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EFFECT OF CONTRAIL CIRRUS ON SURFACE WEATHER CONDITIONS IN THE MIDWEST - PHASE II

Final Report of NSF ATM 8008812

by
Wayne M. Wendland
and
Richard G. Semonin

Champaign, Illinois 61820
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INTRODUCTION

The research to investigate the effect of aircraft contrails on surface climate began at the Illinois State Water Survey (ISWS) in 1979 funded by a grant from the National Science Foundation. Contrail cirrus are the result of the exhaust of jet aircraft (made up primarily of water vapor, carbon dioxide and some hydrocarbons) expelled into an atmosphere where the micro-environment of the exhaust plume may become saturated. The vapor within the plume condenses, freezes, and the ice particles grow by sublimation, marking the past trajectory of the aircraft. If the ambient air is very dry, contrails may not persist, or may continue only for a few seconds. In humid air, contrails may persist for tens of minutes to several hours, occasionally spreading into linear features tens of kilometers in length and a few kilometers wide. We have investigated the effect of these contrails on surface climate, as indicated by temporal changes in standard surface meteorological observations.

Our work during the first year (Phase I) included gathering data on aircraft traffic density over various parts of the United States, amassing data on the magnitude and frequency of contrails from the mid-1950's to the late 1960's, and an analysis of trends and changes to trends of certain parameters from standard meteorological records (including cloud cover and surface temperature) to identify areas with near coincident trends in both contrail frequency and the meteorological parameter in question. Increased high clouds in areas with increased jet traffic would be presumed to be necessary (but not sufficient) evidence to suggest that jet aircraft impact some components of surface climate.

The area under study included ten Upper Midwest states surrounding the Great Lakes. During the 13 years for which we had adequate contrail observation data (observations made by U. S. Air Force SAC crews from 1957-1969), changes in the amount of cloud cover, and surface temperature measured from National Weather Service (NWS) First Order Stations (FOS) were analyzed. During that interval, the contrail data from military jet traffic were most frequently located within a broad corridor roughly running from northern Ohio through northern Illinois to the Iowa-Missouri border. This pattern provided the basis for a "control" area (i.e., an area with few jet aircraft and contrails, and a "test" area (the corridor with frequent jet traffic and contrails)).

Phase I revealed that weather stations within the heavy traffic corridor experienced a decreased number of clear days (increased number of cloudy days) coincident with the time during which jet traffic increased. Also within the corridor, percent possible sunshine decreased. At stations with less frequent jet traffic, percent possible sun either increased or remained constant. Interestingly, stations in the test area experienced the greatest decrease in percent possible sun and increase in cloud cover in autumn, the season with typically minimal cloud cover in the Upper Midwest. An increased frequency of moderated temperatures (difference between daily maximum and minimum) was observed over northern Illinois and Indiana, beginning during the last 1940's and continuing to the present. Moderated temperatures can result from decreased outgoing longwave radiation (supported by increased cirrus cloud).

The frequency of high clouds increased between 1951 and 1976 at all first-order stations within the area of high traffic density. A similar result was found when the data base was stratified to include only high cloud observations with 0.4 or less low and/or middle clouds. Four-tenths low or middle cloud cover was chosen as the upper limit to minimize obscuration of cirrus clouds by lower decks.

The above changes were noted over more than a decade, and during a time when hemispheric temperatures were cooling (Brinkmann, 1976), with concomitant changes in general circulation (Kalnicky, 1974). We have made no attempt to extract a global climatic trend from our data. However, we also know of no reason why global trends would preferentially affect areas with high jet traffic as opposed to those areas with little jet activity, particularly since our control and test areas are subsynoptic in areal extent.

Contrail observations from several thousand Combar Meteorological Aircraft Reports (COMBAR) from military aircraft suggested that about three-fourths of all observed contrails are persistent, that contrail observations tend to be slightly more frequent in winter and spring than in summer and autumn, and are more frequently associated with turbulence, than are non-contrail observations. About 70% of all contrail observations occurred with some cloud cover below aircraft altitude. Therefore, up to two-thirds of all contrail cirrus may be obscured from ground viewing by lower "natural" clouds, and therefore the impacts of contrail cirrus on global albedo may be of less magnitude than previously perceived. Contrails were most frequently located near mid-tropospheric troughs, as opposed to ridges, i.e., they tend to form and persist when a natural cloud shield is moving into the area.

OBJECTIVES

The objectives of this year's proposal (Phase II) were fourfold: (1) determine the frequency and areal extend of false cirrus and their effect on surface temperature and insolation as well as other climatic parameters, (2) estimate the effect of contrail cirrus on past (last 25 years) observations of cloud cover, (3) delineate typical areas of persistent contrails on a daily basis in order to estimate the total areal depletion of solar radiation due to contrail cirrus, and (4) determine the temperature and insolation changes due to partial interception of sunlight by an individual contrail.

In order to fulfill these objectives, we proposed analyses of three data bases, (1) COMBAR observations to identify areas with persistent, dense contrails, as opposed to adjacent areas with neither contrails or natural clouds; (2) FOS cloud cover observations to verify whether contrails in the areas identified from COMBAR observations were perceived by the observer as natural cloud cover; and (3) Champaign, Illinois insolation and temperature records at those times when a nearby all-sky camera recorded sky conditions as clear, except for a single or a few contrails drifting across the sky.

The above objectives were all tested using the described data sets with the results exhibiting varying degrees of success. False cirrus frequency has been assessed using several independent methods and we believe that contrail cirrus frequency through a year in the Upper Midwest is now generally known. We have been able to partially determine the areal extent of contrail activity on any given day of four months of. 1981 within Illinois by. means of a cooperative observer network, but have not been able to make such delineations outside the state of Illinois. Our limited ability to define the areas of persistent contrails on any given day have therefore limited our capability to estimate the effect of increasing contrail cirrus over the past 25 years on standard cloud observations, or to estimate the total loss of solar radiation to a given area of the earth's surface. We have been able to evaluate the changes to surface temperature and solar radiation due to contrail interference of the solar beams as learned from the case studies involving the all-sky camera. The study of more than 30. cases when contrail cirrus passed between the sun and ISWS instruments documented changes to temperature and solar radiation from a clear sky condition to that with a well-defined contrail.

CONTRAIL FREQUENCY OBSERVATIONS

Contrail frequency in a general sense was measured using two techniques: systematic visual observations from a point, and images from an all-sky camera.

Surface Visual Observations

Surface observations of contrail frequency were made daily by the (ISWS) weather observer. For the period from January through October 1981, measurement of percent cloud cover were made 3 times each day (0700, 1200, and 1800 local time) along with comments as to the frequency and character of contrail activity. Cloud days were defined as those where the 3 observation average was equal to or greater than 0.8 cloud cover.

Table 1 shows the frequency of cloudy and contrail days at Champaign for the period September 1979 through October 1981 with breaks. Note that the contrail frequencies are greatest during winter, spring and early summer with diminished frequencies thereafter regardless of the observing method. Visually, winter frequencies (January through June) vary between 30% and 67%, whereas those of summer and fall from 0% to 17%. The zero reading for July is probably nonrepresentative due to incomplete observations, however the seasonal differences are consistent.

It is clear that contrails were sighted more frequently during winter and spring than summer and fall. This annual change corresponds to natural cloud cover in the Midwest. Clearly, there is great variability from year-to-year, although the annual change is apparent.

Even more striking however, is the apparent difference in frequency from the observations of the all-sky. camera and those taken visually by the ISWS observer. The camera observations are generally 50% or even less than those determined by eye.

Table 1. Contrail Frequency Determined from All-Sky Camera Film and Visual Observation, Both at Champaign, IL. Values Reported as Percent of Non Cloudy (<0.8) Days.

Month	Year	From Camera	Visually
Sep	1979	7%	
Oct		18	
Nov		18	
Dec		15	
Jan	1980	16	
Feb		37	
Mar		24	13
Apr		22	11
May		9	14
Jun		9	31
Jan	1981		50
Feb			67
Mar			54
Apr			55
May			33
Jun			30
July			0
Aug			15
Sep			17
Oct			14

As reported in the final report of Phase I (Changnon et al., 1980), contrail frequency gleaned from the all-sky camera located at the ISWS building, was very low. During about 3 1/2 years of observations, beginning in 1976, only 3% of the total days indicated contrails. We suspect that this is due to several conditions: (1) Difficulty of identifying contrails on the small format film, (2) further identification problems with contrails located nearer than about 20 from the horizon, and (3) inability to see contrails when natural clouds occur, (both above and beneath the contrails).

GROWTH RATE OF CONTRAILS

We have reported growth and contraction rates of contrails in the Phase I final report. However, that sample was very small and the all-sky film viewer used at that time was of poorer quality than that used for the results which follow. For those reasons, we review the growth characteristics of contrails.

The ISWS has maintained an all-sky camera (to record cloud cover) at regular intervals for several years. The data proved to be invaluable for this study since the longevity of the record was sufficient to permit the extraction of significant conclusions concerning frequency, and growth characteristics of aircraft cirrus.

Camera Description

A Bell and Howell 200 magazine camera has been used for time-lapse 16 mm color pictures of the Champaign-Urbana sky for five years, 1976 through 1980 (Table 2). Interruptions during that period were caused by mechanical malfunctions (film slippage, poor electrical connections, frozen film) and human error (improperly focused lens, and failure to change film). A major interruption between 28 May 1977 and 1 May 1978 was created when the camera was removed to allow for repair of the roof.

Table 2. Period of Record for All-Sky Camera Operation.

Begin	End	Number of Days
21 APR 76	5 MAY 76	14
10 MAY 76	16 JUN 76	37
3 JUL 76	25 DEC 76	175
25 JAN 77	28 MAY 77	123
1 MAY 78	4 NOV 78	187
11 DEC 78	21 AUG 79	253
5 SEP 79 .	17 DEC 79	103
11 JAN 80	30 JUN 80	171
		1063

The camera is located atop the cupola of the Water Resources Building (about 2 1/2 stories above the surface). The camera is pointed earthward and is centered 70 cm above a silvered hemispheric dome about 0.5 m in diameter. Since 25 May 1978, an f2.8, 16 mm focal length lens has been used. Prior to that date, an f2.5, 17 mm lens was used. The camera was timed to automatically expose one frame every five minutes. At that rate, one magazine of film, approximately 15.24 meters in length, would photograph for 15 consecutive days. In addition, a clock and digital calendar are positioned in such a manner so as to be photographed each frame.

Two enlarged examples of the exposures are shown in Fig. 1. The two examples record clear day images with two contrails each. The bright upper left hand portion is due to sun glare. The two white streaks passing through about 40 altitude are contrails, and the white band about the limb represents haze — a characteristic common to most photographs. Even on clear days (as these examples show), sighting of contrails was limited to an area less than the total celestial hemisphere (due to sun glare, horizon haze, cloud cover, and image quality).

Reduction of Data

The initial step in the reduction of data was to review each film, 75 rolls in all, and identify those days on which contrails were present. This process was accomplished through the use of two reader-printers. The lens in each viewer magnified each frame by 12.05. Differences in measurements between the two viewers were noted and are now reviewed in detail.

Comparison of Microfilm Viewers

Two different microfilm viewers were used to examine all-sky camera film throughout the contrail project. These were 3M Reader-Printers, model numbers

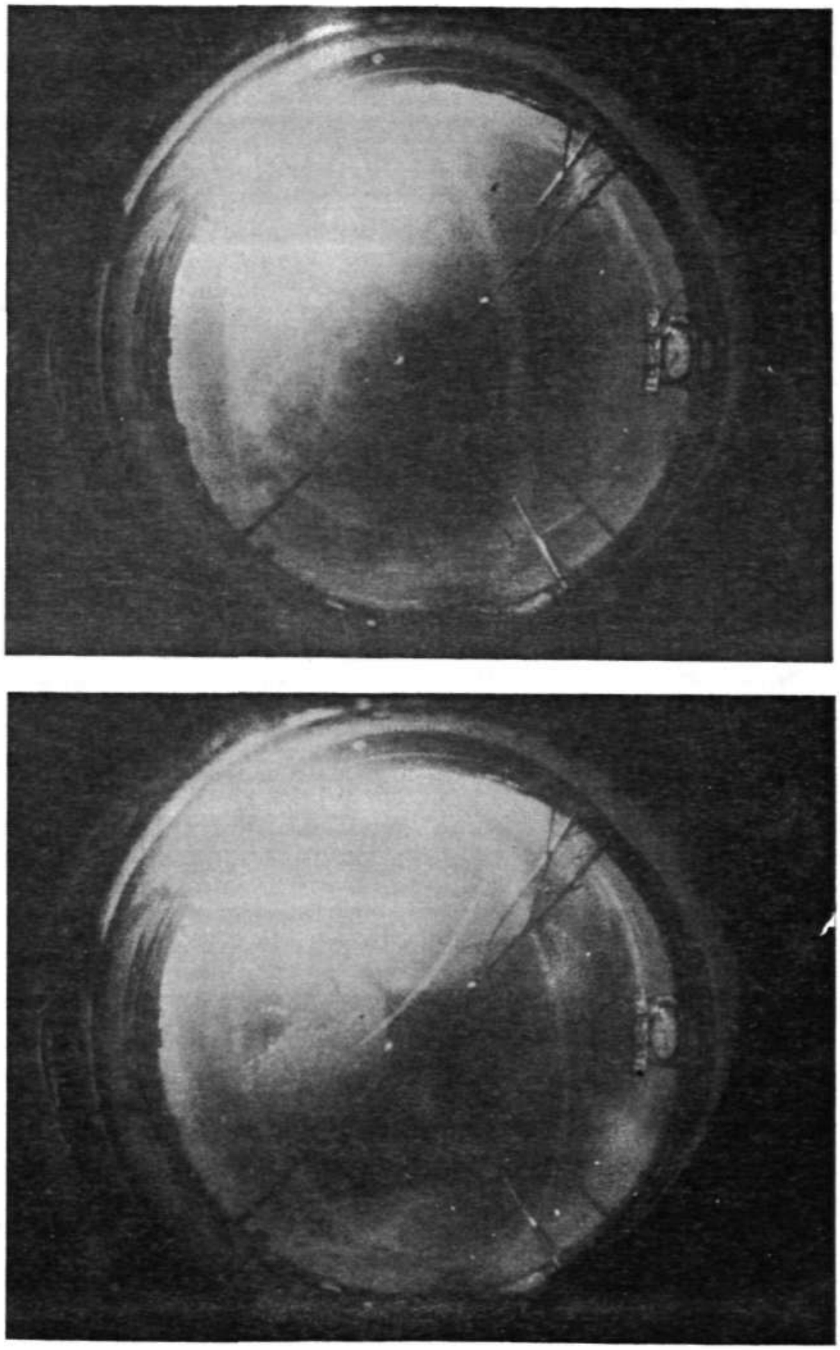

Figure 1. Examples of the image recorded on the all-sky camera. Note clock and date on right.

400 and 500, the use of the former preceded that of the latter. "OLD" will henceforth be used to refer to data measured on the "400," and "NEW" will refer to that measured on the "500" viewer. As previously mentioned, the NEW data contain more contrails than the OLD, in both the number of daily observations and total number observed. We have no reason to believe that air traffic frequency over Champaign changed, or that conditions pertinent to contrail formation changed, therefore we believe that the increase is due to changes in the method of data reduction.

Contrail observations from the same frames of 1976 film were viewed on both the "400" and "500" models, and were compared. The period of record consisted of 226 days. Thirty contrails were identified from 20 days using the "400," whereas 83 contrails were identified from 28 days with the "500!" On the additional eight days of the latter data set, only one contrail per day was observed. In comparison of like days, the "500" increased the number of observed contrails from 30 to 75.

The reason for this difference is due to the clearer image of the "500." , Distinguishing between contrails and cirrus clouds, haze, and sunshine proved more difficult with the "400." In more than one instance, a twin contrail — two contrails overlapping at one point — would appear as a single contrail on the "400."

Distinguishing the. horizon from the film images also proved to be difficult, especially during early morning and late afternoon hours, primarily due to film quality. A comparison of measurements of the same contrails taken from the two different viewers was made. Specifically, both the angles above the horizon, and the width of 19 contrails were compared from the two viewers. Measurements, made with the "500," resulted in increased angles from the horizon to the contrail base — almost 2 degrees greater. This places the lower edge of the contrail at a higher altitude than that previously measured.

The comparison of contrail <u>widths</u> was similar in method in that it was accomplished by taking the difference between the measurement of contrail upper and lower angle of each observation. The newer measures placed the mean upper edge of the contrails one degree higher in elevation. This resulted in NEW contrail widths over 2 km (2.18) narrower than the previous measurements.

The improved quality of the model "500" over the "400" makes the results of the "NEW" data analyses more reliable than those of the old.

Once a contrail was observed, the time was noted, and the contrail's characteristics documented. Characteristic features pertaining to the "origin" and "nature" of the contrail were recorded. "Origin" referred to whether the contrail formed within, or was advected into the camera's field of view. "Nature" referred to. whether the contrail spread, remained unchanged, or contracted as it progressed from one edge of the film to the other.

Contrail width was measured by the following method. Perpendicular linear measurements were made from a point on the horizon to the near, and far sides of the contrail. These distances were then converted to angular degrees.

The horizontal width of the contrail (in kilometers) was determined from the angular width and by assuming all contrails were located at 30,000 ft (9.14 km). An assumed altitude was necessary in the absence of recorded observations.

Table 3 contains a quantitative summary of contrail observations determined from the all-sky camera. "OLD" refers to those contrails observed on or before

Table 3. Catolog of Contrail Observations. Those before 31 May 79 Referred to as VOLD," those after, as "NEW." Percents Given in Parentheses.

	Days of Record	Number of Days with. Contrails	Number of Contrails	Spreading . Contrails	Non-Spreading Contrails
OLD	708	35 (5.1)	55	24 (43.6)	31 (56.4)
NEW	355	58 (16.3)	185	101 (54.6)	84 (.45.4)
TOTAL	1063	93 (8.8)	240	125 (.52.1)	115 (47.9)

Number of Days with N Contrails

	N=1	N=2	N=3+
OLD	23 (65.7)	8 (22.9)	4 (11.4)
NEW	23 (39.7)	12 (20.6)	23 (39.7)
TOTAL	46 (49.5)	20 (21.5)	27 (29.0)

31 May 1979 (observations reviewed in the first year's final report; Changnon et al., 1980), while "NEW" includes data after that date. Days of Record (Table 3) refers to the number of days included in this study. Number of contrails refer to the number of individual contrails observed. Spreading and Non-Spreading - indicate the growth character of contrails.

Table 3 shows that the NEW data, with only about half the number of OLD days of observation, contain 1.7 times as many contrail days, and 3.4 times as many contrails. This increase appears to be primarily due to differences in quality of the film viewers. This is further supported by the greater number of multiple contrails observed from the NEW data.

The lower portion of the table refers to the number of days in which one, two, three, or more contrails were observed. The majority of frames included only one contrail. Surprisingly, the second most popular group was three or more contrails. An examination of the raw data showed that when more than one contrail was observed, several (as many as eight) would tend to be seen.

Contrail Persistence

Contrail persistence growth rates were calculated for contrails found at angular altitudes greater than 20 degrees above the horizon. Angles of 20 degrees or less were eliminated from the study because the magnitude of potential error was large. If a contrail is located closer to the horizon, the translation from degrees altitude to horizontal distance becomes so large and non-linear, that reliable measurements can no longer be made. Measurements were made to the nearest 0.25 mm on the viewer, where an error of 0.5 mm changed the width of the contrail by as little as about 0.02 km (near the zenith), to as much as about 200 km (near the horizon). At angles greater than 20 degrees, the maximum error in width associated with a 2 degree measurement error is only about 2.7 km.

Measured contrails, as opposed to total contrails, consist of those contrails, or portions thereof, observed in two or more consecutive frames at angles greater than 20 degrees above the horizon. Table 4 presents a summary of the cases studied. Obviously there are more daylight hours during June than during December and hence the absolute numbers of contrails by month in Table 4 may be biased. However, when grouped by season, the totals show no systematic enhancement for summer (47 contrail days) compared to 45 contrail days in winter, 45 in spring and 32 in fall. Therefore it does not appear that the length of day has biased the results.

It is apparent from Table 4 that contrails were more persistent during the warmer half-year. The average persistence from April through October was 17.7 minutes (3.53 frames), whereas that for November through March was 13.1 minutes (2.62 frames). Standard deviations were on the order of 11 minutes during the warm period and 7 minutes during the cold. The seasonal variation in persistence may be due to the annual march of wind speed at contrail height.

To compensate for the different number of observations for each month, persistence was calculated on a seasonal basis, the results of which are shown in Table 5. Data from the summer season exhibit the greatest persistence as shown by the 4.23 frames/contrail (21 min) as opposed to 2.64 frames per contrail (13 min) in winter. The values for spring and fall were similar to each other and are between the two extremes. The number of contrails quoted by season in Table 5 are the result of only 12 months observations.

Growth/Decay Rates

Growth rates were calculated using the initial contrail width as a reference. This value was subtracted from the contrail width in the subsequent frame. A positive departure implied a growing contrail while a negative departure implied a decaying contrail. Monthly growth (GRW) and decay (DCY)

Table 4. Monthly Measured Number of Contrails and Their Persistency, determined from the all-sky camera (daytime obs. only)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Number of contrails	4	31	25	18	2	27	19	1	8	17	7	10
Number of frames	9	85	72	58	7	112	84	3	23	60	19	25
Mean (frames/contrail)	2.25	2.74	2.88	3.22	3.50	4.15	4.42	3.00	2.88	3.53	2.71	2.50
Standard deviation	0.50	1.44	1.48	1.40	3.54	2.33	1.77	----	1.13	2.58	0.95	0.97

Table 5. Measured Number of Contrails, Their Persistency, and Their Growth Rates for Spring (March-May), Summer (June-August), Fall (September-November), and Winter (December-February).

	Winter	Spring	Summer	Fall
Number of Contrails	45	45	47	32
Number of Frames	119	137	199	102
Mean Longevity (Frame/Contrail)	2.64 (13 min)	3.04 (15 min)	4.23 (21 min)	3.19 (16 min)
Standard Deviation	1.28	1.51	2.09	2.01

		Winter	Spring	Summer	Fall
Weighted	GRW	7.28	6.48	4.09'	6.22
	DCY	-8.74	-4.59	-3.80	-5.20
	NET	3.86	5.16	1.44	3.45
	ABS	7.59	6.26	3.94	5.97

		Winter	Spring	Summer	Fall
Unweighted	GRW	9.10	8.40	5.02	7.15
	DCY	-7.59	-4.47	3.92	-5.98
	NET	3.82	6.10	1.14	3.25
	ABS	8.62	7.70	4.53	6.80

rates, along with net (NET) and absolute (ABS) growth rates are given in Table 6. The former two categories included only growing or dissipating data respectively. Net and absolute data are frequency-weighted means.

Two methods were used to calculate the various means. The "weighted" values are comprised of mean values adjusted to reflect the persistent nature of individual contrails. That is, the mean growth rate for each contrail was multiplied by the number of frames minus one (N-1), in which it was observed. Thus, persistent contrails influenced these values more than short-lived contrails. Unweighted values represent the simple sample means.

The equations used to calculate the weighted values are:

GRW = Σ (mean positive rate x (N-1))/Σ N-1

NET = Σ (mean positive and negative rate x (N-1))/Σ N-1

DCY = Σ (mean negative rate x (N-1))/Σ N-1

ABS = Σ (absolute value of rate x (N-1))/Σ N-1

where N = # cases

Similarly, the equations used to calculate the unweighted values are:

GRW = Σ (positive rate/N)

NET = Σ (positive and negative rate/N)

DCY = Σ (negative rates/N)

ABS = Σ (absolute value of rate/N)

The mean growth rates exhibit an annual variation, i.e., summer values are roughly 60% of those during winter (including only months with adequate sample size). The same conclusion is found for decay rates. This may reflect the higher wind speeds at the contrail altitude, or higher relative humidities during the winter as opposed to the summer. A similar annual change is noted in the month-to-month values of net and absolute rates of change.

Seasonal growth/decay rates were also calculated. Both rates were greater during winter, least in summer and intermediate in spring and fall.

Table 6. Mean Monthly Growth Rates, in Kilometers Per Hour, for Contrails Observed Between 1 June 1979 and 30 June 1980. The Number of Cases Per Month is Shown in Table 4.

		Jan*	Feb	Mar	Apr	May*	June	July	Aug*	Sep*	Oct	Nov*	Dec
Weighted**	GRW	8.20	6.42	7.77	4.21 ,	7.20	4.21	3.92	0	4.73	6.58	6.90	13.82
	DCY	13.02	4.54	-	4.59	-	4.59	2.67	2.04	3.06	3.48	7.35	10.12
	NET	-0.29	5.42	7.77	1.84.	7.20	1.84	0.88	-2.04	2.66	5.41	-2.60	-0.54
	ABS	10.13	6.25	7.77	4.36	7.20	4.36	3.34	2.04	4.29	6.22	7.20	11.60
Unweighted**	GRW	7.35	8.56	10.01	5.17	7.20	5.17	4.83	0	6.90	7.42	6.90	13.82
	DCY	13.02	4.59	-	4.47	-	4.47	3.13	2.04	3.44	5.80	7.85	8.47
	NET	-2.84	6.04	10.01	1.20	7.20	1.20	1.06	-2.04	4.32	4.11	0.57	-0.11
	ABS	10.19	7.79	10.01	4.88	7.20	4.88	4.03	2.04	6.04	7.01	7.31	10.48

*Data may be suspect due to few observations (see Table 4).
**See text for explanation

Summer values are about one-half those of winter. The greater winter rate may be related to seasonal humidities (unknown) or to higher winter wind speeds. Growth decay rates were also calculated for those contrails located only 40 or more degrees above the horizon (Table 7). In this range, the maximum error associated with a 2 degree measurement error is 0.7 km. Restricting the measurements to those contrails at 40 or more degrees above the horizon severely reduced the number of observations. Less than half as many contrails could be measured. With the reduction in the number of contrails, a like reduction was found in the number of frames. Reductions to persistence were common to all seasons.

The results found from this sub-group are quite different than that found from the entire sample. Growth rates are larger during summer, least in spring and intermediate during winter and fall. Decay rates are greatest in fall, least in spring and summer and intermediate in winter. The variation between growth and decay rates suggests that the small sample size was not sufficiently large to yield reliable results. In spite of potential errors when using the entire data set, we suggest that those results are more reliable.

Growth rate measurements were recalculated from the data from 1976, 1978, 1979 reported in Phase I, only restricting the data to those contrails located above 20 degrees of the horizon. When this restriction was imposed on the earlier data set of 55 cases reported in Pase I, the mean rate of change "was virtually unchanged for growth and decay, i.e., 17 km/hr. However, the rate of decay was reported at 35 km/hr for the whole data set, whereas those contrails over 20 yield a value of 17.8 km/hr.

' The reason for the difference between the calculated growth rates from those data reported in Phase I and those reported herein is probably due to the use of two film viewers with differing degrees of precision.

Table 7. Mean Seasonal Growth Rates (km/hr). Only Contrails Located above 40 Altitude Angle Included in This Sample.

		Winter	Spring	Summer	Fall
Number of Contrails	GRW	16	19	22	18
	DCY	6	8	21	10
	NET	22	27	43	28
	ABS	22	27	43	28
Weighted (km/hr)	GRW	4.31	2.85	6.32	4.29
	DCY	-3.04	-2.08	-2.63	-4.64
	NET	2.31	1.39	1.95	1.10
	ABS	3.97	2.62	4.51	4.41
Unweighted (km/hr)	GRW	4.16	2.19	7.46	3.73
	DCY	-3.52	-1.52	-3.23	-4.21
	NET	1.42	1.60	1.58	0.33
	ABS	3.93	2.50	5.13	3.93

BASIC STATISTICS OF OBSERVED CONTRAILS

Width/Length Observations

For the 55 cases from 1976, 1978, and 1979 (OLD data) when contrails were located above 20 degrees elevation, several mean statistics were calculated. The average length of contrails was found to be 105 km, with the shortest mean lengths found in June, July, and August (70-90 km). The mean width of all contrails was 3.7 km, with little significant variation exhibited during the year. The mean width of the observations of 1979 and 1980 (NEW data) was 8.5 km, with the narrowest values reported from July through November (4-7 km), and the maximum values reaching 12 km in January. The mean width found for the 1979-80 data is about twice that found in 1976, 1978, and 1979. These differences may be due to the restricted sample size.

Contrail Appearance/Disappearance on the Film

Contrail longevity measurements began with the initial sighting of a contrail on the film. There were two methods by which a contrail appeared. One was by advection into the field of view. The other was through formation within the field. There were, however, several different methods by which contrail measurements ceased. These included advection out of the field of view, dissipation within the frame, darkness, or contrail obliterated by bright solar disk or haze or other natural clouds. Of the 176 contrails studied, 39% disappeared by advecting out of the field of view. Twenty-five percent disappeared or dissipated within the field of view and 23% disappeared through intermixing with an individual cloud or cloud deck. Measurements also were discontinued as contrails were obliterated by passing between the sun and the camera (11%), or as the image became too dark to distinguish features (2%). That 39% were lost to further observation by being advected out of the camera view supports the statement that typical contrail longevities are probably greater than those times given in Tables 4 or 5.

CONTRAIL EFFECTS ON SURFACE METEOROLOGICAL PARAMETERS

The major objective of this research was to determine if an impact of contrail presence could be detected in the record of certain meteorological parameters measured at the surface. One would obviously expect an impact on temperature and insolation if the contrail was of sufficient density and persistence.

The effect of contrail cirrus on surface temperature, humidity, and insolation was estimated by viewing frames of the 16 mm film from the ISWS all-sky camera, to differentiate clear days (with or without contrails) from cloudy days. For those days when no natural clouds were present, but contrails were observed, the beginning, end, and hence longevity of time that a contrail passed between the sun and the all-sky camera were documented. Coincident measurements were made of the intensity of sunlight (measured by actinometer located about 30 m east of the all-sky camera); and changes to air temperature and humidity, recorded at the Morrow Plots Weather Observing Station, located about 1 km south of the all-sky camera. In virtually all cases, and clearly in the mean, these parameters experienced changes in the expected direction with the onset of contrail cirrus (with otherwise clear skies), and returned to near initial conditions once the contrail had moved off.

Attenuation of Insolation

Insolation attenuation by contrails was studied by means of mechanical actinograph measurements taken at the ISWS during the last 6 years. The time lag of the instrument is about 5 minutes, and is of no influence to this study since 5 minutes is the increment of 16 mm filming. A data set was chosen which consisted of those days in which either a single or several contrails passed between the sun and the recording instrument for a minimum of five minutes (two consecutive frames on the 16 mm film). Eighteen cases met this requirement, and Table 8 shows the percent change in insolation resulting from the passage of a contrail (or contrails) between the sun and the instrument. Several of these cases included the influx of several contrails which eventually formed a cirrus cloud deck. The time interval (T_{on} to T_{off}) indicated the period during which one or more contrails intercepted the sun. "Before" (Table 8) refers to the value prior to the onset of contrail passage. "During" refers to the measured insolation once the contrail had positioned itself between the sun and the instrument, and the instrument had come to equilibrium (at least 5 minutes). "Change" was the difference (Ly/min) between these two values, while "Percent" notes this change in percent.

The average decrease is 0.17 langley per minute, corresponding to a 23% decrease in global solar radiation. The greatest individual decrease was 64% during a 20 minute occultation on 30 October 1979. The smallest decrease was 5% during a 15 minute occultation on 12 April 1979. There is no obvious relationship between duration of occultation and attenuation, since attenuation depends on many other conditions, e.g., atmospheric turbidity, sun angle, thickness and width of the contrail, as well as horizontal speed of movement of the contrail. However, Fig. 2 indicates a direct relationship between the percent attenuation and cosine of the sun angle, i.e., a vertical sun is' attenuated least by contrails at angles above about 40 ($0 < COS < 0.77$). At angles less than <u>ca</u>. 40° ($COS > 0.77$), the attenuation varies from about 12 to 64%, depending on contrail thickness, density and horizontal extent. It must be remembered that at low sun angles even clear sky insolation is meager. Therefore even a relatively large percent attenuation represents only a small diminution to the <u>daily</u> total. At sun angles greater than ca. 40 , from 5

Table 8. Percent Change in Actinometer Traces Due to Contrail Passage.

Date	Contrail Passage T_{on}	Contrail Passage T_{off}	Actinometer Reading (Ly/min) Before	During	Reduction Actual	Reduction Percent
26 APR 76	1340	1425	1.07	.99	.08	8
1 MAY 76	0625	0700	.43	.38	.05	12
3 JUN 76	0630	0730	.59	.24	.35	59
31 AUG 76	0800	0815	.76	.53	.23	30
5 AUG 78	0630	0705	.43	.35	.08	19
2 SEP 78	0840	0910	.84	.71	.13	16
12 APR 79	1215	1230	1.02	.97	.05	5
22 JUN 79	0725	0810	.59	.39	.20	34
25 JUN 79	1200	1240	1.27	.77	.50	39
27 JUN 79	0805	0835	.77	.61	.16	21
6 JUL 79	0830	1200	.99	.84	.15	15
20 SEP 79	1025	1045	.92	.77	.15	16
5 OCT 79	1500	1505	.65	.52	.13	20
24 OCT 79	0730	0815	.45	.31	.14	31
30 OCT 79	1020	1040	.33	.12	.21	64
5 NOV 79	1030	1200	.71	.54	.17	24
3 MAR 80	0915	0950	.31	.17	.14	45
16 APR 80	1125	1205	1.12	1.05	.07	6
MEAN			.74	.57	.17	23

45 rain mean duration
34 min: σ

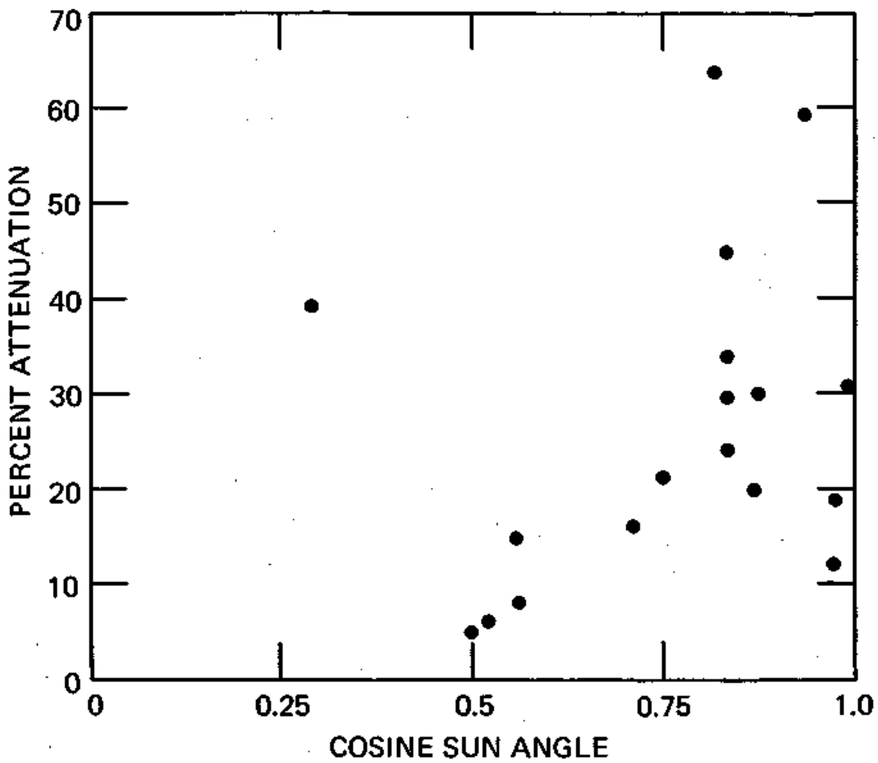

Figure 2. Relationship between insolation attenuation (%) by contrail and cosine of sun angle at time of observation.

to 20% of global insolation was attenuated by a contrail which persisted for at least 5 minutes, again dependent on contrail thickness, density and horizontal extent.

The mean duration of a contrail intercepting insolation at Champaign was found to be 45 minutes, ranging from 5 to 150 minutes. The median was ca. 35 minutes.

Changes of Temperature

The all-sky camera was also utilized to determine the impact of contrails when they blocked the direct sun on ambient air temperature.

There were no frontal passages during any of the sequences of these observations, nor did the wind direction shift significantly when speeds were greater than about 5 mph. With no natural cloud cover, changes in temperature (and relative humidity) were due solely to the partial interception of sunlight by the contrail.

The temperature trace from a nearby hygrothermograph was used as a basis for the study. Since air temperature would naturally change (with the diurnal cycle) during the time that a contrail obscures the sun, simple temperature differences from before a contrail, to during an obscuration, to after, would not yield meaningful results. Therefore a regression technique was used to evaluate the temperature change imposed by the contrail obscuring the sun. Temperatures at 1/2 hour intervals from two hours prior to the onset of the contrail up to just prior to solar obscuration (5 values) were utilized to calculate the linear trend of temperature. These data gave an overall linear slope of the trend of temperature prior to the contrail onset. Assuming a linear trend of temperature over an episode of one to two hours is acceptable, particularly if the observations do not coincide with the time of rapid change in temperature trend (e.g., early to mid afternoon). Only 2 of the 21 observations occurred within 2 hours of daily maximum temperature, therefore the linear assumption seems legitimate.

The slopes of the 2-hour line segments are given in Table 9 (F hr). The correlation between the actual observed temperatures (5 values at half-hour intervals) and the regression line is also given. Clearly, the closer this number is to unity the more linear was the actual temperature change prior to the advent of the contrail. Note that all correlations (except 2 of the 21 cases) were greater than 0.88, strongly supporting the linear character of temperature change in these examples.

Next, the slope of the regression line for the 2 hrs prior to contrail obscuration was projected 1 1/2 hours into the future. This resulted from a hypothesis that if the temperature was increasing (decreasing) without the presence of a contrail, it should be expected to continue to do so for a limited time thereafter, unless the interval is near the time of the daily maximum temperature. The "comments" section of Table 10 briefly characterizes the linearity of the data in each instance.

A forecast temperature (based on the regression) for each 1/2 hour increment into the time of the contrail episode was made. The difference between the forecast and actual temperature at each half hour provided a measure of the impact of contrails on temperature trend. Positive differences indicate that the forecast was too high, negative indicates that the forecast temperature underestimated the actual temperature. Intuitively, we would expect forecast temperatures to overestimate actual observed values (for times prior to daily max temperature), during contrail occultations. The mean (through various intervals of the contrail tenure) error is shown in Table 9. A positive error indicates cooling due to contrail cloudiness, shown by a decrease in the

Table 9. Temperature Change Information with Onset of Contrail Event. Twenty-One Cases from Champaign.

Case No.	Date	Time contrail blocked sun (LST)	Temperature prior to onset of contrail (-2 hrs to 0 hrs) forecast regression: Slope °F hr⁻¹	r	Temperature projections into contrail event from forecast regressions: Beginning of contrail Temp °F	Error °F	Middle of contrail Temp °F	Error °F	End of contrail Temp °F	Error °F	Mean error °F	Actual temperature information within contrail to 1/2 hr past contrail: Slope °F hr⁻¹	r	Did slope increase after potential effect period?	Likely	Slight Change	Indeterminate	Unlikely	Comments
1	4/26/76	11:40 to 12:20	+2.0°	1.00	48.0°	0°	49.0°	-1.0°	50.0°	0°	-0.3°	+1.2°	0.77	Y	X				
2	4/26/76	13:40 to 14:20	+1.2°	0.77	51.0°	-1.0°	51.6°	-0.4°	52.2°	+0.2°	-0.4°	0°	1.00	Y	X				Earlier contrail∴forecast regression insignificant
3	5/01/76	7:20 to 8:00	-0.8°	0.89	52.5°	-0.5°	52.1°	-0.9°	51.7°	-2.3°	-1.2°	+1.0°	0.86	Y			X		Occurred early∴ Forecast regression insignificant
4	6/03/76	7:30 to 8:30	+3.4°	0.99	59.5°	-0.5°	61.2°	-1.8°	62.9°	-1.1°	-1.1°	+3.2°	0.96	Y		X			Slope increased in contrail, decreased afterwards
5	8/31/76	9:00 to 9:20	+5.6°	0.99	67.2°	+0.2°	70.0°	+1.0°	72.8°	+2.8°	+1.3°	+3.0°	0.98	Y	X				
6	8/05/78	7:30 to 8:10	+3.2°	0.96	59.4°	-0.6°	61.0°	-1.0°	62.6°	-1.4°	-1.0°	+4.0°	1.00	N				X	
7	9/02/78	9:40 to 10:20	+6.8°	0.97	72.6°	+1.6°	78.4°	+4.4°	81.3°	+6.3°	+4.1°	+2.0°	1.00	N	X				
8	4/12/79	12:15 to 12:30	+2.0°	1.00	71.0°	0°	72.0°	0°	73.0°	+1.0°	+0.3°	+0.6°	0.76	Y	X				Nearing climatological mid-day leveling
9	5/21/79	8:40 to 10:10	+1.8°	0.97	54.0°	0°	54.9°	-1.1°	55.8°	-2.2°	-1.1°	+4.0°	1.00	N				X	
10	6/22/79	8:20 to 9:10	+2.0°	0.91	77.5°	+1.5°	78.5°	+1.5°	79.5°	+0.5°	+1.2°	+3.0°	0.98	Y				X	Slope levels off prior to contrail and increases in contrail
11	6/25/79	13:00 to 13:40	+0.8°	0.89	76.5°	+0.5°	76.9°	-0.1°	77.3°	-0.7°	-0.1°	+2.0°	1.00	Y				X	
12	6/27/79	9:10 to 9:40	+5.6°	0.99	79.0°	+1.0°	81.8°	+1.8°	84.6°	+3.6°	+2.1°	+3.0°	0.98	Y	X				Nearing climatological mid-day leveling
13	7/06/79	10:30 to 13:00	+2.0°	1.00	74.0°	+1.0°	75.0°	+1.0°	76.0°	+2.0°	+1.3°	+0.8°	0.94	N	X				" " "
14	9/20/79	11:20 to 11:45	+3.8°	0.93	83.5°	+1.5°	85.4°	+2.4°	87.3°	+4.3°	+2.7°	+1.0°	0.87	N		X			" " "
15	10/05/79	16:00 to 16:50	+0.6°	0.57	57.8°	+0.8°	58.1°	-0.9°	58.4°	+0.4°	+0.1°	-1.4°	0.53	N		X			Nearing climatological drop-off of late afternoon
16	10/24/79	8:30 to 9:15	+1.7°	0.99	40.8°	-1.2°	41.6°	-2.4°	42.5°	-0.5°	-1.4°	+2.0°	0.87	Y			X		Temperature drops off >1/2 hour after contrail
17	10/30/79	10:20 to 10:40	+4.0°	1.00	60.0°	0°	62.0°	+2.0°	64.0°	+4.0°	+2.0°	0°	1.00	Y	X				
18	11/05/79	10:30 to 12:00	+5.2°	0.98	56.0°	+1.0°	58.6°	+2.6°	61.2°	+4.2°	+2.6°	+2.4°	0.99	Y	X				

Table 9. Temperature Change Information with Onset of Contrail Event. Twenty-One Cases from Champaign. (Continued)

Case No.	Date	Time contrail blocked sun (LST)	Temperature prior to onset of contrail (-2 hrs to 0 hrs) forecast regression: Slope °F hr^{-1}	r	Temperature projections into contrail event from forecast regressions: Beginning of contrail Temp °F	Beginning of contrail Error °F	Middle of contrail Temp °F	Middle of contrail Error °F	End of contrail Temp °F	End of contrail Error °F	Mean error °F	Actual temperature information within contrail to 1/2 hr past contrail: Slope °F hr^{-1}	r	Did slope increase after potential effect period?	Likely	Slight Change	Indeterminate	Unlikely	Comments
19	2/18/80	11:30 to 12:50	+3.4°	0.99	31.0°	+1.5°	32.7°	+3.3°	34.4°	+4.4°	+3.1°	+0.6°	0.91	Y	X				Nearing climatological mid-day leveling
20	3/03/80	9:15 to 9:30	+4.0°	1.00	23.0°	-1.0°	25.0°	-1.0°	27.0°	0°	-0.7°	+3.0°	0.98	Y			X		Slope test hints at a slight effect
21	4/16/80	11:20 to 12:10	+3.4°	0.99	53.5°	+0.5°	55.2°	+3.2°	56.9°	+2.9°	+2.2°	+1.0°	0.50	Y	X				
														Σ	11	3	3	4	
														%	52.4	14.3	14.3	19.0	
															66.7%				

positive slope of the actual temperatures after the contrail (partially) intercepted the solar beam. This result occurred in 12 of the 21 cases in the mean (57.1%).

It should be noted that the regression overforecast in the temperature in 11 cases (52%) at the beginning of the contrail episodes and increasing to 13 cases (62%) at the end of the episodes. In addition, the mean absolute error increased from 0.76 at the episode beginning, to 1.44 at the end. Both these characteristic changes agree with each other and satisfy the hypothesis.

The results of Table 9 were visually inspected in order to determine how well the linear model explained the observed temperature change. One problem arose when the temperature sporadically or momentarily fell or rose briefly just <u>prior</u> to the contrail onset. This short-term temperature change was not incorporated into the regression calculation since the latest datum used in the regression formulation was as of 30 minutes prior to the advent of the contrail(s).

A hypothetical example may clarify this problem. Using Fig. 3 as a guide, assume the temperature was rising at 3 F hr^{-1} for two hours before the onset of the contrail. Twenty-five minutes prior to the first contrail observation, the temperature trend changed to 5 F hr^{-1}. During the 1/2 hour after the contrail interception began, the rate of rise was 3 F hr^{-1}. The pre-contrail regression is a perfect fit for a 3 F hr slope. Yet, the projection underestimates the actual temperature during the time of the contrail event. An attempt was made to minimize the effects of this problem by simply analyzing the slopes of the temperature traces prior to and during the contrail episode.

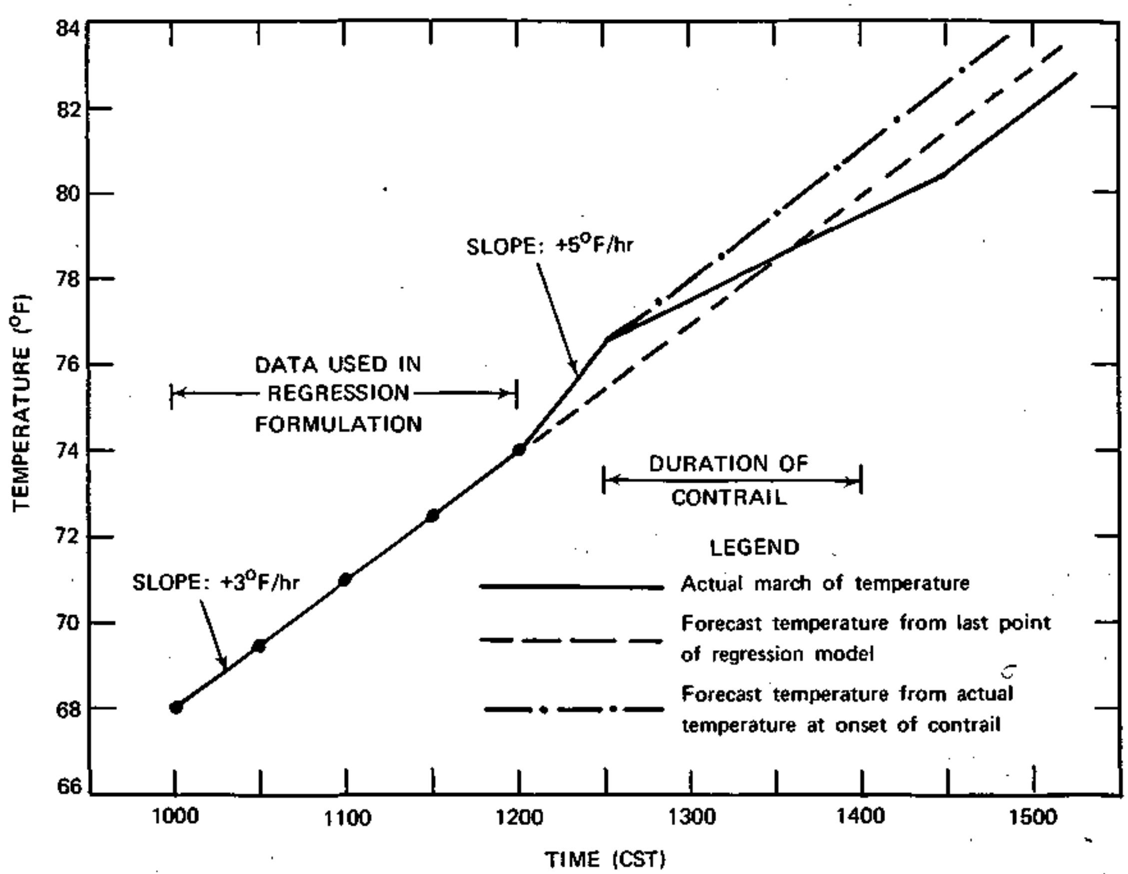

Figure 3. Hypothetical temperature trace before, during and after a contrail intercepted the solar beam.

The slope of the temperature trace from the beginning of each contrail episode to 1/2 hour after the contrail moved out of the sun's beam was calculated. The goodness-of-fit between the regression lines and all temperatures is also shown by the correlation method in Table 9. The slope of temporal temperature change was calculated during a contrail episode as well as before each episode. If the slope during a contrail episode was less than before the episode, this is supportive of temperature modification by contrails. This was the case in 15 of the 20 cases (75%) which occurred before the time of daily maximum temperature.

The final columns of Table 9 show a more subjective approach to the evaluation of evidence. First, the quantitative results were evaluated after which the graphs were again visually inspected to determine if the temperature slope again increased after the contrail event. This helped to indicate whether an afternoon temperature maximum had already been reached, in which case the temperature evidence was merely reflecting the diurnal trend. The quantitative and subjective results yielded similar results. Eleven cases (52%) exhibited probable contrail effect. Three additional cases exhibited a slight change. This subjective conclusion suggests that 14 of the 21 cases (67%) support the hypothesis that surface temperatures were modified by contrails intercepting the solar beam.

In conclusion, between 60 and 70% of the cases studied showed an expected change to the temperature trend in apparent response to contrail attenuation of insolation.

If we assume a mean longevity of a contrail to be 45 minutes (suggested by the data in Table 9), then the surface air temperature at the end of contrail tenure would be about 1.6 F cooler than that under clear conditions for those times of day preceding time of daily maximum temperature. During times after the time of daily maximum temperature, air temperature is about 3.7 F warmer than what it would have been without contrails. The latter value is less certain since it is based on only two data.

That all temperature trends did not support this hypothesis is not particularly surprising since temperature is a function of several other variables, notably advection of air over differing surfaces.

Changes of Relative Humidity

A second impact of the effect of solar occultation by a contrail was evaluated using relative humidity observations before and during the contrail event. The evaluation technique was virtually the same as that used with temperature. Results were expected to be essentially the same as those of temperature, since relative humidity is virtually solely a function of temperature if absolute humidity is constant (a fair assumption over a period of a few hours without frontal passage).

The hygrothermograph traces were also utilized to. quantify changes in relative humidity from episodes when contrails blocked the direct solar beam. The same design (linear regression and slope tests, previously described for temperature) was used to document changes in the character of the relative humidity in 21 cases between April 1976. and April 1980.

The linear regression trend was used to determine if the march of relative humidity changed with the onset of a contrail. The linear regression from 2 hours prior to the contrail event was projected to the time when the contrail (partially) blocked the sun, and the change in the relative humidity trace was recorded.

Tables 10a and 10c indicate the results of this test. A negative mean error (3rd last column) indicates an increase in humidity in response to contrails (an expected result prior to daily maximum temperature). Such a result occurred in 16 of the 21 cases (76.2%). This is not an unexpected result

Table 10a. Humidity Change Information with Onset of Contrail Event.

			Relative humidity prior to onset of contrail (-2 hrs. to 0 hrs.) Forecast Regression		Relative humidity projections into contrail event from forecast regressions							Actual Relative humidity information with contrail to 1/2 hr. past contrail	
					+ ½ hr.		+ 1 hr.		+ 1 ½ hrs.				
Case #	Date	Time Contrail blocked Sun (LST)	Slope % hr.$^{-1}$	r	R.H. %	Error %	R.H. %	Error %	R.H. %	Error %	Mean Error %	Slope % hr^{-1}	r
1	4-26-76	11:40-12:20	-9.6	1.00	39.0	-4.0	34.2	-5.8	29.4	-9.6	-6.5	-3.8	0.98
2	4-26-76	13:40 14:20	-3.8	0.98	35.0	-1.0	33.1	-2.9	31.2	-4.8	-2.9	0	1.00
3	5-1-76	7:20 8:00	+2.8	0.94	90.0	+6.0	91.4	+15.4	92.8	+23.8	+15.1	-15.0	1.00
4	6-3-76	7:30-8:30	0	1.00	74.0	0	74.0	0	74.0	+4.0	+1.3	-4.0	0.87
5	8-31-76	9:00-9:20	-10.4	0.96	57.0	-3.0	51.8	-6.2	46.6	-9.4	-6.2	-4.0	1.00
6	8-5-78	7:30-8:10	-8.6	0.85	62.0	+3.0	57.7	-0.3	53.4	-3.6	-0.3	-2.0	1.00
7	9-2-78	9:40-10:20	-17.0	0.90	63.5	+0.5	55.0	-5.0	46.5	-10.5	-5.0	-6.0	1.00
8	4-12-79	12:15-12:30	-5.2	0.94	50.2	-3.8	47.9	-5.1	45.3	-7.7	-5.5	-1.0	0.87
9	5-21-79	8:40-10:10	-5.2	1.00	62.5	-0.5	59.9	-0.1	57.3	+1.3	+0.2	-6.0	0.98
10	6-22-79	8:20-9:10	-2.0	0.75	58.0	-1.0	57.0	-1.0	56.0	+1.0	-0.3	-4.0	0.96
11	6-25-79	13:00-13:40	-0.8	0.63	37.0	0	36.6	+0.6	36.2	+0.2	+0.3	-1.0	0.87
12	6-27-79	9:10-9:40	-5.8	0.99	50.0	0	47.1	-0.9	44.2	-2.8	-1.2	-3.0	0.98
13	7-6-79	10:30-13:00	-5.2	0.98	46.0	-3.0	43.4	-5.6	40.8	-7.2	-5.3	-1.0	0.87

Table 10b. Further.Evaluation of Humidity Change Information with Onset of Contrail Event.

Case #	Date	Time Contrail blocked Sun (LST)	Did Slope Increase after potential effect period:	Subjective likelihood of effect: Likely	Slight Chance	Indeterminate	Unlikely	Comments
1	4-26-76	11:40-12:20	Yes	x				Nearing climatologlcal mid-day leveling
2	4-26-76	13:40 14:20	Yes	x				Nearing climatologlcal mid-day leveling
3	5-1-76	7:20 8:00	No			x		Occurred at sunrise: Climatologlcal max of R.H.
	6-3-76	7:30-8:30	Yes			x		R.H. remained constant during contrail yet temp.
5	8-31-76	9:00-9:20	Yes					
6	8-5-78	7:30-8:10	Yes					
7	9-2-78	9:40-10:20	No					
8	4-12-79	12:15-12:30	Yes	x				
9	5-21-79	8:40-10:10	No					
10	6-22-79	8:20-9:10	Yes					
11	6-25-79	13:00-13:40	Yes					
12	6-27-79	9:10-9:40	Yes	x				
13	7-6-79	10:30-13:00	No					

Table 10c. Humidity Change Information with Onset of Contrail Event.

Case #	Date	Time Contrail blocked Sun (LST)	Relative humidity prior to onset of contrail (-2 hrs. to 0 hrs.) Forecast Regression Slope % hr.$^{-1}$	r	Relative humidity projections into contrail event from forecast regressions: + ½ hr. R.H. %	+ ½ hr. Error %	+ 1 hr. R.H. %	+ 1 hr. Error %	+ 1 ½ hrs. R.H. %	+ 1 ½ hrs. Error %	Mean Error %	Actual Relative humidity information with contrail to 1/2 hr. past contrail: Slope % hr^{-1}	r
14	9-20-79	11:20-11:45	-5.8	0.97	48.5	-3.5	45.6	-5.4	42.5	-6.5	-5.1	-3.0	0.98
15	10-5-79	16:00-16:50	-1.4	0.95	46.0	0	45.3	+1.3	44.6	-2.4	-0.4	+1.0	0.33
16	10-24-79	8:30-9:15	-11.0	1.00	62.7	-2.3	57.2	-4.8	51:7	-9.3	-5.5	-2.0	1.00
17	10-30-79	10:20-10:40	-5.4	1.00	61.0	-1.0	58.3	-6.7	55.6	-13.4	-7.0	+7.0	1.00
18	11-5-79	10:30-12:00	-10.4	0.99	51.5	-1.5	46.3	-5.7	41.1	-6.9	-4.7	-5.0	0.94
19	2-18-80	11:30-12:50	-10.0	0.97	44.3	-4.7	39.3	-9.7	34.3	-14.7	-9.7	0	1.00
20	3-3-80	9:15-9:30	-4.0	0.98	57.5	-0.5	55.5	-0.5	53.5	-0.5	-0.5	-4.0	1.00
21	4-16-80	11:20-12:10	-0.8	0.89	40.5	+0.5	40.1	+1.1	39.7	+1.7	+1.1	-2.0	1.00

Table 10d. Further Evaluation of Humidity Change Information with Onset of. Contrail Event.

Case #	Date	Time Contrail blocked Sun (LST)	Did Slope Increase after potential effect period:	Subjective likelihood of effect: Likely	Slight Chance	Indeterminate	Unlikely	Comments
14	9-20-79	11:20-11:45	Yes	x				
15	10-5-79	16:50-	No			x		Increase in R.H. after contrail
16	10-24-79	8:30-9:15	No		x			
17	10-30-79	10:20-10:40	Yes	x				Dramatic increase in R.H. (maybe tront?)
18	11-5-79	10:30-12:00	No	x				
19	2-18-80	11:30-12:50	Yes	x				
20	3-3-80	9:15-9:30	No		x			
21	4-16-80	11:20-12:10	No				x	
				12	2	3	4	
				' 14 (66.7%)		7 (33.3%)		

in light of the temperature study and the strong dependence of relative humidity on temperature.

The slope test, which compared the slope of the trace prior to the contrail onset to that during and immediately after the contrail episode, indicated that a majority of cases satisfied the hypothesis. Again the goodness-of-fit (r) was used to assess the linearity of the trace prior to, and after the contrail. Leveling of the slope could have been a "normal" diurnal response rather than that due to contrail effects. Therefore, an increase in the absolute value of the slope, noted in Tables 10a and 10c are indicative of a possible effect of contrails on the surface relative humidity. Mean absolute deviations between the actual and forecast relative humidity at 1/2, 1, and 1 1/2 hours increased (greater error) from 1.90 to 4.01 to 6.73% hr , whereas the mean deviations decreased (indicating increasingly underestimates of relative humidity) from the linear regression of -0.99 to -2.25 to -3.68% hr at the same time intervals. Both these conditions indicate increasing relative humidities due to decreases to air temperature with the onset of contrail occultation.

The 21 cases of Table 10 are further referenced in Tables 10b and 10d. A "yes" in the fourth column further supports the hypothesis that contrails had an effect on the relative humidty. The results of the slope test supported the hypothesis in 12 of the 21 cases (57.1%), indicating either an increase, or a reduced rate of decline in the relative humidity slope during and immediately after contrails.

The subjective approach suggested that 12 of the 21 cases (57,1%) exhibited likely support of the hypothesis. Two additional cases exhibited a slight chance, for a total of 14 cases (66.7%) as fulfilling the hypothesis. Seven cases (33.3%) did not support the hypothesis. These results agree well with the quantitative tests.

In conclusion, between 65 and 75% of the cases supported the hypothesis of contrails impacting relative humidity. These results closely agree with the temperature results, as expected.

SEQUENCE OF CLOUDY, CLEAR, AND CONTRAIL DAYS

Casual observations, and some prior research (Beckwith, 1972) suggested that contrails tend to be more frequent on days just preceding the advent of natural high clouds, i.e., on days with high relative humidity at contrail altitude. The COMBAR records give us the opportunity to test the sequence of clear, contrail, or cloudy days over all months of the year within the upper Midwest to investigate whether the sequence hypothesis was supported in fact.

When the more than 16,000 COMBAR observations for each latitude-longitude intersection were scanned, it was found that cloudy days follow contrail days over 5 times more often than clear days tend to follow contrail days. On the other hand, contrail days tend to follow cloudy days about 3 times more often than clear days tend to follow cloudy days (>1400 observations). In the above test, each of the 3 categories were mutually exclusive, i.e., a clear day experienced neither clouds or contrails by definition.

We also studied 3-day sequences of clear, cloudy, or contrail days. The frequency of each sequence of the 2,551 observations is shown in Table 11.

Of those eleven categories, the most frequent sequences (77% were composed) of adjacent days with contrails and cloudy conditions, while those sequences including clear days as one of the variables were substantially less frequent (23%), with no sequence case being more than 5% of the total observations.

COMBAR report locations were recorded in whole degrees latitude and longitude. Cloud data from any of the surrounding eight intersections (maximum distance 85 nm) were used for verification purposes.

Table 11. Frequency and Percent of Occurrence of Given Three Day Sequences, Gleaned from COMBAR Observations.

	Frequency	Percent
CONTRAIL-CLOUDY-CLOUDY	583	Z2
CLOUDY-CONTRAIL-CLOUDY	517	20
CONTRAIL-CONTRAIL-CLOUDY	505	19
CLOUDY-CONTRAIL-CONTRAIL	425	16
CLOUDY-CLOUDY-CLEAR	141	5
CLOUDY-CONTRAIL-CLEAR	124	5
CLEAR-CONTRAIL-CONTRAIL	109	4
CLEAR-CONTRAIL-CLOUDY	108	4
CLOUDY-CLEAR-CLEAR	53	2
CLEAR-CLEAR-CONTRAIL	42	2
CLEAR-CONTRAIL-CLEAR	34	1

POTENTIAL EFFECT OF CONTRAILS ON EARTH'S RADIATION BUDGET

Although changes to surface radiation, temperature and humidity have been measured in several case studies, there is considerable interest in evaluating the effect to the large scale radiation balance for areas within which contrails are relatively numerous, dense, and persistent. These areas are thought to be several states in coverage, (although they may change with seasons), and experience suggests that they persist for perhaps 12 hrs to a few days in length.

If an area of contrails persisted for a day or so, and if there was no natural cloud cover, the impact of the contrails upon the "natural" radiation budget could be substantial, i.e., sufficient to further impact areal temperature, radiation balance, local winds, and perhaps photosynthesis.

In order to estimate the change to the areal radiation budget of the earth due to contrails, one must know (1) the mean attenuation due to contrails; (2) the area within which contrails are occurring during a given episode; (3) the number, length, and width of contrails within the area, or some index of their density; and (4) the frequency with which these areas typically occur. Direct radiation attenuation can be estimated from our case studies or from work of others. Our limited sample of data suggests that insolation is attenuated by up to 20% with sun angles greater than about 40 . Below this angle, the <u>percent</u> attenuation is much greater, but the absolute loss is relatively unimportant to the daily total. The second characteristic above, is rather more difficult to determine., The third and fourth characteristics can be determined by means of systematic observations at several locations, extending over several years. Some estimates are already available.

NWS regulations do not require the reporting of contrails, therefore they may or may not be incorporated in cloud observations. The COMBAR reports, too, were insufficient since the aircraft tended to fly "favored" routes, and most flights were concentrated between the hours of about 1200 and 0200, Monday through Friday. The COMBAR sample is therefore biased temporarily and spatially.

Determination of Areal Extent of Contrails

The frequency of, and resolution of LANDSAT satellite imagery is insufficient to evaluate either the spatial coverage or contrail density. The return frequency of LANDSAT over a given location is much too long (14 days) for this kind of analysis. Although the GOES resolution is sufficiently fine scale, and frequency is adequate, the United States appears near the northern limb of the image, and the viewing angle is therefore oblique to precisely view the relatively fine detail of contrails for inventory purposes.

Areas defined by COMBARs and NWS observations

The COMBAR data offered another alternative method whereby contrail-containing areas could be defined. COMBAR observations were obtained from March 1957 through April 1962. The parameters utilized from the COMBARs included the altitude of the contrails, time of the contrail observation, location of the contrails (nearest 1° latitude and longitude), and sky condition. Only cases where no other (natural) clouds were reported in addition to the contrails were utilized in the study.

Surface temperature, relative humidity and cloud cover information were obtained from climatological magnetic tapes of National Weather Service (NWS) first order station data from the National Climate Center in Asheville, North Carolina. These were collected to determine if changes in some parameters could be found which were coincident with the time of contrail occurrence (discussed below). The time intervals corresponding to $\pm$ 12 hours from each contrail observation were retained for further analysis. Stations utilized are shown in Table 12.

Table 12, , First-Order Stations Used in COMBAR Study.

	Station ID	Station
1.	BNA	Nashville, TN.
2.	BRL	Burlington, IA
3.	DBQ	Dubuque, IA
4.	DET	Detroit, MI
5.	DLH	Duluth, MN
6.	DSM	Des Moines, IA
7.	EW	Evansville, IN
8.	FTW	Ft. Wayne, IN
9.	GRB.	Green Bay, WI
10.	GRR	Grand Rapids, MI
11.	IND	Indianapolis, IN
12.	LAN	Lansing, MI
13.	LSE	La Crosse, WI
14.	MCI	Kansas City, MO
15.	MDW	Chicago, IL
16.	MEM	Memphis, TN
17.	MKG	Muskegon, MI
18.	MLI	Moline, IL
19.	MQT	Marquette, MI
20.	MSN	Madison, WI
21.	PIA	Peoria, IL
22.	RST	Rochester, MN
23.	SBN	South Bend, IN
24.	SGF	Springfield, MO
25.	SPI	Springfield, IL
26.	SSM	Sault Ste. Marie, MI
27.	STL	St. Louis, MO

Since location, altitude, occurrence and persistence characteristics of contrails were reported on the COMBAR form, surface observations of clouds from NWS stations near the aircraft contrail observation were utilized for study purposes.

Visual inspection of computer-developed spatial plots of contrail reports on any given day, made it apparent that on certain days, contiguous observations exhibited a dense area of contrails. Since the number of COMBAR reporting days was large, a quantified technique was developed so the spatial and temporal contiguous areas of contrails reports (i.e., contrail clusters) could be efficiently catalogued.

The rules defining a contrail "cluster" were as follows:

1. Two or more COMBAR observations reporting contrails not greater than 1 hour apart.
2. Two or more observations not greater than 1 degree of latitude of longitude apart.
3. If several data of a given day meet these criteria, the area is bounded by a line 1/2 degree outside of the observations, indicating a contrail "region."

NWS/FOS within the bounded areas were catalogued and the data collected for - 12 hours, centered on the mean contrail observation within the cluster. There were 54 days with contrail episodes which met the above criteria from 1957 through 1962.

The area of each contrail cluster was measured by means of a planimeter. Of 76 clusters, the mean area was about 43,000 km^2 (16,800 mi^2) with a sample standard deviation of about 13,000 km^2 (5,000 mi^2). The smallest contrail cluster encompassed about 32,000 km^2 (13,000 mi^2) while the largest covered about 97,000 km^2 (38,000 mi).

Discrepancies Between COMBAR Reports and Cloud Cover at NWS Reporting Stations

The aim of clustering was to define areas within which contrails observed by aircraft (COMBARs) could be compared to cloud observations from NWS stations. Since only COMBARs reporting contrails (but no natural clouds) were utilized, it was expected that the majority of the surface data would not report non-cirriform clouds. This was not always the case, however. Over the 82 surface stations included in this study, the mean non-cirriform cloud cover was 0.13 (a = 0.29). The discrepancies occurred on 17 of the 82 station cases (20.7%). Therefore, about 1/5 of the sample cases exhibited a discrepancy between pilot observations and those from FOSs in the same general area and from about the same time. The time interval (- 1 hour) may have been too long to permit a greater correlation.

Another discrepancy occurred when no clouds were reported at any of the NWS reporting stations within a contrail area defined by aircraft observations. This might mean that the clustering procedure may have failed to identify the presence of contrails from surface observations, or that the surface stations did not report contrails as a part of their observed cloud cover. The latter is most likely since there is no requirement to report contrails on observation forms. This occurred during 52 of the 82 stations cases. (63.4%). These cases account for 11 of the 17 station cases previously mentioned where there were low and middle clouds. If the remaining 6 cases are added to the 52 station cases with no cirriform clouds, 58 station cases (70.7%) of the total number of cases have questionable properties and will likely degrade the analysis. As a result, the findings will be presented in two distinct groups: (1) the total sample of 82 station cases, and (2) the smaller subset of the 24 most reliable station cases.

<u>Results using all cases</u>

Table 13 lists each station case from 1957 through 1962. The trends of <u>total</u> cloud cover through each contrail episode were examined by noting if there was an increase in the total cover reported prior to the time of the aircraft contrail observation, to that during the contrail time, or to that

Table 13. Data to Evaluate Cloud Clusters Observed by Air and from the Surface. See Text for Explanation.

Case #	Date	Times of Con-trails LST	Stations, in Cluster	Total Cloud Cover				Cirrus Cloud Cover				Temp-erature	Relative Humidity	Comments
				prior	during	after	change	prior	during	after	change	Was slope decreased (Moderated)	Did slope decrease if falling or more R.H. hr^{-1} (Moderated)	
1	3-4-57	1445-1530	STL	0.3	0.3	0.9	+0.6	0.3	0.3	0.9	+0.6	Yes	Yes	Nearlng climato-logical dropoff of temp.
			BRL	0.6	0.9	0.9	±0.3	0.3	0.3	0.2	-0.1	Yes	Yes	
			SPI	0.7	0.6	0.7	±0.1	0.7	0.6	0.7	-0.1	No	Yes	
2	3-13-57	1030-1055	SGF	0	0	0	0	0	0	0	0	Yes	Yes	
3	4-30-57	1300	PIA	0	0	0.2	+0.2	0	0	0.2	+0.2	Yes	Yes	
			BRL	0.1	0.2	0.2	+0.1	0.1	0.2	0.2	+0.1	Yes	Yes	
			SPI	0	0.1	0.1	+0.1	0.1	0	0.1	-0.1	Yes	Yes	
4	4-30-57	1300-1320	FTW	0	0	0	0	0	0	0	0	Yes	Yes	
			SBN	0	0	0	0	0	0	0	0	Yes	No	
5	5-7-57	0100-0150	LSE	0	0	0	0	0	0	0	0	Yes	Yes	
			RST	0	0	0	0	0	0	0	0	No	Yes	
			D	B	Q	0	0	0	0	0	0	0	0	
			DSM	0	0	0	0	0	0	0	0	No	No	
6	7-23-57	2100-2200	DSM	0.1	0	0	-0.1	0	0	0	0	No	Yes	
7	10-2-57	1550-1600	MLI	-	-	_	_	_	_	_	_			
			MSN	0	0	0	0	0	0	0	0	Yes	Yes	Nearing climato-logical dropoff of temp.
			DBQ	0	0	0	0	0	0	0	0	Yes	Yes	
			LSE '	0	0	0	0	0	0	0	0	Yes	Yes	
8	10-8-57	0300-0400	BRL.	-	-	_	_	-	-		_	No	No	

Table 13. Data to Evaluate Cloud Clusters Observed by Air and from the Surface. (Continued)

Case #	Date	Times of Contrails LST	Stations in Cluster	Total Cloud Cover: prior	during	after	change	Cirrus Cloud Cover: prior	during	after	change	Temperature: Was slope decreased (Moderated)	Relative Humidity: Did slope decrease if falling or more R.H. hr^{-1} (Moderated)	Comments
9	10-18-57	1704-1715	MCI	0	0	0	0	0	0	0	0	Yes	Yes	Nearing climato-loglcal dropoff of temp.
10	10-28-57	1500-1600	SBN	0	0.1	0.2	+0.2	0	0.1	0.2	+0.2	Yes	No	Nearing cllmato-logical dropoff of temp.
			GRR	0.3	0.5	0.5	+0.2	0.3	0.5	0.5	+0.2	Yes	Yes	
			MKG	0.1	0.1	0.1	0	0.1	0.1	0.1	0	Yes	Yes	
11	11-9-57	1330-1350	MLI		-	-	-		-		-	-	-	
			BRL	0	0	0	0	0	0	0	0	Yes	Yes	
			PIA	0	0	0	0	0	0	0	0	Yes	Yes	
12	11-26-57	1500-1700	SGF	0.1	0	0	-0.1	0.1	0	0	-0.1	YeS	Yes	Nearing cllmato-logical dropoff of temp.
			MCI	0.1	0.1	0	-0.1	0.1	0.1	0	-0.1	Yes	Yes	
13	12-4-57	1415-1445	EVV	1.0	-	1.0	0	0	0	0	0	No	No	
14	12-21-57	1350-1400	SPI	0.7	0.5	0.1	-0.6	0.7	0.5	0.1	-0.6	Yes	No	Nearing climato-logical dropoff of temp.
			PIA	0.1	0.1	0.1	0	0.1	0.1	0.1	0	Yes	Yes	
15	8-25-58	2000-2100	DSM	0.1	0.1	0.1	0	0	0	0	0	Yes	No	Nearing climato-logical dropoff of temp.
16	9-3-58	2155-2205	RNA	0.2	0	0	-0.2	0.2	0	0	-0.2	Yes	No	Temp was dropping and leveled off during contrail time
17	9-9-58	2100-2200	STL	1.0	1.0	0.8	-0.2	0.9	0.8	0.7	-0.2	No	Yes	
			SPI	0.8	0.3	0.9	+0.6	0	0	0	0	Yes	No	R.H. decreased sharply during 2100-2200 LST
				''										
			PIA	1.0	1.0	1.0	0	0	0	0	0	Yes	No	
18	10-27-58	1800-1840	SSM	0	0	0	0	0	0	0	0	Yes	No	

Table 13. Data to Evaluate Cloud Clusters Observed by Air and from the Surface. (Continued)

Case #	Date	Times of Contrails LST	Stations in Cluster	Total Cloud Cover prior	Total Cloud Cover during	Total Cloud Cover after	Total Cloud Cover change	Cirrus Cloud Cover prior	Cirrus Cloud Cover during	Cirrus Cloud Cover after	Cirrus Cloud Cover change	Temperature: Was slope decreased (Moderated)	Relative Humidity: Did slope decrease if falling or more R.H. hr^{-1} (Moderated)	Comments
19	10-27-58	1800-1900	RST	0.1	0	0	-0.1	0.1	0	0	-0.1	Yes	No	
20	10-28-58	1715-1800	STL	0	0	0	0	0	0	0	0	No	No	
21	10-28-58	1900-2100	EVV	0	0	0	0	0	0	0	0	Yes	No	
			STL	0	0	0	0	0	0	0	0	Yes	No	
22	10-29-58	1300-1400	DLH	0.1	0.1	0.1	0	0.1	0.1	0.1	0	No	Yes	
23	10-30-58	1500-1600	IND	0.1	0.0	0.1	±0.1	0.1	0	0.1	-0.1	Yes	Yes	Nearing climatological drop off in temp.
24	12-11-58	1150-1200	MSN	0.8	0.7	0.1	-0.7	0.6	0	0	-0.6	No	No	
			DBQ	0.4	0.1	0.1	-0.3	0	0.1	0.1	+0.1	No	No	
25	12-17-58	1120-1125	MCI	0.1	0	0	-0.1	0	0	0	0	No	Yes	
26	12-18-58	1100-1110	SPI	0	0.1	0.2	+0.2	0	0.1	0.1	+0.1	Yes	Yes	
			PIA	0.1	0.6	0.6	+0.5	0.1	0.4	0.4	+0.3	Yes	Yes	
			BRL	0.4	0.5	0.7	+0.3	0.4	0.5	0.5	+0.1	No	Yes	
			MLI	-	-	-	-	-	-	-	-			
27	12-19-58	1130-1150	SSM	0	0	0	0	0	0	0	0	Yes	Yes	

Table 13. Data to Evaluate Cloud Clusters Observed by Air and from the Surface. (Continued)

Case #	Date	Times of Contrails LST	Stations in Cluster	Total Cloud Cover				Cirrus Cloud Cover				Temperature	Relative Humidity	Comments
				prior	during	after	change	prior	during	after	change	Was slope decreased (Moderated)	Did slope decrease if falling or more R.H. hr^{-1} (Moderated)	
28	1-9-61	1800-1830	RST	0.6	0.1	0.1	-0.5	0.6	0.1	0.3	-0.5	No	No	
			LSE	0.4	0.3	0.1	-0.3	0.4	0.3	0.1	-0.3	No	Yes	
			DBQ	0.5	0.4	0.3	-0.2	0.5	0.4	0.3	-0.2	Mo	No	
29	1-10-61	1800-1830	RST	0.1	0	0	-0.1	0.1	0	0	-0.1	No	No	
30	1-20-61	1600-1700	DLH	0	0.2	0	±0.2	0	0.2	0	±0.2	No		
31	1-27-61	0300-0400	MCI	1.0	0.4	0.5	-0.6	0	0.4	0.3	+0.4	No		
32	2-3-61	2010-2019	SGF	0.4	0.6	0.6	+0.2	0.4	0.6	0.6	+0.2	Yes	No	
33	2-9-61	1300-1400	RST	1.0	1.0	1.0	0	0.9	0.4	0.	-0.9	No	No	
34	2-10-61	2000-2100	BNA	0.1	0	0	-0.1	0	0	0	0	No	No	
35	2-15-61	2028-2030	MCI	0.3	0.2	0.2	-0.1	0.3	0.2	0.2	-0.1	No	Yes	
36	2-16-61	2015-2115	MKE	1.0	1.0	1.0	0	1.0	0	1.0	-1.0	Yes	Yes	
			MDW	1.0	1.0	0.5	-0.5	0	0	0.2	+0.2	No	No	
37	2-24-61	1710-1805	SGF	1.0	0.8	0.8	-0.2	0	0.2	0.1	+0.2	No	No	
38	3-2-61	0928-1017	STL	0.2	0.4	0.3	+0.2	0.1	0.3	0.2	+0.2	No	Yes	
39	3-11-61	0000-0100	MCI	0.2	0	0	-0.2	0.2	0	0	-0.2	Yes	Yes	
40	6-2-61	0100-0125	BNA	0.6	0.6	0.6	0	0.6	0.6	0.6	0	No	No	
41	7-28-61	2245-2300	MCI	0.6	0	0	-0.6	0	0	0	0	Mo	No	
42	10-30-61	2300-0000	DSM	0	0	0.1	+0.1	0	0	0	0	Yes	Mo	

Table 13. Data to Evaluate Cloud Clusters Observed by Air and from the Surface. (Continued)

Case #	Date	Times of Contrails LST	Stations in Cluster	Total Cloud Cover prior	Total Cloud Cover during	Total Cloud Cover after	Total Cloud Cover change	Cirrus Cloud Cover prior	Cirrus Cloud Cover during	Cirrus Cloud Cover after	Cirrus Cloud Cover change	Temp. Mod-erated	R.H. Mod-erated	Comments
			MCI	0.1	0.1	0.1	0	0.1	0.1	0.1	0	No	No	
43	11-7-61	0900-1000	SGF	0.1	0	0	-0.1	0.1	0	0	-0.1	Yes	No	
44	1-15-62	1930-2030	EVV	0	0	0	0	0	0	0	0	Yes	No	
45	1-16-62	2230-2330	STL	0.7	0.7	0.8	+0.1	0.7	0.7	0.8	+0.1	No	No	
46	1-23-62	0925-0938	BRL	0.1	0.1	0.1	0	0.1	0.1	0.1	0	Yes	No	
47	1-25-62	0215-0230	SBN	0	0	0	0	0	0	0	0	No	No	
			GRR	0	0.4	0.8	+0.8	0	0	0	0	Yes	Yes	
			FTW	0	0	0	0	0	0	0	0	No	No	
			DET	0	0	0	0	0	0	0	0	No	No	
			LAN	0	0	0.4	+0.4	0	0	0	0	Yes	Yes	
48	3-2-62	0200-0250	MCI	0	0	0	0	0	0	0	0	No	No	
49	3-2-62	1010-1020 (CST)	GRB	0.1	0	0	-0.1	0.1	0	0	-0.1	No	No	
			MQT	-	-	-	-	-	-	-	-	No	No	
50	3-6-62	1500-1600	MEM	0	0	0	0	0	0	0.1	+0.1	Yes	Yes	Nearing climatological drop off in Temp.
51	3-15-62	1020-1030	GRB	1.0	1.0	1.0	0	0	0	0	0	No	No	
52	3-23-62	1130-1140	SSM	1.0	0.7	0.8	-0.3	0	0	0	0	No	No	
53	4-3-62	2300-0000	MCI	1.0	1.0	1.0	0	0	0	0	0	No	No	
54	4-18-62	2300-0000	LSE	-	-	-	-	-	-	-	-	No	No	
			RST	0	0	0.1	+0.1	0	0	0.1	+0.1	No	No	
							$\bar{X}$ = -.01 σ = .25 N = 82				$\bar{X}$ = -.03 σ = .22 N = 92	44 Yes 40 No	44 No 38 Yes	

after the contrail time. The greatest change was also recorded. There was no change in total cloud or cirrus cloud cover during the mean contrail episode, i.e., in these instances, NWS observers did not incorporate aircraft contrail cirrus into high cloud observations. This is interesting since when cloud observations from several stations, over several decades were analyzed (above), high clouds were found to increase with the increase in jet traffic since ca. 1960.

The "change" columns of Table 13 indicate great variability concerning changes to cloud amount observed from the surface during a contrail event identified by a pilot. Indeed, 35 of the 54 total cloud cases (65%) showed no change. Seventy-two percent of cirrus cloud observations showed no change.

The temperature trace of surface NWS stations within a contrail region was also analyzed. Our hypothesis was the same as that used in the ISWS all-sky camera study reported above, i.e., if a contrail moved overhead during the daytime, there should be a moderation or decrease in the rate of heating (prior to time of maximum temperature) due to a depletion of insolation. From late afternoon through the evening (when the temperature is naturally cooling) our hypothesis was that there should be a moderation or decrease in the rate of cooling due to cloud cover blocking some of the outgoing long-wave radiation.

These results were also non-conclusive (see Table 13) as 44 station cases (52%) appeared to be moderated, while the remaining 40 cases (48%) showed no moderation.

A similar process was. used to analyze surface relative humidity changes. The hypothesis was that if the temperature were increasing the relative humidity should decrease, and a contrail should moderate the rate of temperature change, thereby moderating the rate of relative humidity change as well. A positive response would indicate a moderation, while a negative response would indicate no detectable moderation. Table 13 shows 38 positive responses (46.3%) and 44 negative responses (53.7%). Therefore, the hypothesis must be rejected. These results suggest that NWS stations are probably too widely separated for a synoptic scale comparison of contrail observations from pilots and NWS observers. Furthermore NWS observers are not required to report contrail cirrus, so the chance of finding a relationship with single observations is remote.

Results using the 24 Best Cases

The mean change in total cloud cover again was zero with a standard deviation of 0.3. The cirrus-only cloud cover was also zero with standard deviation of 0.3. The mean cirriform cloud cover during a contrail event was 0.3 with a standard deviation of 0.2.

Of the 24 cases, the temperature change did not support the hypothesis in 13 cases (54.2%). Again the results are non-conclusive. The relative humidity trend supported the hypothesis in only 12 cases (54.5%). These results are similar to those from the larger data group. /

The attempt to document discernable effects of cirriform clouds (man-induced or natural) on NWS first order station observations using COMBAR reports, to identify the contrail regions demonstrated no relationship. There are at least two possible reasons: First, the lack of time or space congruence between areas identified from COMBARs and those from surface observations. There were instances of low- and mid-level clouds reported at the meteorological stations, yet the COMBAR reports made no reference to clouds other than contrails. Part of this problem undoubtedly is because NWS observers are not required to report contrails, nor are guidelines given in the Federal Meteorological Handbook-1 when/if contrails are to be included in the cloud cover. In the 1950s and 1960s, contrails were often included in the comments of hourly observations because they were unique. As they became more common place, however, their mention decreased. The non-consistency of contrail observing practices among NWS observers, and the results of this study corroborate each other and suggest that high cloud observations may or may not contain contrail frequency information, depending on time of day, the observer, etc.

Second, lack of specificity of COMBAR locations. COMBAR observation locations were recorded to the nearest whole degree of latitude-longitude, therefore the actual location could have been ± 30 nm away from that recorded. Attempting to define an effect in surface temperature within 1 hour of a contrail observation from as far as 30 miles from the reporting station may be beyond the capability of the data. We believe contrail observations from COMBAR reports to be the best quality and most frequent observations of contrails available. Although specific and meaningful information concerning contrail height, association with natural clouds, outside air temperature etc. can be extracted from these records, defining areas with persistent contrails cannot be accomplished with occasional, point measurements such as COMBARs.

Observations of County Agricultural Extension Agents

In order to obtain more frequent contrail observations from a relatively dense network and define area within which contrails are frequent, county agricultural extension agents from Illinois were contacted to participate in a contrail observing network. About 40 people (all except 4 in separate counties) agreed to make one observation in the morning and another in the afternoon during December 1980; January, April, July, and October 1981. The observation form (shown in Figure 4) required only a few minutes time (hence we most often received complete or near complete observations from each observer). With the description and instructions which we provided, there appeared to be few problems. The observer noted the time of observation, and whether the sky was cloudy, as opposed to partly cloudy or clear. If not

Name________________________ Location________________________ Date__________
(please print) (month/year)

DAY	TIME	CLOUDY	NO CONTRAILS	CLEAR OR PARTLY CLOUDY				
				Few Contrails		Many Contrails		
		Can't see sky		Mostly Short	Mostly Long	Mostly Short	Mostly Long	Spreading Contrails
1								
1								
2								
2								
3								
3								
4								
4								
5								
5								
6								
6								
7								
7								
8								
8								
9								
9								
10								
10								
11								
11								
12								
12								
13								
13								
14								
14								
15								
15								
16								

Comments____

Figure 4. Speciman copy of contrail observer form.

cloudy, the observation was continued, indicating whether contrails were seen (few or many, long or short; conditions which we had described in our letter of instruction), and whether the contrails were spreading. These observations too, were plotted for subsequent analysis of contiguous areas of contrail formation.

Distribution of Observations About the State

The maps shown on Figure 5 indicate the number of observations during each of the months of the study which were made from each of the participating counties. One can note that the continuity of record was generally very good, i.e., if a person had been designated as a contrail observer, he/she tended to take upward of ca.. 40 observations for the month (about 2/3 of the potential). However there are large "silent" areas within the state, i.e., areas of contiguous counties where no observations were made. These silent areas were mostly located in the central and northwest regions of Illinois. If these observations are to be continued in the future, a determined effort would be launched to find satisfactory observers in those counties which have, up to now, not reported.

Cloud Analysis

Although the primary objective given to the county extension agents and their representatives was to document contrail frequency in their area, a parameter which they also observed was cloud cover. At each time of observation the observer first recorded whether the sky was overcast or was less than overcast. If the sky was overcast, the contrail observation was not continued. For each of the five months of observations, we have counted the number of observations with cloudy skies to present those totals as a percent of the total number of observations. These analyses are shown on Figures 6 through 10.

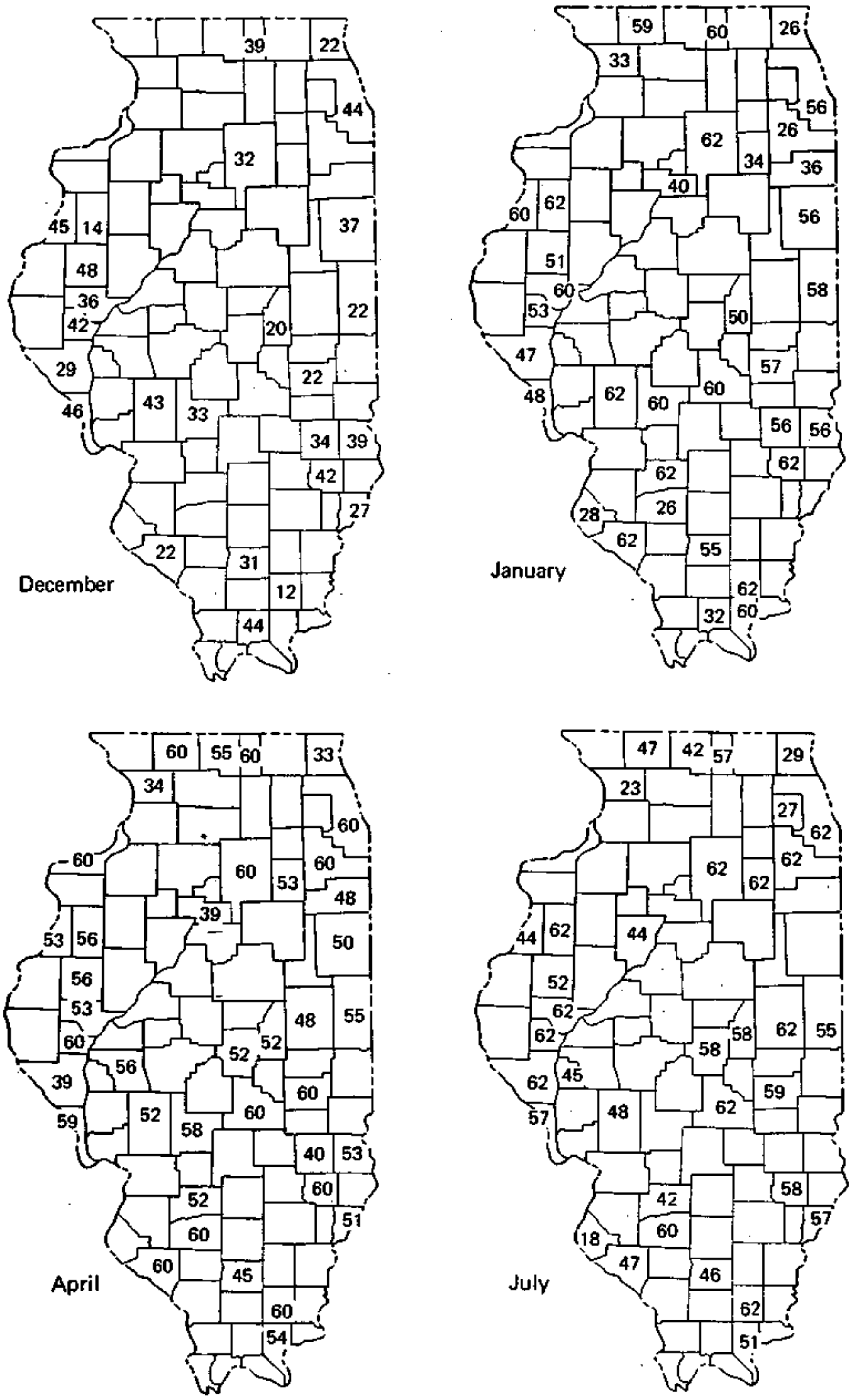

Figure 5. Distribution and frequency of county contrail observers.

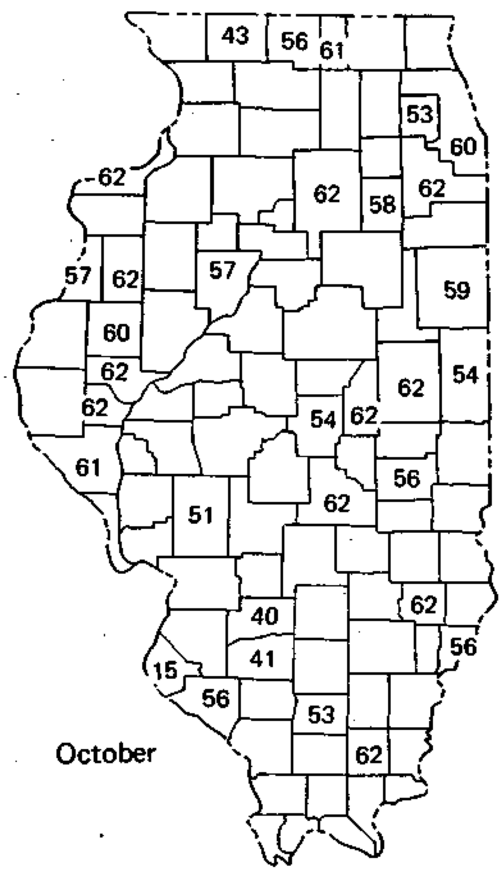

Figure 5. Distribution and frequency of county contrail observers. (Continued)

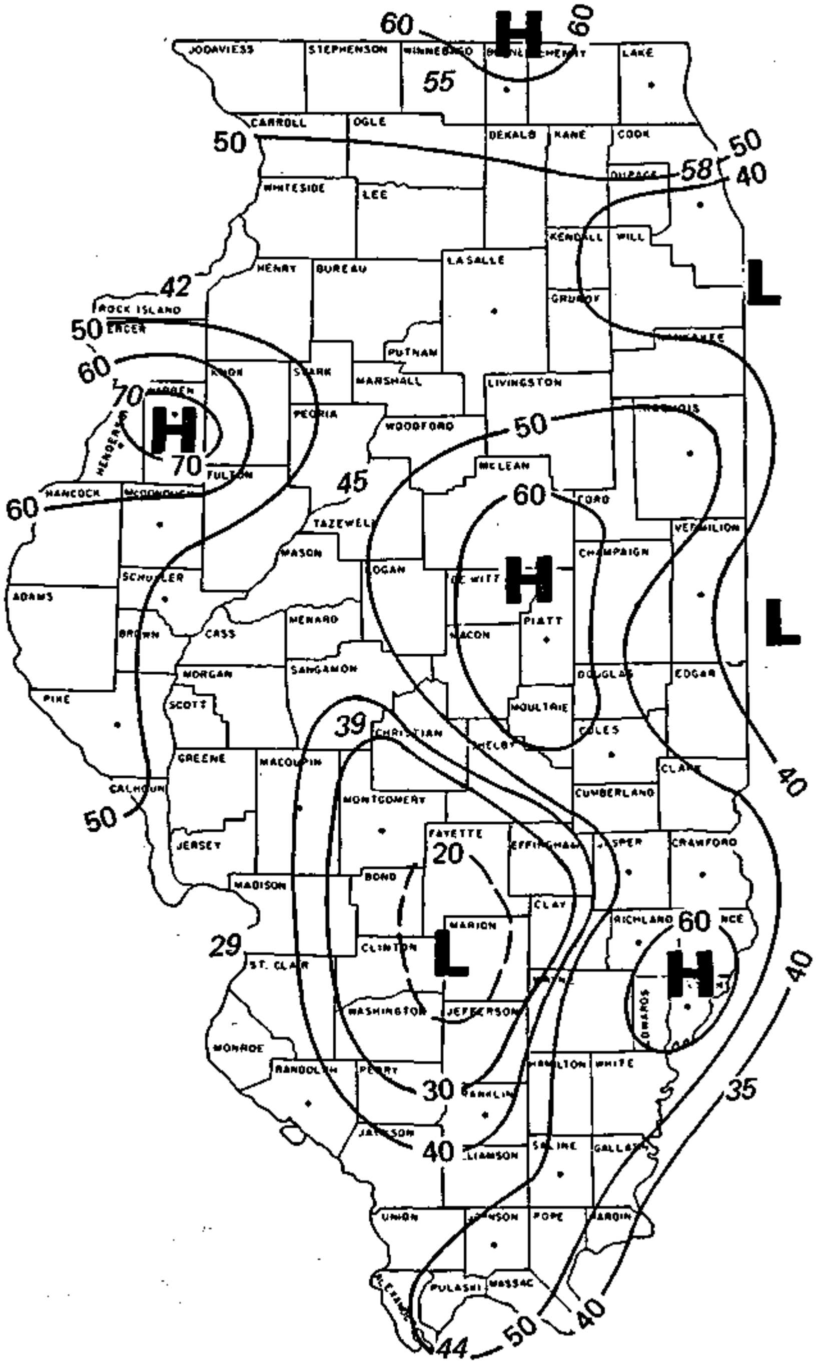

Figure 6. Percent of monthly observations with overcast skies. December 1980.

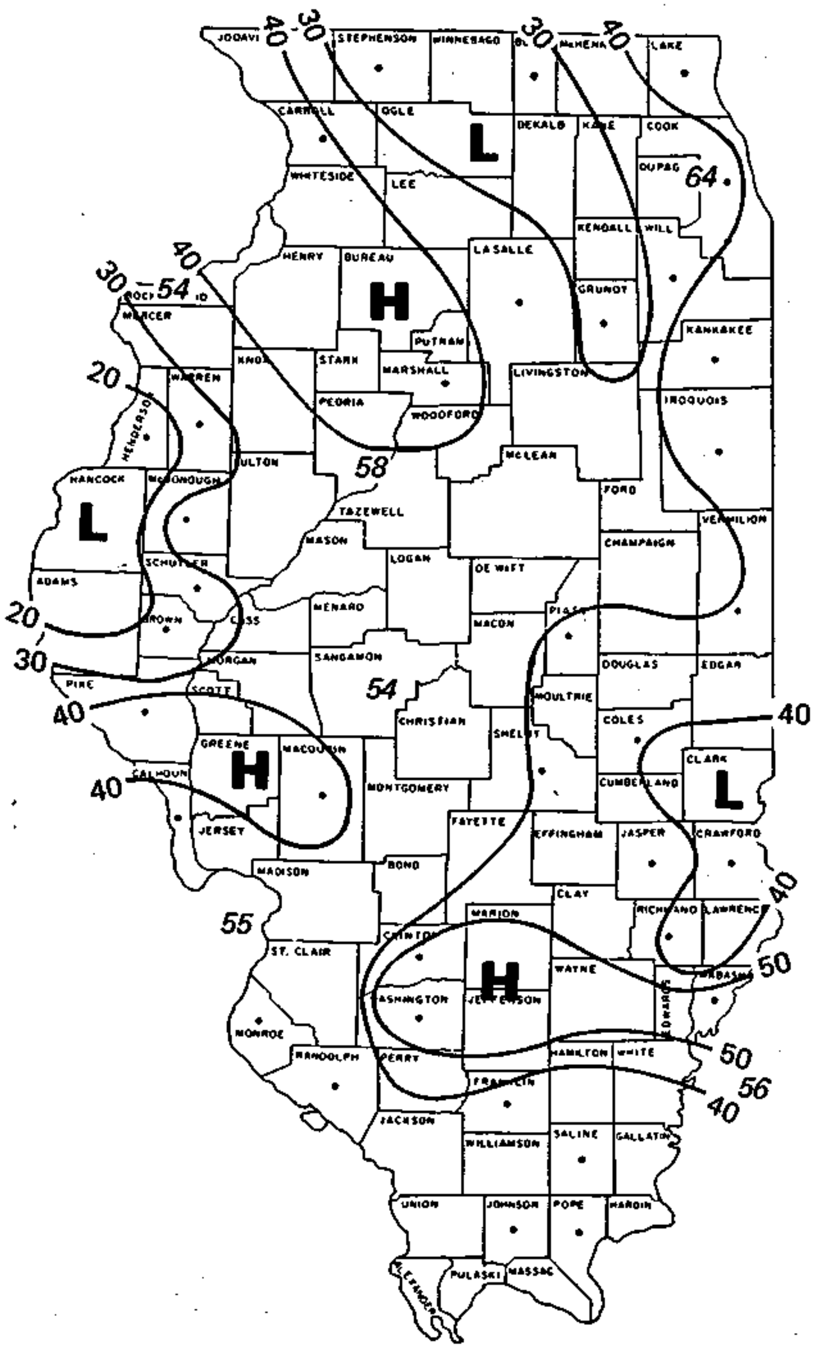

Figure 7. Percent of monthly observations with overcast sVies.
January 1981.

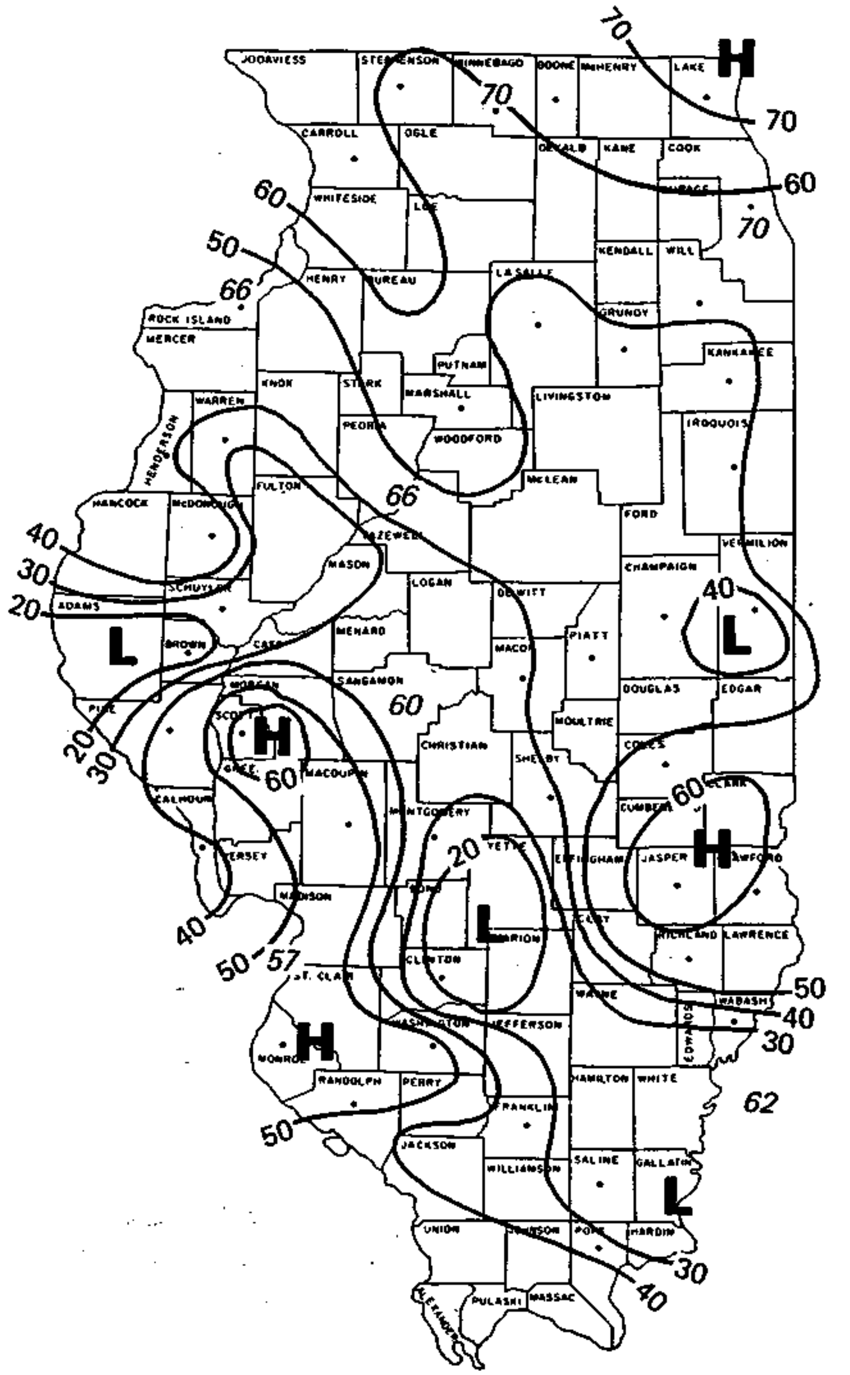

Figure 8. Percent of monthly observations with overcast skies. April 1981.

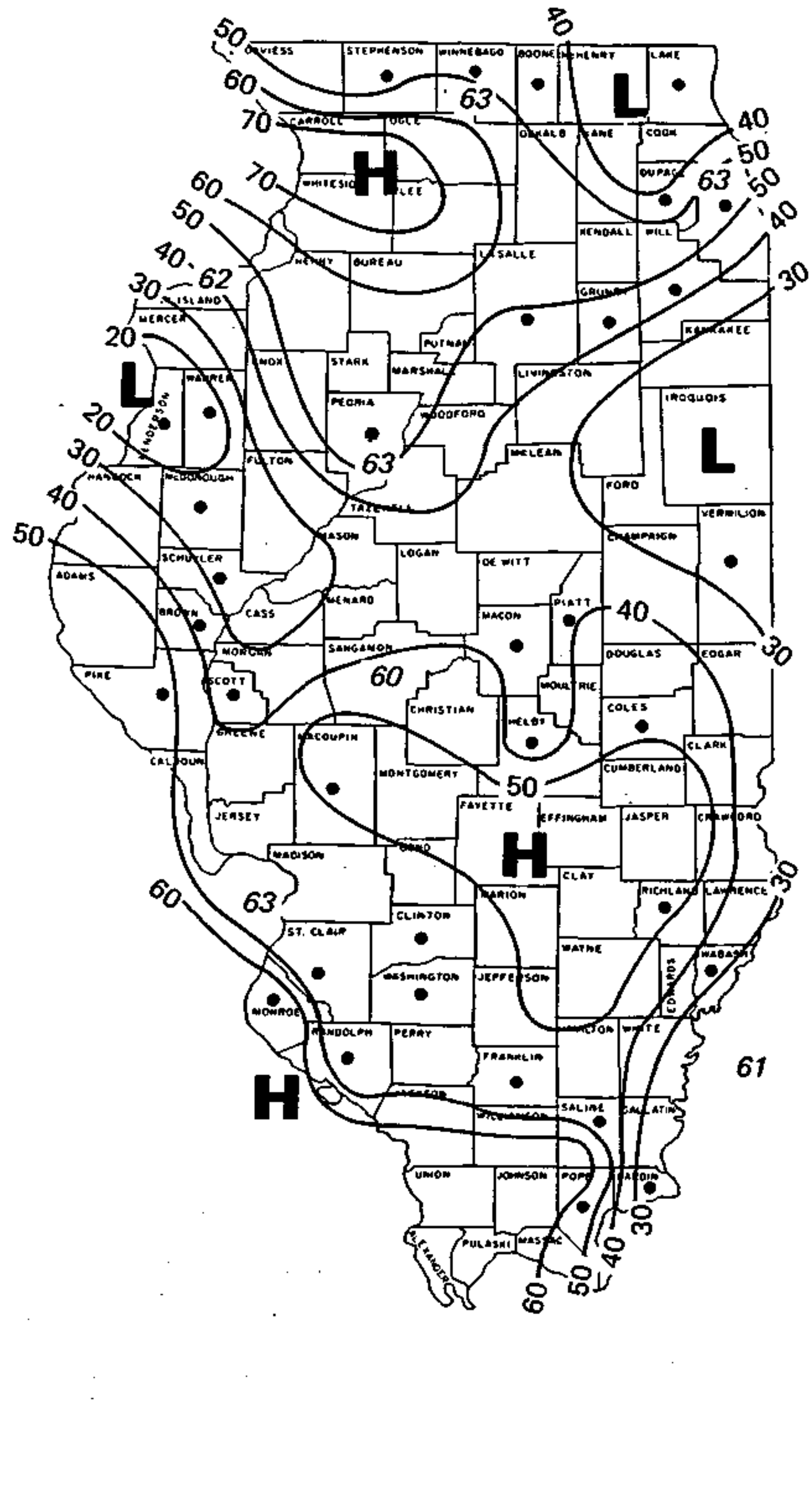

Figure 9. Percent of monthly observations with overcast skies.
July 1981

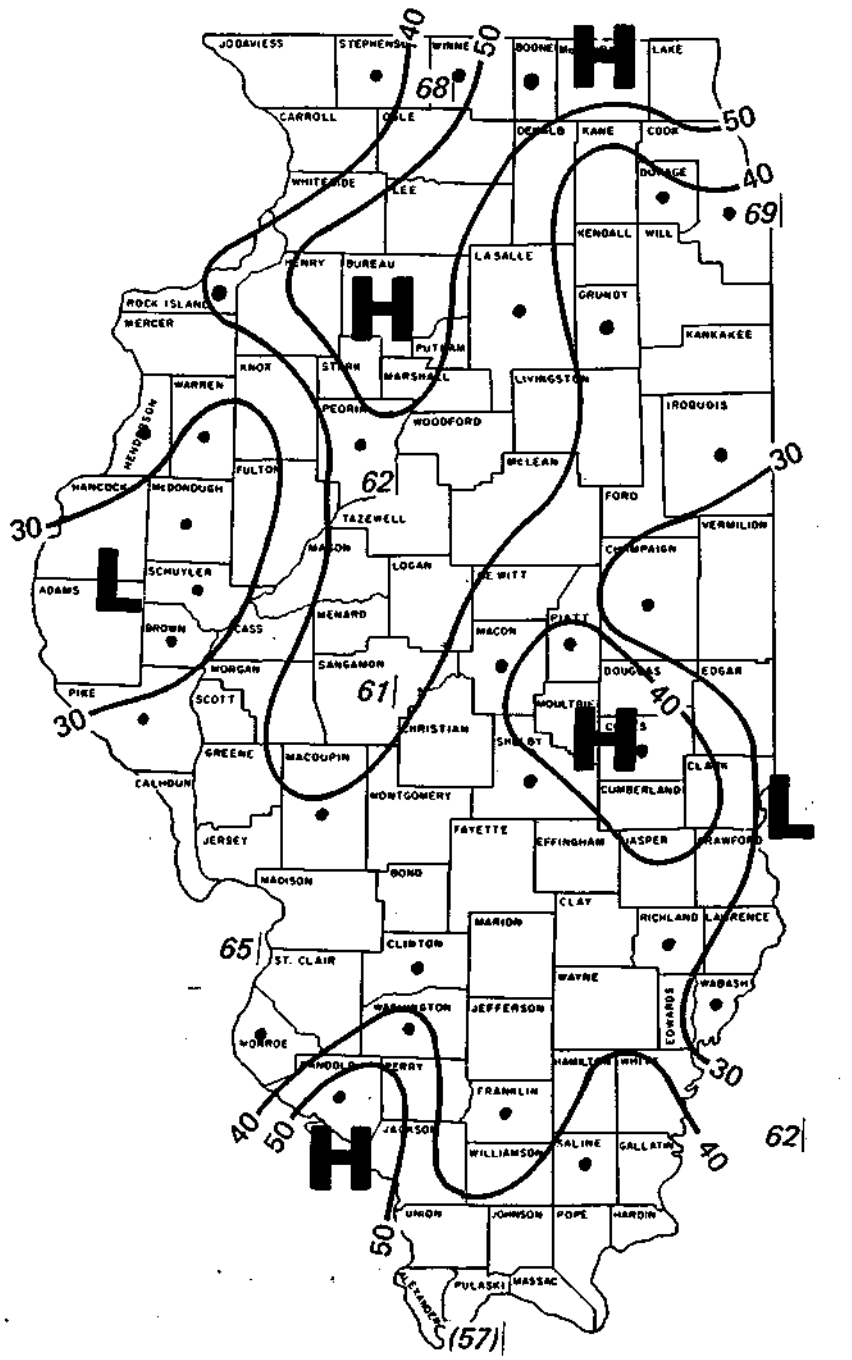

Figure 10. Percent of monthly observations with overcast skies. October 1981.

The dots in the centers of counties indicate counties from where data were received. It is important to remember that the cloud values presented on Figures 6 through 10 should not be interpreted as mean monthly cloud cover per se. Rather, they represent the percent of up to 62 observations per month (once each morning, once each afternoon) during which the sky was overcast. Percent total cloud cover at the time of observation was not measured. The italicized numbers on each of the five figures represent the mean daytime (sunrise to sunset) cloud cover at each of the first order NWS stations around the state.

The magnitudes of the gradients and patterns appear to be about the same on each of the five monthly charts. There is no apparent persistence in the location of relatively cloudy or cloud-free areas, which might suggest a bias on the part of certain observers.

In each of the five months with observations, the percent of the total observations which were cloudy (determined by our cooperative observers) were systematically less than the mean daytime cloud cover measured at the nearest first order station. In December 1980, the difference was only about 3%, whereas during January, April and July the difference was about 17%. During October the difference was 23%. The systematic difference is because our reports represent the percent of total observations with overcast skies, whereas the NWS values represent the monthly mean percent of daytime cloud cover.

Contrail Observations

Figures 11 through 15, and 16 through 20 show the percent frequency of contrails from the monthly observations, expressed as percent of non-cloudy observations in the former, and percent of total observations in the latter. The large scale (several counties or larger) patterns and distribution of the gradients are similar for each of the two charts for each month. The percent

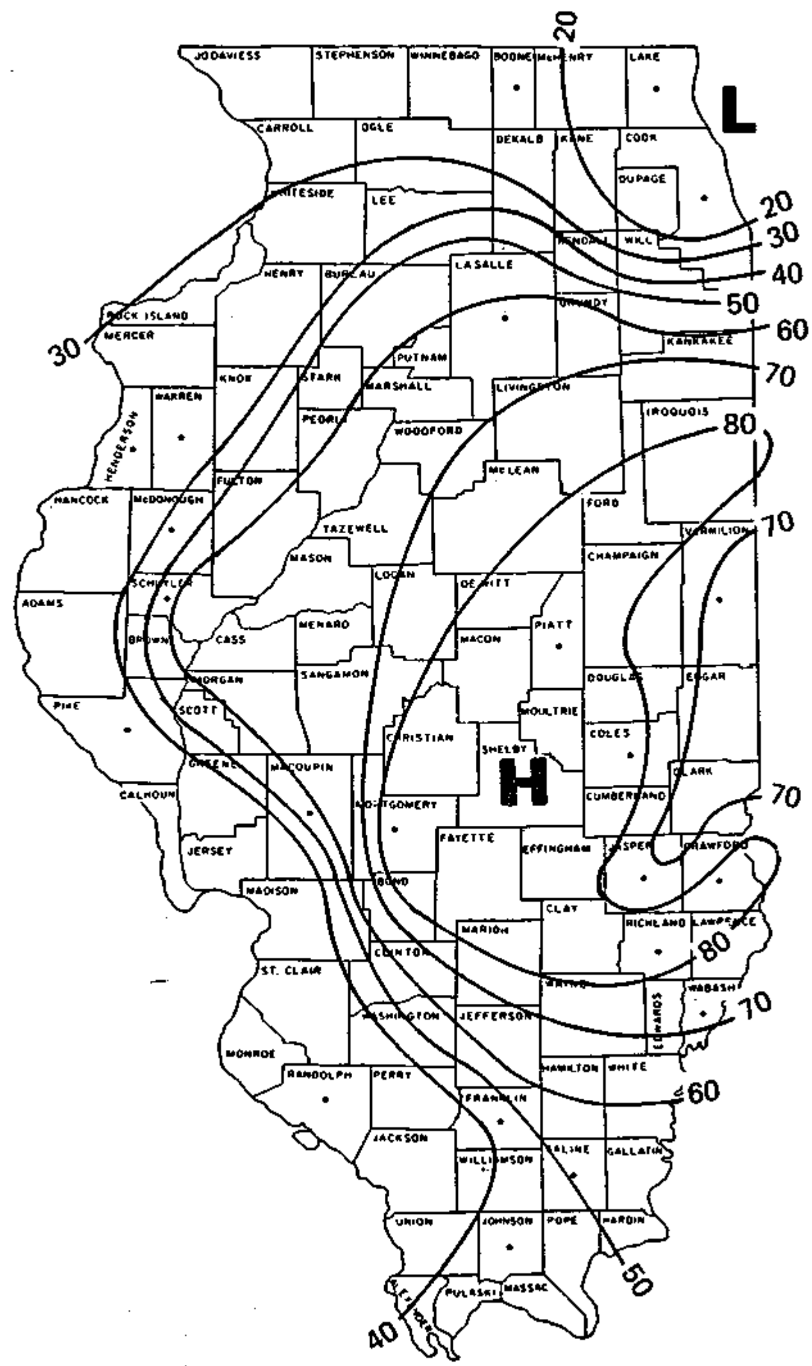

Figure 11. Contrail frequency, percent of non-cloudy observations, December 1980.

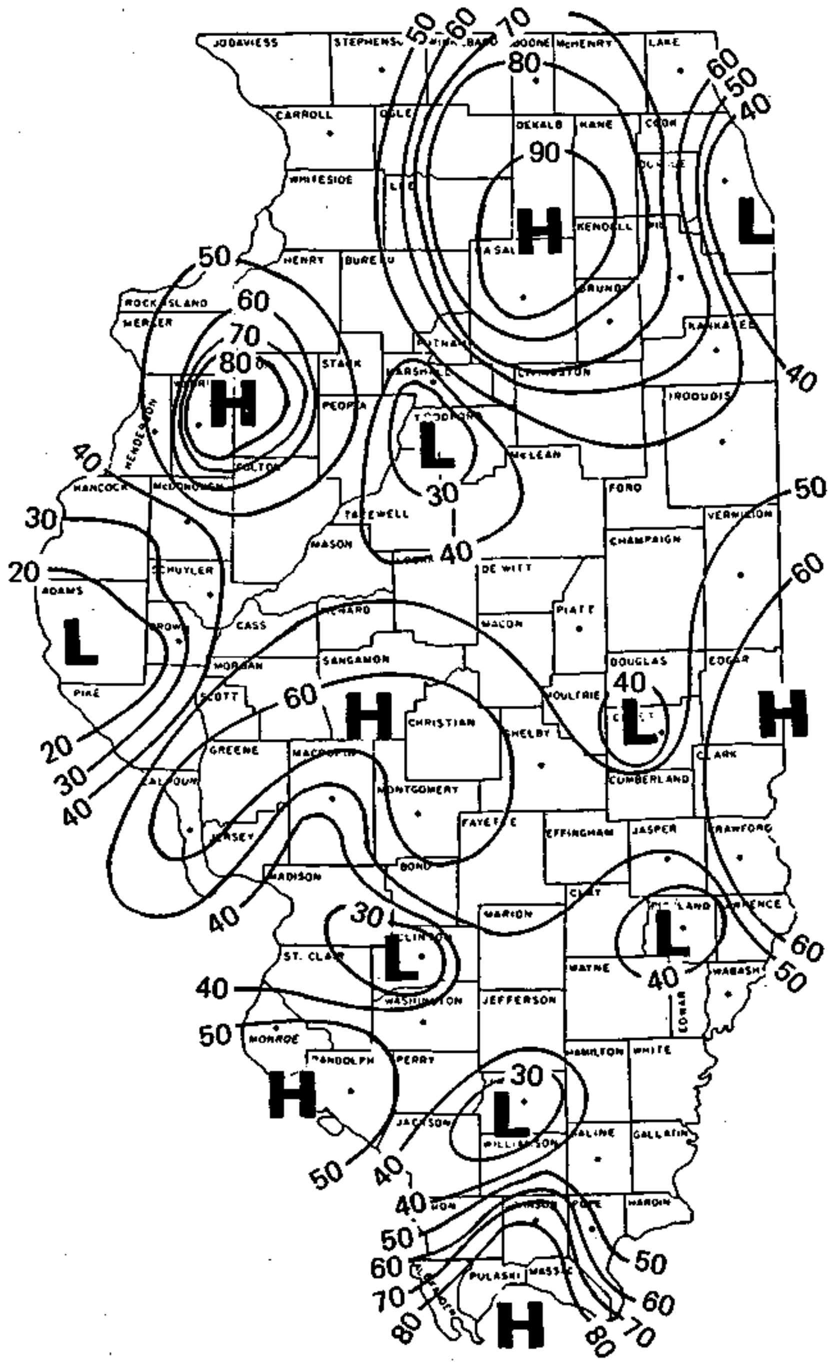

Figure 12. Contrail frequency, percent of non-cloudy observations, January 1981.

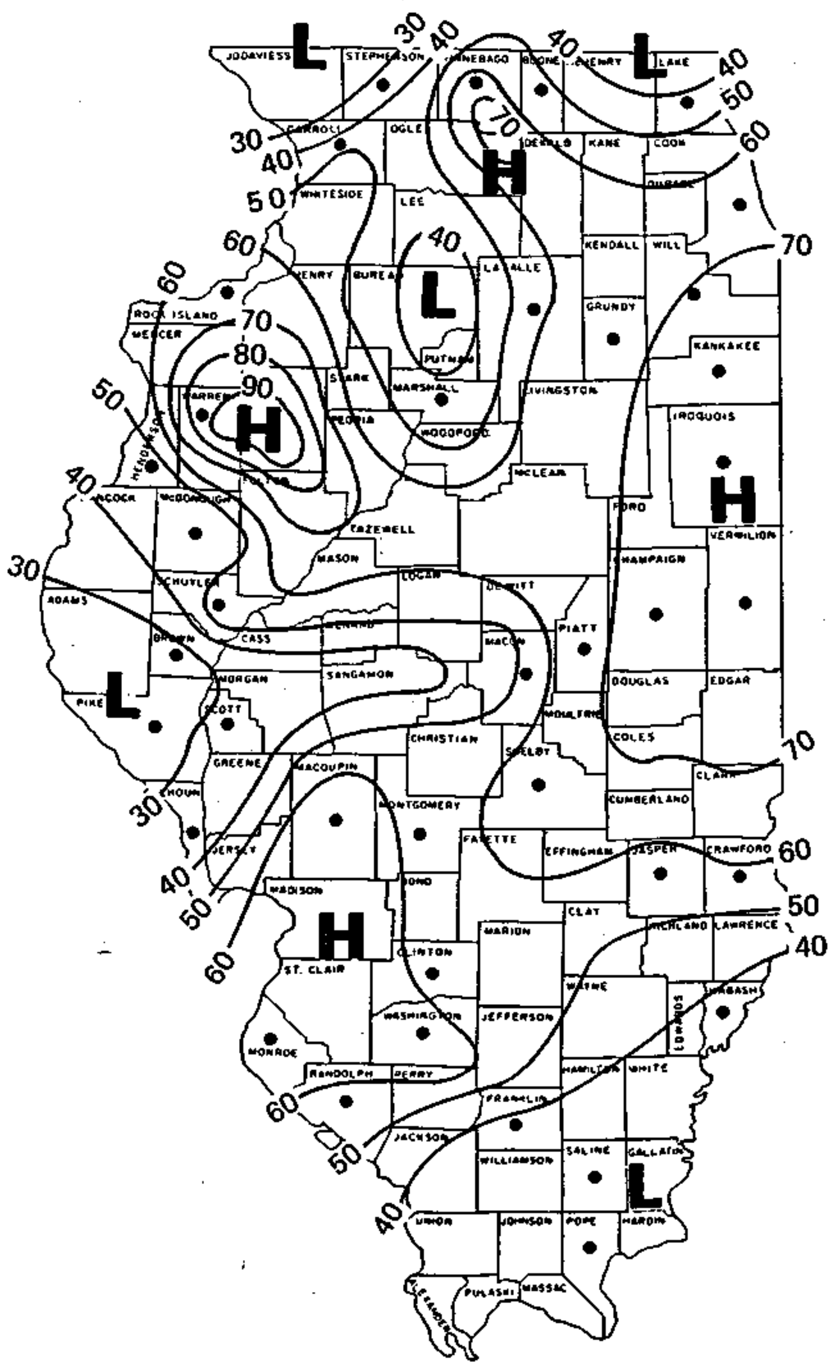

Figure 13. Contrail frequency, percent of non-cloudy observations, April 1981

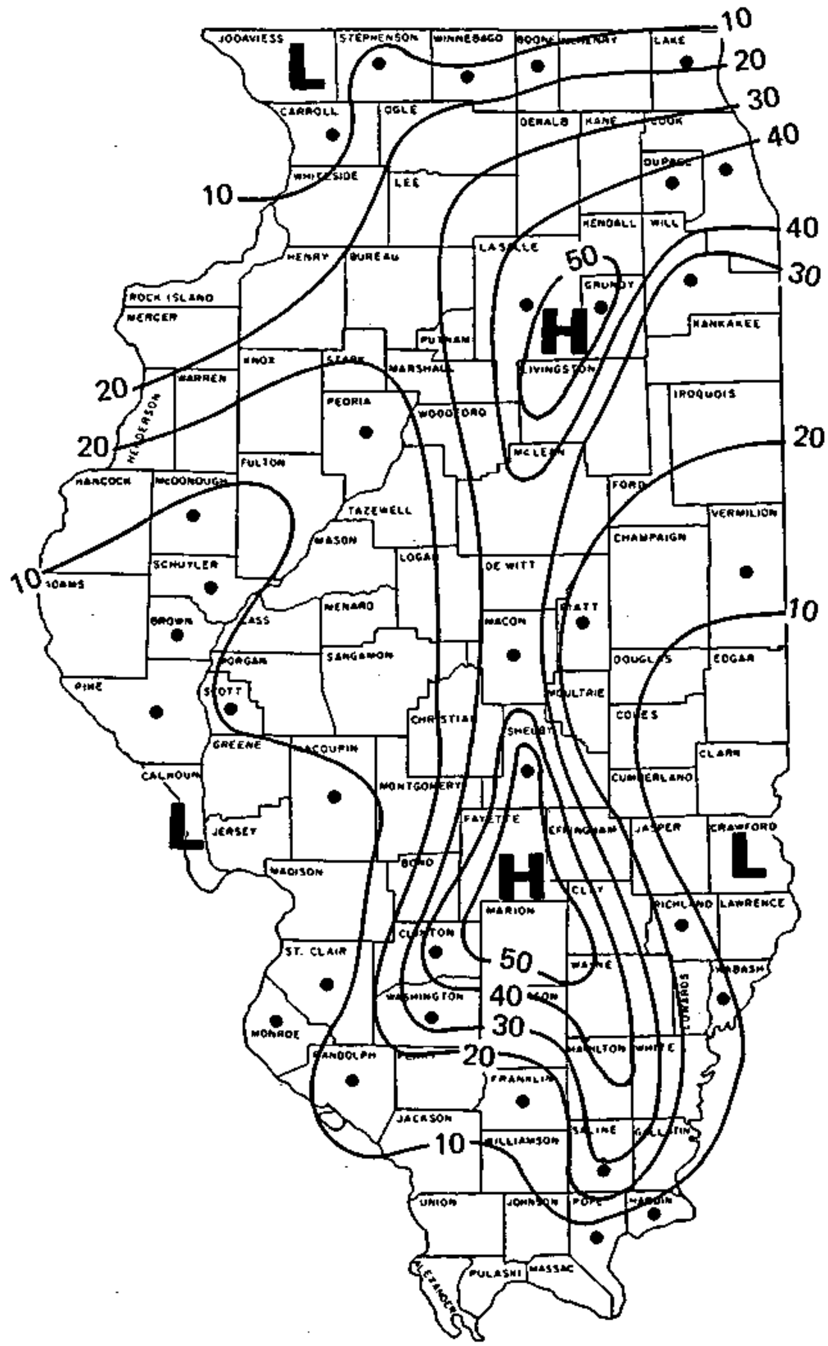

Figure 14. Contrail frequency, percent of non-cloudy observations, July 1931.

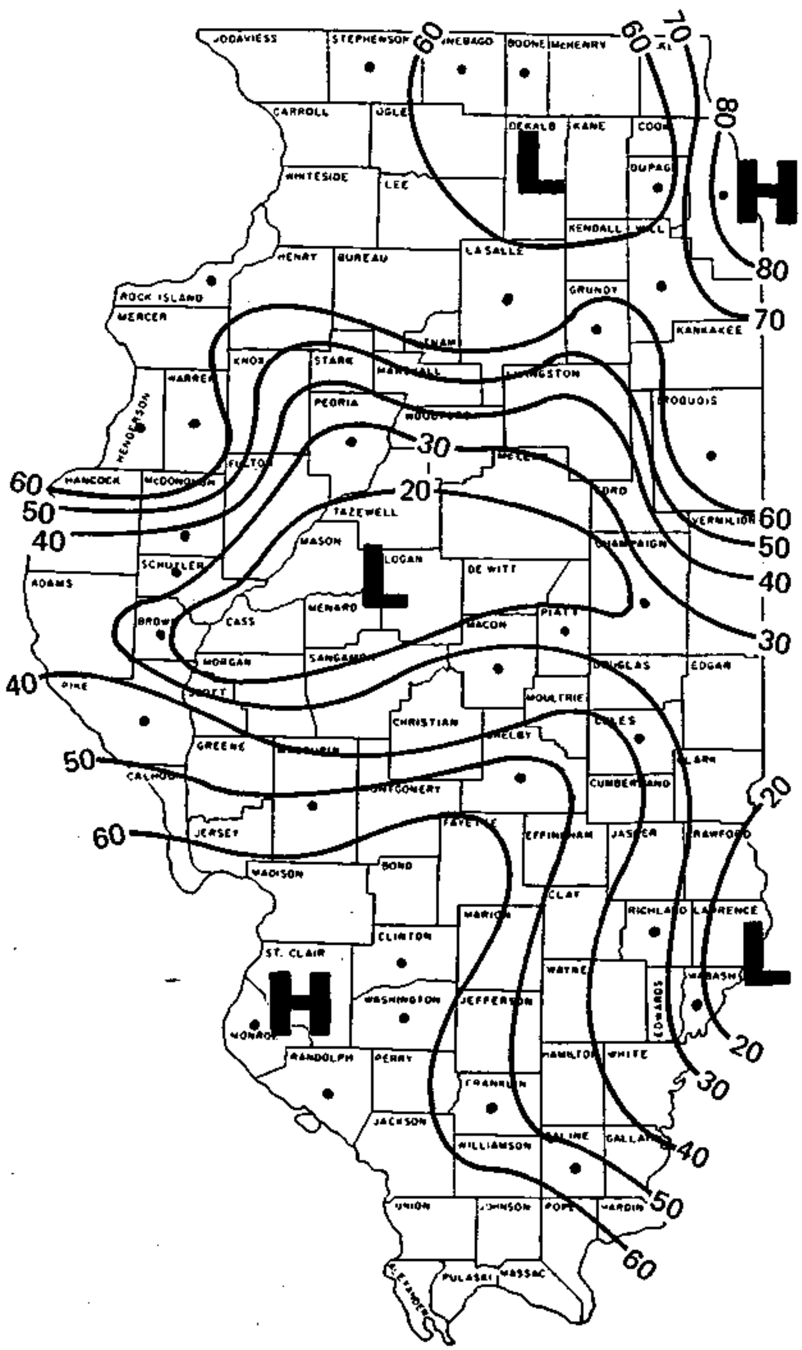

Figure 15. Contrail frequency, percent of non-cloudy observations, October 1981.

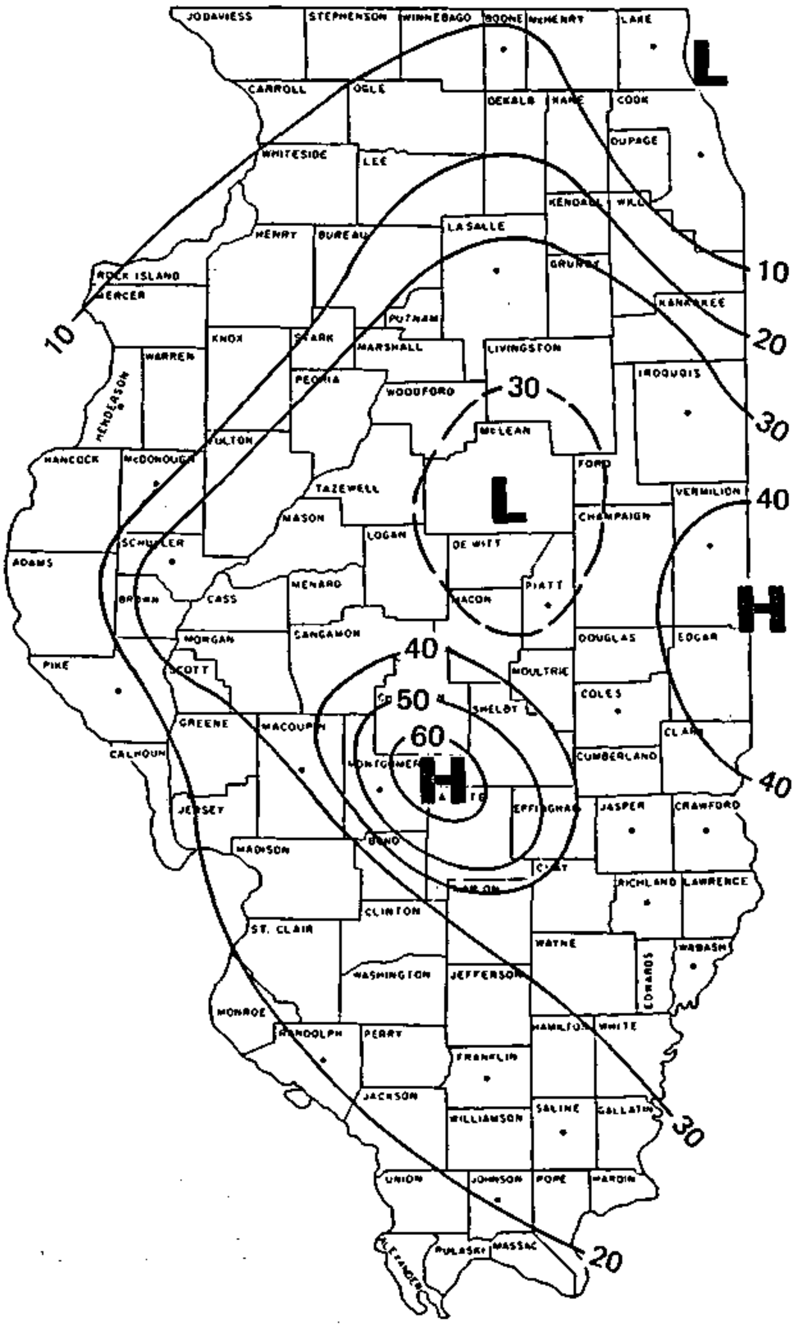

Figure 16, Contrail frequency, percent of all observations, December 1980.

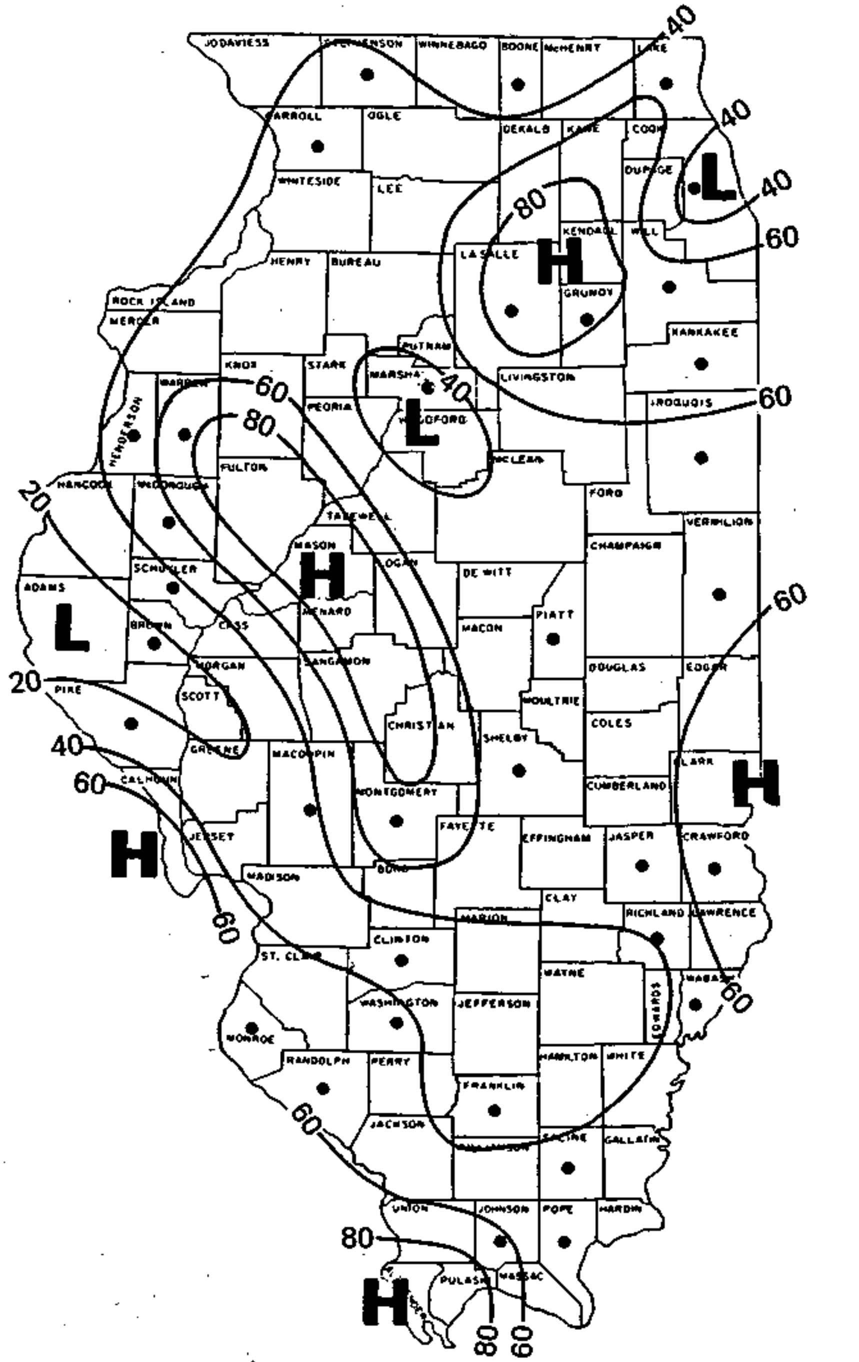

Figure 17. Contrail frequency, percent of all observations, January 1981.

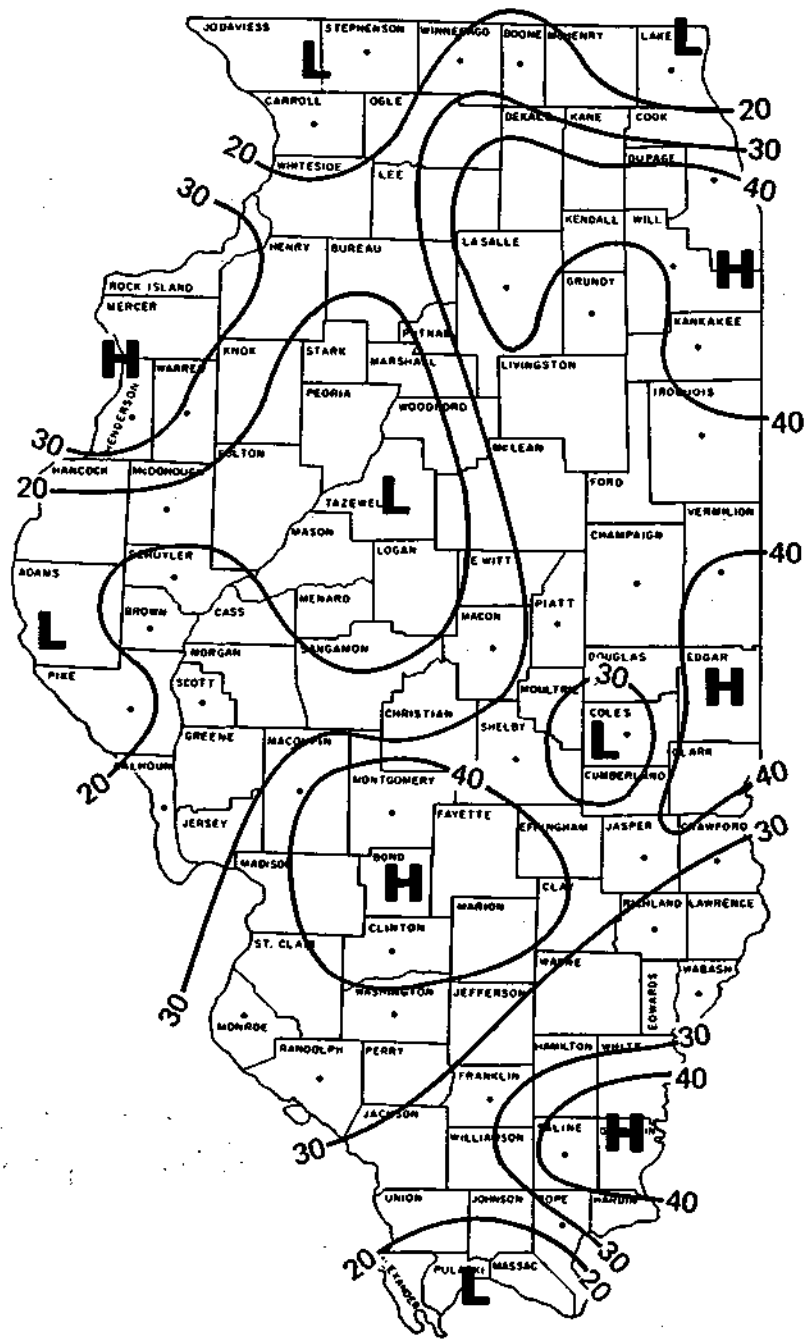

Figure 18. Contrail frequency, percent of all observations, April 1981.

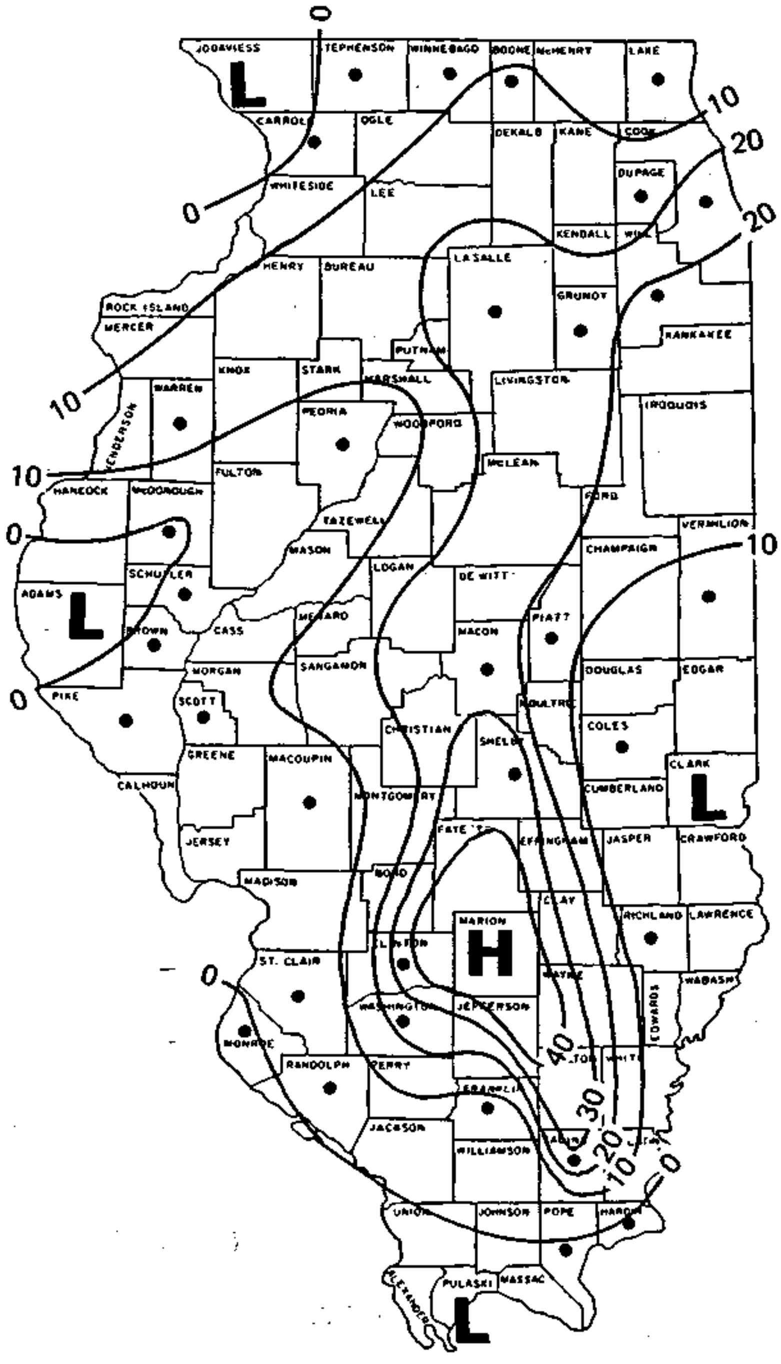

Figure 19. Contrail frequency, percent of all observations, July 1981.

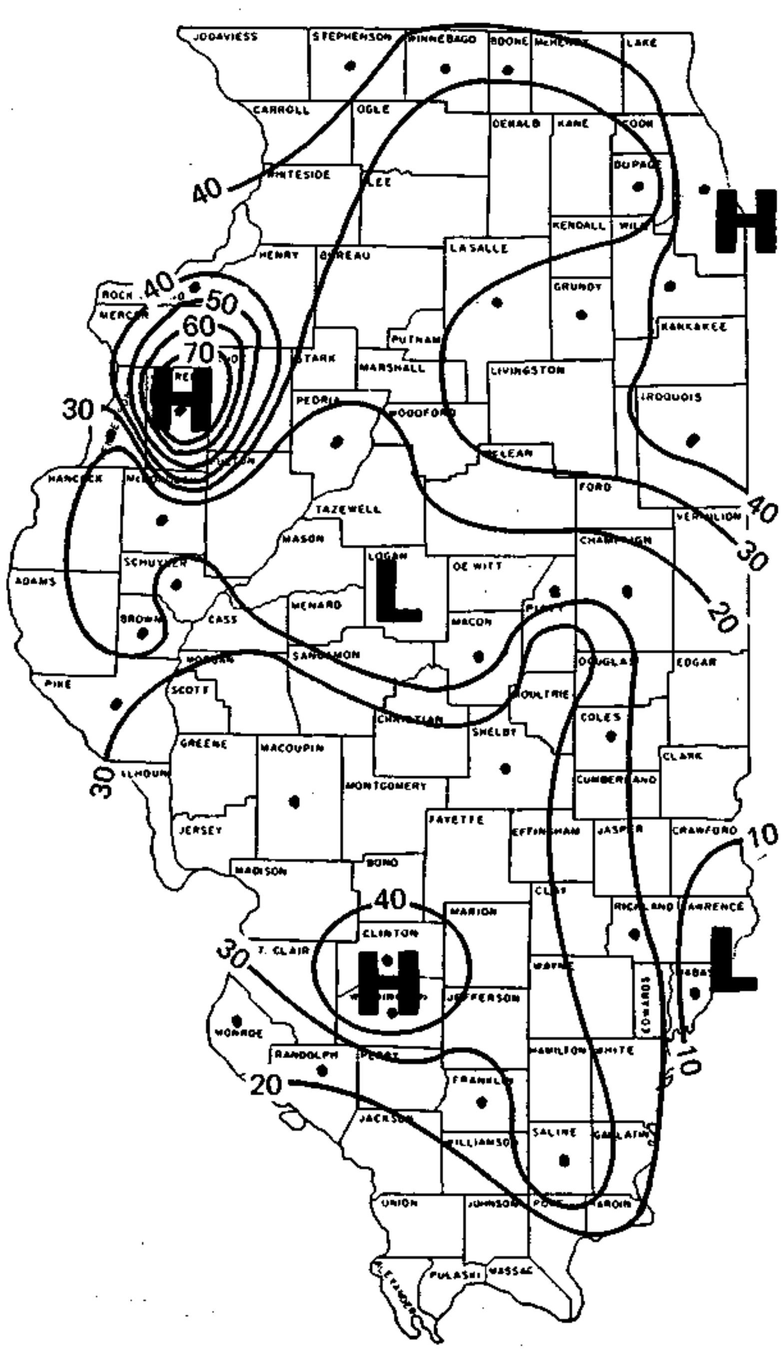

Figure 20. Contrail frequency, percent of all observations, October 1981.

of observations expressed as percent of non-cloudy observations, are greater than those expressed as a percent of total observations by between 10 to 30%. The difference in magnitude is as expected since the devisers in the non-cloudy calculations are necessarily equal to or less than the total number of observations.

During the months with data, contrails were observed between 10 and 90% of all observations, with the smallest percentages reported during summer. Contrails were reported in about 50 to 55% of non-cloudy days during December, January, April and October, whereas they were reported only in about 20% of the non-cloudy days during July. These values support the findings reported in the final report of our first year's grant (Changnon et al., 1980), based upon a subset of COMBAR data. The subset included about 300 observations per month randomly extracted from the total COMBAR data set which consisted of more than 15,000 observations. Between 40 and 50% of February, March and October COMBAR observations reported contrails whereas the remaining months reported between about 5 and 15% contrails.

Although the relatively higher percent reported for October in Changnon et al., (1980) was not duplicated in the present study, both data sets, those made up of the subset of COMBAR observations as well as the observations of the county extension agents were relatively small.

The patterns of contrail frequency vary considerably from month to month. Rather simple patterns were found in December 1980, July and October 1981 (Figs. 11, 14, 15, 16, 19 & 20) whereas those of January and April 1981 (Figs. 12, 13, 17 & 18) are discontinuous and complex. The simple patterns of Figs. 11 and 16 are in large part due to the relatively fewer observations.

During three of the months, northeastern Illinois exhibited relatively frequent contrails, and the most frequent area extend from the northeast to the south and southwest, not necessarily following the area expected to contain most jet traffic (an east-west band across northern Illinois). Surprisingly, the December and January distributions exhibit contrail minima over the Chicago region.

During two of the five months data, at least one observer appears to have overemphasized contrail frequency (Warren County in northwestern Illinois).

Spreading Characteristics of Contrails

The county observers were asked to indicate whether observed contrails were spreading as opposed to dissipating or remaining steady. The percent of contrails which were judged to be spreading are shown for each month in Figures 21 through 25. (Notice that the isolines are drawn for different increments on the various figures.) Although the central portions of southern Illinois exhibit a high frequency of spreading contrails during January, July and October, a similar pattern was not found during December and April. It is interesting to note that the Chicago area is always located within or near one of the areas indicating a high frequency of spreading contrails.

The percent frequency of spreading contrails (as opposed to those which dissipate) was highest during winter and summer months (December, January and July). The months exhibiting the greatest mean percent of spreading contrails were January (ca. 50%) and July (ca. 60%). The remaining months exhibited mean values of between 30 and 40%.

The frequency of persistent contrails was also calculated for each of the months from the more than 16,000 COMBAR observations gathered between the years 1957 and 1969. The frequencies are shown in Table 14. Persistent contrails are most frequent during the winter half-year with lesser frequencies during summer, although persistent contrails always represented at least 72% of all contrails. The months exhibiting the highest frequency of persistent contrails are January, February and April, whereas the months with the lowest frequencies were June, August and September.

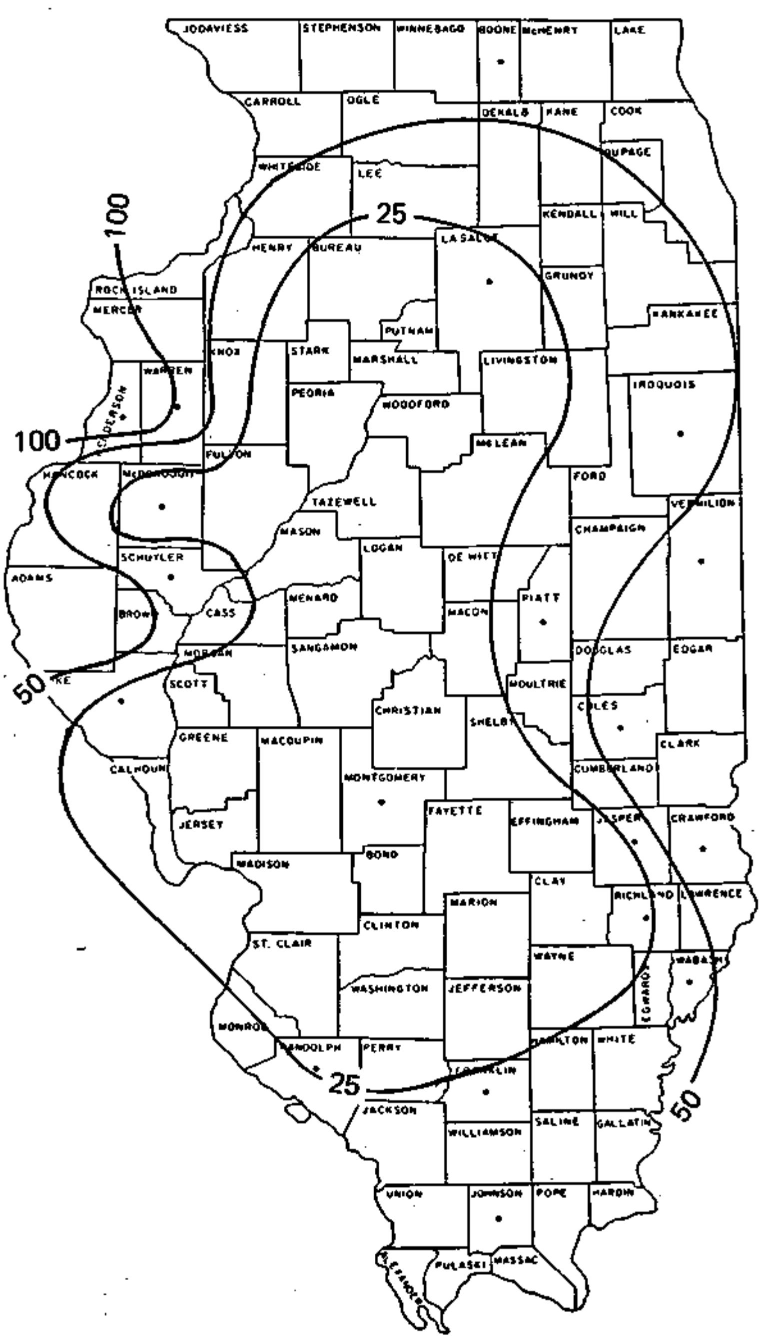

Figure 21. Percent of contrail observations with spreading characteristics, December 1980.

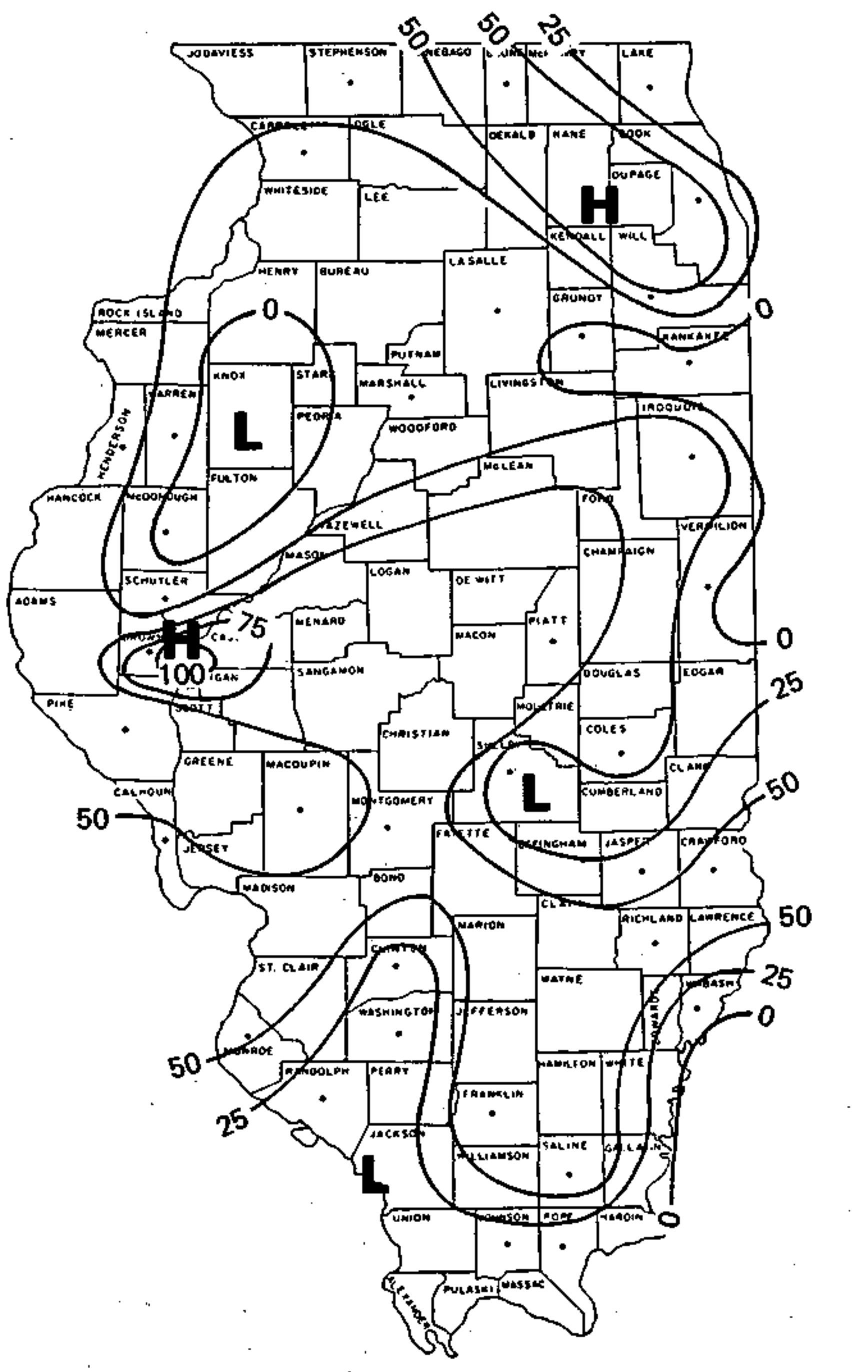

Figure 22. Percent of contrail observations with spreading characteristics, January 1981.

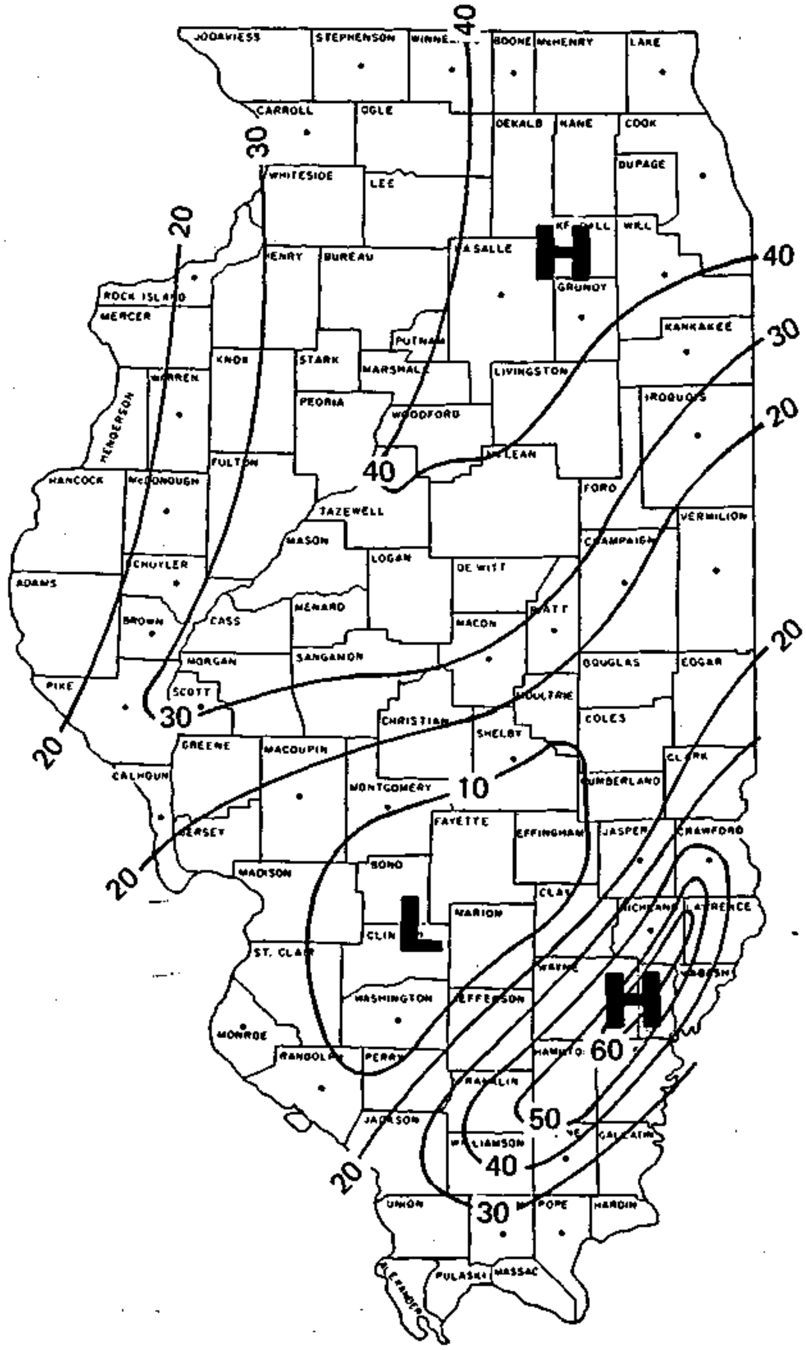

Figure 23. Percent of contrail observations with spreading characteristics, April 1981.

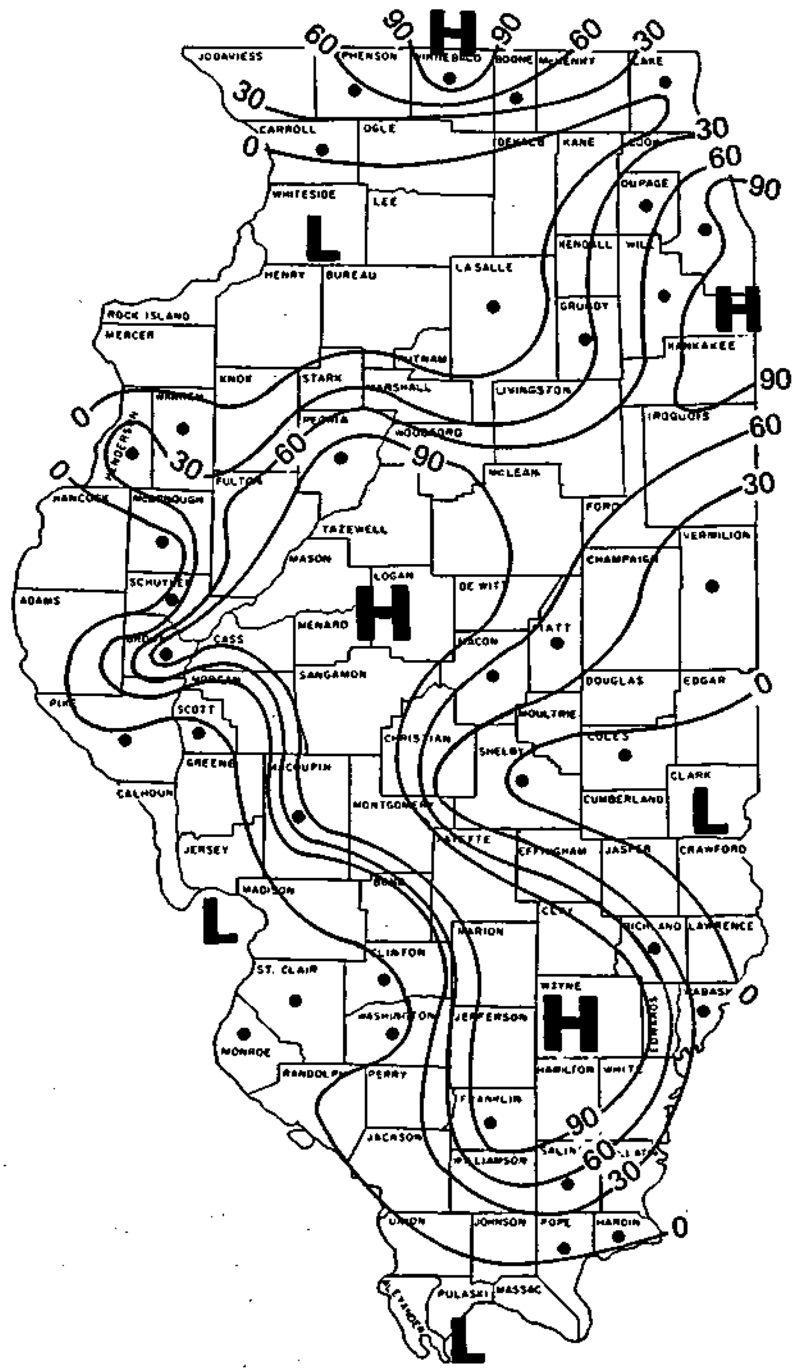

Figure 24. Percent of contrail observations with spreading characteristics, July 1981.

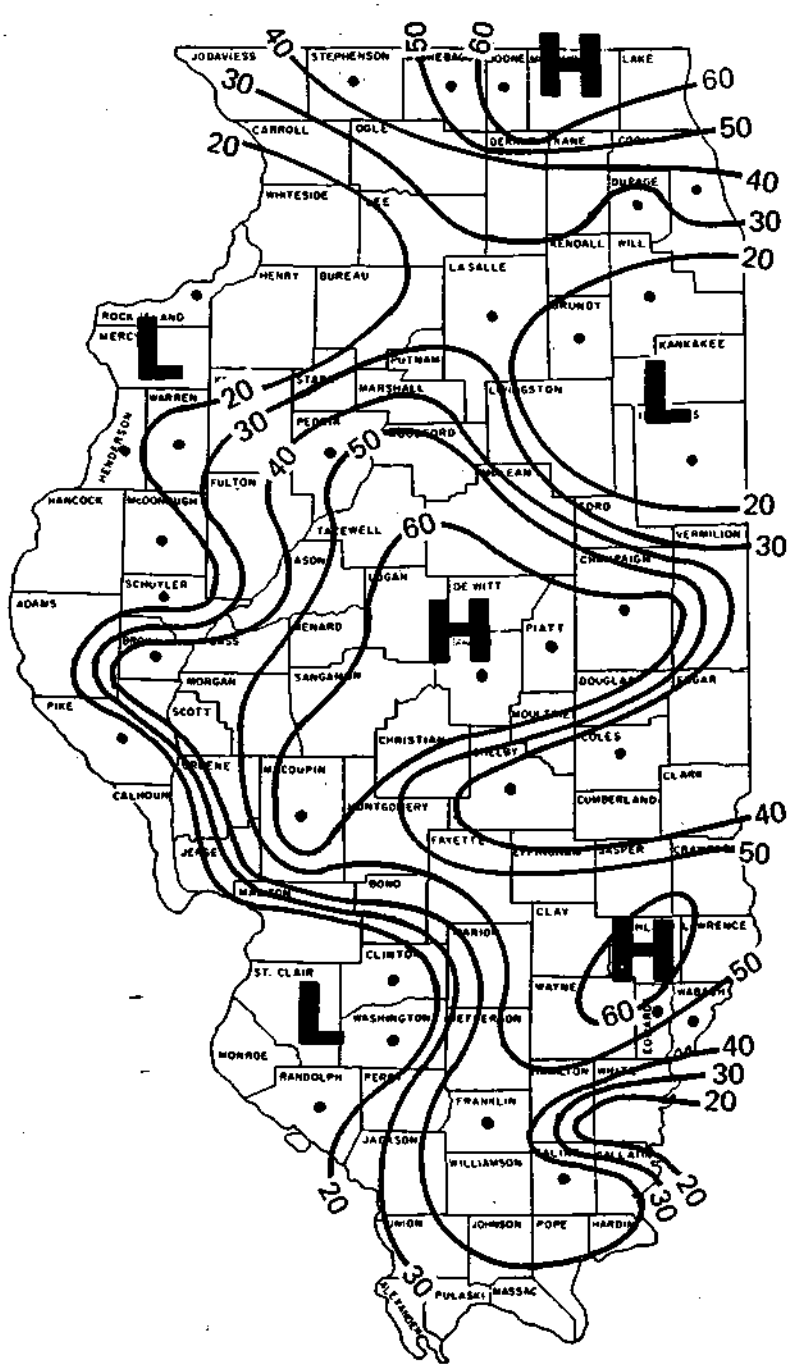

Figure 25. Percent of contrail observations with spreading characteristics, October 1981.

Table 14. Percent of Contrails Which were Judged Persistent By Pilots. Conclusions Drawn from More than 16,000 COMBAR Observations.

Month	Persistent Contrails (%)
Jan	87.7
Feb	90.2
Mar	80.0
Apr	85.1
May	78.4
June	76.0
July	79.8
Aug	75.4
Sep	72.1
Oct	80.3
Nov	81.9
Dec	80.4
Annual	80.6

Discussion

Estimation of contrail areas was attempted because of the importance of this parameter when considering the amount of solar radiation lost to the earth's surface by reflection and absorption, The NWS and COMBAR reports are unable to delineate these areas for reasons stated above. The cooperative network is a means with sufficient areal coverage, resolution and frequency to provide estimates of this important parameter. Our state network is probably too small in areal coverage, sine experience suggests that persistent contrails typically are seen over multi-state areas. Whether this is the rule is not known, but the development of a multi-state cooperative network could answer the question.

Although we recognize that the contrail areas observed by the Illinois network may severely underestimate actual conditions, they at least provide a lower boundary.

DISCUSSION AND CONCLUSIONS

We believe that the results of our first year's study (Phase I) presented a substantial body of evidence supporting a conclusion that cloudiness in general, and high cloudiness in particular, have increased over the last few decades, coinciding with the increase in jet traffic since about 1960. The increase in cloud cover was greatest in those areas of the Upper Midwest with the greatest jet traffic. In addition, the evidence gleaned more than 16,000 COMBAR observations enabled certain mean meteorological information to be obtained from pilot reports experiencing contrails and no contrails. In addition, we showed certain relationships between air temperature, turbulence, natural clouds, altitude, and conditions with and without contrails, during the months of the year.

The results presented in Phase I do not prove that jet aircraft and attendant contrail cirrus have impacted clouds and surface climate. However, coincident changes in trends of jet aircraft, frequency and the surface meteorological parameters in question strongly infer such a relationship.

In the second year of this study (Phase II), we have investigated the consequences of specific contrail cirrus on a few surface meteorological parameters, and attempted to define the areal extent of areas containing persistent contrails. From about 30 case study days, we identified days with clear skies other than isolated contrails over Champaign by means of an all-sky camera regularly photographing the sky at five minute intervals, and observed simultaneous changes to insolation intensity as well as rate of temperature change with time. As with the longer term (multi-decade) trends in cloud cover (learned from Phase I), changes to these variables were in the expected direction, and of reasonable magnitude, again supporting the original hypothesis.

In all cases, when a contrail obscured or partially obscured the direct solar beam, solar insolation was attenuated to some degree. The greatest percentage attenuation occurred at low solar angles, i.e., at times when the absolute magnitude of insolation is small relative to a daily total. The attenuation with sun angles greater than about 40 degrees was relatively constant, being 10% to 20%. The variable attenuation with solar angles was probably dependent upon contrail thickness, density and horizontal extent.

Coincident with the observation of attenuated insolation due to the contrail passage, the rate of temperature increase (decrease) prior (after) to the time of daily maximum temperature was determined. In the mean, the observed change was in the expected direction, i.e., during morning or early afternoon, solar attenuation due to a contrail was associated with a decrease in the rate with which surface temperature was increasing (relative to the time prior to contrail occultation). The average length of time (from ca. 30 cases) that a contrail attenuated insolation at a point was 45 minutes. For that tenure, the "normal" rate of temperature increase (prior to contrail occultation) would be decreased by about 1.6 F (0.9 C).

Our attempt to define areas with persistent contrails by means of the COMBAR reports was not productive. Even with an excess of 16,000 observations, the density in both space and time of observations on any one day was too sparse to allow the demarcation of persistent contrail areas from those without contrails. In addition to.the limitation imposed by the relatively few observations from a specific area, altitude, and time, the fact that COMBAR observation locations were recorded in only whole degrees latitude and longitude permitted observations from as far as 60 nm separation to be combined as observations of a common point. In addition, COMBAR observations were usually systematically completed each hour of a flight, usually on the hour, with the result that consecutive observations were displaced from each other by several hundred nautical miles.

The use of agricultural extension agents or their representatives as cooperative observers to report contrail frequency and persistence is a viable new idea. Four months of experience with about 40 observers suggests that once an individual committed him/herself to making observations, regular twice-daily observations are seldom missed. Further, statewide patterns of cloud cover, either determined from NWS daylight hourly reports or from our cooperative network were essentially congruent, although the magnitudes of mean cloud cover were different resulting from different observation techniques. In spite of the fact that quality observers participated in the program, we were limited in conclusion since observers from only 40 counties in Illinois contributed. Certain areas of Illinois were not well represented in our network' (particularly the central and northwestern parts of the state) ; and persistent contrail areas are not necessarily limited to one state. Indeed, from synoptic considerations, one would expect persistent contrail areas to be multi-state in scope. We suggest that the use of a cooperative network of observers, separated from each other by about 50 km, from several contiguous states, would provide a quality data base from which to estimate areas of persistent contrails on any given day, and provide that information at a reasonable cost.

Our attempt to identify contrail presence within the normal observation format of NWS/FOS proved fruitless. Contrail areas were first identified from the COMBAR observations, after which surface FOSs were sought to determine if the contrails were incorporated in the cloud observations. From the several tens of cases which we studied, there was no evidence to suggest that either contrail or cloud observations from a COMBAR-reported contrail area, were reflected in the cloud observations of a nearby NWS station. In fact, even the presence of middle or low clouds reported on COMBAR reports were not necessarily reflected in nearby surface observations. This deficiency is at least in part due to the poor resolution of our COMBAR observation. records (± 60 nm and ± 1 hr), relative to each other and to their precise location.

Because of the difficulty in establishing a relationship between COMBAR contrail observations and high cloud observations made at a nearby NWS station at any given time, we were unable to reconstruct the probable influence of contrails on NWS cloud cover observations, other than suggest that long term trends of high cloud cover appear to be reflected in the NWS observations (presented in Phase I).

To estimate the effect of contrails on the areal energy budget, several parameters must be specified, namely the momentary attenuation by one contrail areal coverage of one contrail, the average density of contrails within a "persistent area" and the total area containing persistent contrails as well as "natural" cloud cover, and insolation at the top of the atmosphere. Each of these parameters can be obtained by either calculation or observation, and are currently available except for the size of the area containing persistent contrails. This parameter could be obtained from a multi-state cooperative observer network (a system which we recommend) or a jet aircraft on call to be used to fly the periphery of several areas to accumulate a data base.

The following statements are given to simply present the major conclusions from this phase (Phase II) of our contrail research program.

1. Visual observations from Champaign exhibit greater contrail frequencies from January through April (50 to 67% of all observations), with decreasing frequencies during the remainder of the year (about 14% to 33%).

2. All-sky camera observations yield the same trends, although the magnitudes are in all cases less. This is apparently due to limitations in viewing 16 mm format images of the silvered hemisphere, e.g., limitation due to distortion and haze near the horizon.

3. Film images from the all-sky camera suggest that slightly more than half (55%) of all contrails sighted were expanding, whereas 45% are either nonspreading or contracting.

4. Film images from the all-sky camera from Champaign exhibited only . one contrail per frame in 50% of all the frames studied, 21% contained two contrails and interestingly, 29% contained three or more contrails. If more than one contrail was present, three or more were favored.

5. Growth/decay rates, i.e., lateral change of contrails, were greatest in winter (7 km/hr) and least during the warmer half-year (4 km/hr), with the former being about twice the rate of the latter. Growth and decay rates during intermediate seasons averaged about 6 km/hr.

6. Contrails were more persistent from April through October (17.7 minutes), whereas those from November through March exhibited a mean persistence of 13.1 minutes, noted from the all-sky camera observations.

7. All-sky camera observations suggest a mean contrail length of about 105 km (somewhat shorter during summer), and a mean width of about 8.5 km, again narrower during the warmer half-year (4 to 7 km), with the maximum found in January (12 km).

8. The mean duration of contrails sighted from one location identified by the all-sky camera was 45 minutes (standard deviation of 34 minutes).

9. Of all the contrails studied on the all-sky camera film, 39% were lost from view by advection, 25% dissipated within the field of view, and 23% were lost from view by apparent mixing with natural clouds. The remainder (14%) were lost from view by darkness or by passing between the camera and the sun.

10. With one contrail passing between the sun and the ISWS actinometer, the mean depletion of insolation was 17 ly/min (about 23% of the global radiation). No relationship was found between per minute attenuated insolation and duration of contrail occultation.

11. Insolation attenuation by contrail occultation was related to solar angle. With the sun greater than about 40 from the horizon, insolation

attenuation was always less than 20%, with a mean between 5% and 10%. With sun angles less than about 40 , attenuation was found to be as great as 65%, although the absolute magnitude of attenuation was small and relatively insignificant to the daily sum.

12. When a contrail attenuated part of the solar beam for at least several minutes, we found that surface temperatures responded. From observations prior to the time of daily maximum temperature, the normal (with no contrails or clouds) rate of temperature rise in the morning was decreased by about 2.1 F/hr (1.2 C/hr). Assuming a mean residence time of 45 minutes for contrail tenure, the normal morning temperature rise was decreased by 1.6 F (0.9 C). Clearly, these changes to the normal temperature change rate should not be expected to hold for extended periods of time. Between 60 and 70% of all cases supported the above mean conditions.

13. Relative humidity was modified in a similar fashion to that reported for temperature above. This is not unexpected because of relative humidity's dependence on temperature when absolute humidity is near-constant.

14. Cloudy days tend to follow contrail (but no natural cloud) days about 5 times more frequently than clear days follow contrail days. In addition, contrail days tend to follow cloudy days about 3 times more often than do clear days follow cloudy days.

15. When looking at various sequences of cloudy, contrail and clear days, we found that contrail days were more often preceded or succeeded by cloudy days than by clear.

16. Areas with persistent contrails are of synoptic scale and are associated with upper air troughs and cyclones, as opposed to ridges and anticyclones. Our attempts to delineate persistent contrail regions from areas without contrails by means of COMBAR reports or NWS/FOS cloud observations were fruitless.

17. Our network of cooperative observers proved to be an effective mechanism to obtain relatively frequent, and quality observations of contrail frequency. That the observers were restricted to Illinois limited the potential for delineating persistent contrail areas from those areas without contrails, except on an in-state scale. Observations from this network showed that contrails were most frequent during the winter half-year (50 to 55%) and less frequent in summer (ca. 20%).

18. According to the cooperative network, spreading contrails exhibited the greatest frequency in January (50% of all contrails) and July (60% of all contrails). The remaining months exhibited frequencies between 30 and 40%.

FUTURE RESEARCH

Mean frequency, persistence, length and width, altitude dominant locations, and relationships between contrail occurrence and air temperature and turbulence, have been determined from (1) more than 16,000 COMBAR pilot reports between 1957 and 1969, (2) more than 12,000 observations made by Illinois Agricultural Extension agents or their representatives, (3) several hundred days of sky conditions measured by an all-sky camera at five-minute intervals over Champaign, and (4) several tens of NWS-FOS observations of cloud cover. Depletion of global solar radiation and change to the normal (without natural cloud cover) diurnal march of temperature and relative humidity were measured from several tens of case studies at Champaign. Because of the large size of the sample population, particularly of COMBAR observations, the findings based on that sample are probably stable. However, (1) we recommend that the impact of contrails on global radiation and temperature trends at a point should be assessed from a larger data sample, using precision pyranometers and pyrheliometers. In this way, changes to the direct, diffuse and total fluxes could be assessed under different solar angles and contrail densities, thickness etc.

Although observations from a data sample as stated above permit some estimate to be made of solar depletion at a point due to contrail occultation, the total radiation loss to an area experiencing many and persistent contrails cannot be estimated until the size of the area containing those contrails is known. The observations presented above, made by county extension agents and their representatives, are a first step toward the solution of this problem, however only areas within Illinois have been thus far measured. (2) We strongly support the initiation of a Ground Observer Corps from an area of several contiguous states to follow essentially the same observing procedure as that used by the Illinois observers to establish the mean (and variation) area of persistent contrails on given days.

The effect of contrails and natural cirrus on the radiation budget has been examined in a few instances by instrumented aircraft. (3) We suggest that a jet aircraft be used for a short, but intense, period to observe changes to the long- and short-wave radiation budgets above, in, and below contrails cirrus. We propose measuring both upward and downward components of the short- and long-wave budgets. In addition, net radiation should be measured with a flux plate radiometer, similar to the instrument used on a turbo prop aircraft to altitudes of about 9km (Peterson, 1968). In particular, the infrared (IR) characteristics of contrail cirrus, e.g., specification of emissivity and IR reflectivity could be measured as a function of contrail thickness, ice crystal size distribution, and density. The transmission, absorption and reflection of energy by contrails cirrus is yet unspecified because there are conflicting suggestions as to whether the earth's surface is warmed or cooled by the presence of contrail cirrus. For example, Cox (1971) found surface cooling in middle and high latitudes. The observations were corroborated by the modeling of Roe and Liou (1978), who found that in mid-latitudes atmospheric cooling would be reduced by about 60% with thick cirrus. However, Stephens and Webster (1981) suggest that even thin cirrus result in surface warming at any latitude. Observations of the short-, long-, and net-radiation could provide additional information as to the transmissivity of cirrus under different thickness and moisture conditions (relative to the work reported in Kuhn and Weickmann, 1969).

Although total flight time with an instrumented jet aircraft would probably be restricted to only a few weeks, the aircraft's range and speed would permit sampling a relatively large number of cases, and would give further ability to independently assess the area within which contrails are relatively frequent and persistent on given days. Again, areal measurements of persistent contrail regions is necessary before the impact of contrail cirrus on an areal heat budget can be estimated.

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The contribution of the cooperative observers, including county agricultural extension agents, and other private citizens, has provided an avenue which will likely provide an inexpensive and convenient method to measure the areal extent of persistent contrails in the future. Their twice daily observations made this study possible, and we are indebted to their diligence and commitment.

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REFERENCES

Beckwith, W. B., 1972. Personal notes and flight records. Unpubl.

Changnon, S. A., R. G. Semonin and W. M. Wendland, 1980. "Effect of contrail cirrus on surface weather conditions in the Midwest - Phase I." Final report to NSF Grant #NSF ATM 78-09568, Illinois State Water Survey, Champaign. 141 p.

Cox, S. K., 1971: Cirrus clouds and the climate. J. Atmos. Sci., 28: 1513-1515.

Cox, S. K., 1976: Observations of cloud infrared effective emissivity. J. Atmos. Sci., 33:287-289.

Derr, V. E., 1980: "Attenuation of solar energy by high, thin clouds." Atmos. Envir., 14:719-729.

Griffith, K. T., S. K. Cox and R. G. Knollenberg, 1980:. "Infrared radiative properties of tropical cirrus clouds inferred from aircraft measurements," J. Atmos. Sci., 37:1077:1087.

Joint Organizing Committee, GARP, 1978: Report of the JOC Study Conference on parameterization of extended cloudiness and radiation for climate modesl. WMO, Geneva.

Kuhn, P. M. and H. K. Weickmann, 1969: High altitude radiometric measurements of cirrus. J. Appl. Meteor., 8:147-154.

Paltridge, G. W. and C M . R. Platt, 1981: "Aircraft measurement of solar and infrared radiation and the microphysics of cirrus clouds." Quar. J. Roy. Met. Soc. , 107:367-380.

Peterson, J. T., 1968: "Measurement of atmospheric aerosols and infrared radiation over Northwest India and their relationship. Tech. Rep. 38, ONR Contract 1202(07) and NSF Grant GP-5572X. Dept. of Meteor., Univ. of Wisconsin. Madison. 165 p.

Platt, C. M. R., 1973: Lidar and radiometric observations of cirrus clouds. J. Atmos. Sci., 30:1191-1204.

Platt, C. M. R. and A. C. Dilley, 1979: "Remote sounding of high clouds: II Emissivity of cirrostratus." J. Appl. Meteor., 18:1144-1150.

Roewe, D. and K-N. Liou, 1978: Influence of cirrus clouds on the infrared cooling rate in the troposphere and lower stratosphere. J. Appl. Meteor. 17:92-106.

Stephens, G. L., 1980: "Radiative properties of cirrus clouds in the infrared region." J. Atmos. Sci., 37:435-446.

Stephens, G. L. and P. J. Webster, 1981: Clouds and climate: Sensitivity of simple systems. J. Atmos. Sci. , 38:235-247.