

# State Water Survey Division

CLIMATE AND METEOROLOGY SECTION

AT THE  
UNIVERSITY OF ILLINOIS

# ENR

Illinois Department of  
Energy and Natural Resources

SWS Contract Report 379

## IDENTIFICATION OF LONG RANGE PEST FLIGHT PATTERNS VIA WIND TRANSPORT MODELING

*by*

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Champaign, Illinois

March 1986



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## FORWARD

This report presents results from part of a joint study on the migration of insect pests into Illinois conducted by scientists from the Natural History Survey and State Water Survey Divisions of the Illinois Department of Energy and Natural Resources (Achtemeier et al., 1986). The overall objective of this program was to contribute toward the information base necessary for improving the prediction of the timing and quantity of insect pests migrating into Illinois. This goal is noteworthy due to the maleficent effects pests have on Illinois agriculture, one of the major industries of the state.

The project encompassed many scientists from both organizations representing a wide variety of expertise. Studies included laboratory research on the physiological and genetic links of locally captured specimens to pests in potential source regions, and field operations which involved the sampling of insects on the ground and also while in flight via kites and aircraft. In addition, pest movements were monitored with the use of Doppler radar.

The focus of this report deals with an investigation of the contribution made by surface and near-surface winds during migration events. A numerical algorithm is employed which calculates trajectories of the wind in the lower atmosphere, providing an estimate of the pathways of air that passed over a particular location. Intuitively, this points to potential source regions for passive travelers within the airflow.

#### ACKNOWLEDGEMENTS

This work was supported under a special Board of Natural Resources initiative designed to encourage inter-disciplinary collaboration between the Surveys. Specifically, funds for this research were provided through the Department of Energy and Natural Resources of the State of Illinois under contracts STILENRAQ14-ISWS635, STILENRWEATHAQ14-752 and STILENRAQ16WEATHR880. The authors would like to thank Donna Isard for preparing the figures.

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## IDENTIFICATION OF LONG RANGE PEST FLIGHT PATTERNS VIA WIND TRANSPORT MODELING

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Climate and Meteorology Section

### 1. Introduction

Relationships between air movement and the migration of biota have been investigated for many years, mainly by researchers within the biological sciences. Many techniques have been adopted in an effort to characterize the movement of biota through the description of air movement. These include the use of wind roses and climatological prevailing winds at one or more points, streamlines, and trajectories at a variety of elevations. In many cases incorrect assumptions have been made in the use of these techniques for interpreting migratory pathways, leading to wide divergence between these estimated migratory tracks and the actual trajectory of the air in which the biota traveled.

A number of these studies addressed the highly productive farming regions of the central United States where migrations of agricultural pests are obviously of much concern. Results indicate a close association between pest migrations in this region and a particular weather configuration: high pressure along the east coast of the United States and low pressure over the Great Plains (Hodson and Cook, 1960; Pienkowski, 1962; Peterson et al., 1968-1969). In general, this pattern creates conditions that favor a warm southerly flow of air from the Gulf states into the North Central region of the country, an important transport factor in many pest migration studies (Wallin et al., 1967; Wallin and Loonan, 1971; and Kieckhefer et al., 1974). In addition, a frontal system is often present in the catch area, which has been cited as a barrier to further migration (Huff, 1963; Pienkowski and Medler, 1964; Nichiporick, 1965; Rose et al., 1975; Dickinson et al., 1983). Hughes (1970) and Drake et al. (1981) have observed nearly identical relationships between synoptic patterns and pest flights over Australia.

The role of weather is equally important on the small scale, where insects in flight are transported almost entirely by the local wind regime. Most migrants participate actively by launching themselves into the air and continuously flapping their wings to remain aloft (Johnson, 1969). However, many fly only at temperatures above certain threshold values (Berry and Taylor 1968; Jensen and Wallin, 1965). Furthermore, recent research indicates the ability of some pests to locate the levels of warmest temperatures and highest wind speeds (Rose et al., 1975; Hendrie et al., 1984). Despite this apparent resourcefulness, most individual insects have such small mass that all but the largest have negligibly small air speeds, i.e., their transport is essentially passive (Rose et al., 1975).

Due to the potentially severe effects on agriculture, migrations of particular pests stimulate research interests, in part, towards a determination of source regions. An eventual objective of these studies would be the ability to control the pest at its origin, thereby preventing or lessening the effects of a subsequent migration into agriculturally sensitive regions.

In the past, origins have been estimated by "backtracking" pests of suspected migrations using wind data for the area near the time of insect arrival. For the most part, these studies have relied upon readily available meteorological charts, most noticeably, daily charts that depict winds at ground level and 850 mb (approximately 1500 m). However, these charts show only general weather conditions and are often unsuitable for describing the wind fields at levels favored by migrating insects. Consequently, back-trajectories which are produced can be in error and misleading in the interpretation of insect behavior. The numerical trajectory analysis scheme we have developed provides a means for incorporating the large variability that occurs in wind velocities throughout the lower troposphere in estimating pest origin.

An accurate method for plotting air movement at any elevation within and just above the planetary boundary layer of the atmosphere (lowest 1-1.5 km) is necessary to provide the direction taken by small insects such as aphids during long-distance flights. The method must achieve a high degree of accuracy with data from the National Weather Service upper atmosphere soundings measured twice daily from an irregular grid of widely-spaced monitoring sites. Additionally, the algorithms used must not be so complex as to be prohibitively expensive or so time-consuming that they would be of little value in a predictive mode. The trajectory model presented in this paper is designed to be computationally fast (and therefore relatively inexpensive to use) as well as accurate.

To obtain the desired accuracy, the mathematical algorithms must minimize inherent interpolation and extrapolation errors that are commonplace to objective trajectories and include the available meteorological data necessary to describe air motions on the scale of the insect migrations. In developing our trajectory model, we considered 1) the accuracy of the method for gridding weather data collected from an irregularly spaced array of observing sites, 2) the theoretical error of the mathematical algorithms that generate the trajectories from the gridded wind data, 3) the vertical resolution necessary to describe the winds at levels the insects fly, 4) the horizontal resolution necessary to describe the weather systems transporting the insects, and 5) the temporal resolution of these same weather systems, particularly those disturbances with life spans shorter than the interval between data collection.

The methods employed to develop and test the trajectory model are explained in the following sections. Section 2 describes the methods to grid the meteorological observations. Section 3 presents the theoretical development of the algorithm that creates back-trajectories from the fields of gridded data. Section 4 presents the results from studies to evaluate the temporal and spatial resolution of the method. Section 5 gives comparisons between the trajectory model and methods used by other investigators to estimate migratory tracks. Section 6 presents analyses of weather systems that could lead to wide divergence between the estimated trajectory tracks and the actual trajectories of the air in which the biota traveled. The results from the evaluation of the trajectory model are summarized in Section 7.

## 2. Objective Analysis of Meteorological Data

Figure 1 shows the National Weather Service network for the measurement of winds aloft. These stations are separated by roughly 225 miles (365 km) with the greatest separation between stations located, unfortunately, through the region of greatest importance to the study of insect movements into Illinois, the Mississippi River basin. Our analysis region is extensive, bounded by the Rocky Mountains on the west, the Gulf Coast on the south, the Canadian border on the north, and near the eastern coast of the United States. This large region is required because insect migrations may occur over periods of several days and involve movements of great distances on those occasions when winds in the planetary boundary layer are strong.

The twice daily wind observations are taken at 0600 and 1800 CST using specially equipped balloons. These data are taken at select levels above sea level (msl) to very high elevations within the stratosphere or until the balloons burst. The program we have developed includes methods to reorder the data so that all levels are sequential and are in elevations msl.

Even though the Rocky Mountains are not included within the analysis region, the elevations of the wind observing sites vary greatly, anywhere from sea level to 1500 meters msl. Air near the ground tends to blow parallel to the ground, but at higher elevations, near 2000 meters, the air tends to blow along surfaces of constant pressure except near weather fronts. We have therefore designed the trajectory model so that the lower coordinate surface is parallel to a smoothed ground surface and the upper coordinate surface at approximately 2 km is a surface of constant pressure. This "hybrid sigma" coordinate, a modification of a sigma coordinate presented by Phillips (1957), is described in an article by Achtemeier and Ochs (1986). National Weather Service network winds are interpolated to seven sigma levels from the ground to 2 km.

The method for gridding the wind data represented on sigma levels is a modification of a successive correction technique developed by Barnes (1964) and used widely in analysis of irregularly spaced meteorological data. This objective map analysis scheme is a computationally simple, Gaussian weighted-averaging technique which assigns a weight to a datum solely as a known function of distance between the datum and the grid point. The weight,  $w_m$ , is assigned according to the distance,  $r_m$ , between the datum  $f(x_m, y_m)$  and the  $(i, j)$  grid point as

$$w_m = \exp\left(-\frac{r_m^2}{b}\right), \quad (1)$$

where  $b$  is a parameter that determines the shape of the weighting curve and thereby the magnitude of the weight accorded to any datum. In his analysis of the filtering characteristics of (1), Barnes showed that the choice of  $b$  determines the minimum allowable scale of the weather disturbances that will be retained through the gridding process. This minimum allowable scale can not be smaller than the minimum resolvable scale permissible by the data, in this case, approximately 450 miles (730 km).

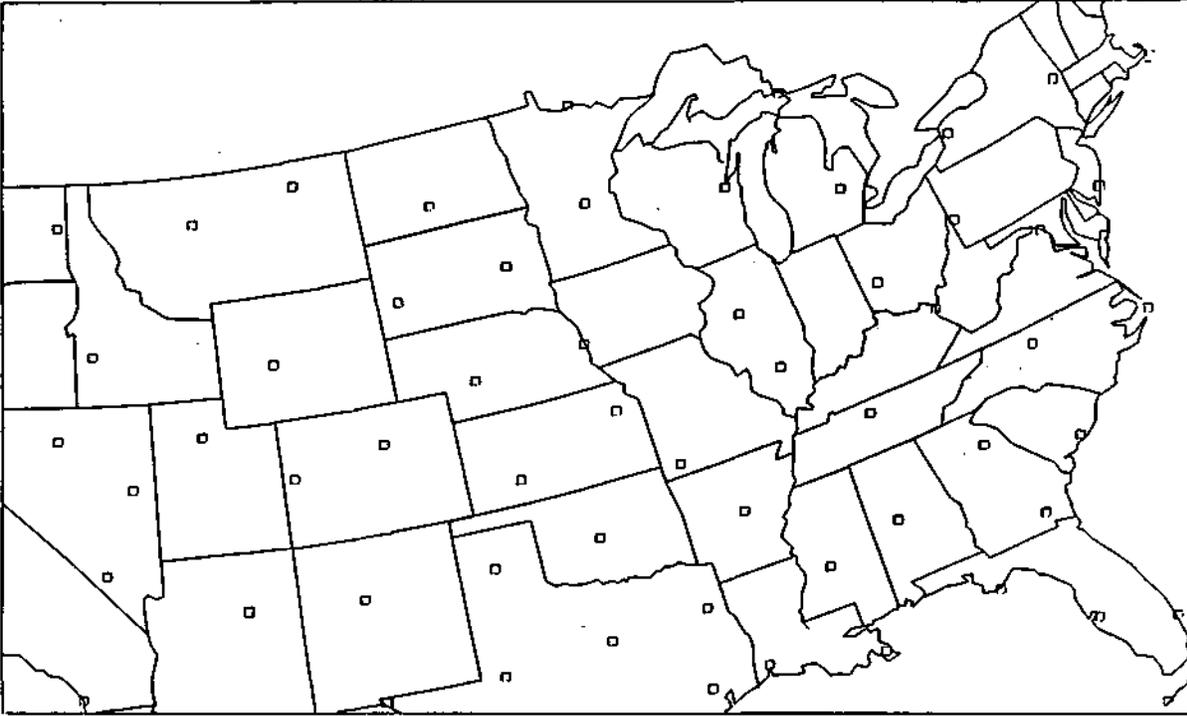


Figure 1. Map showing the distribution of National Weather Surface (NWS) winds aloft observing sites.

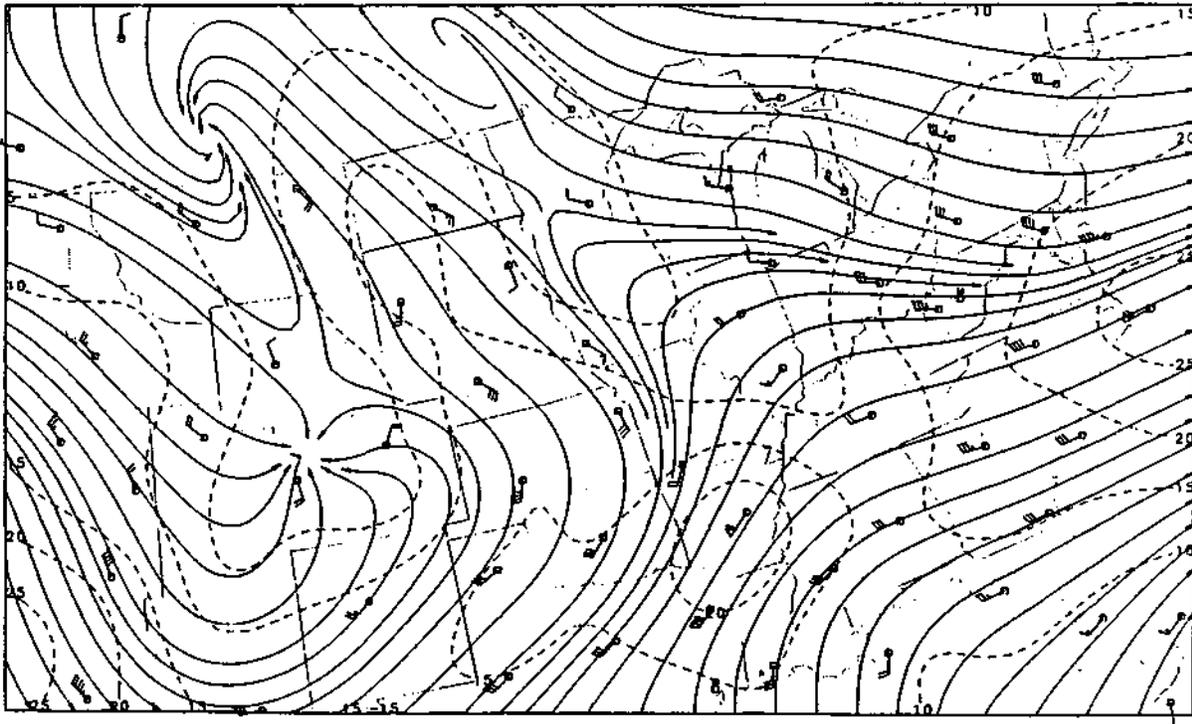


Figure 2. Streamlines and isotachs ( $\text{m s}^{-1}$ ) for wind field gridded from observations identified by the standard wind symbols (1-barb =  $2.5 \text{ m s}^{-1}$ ); . The analysis is for level 7 (800 mb) for 10 April 1979.

When only one pass is made through the data, the value at any grid point is simply the sum of the products of the surrounding data with their respective normalized weights. The correction pass grid field results from adding the weighted residual differences between the observed data values and the first pass estimated values which have been interpolated from the grid points back to the original observation locations. We have used a simple bilinear interpolation between the four grid points that surround the data location. The correction pass values at each grid point  $g_1(i,j)$  after the gridding of  $M$  observations are given by

$$g_1(i,j) = \frac{\sum_{m=1}^M W_m f(X_m, Y_m)}{\sum_{m=1}^M W_m} + \frac{\sum_{m=1}^M W'_m [f(X_m, Y_m) - g_0(X_m, Y_m)]}{\sum_{m=1}^M W'_m} . \quad (2)$$

The Barnes technique produces an acceptably accurate gridding of the wind field if the shape parameter of the weight function is properly chosen and if there are enough data to describe the actual wind field. The method does not work as well where the wind field is interrupted by a discontinuity such as a frontal zone. In this case, the Barnes objective analysis tends to smooth over the sharp wind shifts and to place the smoothed frontal zone midway between the observation sites. Efforts to improve the objective wind fields near frontal zones will be described in Section 7. Figure 2 gives an example of a gridded wind field. The standard wind symbols (1 barb equals 2.5 m/sec) locate the observed wind directions and speeds. Streamlines and isotachs (dashed lines in m/sec) describe the gridded wind field.

### 3. Theoretical Basis for an Accurate Back-Trajectory Method

An automated back-trajectory analysis technique should accurately describe the evolving field of flow. Since the sequence of extrapolated line segments is an approximation to the trajectory, some analysis error should be expected. A foreknowledge of the magnitude and character of this error is essential to knowing the level of confidence that should be placed on an analysis. As applied to the studies of insect migrations, an accurate back-trajectory analysis should lead to confidence in the estimation of the migratory pathways of insects. Therefore, a knowledge of the character of these errors gives some insight into the limitations of the method and reveals those areas of the back-trajectory fields which should be interpreted with caution.

This back-trajectory analysis method is an adaptation of a predictor-corrector (PC) method developed by Achtemeier (1979) for the analysis of streamlines. Consider the subgrid square illustrated in Fig. 3. The corner angles  $\alpha_i$ ,  $i=1,4$  have been found by bilinear interpolation from  $u$  and  $v$  components or the wind at points on a larger master grid at some time  $t$ . A schematic trajectory segment begins within the subgrid square at point A at the wind direction  $\alpha_b$  determined by interpolation of the wind field at some time  $t - \Delta t$ . A line segment tangent to the beginning angle is extrapolated forward a distance determined by the product of the wind speed with the time interval  $\Delta t$ . This line AC forms a first-guess trajectory segment. The speed

and wind direction at C,  $\alpha_e$ , are found by linear interpolation between the four corner angles. The beginning and ending velocities of the segment are averaged and the PC segment (i.e., the segment determined by the predictor corrector method) is extrapolated forward at this average wind direction  $\alpha_a$ . Perhaps the actual trajectory segment is the line AB. The distance BD would then be a measure of the PC method error for that trajectory segment.

For an arbitrary predictor-corrector method, we approximate the chord angle  $\alpha_t$  by some linear combination of the begin-of-segment angle  $\alpha_b$ , and the end-of-segment angle  $\alpha_e$ . Then the angular error between the approximated and true values of  $\alpha_t$  is given by

$$R = \alpha_t - (\alpha_b + W\alpha_e)/(1 + W) . \quad (3)$$

We then let  $R^* = \tan(2R)$ , so that

$$R^* = \tan[2\alpha_t - 2(\alpha_b + W\alpha_e)/(1 + W)] . \quad (4)$$

These angle sums and differences can be removed by the successive application of trigonometric identities. For the back-trajectory PC method,  $W = 1$ . Then  $R^*$  is expressed by

$$R^* = \frac{2\tan\alpha_t(1 - \tan\alpha_b\tan\alpha_e) - (1 - \tan^2\alpha_t)(\tan\alpha_b + \tan\alpha_e)}{(1 - \tan^2\alpha_t)(1 - \tan\alpha_b\tan\alpha_e) + 2\tan\alpha_t(\tan\alpha_b + \tan\alpha_e)} . \quad (5)$$

If the projection of the trajectory that passes through points A and B in Fig. 3 onto this cartesian plane is given by  $y = f(x)$  and the projection of the trajectory that passes through point C is given by  $y = g(x)$ , the following are true:

$$\begin{aligned} \alpha_b &= \arctan f'(X_1) \\ \alpha_e &= \arctan g'(X_2) \\ \alpha_t &= \arctan \left[ \frac{f(X_4) - f(X_1)}{X_4 - X_1} \right] = \arctan \bar{f}'(X) \end{aligned} \quad (6)$$

and (5) becomes

$$R^* = \frac{2\bar{f}'(X)[1 - f'(X_1)g'(X_2)] - [1 - \bar{f}'(X)^2][f'(X_1) + g'(X_2)]}{[1 - \bar{f}'(X)^2][1 - f'(X_1)g'(X_2)] + 2\bar{f}'(X)[f'(X_1) + g'(X_2)]} . \quad (7)$$

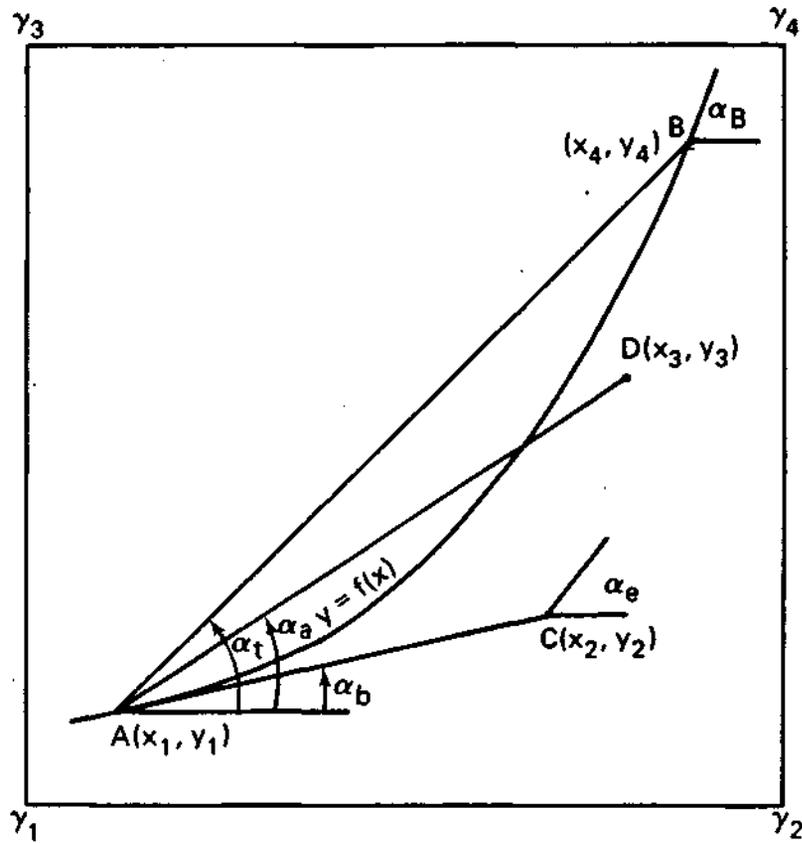


Figure 3. Schematic diagram showing the method of approximation of a trajectory segment in a subgrid square by the predictor-corrector method.

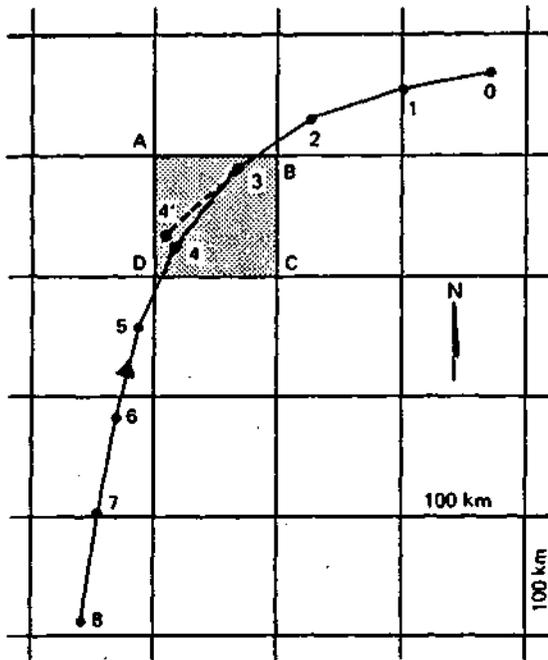
If the equations for the trajectory segments are known, (7) can be solved for  $R^*$ . Then (3) will give the angular errors for each PC trajectory segment. For small angular errors, the trajectory position error  $Z$  can be approximated by

$$Z = R \Delta X, \quad (8)$$

where  $x$  is the projection of the length of the trajectory segment onto the  $x$  axis.

Now if the difference between  $x_4$  and  $x_2$  is small, (7) becomes identical to the diagnostic equation developed by Achtemeier (1979) for the error analysis of operational objective streamline methods. In that paper, Achtemeier showed that the predictor-corrector method for the objective calculation of streamlines was superior to other methods. It produced negligibly small error for most of the analytical curves tested. It was found that the PC method underestimates curvature where the step increment is directed toward decreasing curvature and always overestimates curvature where the step increment is directed toward increasing curvature. Thus errors that were locally significant were compensated at points further along the curves. This compensation for the extrapolation errors should occur for all curves except the spiral for which the curvature always increases or decreases depending upon the direction of the trajectory. Thus this trajectory analysis algorithm will not increase the error incurred in generating objective trajectories over the error already inherent in the gridded wind fields.

The objective trajectory analysis model combines the method for gridding the observations of winds above ground with the trajectory algorithm to produce back-trajectories. First, the 12-hourly wind observations are gridded onto the seven sigma levels. Then the 12-hour gridded wind fields are interpolated linearly in time to produce estimated wind fields at three hour intervals. The wind directions are reversed 180 degrees and the wind fields are ordered with the latest time first. Back-trajectory calculation proceeds as illustrated by Fig. 4. Eight back-trajectory segments begin at some initial time and step back 24 hours in 3-hr intervals. The construction of the trajectory segment between  $t-9$  and  $t-12$  hours (steps 3 and 4 in the shaded panel of Fig. 4) is illustrated in detail in Figs. 4a-f. The trajectory segment ending at  $t-9$  hours (point 3) hours is shown on the grid square (Fig. 4a) along with the estimated winds at  $t-9$  hours that were interpolated from the gridded winds at  $t$  and  $t-12$  hours. Using the winds at the surrounding four grid points, we find the wind at point 3 by bilinear interpolation. We reverse the wind direction by 180 degrees and extrapolate backwards to 4' assuming the velocity at 3 blows steadily for three hours (Fig. 4c). Next, using the wind velocities gridded at  $t-12$  hours, we find the velocity at 4' by bilinear interpolation (Fig. 4d). The final estimate of the 3-hour backwards extrapolation uses the average of the velocities at 3( $t-9$ ) and 4'( $t-12$ ) to locate point 4 (Fig. 4e). Having determined the back-trajectory segment location at  $t-12$  hours and having the interpolated winds at the surrounding grid points, we are ready to repeat the calculations for the next 3-hour back-trajectory segment (Fig. 4f).



Plan view of a typical 24-hour back-trajectory commencing at observation point 0 (time  $t$ ), and represented as eight 3-hour straight line segments at elevation  $Z$ . It overlays the 100 km grid of interpolated wind data. The numbered points ( $n$ ) on the back-trajectory represent estimated locations of the observed aphid (air parcel) at time  $t-3n$  hours. The method used is illustrated in a-f below using the 3-hour trajectory segment 34 in grid cell ABCD.

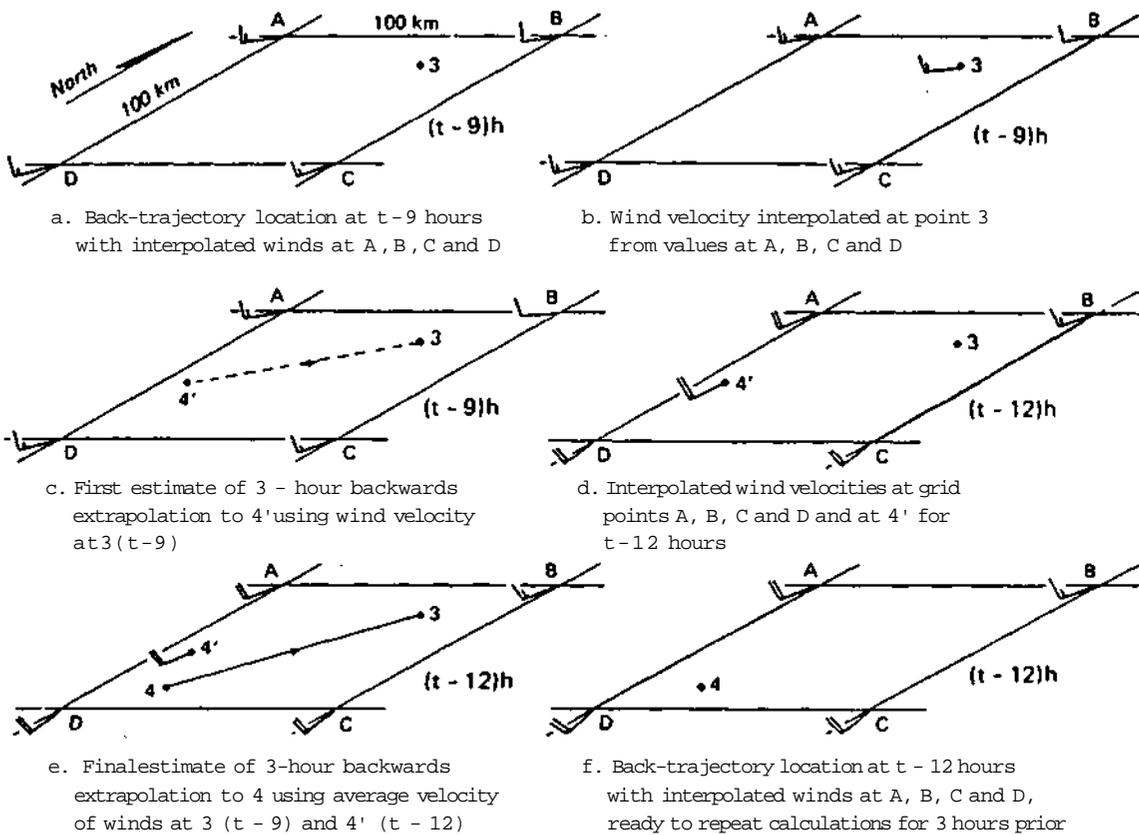


Figure 4. Schematic diagram showing the construction of a back-trajectory segment within arrays of gridded wind data interpolated over 3-hr intervals.

#### 4. Temporal and Horizontal Resolution Studies of the Numerical Trajectory Analysis

Pest migration occurs on a local scale, and although insects are transported primarily by the large scale air flow, small scale meteorological features may play an important role in some migrations. It was stated in Section 2 that the numerical procedures of this research are able to resolve features of approximately 730 km and larger, while in addition, upper air observations are routinely taken at only 12-hour intervals. Substantial changes in the actual wind fields may occur at smaller time and space scales and can create large changes in the length and direction of calculated trajectories. Therefore, an investigation was conducted on the effects that greater frequency of rawinsonde data and/or increases in the number of rawinsonde sites may have on trajectory calculations.

Data for this investigation were obtained from three special meteorological field experiments conducted during the last 10 years across portions of the eastern United States by the National Aeronautics and Space Administration (NASA). The significance of these projects is twofold: 1) the upper air sounding interval was reduced from 12 hours to 3 hours, and 2) in two of the three experiments, supplemental sounding sites were added to the existing upper air network. Figure 5 shows both the regular and supplemental sites used in these experiments. The experiments, with this enhanced observational resolution, lasted for 24 hours.

For the analysis described in this section, hypothetical pest catch sites were chosen from which back-trajectories were initiated. Incorporation of these special upper air data into the trajectory analysis allows for the replacement of the 3-hour soundings interpolated from routine 12-hour rawinsonde data with actual 3-hour data and also nearly doubles the number of upper air stations at any given time. These changes increase both the temporal and horizontal resolution of the analysis, which should create more accurate trajectories.

Calculations were made using observations at intervals of 12-, 6-, and 3-hours over the regular sounding site network and then over the enhanced network when available. Results show that differences between the 12- and 3-hour trajectories and the 12- and 6-hour trajectories are very similar. Therefore, only the 12- and 3-hour comparisons are shown here.

Figures 6 a and b present trajectory calculations ending at 1200 GMT on 11 April 1979, using 12- and 3-hour data, respectively. Surface backtracks covered a 24-h interval while the upper air trajectories were terminated after 12 hours when they entered the data void region over the Gulf of Mexico.

Both analyses indicate that the winds associated with this weather situation were increasing in speed and veering with height, creating large magnitudes of vertical shear in the lower troposphere. The distances traveled by 24-hour trajectories at the surface were surpassed by trajectories at higher levels in only 9 to 12 hours and at directions that differ by as much as 70°. Vertical variations of the wind such as this are not infrequent in large, springtime weather systems and, as is evident in the figures, can create substantial differences in the locations of the trajectory endpoints.



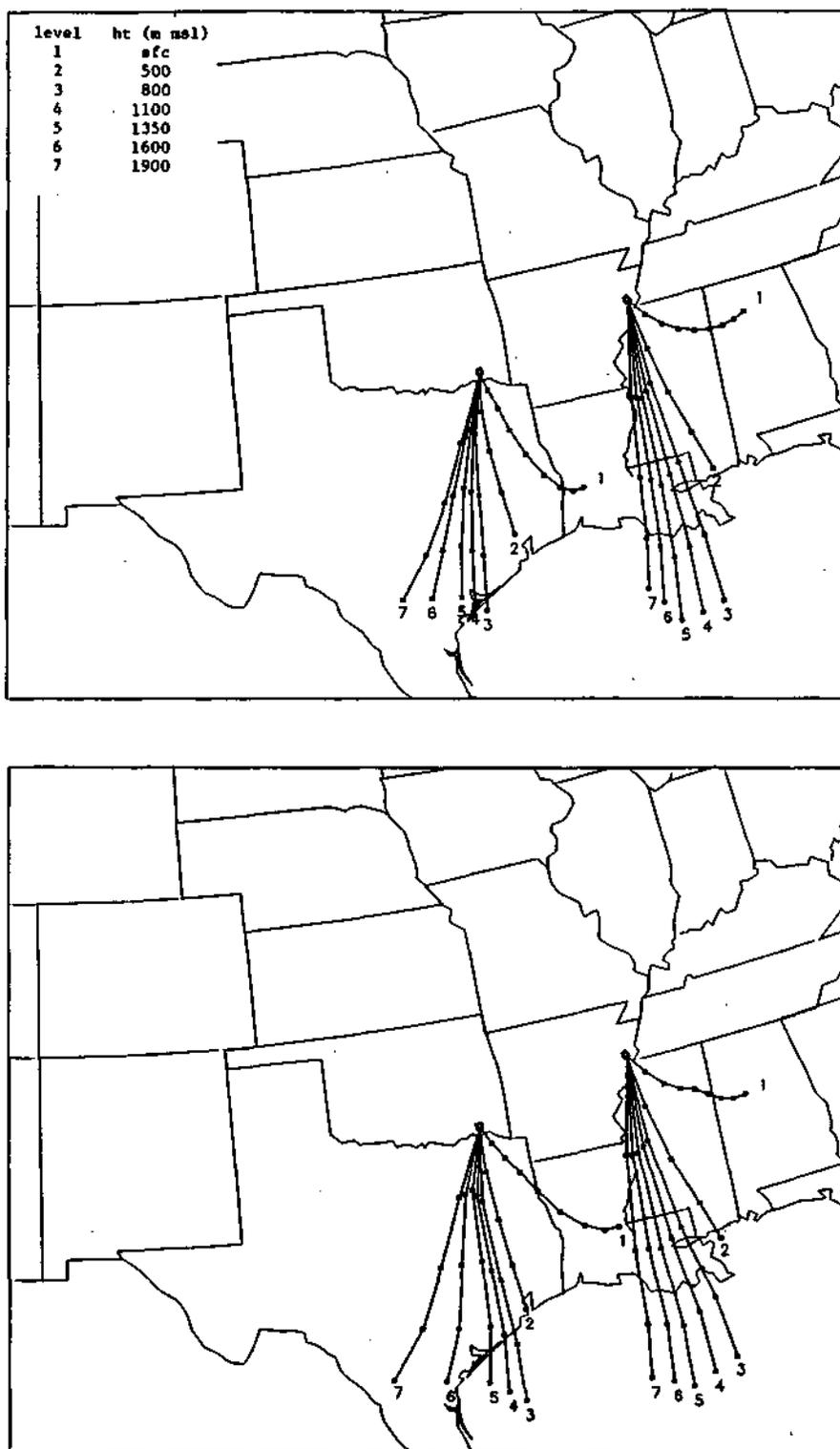


Figure 6. Back-trajectories beginning from pest catch sites at 1200 GMT on 11 April 1979, using (a) 12-h data and (b) 3-h data over the regular rawinsonde network of station. Dots along each line represent 3-h trajectory positions. Backtracks last for 24 h, except for 12 h where trajectories entered a data void region such as the Gulf of Mexico.

Additional soundings at 3-hour intervals generated only small changes compared to backtracks using 12-hour data. Trajectory endpoints at the same level over southern Texas differed by as much as 100 km within a 12 hour period. This may not be an insignificant change for a pest migration study. Nevertheless, it is still substantially smaller than the trajectory variations observed with height. However, this particular weather system was apparently well developed and in a near steady state during the time of the trajectory analysis. This probably allowed the interpolated 3-hour soundings to be representative of the airflow for the entire period, reducing the need for more frequent soundings.

The addition of supplementary sites also had only a small effect on the backtrack calculations (Fig. 7). This indicates that the regular synoptic scale network was sufficient to resolve the near-surface winds in this case study. Again this may be attributed to the state of the weather system being measured. However, a young developing system, undergoing rapid cyclogenesis in a region smaller than that covered by a well developed cyclone, may produce substantially different results when the number of stations are increased.

Trajectory analyses from hypothetical pest catch sites on 26 April 1979, generated from the 12- and 3-hour data are shown in Figure 8. This system also shows evidence of large low level vertical wind shear. At the eastern site the lengths of trajectories at the higher levels are several times greater than near the surface, and in the west, directions from the catch sites differ by up to  $90^\circ$ . In addition, some of the trajectories appear to have encountered a frontal pressure system, as indicated by a sharp change in direction during the last half of the trajectory period.

In general, trajectory beginning points calculated from 3-hour data were farther from the end points (longer trajectories) than were the trajectories calculated with interpolated data. In addition, back-trajectories from the western site veered to a more westerly direction at a lower level than was observed from 12-hour data alone. These results indicate that the winds were stronger and shifted to a more westerly direction earlier in the 24-hour period of the trajectory analysis than was interpolated from the 12-hour data. Nevertheless, these changes were small when compared with differences observed with elevation.

Trajectories calculated from the rawinsonde network including supplemental stations, also show only small changes when comparing the 12- and 3-hour data (Fig. 9). Again, it is the altitude of the suspected pest flight which is the critical factor in the trajectory analysis. As stated earlier, the stage of development of each individual weather system may play a large role in determining the significance of increased temporal or spatial resolution on pest origin calculations. In addition, fast-moving systems could increase the need for higher resolution data.

The final comparison of the effect of a 3-hour data interval on trajectory calculations is presented in Figure 10. This NASA experiment, which ended at 1200 GMT on 8 June 1979, differed from the first two in that no supplemental rawinsonde sites were added.

Unlike conditions during the previous experiments, the wind direction did not change much in the vertical. Back-trajectories calculated from just the 12-hour data yielded an indication of a low-level wind maximum; the backtrack at level 5 was located the greatest distance from the ending point. However,

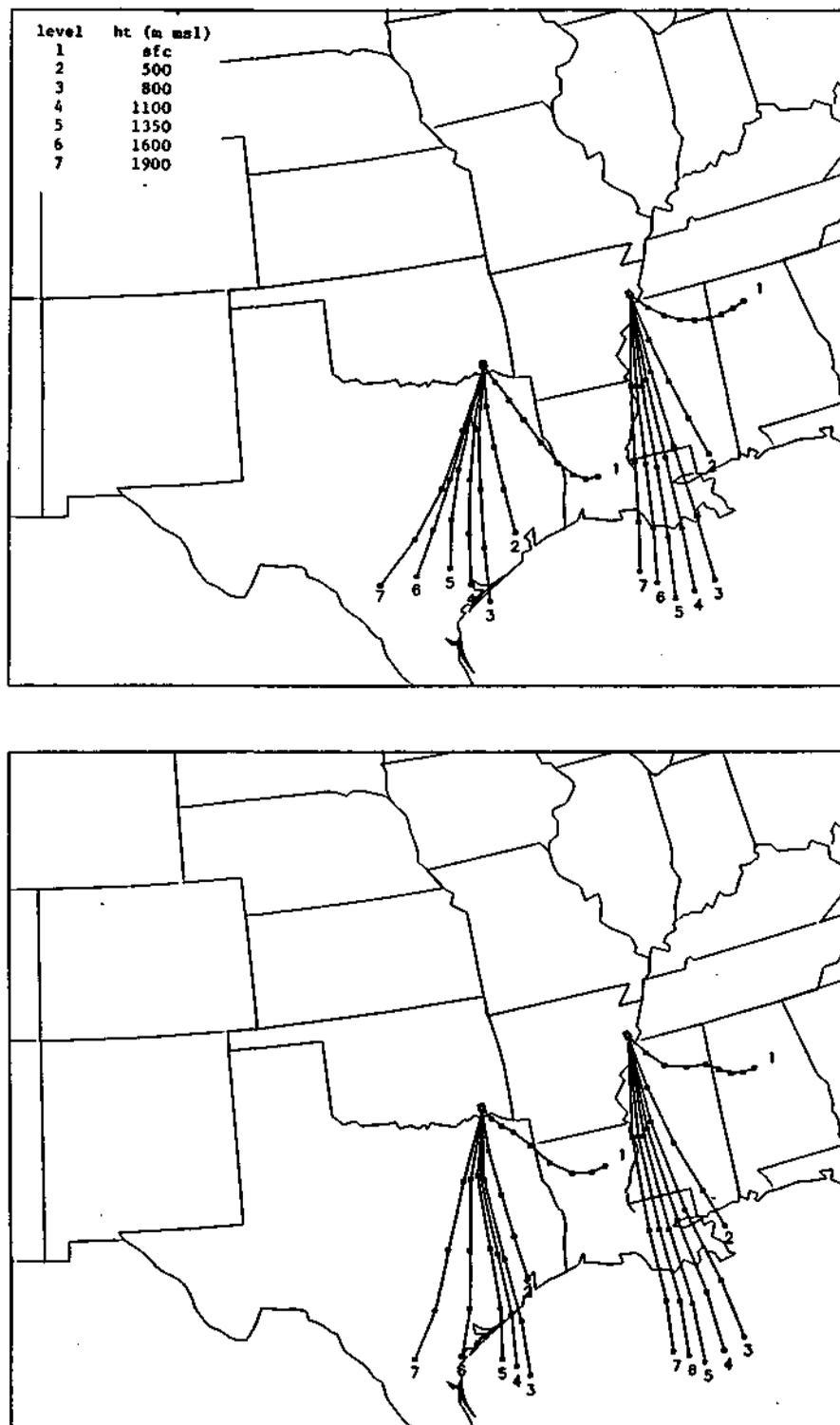


Figure 7. Same as Fig. 6, except for being calculated over the regular plus supplementary rawinsonde network.



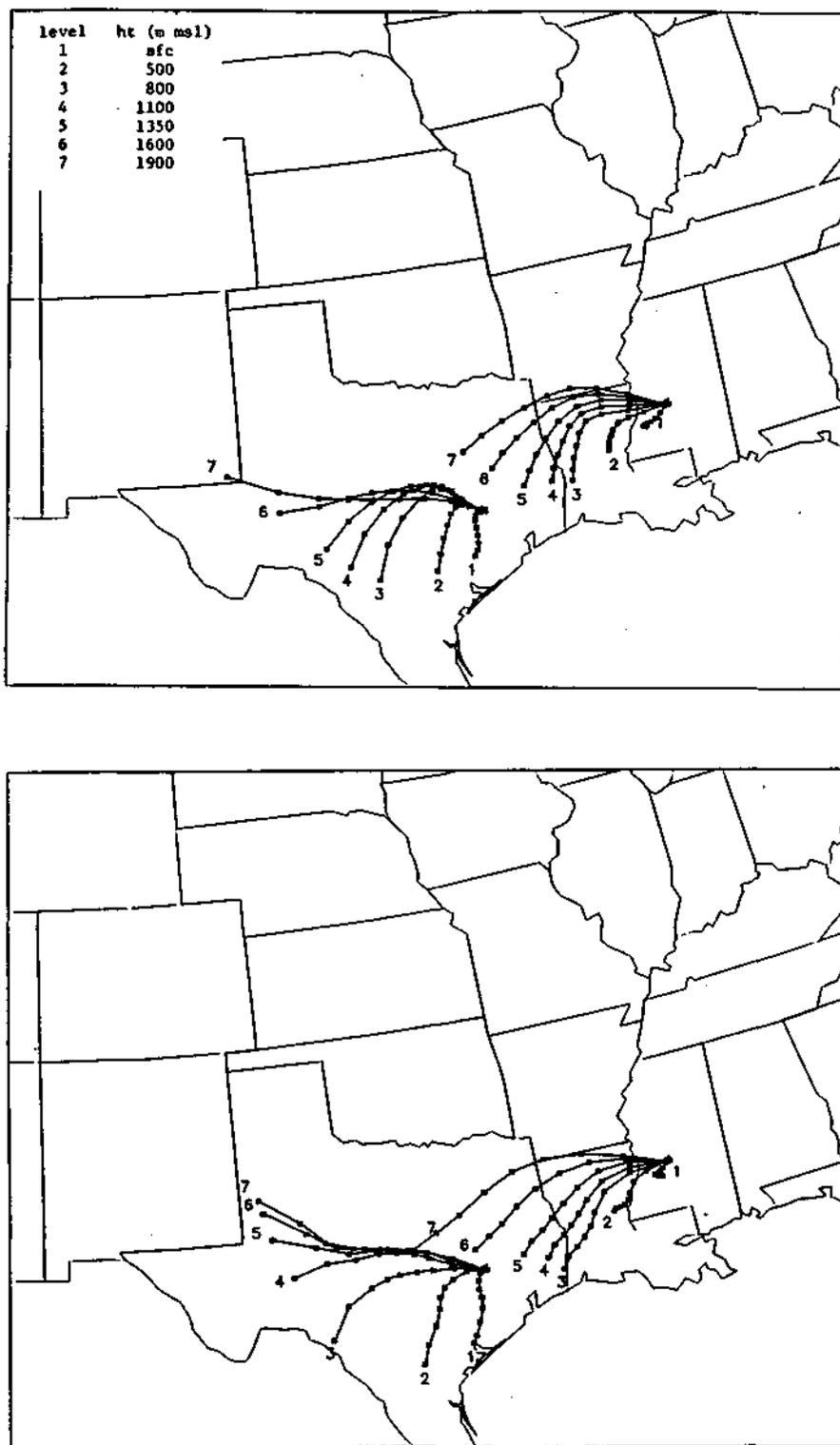


Figure 9. Same as Fig. 7, except at 1200 GMT on 26 April 1979.

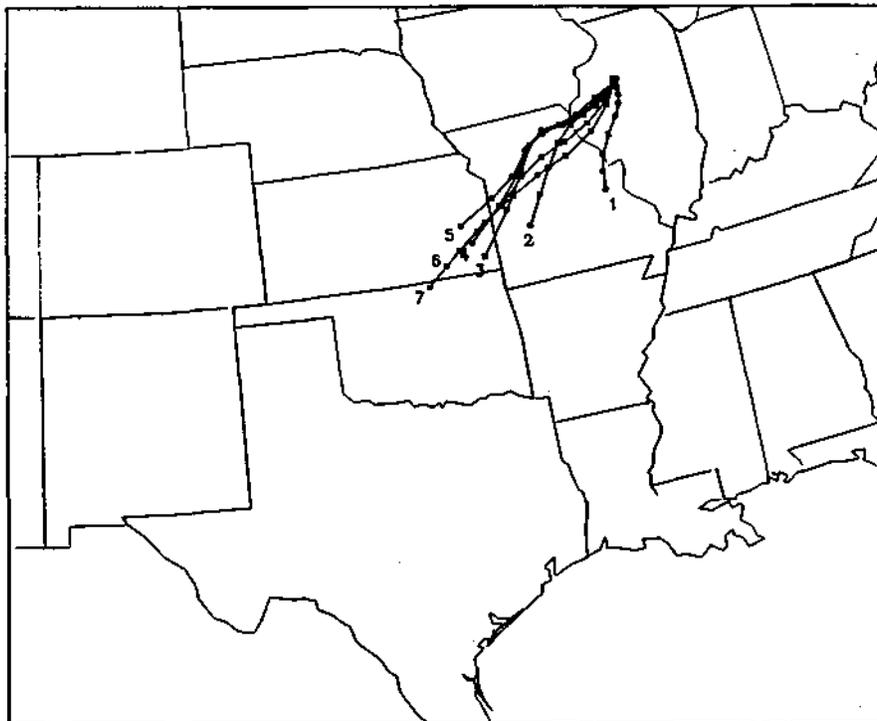
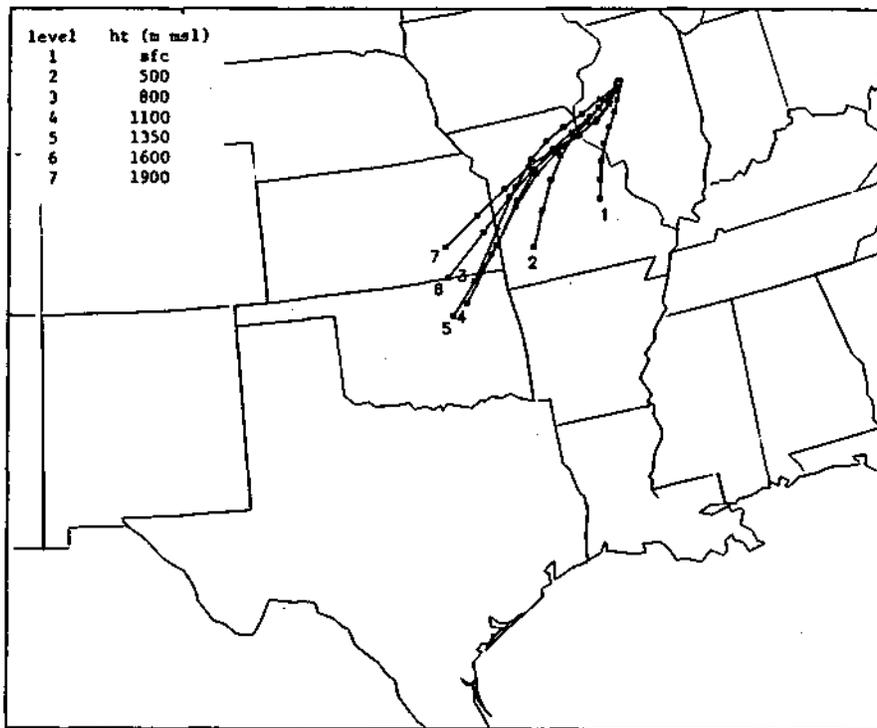


Figure 10. Same as Fig. 6, except at 1200 GMT on 8 June 1979.

this wind maximum was not observed with 3-hour data (Fig. 10b). Wind speeds, therefore, were strongest at the beginning of the NASA experiment, and decreased rapidly within the first 3 hour. In this manner, the trajectories generated from the observed 3-hour data would be influenced by these large values only in the earliest 3-hour trajectory segment, whereas trajectories calculated from the 12-hour data set would have incorporated this information throughout the first 12 hours. Complete results, however, again show that the largest differences in beginning points of the trajectory analysis occurred as a function of the height of the calculated backtracks.

One of the relationships between weather and pest migration that was reported in the literature states that southerly winds frequently persist for several days prior to the pest catch. In our selection of catch sites, we attempted to choose locations where this relationship was valid. Therefore, we found small changes in the temporal and horizontal resolution of the observations. However, this relationship may not hold for weather systems that are rapidly changing through either development, decay, or movement.

#### 5. Comparative Studies of Previous Research for Estimating Origins of Migrants

As we indicated earlier, there have been previous studies of insect migration into the agricultural midwest in which source regions have been identified based on simpler trajectory schemes. A comparison has been carried out between the back-trajectories using some of these methods and our numerical method.

Table 1 provides a summary of studies (conducted primarily by entomologists) based on various techniques for estimating source regions of migrants. The first section of the table lists investigators who subjectively backtracked pests to their origins through the use of various graphical procedures based on data from daily meteorological charts. Studies in the latter part of the table relied more heavily on general weather conditions and other circumstantial evidence.

Collectively, these studies have linked the following events with large scale insect flight:

- 1) a weather pattern typified by high pressure along the east coast of the United States and low pressure over the Great Plains,
- 2) a strong southerly flow of warm air from the Gulf states into the Midwest that persists for several days prior to the influx of insects,
- 3) a frontal system (usually a cold front) approaching the pest catch area from the west or northwest that can provide a possible means of terminating pest flight, and
- 4) evidence of heavy pest infestations upwind from the catch site.

In addition, a few of the researchers used known physiological information of particular pest such as typical take-off time, length of flight, flight level, etc. to assist in their estimates.

Some of the graphical methods employed are quite different and upon application to the same weather situation should result in diverse pathways of migration. Five of the backtracking methods are described in sufficient

Table IV-1. Summary of methods used by previous researchers to estimate source regions of pests during migrations.

Researchers	Pest	Date	Location of Catch	Source Region	Trajectory Method
Chiykoski and Chapman (1965)	leafhopper	27 Apr- 3 May 1957	north WS north MN north ND	southwest AR	subjective backward trajectories drawn from 0600 and 1800 GMT surface maps (poor station density); assumed wind and temperature data valid for flight level and that pests flew only at temperatures of > 60 F (15.6 C)
Nichiporick (1965)	leafhopper	27 June 1962	Winnepeg Manitoba	southwest MN - west OK	after positive catch, arrival time taken to be 1800 GMT on that day or first antecedent day with southerly wind > 10 mph; subjective backward trajectories drawn using 6h surface and 12h 850mb charts; trajectories terminated after 24h, or when entered areas of light winds (<10mph), rainfall, or suitable vegetation; source region defined by 50-mile wide band joining surface and 850mb endpoints
Hartstack et al. (1982)	corn ear worm	7 Mar 31 Mar 1981	northeast Mexico	south TX	subjective backward trajectories from 3h surface and 6h interpolated 850mb charts; 12h downtime provided for each day since pests are nocturnal
Bushman et al. (1981)	velvetbean caterpillar	April 1981	west FL or Yucatan	south MS	subjective backward trajectories taken from Daily Weather Map series; direction assumed to be parallel to isobars; speeds used to estimate distance travelled; recognizes that moths would fly faster at higher levels but does not incorporate upper air data in study
Rose et al. (1975)	aphid	6 Aug 1973	Sault Ste Marie, MI	central WS	subjective backward trajectories drawn from surface and 850mb wind fields and vertical profiles of temperatures and winds en route; used meteorological and physiological
	moth	4 Sept 1973	Sault Ste Marie, MI	north MS	reasonings to determine flight level, time of day for take-off, length of flight, etc.; matched estimated source region to known area of heavy infestation upwind
Pienkowski and Medler (1964)	leafhopper	. May 1951- 1960	south WS	south or central MS Valley	trajectories used but method not provided; checked for sufficient temperatures at flight level to sustain flight
French (1969)	locust	1965	England	Spain or Morocco	subjective backward trajectories drawn from surface geostrophic wind; high validity in this region since most of flight over water where surface friction is low
Mikkola and Salmensuu (1965)	locust	1962	northwest Europe	northwest Africa	subjective backward trajectories drawn from surface geostrophic wind multiplied by estimated daily flight time based on the length of darkness

Table IV-1. continued

Mikkola (1971)	gypsy moth	26 July 1958	Moscow	Finland	subjective geostrophic trajectories drawn from 3-h surface isobars and 6-h 850 mb contours; also, geostrophic night trajectories at about 500m
Rosenburg and Magor (1983)	brown planthopper	Sept 1978	south and east Asia	south and east Asia	subjective forward trajectories from 12-h surface and 850 mb streamlines if temperatures above 17 C; recognized importance of the frequency of both weather and pest data
Farrow (1975)	locust	8-9 Nov 1973	southeast Australia	coastal south Australia	subjective backward trajectories drawn from 3h surface streamlines and isotachs; said representative of geostrophic layer no lower than 300m.AGL
Close and Tomlinson (1975)	aphid	1 Nov 1967	southeast Australia	New Zealand	subjective forward trajectories calculated from 12h 1000m and 3000m geostrophic winds
Peterson et al. (1968)	leafhopper  aphid	Spring 1952-68  Spring 1961-68	Minnesota	south or southwest of MN	no trajectories presented; associated first appearance of pests with: 1) several antecedent days of strong southerly winds, often terminated by a frontal passage, and 2) pests sighted in large numbers at some southerly location along suspected flight route
Hodson and Cook (1960)	harlequin bug and greenbug	4 May 1959	southwest Minnesota	KS and MO	no trajectories presented; migration assumed since: 1) first harlequin bug ever collected in MN, 2) winged forms of both pests observed in large numbers in KS and MO just prior to catch, and 3) strong southerly winds with high pressure to the east and low pressure with an approaching front to the west matched previous literature studies as that weather necessary for long-range pest transport
Kieckhefer (1974)	aphid	Spring 1963- 1969	South Dakota	south of SD	no trajectories presented; high proportion of pest migrations are coincident with low-level jet winds between east coast high pressure and Great Plains low pressure systems, but relationship is not statistically significant
Dickison et al. (1983)	moth	4-5 July 1975	central New Brunswick	50-100 km south of catch site	no trajectories presented; short flight ahead of frontal system via pre-storm low-level convergence and washed-out by downdraft; heavy recent moth emergence noted just upwind
Drake et al. (1981)	noctuid	Sept 1973	Tasmania	southeast Australia	no trajectories presented; southward movement of insects associated with warm anticyclonic airflows which occur ahead of cold fronts

Table IV-1. continued

Drake and Chapman (1965)	leafhopper	Spring 1950- 1952	Wisconsin	southwest of WS	no trajectories presented; source region assumed to be a considerable distance from WS where the weather was in advance of that in WS by a month or more; migration assumed to occur with strong, warm southerly flow of early spring
Huff (1963)	leafhopper	Spring 1951- 1959	east cen- tral IL	Louisiana	no trajectories presented; most influxes preceded by a persistent southerly flow of Gulf air ahead of frontal system in region of influx

detail to be used for an intercomparison study. These are outlined briefly in the following paragraphs.

In a 1965 paper, Chiykowski and Chapman (hereafter CC) describe a backtracking method they used to follow a suspected migration of the six-spotted leafhopper into the northern Midwest during May, 1957. Wind velocities and maximum and minimum temperatures at pest catch sites were estimated from surface weather charts available once a day. Pest flight was assumed to occur whenever the temperature exceeded 15.6 C. A daily estimate of flight hours (the time in excess of this threshold) was obtained from a linear interpolation between the daily maximum and minimum temperatures. Backtracks were drawn upwind from each site for a distance equivalent to the area's wind speed multiplied by the number of flight hours available. No precise method was given for terminating the trajectories. However, starting points for possible migratory pathways were implied when back-trajectories converged to a central region.

Nichiporick (1965; hereafter N) reported on a suspected migration of six-spotted leafhoppers in June, 1962, and estimated the origin of the pests by calculating separate backtracks from streamlines based on 6-hour surface and 12-hour 850-mb winds. The procedure was the same as used by CC. Line segments were constructed upwind from the catch site. However, each segment represented a shorter period than that of CC through the use of charts at closer time intervals. The inclusion of a 850 mb level in the analysis helped take into consideration the possibility of wind variability with height. An 80-km wide band joining the endpoints of the backtracks for surface and 850 mb levels outlined the estimated source areas. The surface charts available to N included substantially more stations than those used by CC, resulting in greater horizontal resolution of surface data as well. The criteria used to terminate the trajectories are listed in Table 1.

Hartstack et al. (1982; hereafter H) extracted wind data from analyzed weather charts to backtrack a March, 1981, flight of mature corn ear worms. The migrants reportedly had been transported from northeastern Mexico to southern Texas. These authors used 3-hourly surface charts and 6-hourly 850-mb charts which had been interpolated from charts at 12-hour intervals. Source regions were defined as the entire area between the surface and 850-mb backtracks and the line joining their endpoints.

A different approach was employed by Mikkola (hereafter M) in a 1971 paper in which trajectory analyses of eastern European pest movements was based on geostrophic winds calculated from the 3-hourly surface and 6-hourly 850-mb pressure fields. In these geostrophic calculations wind directions are assumed to be parallel to surface isobars or upper air height contours, while wind speeds are calculated using an inverse proportionality to the spacing between these lines. The procedure produces wind fields which can differ substantially from the actual wind field near the surface because frictional drag (neglected in the geostrophic calculation) slows the air flow turns the wind direction towards lower pressure. These surface wind velocities are more representative of actual winds a small distance above the ground where the frictional force is less important. At heights greater than about 1000 m, the airflow approaches geostrophy.

Buschman et al. (1981; hereafter B) backtracked the velvetbean caterpillar across the Gulf of Mexico during April 1978. The geostrophic method was

used to obtain wind directions for trajectory calculations; wind speeds were estimated from observations nearby the catch site. Like CC, their analysis was based only on surface observations from a single daily weather map, however, there was no temperature threshold for pest flight. Therefore, with minimum temperatures of 60° F and higher, the two methods yielded trajectories of equal length, although the trajectory tracks generally differed in direction by about 30° - 50°. Although B stated their recognition of the importance of vertical shear in the boundary layer, upper air data were not incorporated into their analysis.

These various empirical back-trajectory methods are compared below with the numerical trajectory analysis technique described in Section 3. The data from the three special NASA field experiments described and used in Section 4 were used in the analysis in this part of the study. The numerical procedure includes data at about every 300 m throughout the lower troposphere instead of just the one level at about 1500 m (850 mb) used in some of the earlier trajectory estimates. The upper and lower boundaries are defined, as described in Section 3, by the earth's surface and 800 mb (approximately 2000 m), respectively. Data are analyzed for five levels between these two limiting surfaces. In view of results of the study concerning the sounding frequency discussed in Section 4, input data for this analysis came from regular 12-hour upper air rawinsonde soundings which were gridded onto a regional mesh of 100 km grid spacing and then interpolated to 3-hour intervals.

All three NASA experiments took place when weather conditions were representative of situations that have been cited as favorable for pest migration. Hypothetical catch sites were chosen for the cases, each located in regions within the "warm" sector of surface cyclonic systems to allow the calculated trajectories to remain in the same air mass. Second sites also were chosen close to frontal activity at the ending time of each NASA experiment. Again, these are areas where pest migrations may be expected to terminate due to the approaching inclement weather. Back-trajectories lasting 24 hour were produced by the five graphical techniques and the numerical method. All synoptic charts shown in figures that follow are for the ending times of the experiments.

#### Case A: 10 - 11 April 1979

The surface and 850-mb synoptic charts at 1200 GMT on 11 April 1979 are presented in Fig. 11. Both maps show a large low pressure system over the west central Great Plains and higher pressure to the east. During the preceding 24 hours, the center of low pressure had moved slowly eastward and deepened slightly. At the same time, a warm front, initially stationary along the northern Gulf of Mexico, began moving northward to northern Oklahoma and central Tennessee. Twelve to 24 hours prior to the start of the NASA experiment, a cold front formed to the south of the Colorado low in central New Mexico. As the map shows, it had moved into central Texas and western Oklahoma as the NASA experiment ended 36-48 hours later.

At 850 mb, southerly and southwesterly winds covered the central and southern Plains throughout the experiment. The areal coverage of this flow expanded slowly eastward during the field program and had reached the Appalachians as the experiment ended. The area of highest wind speeds, initially located from northern Texas and eastern Oklahoma, moved eastward during the period to the eastern Plains and western Gulf states while magnitudes

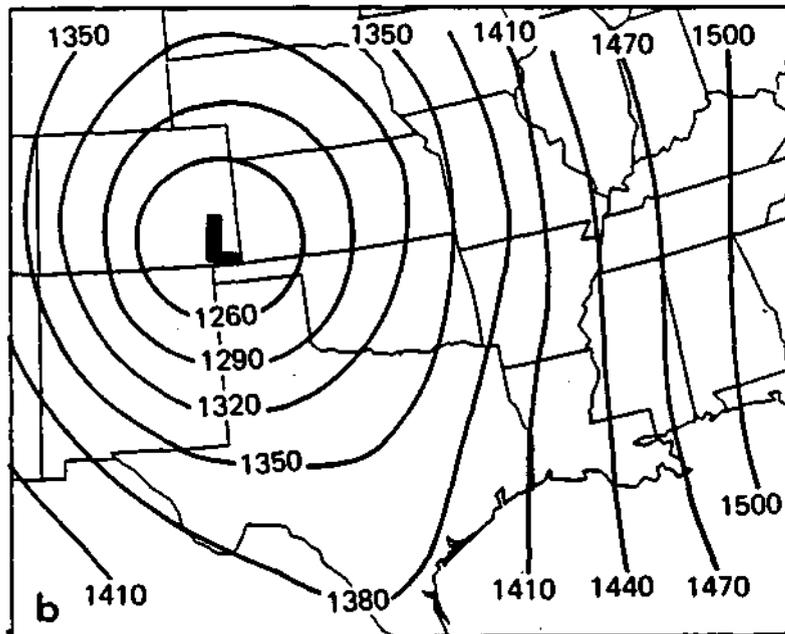
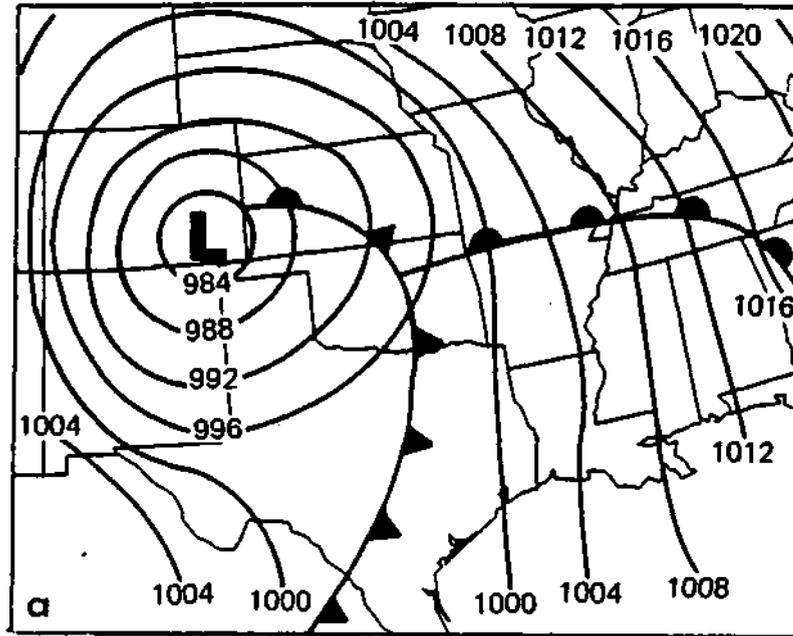


Figure 11. Synoptic charts at 1200 GMT on 11 April 1979. Lines represent surface isobars (mb) in chart (a) and 850 mb height contours (m) in chart (b).

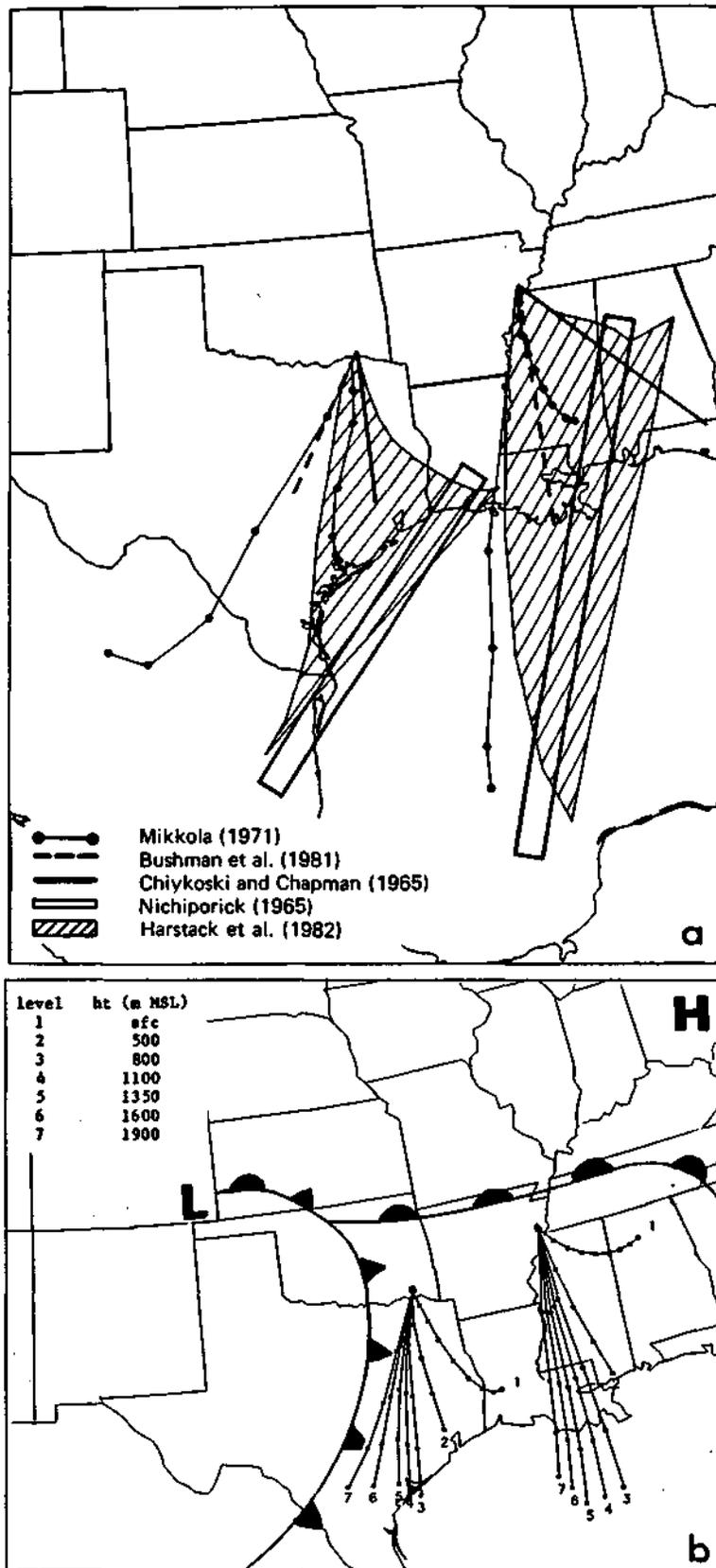


Figure 12. Graphical (a) and objective (b) back-trajectories at 1200 GMT on 11 April 1979. The easternmost backtrack of Mikkola is for the surface.

increased from 10 - 15 m s<sup>-1</sup> to 20 - 25 m s<sup>-1</sup> .

Pest source regions, estimated from the different graphical trajectory methods, appear in Fig. 12a. The two hypothetical pest sites chosen are in northeastern Arkansas and southeastern Oklahoma and are the points from which all methods initiate calculations for pest origin estimates. The surface back-trajectories by CC and B are represented by a heavy solid line and a heavy dashed line, respectively. M's surface and 850 mb backtracks are indicated by a thin line with dots and H's back-trajectories from the same levels outline the hatched area. The back-trajectories developed by N form the endpoints of the boxed area. The westernmost trajectory by M, N, and H from each site are at the 850 mb level.

All surface-based trajectory backtracks remain on the land but their various endpoints differ greatly. The methods developed by CC and B, which rely on one surface chart, create trajectories that travel further than the trajectories estimated by the remaining methods. This is due to a relatively high surface wind at the catch site for the time at which these methods are based. The use of geostrophic wind<sup>6</sup> in procedures by B and M cause their trajectories to track west of the others and more parallel to the pressure field in the region. N's and H's techniques outline very different source regions, but the endpoints of their surface and 850 mb backtracks are quite similar, even though their methods of calculation differ in temporal frequency. This provides a graphical confirmation of results in Section 4 which indicate that under relatively steady state conditions, 12-hour data is generally sufficient to provide adequate back-trajectories.

Wind velocities at 850 mb were very different than those at the surface and created back-trajectories by the graphical methods that indicate pest origins well to the south of the surface locations. The differences between the backtracks at the two levels gives indications of the large vertical variability in the wind velocity of the lower troposphere. One result is the generation of large source regions by procedures such as those of N and H who connect their surface and 850 mb tracks. When areas become so large, the usefulness of such methods for locating the origins of pests is reduced.

The objectively analyzed trajectories calculated for seven constant-height levels are shown in Fig. 12b. As in Section 4, dots along the backtracks represent each 3-hour position in the calculations. It is noted that, for comparisons with the graphical analyses, 850 mb is represented approximately by level 5. The calculations at all levels above ground (level 1) were terminated after only 12 hours because the trajectories backtracked over the data-void region of the Gulf of Mexico.

Surface trajectories from both pest catch sites indicate that the numerically generated backtracks compare most favorably with the methods by N and H. Back-trajectories by these two graphical procedures terminate just south of the numerical location. M's surface backtrack, which actually relates better to level .2 than the surface, compares well at the eastern catch site but not so well in the west. The two remaining surface back-trajectories end in quite different areas than the mathematical procedure.

In the upper air, the lack of numerical data over the Gulf prohibits a 24-hour comparison with the graphical procedures. Nevertheless, during the first 12 hours of the experiment, M, N and H compare well with the numerical method, backtracking just slightly to the west of its location.

Despite the good performance by two of the graphical methods, only the objectively analyzed data show how large wind changes near the ground cause a vast difference in indicated source regions. This emphasizes the importance of information concerning the flight levels at which insects migrate, information that when merged with numerical trajectory analyses will substantially reduce the size of the estimated location of pest origin.

Case B: 25 - 26 April 1979

In an example of an evolving weather system, a slow-moving cold front stretched across the central United States. High pressure remained along the east coast of the United States during the entire 24 hour period prior to 1200 GMT, 26 April. This pattern created a flow of warm, southerly winds across most of the states east of the frontal region. However, by 2100 GMT on 25 April, a weak cyclonic system had moved inland from the Gulf of Mexico over Florida and Georgia, causing the winds over the southern states to shift to westerly in the area of the hypothetical catch sites (Fig. 13). Synoptic patterns at 850 mb (Fig. 13b) generally reflected the surface features. Wind speeds of 10 - 15 m s<sup>-1</sup> were common across most of the NASA network during the entire experiment.

At the eastern site (southern Mississippi), surface-based source region estimates were located closer to the catch site than in the previous case due to lower wind speeds over the area (Fig. 14a). Although no scheme indicated origins at a very far distance from the catch site, these conditions resulted in widespread trajectories by the different graphical methods. H's technique tracked slowly to the east, M and B to the west, and CC to the south (although shortened due to minimum temperatures below 60 F) while the wind speeds were too low for N's procedure to calculate a backtrack at all. At the western site, wind speeds were high enough that backtracks by the graphical techniques were directed to the south or southwest.

Numerical back-trajectories (Fig. 14b) were also fairly short at the eastern site (all are for 24 hours). M's method seems to have compared most closely with the numerical trajectories; his surface backtrack (which is based on geostrophic assumption) is approximately equivalent to level 2 or 3. N and H also show close agreement but overall, not quite as close as M. At 850 mb, all of these graphical techniques overestimate the distance traveled from the western station compared to the numerical backtracks; these procedures extend too far to the west, especially H's. Neither of the solely, surface-based backtracks related well to the numerical procedures.

The numerical trajectories in this case indicate similar results to those observed in the previous experiment: a large clockwise turning with height of the direction of the possible migratory pathways, and a concomitant lengthening of the backtracks. Again, this rapid change with height in the direction and length of the calculated trajectories cannot be estimated graphically from the two levels of meteorological charts used by many previous researchers. For example, at the eastern site surface backtracks are much shorter than trajectories at higher levels while the distance traveled at level 3 (800 m MSL) is comparable to tracks at greater heights. A linear interpolation between just the surface and 850 mb level would generate wind speeds that are too low. Since pests tend to fly in layers with favorable winds and temperatures, accurate back-trajectories depend upon a method that uses detailed vertical information.

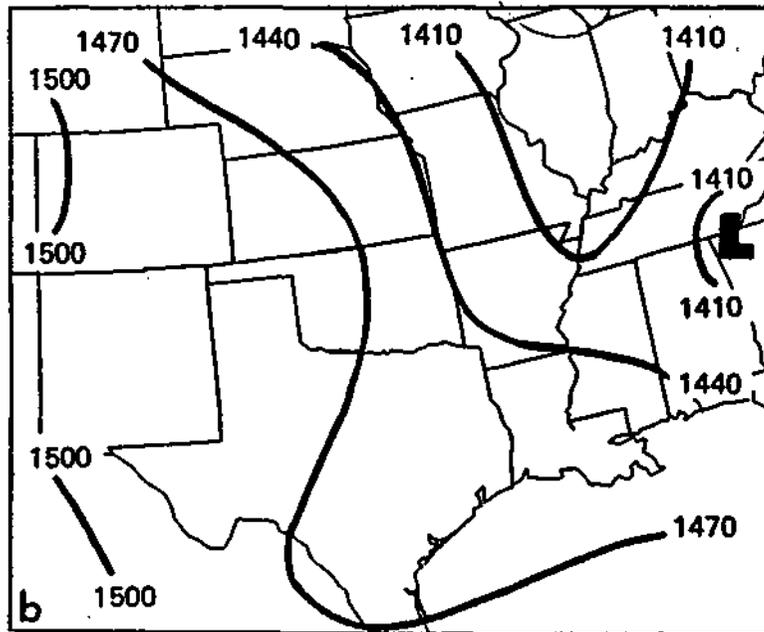
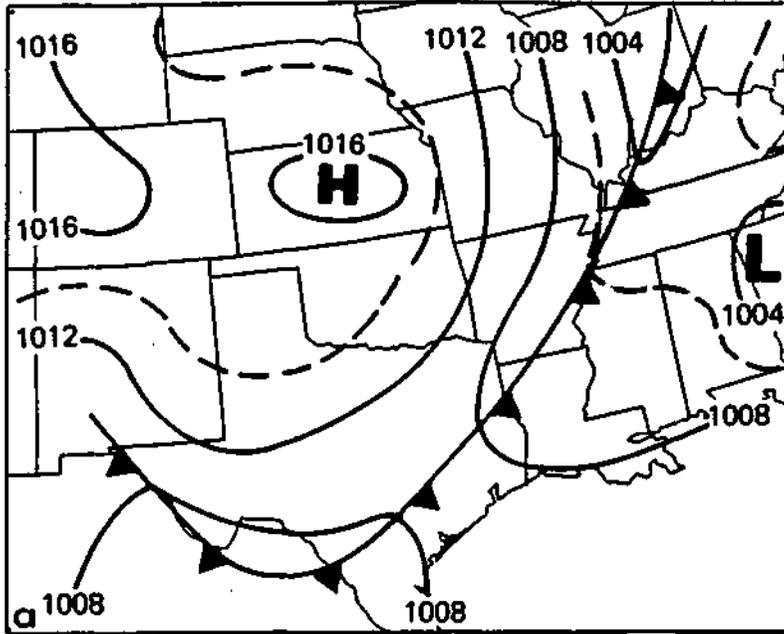


Figure 13. Same as Fig. 11, except for 1200 GMT on 26 April 1979.

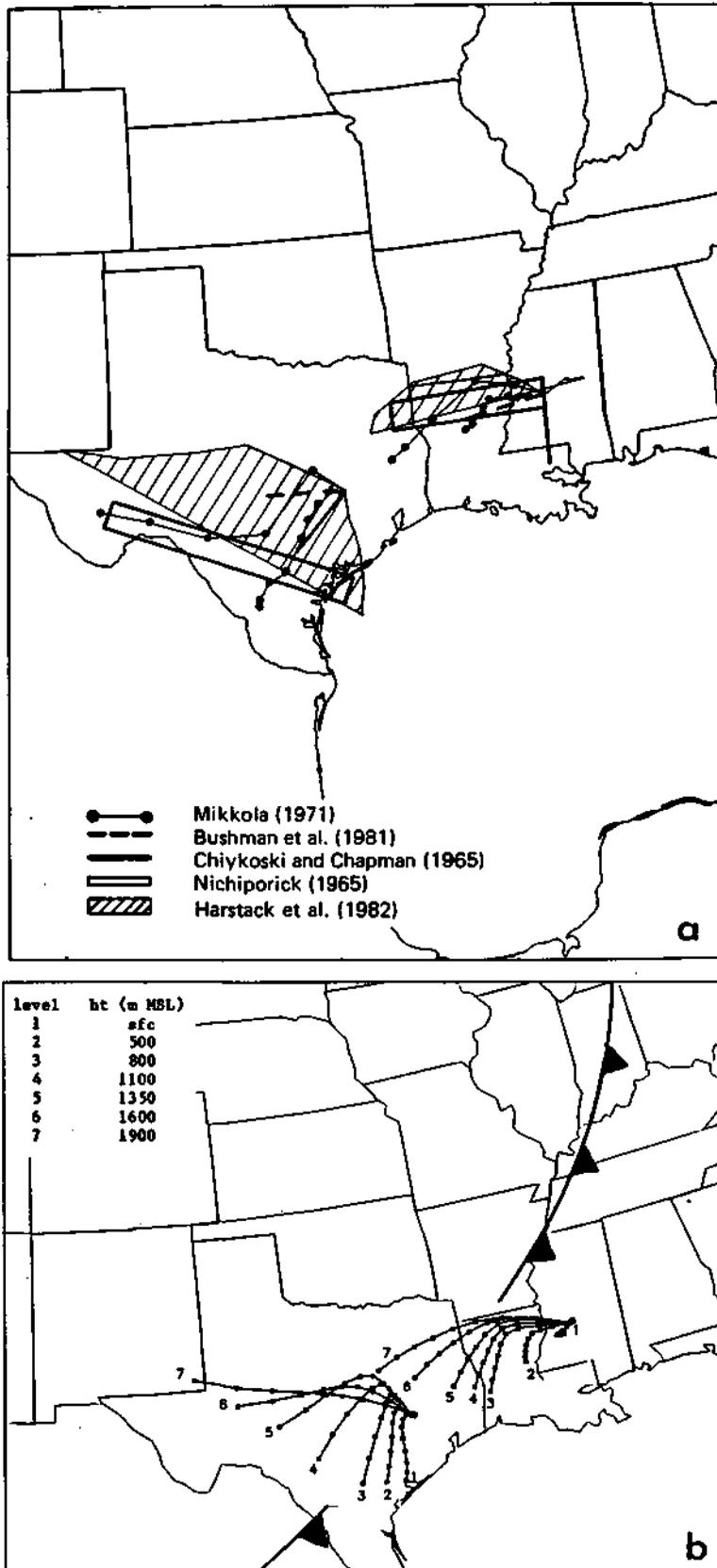


Figure 14. Graphical (a) and objective (b) back-trajectories at 1200 GMT on 26 April 1979.

Case C: 7 - 8 June 1979

The third case was characterized by persistent high pressure in the eastern United States while a cold front moved slowly eastward across the central Plains, becoming stationary across the southern Plains and western Midwest (Fig. 15a). Southerly winds were observed everywhere east and south of the frontal region. At 850 mb (Fig. 15b), weather patterns basically reflected the surface features. Twenty-four hours earlier, a trough had existed over the central part of the country with high pressure along the Atlantic coast. Subsequently, this trough had moved slowly eastward but had weakened considerably as a separate closed circulation developed in the southwest. Highest wind speeds of 15 - 20 m s<sup>-1</sup> were found near the southern end of the trough in the south central part of the country.

Twenty-four hour graphical backward trajectories for this project are shown in Fig. 16a. A hypothetical pest catch site in west central Illinois was chosen. The estimated source regions were again spread over a relatively wide area due in large part to differences arising from use of surface and upper air backtracks. Most surface back-trajectories ended in east central Missouri and were much shorter than the 850 mb backtracks, especially CC's and B's techniques. At the same time, the 850 mb procedures backtracked to southeastern Kansas or northeastern Oklahoma.

Considering the numerical trajectories (Fig. 16b), we find once more that trajectory endpoints change rapidly in the vertical from the surface to 800 mb. The surface and near surface backtracks ended in east central and southwestern Missouri, respectively, while the five highest levels terminated in east central and northeastern Oklahoma. The apparent low level wind maximum at level 5, discussed in the previous section, is precisely the type of feature that numerical analyses are able to take into consideration but which often are not detected in trajectories based on meteorological charts. Surface trajectories from all the graphical techniques compare well with the numerical backtracks, but none match level 5 (approximately 850 mb) very well in their upper air backtracks.

#### Summary

The numerical results from these three case studies indicate that back-trajectories can, and often do, change direction and length greatly with height throughout the lower troposphere. The back-trajectories presented in this chapter were for 12 - 24 hours in length. It is apparent that pest origins estimated by this method would show an even larger geographical spread with investigations of pest migrations lasting longer than 24 hours. The level at which the strong wind shear occurs cannot be determined with surface and 850 mb charts whereas the use of a numerical procedure that incorporates data throughout the lower troposphere can show this important fact. These results indicate that a determination of preferred flight levels of insects is essential for an adequate estimate of pest origins.

#### 6. Weather Systems that Complicate Trajectory Analysis

The back-trajectory model was developed under the assumption that the weather disturbances through which the insects are carried by the prevailing

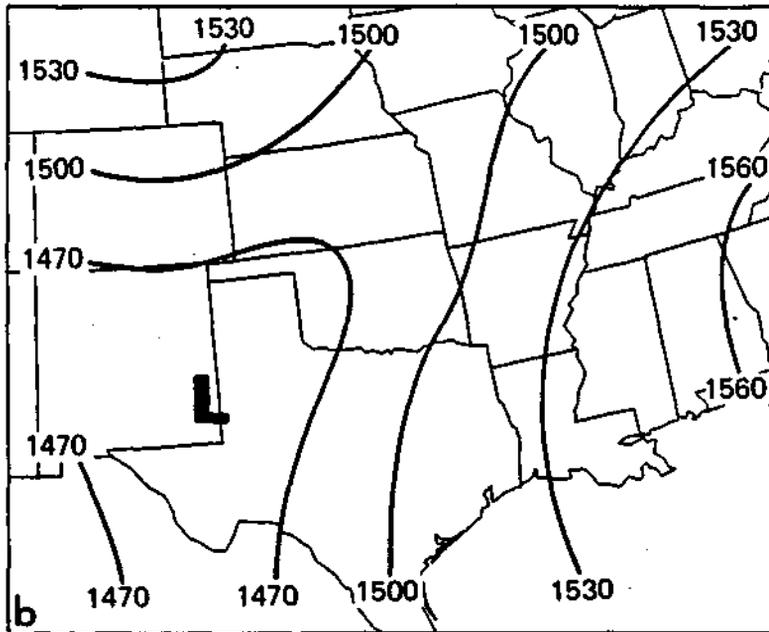
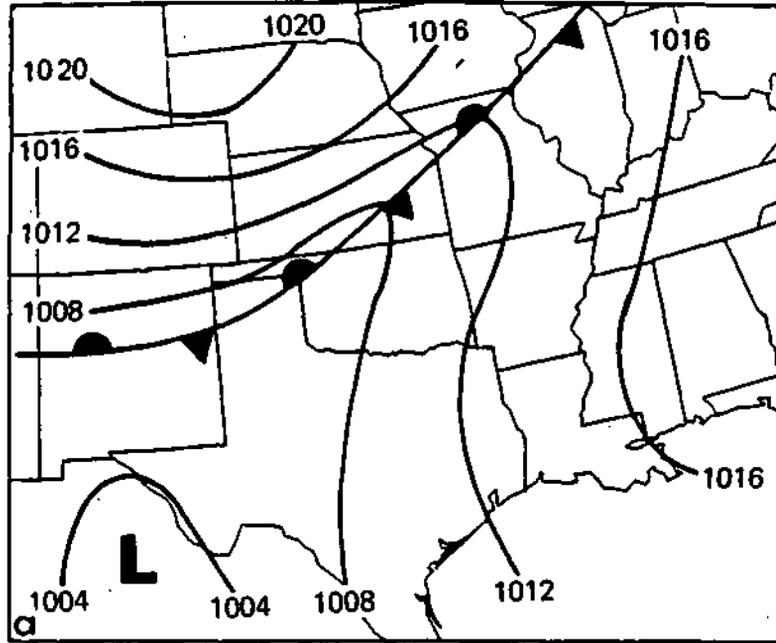


Figure 15. Same as Fig. 11, except for 1200 GMT on 8 June 1979.

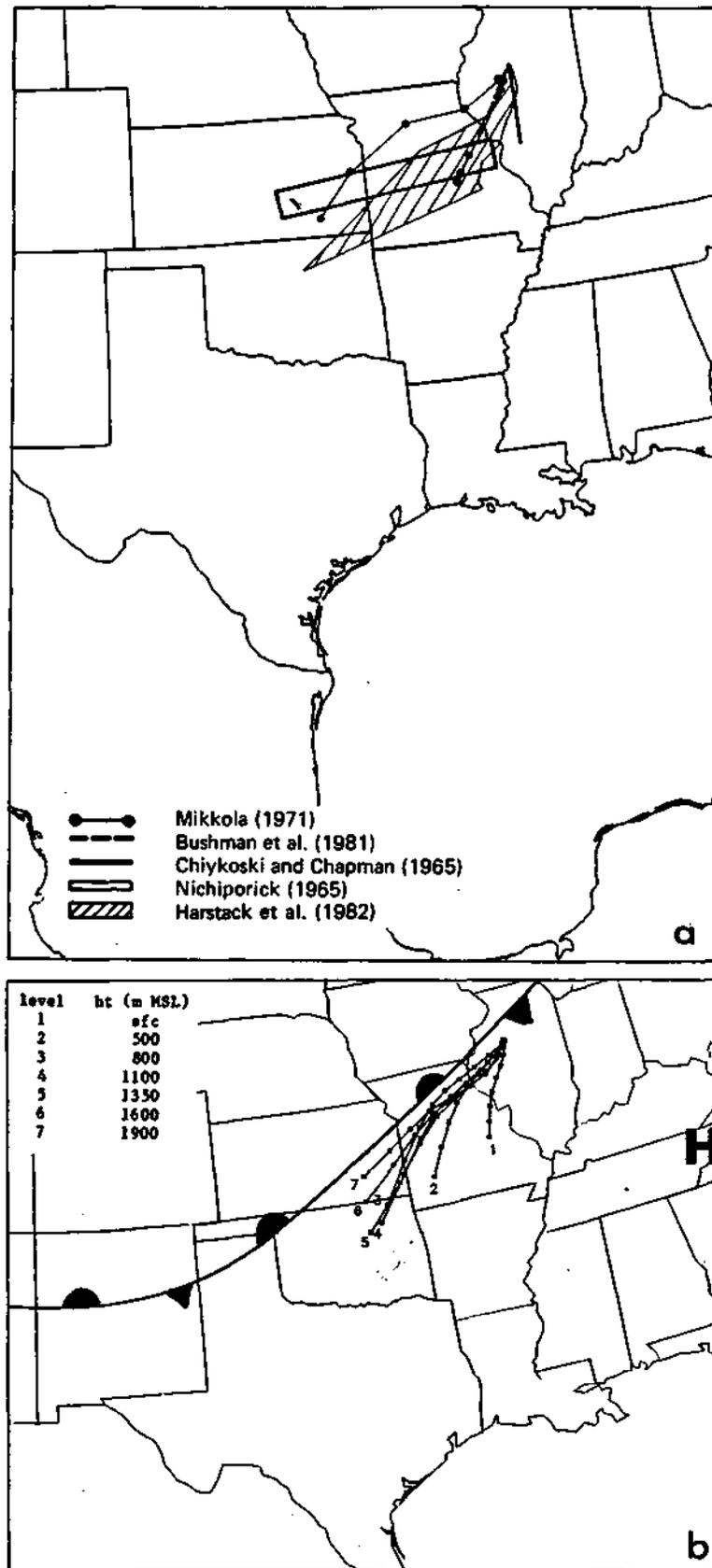


Figure 16. Graphical (a) and objective (b) back-trajectories at 1200 GMT on 8 June 1979.

wind cover a sufficiently large area to be resolved by the NWS winds aloft network. Further, it also has been assumed that the life span of the weather system is long enough to be resolved by the 12-hour sampling frequency of the same network. When either or both of these conditions are not satisfied, the actual migratory paths may depart significantly from the calculated back-trajectories. Weather systems that are endemic to the Middle West during spring and summer that fail to satisfy the assumptions made in deriving the back-trajectory model include precipitation systems, nocturnal wind maxima and frontal zones.

Precipitation systems usually occur as lines or bands of convective showers that develop in association with frontal zones, especially during spring. These systems interrupt migratory paths. Biota (especially small insects such as aphids) can become trapped within updrafts and carried to levels where the wind speeds and directions differ greatly from the vector wind of the prestorm trajectory. Alternatively, the migrants may rain out or be stimulated to fall out in advance of the precipitation and the migration stops, at least temporarily.

Precipitation systems do not pose as serious a problem for the establishment of migratory paths as it might seem. The reason for calculating back-trajectories is to determine the origin of insects that have already arrived at some sampling site. Either the migrants have arrived directly from their point of origin or they have arrived from some interim area the location of which can be determined from an analysis of precipitation maps.

The remaining two weather systems, the nocturnal wind maximum and the frontal zone, can cause our method to calculate back-trajectories that diverge significantly from the original migratory path. Therefore we will devote the remainder of this section to the description of these systems and the presentation of ways to include their effects in the objective back-trajectory analysis.

#### The Nocturnal Wind Maximum

Blackadar (1957) has found a sharp maximum, frequently observed at night, in the wind speed profile below 1 km. The wind speed maximum, usually at the top of the nocturnal inversion, is greater than predicted by the balance between the pressure forces that move airmasses and the earth's rotation (the geostrophic wind), and is often associated with extremely large values of wind shear in low levels. This nocturnal jet significantly impacts upon our efforts to accurately determine the origin of migrating insects because 1) many kinds of insect pests fly at night, 2) the wind maximum tends to occur at the level of maximum temperature, the suspected level of preferred insect flight, 3) the nocturnal jet is a climatological feature of the High Plains, but over the Middle West, including Illinois, its occurrence is sporadic and its association with synoptic weather systems is not known with certainty, 4) the nocturnal maximum tends to initiate during early evening (about the time of the 0000 GMT winds aloft observations), reach peak wind velocity around midnight or a few hours later, and dissipate by sunrise (about the time of the 1200 GMT winds aloft observations). Thus the phenomenon tends to occur between observation times.

Since the nocturnal jet occurs mostly during a period for which there are no winds aloft observations, it must be parameterized in some way from existing data sets. However, before we parameterize this weather system, we first determine if the jet is a major cause for the departure of the calculated back-trajectories from the actual nocturnal migration path and, if so, determine under what larger scale weather conditions the nocturnal jet occurs.

The diurnal wind variation which is characteristic over land surfaces is the result of vertical transport of momentum by turbulence. A maximum during the heated part of the day, the loss of momentum to the underlying surfaces decreases the wind to subgeostrophic velocities. After the period of maximum heating, usually near sunset, cooling near the ground forms the nocturnal inversion, a layer of air through which the temperature increases with height. Blackadar (1957) postulated that the turbulent mixing very rapidly dies away above the inversion and ceases to have any important effect upon air motion at these levels. With the restraining turbulence greatly reduced or gone, the air is free to accelerate in proportion to the magnitude of the imbalance between the pressure forces and the Coriolis force (caused by the earth's rotation).

Within the deepening nocturnal inversion, some turbulence is maintained because of the large wind shear. According to Blackadar, heat is transferred downward to the surface where it is lost by radiation. This heat loss, which is not compensated in the upper layers, results in the continuous upward growth of the inversion during the night. Blackadar showed that the wind maximum tends to collocate with the top of the inversion. Therefore, the behavior of the nocturnal jet is such that it is progressively found at higher elevations and the vector wind is always evolving as the airmass accelerates. Figure 17 shows schematically how the forces act to accelerate the air to develop super geostrophic winds. The velocity the air would have if the pressure gradient forces exactly balance the coriolis force is given by  $V_g$ . The downward transport and dissipation of horizontal momentum at the surface reduces the wind speed and changes the direction toward low pressure. This boundary layer wind is given by  $V_0$ . Upon formation of the nocturnal inversion at about sunset, the turbulent dissipation of horizontal momentum rapidly declines and the removal of this retarding force allows the horizontal wind to accelerate according to the difference between the pressure gradient and Coriolis forces, i.e., the geostrophic deviation  $W_0$ . The pressure gradient accelerates the wind to the left of the pre-existing direction of motion. Then, as the wind speed increases, the Coriolis force increases to turn the wind to the right. Blackadar showed that the interplay of these two forces would, in the absence of other forces, cause the wind vector  $V(t)$  to rotate along the dashed circle with the center located at  $V_g$  and the radius equal to the geostrophic departure  $W$ .

That part of the wind vector which is the component of rotation is known as the inertial component of the wind. If no other forces act upon the airmass, the wind will follow the dashed circle in Fig. 17 indefinitely. The period for one complete revolution is one-half pendulum day. If  $W_0$  is a typical geostrophic deviation at the time of sunset, a supergeostrophic maximum of the wind speed is reached about six pendulum hours later - about 12 hours at San Antonio and 9.5 hours at Washington, D.C. (Blackadar, 1957). An example of how the nocturnal wind maximum can alter the local airflow as given in Fig. 18. During the daytime (1500 C), the downward transport of horizontal

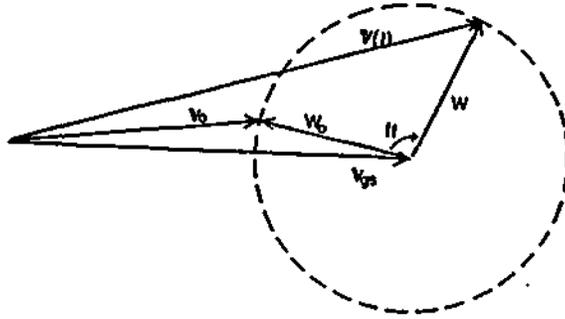


Figure 17. Relation of the time-varying geostrophic departure  $W$  and the wind vector  $V(t)$  to the initial values  $W_0$ ,  $V_0$ , and the geostrophic wind vector  $V_g$  upon the decline of turbulent dissipation of horizontal momentum (After Blackadar, 1957).

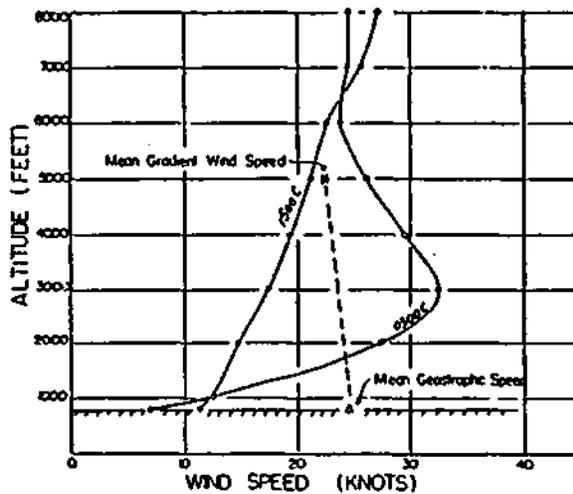


Figure 18. Average wind speed profile for 16 significant boundary layer jets at San Antonio, Tex., during January 1953 (after Blackadar, 1957).

momentum and its dissipation at the surface causes a linear decrease in the wind speed from 21 knots at 5000 feet to about 11 knots at the surface. The mean gradient wind speed increases from 22 knot at 5000 feet to 25 knot at the surface. Thus the geostrophic departure ranges from 1 knot at 5000 feet to 14 knots at the surface. Twelve hours later (0300 C), there is found a wind maximum of 33 knots at 3000 feet. This represents an approximate two-fold increase over the daytime wind speed at this elevation. Below 3000 feet, the nocturnal jet decreases because of turbulent mixing within the strong vertical wind shear below the nocturnal inversion.

Having established that the nocturnal jet can cause substantial changes in the local vector wind, we now show that the nocturnal jet can also cause widely divergent values in calculated back-trajectories. The time rate of change of the horizontal wind at a particular location is given by the sum of 1) the advection (transport) of a different velocity regime by the horizontal wind, 2) the vertical transport of horizontal wind, 3) the magnitude of the pressure gradient force, 4) the Coriolis force, and 5) frictional and turbulent dissipation forces. If we assume a) the horizontal wind field is uniform, b) there is no large scale vertical velocity, and c) the geostrophic wind is unchanging, the equations that describe the motion of the atmosphere can be simplified to the time rate of change of the horizontal wind in response to the pressure gradient force, the Coriolis force, and dissipation forces. The abbreviated equations are

$$\begin{aligned} du/dt &= f(v-v_g) - ku \\ dv/dt &= -f(u-u_g) - kv \end{aligned}$$

where  $f$  is the Coriolis parameter,  $k$  is a dissipation constant,  $u$  and  $v$  are the east and north wind components, respective, and the subscript  $g$  identifies the pressure gradient terms.

Beginning with a known boundary layer wind profile, we can integrate the above equations and calculate back-trajectories from the resulting sequence of wind vectors. We assume that nocturnal insects travel over a period of two days. We develop an initial linear wind profile by assuming  $k=f=10^{-4} \text{ sec}^{-1}$  at the surface and  $k$  decreases linearly to zero at 1000 meters elevation. The geostrophic wind is  $10 \text{ m sec}^{-1}$ . We make no allowances for the growth of the nocturnal inversion. Figure 19 shows the growth of the nocturnal jet for two cases of decay of the dissipation term; the first being at the rate of 20 percent per hour and the second at the rate of 10 percent per hour. If the decay rate is 20 percent, the dissipation term reduces to zero after five hours. After that, the solution is for purely inertial flow. Figure 19a shows that the wind speed peaks at nine hours after the reduction of the dissipation term. After that, the wind decreases as the vector rotates around the inertial circle (dashed line in Fig. 17). Speeds peak at  $18 \text{ m sec}^{-1}$  at 200 meters. Wind speeds have decreased at all levels by  $t=12$  hours. Note that the wind at the surface has been held constant. Retaining the dissipation longer into the integration increases the time for the development of the nocturnal jet (Fig. 19b). The maximum is now found at  $t=12$  hours and the peak speed is about  $16 \text{ m sec}^{-1}$ , a reduction of  $2 \text{ m sec}^{-1}$ .

Figure 20 shows three sets of calculated back-trajectories with different histories for the dissipation term. The back-trajectories for the first (Fig 20a) result if  $k$  is constant at its initial value over the period of

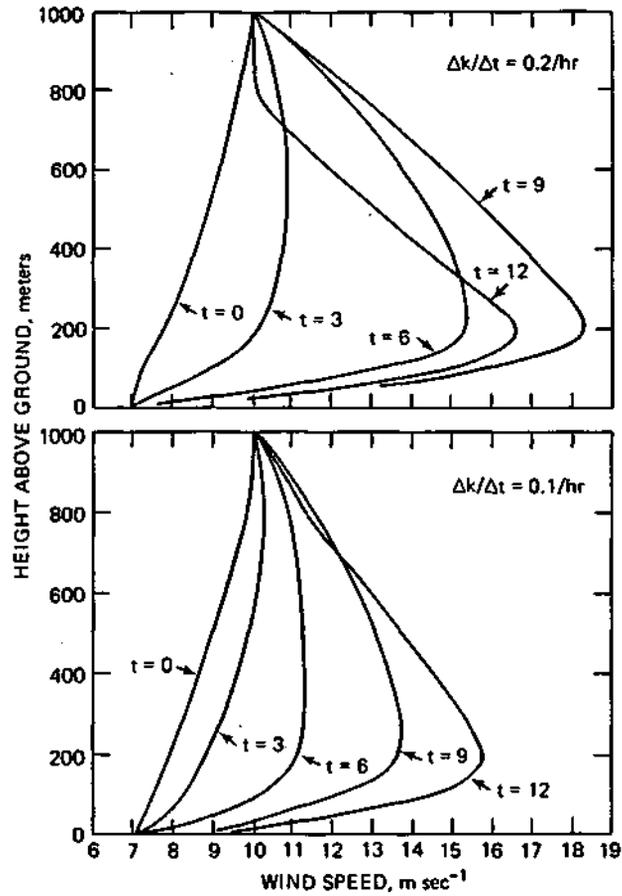


Figure 19. Simulation of a nocturnal jet between the surface and 1 km for a)  $k$  reduced at 20 percent per hour and b) for  $k$  reduced at 10 percent per hour.

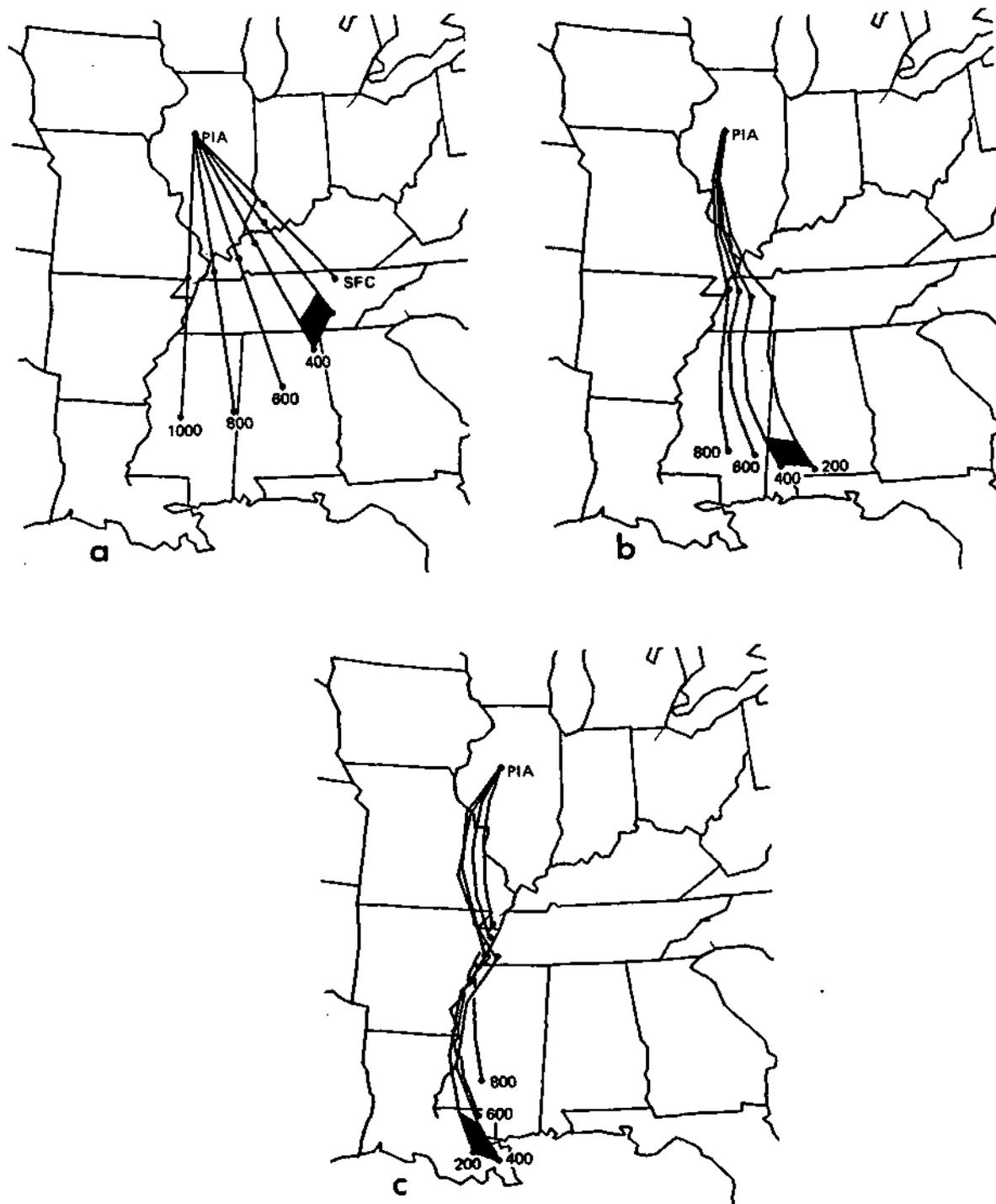


Figure 20. Calculated nocturnal back-trajectories for insects flying for two nights between 200-400 meters agl. Back-trajectories for a)  $k$  constant at its initial value over the period of integration, b)  $k$  decreased at 10 percent per hour for 10 hours, and c)  $k$  decreased at 20 percent per hour for five hours.

integration. Here no allowances are made for the nocturnal jet. If the insects fly within the 200-400 meter layer and if the insects were trapped at 3-hour intervals, insect arrivals at a point near Peoria, Illinois, after 24 hours could be traced to an initial lift-off somewhere over southeastern Tennessee. However, if  $k$  is decreased at 10 percent per hour for the first 10 hours, the initial lift-off would be traced to southwestern Alabama (Fig. 20b). This represents a significant error in the calculated back-trajectories, an error of 440 km (275 mi). This error is larger still if  $k$  is decreased at 20 percent per hour for the first 5 hours of integration (Fig. 20c). The point of lift-off shifts to southeastern Louisiana, a distance of 723 km (450 mi) from the estimated source when inertial accelerations were ignored. Therefore, the inertially generated nocturnal wind maximum can have an immense impact upon the calculated back-trajectories. Furthermore, it is also shown that the decay rate for the dissipation constant is also important in any parameterization of the nocturnal jet.

Having demonstrated that the nocturnal jet can significantly impact the calculated back-trajectories, we sought to find how frequently the phenomenon occurs over the Middle West and is found within what types of larger scale weather systems. Our approach was to acquire data from a number of special regional scale projects, data that included winds aloft observations over three hour intervals, and to analyze the morphology of the nocturnal wind. These special data sets are summarized in Table 2. We were unable to find a single unequivocal nocturnal jet with these data. Therefore, we were forced to abandon further development of a suitable parameterization scheme for it. The problem of the inertial acceleration of the nocturnal wind remains to be solved if accurate nocturnal back-trajectories are to be calculated.

Table 2. NASA field experiments checked for the inertial wind.

Experiment	Date
AVE II	11-12 May 1974
AVE IV	24-25 April 1975
AVE-SESAME I	10-11 April 1979
AVE-SESAME II	19-20 April 1979
AVE-SESAME III	25-26 April 1979
AVE-SESAME V	20-21 May 1979
AVE-SESAME VI	7- 8 June 1979

#### The Frontal Zone

The gridded wind fields for the nonstandard 3-hour data sets are obtained by linear interpolation between the standard 12-hour NWS observations. There is an inherent assumption that the wind at any point varies linearly in time. This assumption is not valid near frontal zones where the wind typically blows steadily from one direction for part of the period of time and then abruptly shifts to another direction for the remainder of the period. This problem can be corrected by increasing the temporal resolution of the wind field. The

surface data, collected hourly, offer the only routinely available means for accomplishing this. However, some method must be devised to estimate the winds above the surface. One method, which uses the surface pressure field to calculate the winds aloft, requires the assumptions that the winds aloft are geostrophic and that the surface pressure field is not contaminated by observation errors or by smaller scale weather disturbances that do not extend much above the ground.

This method to increase the temporal resolution of the winds aloft through calculating the geostrophic wind from the surface pressure data was tested with a case study of 9 July 1984. On this day, the general surface weather conditions at 1200 GMT showed a warm front extending out of a weak low pressure region in southeast South Dakota, across southern Minnesota, and then southeastward to Alabama and southeastern Georgia. A stationary front stretched to the southwest of the low center to eastern Colorado and then westward into the central Rockies. High pressure existed over the entire east coast and Gulf states. A low-level wind maximum stretched from the central Plains into the Midwest.

Comparisons were made of streamlines and isotachs calculated from three different sets of data: hourly surface wind reports, a geostrophic wind analysis of the pressure field, and wind fields generated from analysis of rawinsonde data just off the ground. Streamlines and isotachs calculated from the observed wind data at 0000 GMT on 9 July are shown in Fig. 21. A wide band of southerly and southeasterly winds with speeds in excess of  $5 \text{ m s}^{-1}$  existed from western Texas to Illinois and southwestern Wisconsin. Convergence along an apparent frontal zone was located to the northwest of this band in northwestern Nebraska and central South Dakota while a large anticyclonic (clockwise) circulation was found in eastern West Virginia. Further south, a small, weak cyclonic (counterclockwise) circulation was observed in southern Georgia, in the vicinity of the frontal system located across the Southeast.

After initial work to rid the data set of many observation or transmission errors, the geostrophic surface winds (Fig. 22) reveal many different features that are in stark contrast to the analysis of the observed winds. Southerly winds existed in the central United States but in a much narrower band over the upper Mississippi valley, and much stronger  $10$  to  $20 \text{ m s}^{-1}$  instead of less than  $10 \text{ m s}^{-1}$ . The circulation around the high pressure in the eastern U. S. was larger than indicated by the observed surface winds. The weak low pressure center in southern Georgia does not appear while a secondary anticyclonic circulation occurs in western Texas. The geostrophic wind pattern approximated the directions in the observed wind field over the eastern United States fairly well, especially since surface friction causes low level winds to turn toward lower pressure. However, over the central Plains, the patterns were greatly different: directions differ by  $180^\circ$  in western Nebraska. The apparent frontal feature in the observed winds was replaced by a weak trough located slightly further to the south.

Analyses of the observed winds on level 2 (approximately 400 m above ground in the eastern U. S.) is shown in Fig. 23. Except for the extreme southeastern part of the country, the streamlines in this analysis closely matched that seen in the observed surface winds. No troughing was evident over the Plains states as was seen in the geostrophic analysis. In fact, the only similarity with the geostrophic wind analysis was the large anticyclone in the east and partial agreement with high wind speeds in Iowa and Missouri.

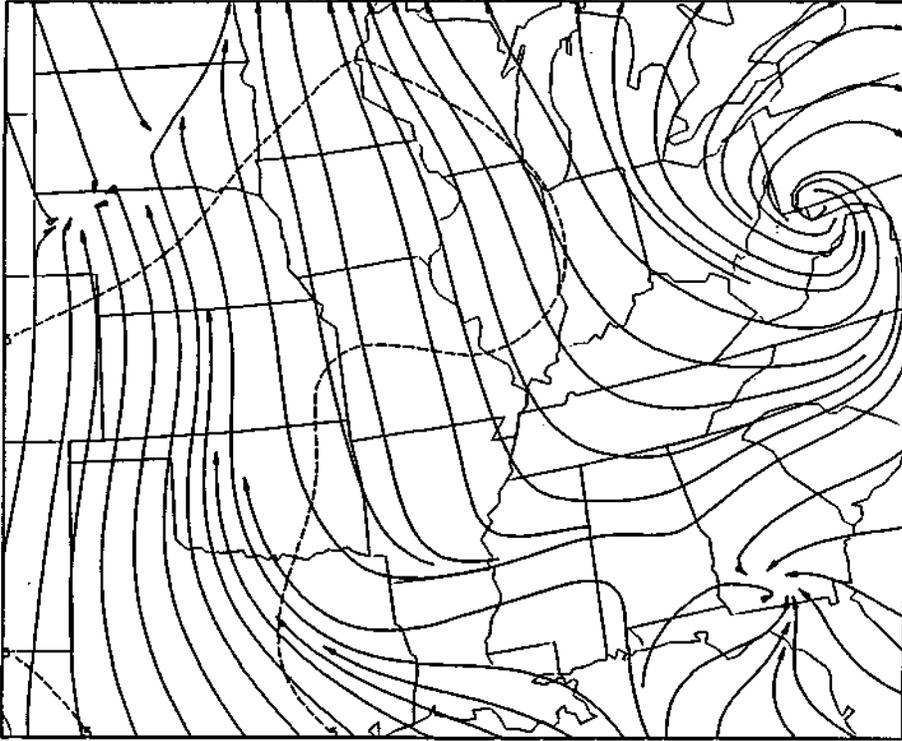


Figure 21. Streamlines and isotachs from observed surface wind data at 0000 GMT on 9 July 1984.

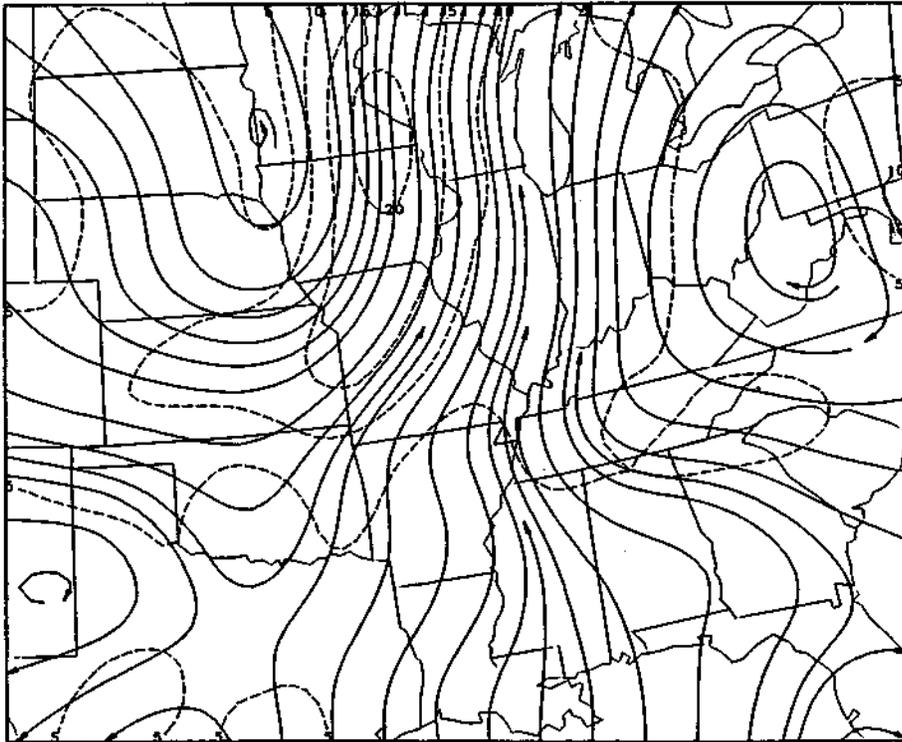


Figure 22. Streamlines and isotachs from a geostrophic analysis of the surface pressure field at 0000 GMT on 9 July 1984.

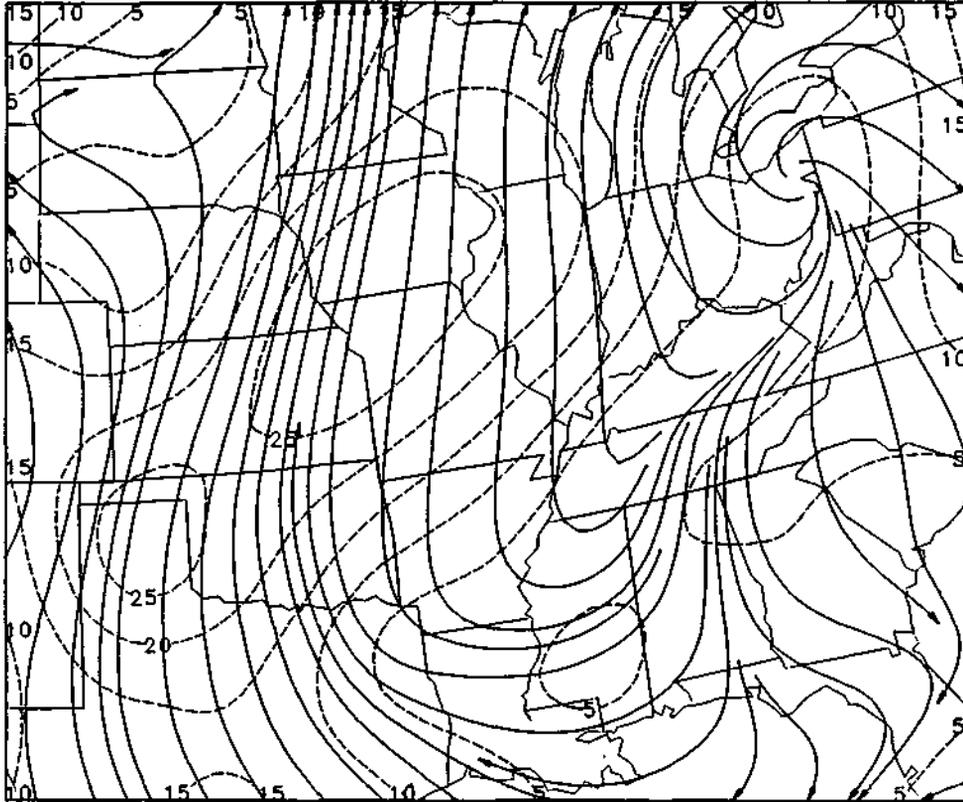


Figure 23. Streamlines and isotachs from observed upper air data on level 2 at 0000 GMT on 9 July 1984.

At the 400 m level, a band of 20 - 25 m s<sup>-1</sup> wind speeds was observed from the Texas panhandle to Wisconsin.

As a summary, it is apparent that in this particular case, large areas of the wind field were strongly ageostrophic. Therefore, the use of surface geostrophic analyses in the vicinity of frontal zones are not encouraging and may even introduce errors into the trajectory analysis.

## 7. Summary of Findings and Future Needs

This chapter has presented the methodology for the development and evaluation of an objective method for the calculation of back-trajectories as part of the comprehensive study of the transport of insect pests by the atmosphere. We have examined the sensitivity of this technique to the spatial and temporal frequency of the observations. Further, we have compared trajectories calculated by the objective technique with trajectories obtained by empirical methods developed by other investigators. Some of the findings of this study are summarized below.

1) With a minor assumption, the objective trajectory algorithm was shown to reduce to the same mathematical form as the objective streamline algorithm developed by Achtemeier (1979). This method attains to a level of precision that allows confidence that the trajectory algorithm does not introduce either interpolation or extrapolation error of significance. Thus the accuracy of the trajectories can be considered as determined by the accuracy and representativeness of the data and the accuracy of the methods to grid and to perform temporal interpolation of the gridded fields.

2) Increasing the data density by the addition of supplemental wind observation sites to the regular winds aloft observation network appears to have little impact upon the locations of the origins of the back-trajectories, at least for the weather systems studied. However these weather systems are typical of the spring and early summer weather systems that are suspected of bringing insect pests into Illinois from the southern states.

3) Increasing the frequency of the winds aloft observations from 12 hours to 3 hours has no significant impact upon the locations of the end points of the back-trajectories (i.e., pest source) as long as the weather systems have the size and movement of the large scale synoptic weather system. There are significant divergences between the 12 hour and the 3 hour back-trajectories in the vicinity of frontal zones.

4) Of the graphical back-trajectory estimation methods that were compared with the objective back-trajectories, the geostrophic method developed by Mikkola (1971) provides the best estimate of insect source regions although one should be aware that the envelope of the endpoints created by this method can cover a large area if the boundary layer winds are characterized by large veering and shearing in the vertical.

5) Most of the graphical methods compare fairly well with the objective back-trajectories except when there exists a wind maximum below 850 mb. Then the trajectories estimated by all of the other methods diverge significantly from the numerical trajectories.

6) Trajectories developed from the surface winds often fail to approximate the trajectories at levels just above the ground. This lowest 100-200 meters is frequently a layer of strong vertical wind shear. Thus, if it were known that insects were flying within this layer, the use of surface winds exclusively could lead to significant error in the estimation of the migration source.

7) Our analysis and modeling of the nocturnal jet and the air flow near frontal zones indicates that, where and when these two weather systems exist, they can cause very large errors between the calculated back-trajectories and the actual migratory paths. Our efforts to parameterize the nocturnal jet were not successful because we were unable to find a single unequivocal instance of a nocturnal jet in the special network data analyzed. Furthermore, our efforts to increase the temporal resolution of the 12-hour observations by building in a relationship with the hourly surface geostrophic wind showed some promise. However, there were large areas where the surface pressure was complicated by mesoscale events and the wind field was largely ageostrophic. This is expected to increase, not decrease, the expected uncertainty in the calculated back-trajectories near frontal zones.

8) Most importantly, the objective back-trajectory method, with its greater vertical detail, offers much improved resolution in the estimation of the source regions of migrating insects. However, this improved resolution is dependent upon knowledge of the levels at which the insects fly and upon a more frequent insect trapping (sampling) interval, for example, three hours.

Although significant progress has been made in developing an objective trajectory analysis technique, some additional research is necessary before the method can be converted into a useful tool for the prognosis of insect migrations into Illinois which is one of the ultimate objectives of this project. The trajectory analysis has been designed for easy conversion from a diagnostic back-trajectory analysis into a prognostic trajectory analysis. However, it is much more difficult to acquire and process data on a real time mode for a prognostic model than it is to use preprocessed data in the diagnostic mode. Further, the prognostic trajectory analysis will require as input winds predicted by some prognostic numerical model. Predicted winds are currently available from routinely operated numerical models, however the vertical resolution is not sufficient to describe the variability of the boundary layer wind field. Either these winds will have to be used with the knowledge that the resulting trajectories will be less accurate than their diagnostic counterparts or some other means to obtain the predicted wind fields will have to be sought.

Finally, some of the meteorological problems discussed in this chapter need further study. A Middle West climatology of the nocturnal wind needs to be developed in order to determine the importance of this transient disturbance for the movement of nocturnal insects. New methods to calculate trajectories near frontal zones should be developed. And lastly, once the flight behavior of migrating insects is established, it may become necessary to modify the existing trajectory model to accommodate insect movements between levels.

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