s and was located between 400 m and 600 m AGL. Nightly atmospheric trajectories at 500 m AGL were calculated from an origin near Weslaco, Texas, on the northern perimeter of an expansive corn growing area. Atmospheric trajectory endpoints representing two-night displacement from Weslaco were scattered annually across Texas, except west of the Big Bend area. Trajectory endpoints were frequently located in Oklahoma and less frequently in Arkansas and Louisiana. Atmospheric trajectory calculations underestimated moth flight from the LRGV that was measured by an airborne radar on the night of 20 June 1989. An error of 164 km, over the 7.67 h radar tracking period, was likely due to a combination of wind speed acceleration along the flight path, wind direction changes along the flight path, moth flight speed, and the moth flight crab angle with respect to the ambient wind direction. Results of this study will contribute to the predictability of long-distance dispersal and subsequent infestations by migratory pest insects.

INTRODUCTION

Many of the lepidopteran pests of U.S. agriculture are nocturnally active, highly mobile and capable of long distance flights. Fitt (1989) described mobility as one of four significant characteristics contributing to the major pest

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status of the *Heliothis/Helicoverpa* complex. The corn earworm, *Helicoverpa zea* (Boddie), and the fall armyworm, *Spodoptera frugiperda* (J.E. Smith), cause estimated losses of over one billion dollars annually to U.S. agriculture when yield and control costs are considered.

Both control and population monitoring technology for these pests require a basic understanding of the biotic and abiotic processes involved in their dispersal. Farrow and Daly (1987) and Stinner et al. (1983) emphasized that a holistic research approach to identification of insect movement is required for forecasting pest outbreaks.

Over the past decade several studies have been performed in the U.S. that utilize different techniques to demonstrate movement capabilities of selected noctuid pests. Hendrix et al. (1987) detected pollen of false mesquite, *Caliandra*, and ape's earring, *Pithecellobium*, on corn earworm males captured in pheromone traps in Arkansas. These authors concluded that the moths had migrated a minimum of 750 km from southern Texas, the nearest region which supported populations of these plants. Lingren (personal communication) found that 34% of corn earworm males captured in the spring of 1989 near Lane, OK, were marked with citrus pollen. However, only 3% of the corn earworm moths captured in Lane in the spring of 1990 were similarly marked. This followed a severe freeze in late December of 1989 that eliminated citrus blooming in southern Texas and northeastern Mexico, thus implicating that region as a possible source area. Showers et al. (1989) released internally-marked, laboratory-reared *Agrotis ipsilon* Hufnagel adults in the south-central U.S. and captured specimens which traveled northward more than 1200 km in two to four nights. The detection of early spring corn earworm populations prior to emergence of local overwintering populations has also provided evidence of long distance movement. Hartstack et al. (1982) captured corn earworm adults in pheromone traps at College Station, Texas, and Portland, Arkansas, 19 and 33 days prior to local emergence, respectively. Rummel et al. (1986) observed corn earworm infestations in cotton in Lubbock, Texas, several weeks prior to overwintering emergence.

Ecological, entomological and meteorological studies in Texas and northeastern Tamaulipas, Mexico, have provided evidence of the regional interrelationships of corn earworm and fall armyworm populations produced in major corn growing areas. The approximately 200,000 ha irrigated corn crop grown in the Lower Rio Grande Valley (LRGV) of southern Texas and northeastern Tamaulipas, Mexico, produces from 1.5 - 7.0 billion *S. frugiperda* annually (Raulston et al. 1986, Sparks et al. 1989, and Pair et al. 1991, Raulston et al. 1992). Wolf et al. (1990) observed that the peak *H. zea* infestation on cotton at Uvalde, Texas in 1989 occurred during the peak emergence period from corn in the LRGV and 12 days prior to the local emergence peak from corn. Using an airborne radar, they were able to track moths from the LRGV to San Antonio, Texas (150 km east of Uvalde), during the *H. zea* emergence cycle in the LRGV. This strongly suggests that the *H. zea* infestation on cotton at Uvalde resulted from adults migrating from the LRGV. Further, Pair et al. (1991) provided evidence that an unusually large fall armyworm population developing on corn in the LRGV in 1989 migrated to Uvalde, the High Plains of Texas, and Ankeny, Iowa.

The present paper documents synoptic-scale weather patterns and climatological conditions that affect high-altitude flight during the period of peak emergence of *H. zea* and *S. frugiperda* from corn grown in the LRGV. Long-distance moth flight is simulated by atmospheric trajectory calculations. Also, a calculated atmospheric trajectory is validated here with respect to an airborne radar track of an insect cloud for a distance of 400 km from the LRGV in 1989 which was documented by Wolf et al. (1990).

MATERIALS AND METHODS

Nightly meteorological and radar observations were made in the LRGV from 8-20 June 1984, 7-23 June 1985, 3-12 June 1986, 27 May to 12 June 1987, 29 May to 17 June 1988, 2-21 June 1989, and 31 May to 14 June 1990 following the methods of Wolf et al. (1986). The term "ARS normal period" is used to describe the set of all ARS observations from 1985 to 1990. Free-ascent pilot balloons were launched at one-hour intervals beginning at sunset and continued until moth densities decreased from the maximum nightly value by at least one order of magnitude. The pilot balloons were tracked by optical theodolite or radar to determine successive balloon displacements, wind speed, and wind direction. A radiosonde was attached to approximately every third pilot balloon to measure air temperature, wet bulb temperature and barometric pressure. The dates encompassed the *H. zea* and *S. frugiperda* emergence cycles from the maturing regional corn crop. With the exception of 1984, the worksite was located south of Donna, Texas, adjacent to the Rio Grande River (26.0°N, 97.97°W) and downwind of the main corn growing area situated south of the river in Mexico. Meteorological data are not presented for 1984 due to wind instrument failure. An entomological radar documented the nightly exodus of moths from the region. Visual observations of amount and type of cloud cover were recorded occasionally. Cloud height was determined by estimation or by the disappearance of a light attached to an optically tracked, ascending helium-filled balloon.

Daily synoptic weather maps were examined to describe large-scale atmospheric circulation patterns present during the period of peak *H. zea* emergence and flight from the LRGV. The synoptic weather maps present surface fronts, high- and low-pressure systems, upper-level troughs of low pressure, areas of precipitation, surface wind speed, and wind direction. Daily synoptic weather maps, valid at 0700 Eastern Standard Time (EST), were available for the period 1985 to 1990 (USDC-NOAA 1985-1990).

Atmospheric trajectories were calculated based on a two-dimensional (constant-altitude) derivation of a three-dimensional trajectory algorithm developed by Reap (1972). The atmospheric trajectories estimate the path of an air parcel and have been used to assess the movement of airborne insects. A Coriolis parameter is included in the trajectory algorithm to account for eastward deflection of northward trajectories, and vice versa. Twice-daily (0000 Universal Coordinated Time [UTC] and 1200 UTC) NWS upper-air data were interpolated to 500 m Above Ground Level (AGL) altitude for the trajectory analyses (Westbrook et al. 1990). The active contribution of insect flight has not been incorporated in the present model. Therefore, the difference between the track of long-distance moth flight and an atmospheric trajectory estimates the active behavioral flight component of the moths.

The calculated atmospheric trajectories originated from the ARS field site (26.06°N, 97.97°W) near Donna, Texas (south-southwest of Weslaco, Texas). The trajectories were calculated for an altitude of 500 m AGL, 12 h duration commencing at 0000 UTC (1900 CDT), and two successive nights of atmospheric transport. Nightly atmospheric trajectories were calculated for the period 15 May to 30 June for the years 1984 to 1990. This period (identified as the "NWS normal period") encompassed the dates of peak emergence and allowed for annual comparisons of the atmospheric trajectory endpoint distribution. The period of 15 May to 30 June was further subdivided into three subperiods: (1) prior to ARS radar/meteorological field measurements, (2) during these ARS field measurements (synchronous with the period of peak corn earworm emergence), and (3) after these ARS field measurements.

RESULTS

Climatic Summary. The average relative humidity (RH) for the ARS normal period generally decreased from 80% to 64% from 100 m to 1200 m altitude, but RH exhibited a maximum of 84% at 400 m altitude. The altitude of maximum RH values for 2000 to 2100 CDT occurred at 500 m AGL, but the altitude steadily lowered to 300 to 400 m AGL by 2400 to 2500 CDT. Relative humidity values ranged from a minimum of 13% in 1989 to a maximum of 100% in 1987 to 1990. The maximum average RH ranged from a low of 80% in 1985 to a high of 90% in 1987 and 1990. The height of the maximum average RH ranged from 400 m to 600 m altitude. The average relative humidity at 500 m altitude was significantly less in 1985 than in 1987 and 1990 (Table 1), but RH was not significantly different from that in 1986, 1988 or 1989. The variances were similar for 1985 to 1990.

Average cloud cover ranged from 24% to 58% with an overall average of 35% for the ARS normal period (Table 2). The average cloud cover for 1987 was significantly greater than for the other years of the ARS normal period. The average cloud cover for 1988 was signficantly greater than for 1989, but cloud cover was not significantly different among the other years. The variances were homogenous among years of the ARS normal period.

Inversions were absent from the vertical profile of the average air temperature for the ARS normal period. Generally, the lapse rate (decrease of temperature with respect to altitude) was less than the standard lapse rate of 6.5°C/km from 100 m to 1200 m altitude, revealing a monotonic decrease of average air temperature from 25.8°C at 100 m to 21.0°C at 2100 m altitude. Air temperature ranged from 16.7°C in 1987 to 31.2°C in 1988 between 100 m and 1200 m altitude. This range of air temperature is well within reported thresholds for moth

TABLE 1. Mean Relative Humidity (%) and Air Temperature (°C) near Weslaco, Texas by Altitude and Year.

Altitude (m AGL)	1985 (N=30)		1986 (N=15)		1987 (N=24)		1988 (N=30)		1989 (N=38)		1990 (N=20)		Mean[b] (N=157)	
	RH	Temp.	RH	Temp.	RH	Temp.	RH	Temp.	RH	Temp.	RH	Temp.	RH	Temp.
100	77	26.0	83	25.8	86	25.0	78	25.9	79	25.9	83	25.8	80ab	25.8a
200	78	25.6	83	25.5	87	24.4	78	25.5	80	25.4	84	25.3	81ab	25.3b
300	79	25.1	83	25.0	88	23.9	80	24.8	82	24.8	87	24.5	83a	24.7c
400	79	24.5	83	24.5	88	23.2	81	24.1	83	24.2	88	23.8	84a	24.0d
500	79	23.8	83	23.9	88	22.5	80	23.6	81	23.7	90	22.9	83a	23.4e
600	77	23.3	82	23.3	88	22.0	78	23.1	76	23.4	88	22.2	81ab	22.0f
700	75	22.8	79	22.9	88	21.6	76	22.7	70	23.3	84	21.8	77bc	22.6g
800	72	22.4	76	22.6	84	21.4	76	22.1	66	23.2	78	21.6	74cd	22.3h
900	69	22.0	73	22.3	82	21.1	73	21.7	62	22.0	70	21.5	71de	22.0i
1000	66	21.6	72	21.9	81	20.8	71	21.3	59	22.8	66	21.3	68ef	21.7j
1100	64	21.2	71	21.5	81	20.3	67	21.1	57	22.5	63	21.1	66fg	21.4k
1200	61	20.8	70	21.0	80	19.8	64	20.8	56	22.1	59	20.9	64g	21.01
Mean[c] RH	73cd		78b		85a		75c		71d		78b			
Mean[c] Temp		23.3bc		23.4b		22.2e		23.1c		23.6a		22.7d		

[a]Data were obtained from Radiosonde launches at an ARS Field Site near Weslaco, Texas, from 2000 to 2500 CDT between 15 May and 30 June in 1985 to 1990.

[b]Means within columns followed by the same letter are not significantly different as determined by Duncan's Multiple Range Test ($P<0.05$).

[c]Means within rows followed by the same letter are not significantly different as determined by Duncan's Multiple Range Test ($P<0.05$).

flight (Carpenter et al. 1981). The average air temperature at 500 m altitude was significantly cooler in 1987 than for all other years of the ARS normal period except 1990 (Table 3). The variances were nonhomogeneous among years.

TABLE 2. One-Way Analysis of Variance for Cloud Cover for Several-Week Periods of ARS Field Operations between 15 May and 30 June 1985-1990.

		Cloud Cover		
Year[b]	N	Mean	95% Tukey HSD interval	
1985ab	129	0.34	0.28	0.40
1986ab	57	0.34	0.25	0.44
1987c	125	0.58	0.52	0.64
1988b	142	0.37	0.31	0.42
1989a	174	0.24	0.19	0.29
1990ab	100	0.26	0.19	0.33
1985-1990	727	0.35	0.33	0.38

[a]N is the number of cloud cover observations.
[b]Means in years followed by the same letter are not significantly different at α= 0.05. Significant differences of means among years (F=16.11, α=0.05) are supported by homogeneous variances among years at α=0.05 (Cochran's C test: 0.21, *P*=0.15).

TABLE 3. One-way Analysis of Variance for Air Temperature at 500 m Altitude for Several-Week Periods of ARS Field Operations between 15 May and 30 June 1985-1990.

		Air Temperature (°C)		
Year[b]	N	Mean	95% Tukey HSD intervals	
1985b	31	23.8	23.4	24.3
1986b	15	23.9	23.2	24.6
1987a	24	22.5	22.0	23.1
1988b	30	23.6	23.1	24.1
1989b	38	23.7	23.3	24.1
1990ab	22	22.9	22.3	23.4
1985-1990	160	23.4	23.2	23.6

[a]N is the Number of Air Temperature Measurements
[b]Means in years followed by the same letter are not significantly different at α=0.05. Significant differences of means among years (F=4.40, α=0.05) may be questionable because variances among years are nonhomogeneous at α=0.05 (Cochran's C test: 0.33, P=3.48x10^{-3}).

The average wind speed at 100-m intervals from 100 to 1200 m altitude ranged from 5.1 m/s at 1200 m in 1988 to 15.2 m/s at 600 m in 1989. The vertical shear of the average wind speed values are +2.0, +0.9, +0.7, +0.2, -0.1, -0.7, -0.5, -1.0, -0.9, 0.5, and -0.4 m/s/100m between successive 100-m altitudes from 100 m to 1200 m, respectively. Hourly wind speed ranged from a minimum of 0.4 m/s in 1988 to a maximum of 38.3 m/s in 1990. Maximum average wind speed varied from a low value of 9.3 m/s in 1987 and 1988 to a high value of 15.2 m/s in 1989. Maximum average wind speed was located at an altitude of 400 m in 1986, 1987, and 1988 and 600 m in 1985, 1989, and 1990. The average wind speed at 500 m altitude was significantly greater for 1989 and 1990 than for 1985 to 1988 (Table 4). Variances for 1985 to 1990 were nonhomogeneous.

TABLE 4. One-Way Analysis of Variance for Wind Speed at 500 m Altitude for Several-Week Periods of ARS Field Operations between 15 May and 30 June 1985-1990.

		Wind Speed (m/s)		
Year[b]	N	Mean	95% Tukey HSD intervals	
1985a	58	10.7	9.8	11.7
1986a	28	9.9	8.5	11.3
1987a	38	9.0	7.8	10.2
1988a	65	9.0	8.1	10.0
1989b	83	14.9	14.1	15.7
1990b	52	14.9	13.9	15.9
1985-1990	324	11.9	11.4	12.3

[a]N is the number of wind speed measurements.
[b]Means in years followed by the same letter are not significantly different at α=0.05. Significant differences of means among years (F=33.59, α=0.05) may be questionable because variances among years are nonhomogeneous at α=0.5 (Cochran's C test: 0.28, $P=1.32\times10^{-3}$).

Wind direction can be described as a unit vector, and we present mean wind direction by 100-m altitudes to reduce vector-averaging of a wide range of directions. Average wind direction values ranged from 126 degrees to 138 degrees for pooled data between 100 m and 1200 m for 1985 to 1990. The vertical shear of the average wind direction values are +2, +4, +1, +2, +2, +1, 0, -4, +2, 0, and -1 degrees/100m between successive 100-m altitudes from 100 m to 1200 m, respectively. The minimum absolute value of the vertical shear of the average wind direction was found between 700 - 800 m and 1000 - 1100 m altitude. Perhaps one of the more surprising features evident in the average annual vertical profiles of wind direction was the diverse array of profile shapes. Average wind direction profiles were nearly constant in 1985, 1987 and 1990, and veered (rotated clockwise) in 1986, 1988, and 1989. The average wind direction at 500 m AGL for 1988 was signficantly less (more easterly) than for 1987 and 1989 (Table 5). Variances for 1985 to 1990 were nonhomogeneous.

TABLE 5. One-Way Analysis of Variance for Wind Direction at 500 m Altitude for Several-Week Periods of ARS Field Operations between 15 May and 30 June 1985-1990.

		Wind Direction (degrees)		
Year[b]	N	Mean	95% Tukey HSD intervals	
1985ab	58	128	116	139
1986ab	28	140	124	157
1987b	37	151	136	165
1988a	65	117	107	128
1989b	84	141	131	150
1990ab	52	140	128	152
1985-1990	324	135	130	140

[a]N is the number of wind direction measurements.
[b]Means in years followed by the same letter are not significantly different at α=0.05. Significant differences of means among years (F=4.01, α=0.05) may be questionable because variances among years are nonhomogeneous at α=0.05 (Cochran's C test: 0.57, P=1.33x10^{-14}).

Atmospheric Trajectories. Prior to the period of peak emergence in the LRGV in 1984, the trajectory endpoints were scattered from north-central Mexico to Oklahoma (Table 6; Fig. 1). During the period of peak emergence in the LRGV, the trajectory endpoints targeted an area of north-central Texas near Stephenville. Following the period of peak emergence in the LRGV, the trajectories decreased in displacement and their endpoints were located due north of San Antonio, Texas.

The diverse clustering of trajectory endpoints during the three periods projected a significant temporal trend in the synoptic circulation. There were four frontal passages from 20-28 May and none from 29 May to 30 June. During the period of peak emergence (8-22 June), fronts and troughs were located across western Texas. Fronts advanced southeast to a line from Del Rio to Houston from 23-30 June. In 1985, a significant number of trajectories terminated along the lower Rio Grande River near Laredo and Del Rio, Texas (Fig. 2).

The dispersal of trajectory endpoints is indicative of a dynamic synoptic circulation associated with mid-latitude storms. Five fronts passed through the LRGV between 15 May and 26 June. The fronts brought a northwesterly wind direction to the LRGV approximately every ten days.

In 1986, during the period of peak emergence in the LRGV, the trajectory endpoints were clustered along a southwest-northeast line from San Antonio to College Station, Texas (Fig. 3). The trajectory endpoints were extremely

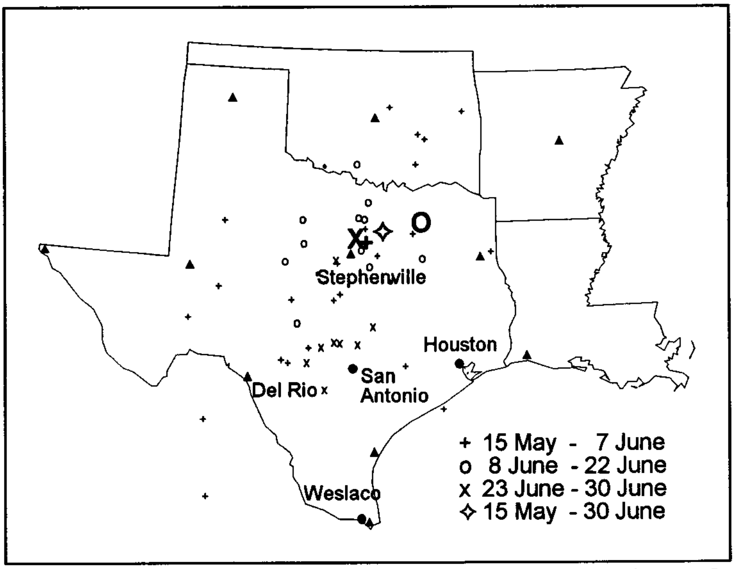

FIG. 1. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1984. The symbols **+**, **o**, **x**, and **✧** represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1984, respectively.

dispersed from southwest-northeast.

The extreme southwest-northeast dispersal resulted from encroachment of mid-latitude storms to Oklahoma and northern Texas. Two fronts from 16-27 May and one on 12 June passed the LRGV. A significant southwest-northeast alignment of the fronts occurred frequently across central Texas. An easterly wave (upper-level low-pressure trough of tropical origin moving westward) and Hurricane Bonnie crossed coastal Texas from 15-26 June.

In 1987, significant short-distance displacements terminated in the vicinity of Corpus Christi and Victoria, Texas (Fig. 4). At the onset of ARS field observations, trajectory endpoints were located in southeastern Texas. During the period of peak emergence in the LRGV, many trajectory endpoints were located in an area from north-central Mexico through Del Rio to Stephenville, Texas.

Two fronts passed the LRGV from 1-12 June and another from 23-28 June. Fronts and troughs dissipated over Texas, lacking strong circulation support. Transport conditions were consequently rather weak and variable over the LRGV.

In 1988, atmospheric trajectory endpoints displayed significant southeast-northwest dispersal (Fig. 5). During the period of peak emergence in the LRGV, numerous trajectory endpoints were located in western Texas from Del Rio to San Angelo. Trajectory displacements increased during the period of peak emergence in the LRGV with one endpoint located in northern Oklahoma.

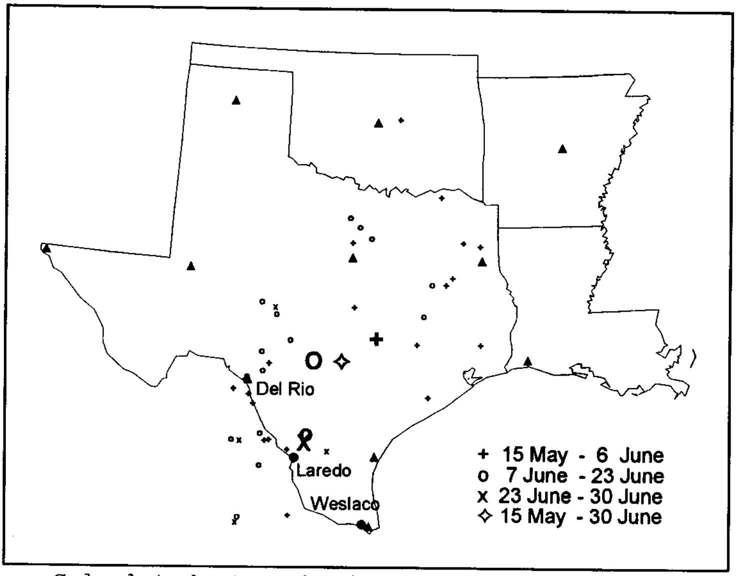

FIG. 2. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1985. The symbols **+**, **o**, **x**, and ✧ represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1985, respectively.

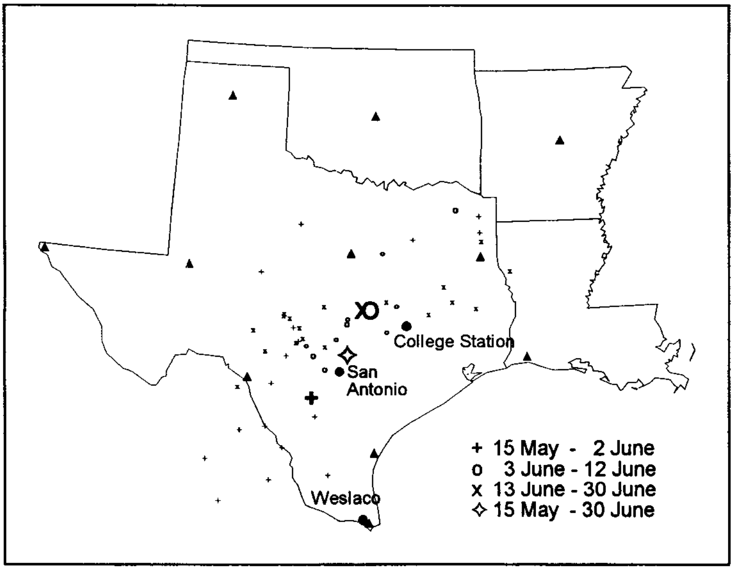

FIG. 3. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1986. The symbols **+**, **o**, **x**, and ✧ represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1986, respectively.

TABLE 6. One-Way Analysis of Variance for Calculated Atmospheric Trajectory Endpoints that Represent Two Successive Nights of 12-h Displacement at 500 m Altitude from Donna, Texas (near Weslaco) for Several-Week Periods of ARS Field Operations between 15 May to 30 June 1984-1990.

		Longitude (degrees W)			Latitude (degrees N)		
Year	N	Mean	95% Tukey HSD		Mean	95% Tukey HSD	
1984	15	98.13	99.07	97.18a	32.49	31.18	33.81bc
1985	17	99.40	100.29	98.51a	29.71	28.48	30.95a
1986	10	97.76	98.92	96.60ab	30.86	29.25	32.47abc
1987	17	99.61	100.50	98.72a	29.57	28.34	30.80a
1988	20	99.66	100.48	98.84a	29.55	28.42	30.69a
1989	20	98.71	99.53	97.89a	30.56	29.43	31.70ab
1990	15	96.12	97.07	95.17b	33.03	31.72	34.35c
1984-1990	114	98.61	98.96	98.27	30.72	30.24	31.19

[a]N is the number of nightly trajectories during the respective period.
[b]Mean intervals followed by the same letter are not significantly different at ∝=0.05. Although there are significant differences among years for longitude (F=8.60, ∝=0.05) and latitude (F=5.67, ∝=0.05), variances among years are nonhomogeneous for longitude (Cochran's C test: 0.28, *P*=0.04) and latitude (Cochran's C test: 0.40, *P*=1.26×10^{-4}).

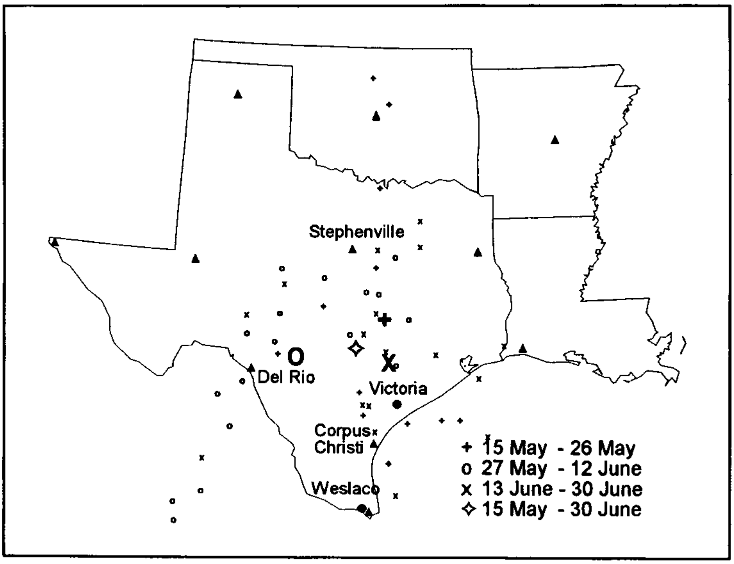

FIG. 4. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1987. The symbols **+**, **o**, **x**, and ✧ represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1987, respectively.

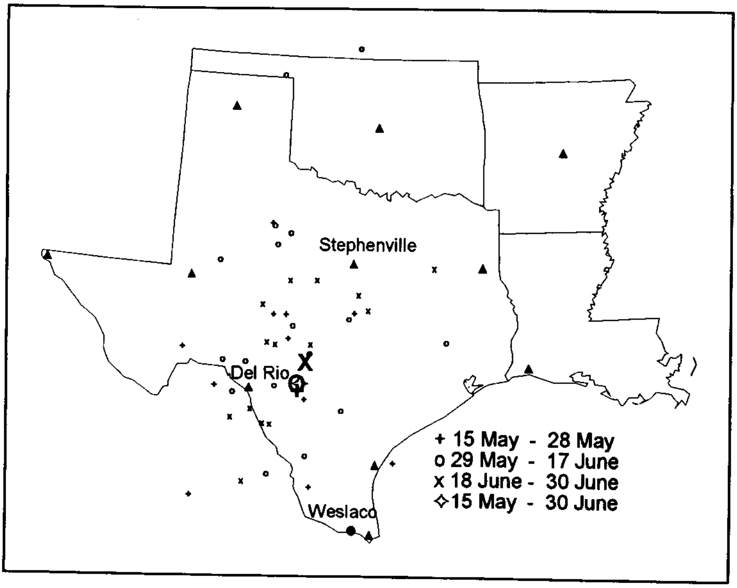

FIG. 5. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1988. The symbols **+**, **o**, **x**, and ✧ represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1988, respectively.

Two fronts moved across the LRGV from 15-22 May, followed by another between 29 May and 2 June. Excluding the frontal passage (29 May to 2 June) during the first week of ARS observations, the trajectory endpoints characterized frequent frontal encroachment into Oklahoma and the Texas High Plains. A surface high-pressure system with associated light wind was followed by an easterly wave over coastal Texas from 18-24 June, significantly eroding the northward atmospheric transport mechanism.

In 1989, broad dispersal characterized the trajectory endpoint distribution for single-night transport (Fig. 6) and two-night transport (Fig. 7). Extended northward displacements

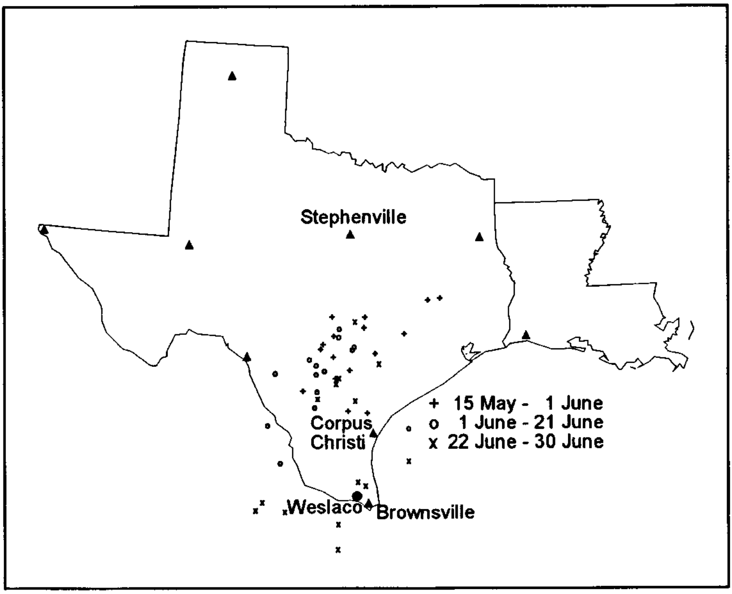

FIG. 6. Calculated atmospheric trajectory endpoints for single 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1989. The symbols **+**, **o**, and **x** represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1989, respectively.

into Oklahoma and northeastward displacements into northern Texas and Arkansas were noted prior to the period of peak emergence in the LRGV. During the period of peak emergence in the LRGV, numerous trajectory endpoints were clustered near Stephenville, Texas. Following the period of peak emergence, the northward transport system disintegrated with only one of nine trajectory endpoints displaying a significant northward component; in fact, four endpoints were clustered within a 300 km radius of the midpoint between Brownsville, and Corpus Christi, Texas.

The spread of trajectory endpoints indicated highly variable synoptic circulation patterns such as the passage or approach of mid-latitude storms from the northwest and tropical storms along the western Gulf of Mexico. Following the

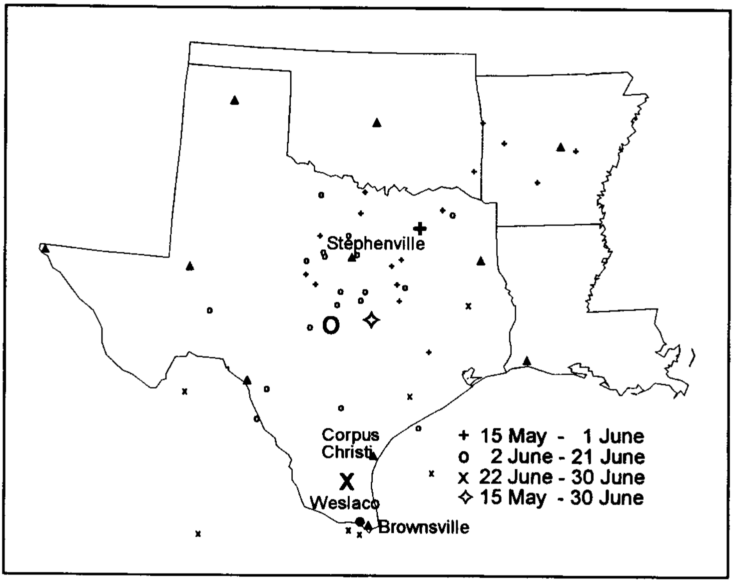

FIG. 7. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1989. The symbols **+**, **o**, **x**, and ✧ represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1989, respectively.

southward advance and dissipation of fronts and troughs into northern Texas from 15 May to 14 June, a front passed the LRGV on 15 June. The movement of Hurricane Allison along the Texas coast significantly disintegrated the atmospheric transport northward from the LRGV.

In 1990, southwest-northeast dispersal of the trajectory endpoints was apparent before, during, and following the period of peak emergence in the LRGV (Fig. 8). The endpoints were tightly clustered along a line passing from Del Rio through Stephenville to eastern Oklahoma. This dispersed pattern indicated frequent frontal passages across the Texas High Plains and Oklahoma, but not penetrating into southern Texas. A single front passed the LRGV on 22 May.

The spatial distribution of trajectory endpoints was examined separately for the periods of ARS field operations and the period 15 May to 30 June. The analysis of variance of trajectory endpoints for the periods of ARS field operations show that trajectory endpoints were significantly more northeastward in 1990 than in any year except 1986 (Table 6). Analysis of variance of trajectory endpoints for 15 May to 30 June revealed significantly greater northward displacement in 1990 than in any other year except 1984 (Table 7).

Validation of Trajectory Calculations. Atmospheric trajectory calculations for the night of 20-21 June 1989 were compared (Fig. 9) with airborne radar measurements of moth flight from the LRGV (Wolf et al. 1990). The airborne radar tracked the leading edge of a "cloud" of moths migrating

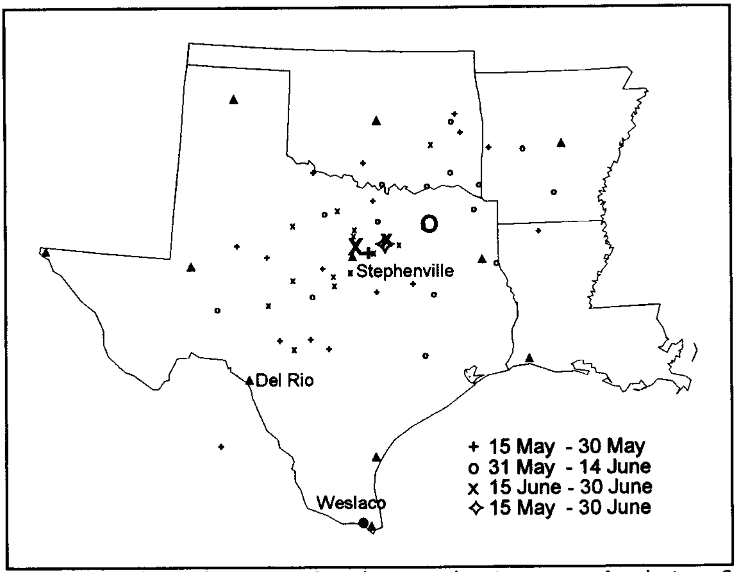

FIG. 8. Calculated atmospheric trajectory endpoints for two successive 12-h nights of transport at 500m AGL originating near Weslaco, Texas, for 15 May - 30 June, 1990. The symbols +, **o**, **x**, and ✧ represent the average endpoints for periods +, o, x, and 15 May - 30 June, 1990, respectively.

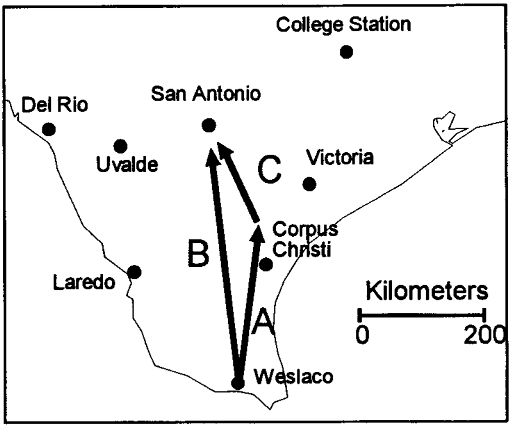

FIG. 9. Calculated atmospheric trajectory at 500 m AGL and trajectory of a moth cloud originating near Weslaco, Texas, on the night of 20 June, 1989 and continuing for 7.67-h duration. Vectors labeled **A**, **B**, and **C** represent the estimated atmospheric trajectory, measured moth cloud trajectory, and resultant vector, repectively. The resultant vector **C** approximates the component due to moth flight behavior.

from the LRGV to San Antonio in 7.67 h. The airborne radar measured the cloud edge at only one position as the aircraft passed from inside to outside of the cloud. The relative

TABLE 7. One-Way Analysis of Variance for Calculated Atmospheric Trajectory Endpoints that Represent Two Successive Nights of 12-h Displacement at 500 m Altitude from Donna, Texas (near Weslaco) for 15 May to 30 June 1984-1990.

Year	N	Longitude (degrees W)			Latitude (degrees N)		
		Mean	95% Tukey HSD intervals for the mean[b]		Mean	95% Tukey HSD intervals for the mean[b]	
1984	47	98.34	98.98	97.69ab	31.52	30.74	32.31bc
1985	47	98.55	99.19	97.90ab	29.72	28.94	30.50a
1986	47	98.37	99.02	97.73ab	30.01	29.23	30.79ab
1987	47	98.09	98.74	97.45b	29.78	29.00	30.56a
1988	47	99.58	100.23	98.94a	29.63	28.85	30.42a
1989	47	97.69	98.33	97.04b	30.81	30.02	31.59ab
1990	47	97.40	98.04	96.75b	32.58	31.80	33.36c
1984-1990	329	98.29	98.53	98.04	30.58	30.28	30.87

[a]N is the number of nightly trajectories during the respective period.
[b]Mean intervals followed by the same letter are not signficantly different α=0.05. There are significant differences among years for longitude (F=5.22, α=0.05) and latitude (F=9.03, α=0.05), and variances among years are homogeneous for longitude (Cochran's C test: 0.28, *P*=0.04) and latitude (Cochran's C test: 0.40, *P*=1.26×10^{-4}).

position of this point with respect to the corresponding point at the edge of the source area is unknown. Atmospheric trajectory points were calculated from three NWS upper-air stations (Brownsville, Del Rio, and Victoria, Texas). The distance between synchronous trajectory waypoints and the airborne radar waypoints increased monotonically to a value of 164 km at 7.67 h duration (0456 CDT). The origin and endpoints of the calculated wind displacement and measured cloud edge displacement were used as respective vectors. The difference between the two vectors was our best estimate of the dispersal attributed to active insect flight behavior.

DISCUSSION

Meteorological field measurements documented the nocturnal boundary layer near dense sources of migrating corn earworm and fall armyworm adults. Vertical profile measurements of air temperature, wet-bulb temperature, barometric pressure, wind speed, and wind direction supported concurrent measurements of long-distance adult flight behavior and airborne insect density (Wolf et al. 1995). NWS upper-air data were analyzed to estimate aerial pathways available nightly to migrating insects.

In situ meteorological measurements are proving instrumental in documenting the nocturnal atmospheric transport climatology of an annually dense corn earworm source area. Furthermore, the meteorological measurements can be merged with entomological observations, particularly radar entomological measurements, to resolve adult flight behavior from total displacement of adults. The summary of meteorological observations presented here complements the twice-daily NWS upper-air measurements recorded at widely-scattered locations across the U.S.

In situ meteorological measurements documented the climatology of the nocturnal boundary layer in the LRGV during periods of peak corn earworm emergence. Average relative humidity generally decreased with altitude from 80% at 100 m AGL to 64% at 1200 m AGL, but exhibited a maximum of 84% at 400 m AGL. The altitude of maximum relative humidity was also the approximate altitude of the base of stratus clouds which covered an overall average of 35% of the sky; average cloud cover was signficantly greater in 1987 than in any other year of the ARS normal period. Flight at the level of maximum RH would reduce the desiccation rate of insects compared to that in drier air. The presence of a stratus cloud overcast may lead to differences of insect orientation between insects flying below the cloud and cohorts flying above the cloud. For example, insects flying below the clouds could not use celestial navigation, while cohorts flying above the clouds could not use geographic navigation.

Average air temperature decreased with altitude from 25.8°C at 100 m AGL to 21.0°C at 1200 m AGL with extreme hourly values of 16.7°C in 1987 and 31.2°C in 1988. Average air temperature was significantly cooler in 1987 than for all other years of the ARS normal period except 1990. Average air temperatures were always higher than the threshold for flight.

Maximum average wind speed was located between 400 m AGL and 600 m AGL during the ARS normal period. Average maximum wind speed ranged from 9.3 m/s in 1987 and 1988 to 15.2 m/s in 1989. Minimum vertical shear of average wind speed was located between 500 m AGL and 600 m AGL with positive shear below and negative shear above this altitude band. Average wind speed at 500 m AGL was significantly greater in 1989 and 1990 than for 1985 to 1988. Radars often detect highest concentrations of insects at the altitude of maximum wind speed. Flight at the altitude of maximum wind speed will increase the transport distance.

Average wind direction values ranged from 126 degrees to 138 degrees. Average wind direction was significantly more easterly in 1988 than in 1987 and 1989. A more easterly wind decreases the upwind extent of the insect source area due to the coastal boundary. Therefore, shorter periods of nocturnal overflight should have been reported by the scanning radar in 1988.

Calculated atmospheric trajectories were longer and their endpoints more concentrated in years when fronts stalled across northern Texas. Shorter-length trajectories of various directions were common for synoptic circulations that supported frequent frontal passages, troughs, high pressure, and easterly waves near the LRGV. Trajectory endpoints scattered across Texas annually, except west of the Big Bend area. Trajectory endpoints frequently dispersed into Oklahoma with fewer occurrences in Arkansas and Louisiana. Calculated one-night atmospheric trajectories from 15 May to 30 June 1989 documented a smooth northern perimeter from Uvalde through Austin to College Station. Cropping areas in Texas south of this perimeter would be particularly at risk of migrations, especially considering insect fallout along the flight path.

Atmospheric trajectory calculations for the night of 20-21 June 1989 underestimated by 41% moth flight from the LRGV measured by airborne radar. The distance between atmospheric trajectory waypoints and the airborne radar waypoints increased monotonically to a value of 164 km at 7.67 h duration (0456 CDT). Thus, an average speed differential of 5.9 m/s at 37 degrees to the left of the wind direction could be accounted for by four factors: (1) the difference between interpolated NWS wind velocities and actual wind velocities at insect flight altitudes along the flight path, (2) the moth flight speed, (3) the moth flight crab angle with respect to wind direction along the flight path, and (4) the relative position of the cloud edge measurement and the corresponding point on the perimeter of the source area. Assuming a migratory moth flight speed (factor 2 above) of 5 m/s, factors 1, 3, and 4 would have accounted for 0.9 m/s (or 15%) of the average transport speed differential. No significant alignment axis of moth orientation was observed by the scanning radar which was located in the LRGV near Donna, Texas, but the moths may have maintained a common orientation along the flight path. Mean 24-h atmospheric transport based on 500 m AGL wind velocities measured by nocturnal atmospheric sounding at Weslaco during the ARS normal period indicated a 90% increased distance (from 466 km to 986 km) compared to that calculated using mean NWS wind velocity data at 500 m AGL. Further, the average ARS trajectories deflected 39 degrees counterclockwise from the average NWS trajectories. These results indicate that the nocturnal atmospheric displacements based on NWS data are underestimated, and that substantial clockwise change (veering) of heading occurs downwind of the source area. These results are consistent with measured trajectories of tetrahedral-shaped, mylar balloons (tetroons) launched from Weslaco and other locations in the LRGV (Westbrook et al. 1995).

The comparison of trajectory calculations with respect to moth flight tracks (measured by airborne radar or other Lagrangian platforms) has been the most appropriate validation method to-date. However, other alternative measurement platforms may be available. For example, superpressure balloons could be transported passively at the time and altitude of peak moth flight to document long-distance atmospheric trajectories. The superpressure balloon trajectories could be used to validate the computed atmospheric trajectories and reveal the representativeness of NWS upper-air data for nocturnal insect migration research. Furthermore, the superpressure balloon trajectories can be compared with simultaneous moth flight trajectories to derive the biological component of migratory flight displacements. Mark-recapture experiments can also be used to effectively validate trajectory calculations but require large numbers of marked adults and strategic trap placement to acquire even relatively small samples of marked moths. Thus, superpressure balloon trajectories and airborne radar trajectories could significantly increase the efficacy of mark-recapture studies.

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