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Cloud Cover Statistics

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Cloud height data has been collected for 4 years over the CONUS and one year globally using the multi-spectral infrared senors GOES/VAS and NOAA/HIRS. The analysis technique distinguished partially transmissive cirrus from other cloud forms. Cirrus were commonly found from 13 to 40% of the time over the CONUS. Seasonal and diurnal variations were small over the CONUS. More significant seasonal variations were found over the oceans from the movement of the subtropical high pressure systems and cyclonic storms and fronts in high latitudes. One half of the cirrus was associated with radar echoes in the summer while the other half was not. In winter only 22% of the cirrus were associated with radar echoes because of the lack of echo activity. Cirrus were slightly more numerous in winter than in summer. One half of the cirrus detected over the CONUS in January also was associated with jet streams. In summer this reduced to 10 to 30 % because of weaker upper air winds.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Cloud cover statistics are being collected at the Space Science and Engineering Center of the University of Wisconsin-Madison using two satellite systems: 1) the geostationary GOES/VAS over the CONUS, and 2) the NOAA/HIRS for global coverage. CONUS data have been collected for 4 years. Geographical, annual, seasonal and diurnal variations in cloud cover over the CONUS from these data are discussed in Section 2. The relationship between some atmospheric dynamical features and cirrus clouds is also discussed in order to identify causes of cirrus cloud formation and dissipation. Satellite derived cloud observations also were compared to the conventional ground based observations to show the differences in cloud statistics obtained from different data sources. Spatial probability statistics derived from satellite cloud observations are discussed in Section 3. These statistics show the size scales of cloud systems and cloud free regions. Global cloud statistics from the NOAA/HIRS satellites are discussed in Section 4.

2. SEASONAL AND DIURNAL CHANGES IN CONUS CLOUDS AS SEEN IN FOUR YEARS OF OBSERVATIONS WITH THE VAS

(Co-Authors of this section are W. P. Menzel, NOAA/NESDIS Advanced Satellite Products Project, Madison, Wisconsin, and K. I. Strabala, University of Wisconsin Space Science and Engineering Center.)

2.1. Detection Algorithm

Clouds are actively involved in modulating the radiation budget in the earth's climate system. Variations in the amplitude and phase of the seasonal and diurnal cycles of the outgoing longwave radiation can be physically interpreted as variations in the surface temperature and cloudiness (Short and Wallace, 1980). Past estimates of the variation of the earth's outgoing longwave radiation or clouds have been derived primarily from the longwave infrared window (10-12 microns) radiances as observed from polar orbiting and geostationary satellites.

In this study, multispectral VAS (VISSR Atmospheric Sounder) observations in the carbon dioxide absorption band at 15 microns have been used to calculate cloud statistics over the Continental United States (CONUS) for the past four years. The CO_2 algorithm calculates both cloud top pressure and emissivity from radiative transfer principles. Transmissive clouds that are partially transparent to terrestrial radiation have been reliably separated from opaque clouds in the statistics of cloud cover (Wylie and Menzel, 1989).

Various CO_2 algorithms have been described in the literature (Chahine, 1974; Smith et al., 1974; Smith and Platt, 1978; Menzel et al., 1983) and applications to data from the geostationary sounder VAS (VISSR Atmospheric Sounder) and the polar orbiting sounder HIRS (High resolution Infrared Sounder) have been published (Wylie and Menzel, 1989; Menzel et al., 1986; Susskind, 1987; Eyre and Menzel, 1989). The investigation of seasonal and diurnal changes in the cloud cover over North America with four years of data from the VAS is here reported on. In addition, the satellite observations of cloud cover are compared with ground observations for several seasons. The technique description and its application to the VAS radiances is available in Wylie and Menzel (1989).

In the study of Wylie and Menzel (1989), the CO_2 cloud heights derived from VAS data were found to be of good quality when compared to three other independent sources of cloud height information. (a) For about thirty different clouds, the CO_2 heights were within 40 mb rms of radiosonde moisture profiles. (b) In 100 comparisons with lidar scans of clouds, the CO_2 heights were 70 mb lower on the average and were within 80 mb rms. (c) Satellite stereo parallax measurements in 100 clouds compared to within 40 mb rms. The CO_2 heights appear to be good to 50 mb and the effective emissivities to .20 in most cloud types (broken clouds and stratocumulus at low levels remain elusive). VAS cloud parameter determinations reveal reasonably good agreement with the manual weather observations of Warren et al. (1986) and Hahn et al. (1982).

2.2. Mean Statistics

A statistical summary of all the cloud observations made from October 1985 through February 1990 is shown in Table 1. This covers the area from 27 to 51 N latitude and 60 to 140 W longitude. Over 15 million observations were processed. The cloud top pressure determinations were subdivided into ten vertical levels from 100 mb to 1000 mb in each row of Table 1. High clouds above 400 mb comprised 26% of the observations. 19% of the observations were of clouds between 400 mb and 700 mb. Low clouds below 700 mb were found 24% of the time. Clear sky conditions, labelled as 1000 mb, were found 31% of the time.

The values appearing in the right column of Table 1 are particularly interesting because the vertical resolution is not otherwise available for such a large cloud data base. However, these values are not the probabilities of clouds within each 100 mb interval. Rather, they are conditional probabilities of opaque cloud tops within each 100 mb interval; the condition being that no clouds occur in any interval above. For example, the right column indicates that the likelihood of finding opaque cloud tops over the CONUS within the interval 600 -699 mb with no opaque cloud above that level is 10%.

Table 1: VAS Determinations of Cloud Statistics for the United States 27 to 51 N and 50 to 140 W for Oct 1985 through Feb 1990

	Effective Emissivity				
	.00-.25	.26-.50	.51-.75	.76-.94	.95-1.0
Level (mb)					
100-199	0%	0%	0%	0%	1%
200-299	2	3	2	4	2
300-399	1	3	3	3	2
400-499	0	1	2	2	1
500-599	0	0	0	0	3
600-699	0	0	0	0	10
700-799	0	0	0	0	11
800-899	0	0	0	0	9
900-999	0	0	0	0	4
1000 (clear)	31	0	0	0	0
	34%	7%	7%	9%	43%

The effective cloud emissivities were subdivided into five intervals shown in each column of Table 1. *The right column contains the opaque or near opaque cloud observations.* Effective emissivity observations greater than 0.95 are considered to be opaque clouds, since the cloud top height derived from the CO2 technique is very close to the height derived from the window channel by itself. The other four columns separate the cloud height reports by effective emissivities ranging from the thin low emissivity clouds on the left to the thick high emissivity clouds on the right. Most clouds below 700 mb were determined from the infrared window channel and thus were assumed to have an effective emissivity of one. This precludes the interpretation of low broken cloud as cirrus.

Cirrus clouds are defined as observations with effective emissivities less than 0.95. 26% of our observations fell into this category ranging from 100 to 500 mb. Clouds opaque to infrared radiation with effective emissivities greater than 0.95 (right column) were found 43% of the time. The remaining clear sky observations, noted as 1000 mb, were found 31% of the time. Thus, 69% of our satellite observations over North America for the past four years found clouds. These four year results are very similar to the two year statistics reported in Wylie and Menzel (1989).

2.3. Geographical Coverage and Seasonal Changes

The seasonal and geographical distribution of VAS observations for four years is summarized in Figure 1. Four winter and summer seasons were included in these data. The winters covered December through February of 1985-86, 1987-88, 1988-89, and 1989-90. No data were taken in the winter of 1986-87 because VAS operations were restricted for a reconfiguration of the data transmission system. The summers covered June through August 1986, 1987, 1988, and 1989. Cloud cover was divided into two types: (a) clouds opaque to terrestrial radiation with effective emissivities greater than 0.95, and (b) semi-transparent cirrus with effective emissivities less than 0.95. All VAS observations were classified as opaque cloud, cirrus, or clear sky.

The four year summary shown in Figure 1 has not changed substantially from the two year summary presented in Wylie and Menzel (1989). Some small regional features appear due to finer contour intervals (10% probability instead of the previous 20%). Similar winter to summer seasonal changes in the locations of cloud cover minima (top panels) and clear sky maxima (bottom panels) can be found in both the two and four year studies. The migration of the sun belt from Arizona, New Mexico, and Texas in the winter (lower left panel) to southern California and southern Nevada in the summer (lower right panel) is again apparent.

The probability of clear sky (lower panels) again shows the same general trends as the probability of opaque (upper panels) between the seasons. As reported in the two year study, cirrus clouds (middle panels) exhibit very small geographical and seasonal variances over the continental United States. They are found 20 to 40% of the time.

One difference between the two and four year studies is noteworthy. An opaque cloud minima is found in Montana extending down into Wyoming and Colorado (upper right panel), which appeared after the extreme drought of summer 1988.

The effects of the mountain ranges are apparent, especially in the summer months. A local minimum in clear sky occurs along the Rocky and Appalachian mountains in the summer

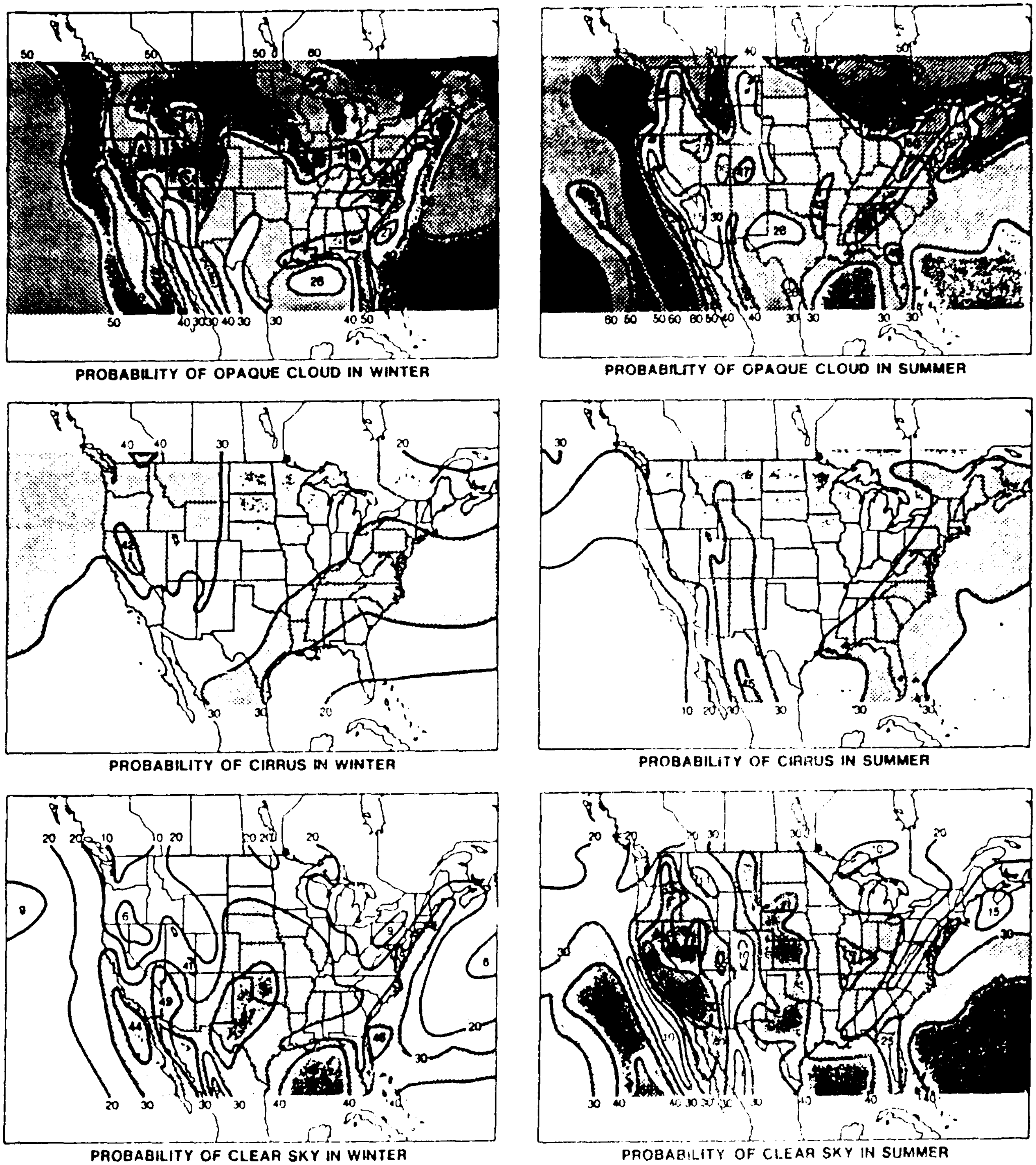

Figure 1: The probability of VAS cloud observations being opaque cloud, semi-transparent cirrus, or clear sky in summer (June-August) or winter (December-February) based on four years of data.

(lower right panel). These mountain ranges are also evident as the summer cirrus maxima (middle right panel). The Ozark mountains are revealed in a small opaque cloud maxima in western Missouri in the summer (upper left panel). Cloud cover maxima in the winter were found in Washington and Oregon corresponding to the coastal mountains (upper left panel).

Along the ocean coasts several seasonal changes are noticeable. The increase of cloud cover off the west coast (top panels) occurs as the marine stratus clouds become predominant in the summer. Also a considerable decrea:e in cirrus is noted over the eastern Pacific Ocean in the summer months. A minimum in cloud cover along the east coast appears in the winter (upper left panel) and disappears in the summer (upper right panel).

Several local features are now apparent because of the finer contour interval. Small opaque cloud maxima are now apparent over Lake Michigan in the winter (upper left panel). The Florida peninsula is noticeable for the local cloud maxima in both seasons (upper panels) as well as the clear sky minima in both seasons (lower panels). The northern Rocky mountains in Idaho and Montana show more detail in both seasor :.

2.4. Diurnal Changes

The average diurnal changes in VAS determinations of cloud cover from the CO_2 technique are found in Table 2. In the winter, clear skies peaked at 18 UT as opaque cloud dropped to a minimum. Cirrus cloud cover showed very little diurnal variation. In the summer, clear skies were at a minimum between 18 UT and 00 UT as clouds reached a maximum associate' with afternoon convection. Opaque clouds showed a modest peak at 18 UT followed by a maximum for cirrus at 00 UT. Similar trends were noted by Menzel et al. (1989) in the Amazon Basin.

Table 2: VAS Determinations of Winter to Summer Seasonal Changes in Diurnal Cloud Cover for 27-51 N, 60-140 W

	Winter Time (UT)				Summer Time (UT)			
	12	18	00	06	12	18	00	06
Percentage								
Cirrus clouds	26	26	28	27	23	25	28	25
Opaque clouds	46	40	46	46	38	43	39	36
Clear skies	28	35	26	27	39	32	32	38

Diurnal changes showed some moderate geographical preferences over the United States. Figure 2 shows the diurnal trends for summer cirrus, summer clouds (both cirrus and opaque), and winter clouds in six hourly intervals. The observations for all four time intervals have been averaged and the deviation from the average at each time is noted. Positive numbers indicate an increase with respect to the average. Semi-transparent cirrus had smaller changes on the average than opaque clouds; in the winter, cirrus changes were insignificant and are not shown in Figure 2. A few summer features are noteworthy. (a) Over the Rocky mountains, cirrus increases by as much as 20% between 18 and 00 UT due to convection in the mountains, spreading east into the plains by 06 UT as convective debris. (b) Over Florida and the Gulf coast, cirrus increases by 10 to 15% between 12 [illegible] 00 UT as convective cirrus develops in the moist Gulf airmass.

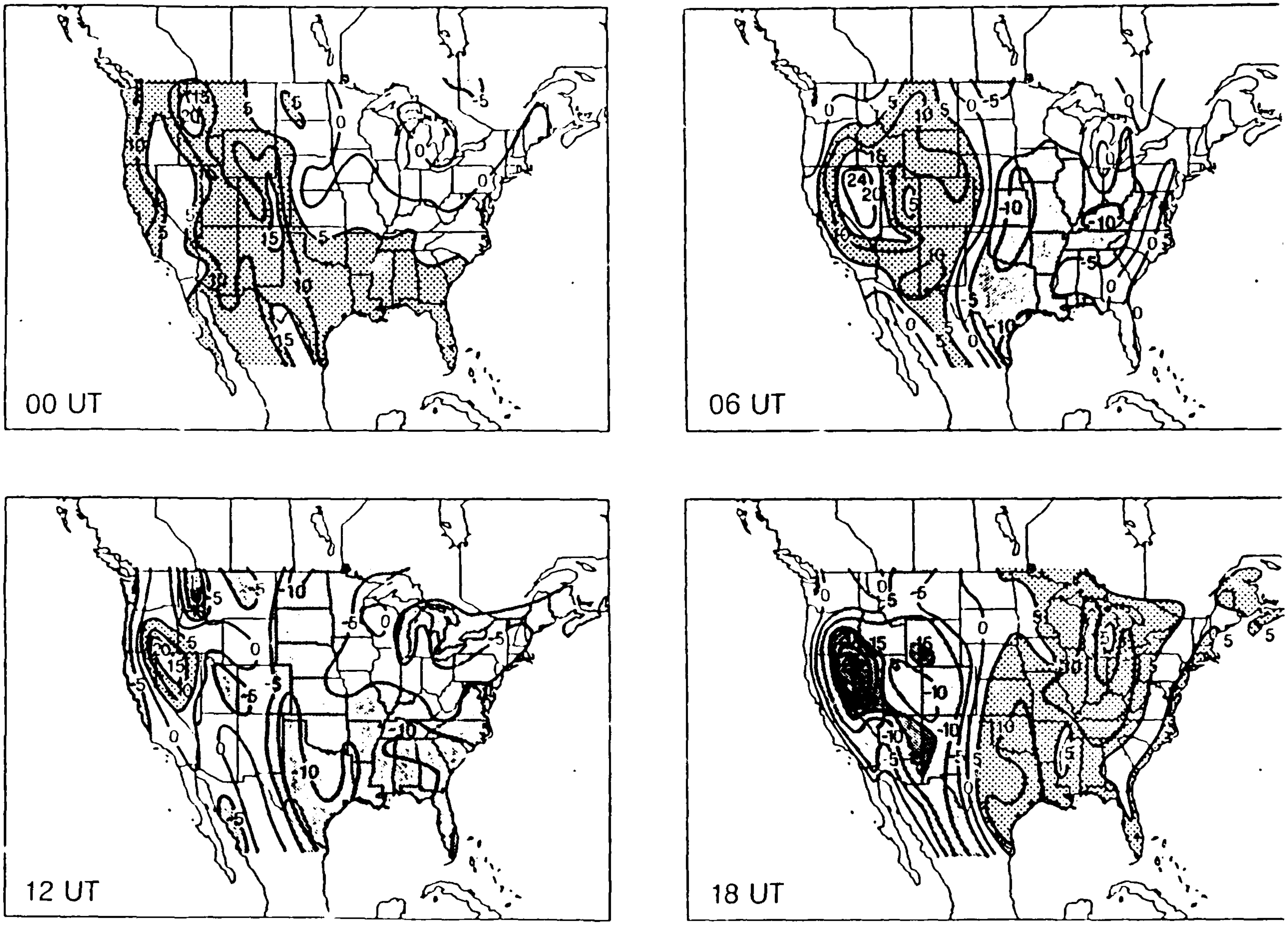

Figure 2 (a): The diurnal change in six hour intervals in total (opaque and cirrus) cloud observations over the United States during the summer months (June, July, and August) in 1986, 1987, and 1988.

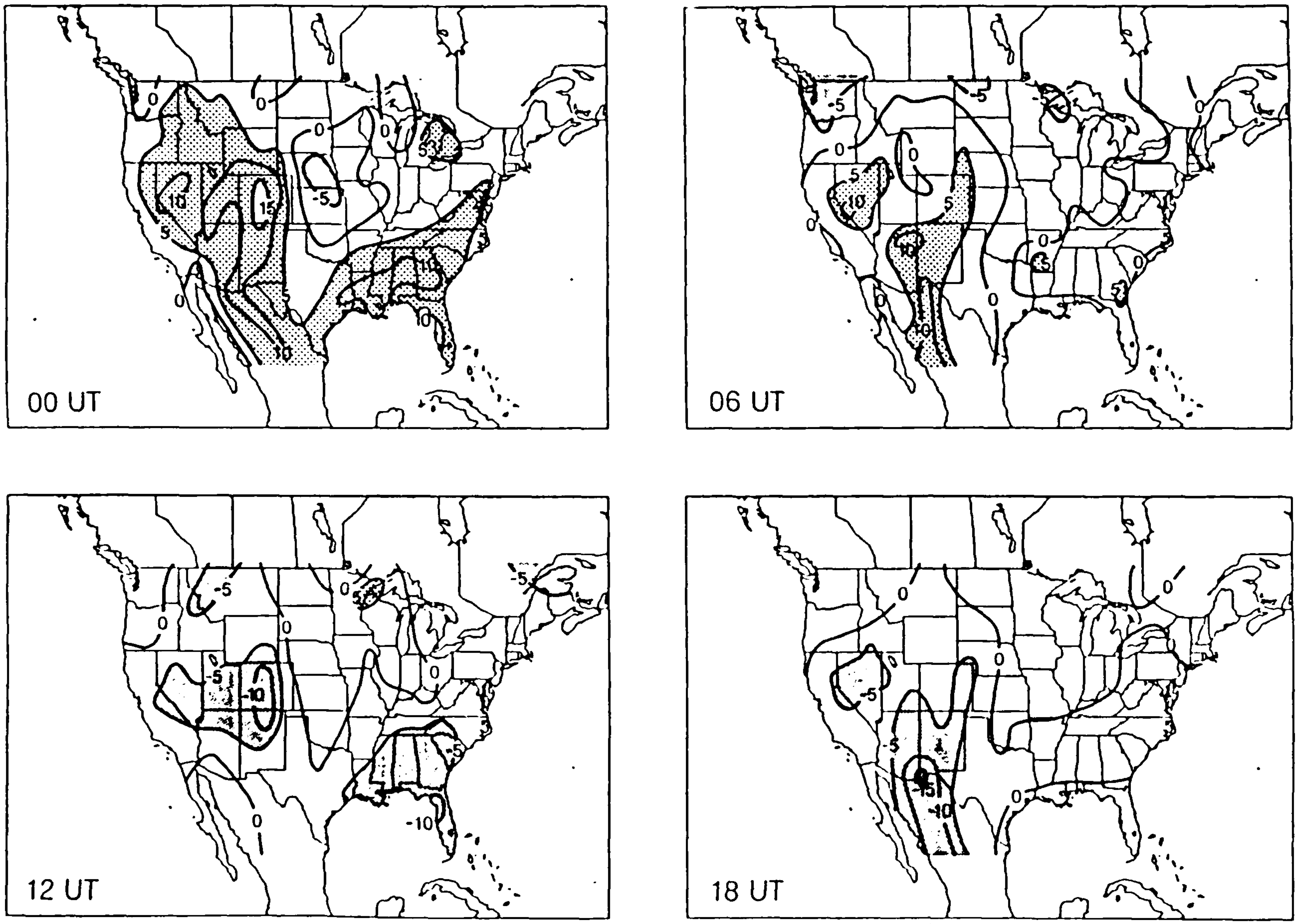

Figure 2 (b): The diurnal change in six hour intervals in cirrus (transmissive) cloud observations over the United States during the summer months (June, July, and August) in 1986, 1987, and 1988.

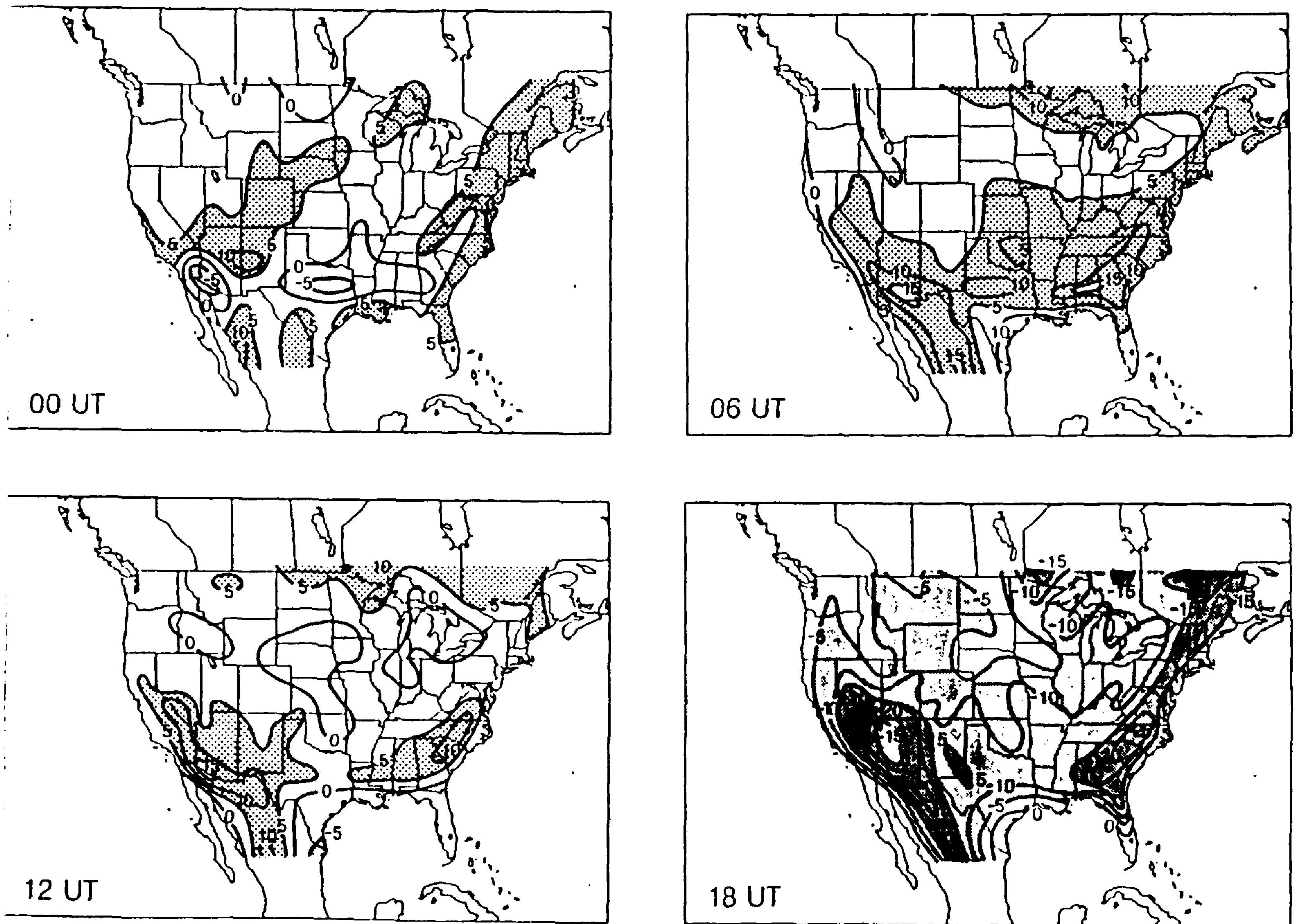

Figure 2 (c): The diurnal change in six hour intervals in total (opaque and cirrus) cloud observations over the United States during the winter months (December, January, and February) *in 1985-86, 1987-88, and 1988-89.*

(c) Over the eastern half of the United States, the cloud cover increases between 12 and 18 UT as daytime heating initiates cloud development. The winter features include (d) very little diurnal change in cirrus and (e) more cloud cover at 06 UT over the continental United States probably due to increased fog and low stratus at night.

2.5. Relationships with Atmospheric Dynamics

The locations of transmissive cirrus clouds were also compared to the locations of precipitating convection and jet streams, two atmospheric dynamical features that are commonly used to explain the existence of cirrus. The VAS data provide an opportunity to statistically quantify the relationship of cirrus to these weather phenomena.

To find out what portion of the cirrus are associated with convection, the VAS determinations of cirrus were compared with the radar summaries from the National Weather Service (NWS) which show the regions in which echoes were reported (see Figure 3). Radar summaries covering 60 days in the months of January 1988 (winter) and June 1986 (summer) were processed. The number of transmissive cirrus both in the area of the echoes and outside of this area were counted on each of the radar summaries. Allowances were made for the cirrus anvils to blow away from the radar echoes using the 300 mb wind analysis from the Nested Grid Model (NGM) of NOAA's National Meteorological Center (NMC). The echo area was extended 100 to 300 km in the downwind direction, depending on the strength of the 300 mb winds. It was also extended 50 km in the crosswind and upwind directions. The extended echo area defines the region in which all cirrus clouds observed by the satellite could be associated with precipitating convection. Those observations outside the extended echo region were considered to be separate from the precipitating convection. Figure 3 shows a radar summary for 4 June 1986; the bold lines define the area within which all VAS determinations of cirrus cloud were considered to be associated with precipitating convection over the CONUS.

In June 1988, 52% of the VAS cirrus reports were found inside the extended echo region. This region covered roughly 30% of the CONUS. In January 1988, only 22% were found in the extended echo region, which was much smaller and covered only 14% of the CONUS. Cirrus were just as numerous in January as June, but it appears that only one fifth of the cirrus were near or associated with precipitating convection in the winter compared to one half in the summer. Daily fluctuations in the extended echo region ranged from 20 to 60% of the CONUS, and as one would expect more cirrus were found on those days with larger echo areas. The correlation coefficient between the two was 0.42 in June 1988, indicating a marginally significant relationship.

Jet streams and cirrus clouds were studied for 245 days spanning the four seasons in 1986 through 1988. Table 3 summarizes the intercomparison. The study area was 24 to 50 N and 60 to 140 W. The jet stream was defined by the region where 300 mb winds exceeded a threshold level in the NGM analysis. In winter, the threshold was set at 35 m/s which covered 42 to 51% of the study area. In the spring months, April 1986 and 1988, slightly lower wind speeds were found and a lower threshold of 25 m/s was used. In the summer and fall months, July and October 1986-1988, winds varied radically from month to month. Winds over 25 m/s were nearly non-existent in some of these months, such as July 88 and October 86, where they only covered 5 to 8% of the CONUS on the average, while in other months, such as June 88 and October 1987, they covered

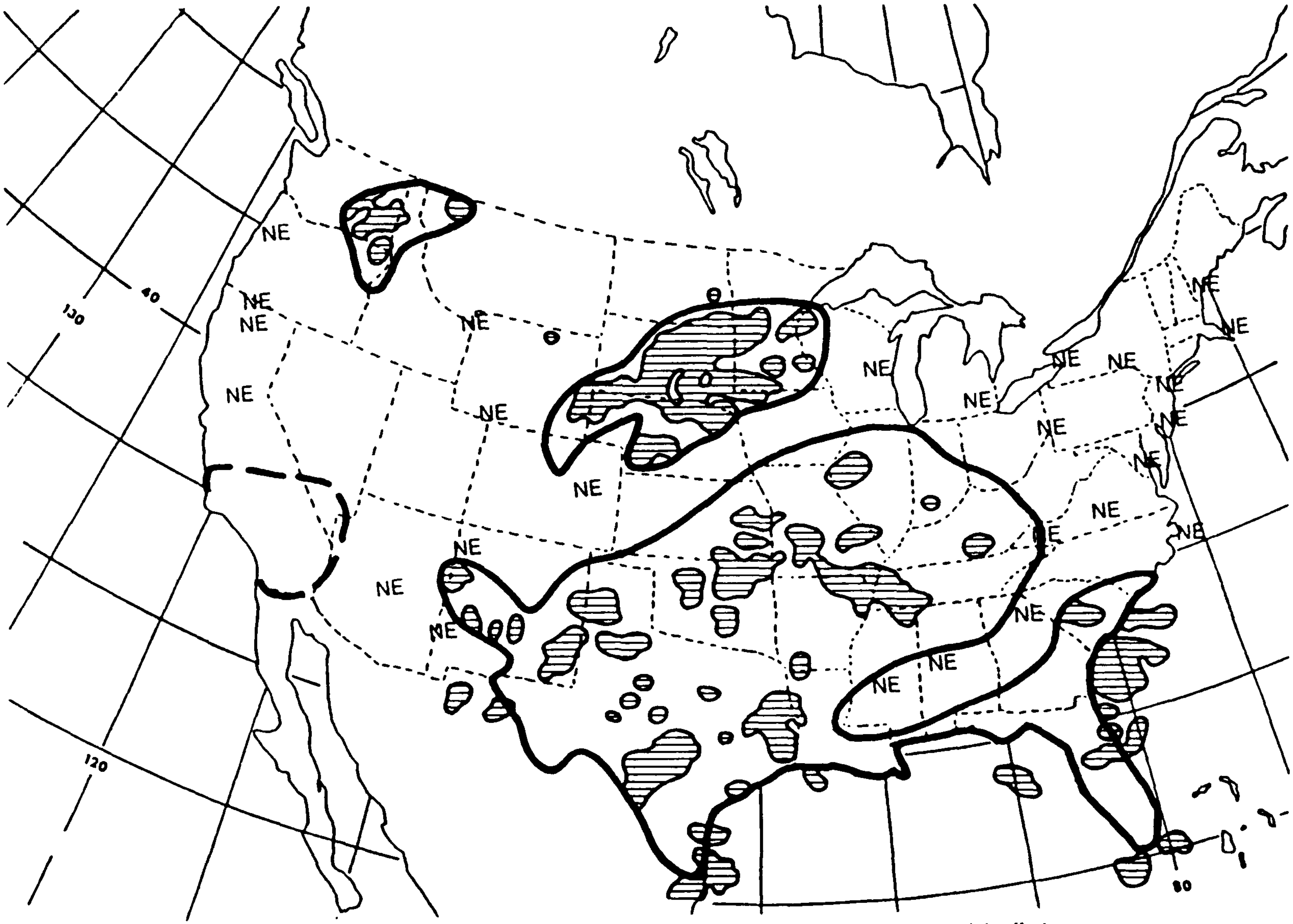

Figure 3: NWS radar summary for 4 June 1986. The bold line defines an area in which all cirrus cloud reports were considered to be associated with precipitating clouds.

23% to 48% of the area. These thresholds are based on the 50 and 70 knot contour shading that NMC applies to their upper air analyses to qualitatively define jet streams for forecasters.

Table 3: Fraction of Satellite Observed Cirrus within Jet Streams

Season	Fraction of CONUS under Jet	Fraction of Cirrus in Jet	Fraction of CONUS under Cirrus
Winter			
Jan-Feb 86	42%	40%	29%
Jan 88	51	60	28
Spring			
Apr 86	46	47	26
Apr 88	60	58	26
Summer			
Jul 86	13	13	26
Jul 87	15	14	25
Jun 88	23	29	23
Jul 88	8	12	25
Fall			
Oct 86	5	6	23
Oct 87	48	55	24

Cirrus occurred in nearly the same frequency during all months studied, regardless of the changes in wind speeds. It covered from 23 to 29% of the CONUS in all of these months whether the winds were low or high. The small seasonal variability is consistent with the results reported in section 3. In the months where the jet streams covered more than 40% of the CONUS, 40 to 60% of the cirrus were found inside the jets. During the months of low winds and smaller coverage over the CONUS, only 6 to 29% of the cirrus observations were in the jets. These statistics suggest that the percentage of cirrus within the jets is largely related to the size of the area of the jet and that cirrus occurs with equal probability over the CONUS. It appears that cirrus are generated and supported by weak dynamical features; definition of the jet stream alone does not pinpoint the location of cirrus.

Indirect circulations occur around the jet due to the ageostrophic component of the winds caused by acceleration and deceleration of air entering and exiting the jet core or region of highest winds (Shapiro and Kennedy, 1981; Uccellini and Johnson, 1979). These circulations imply that convergent and divergent regions exist around the jet core and that cirrus might be asymmetrically distributed there (Stone, 1957). As air enters the jet core from the rear, it accelerates and thus produces an ageostrophic component toward the lower pressure because the pressure gradient force is stronger than the coriolis force. As it exits the jet core at the front, it decelerates thus producing an ageostrophic component toward higher pressure. These ageostrophic components imply that convergence should occur northwest of the core in the accelerating region and southeast

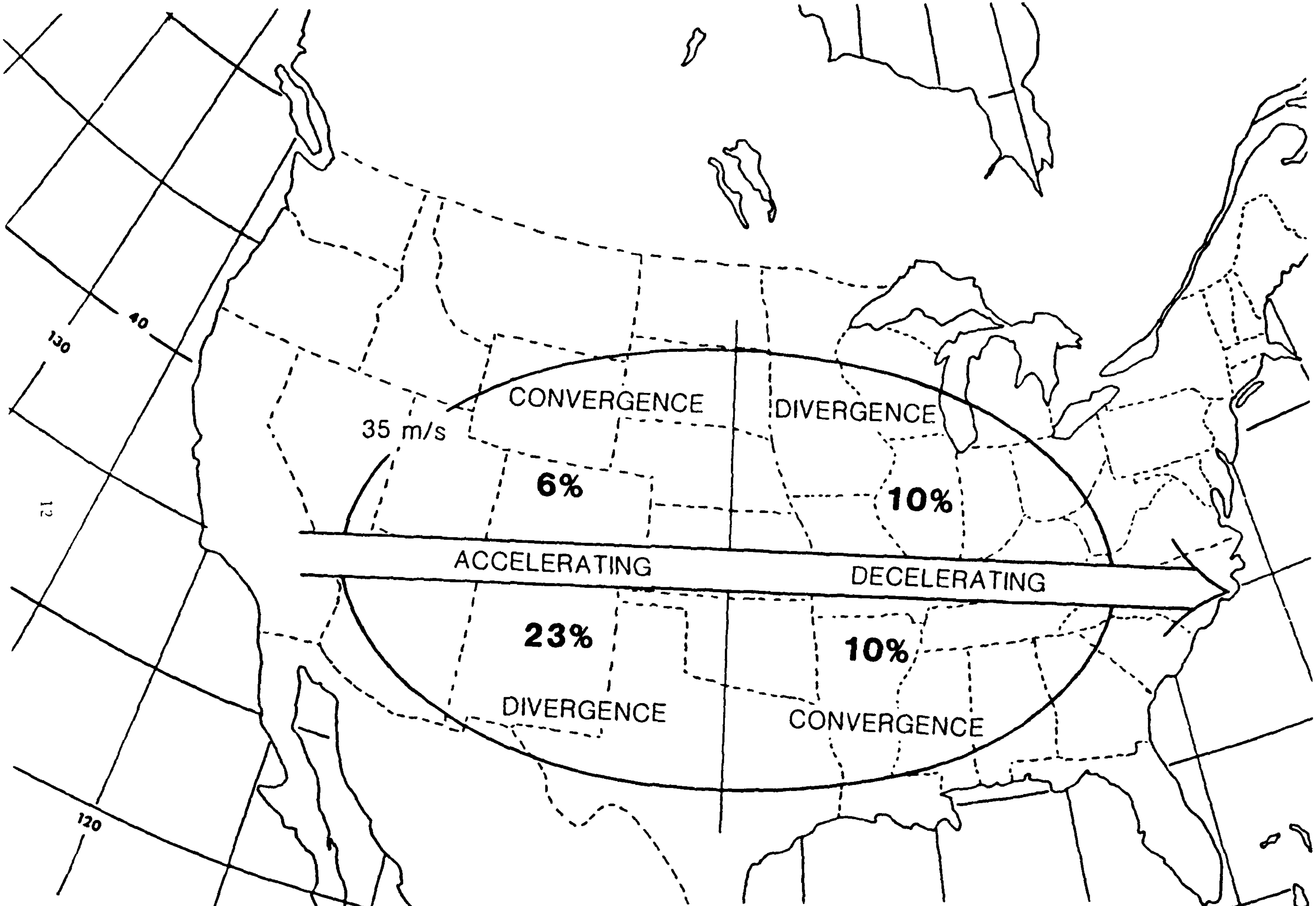

Figure 4: The distribution of cirrus around jet cores for Jan-Feb 1986 and Jan 1988. Percentages indicate the fraction of all cirrus inside each quadrant based on the total amount of cirrus both inside and outside the jet.

of the core in the decelerating region. Divergence is expected in the opposite quadrants, southwest in the accelerating region and northeast in the decelerating region. Rising motions and cirrus are expected in these divergent areas.

Table 4: Locations of Cirrus in the Quadrants around the Jet Core Maximum

Season	NW quadrant	NE quadrant	SW quadrant	SE quadrant
Winter				
Jan-Feb 86	7%	9%	13%	9%
Jan 88	6	11	33	10
Spring				
Apr 86	6	9	16	16
Apr 88	10	14	23	11
Summer				
Jul 86	2	1	7	3
Jul 87	1	2	8	3
Jun 88	1	6	18	4
Jul 88	0	2	8	2
Fall				
Oct 86	2	1	1	2
Oct 87	4	10	32	9

To test this theory the frequency of cloud observations were tabulated for each quadrant around the jet core. Table 4 and Figure 4 summarize the results. The most cirrus were found in the southwest quadrant in the accelerating region of the jet axis, in agreement with theory. In the winter months of high winds, 13 to 33% of all the cirrus over the CONUS were found in this quadrant, appreciably more than was found in any other quadrant. The least cirrus were found in the northwest quadrant in the accelerating region, where only 1 to 10% of the cirrus occurred. In the decelerating region, cirrus were found in nearly equal amounts in both the northeast and southeast quadrants. Other studies such as Stone (1957), have also noted that the jet core often forms a distinct cloud boundary with no cirrus north of the core and elongated streaks south of it. This tendency was apparent in the acceleration region only; the deceleration region did not show this relationship. The deceleration region of the jet core is often inside a large ridge where very broad cirrus shields are found. Examples can be found in Starr and Wylie (1990).

2.6. Intercomparison with Ground Reports

The VAS CO_2 cloud parameters (cover, height, amount) were compared with conventional ground observations for two weeks in summer 1989 (July and August), a week in fall 1989 (September), and a week in winter 1990 (February). VAS observations were processed for twenty fields of view (FOV) covering an area 40 X 40 km in the region of high quality surface observations . This is a much denser sampling than the 100 km spacing used for the four year climatology. The 20 VAS observations were categorized by effective emissivities (<0.33, 0.34-0.66, 0.67-0.95, and >0.95) and cloud heights (<400 mb, 400-700 mb, >700 mb, and clear sky). These histograms of VAS reports were inspected for patterns that correlated with the ground observations. Tables 5 through 8 present the satellite responses to different ground characterizations of the cloud cover and weather for the intercomparison period.

The results for surface observations of totally clear sky are in Table 5, the VAS estimates of clear sky agree with the ground observations 74% of the time. The VAS found high or middle level clouds for 5% of the FOVs where ground observers report clear sky. These VAS cloud observations were possibly cirrus that the ground observer ignored because they were near the horizon, cirrus that the observer could not see because of darkness, or clouds included in the VAS analysis that extended beyond the horizon of the observer. VAS also reported low clouds for 21% of the FOV's. The same comments apply to these clouds also, but most likely they are thin cirrus that the VAS incorrectly identified as low clouds. From the study presented in Wylie and Menzel (1989), it is probable that 5% were thin cirrus and out of view of the ground observer. The remaining 16% are failures to distinguish ground from cloud. The VAS CO_2 technique assumes that all FOVs warmer than the known surface temperature are clear and FOVs colder are clouds. This threshold is based on the surface temperature observations and corrected for water vapor absorption in the atmosphere (see Wylie and Menzel, 1989). Any error in this threshold will result in clear FOVs being called cloudy or low clouds being mistaken for clear. In summary for the 26% where VAS found clouds, 10% are probably correct and the remaining 16% are probably errors.

Table 5: Intercomparison of Satellite and Ground Observations of Cloud Cover VAS Results for Ground Reports of Totally Clear Sky (Number of Observations = 850)

	Effective Emissivity			
Cloud Top Pressure	< 0.33	< 0.66	< 0.95	> 0.95
PCT < 400	1	1	1	0
400 - 700	0	0	0	2
PCT > 700	0	0	0	21
PCT = 1000	74	0	0	0

When the ground observations reported a single overcast layer, the VAS derived cloud observations predominantly indicated high clouds above 400 mb. This occurred for observed overcast conditions of low (less than 10,000 feet), middle (between 10,000 and 25,000 feet) and high clouds (greater than 25,000 feet). The discrepancies between satellite and ground height estimates are mainly due to the different vantage points of each observing system. The satellite views cloud tops, while the observer sees cloud bases. Tables 6a-6c show that satellite cloud determinations above 400 mb changed (from 49% to 68% to 65%) as ground observations of the height of the overcast skies increased. Clear skies totalled 7% or less for each category which probably came from breaks of the clouds away from the observers view. When the ground observer reported low overcast and hence had a restricted view, the VAS gave information on clouds aloft (above 700 mb) 72% of the time. This is important in aviation considerations. Conversely, for all the situations when the satellite reported high opaque cloud, the observations provided additional information on lower levels of overcast 52% of the time. The two observing systems complement each other.

When the ground observers reported thundershowers, the VAS CO_2 technique readily sensed the associated cumulonimbus cloud tops. For ground observed thundershowers (Table 7), the VAS showed 47% opaque clouds above 400 mb and only 5% below 700 mb.

Table 6: Intercomparison of Satellite and Ground Observations of Cloud Cover

(6a) VAS Results for Ground Reports of Overcast at less than 10000 feet (Number of Observations = 716)

Cloud Top Pressure	Effective Emissivity < 0.33	< 0.66	< 0.95	> 0.95
PCT < 400	4	9	24	12
400 - 700	1	3	6	13
PCT > 700	0	0	0	21
PCT = 1000	7	0	0	0

(6b) VAS Results for Ground Reports of Overcast Layer between 10000 - 25000 feet (Number of Observations = 16)

Cloud Top Pressure	Effective Emissivity < 0.33	< 0.66	< 0.95	> 0.95
PCT < 400	8	10	42	8
400 - 700	0	2	5	15
PCT > 700	0	0	0	7
PCT = 1000	3	0	0	0

(6c) VAS Results for Ground Reports of Overcast at greater than 25000 feet (Number of Observations = 43)

Cloud Top Pressure	Effective Emissivity < 0.33	< 0.66	< 0.95	> 0.95
PCT < 400	8	23	28	6
400 - 700	2	4	3	15
PCT > 700	0	0	0	9
PCT = 1000	2	0	0	0

Table 7: Intercomparison of Satellite and Ground Observations of Cloud Cover VAS Results for Ground Reports of TRW (Number of Observations = 34)

Cloud Top Pressure	Effective Emissivity < 0.33	< 0.66	< 0.95	> 0.95
PCT < 400	3	12	25	47
400 - 700	0	2	3	3
PCT > 700	0	0	0	5
PCT = 1000	0	0	0	0

The histogram of VAS satellite cloud parameters for the twenty FOVs over a selected ground site can be used to estimate what the ground observer will report. A guideline using the template in Table 8 is presented below. The percentages of VAS observations in each column is indicated by B through E. High clouds, < 400 mb (top row) have the subscript 1 and middle clouds, 400 - 700 mb, have the subscript 2. S_1 and S_2 represent the sums of rows 1 and 2 respectively. The percentage of clear sky observations is denoted by A. Low clouds are indicated by F. An X has been used to indicate categories where VAS satellite observations do not provide additional information.

Table 8: Template for Comparing VAS Results and Ground Reports

Cloud Top Pressure	Effective Emissivity < 0.33	< 0.66	< 0.95	> 0.95
PCT < 400	B_1	C_1	D_1	E_1
400 - 700	B_2	C_2	D_2	E_2
PCT > 700	X	X	X	F
PCT = 1000	A	X	X	X

The method of estimating ground observer conditions is as follows:

a. Ground observations will report precipitation if $E_1 > 25\%$.

b. Overcast conditions will be reported if $A < 7\%$.
Overcast with high cloud if $S_2 < S_1$,
Overcast at middle levels if $S_2 > S_1$.

c. Broken clouds are indicated by $7\% < A < 30\%$
and $C_1 + C_2 > 10\%$.
High broken clouds if $S_2 < 10\%$,
Middle level broken clouds if $S_2 > 10\%$.

d. Scattered clouds are indicated by 30% < A < 70%.
High scattered clouds if $S_1 > 0\%$,
Middle level scattered clouds if $S_2 > 0\%$.

e. Low opaque cloud cover is present if F > 40%.

f. Clear skies are mostly found when A > 70%.

A test predicting the ground observations from the VAS histogram was performed on 4 days, 22-23 September 1989 and 14-15 February 1990. These days presented a variety of cloud types and cloud amounts in different synoptic conditions, both summer and winter. 375 ground observations were compared to VAS observations. VAS estimates of the ground observations were in agreement 26% of the time. In an additional 60% of the data, the VAS estimate disagreed with the ground observation, but both assessments of the situation were probably correct and complementary (such as in multi-layer cloud situations or thick cumulonimbus). The VAS estimation of the ground observation was obviously incorrect 13% of the time. Some of the disagreements were minor such as characterization of broken as scattered clouds, but several were significant such as falsely identifying ground as low cloud. The guideline for interpreting the VAS observations worked equally well in fall and winter conditions.

Snow cover did not compromise the satellite observations. For 250 snow situations in February 1990, 27% of the satellite and ground observations agreed and 41% showed complementary information while 28% showed small disagreement (scattered versus broken ...) and 4% were incorrect.

3. SPATIAL CORRELATIONS OF CIRRUS CLOUDS OVER CONUS

3.1. The Sizes of Cloud Systems

The cloud data base which has been built over the last four years using the multi-spectral infrared data from the GOES/VAS sensors is used to study the sizes of cloud systems and the clear areas in between them. This information is needed because cloud studies are usually made from ground sites, or airplane tracks of 50 to 100 km. These observations only cover parts of the total cloud mass because cloud systems are usually of synoptic scales > 100 km. The question arises as to what size scales represent cloud systems and how large of an area would have to be covered to sample a cloud system continuously?

Cloud field size information is also needed for the planning of astronomical observation systems and solar energy collection systems. These systems require cloud free skies to operate. There is no totally cloud free location in the United States that could be used; however, the success of the operation could be improved above that of a single site if multiple sites were used in a linked system so that the unobstructed areas could be taken advantage of. A network of sites could have a higher probability of being unobstructed than any of the single site components by itself. This leads to the question of "How many sites should be used and how far apart should they be spaced?" To answer this question system designers need statistics on the spatial sizes of cloud fields and cloud free areas. To provide this information, a spatial correlation function was computed for cloud systems and the clear areas in between from the GOES/VAS data.

3.2. High Cloud Spatial Correlations

An autocorrelation function for clouds has to be formed from a binary representation of cloud classes. The GOES/VAS cloud observations were categorized as being either a) clear sky conditions where no cloud was detected, b) light transmissive cirrus, c) dense transmissive cirrus, or d) very dense high level cloud (<400 mb altitude). These categorizations were used so that spatial probability functions could be derived describing the probability of finding a similar cloud observation with distance. The cloud altitude measurement was not used as a numeric value in a normal autocorrelation function because clouds at different altitudes are really different meteorological features not just different values of the same parameter such as temperature. Cloud altitudes can not be averaged; for example, if one location has a high cloud (say 300 mb) and another has a low cloud (say 800 mb), the numerical average of the two is a middle level cloud, 550 mb. But clouds did not exist at 550 mb. An average of the cloud heights observed in a field does not describe the cloud field. From a satellite view the two observations tell us several pieces of information: a) both sites are cloudy, b) the high cloud layer exists (300 mb) over one site and not over the other so the average high cloud coverage is 50%, and c) one site has a low cloud (800 mb) without middle and high cloud layers while nothing is known about the existence of middle and lower cloud layers below 300 mb at the second site because the satellite's view was obstructed by the 300 mb cloud layer. Thus, information from satellite cloud observations has to be used as probabilities of different cloud levels occurring rather than as numerical statistics of the cloud height measurements.

Because satellite sensors are often obstructed from seeing lower clouds, this discussion will be restricted to high cloud levels above 400 mb or clear sky conditions where no cloud was observed at any level. Statistics of low level and middle level clouds will not be discussed since assumptions would have to be made about their presence or absence under high level clouds. To detect a cloud, the satellite has to see at least a 2^{O} K signature colder than the ground temperature. Any thin clouds that do not cause this signature can not be distinguished from sensor noise when viewing the ground. More details on cloud detectability and the technique used for making cloud analyses are given in Wylie and Menzel (1989). The GOES/VAS multi-spectral data also allow unambiguous detection of transmissive cirrus clouds. Transmissive cirrus are often mistaken for middle or lower tropospheric clouds because they appear warmer on the satellite image from radiation penetrating through them. The multi-spectral data allow these clouds to be detected and separated from other middle and lower cloud forms.

Spatial probability functions were formed by examining the GOES/VAS observations at two locations on the image simultaneously. The frequency of the same observation occurring in both locations together, clear sky or high cloud (<400 mb), was tabulated and divided by the total number of cloud observation pairs. This is a restricted form of the Tetrachoric Correlation (Panofsky and Brier, 1968) where only two categories were considered out of four possibilities. If the same observation (clear sky or high cloud) tended to be found together, this function approached 1.0. However, if both observations of the pair were from different categories, the function approached 0.0.

The spatial probability curves will change with different cloud types and meteorological conditions so separate calculations were made for 42 geographical locations across the continental United States and in two different seasons (Figure 5). The clear sky and high cloud probability

probability functions were formed by searching for the clear sky and high cloud observations within 100 km of a central point for each of the 42 locations. If one of these were found on an image, than all observations around that point were compared. The paired comparisons were summed in 100 km width distance bins.

Six months of data were used. January 1988, 89, and 90 were used to represent the winter season. July 1987, 88 and 89 were used for the summer season.

3.3. Results

The spatial correlation functions show different shapes around the United States. Clear sky correlations were highest in the southwest in January (Fig. 5). January correlations were higher than July correlations over most of the southern U. S. This probably occurs because cumulus convection in the summer produces broken cloud fields, where as in winter cloud systems are caused by large scale synoptic features -- fronts and cyclones. This trend reverses in the northern plains, Montana and North Dakota, where the July clear sky correlations were higher than the January correlations. This suggests a latitudinal variation in the correlations.

The shape of the correlation functions is partially summarized in Figures 6 and 7. These figures show the distance over which the spatial correlation of clear sky is above 0.50. In July (Fig 6) this distance is over 800 km in the northern plains. In southwestern California and over the Appalachian Mountains it drops to 100 km. This distance also follows the trend of the level of the correlations. In areas where the distance for the correlation to drop to 0.50 is >800 km, the correlations for < 100 km are over 0.70. In the areas where the correlation drop distance is small, the < 100 km correlation was usually near or below 0.50.

In January the pattern of correlation distance changed from July (Fig. 7). The largest correlations and longest distances were in the southwest U. S. The shortest distances were in the northern states. This exhibited a complete reversal from the summer statistics in the northern plains.

The high cloud correlation function (Fig. 8) had less geographical and seasonal variances than the clear sky function (Fig. 5). The high cloud correlations were slightly higher in January than July over most of the area. The slopes of the functions were similar in winter and summer. Summer correlation functions were not drawn for the Eastern Pacific because of the lack of high clouds in this area which drastically reduced the statistical sums in the computations.

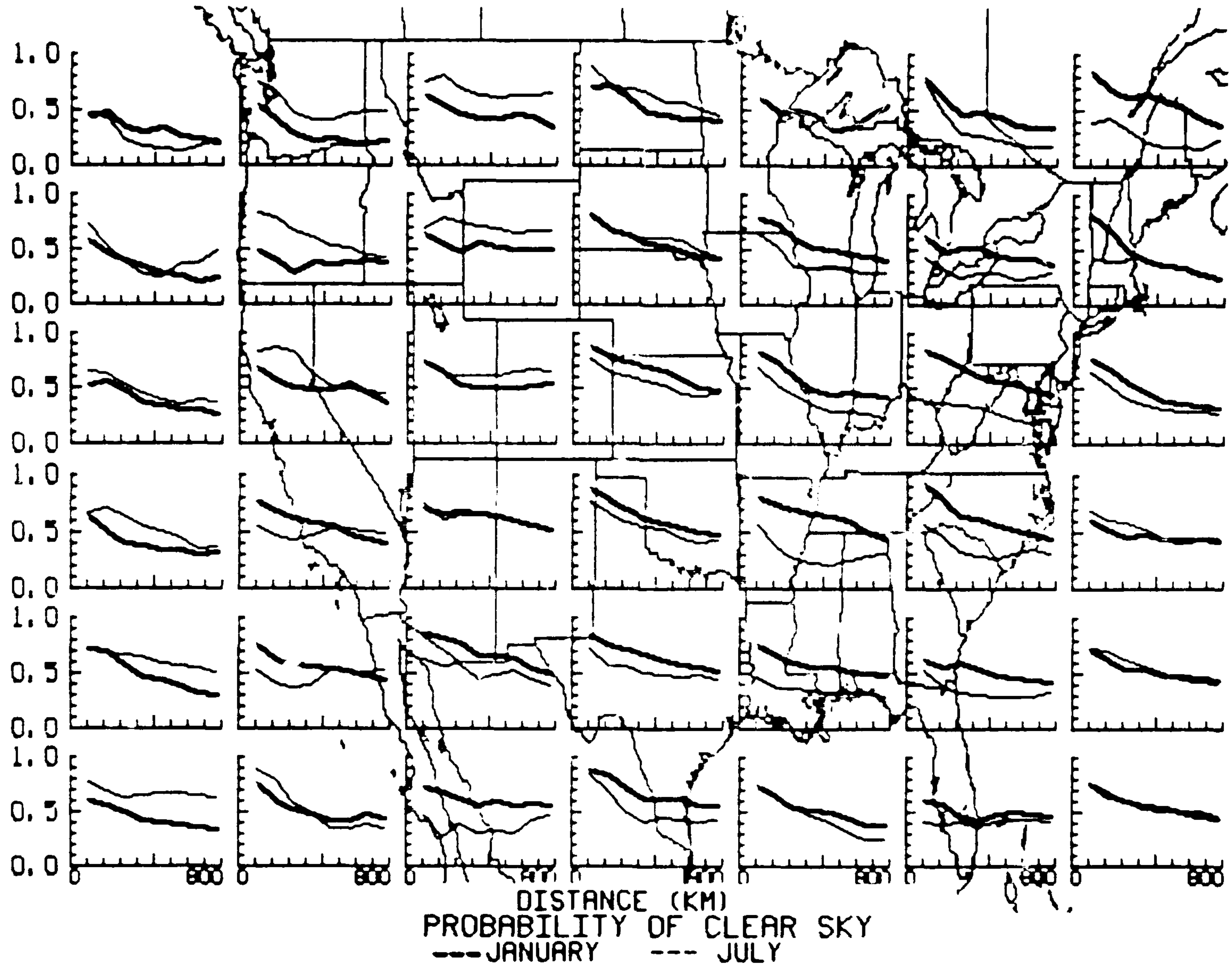

Figure 5: The spatial correlation of clear sky observations from the GOES/VAS cloud climatology.

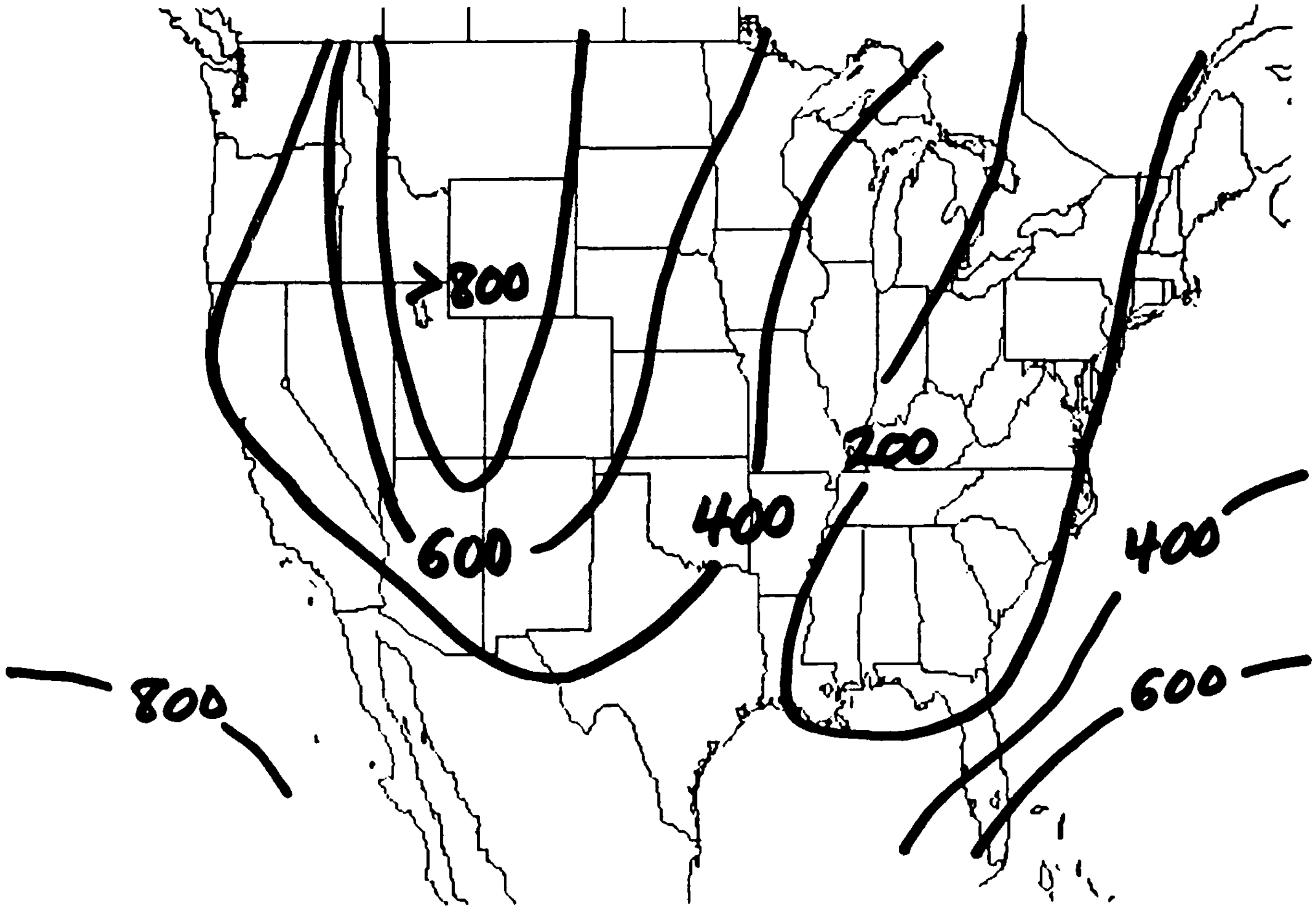

Figure 6: The distance for the spatial correlations in Figure 5 (clear sky) to fall to 0.50 in July.

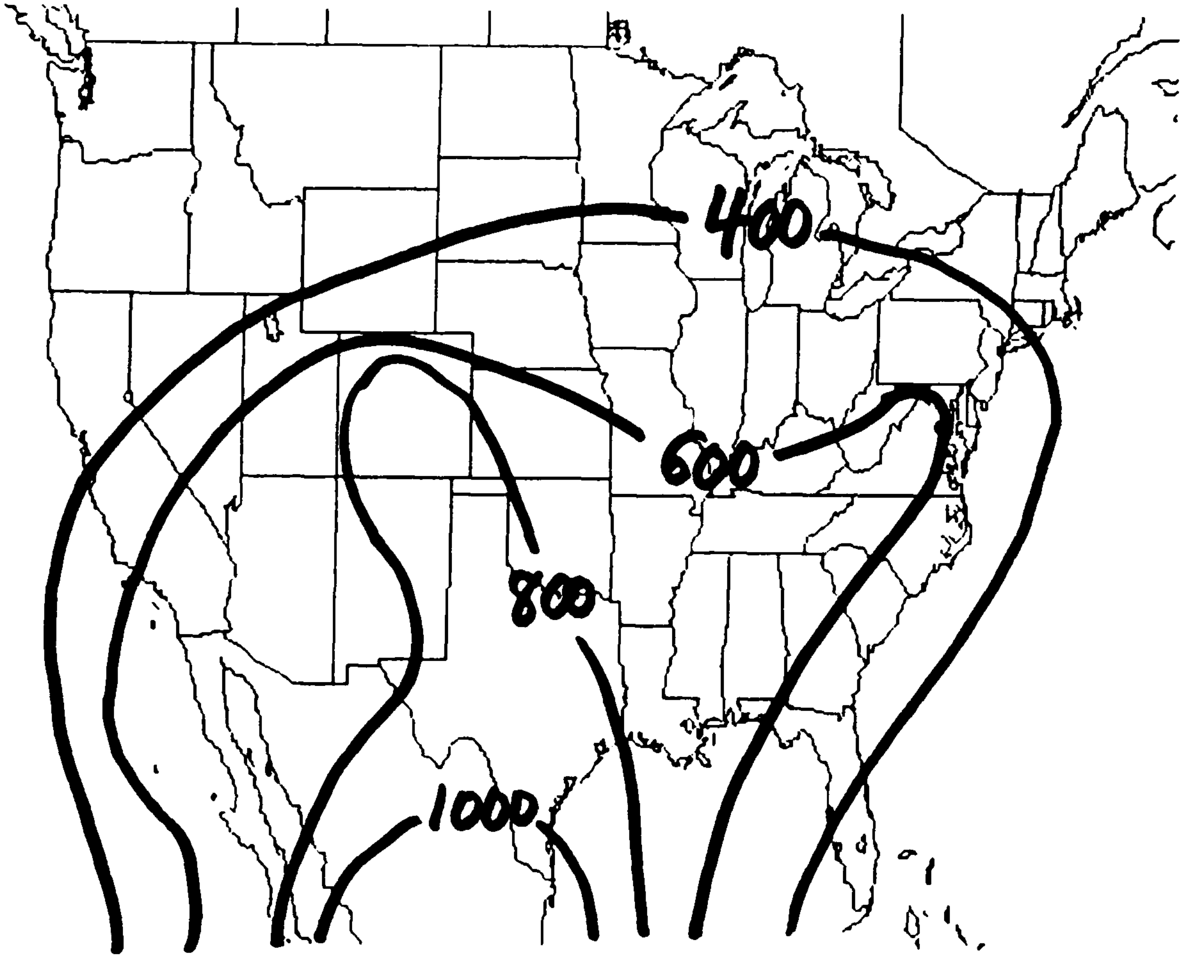

Figure 7: The distance for the spatial correlations in Figure 5 (clear sky) to fall to 0.50 in January.

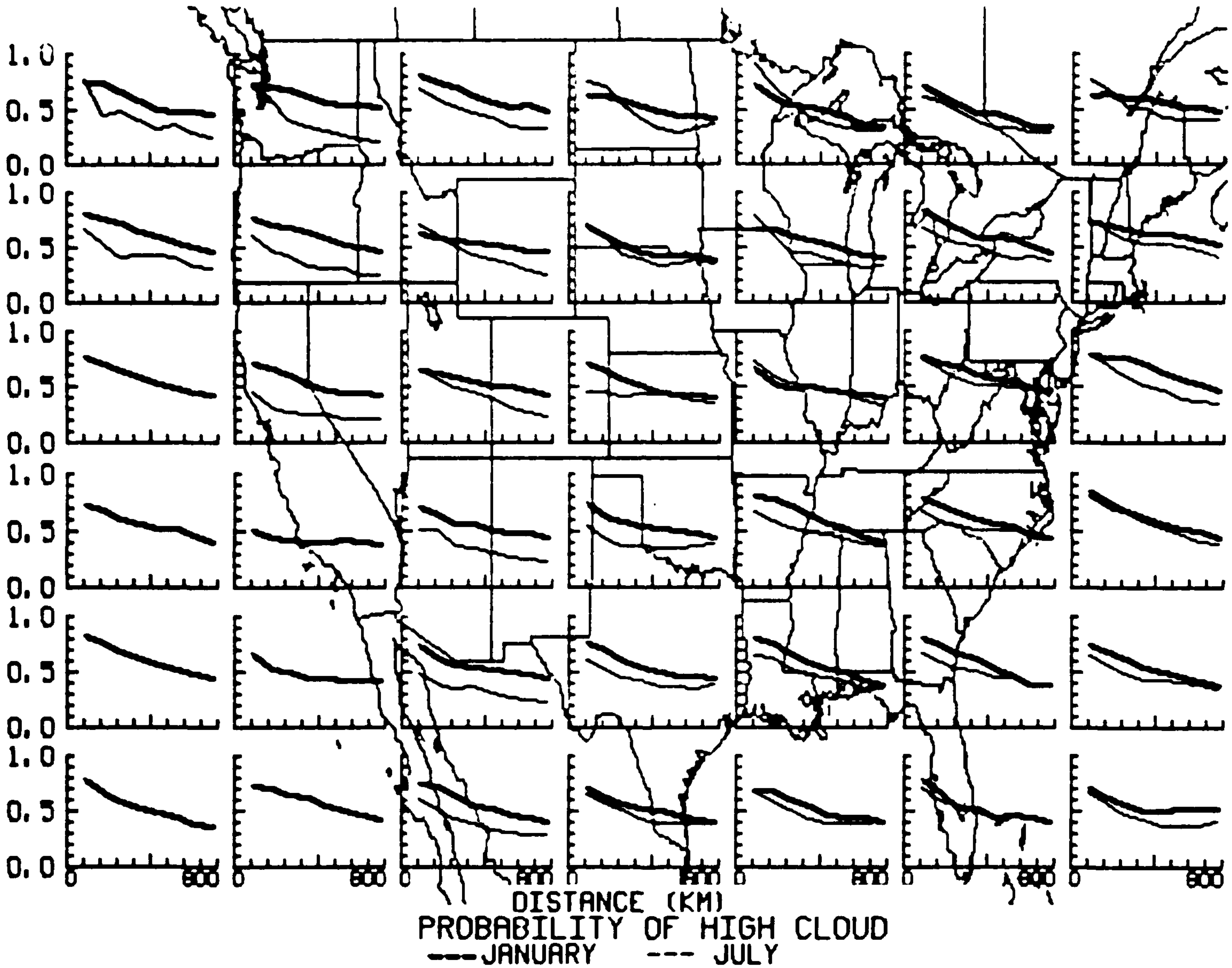

Figure 8: The spatial correlation of high cloud occurrences from the GOES/VAS cloud climatology.

4. GLOBAL STATISTICS

4.1. Polar Orbiting Satellite Data

Global data collection began in June 1989 using the two polar orbiting NOAA satellites, NOAA 10 and NOAA 11. The HIRS on these satellites has similar spectral channels to the VAS on the geostationary satellites from which cloud data have been collect for the last four years. These satellites fly in sun synchronous orbits passing at approximately 2 a.m., 2 p.m., 8 a.m., and 8 p.m. The HIRS data are processed using the same technique discussed in this report.

One year of global data have been collected from the NOAA satellites. These data have been summarized in boxes spanning 2^{o} latitude by 3^{o} longitude. Four to five hundred observations per three month season were collected in these boxes over the oceans (Figure 9). Data collection over land was reduced because diurnal temperature changes greatly affected the cloud detection algorithm. The cold ground in the morning was often mistaken for cloud. To eliminate this problem, all morning (2 a.m. and 8 a.m.) data collected from both satellites over land were discarded, only afternoon data were used over land (2 p.m. and 8 p.m.).

4.2. Global Analysis for Summer 89 and Winter 89-90

Cloud cover for the northern hemispheric winter (December 89 thru February 1990) and summer (June thru August 1989) seasons is summarized in Figure 9. Observations are classified as being one of three categories; transmissive cirrus, opaque cloud, or clear. Altitudes of the clouds are assigned from the radiative properties of the clouds as discussed in Section 2. Figure 10 shows the probabilities of each satellite observation having a cloud (bottom two panels) or of that cloud being transmissive to terrestrial radiation (top panels). The color scheme spans from low probability (white) to high probability (dark).

The most obvious features are the Inter-Tropical Convergence Zone (ITCZ) in the tropics and the storm belts of the mid latitudes. Cloud cover was found from 40 to 80% of the time in these areas. The sub-tropical highs and deserts are also apparent as cloud minima. The cloudy belts are semi-permanent but their edges move north and south with the seasons.

A large seasonal change was found in Antarctica which was cloudy 41-60% of the time in summer (Dec-Feb) and nearly clear in winter (June-August). The vertical temperature sounding channels of the HIRS over Antarctica were used to judge whether the observations were clear or cold ground. The temperature of the continent (220-240 K) was as cold as many mid-latitude cloud tops. However, temperature inversions where the air above the ground was warmer than the ground could be recognized by the lowest two channels of the HIRS. The inversion observations were labeled as clear sky because inversions normally form from radiative cooling of the ground under cloud free conditions. Thus, the air above the ground is warmer than the ground. Under normal conditions the air temperature should decrease vertically in the atmosphere. Along a similar line of reasoning, conditions where the lowest two sounding channels reported nearly the same temperature, were labelled as clouds. The lack of normal temperature decrease with height may be indicative that both channels were viewing the a cloud top. A similar seasonal change is apparent in Greenland, the North Atlantic and Siberia where cloud cover was less frequent in winter than in summer.

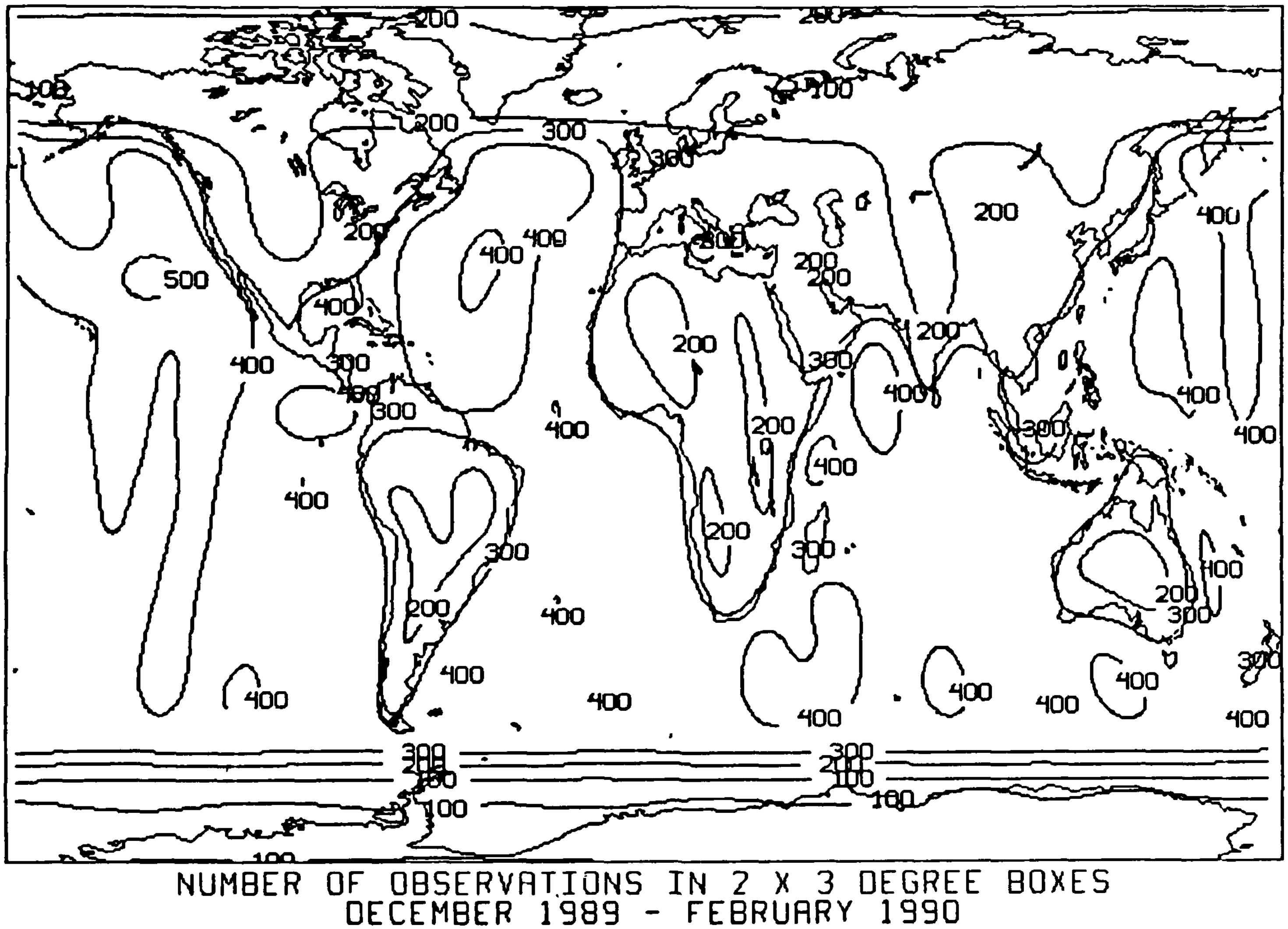

Figure 9: The number of NOAA/HIRS observations collected in 2° latitude by 3° longitude boxes from 1 December 1989 thru 28 February 1990.

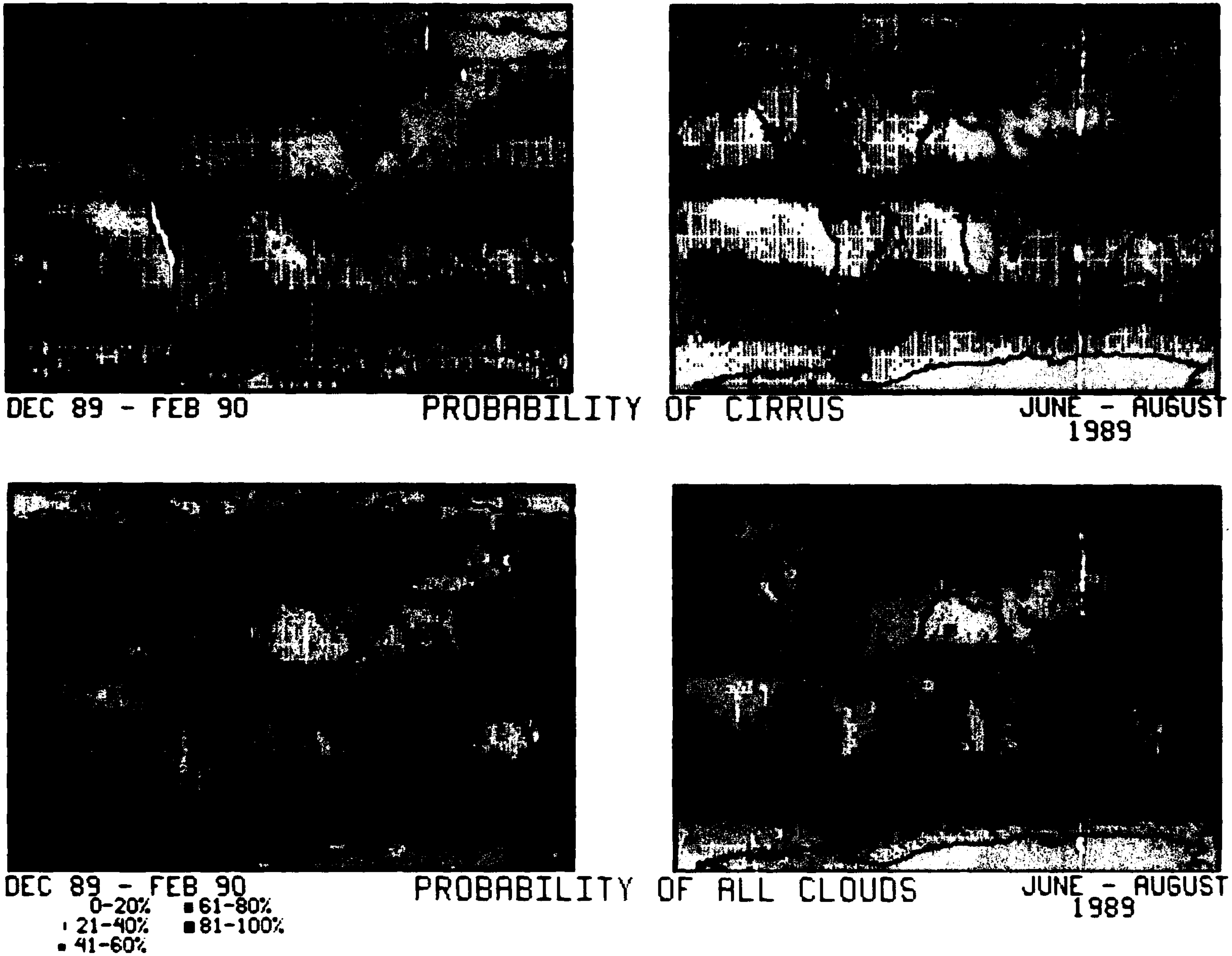

Figure 10: The probability of transmissive cirrus (upper panels) and all cloud forms including cirrus (lower panels) from NOAA/HIRS data.

5. SUMMARY AND CONCLUSIONS OF FOUR YEARS OF DATA

As this study of clouds over the CONUS continues into the fifth year, several trends are being confirmed. The four year results are very similar to the two year results. The most obvious finding remains the high incidence of transmissive cirrus clouds (about 26%) on the average over the continental United States for the past four years in winter and summer. Transmissive cirrus clouds have smaller geographical and seasonal variances than opaque clouds over the continental United States. The small variances appeared in the spatial probability functions as well as the mean frequency statistics. A considerable percentage of cirrus is present all the time over the U.S.

Large seasonal variations of cirrus were found over the Atlantic and Pacific Oceans. These variations reflect the seasonal movement of the subtropical high pressure systems which cover a large portion of the oceans. Cirrus were frequently found in the winter when cyclonic storms and frontal systems were present. In the summer cirrus were sparse as the subtropical highs expanded to higher latitudes.

In the tropics, large quantities of cirrus were found in and around the ITCZ extending north and south from it. The frequency of clouds both transmissive cirrus and opaque clouds, reached as high as 80% in parts of the ITCZ. The boundaries of the cirrus fluctuated in latitude with the seasons, with the largest changes being in the southern hemisphere over South America, South Africa and in the Western Pacific.

Other large seasonal changes in the frequency of cirrus were found at the poles along with seasonal changes in all other cloud forms . Few clouds of any type were found over parts of Antarctica in its summer while during its winter, clouds were found with comparable frequency to other high latitude continental areas, 30-50%. The Arctic had similar but smaller seasonal variations compared to the Antarctic.

Diurnal variances of cirrus over the U. S. were significant only in summer and not in winter. Increases in summer cirrus were found during the middle and later parts of the day and were attributed to the development of convection. These diurnal changes were primarily in the Rocky Mountains and along the Gulf Coast. In winter, when diurnal convective development was absent, there was no obvious diurnal change in transmissive cirrus.

Cirrus are linked to some common atmospheric features. One half of the cirrus over the CONUS were found near radar echoes in the summer; this shrinks to 22% in the winter. In months of high jet stream winds, 40 to 60% of the cirrus over the CONUS are found in the vicinity of the jet; this shrinks to 10 to 30% in the months of low jet winds. The southwest quadrant of the jet, which exhibits divergent rising flow, showed the highest propensity for cirrus. However, the dynamics causing cirrus are complicated; while these data did reveal a majority of the cirrus occurred where dynamic parameters indicate rising vertical motion, considerable cirrus were also found where dynamic support was weak. No clear correlations are apparent between the strength of the dynamics and the frequency of cirrus.

Comparisons of VAS with ground observer reports of clouds indicate that the two corroborate or complement each other 80% of the time. The satellite does better at high levels with its top down view, while the ground observer is more reliable at low levels with his bottom up view. When the ground view is limited by low opaque cloud cover, the satellite sees additional upper level clouds 70% of the time. Conversely, when the satellite sees high opaque clouds, the ground observer sees lower clouds 52% of the time.

The spatial correlation functions of clear sky occurrences show large seasonal changes in the central United States. Reasonable correlations (> 0.5) were found at scales of 500 km and greater for most of the U. S. However, they radically change between the seasons. In summer, high spatial correlations of clear sky conditions were predominant in the upper plains states. While the eastern U. S. from the Appalachian Mountains to the Atlantic coast had very short scales of clear sky conditions. This is a result of the cumulus convection in this area during the summer. In winter the clear sky spatial correlation function had a radically different shape with low spatial distances in the northern plans and high distances in the southern U. S. including the Appalachians. Convection is suppressed in the southern U. S. in winter allowing large clear areas to form. The northern plains are dominated by fronts and cyclonic storms which suppress the formation of large cloudless areas.

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