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ANNUAL PATTERNS OF AERIAL INSECT DENSITIES AT ALTITUDES FROM 500 TO 2400 METERS IN EAST-CENTRAL TEXAS INDICATED BY CONTINUOUSLY-OPERATING VERTICALLY-ORIENTED RADAR

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ABSTRACT

Aerial insect densities were monitored continuously with an automated, vertically-oriented x-band radar system in the Brazos River Valley area of Burleson County near College Station, TX during most of 1990 and 1991. The primary emphasis of the research was the study of long-distance movement and flight behavior of noctuids which are important pests of several agricultural crops. The sensitivity of the radar system was such that noctuid-sized insects could be detected at a maximum altitude of about 2450 m. Aerial densities of flying insects were determined by automatic counting of radar-detected targets in 64 discrete range intervals spanning the altitude range from ground level to 2432 m. Insect densities were typically highest near ground level, they decreased nonlinearly with increasing altitude, and they were considerably reduced at altitudes above 800 m. There were apparent periodicities in the aerial densities during both years which were probably caused by interactions of the flight behaviors of several insect species, insect reproduction cycles, and the effects of seasonal weather patterns. The data indicated that continuously-operating vertically-oriented radar systems can provide information useful to the understanding of the spatial and temporal character of insect movement.

INTRODUCTION

Many insect species have the ability to take advantage of wind flow and fly to new habitats that are more conducive to successful reproduction and survival. Their flight capabilities contribute greatly to their pest status. Increased knowledge of the aerial dispersal behavior of several important agricultural pest species is needed to facilitate the development of improved area-wide management and control strategies.

The use of ground-based radar has become a well-established technique for observing insects in flight. Riley (1974), Schaefer (1976), Drake (1982), Wolf and Pair (1982), and Beerwinkle et al. (1988) have described scanning pencil-beam X-band (3.2 cm) systems used in entomological research of aerial occurrence and movement of insects. Scanning entomological radars have been used extensively in research of nocturnal flight activity and movement behavior of grasshoppers (Schaefer 1976, Riley and Reynolds 1979, Riley and Reynolds 1983, Reynolds & Riley 1988); African armyworms, *Spodoptera exempta* Walker (Rose et al. 1985, Riley et al. 1981, 1983); spruce budworms, *Choristoneura fumiferana* (Clemens) (Schaefer 1976); corn earworms, *Helicoverpa zea* (Boddie) (Wolf et al. 1986, Beerwinkle et al. 1988); Old World bollworms, *Helicoverpa armigera* (Hübner) (Riley et al. 1992); and other macro-insects (Drake et al. 1981, Drake 1984, Drake and Farrow 1985).

In typical field operations with the scanning radars, target echoes were displayed on a plan-position indicator (PPI) as the radar beam was scanned through 360° in azimuth and various degrees of elevation. Insect target echoes displayed on the PPI were analyzed in real time by a radar operator, and the displays were usually photographed to preserve the data for later analyses.

In 1988-89, a scanning radar was operated in East-Central Texas (Burleson County) from sunset to sunrise, five nights per week from June through August, and on selected nights during the spring and fall seasons of both years. Operating in this manner, seasonal nocturnal patterns of aerial insect densities in the study area were determined and several major upper-air insect movement events were detected as they occurred (Beerwinkle et al. 1994). These data showed that continuous monitoring of aerial insect activities with radar could contribute useful information to our understanding of insect flight activity and movement; however, labor costs for such operations were high.

This research led to the development of an automatic, vertically-oriented entomological radar system with rotating, linear polarization and computerized data logging that can be operated in an automatic (unmanned) mode for extended time periods (Beerwinkle et al. 1993). This radar system was operated during most of 1990 and 1991 to continuously monitor the aerial concentrations of airborne insects at altitudes up to 2432 m. The radar study site was in an area of diversified row-crop agriculture (primarily cotton, corn, and sorghum) that has been identified as being in a potential movement corridor for atmospheric transport of noctuid pests (Hartstack et al. 1982, Wolf et al. 1986, Showers et al. 1989). A brief description of the operating characteristics of the vertically-oriented radar system and some results from these studies are presented here.

MATERIALS AND METHODS

Radar System. The basic configuration of the vertically-oriented radar system was similar to those described by Riley and Reynolds (1979) and Smith et al. (1993). A Furuno Model FR-810D marine transceiver, which transmitted a pulsed 9.41 GHz signal with peak power of 10 Kw (pulse repetition frequency = 3 Khz, pulse length = 80 ns) and received with a characteristic noise figure of 6 Db, formed the nucleus of the system. The antenna assembly was composed of a 1.83-m diam. circular parabolic reflector (3-dB power angle = 1.2°) fitted with a rotating (24 rpm) dipole feed and a noise-attenuating shroud. The system had a theoretical range resolution of 12 m for single target detection.

The parabolic antenna was placed in a fixed position so that the radar beam pointed vertically upward. Insects were detected by the radar receiver as they flew or were carried through the pencil-shaped beam by the wind. Signal processing by the receiver electronics determined the vertical range (altitude) to the detected targets and quantized the radar echo pulses over seven levels of amplitude which provided seven levels of detection sensitivity. Range gating circuitry provided timing for distinguishing 64 altitude levels that spanned a range of 0 to 2432 m in discrete intervals of about 38 m. Field calibration of the system (Beerwinkle et al. 1993) indicated that noctuid-sized moths could be detected at a maximum height of about 900 m at the lowest sensitivity level and 2450 m at the highest sensitivity level.

The power of radar return signal echoes reflected from the underside of an insect varies with the angle between the longest body axis of the insect and the polarization angle of the incident radar beam (Riley 1985). Thus, the amplitude of a return signal from an insect flying with a given heading and altitude over a vertically-oriented radar varies with the position of the insect relative to the center of the radar beam and the orientation of the rotating feed of the radar antenna. With appropriate signal detection hardware and data analysis software, this phenomenon can be used to discern insect flight alignment from the radar return data; however, in our application this was not attempted. We simply counted the numbers of discrete radar echoes detected at each of the seven sensitivity levels in each of the 64 range intervals spanning the altitude range from ground level to 2432 m. The rotating radar antenna feed with accompanying beam polarization rotation insured that at least some return signals of maximum amplitude were obtained from insects which had a common orientation. The time duration of echoes from individual insects varied with detected insects' flight speed and position in the radar beam, radar beam polarization, wind speed, continuity of returns from single targets, and actual concentrations of insect targets. Counts signifying detection of single targets increased with increasing target concentrations until the concentrations approached radar saturation levels, and the counts decreased as concentrations increased further.

Data Collection and Analyses. Computer algorithms were written to process the data in a manner such that all radar echoes detected at each of the seven sensitivity levels for each of the 64 range intervals were counted as discrete targets. The software included provisions for minimizing the occurrence of multiple counts from the same target due to discontinuities in radar return signals. Successive 5-minute accumulated counts of echoes were recorded in 7 x 64-element arrays on a computer hard disk for subsequent analyses. The data were edited to remove spurious data caused by precipitation and radar system malfunction. The number of echo counts obtained from birds was considered to be insignificant relative to the counts from insects, and there was no effort to remove bird counts from the data.

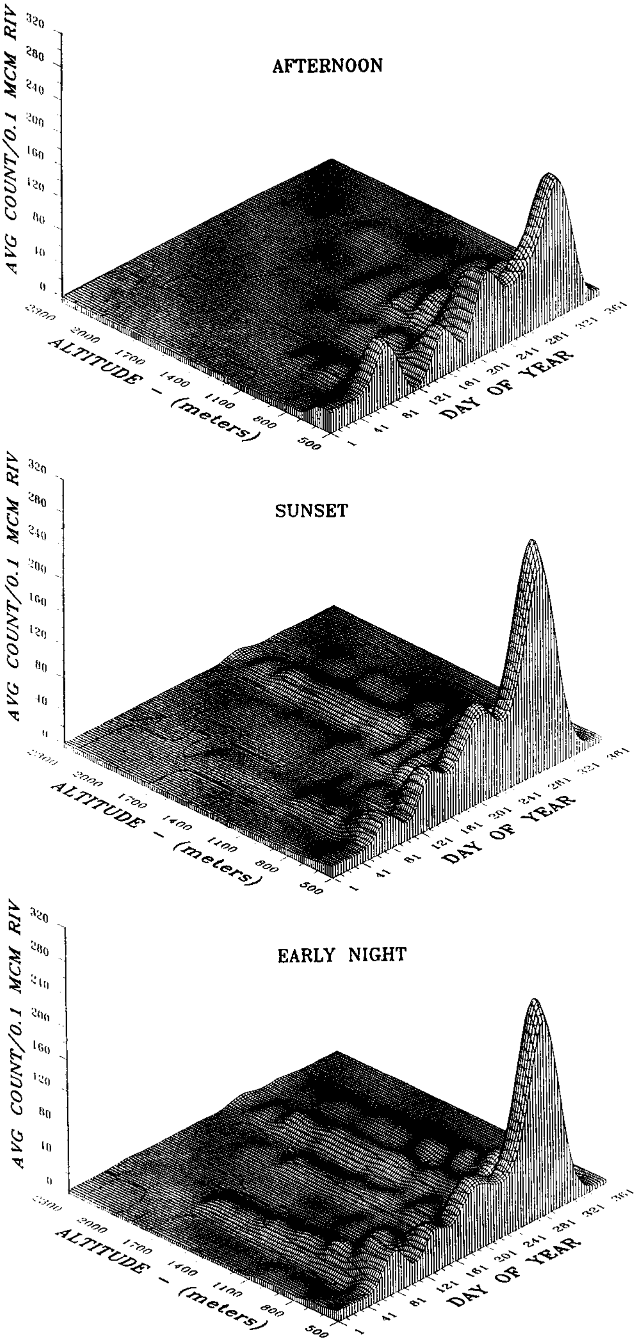
Radar count data used for count density calculations were derived from the original data set in the following manner. First, the highest 5-minute count was selected from each of the seven-count arrays that corresponded to the seven sensitivity levels for each of the 64 discrete range intervals (RIs) which together spanned the altitude range of 0 - 2432 m. Then, the selected high counts, accrued in the respective 5-minute intervals, for the 64 RIs were summed in a manner to yield total 5-minute counts for four new discrete RIs of 38 m spanning the altitude interval of 0 - 152 m, four RIs of 76 m for the interval of 152 - 456, four RIs of 152 m for the interval of 456 - 1064 m, three RIs of 304 m each for the interval of 1064 - 1976 m, and one RI of 456 m for the interval of 1976 - 2432 m. To further condense and summarize the data, the successive 5-minute interval counts for each of the 16 new altitude intervals were subsequently averaged over the following six discrete daily time periods: afternoon - (midday to sunset), sunset - (sunset to 2 hours after sunset), early night - (2 hours after sunset to middle of night), late night - (middle of night to 1 hour before sunrise), sunrise - (1 hour before sunrise to 0.25 hour after sunrise), and morning - (0.25 hour after sunrise to midday). This procedure yielded a single 5-minute count value for each of the reconstructed altitude intervals in each daily time period. The echo count data were subsequently scaled so that each value represented a count density of radar echoes detected in a standard radar range interval volume (RIV) of 0.1 million cubic meters (MCM). Standard RIV's for the different altitudes within the radar detection beam in which noctuid-sized (radar cross section = 0.5 cm^2) targets could be detected were calculated using a modification of the methods given by Riley (1979) for calculating swept volumes for scanning radars.

Related Biological and Climatological Data. In related research during the two years of the radar study, sex pheromone trapping of several agriculturally-important noctuid pests was conducted in the cropping area in the vicinity of the radar site to determine spatial and temporal patterns of trap catches for the various species. During most of both 1990 and 1991, various numbers of wire-mesh cone traps (Hartstack et al. 1979), baited with appropriate pheromone lures, were used to trap corn earworm; tobacco budworm, *Heliothis virscens* (F.); armyworm, *Pseudaletia unipuncta* (Haworth); and black cutworm, *Agrotis ipsilon* (Hufnagel), males. Beginning in April during both years, cone traps were used to monitor the occurrence of fall armyworm, *Spodoptera frugiperda* (J. E. Smith). In addition, international pheromone (IP) traps were used throughout 1990 to monitor the presence of velvetbean caterpillars, *Anticarsia gemmatalis* Hübner, and from April to December 1991, cone traps were used to monitor male activity of variegated cutworm, *Peridroma saucia* (Hübner), in the area. Average numbers of males captured per trap per night for the various species were plotted versus day-of-year, and relationships between radar-observed aerial insect activity patterns and the temporal patterns of pheromone trap catches are discussed.

Summaries of climatological data, including ambient surface temperatures and rainfall for the radar-site area and areas where insects develop in early spring, were obtained from National Oceanic and Atmospheric Administration publications (NOAA 1990, 1991). The data were plotted versus day-of-year, and the effects of weather on the radar-observed insect flight activities are discussed.

RESULTS AND DISCUSSION

Results obtained in 1990 and 1991 are presented in four series of three-dimensional graphs (FIG. 1, 2, 3 & 4) which were



AFTERNOON

SUNSET

EARLY NIGHT

FIG. 1. Average 5-minute count densities of radar-detected targets during the daily time periods of afternoon, sunset, and early night during 1990.

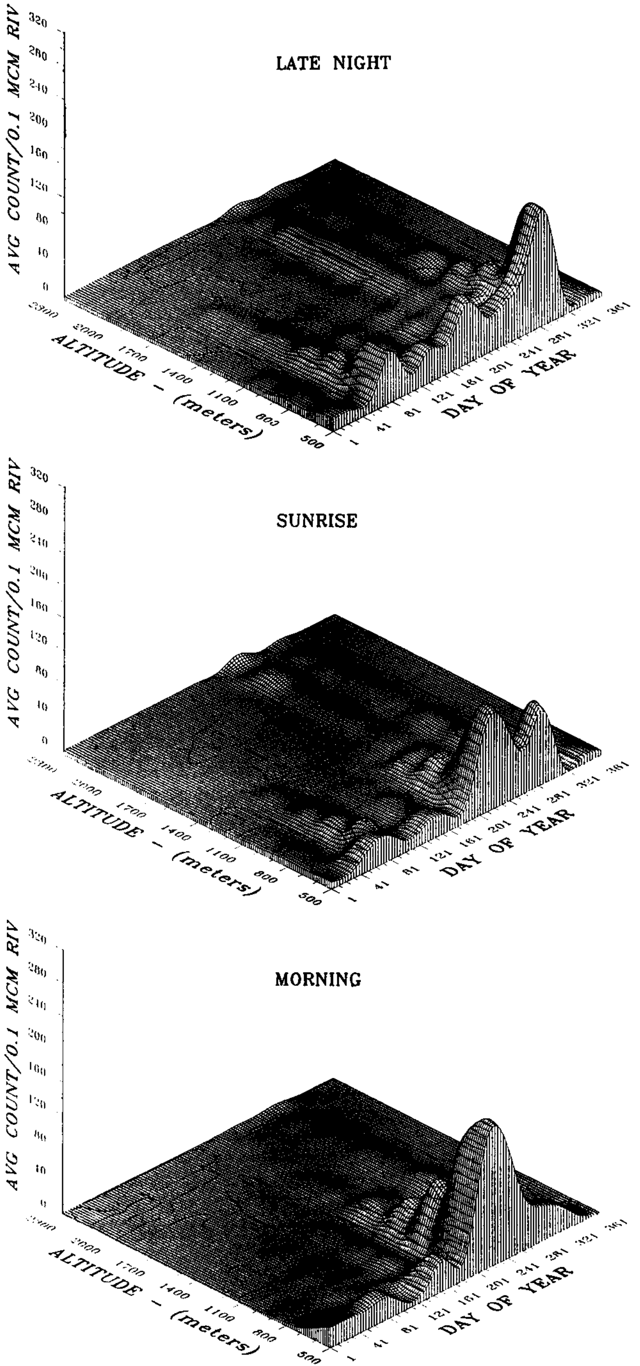


FIG. 2. Average 5-minute count densities of radar-detected targets during the daily time periods of late night, sunrise, and morning during 1990.

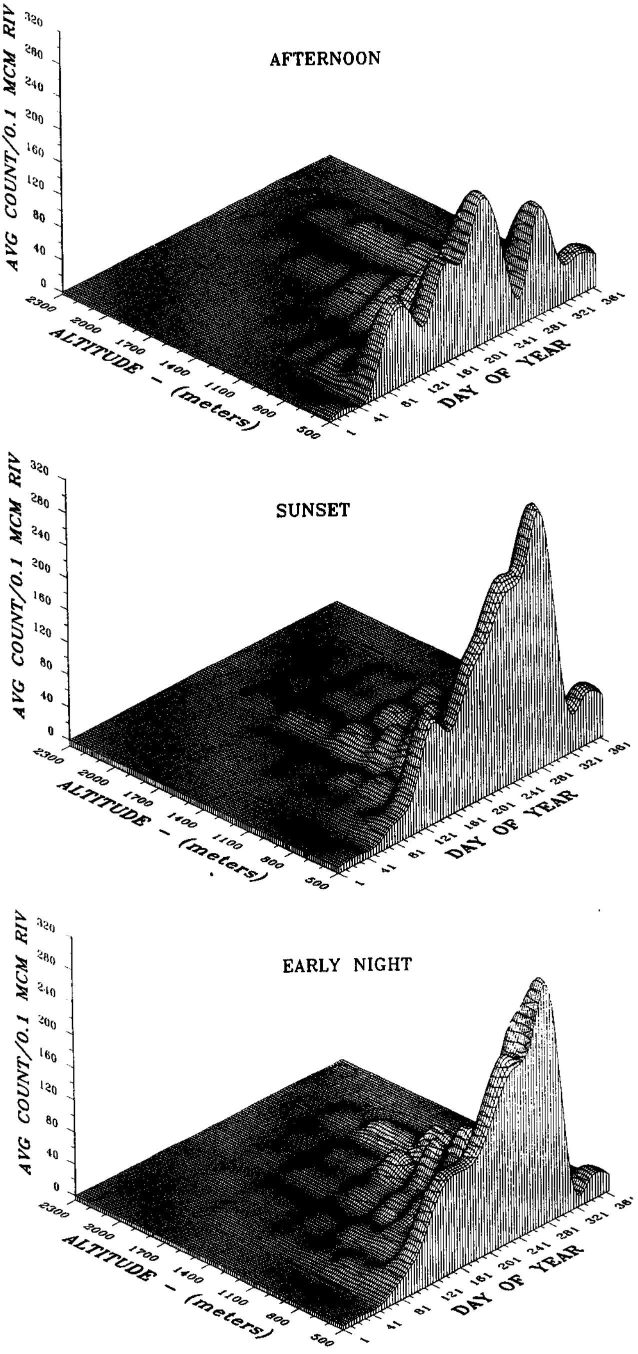


FIG. 3. Average 5-minute count densities of radar-detected targets during the daily time periods of afternoon, sunset, and early night during 1991.

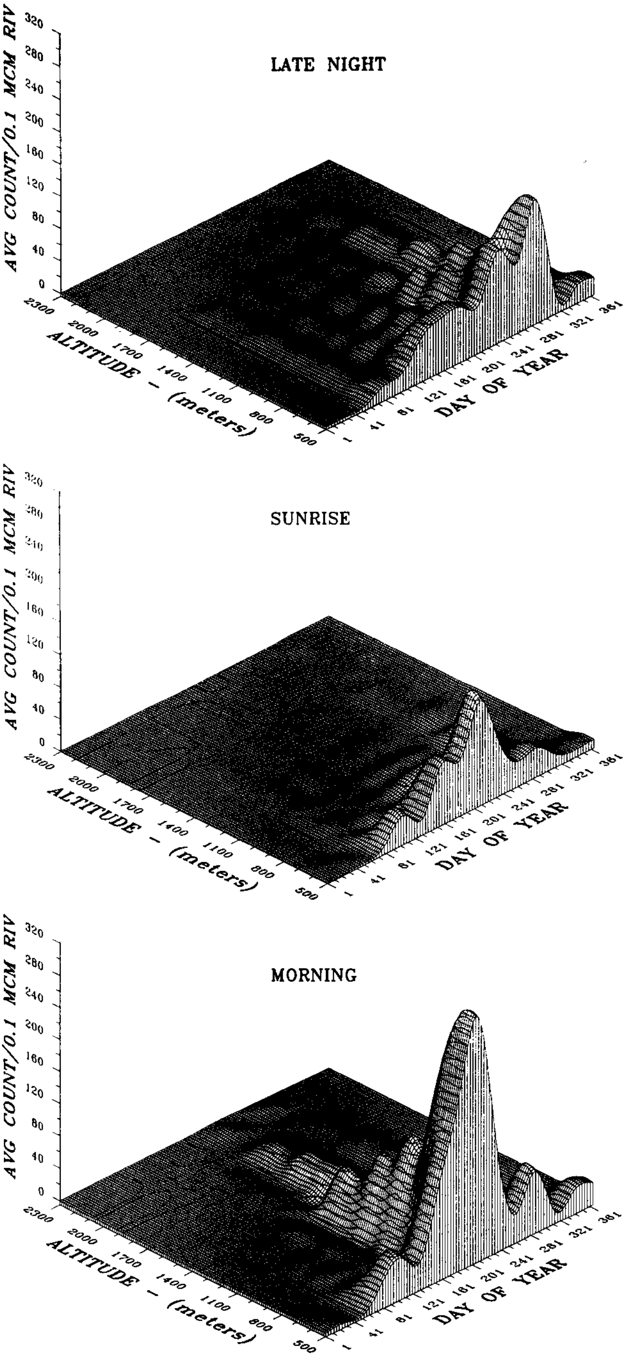


FIG. 4. Average 5-minute count densities of radar-detected targets during the daily time periods of late night, sunrise, and morning during 1991.

plotted using the Surfer computer program (Version 4, Golden Software, Inc., Golden, CO). The averaged radar count data obtained in the six discrete daily time periods during each year are plotted on the vertical axis versus day-of-year (DOY) on one horizontal axis and altitude on the other. The radar was capable of detecting insects as small as planthoppers at altitudes up to about 500 m (Beerwinkle et al. 1993), so numerous small insects were included among the echoes detected and counted in the altitude ranges < 500 m. Since we were primarily interested in the flight activities of noctuid-sized insects involved in long distance movement, only the mean count data for the eight discrete RIs spanning the altitude range from 456 to 2432 m are included in the graphs. The three-dimensional graphs provide a means for summarizing large amounts of data, and certain long-term (periods of several days) periodic relationships of aerial densities with time are readily apparent. However, since the data were averaged, some potentially important short-term events that occurred over a few days may have been obscured.

Several patterns of the data are common to all of the plots for the two years. There were consistently much higher densities of insects at the lower altitudes, and the densities decreased dramatically above altitudes of about 700 m. This was due both to the fact that insect densities likely decreased rapidly with altitude and to the fact that the ability of the radar to detect insects of a given size decreased at a rate proportional to the fourth power of the range distance with increased altitude so that the detection range for smaller insects was limited. The averaging of the count data over periods of several hours in duration and consolidating it into eight discrete vertical RIs contributed to the apparent periodicities over altitude and caused considerable loss of density resolution. Analyses of the data over shorter time periods and smaller RIs would be necessary to detect short-term overflights of dense layers of insects.

The plots of 1990 data (FIG. 1 & 2) generally indicate four distinct peaks of insect flight activity over the year at altitudes below about 700 m and five peaks of activity at the higher altitudes (> 700 m) during the nocturnal flight periods from sunset through late night. Early season peak activities, both at the lower and higher altitudes, occurred in mid-March (DOY ≈ 75). The second peak of activity in the lower altitude (< 700 m) occurred in mid-May (DOY ≈ 135) with one comparatively minor peak in activity in the higher altitude (> 700 m) occurring about two weeks earlier (DOY ≈ 120) and another about two weeks later (DOY ≈ 150). The third peak in activity in the lower altitude occurred in mid-July (DOY ≈ 200), followed by a major peak in the upper-air activity in early August (DOY ≈ 220). The largest peak in lower-altitude nocturnal activity for 1990 occurred in early October (DOY ≈ 280), preceded by a peak in upper-air activity in mid-September (DOY ≈ 260).

Radar-detected diurnal insect flight patterns during the sunrise, morning, and afternoon periods in 1990 had some similarities and some contrasts to those of the nocturnal flight periods. Differences between diurnal and nocturnal flight patterns were most apparent in the plots for the morning period (FIG. 2). The morning period had four distinct peaks of flight activity in the lower altitudes (< 700 m), similar to that which occurred during the night periods, but there were some differences in the timing and relative amplitudes of the four peaks of diurnal and nocturnal insect flight. The largest peak in the low-altitude diurnal flight occurred in early August (DOY ≈ 220); whereas, the largest peak in nocturnal low-level flight occurred much later in the season. There were four peaks in upper-air (> 700 m) diurnal flight activities compared to five peaks in nocturnal flight, and there were some differences in the timing and relative amplitude of the peaks in the day and night periods. In general, there was less insect flight detected at the higher altitudes, particularly above ≈ 1300 m, during the day than during the night. The flight patterns reflected in the afternoon and sunrise periods appear to be transitional from diurnal to nocturnal patterns and from nocturnal to diurnal patterns, respectively.

The plots of 1991 data (FIG. 3 & 4) indicate that insect flight patterns were generally similar to those observed in 1990. As in 1990 (FIG. 1 & 2), five distinct cycles of increased nocturnal flight activity occurred at the higher altitudes (> 700 m). The seasonal timing of the upper-air activity peaks was comparable during the two years, but the early-season activity levels in 1991 were relatively lower than those observed in 1990.

The nocturnal flight activities in 1991 at the lower altitudes (< 700 m) were also cyclic, but the individual cycles were not as distinctly defined as they were in 1990. Nightly lower-altitude flight activity began to increase in early March (DOY ≈ 75), and it continued to generally increase daily throughout the season, reaching a maximum peak in early October (DOY ≈ 280). Minor peaks in nocturnal, low-altitude flight activities were evident in late May (DOY ≈ 150) and late August (DOY ≈ 240). The 1991 patterns of diurnal insect flight activities at both the upper and lower altitudes were similar to those of 1990. As in 1990, the largest peak in diurnal low-altitude flight occurred during the summer (DOY ≈ 200); whereas, the largest peak of nocturnal low-altitude flight occurred in the fall (DOY ≈ 280).

The differences in radar-detected nocturnal and diurnal aerial insect densities and the cyclic nature of the density patterns, observed during both 1990 and 1991, were probably caused by interactions of the flight activities of several different insect species, insect reproductive cycles, and effects of seasonal weather patterns. Numerous insect species likely contributed to the composite flight activities observed; however, due to the detection-sensitivity limitations of the radar, those insects detected flying in the upper air above 1000 m were near the size of noctuids or larger. Some upper-air insect flight activities were apparent during the daylight periods of both years, but considerably more upper-air flight activities were detected during the night periods, particularly during the early night, when noctuids and other night-flying insects such as crickets and grasshoppers would be involved in long distance flight.

Noctuids and other large night-flying insects also probably contributed substantially to the flight activities observed at altitudes below 1000 m. There are apparent correlations during both 1990 and 1991 between the time and magnitude of increases in radar-observed insect densities and local increases in the presence of several noctuid species as indicated by catches in traps baited with pheromones (FIG. 5 &

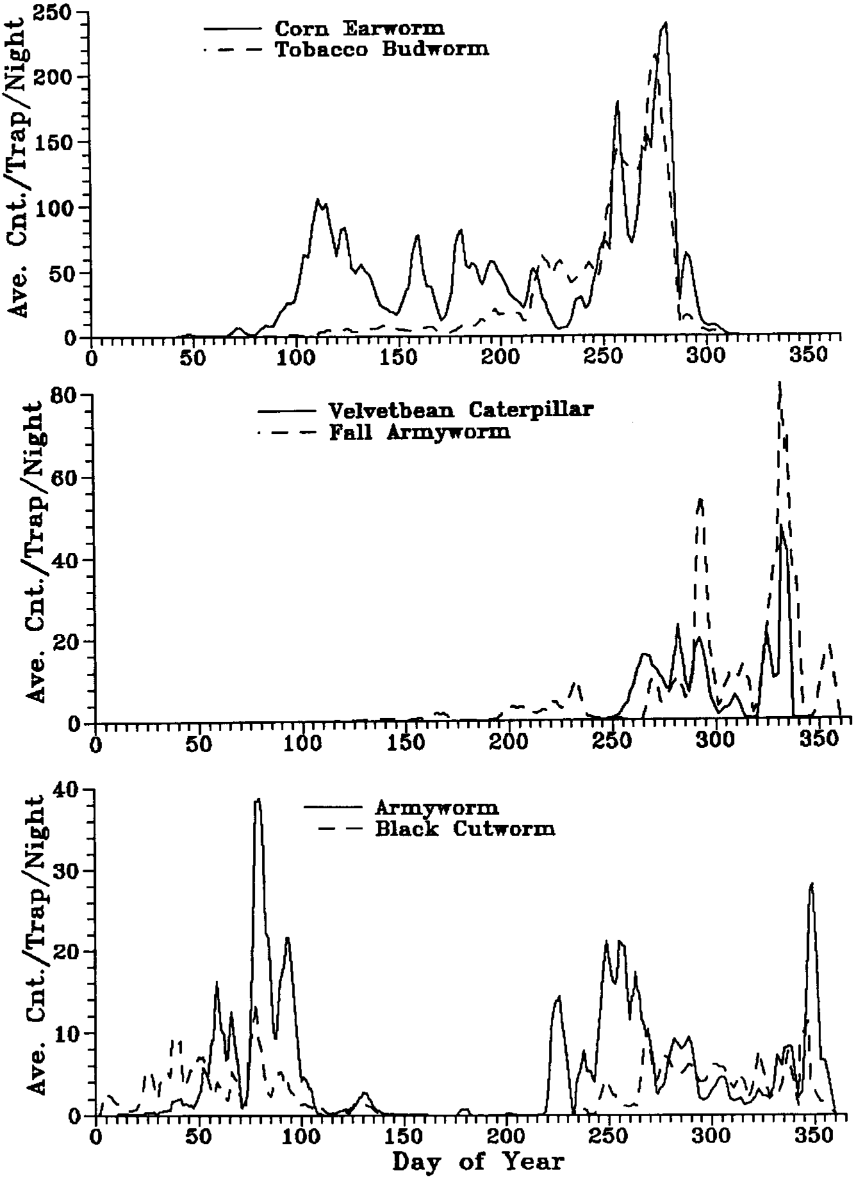


FIG. 5. Average nightly captures of indicated noctuid species males in pheromone-baited traps located in the vicinity of the vertical radar site during 1990.

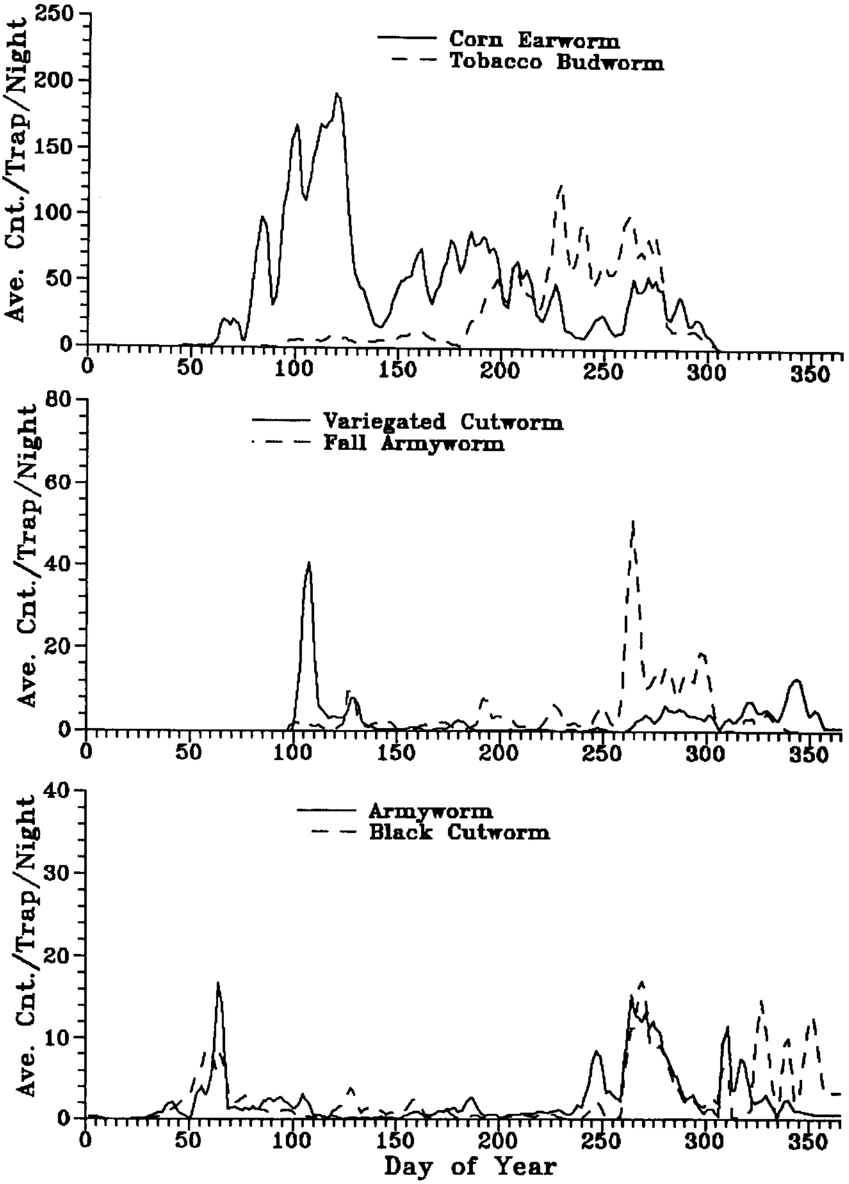


FIG. 6. Average nightly captures of indicated noctuid species males in pheromone-baited traps located in the vicinity of the vertical radar site during 1991.

6). During 1990, the timing of catches of armyworms and black cutworms, that were apparently migrants passing through the area, corresponded to the occurrence of the early-season radar-observed peak of insect flight activities between days 50 and 100. Catches of corn earworms indicated that this species likely contributed to the radar-observed insect flight activities beginning about day 45 and continuing with some variability through the summer into early fall. Local activities of all six noctuid species monitored with pheromone traps (FIG. 5) started increasing during August, and substantial activities of all the species were evident throughout most of September and October. The increased local activities of the noctuid species in early fall corresponded to the time when maximum count densities of night-flying targets were detected with the radar at all altitude levels during 1990. At other times during 1990, correlations between the radar data and trap-catch data are not as obvious. However, this is not surprising because numerous insect species, in addition to those monitored with traps, contributed to the radar counts.

The apparent correlations between noctuid trap catch data (FIG. 6) and radar data (FIG. 3 & 4) for 1991 are similar to those observed for 1990. However, there are differences between the trap catch patterns and between the echo count density patterns, respectively, for the years of 1990 and 1991. Differing weather conditions during the two years, both in the local area and in some suspected source areas of early-season insect migrants, probably contributed to the differences observed. Plots of the average monthly surface air temperatures for College Station, the Lower Rio Grande River Valley (general area extending from McAllen to Harlingen, TX), and the Upper Texas Coast (general area extending from Victoria to Beaumont, TX) (FIG. 7) indicate that temperatures during January and February of 1991 at all three locations were considerably lower than those which occurred during the same months in 1990. In addition, monthly rainfall records (FIG. 8) indicate that the rainfall accumulations in all three areas, particularly at College Station and along the Upper Coast, were considerably higher during January 1991 compared to 1990. The records further indicate that rainfall amounts received throughout 1991 generally exceeded the amounts received during 1990 at all three locations. The occurrence of cool temperatures and high rainfall in the source areas for migrants early in 1991 may have delayed the timing and reduced the numbers of early-season migrants produced. This could have reduced the numbers of early-season insects passing through the area of the radar site in 1991 compared to 1990 as reflected in the plots of radar observations for the two years (FIG. 1, 2, 3 & 4). Other differences in the radar-observed insect flight patterns and noctuid trap-catch patterns for 1990 and 1991 are probably weather related, but it is not possible to discern cause-and-effect relationships of these factors without more complete weather data and explicit knowledge of the insect species composition of the radar targets observed.

Overall, results of this research illustrated that long-term monitoring with vertically-oriented radar can provide important information related to the spatial and temporal character of insect movement in a given area. Technological improvement of the radar equipment and data analyses procedures used in these studies in the manner described by Smith et al.

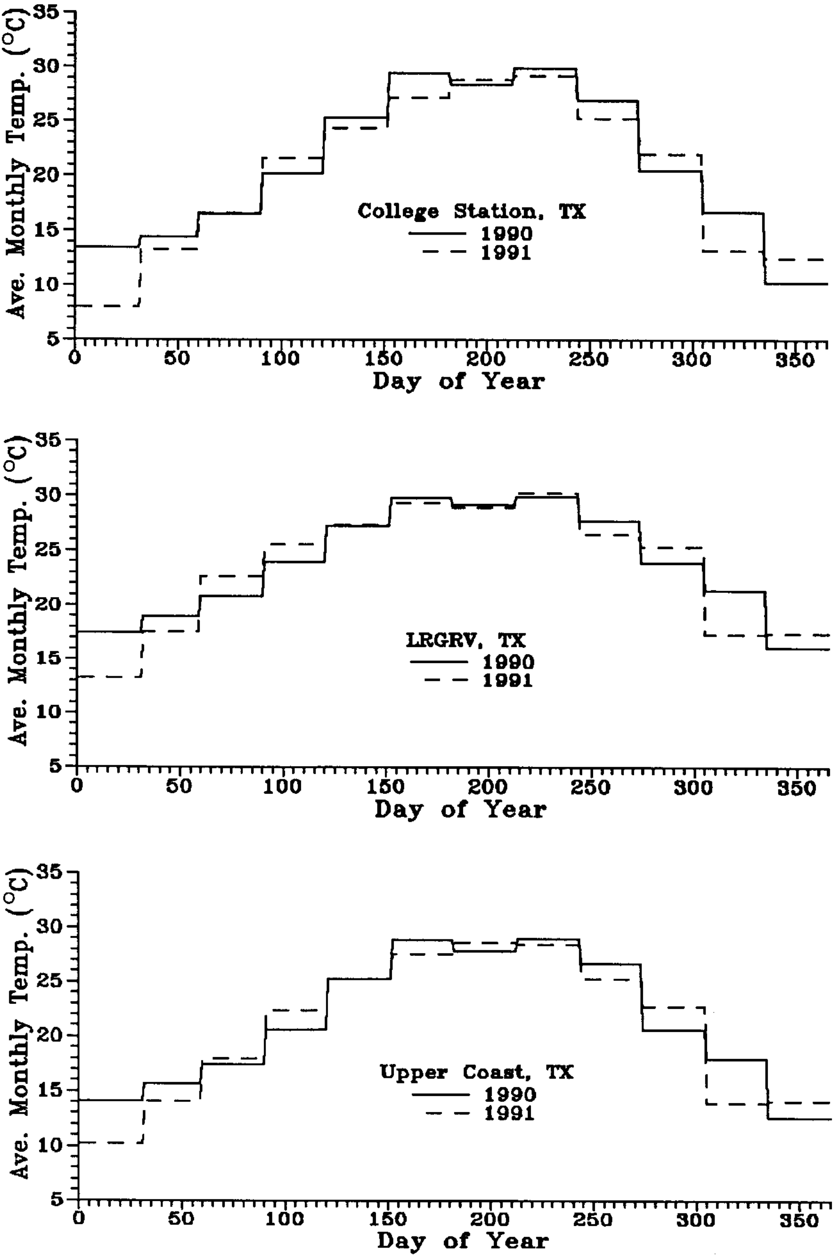


FIG. 7. Average monthly ground-surface (1.5 m) air temperatures recorded at College Station, TX and in the geographic areas of the Lower Rio Grande River Valley (LRGRV) and the Upper Coast of Texas during 1990 and 1991.

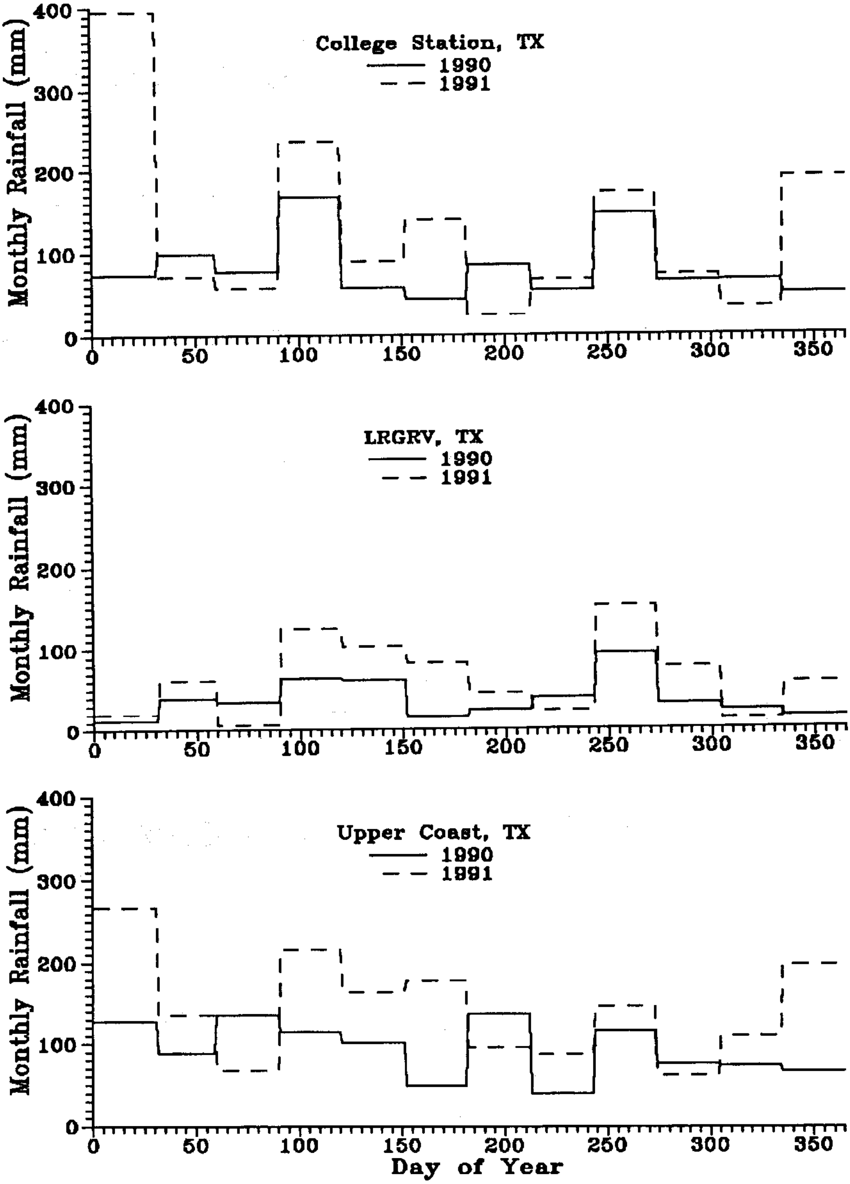


FIG. 8. Monthly accumulated rainfall at College Station, TX and the average monthly accumulated rainfall in the geographic areas of the Lower Rio Grande River Valley (LRGRV) and the Upper Coast of Texas during 1990 and 1991.

(1993) to enable the securing of information on detected insect's flight speed and direction, orientation, size, shape, and wingbeat frequency would enhance the usefulness of vertically-oriented radar for research of insect movement. Deployment of suitably equipped, unmanned, vertically-oriented radar systems in strategic locations to monitor insect movement could provide information for identifying geographic sources of insect migrants. This information would contribute to the development of improved area-wide management strategies for several species of important insect pests.

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