A Final Report to

U. S. Navy

for

The Collection of Statistics on the Frequency of
Cloud Cover Over North America

Contract # N00014-85-K-0581

University of Wisconsin Account #144W850

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1 July 1985 to 30 September 1987

submitted by

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FINAL REPORT

CONTRACT TITLE: The Collection of Statistics on the Frequency of Cloud Cover
Over North America

NUMBER: N00014-85-K-0581

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TECHNICAL OBJECTIVES: To collect statistics on cloud cover and atmospheric
obstructions to lidar propagation.

APPROACH: We are using the GOES/VAS satellite for collecting statistics on
cloud cover. The VAS sensor on this satellite has 12 spectral channels which
can be used for defining the partially transmissive cirrus clouds. These
cirrus clouds have been confused with lower altitude opaque clouds in past
satellite studies. With the GOES/VAS system we are determining what
percentage of the cloud cover is partially transmissive. We have collected
1.75 years of data and are currently studying the geographic, seasonal and
temporal variations in cloud cover--both those that are transmissive and those
that are opaque to terrestrial radiation.

    We are calibrating the satellite data with lidar data. The High Spectral
Resolution (HSRL) lidar measures the vertical profile of extinction of visible
lidar energy by clouds and other atmospheric obstructions. The extinction and
total optical depth measurements of the lidar are being compared to satellite
derived estimates of cloud emissivity and optical depth to calibrate the
satellite data so that geographical statistics of lidar attenuation can be
produced.

ACCOMPLISHMENTS DURING FY 1987: In FY 1987 we completed 1.75 years of
satellite observations. We found that the probability of clouds opaque to
terrestrial radiation is approximately 45 percent. Partially transmissive
cirrus clouds were found 25 to 35 percent of the time and no clouds (clear
skies) were detected 20 to 25 percent of the time. The desert southwest had
the least opaque cloud cover. Partially transmissive cirrus clouds also
varied geographically but the transmissive cirrus cloud cover was more uniform
than the opaque cloud cover. Diurnal and seasonal variances in cloud cover
also were found and are discussed in the attached papers (Appendices A and B).

    We are in the process of analyzing our lidar data. We have data on
clouds with optical depths from 0.01 to 1.0. Many details of the spatial
structure of these clouds also have been revealed by the lidar data.

Quantitative measurements of extinction and optical depth also have been made of "invisible cirrus" clouds which can obstruct aircraft sensors. More details are given in Appendices C and D.

SIGNIFICANCE OF RESULTS: We have found that partially transmissive cirrus clouds account for a large fraction of the cloud cover reported by other studies. This class of cloud cover does not fully block observing systems or energy propagation. With the lidar data we intend to provide radiative transfer information so that the potential obscuration to sensors or energy transmission systems can be predicted.

FUTURE EFFORTS: We intend to continue enlarging our satellite and lidar data sets. More data are needed to produce accurate statistics. We have just begun examining cloud radiative transfer data from the HSRL lidar. Lidar-satellite comparisons will be made in the upcoming year.

PUBLICATIONS:

Wylie, D. P., and W. P. Menzel, 1988: "Cloud cover statistics using VAS", SPIE Conf. Proceedings on Optoelectronics and Laser Applications in Science and Engineering Symposium on Innovative Science and Technology, Los Angeles, CA, January 13, 1988.

Eloranta, Edwin W., and Christian J. Grund, 1988: "Lidar observations of cirrus cloud parameters," SPIE Conf. Proceedings on Optoelectronics and Laser Applications in Science and Engineering Symposium on Innovative Science and Technology, Los Angeles, CA, January 13, 1988.

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Grund, C. J., 1987: "Thermally induced spectral drift cancellation in pressure-tuned Fabry-Perot etalons", App. Opt., in publication (Feb).

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Third Conference on Satellite Meteorology and Oceanography sponsored by the American Meteorological Society, 31 January, 1988, Anaheim, CA

CLOUD COVER STATISTICS FROM GOES/VAS

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1. INTRODUCTION

The frequency of occurrence of cirrus clouds usually has been underestimated in cloud population studies. Satellite methods of analyzing cloud cover often mistake cirrus clouds for lower level clouds or completely miss them, because their infrared brightness temperatures are warmer than the temperature associated with their true altitudes. Thin cirrus are especially hard to identify on visible satellite images because they reflect little solar radiation and appear as dark or broken cloud fields. With the multi-spectral infrared sensor on the GOES-VAS satellite the identification of most cirrus is now possible.

A technique for deriving cloud top altitudes from the VAS infrared sensor was developed by Menzel (1983). It is also applicable to the polar orbiting High-resolution Infrared Radiometer Sounder (HIRS). The technique takes advantage of infrared channels with partial CO_2 absorption where the different channels are sensitive to different levels in the atmosphere. Thus, clouds appear on each channel in proportion to their level in the atmosphere. Low clouds will not appear at all on the high level channels, while high clouds appear on all channels. By modelling the upwelling infrared radiation from the earth atmosphere system in several VAS channels simultaneously, it is possible to infer the cloud top height independent of radiative transmissivity of the cloud. This gives the CO_2 technique the ability to distinguish thin cirrus clouds that would normally be missed by other techniques due to the transmission of terrestrial radiation through the cirrus.

The CO_2 technique has been installed on the Man-computer Interactive Data Access System (McIDAS) at the University of Wisconsin-Madison. It has been run operationally using the GOES-VAS imagery starting in October 1985. Statistics on cloud cover and especially cirrus cloud cover are being gathered for the continental United States and its bordering oceans. This paper describes the techniques and some of the first results of this program.

2. CO_2 TECHNIQUE DESCRIPTION

The VAS radiometer detects infrared radiation in twelve spectral bands that lie between 3.9 and 15 microns at 7 or 14 km resolution in addition to visible reflections at 1 km resolution. The 15 micron CO_2 band channels provide a good sensitivity to the temperature of relatively cold regions of the atmosphere. A demonstration of the vertical resolution of the three relevant CO_2 channels is given by the temperature profile weighting functions shown in Fig. 1. Each curve in the figure shows the sensitivity of the radiance observed in the spectral interval of the indicated channel to local variations in atmospheric temperature. As may be seen, only clouds above the 350 mb level will have strong contributions to the radiance to space observed by the 14.2 micron band (VAS channel 3), while the 14.0 micron band (VAS channel 4) senses down to 700 mb and the 13.3 micron band (VAS channel 5) senses down near the surface of the earth.
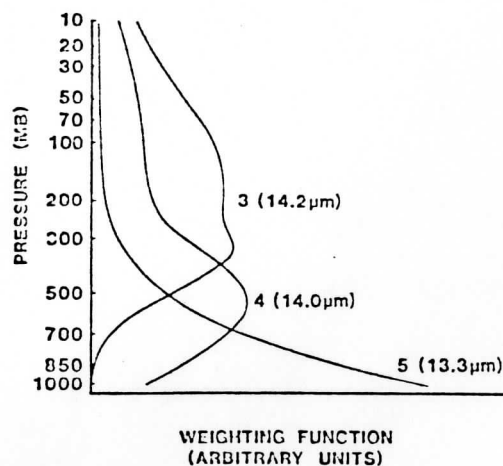

Fig. 1. The temperature profile weighting function of radiance to space as a function of emitting level for the VAS CO_2 spectral bands centered at 14.2, 14.0, and 13.3 microns.

To assign a cloud top pressure to a given cloud element, the ratio of the deviations in cloud produced radiances, $I(\nu)$, and the corresponding clear air radiances, $I_{cl}(\nu)$, for two spectral channels of frequency ν_1 and ν_2 viewing the same field-of-view is written as

$$\frac{I(\nu_1) - I_{cl}(\nu_1)}{I(\nu_2) - I_{cl}(\nu_2)} = \frac{\epsilon_1 \int_{P_s}^{P_c} \tau(\nu_1, p) \dfrac{dB[\nu_1, T(p)]}{dp} dp}{\epsilon_2 \int_{P_s}^{P_c} \tau(\nu_2, p) \dfrac{dB[\nu_2, T(p)]}{dp} dp}$$

In this equation ϵ is the cloud emittance, P_s the surface pressure, P_c the cloud pressure, $\tau(\nu, p)$ the fractional transmittance of radiation of frequency ν emitted from the atmospheric pressure level (p) arriving at the top of the atmosphere (p = 0), and $B[\nu, T(p)]$ is the Planck radiance of frequency ν for temperature $T(p)$. If the frequencies are close enough together, then $\epsilon_1 \cong \epsilon_2$, and one has an expression by which the pressure of the cloud within the field-of-view (FOV) can be specified. The left side of equation (1) is determined from the VAS observed radiances and clear air radiances provided from spatial analyses of VAS clear-sky radiance observations. The right side of equation (1) is calculated from a temperature profile and the profiles of atmospheric transmittance for the spectral channels as a function of P_c, the cloud top pressure (discrete values at ~50 mb intervals spanning 1000 to 100 mb are used). In this study, global forecast temperature and moisture fields from the National Meteorological Center (NMC) are used. The optimum cloud top pressure is determined when the absolute difference |right (ν_1, ν_2) - left (ν_1, ν_2, P_c)| is a minimum.

Once a cloud height has been determined, an effective cloud amount can be evaluated from the infrared window channel data using the relation

$$N\epsilon = \frac{I(w) - I_{cl}(w)}{B[w, T(P_c)] - I_{cl}(w)}$$

Here N is the fractional cloud cover within the FOV, $N\epsilon$ the effective cloud amount, w represents the window channel frequency, and $B[w, T(P_c)]$ is the opaque cloud radiance.

Using the ratios of radiances of the three CO_2 spectral channels, three separate cloud top pressures can be determined (14.2/14.0, 14.0/13.3, and 14.2/13.3). If $(I - I_{cl})$ is within the noise response of the instrument ($\sim$ 1 mW m^{-2} - sr^{-1} - cm^{-1}) the resulting P_c is rejected. Using the infrared window and the three cloud top pressures, three effective cloud amount determinations are made. As described by Menzel (1983), the most representative cloud height and amount are those that best satisfy the radiative transfer equation for the three CO_2 channels.

If no ratio of radiances can be reliably calculated because $(I - I_{cl})$ is within the instrument noise level, then a cloud top pressure is calculated directly from the VAS observed 11.2 micron infrared-window channel brightness temperature and the temperature profile. In this way all clouds are assigned a cloud top pressure either by CO_2 or infrared-window calculations.

The CO_2 technique is independent of the fractional cloud cover; heights and effective cloud amounts can be determined for partially cloudy FOVs. However, the CO_2 technique sees only the highest cloud and cannot resolve multi-layer clouds. Because the VAS FOV resolution is coarse (14 km for this work), very small element clouds are difficult to detect. Also, because the weighting functions for the VAS channels are broad, there is an inherent lack of vertical resolution in the measurements. Nonetheless, reliable cloud statistics can be calculated with appropriate application of the technique.

Since October 1985, the VAS instrument on board GOES-6 has been programmed to gather sounding data over the United States at least twice daily (near 1200 GMT and 0000 GMT) and as often as four times daily (near 00, 0600, 1200, and 1800 GMT). The CO_2 technique has been applied to these data routinely. In this study, radiances for three FOVs were averaged for cloud height and amount determinations (representing an area of 14 by 42 km at the satellite subpoint) at roughly 100 km spacing. Surface observations were used to adjust the global forecast temperature and moisture fields. No adjustments for topography were made. Transmittances were determined from line by line calculations with the spectral response functions for the appropriate VAS channels.

3. VALIDATION

Quantitative comparisons are shown in Fig. 2. The CO_2 (or infrared window where necessary for low clouds) cloud top pressures are shown with the determinations from radiosondes. Cloud-top pressures are estimated from 1200 or 0000 GMT radiosonde temperature and dew point temperature profiles by noting where the dew point temperature profile becomes much drier as it emerges from the cloud and hence indicates cloud-top pressure. Since the profile analysis is not always definitive, a reliable radiosonde cloud height determination is not always available, especially in cirrus clouds. VAS observations were usually within 30 minutes of the raobs and were gathered over a three month period. The range of VAS cloud top pressures is from the four FOVs nearest to the radiosonde location. The VAS
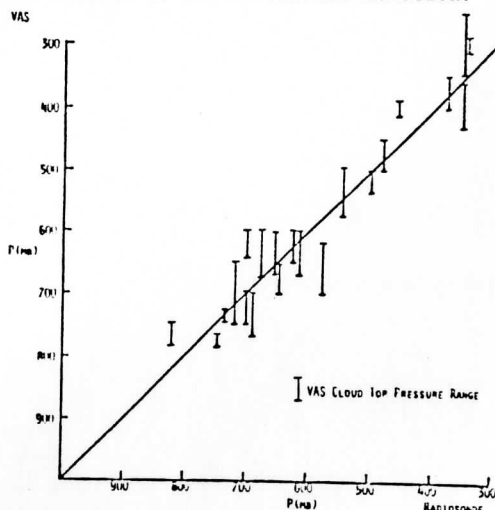

Fig. 2. VAS versus radiosonde cloud top pressures observed during winter 1985-86. RMS difference is 40 mb.

cloud top pressures compare extremely well with the radiosonde determinations; they are within 40 mb rms of each other. It should be noted that most of the height determinations below 600 mb are infrared window calculations. Validation of the cirrus heights will be accomplished with lidar determinations in future work.

4.   EXAMPLE STATISTICS

Cloud cover is a highly variable phenomenon which depends heavily on the storm tracks and other weather conditions. Detailed statistics of the November 1985 cloud summary for two cities in the midwestern United States (shown in Table 1) provide an example of how cloud cover can vary over short distances. Madison, Wisconsin and Chicago, Illinois are separated by approximately 150 km. The statistics of the satellite cloud observations for local noon (1800 GMT) are given for ten intervals of cloud top altitude and for five intervals of effective cloud amount or emissivity. The left column gives the frequency of cloud reports by altitude regardless of the cloud amount/emissivity. The next five columns show the distribution of cloud reports for five intervals of cloud amount or emissivity. The low cloud amount/emissivities (center columns) indicate cirrus clouds which were partially transmitting infrared radiation, while the right column summarizes the reports of opaque clouds that did not transmit upwelling radiation. The sum of the five right columns should account for all of the cloud reports (100%).

Both cities experienced many days of deep opaque cloud cover. This is evident by the high frequency of reports from 400 to 200 mb in the left column. Clear sky conditions were indicated by the 1000 mb reports. Chicago had 29% clear reports, while Madison only had 12%. The frequency of cirrus cloud reports that partially transmitted upwelling infrared radiation (emissivities less than .8) were also higher in Madison (27% summed over columns 2 through 5) compared to Chicago (16%). The thicker opaque cloud cover (right column) was also higher at 61% in Madison compared to 54% in Chicago. These differences reflect the fact that the position of the polar front and cyclone tracks were north of Chicago during the month.

5.   GEOGRAPHICAL COVERAGE

Statistical results for the entire United States plus coastal oceans for 13 months (October 1985 to October 86) are shown in Table 2 (coverage includes 27° to 51°N latitude and 55° to 157°W longitude). Cloud height determinations were made near 1800 GMT using the VAS radiances (the statistics reflect over 984,000 determinations). The most immediate finding is that 26% of the area was covered with thin or cirrus clouds. Approximately 45% of the United States was covered with thick opaque clouds and truly clear sky conditions occurred about 29% of the time. The cloud top pressures were distributed with 10% above 300 mb, 21% between 300 and 500 mb, 40% between 500 and 900 mb, and 29% at the surface (clear sky conditions). The thin clouds were mostly above 500 mb.

The geographical distribution of cloudy, cirrus and clear sky conditions for the year of October 1985 thru October 1986, is summarized in

TABLE 1. Cloud Statistics for Madison, Wisconsin 42°N 90°W November 1985. 483 Observations in a 2°x2° box over 19 days from 1500 to 1800 GMT.

Level(mb)	Cloud Emissivity				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
100-199	0%	0%	0%	0%	0%
200-299	0	1	2	2	6
300-399	0	2	3	4	13
400-499	0	3	3	2	12
500-599	0	1	1	1	6
600-699	0	0	1	1	11
700-799	0	0	0	0	9
800-899	0	0	0	0	3
900-999	0	0	0	0	1
1000-1099	12	0	0	0	0
Total	12%	7%	10%	10%	61%

12% Clear   27% Cirrus   61% Cloudy

Cloud Statistics for Chicago, Illinois 42°N 88°W November 1985. 408 Observations in a 2°x2° box over 19 days from 1500 to 1800 GMT.

Level(mb)	Cloud Emissivity				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
100-199	0%	0%	0%	0%	0%
200-299	0	1	1	0	16
300-399	0	1	2	1	11
400-499	0	1	3	1	4
500-599	1	1	1	1	5
600-699	0	0	0	1	9
700-799	1	0	0	0	8
800-899	0	0	0	0	1
900-999	0	0	0	0	0
1000-1099	29	0	0	0	0
Total	31%	4%	7%	4%	54%

29% Clear   17% Cirrus   54% Cloudy

TABLE 2. Cloud Statistics for United States, 27° to 51°N and 55° to 157°W for October 1985 thru October 1986 near 1800 GMT.

Level(mb)	Cloud Emissivity				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.95	0.95-1.0
100-199	0%	0%	0%	0%	0%
200-299	2	2	2	2	2
300-399	1	3	2	3	3
400-499	1	2	2	2	3
500-599	0	0	1	1	3
600-699	0	0	0	0	6
700-799	0	0	0	0	13
800-899	0	0	0	0	10
900-999	0	0	0	0	5
1000-1099	27	0	0	0	0
Total	31%	7%	7%	8%	45%

29% Clear   26% Cirrus   45% Cloudy

Fig. 3. All reports inside 2° latitude by 2° longitude boxes for each day at 1800 GMT were averaged together to produce the cloud statistics. Cloudy indicates all reports with cloud amounts/ emissivities greater than 0.95 in Fig. 3a. Cloud reports with cloud amounts/ emissivities less than 0.95 were summarized as cirrus in Fig. 3b, and clear sky reports are summarized in Fig. 3c. A large change in cloud cover with latitude is apparent. The states of Arizona and New Mexico in the central southern United States has the lowest frequency of cloudy conditions and the highest frequency of clear conditions. The frequency of clear reports reinforces the descriptor "Sun Belt" associated with southern states bordering Mexico. Transmissive cirrus clouds (Fig. 3b) were found at all locations in frequencies of 10 to 30%. The highest occurrences were in the northwestern mountain states of Utah, Colorado, and Wyoming. An increase in cirrus reports with latitude also is apparent.

6. CONCLUSIONS

This is a preliminary report of an ongoing study of cloud cover. Definitive conclusions on cloud cover statistics must wait until more years of data are compiled. However, these statistics for one year show results which have been reasonably anticipated. The most obvious finding of this study is the high incidence of thin cirrus clouds. Cirrus clouds have been given little attention in the past because they do not yield precipitation or damaging weather. But they do have a large impact on the radiative balance of the earth. Thin cirrus allow solar heating yet at the same time trap upwelling terrestrial infrared radiation. Our cloud statistics indicate that thin cirrus (cloud amount/ emissivities less than 0.95) occur 15 to 40% of the time over the United States. Thus, they are very numerous and must have a large effect on the heat balance of the earth.
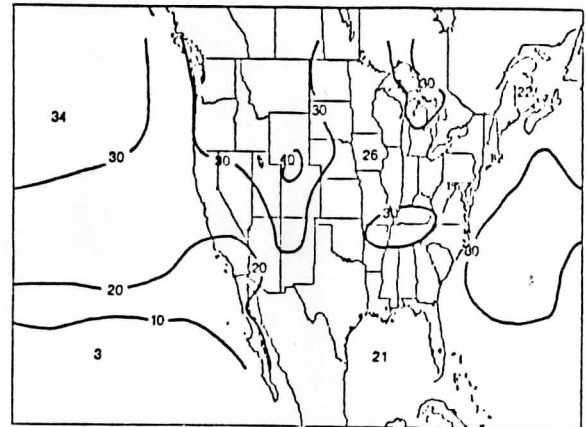
7. REFERENCES

Menzel, W. P., W. L. Smith, and T. R. Stewart, 1983: Improved cloud motion wind vector and altitude assignment using VAS. J. Clim. Appl. Meteor. 22, 377-384.
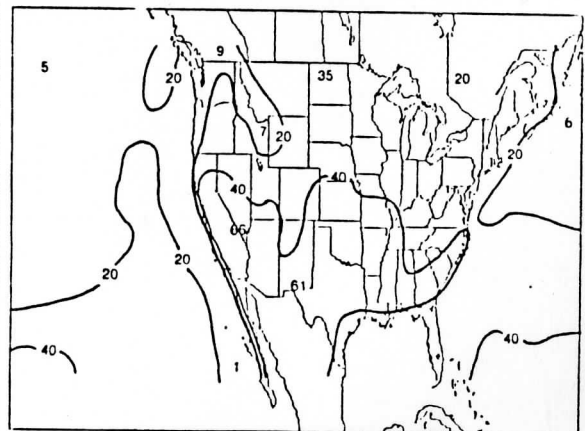
8. ACKNOWLEDGMENTS
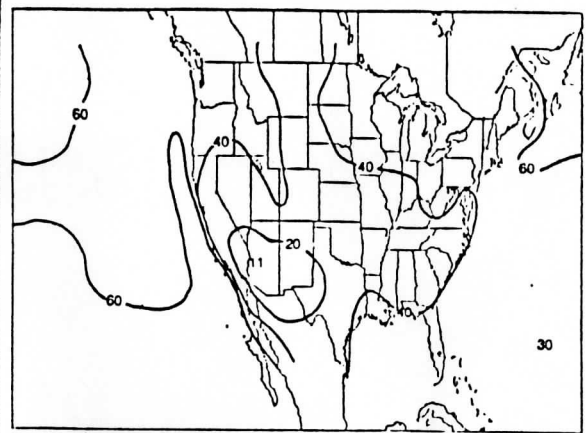
A. Probability of Opaque Cloud Cover (%)

B. Probability of Cirrus Clouds (%)

C. Probability of Clear Sky (%)

Fig. 3. Geographic distribution of VAS determinations of cloudy (a), cirrus (b), and clear (c) sky conditions for October 1985 thru October 1986.

APPENDIX B

Cloud cover statistics using VAS

D. P. Wylie and W. P. Menzel[1]

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ABSTRACT

Statistics of cloud characteristics over North America have been calculated for the past two years. The frequency of cloud cover with the associated heights and infrared attenuation were charted using the CO_2 channel radiometric data from the geostationary VISSR Atmospheric Sounder (VAS). Cloud top pressures were determined from the ratio of VAS CO_2 channel radiances in a radiative transfer equation formulation. Cloud emissivities were then calculated from infrared window channel observations. CO_2 techniques derived height and emissivity assignments have been found to be reliable in all cloud types, including thin cirrus clouds where other techniques have been inconsistent. Observations since 1985 revealed that 25% to 35% of the United States was covered with thin clouds (radiative attenuation was less than 95%), 45% was covered with thick opaque clouds, and 20% to 30% had clear sky conditions. Geographical distribution of cloud cover shows a latitudinal dependence mainly over the Pacific Ocean. Moderate seasonal and diurnal changes were also found.

1. INTRODUCTION

The frequency of cirrus clouds usually has been underestimated in cloud population studies. Satellite methods of analyzing cloud cover often mistake cirrus clouds for lower level clouds or completely miss them, because their infrared brightness temperatures are warmer than the temperature associated with their true altitudes. Thin cirrus are especially hard to identify on visible satellite images because they reflect little solar radiation and appear as dark or broken cloud fields. With the multispectral infrared sensor on the GOES-VAS satellite, the identification of most cirrus is now possible.

A technique for deriving cloud top altitudes from the VAS infrared sensor was developed by Menzel (1983).[1] It is also applicable to the polar orbiting High-resolution Infrared Radiometer Sounder (HIRS). The technique takes advantage of infrared channels with partial CO_2 absorption where the different channels are sensitive to different levels in the atmosphere. Thus, clouds appear on each channel in proportion to their level in the atmosphere. Low clouds will not appear at all on the high level channels, while high clouds appear on all channels. By modelling the upwelling infrared radiation from the earth atmosphere system in several VAS channels simultaneously, it is possible to infer the cloud top height independence of radiative transmissivity of the cloud. This gives the CO_2 technique the ability to distinguish thin cirrus clouds that would normally be missed by other techniques due to the transmission of terrestrial radiation through the cirrus.

The CO_2 technique has been installed on the Man computer Interactive Data Access System (McIDAS) at the University of Wisconsin-Madison. It has been run operationally using the GOES-VAS imagery starting in October 1985. Statistics on cloud cover and especially cirrus cloud cover are being gathered for the continental United States and its bordering oceans. This paper describes the techniques and some of the first results of this program.

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The VAS radiometer detects infrared radiation in 12 spectral bands that lie between 3.9 and 15 microns at 7 or 14 km resolution in addition to visible reflections at 1 km resolution. The 15 micron CO_2 band channels provide a good sensitivity to the temperature of relatively cold regions of the atmosphere. A demonstration of the vertical resolution of the three relevant CO_2 channels is given by the temperature profile weighting functions shown in Fig. 1. Each curve in the figure shows the sensitivity of the radiance observed in the spectral interval of the indicated channel to local variations in atmospheric temperature. As may be seen, only clouds above the 350 mb level will have strong contributions to the radiance to space observed by the 14.2 micron band (VAS channel 3), while the 14.0 micron band (VAS channel 4) senses down to 700 mb and the 13.3 micron band (VAS channel 5) senses down near the surface of the earth.

To assign a cloud top pressure to a given cloud element, the ratio of the deviations in cloud produced radiances, $I(\nu)$, and the corresponding clear air radiances, $I_{cl}(\nu)$, for two spectral channels of frequency ν_1 and ν_2 viewing the same field-of-view is written as
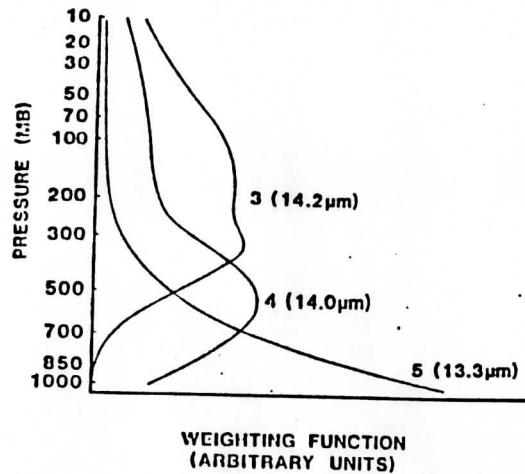
Figure 1. The temperature profile weighting function of radiance to space as a function of emitting level for the VAS CO_2 spectral bands centered at 14.2, 14.0, and 13.3 microns.

$$\frac{I(\nu_1) - I_{cl}(\nu_1)}{I(\nu_2) - I_{cl}(\nu_2)} = \frac{\epsilon_1 \int_{P_s}^{P_c} \tau(\nu_1,p) \frac{dB[\nu_1, T(p)]}{dp} dp}{\epsilon_2 \int_{P_s}^{P_c} \tau(\nu_2,p) \frac{dB[\nu_2, T(p)]}{dp} dp} .$$ (1)

In this equation, ϵ is the cloud emissivity, P_s the surface pressure, P_c the cloud pressure, $\tau(\nu,p)$ the fractional transmittance of radiation of frequency ν emitted from the atmospheric pressure level (p) arriving at the top of the atmosphere (p = 0), and $B[\nu,T(p)]$ is the Planck radiance of frequency ν for temperature $T(p)$. If the frequencies are close enough together, then $\epsilon_1 \approx \epsilon_2$, and one has an expression by which the pressure of the cloud within the field-of-view (FOV) can be specified. The left side of equation (1) is determined from the VAS observed radiances and clear air radiances provided from spatial analyses of VAS clear-sky radiance observations. The right side of equation (1) is calculated from a temperature profile and the profiles of atmospheric transmittance for the spectral channels as a function of P_c, the cloud top pressure (discrete values at ~50 mb intervals spanning 10000 to 100 mb are used). In this study, global forecast temperature and moisture fields from the National Meteorological Center (NMC) are used. The optimum cloud top pressure is determined when the absolute difference |right (ν_1, ν_2) - left (ν_1, ν_2, P_c)| is a minimum.

Once a cloud height has been determined, an effective cloud amount (also referred to as effective emissivity in this paper) can be evaluated from the infrared window channel data using the relation

$$\epsilon = \frac{I(w) - I_{cl}(w)}{B[w, T(P_c)] - I_{cl}(w)} .$$ (2)

Here N is the fractional cloud cover within the FOV, Nϵ the effective cloud amount, w represents the window channel frequency, and $B[w, T(P_c)]$ is the opaque cloud radiance.

Using the ratios of radiances of the three CO_2 spectral channels, three separate cloud top pressures can be determined (14.2/14.0, 14.0/13.3, and 14.2/13.3). If $(I - I_{cl})$ is within the noise response of the instrument (~ 1 mW m^{-2} - sr^{-1} - cm^{-1}), the resulting P_c is rejected. Using the infrared window and the three cloud top pressures, three effective cloud amount determinations are made. As described by Menzel (1983), the most representative cloud height and amount are those that best satisfy the radiative transfer equation for the three CO_2 channels.

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The CO_2 technique is independent of the fractional cloud cover; heights and effective cloud amounts can be determined for partially cloudy FOVs. However, the CO_2 technique sees only the highest cloud and cannot resolve multi-layer clouds. Because the VAS FOV

resolution is coarse (14 km for this work), very small element clouds are difficult to detect. Also, because the weighting functions for the VAS channels are broad, there is an inherent lack of vertical resolution in the measurements. Nonetheless, reliable cloud statistics can be calculated with appropriate application of the technique.

Since October 1985, the VAS instrument on board GOES-East has been programmed to gather sounding data over the United States at least twice daily (near 1200 GMT and 000 GMT) and as often as four times daily (near 600, 1200, 1800, and 0000 GMT). The CO_2 technique has been applied to these data routinely. In this study, radiances for three FOVs were averaged for cloud height and amount determinations (representing an area of 14 by 42 km at the satellite subpoint) at roughly 100 km spacing. Surface observations were used to adjust the global forecast temperature and moisture fields. No adjustments for topography were made. Transmittances were determined from line-by-line calculations with the spectral response functions for the appropriate VAS channels.

3. VALIDATION

Quantitative comparisons are shown in Figure 2. The CO_2 (or infrared window where necessary for low clouds) cloud top pressures are shown with the determinations from radiosondes. Cloud-top pressures are estimated from 1200 or 0000 GMT radiosonde temperature and dew point temperature profiles by noting where the dew point temperature profile becomes much drier as it emerges from the cloud and hence indicates cloud-top pressure. Since the profile analysis is not always definitive, a reliable radiosonde cloud height determination is not always available, especially in cirrus clouds. VAS observations were usually within 30 minutes of the raobs and were gathered over a three month period. The range of VAS cloud top pressures is from the four FOVs nearest to the radiosonde location. The VAS cloud top pressures compare extremely well with the radiosonde determinations; they are within 40 mb rms of each other. It should be noted that most of the height determinations below 600 mb are infrared window calculations. Validation of the cirrus heights has been started by comparing with lidar determinations.
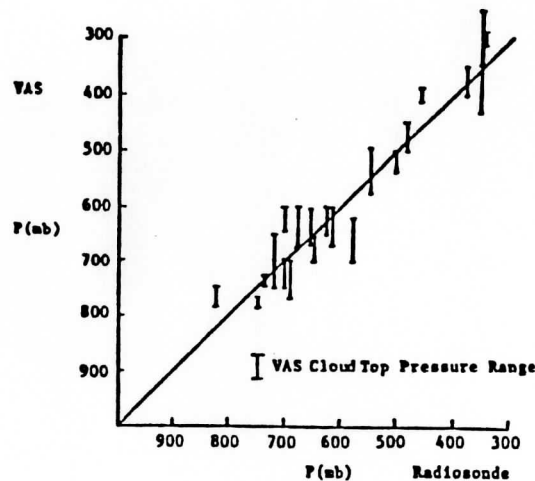

Figure 2. VAS versus radiosonde cloud top pressures observed during winter 1985-86. RMS differences is 40 mb.

4. MEAN STATISTICS

Cloud cover is a highly variable phenomenon which depends heavily on the storm tracks and other weather conditions. A statistical summary of all the cloud observations made from October 1985 through October 1987 are shown in Table 1. They cover the area from 27° to 51°N latitude and 55° to 150°W longitude. Over 2.7 million observations were collected. 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 300 mb comprised 11% of the observations. 42% were between 300 mb and 800 mb. Low clouds below 800 mb were found 17% of the time. Clear sky conditions, labelled as 1000 mb, were found 30% of the time.

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. We consider effective emissivity observations greater than 0.95 to be opaque clouds since the cloud top height derived from equation (1) 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.

Table 1. Cloud Statistics for the United States
27° to 51°N and 55° to 150°W for October 1985 through October 1987

Level (mb)	Effective Emissivity				
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.95	0.95-1.0
100-199	0 %	0 %	0 %	0 %	0 %
200-299	2	3	2	2	2
300-399	1	3	3	3	3
400-499	0	1	2	2	2
500-599	0	0	1	1	2
600-699	0	0	0	0	6
700-799	0	0	0	0	12
800-899	0	0	0	0	12
900-999	0	0	0	0	5
1000 (clear)	30	0	0	0	0
	33 %	7 %	8 %	8 %	44 %
	30% Clear		26% Cirrus		44% Cloudy

Cirrus clouds are defined as observations with effective emissivities less than 0.95. 26% of our observations fell into this category. They were found from 200 to 600 mb. Clouds opaque to infrared radiation with effective emissivities greater than 0.95 (right column) were found 44% of the time. The remaining observations, 1000 mb (clear sky), were found 30% of the time. Thus, 70% of the satellite observations over North America for the past two years found clouds.

5. GEOGRAPHICAL COVERAGE

The geographical distributions of cloudy, cirrus and clear sky conditions from October 1985 through October 1987 are summarized in Figure 3. All reports inside 2° latitude by 2° longitude boxes were averaged together to produce the cloud statistics. The opaque cloud cover panel (Figure 3A) shows the probability of finding cloud cover with effective emissivity >0.95. Cloud reports with effective emissivities <0.95 were called cirrus clouds (probabilities are shown in Figure 3B). The probability of clear sky conditions (no detectable cloud) are shown in Figure 3C. Opaque cloud cover shows large geographical changes between the desert states of Arizona and New Mexico and the rest of the country. The clear sky probabilities reinforce the descriptor "sun belt" associated with the southern states of the U.S. Transmissive cirrus clouds were found in all locations, more frequently in the northwestern mountain states (Utah, Colorado, and Wyoming) and less frequently over the subtropical Pacific Ocean.

6. SEASONAL CHANGES

December, January and February observations were averaged for one winter. June, July and August observations were averaged for two summers. The results are shown in Table 2.

Fewer clouds were found in the summer than in the winter. Opaque clouds comprised 50% in the winter and dropped to 43% in the summer. Non-opaque cirrus were found 31% of the time in the winter while they were found only 26% of the time in the summer. Clear sky observations increased from 19% in the winter to 31% in the summer.

Table 2. Winter to Summer Seasonal Changes in Mean Cloud Cover
for 27°-51°N, 55°-150°W

	Winter	Summer
Cirrus clouds	31 %	26 %
Opaque clouds	50 %	43 %
Clear skies	19 %	31 %

The mean height of non-opaque cirrus observations also changed between the winter and summer seasons. The mean height of all non-opaque cirrus observations is shown in Figure 4A. The cirrus cloud tops appear to be lowest in the Rocky Mountains where an average height of 400 mb was found (this could change if topography were taken into account in the algorithm). Higher cirrus cloud top averages were found east of the Rockies (340 mb) and over the oceans (320 mb).

These height averages were lower in the winter than in the summer. Generally, 50 to 100 mb change occurred in the average height over most of the continental United States (see Figure 4B). The largest changes were in the Ohio Valley and the smallest changes were in the Pacific northwestern states.
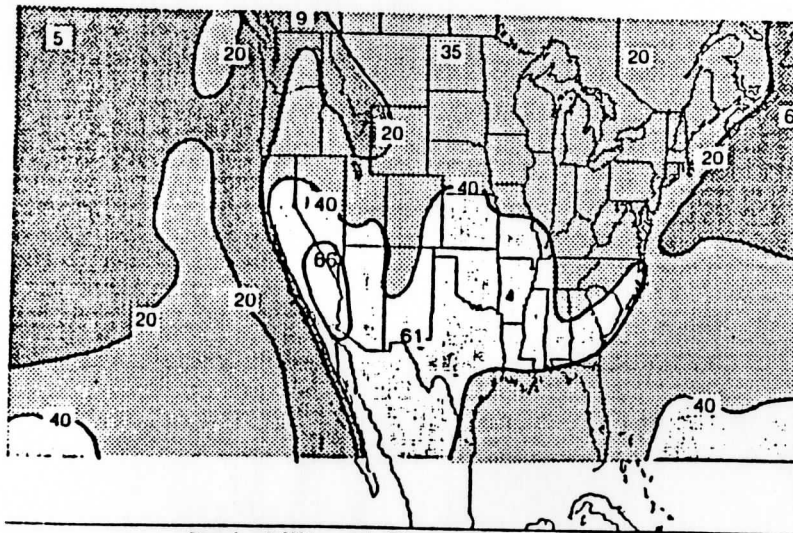
7. DIURNAL CHANGES

Moderate diurnal changes were found in the cloud data from the past two years (see Table 3). Opaque cloud cover over the study area changed from a maximum of 45% at 18:00 GMT to a minimum of 37% at 06:00 GMT. Non-opaque cirrus had smaller changes on the average. They
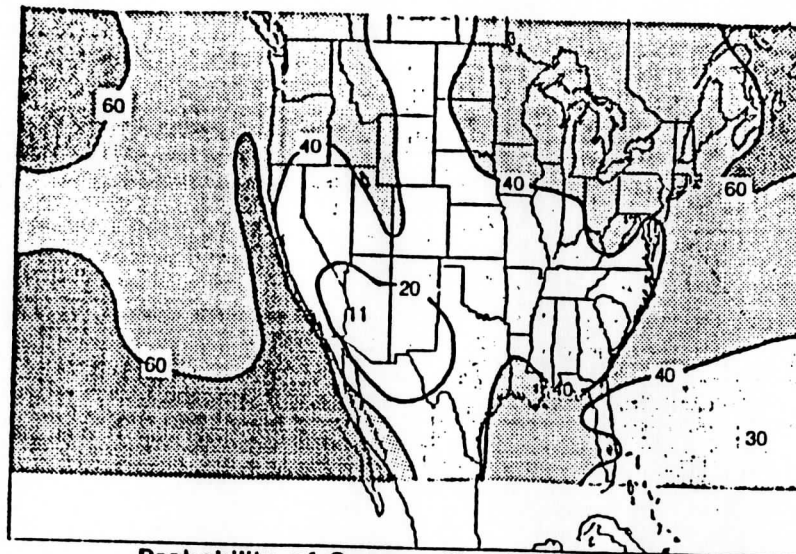
Probability of Opaque Cloud Cover (%)
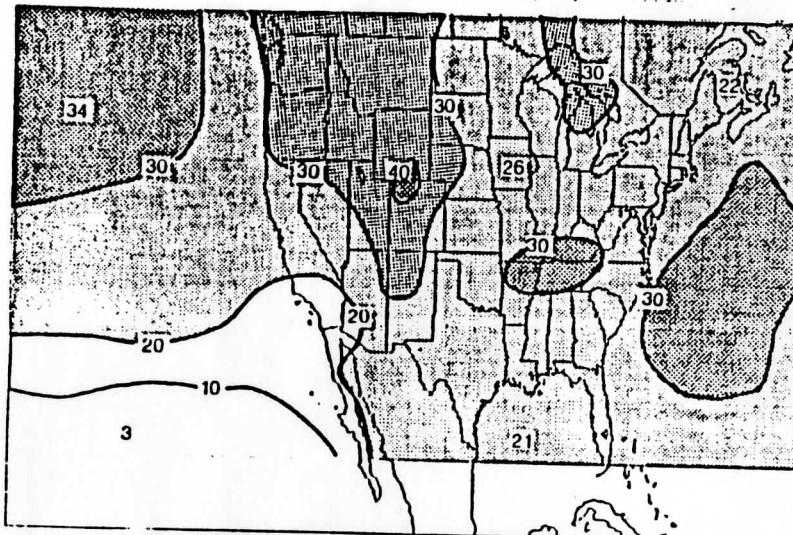
Probability of Cirrus Clouds (%)

Probability of Clear Sky (%)

Figure 3. The geographical distributions of (A) cloudy, (B) cirrus, and (C) clear sky conditions from October 1985 through October 1987.

AVERAGE HEIGHT OF CIRRUS (mb)
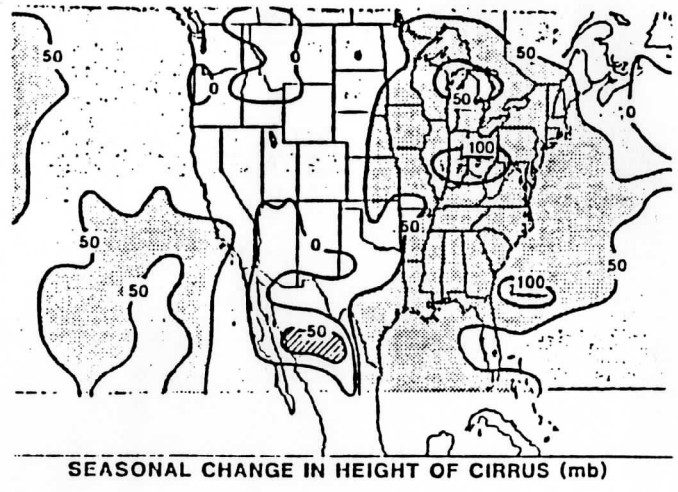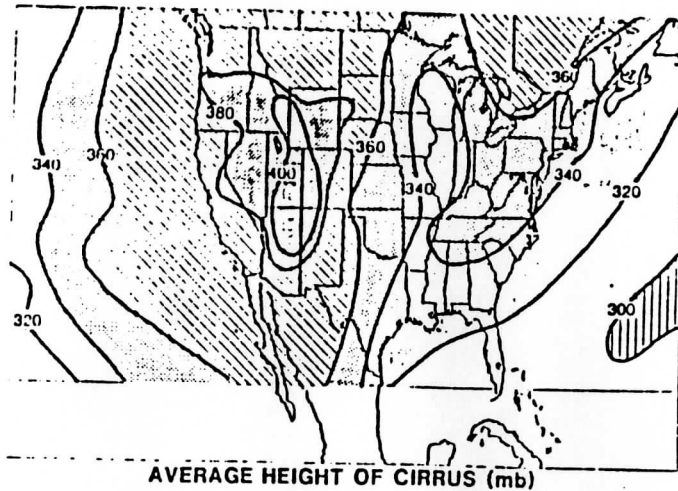

SEASONAL CHANGE IN HEIGHT OF CIRRUS (mb)

Figure 4.   (A) The average heights of the cirrus observations from October 1985 through
October 1987.   (B) The seasonal change in the heights of the cirrus, winter minus
summer.

Table 3.   Average Frequency of Cloud Observations for Four Time Periods Each Day

GMT	Cirrus Clouds	Opaque Clouds	Clear Sky
00	28 %	38 %	34 %
06	24	37	39
12	23	40	37
18	24	45	31

comprised 23 to 24% of the data for all times sampled , except at 00:00 GMT when 28% were
found.   clear sky observations had diurnal fluctuations similar to the opaque clouds
changing from 31% at 18:00 GMT to 39% at 06:00 GMT.   The largest diurnal changes were found
during the summer season.

Geographically, the largest diurnal changes in transmissive cirrus observations occurred
along the Gulf coastal states and in the Rocky Mountains (see Figure 5).   In the Gulf coast
and Colorado where cirrus cloud observations increased over the day, the opaque cloud
observations decreased.

8.   DISCUSSION AND CONCLUSIONS

This is a preliminary report of an ongoing study of cloud cover.   Definitive conclusions
on cloud cover statistics must wait until more years of data and more analyses are
compiled.   However, some interesting trends are emerging.   The most obvious finding is the
height incidence of transmissive cirrus clouds.   Cirrus clouds have been given little
attention in the past because they do not yield precipitation or damaging weather, but they
have a large impact on atmospheric radiation.

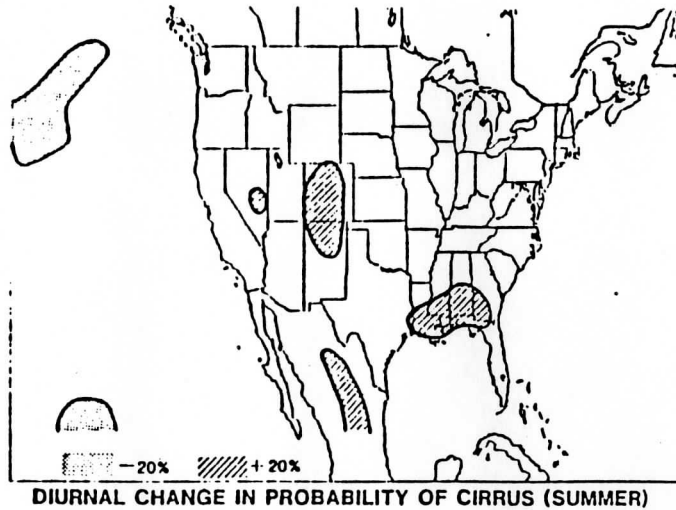DIURNAL CHANGE IN PROBABILITY OF CIRRUS (SUMMER)

Figure 5. Geographical distribution of the diurnal change in the probability of cirrus observations (p.m. minus a.m.) for summer.

These cloud statistics for October 1985 through October 1987 indicate that transmissive cirrus occur 25 to 35% of the time over the continental United States. Small seasonal and diurnal changes in the frequency of cirrus clouds (about 5%) were not strongly connected with those of opaque clouds (about 8%). This suggests that cirrus can be related to large scale synoptic patterns and are not always directly related to other cloud types.

9. ACKNOWLEDGMENTS

The authors gratefully acknowledge the efforts of William Smith, Jr. and Peter Grimm who performed most of the data processing presented here.

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Lidar Observations of Cirrus Cloud Parameters

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Abstract

Cirrus cloud observations obtained with the University of Wisconsin High Spectral Resolution Lidar and High Performance Nd:Yag lidar are presented. These include accurate determination of the optical depths, backscatter phase functions, three-dimensional spatial structure and internal wind fields.

1. INTRODUCTION

Cirrus clouds exert an important influence on the earth's radiation balance by reflecting incoming solar radiation and trapping outgoing terrestrial radiation. Crystal fallout from these clouds can seed underlying supercooled water clouds producing precipitation. The influence of these clouds can profoundly effect a wide range of remote sensors which attempt to look either up through the cloud at objects above the atmosphere, or down from space at objects below the clouds. Scattering and absorption in the cloud attenuates radiation from the target. Thermal radiation from the cloud and scattering of ambient radiation provides increased background noise. Image contrast and the divergence of transmitted optical beams can be adversely affected by the multiple scattering effects of intervening cirrus clouds. Despite the importance of cirrus cloud effects they are our least studied and most poorly understood common cloud form. Many basic questions remain unanswered: we have only rudimentary forecast capabilities, we suspect that subvisible clouds which may have important optical effects occur frequently, we know little about cloud geometry, less about statistics of cloud free lines of sight and very little about the optical properties of these clouds.

The difficulty of making measurements at cirrus altitudes has hampered observations. Recent improvements in both active and passive remote sensors along with a growing realization of the importance of these clouds has sparked new interest in this research topic. This paper presents the preliminary results of one type of observation.

2. LIDAR EQUIPMENT

The University of Wisconsin operates two lidar systems with unique capabilities; one which can make unambiguous remote measurements of optical extinction and backscatter cross sections, and a second system which can acquire high spatial resolution, three-dimensional pictures of atmosphere structure.

The High Spectral Resolution Lidar (HSRL) uses the Doppler broadening of signals scattered from air molecules to distinguish molecular scattering from aerosol scattering. Since the molecular backscatter cross section can be calculated from an atmospheric density profile, the molecular component of the lidar return can be used as a calibration target which is available everywhere in the scanned volume. Backscatter measured from this known target then allows direct calculation of the optical extinction and the backscatter cross section. While the HSRL was designed primarily for the characterization of boundary layer aerosol scattering, we have adapted the system to the demanding task of cirrus measurements.

The molecular scattering component of lidar return, which provides the HSRL calibration, becomes difficult to measure inside the cirrus cloud. This occurs because cirrus clouds have typical altitudes of up to 15 km producing four deleterious effects: 1) the signal is reduced by the additional range to the target, 2) the reduction in air density decreases the molecular scattering cross section, 3) the lower temperature reduces the spectral width of the Doppler-broadened molecular scattering making it more difficult to separate from the unbroadened aerosol component, and 4) the backscatter cross section of the cloud is typically very much larger than the molecular cross section, thus requiring very accurate inversion of the lidar signals to separate the molecular scattering from the cloud scattering.

The UW Nd:Yag lidar has been designed to rapidly scan large atmospheric volumes in order to provide three-dimensional maps of aerosol structure. This lidar has a large aper-

ture (0.5m), rapid angular scanning capability (25 deg/sec), high average power (25 Watts), fast pulse repetition rate (30 Hz) and capability to store large quantities of data on a 2.6 gigabyte capacity write once optical disk system. These characteristics allow observation of cirrus cloud geometries with unprecedented spatial and temporal resolution.

3. OBSERVATION PROGRAM

The HSRL was operated for a total 124 hours during the FIRE field experiment during the period of October 15 to November 2, 1986, with periodic operations adding another 65 hours in the period between the experiment and Dec. 1, 1987. During all of these observations the HSRL was operated from a site on the campus of the University of Wisconsin in Madison, Wisconsin.

The Nd:Yag lidar was operated as a part of the NASA FIFE experiment from a site just south of Manhattan, Kansas during the period from June 30 to July 9, 1987. From September 23 to November 6, 197 this lidar was operated from a field site approximately 30 miles south of Madison, Wisconsin. During of these measurement campaigns the lidar was used for both the observation of cirrus clouds and the atmospheric boundary layer. In this paper we report on the cirrus cloud measurements.

4. MEASURED OPTICAL PROPERTIES

The HSRL has been used to measure optical depths, mean backscatter phase functions and backscatter cross section profiles in cirrus clouds. Results of these measurements will be presented in this paper. Figure 1 provides a typical example of the backscatter cross section profile measured in an optically thin cirrus cloud. Table 1 summarizes optical characteristics thus far established for cirrus clouds observed as part of the FIRE experiment.

$X10^{-5}$ Backscatter X-Section $(M^{-1}SR^{-1})$ 16:25 GMT 10/31/86
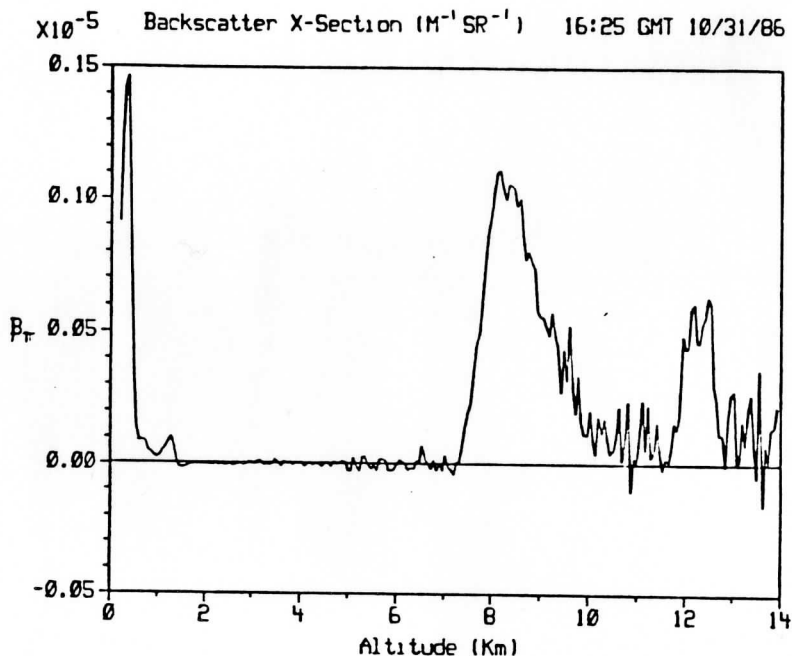

Fig. 1 Autumn "warm sector" cirrus backscatter cross section profile. The two layer structure is often observed in this type of formation.

Table 1: HSRL Measured Cirrus Cloud Optical Properties

Date	Time GMT	Altitude km	Optical Thickness	$P_a(\pi)/4\pi$ Sr^{-1}	T C°
10/27/86	23:00	8.0	.03 ± .006	.028	-32.6
10/31/86	14:25	10.5	.11 ± .037	.030	-59.0
10/31/86	15:05	10.2	.09 ± .034	.032	-51.5
10/31/86	15:45	9.1	.12 ± .049	.024	-41.5
10/31/86	16:25	8.6	.07 ± .032	.039	-38.0
10/31/86	16:25	12.1	.02 ± .012	.023	-66.5
10/31/86	17:05	8.8	.05 ± .019	.034	-39.3
10/31/86	17:05	12.1	.01 ± .007	.045	-66.5

Observations of Cirrus backscatter phase functions made by Platt and Dilley show a marked dependence on cloud temperature. Our HSRL derived backscatter phase functions made over Madison, Wisconsin have thus far provided no evidence to support a cloud temperature dependence (see fig. 2).

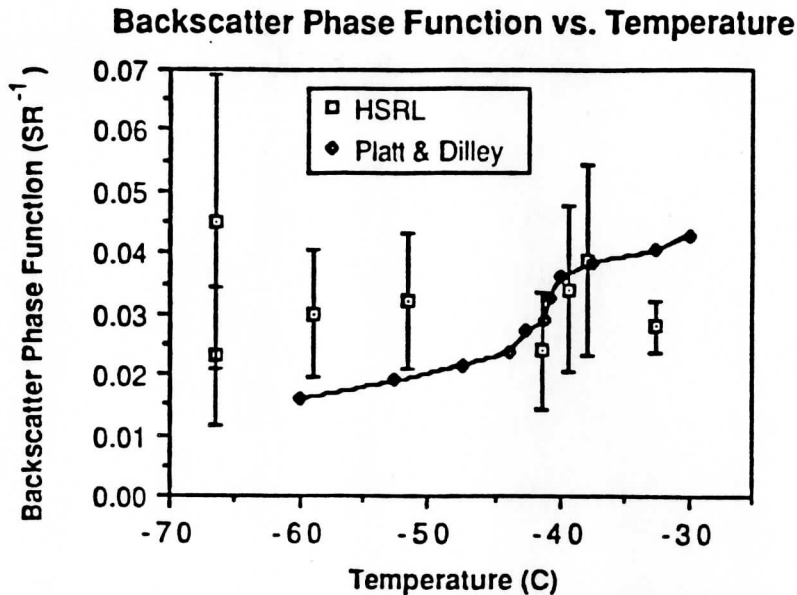## Backscatter Phase Function vs. Temperature

Fig. 2. The relationship of $P_a(\pi)/4\pi$ to temperature as reported by Platt & Dilley is compared with the independent HSRL measurements acquired during FIRE. A clear cut relationship between backscatter phase function and temperature is not apparent in the latter data set. Mie calculations show that an ensemble of liquid water spheres with an average size parameters of 500 could be expected to exhibit a backscatter phase function of .072 SR^{-1}.[2]

In our presentation, we will show examples of zenith angle specular backscatter from oriented ice crystals observed with the Nd:Yag system. In some cases the cone of enhanced backscatter exhibits 1/e full widths on the order of 1 degree, indicating crystals with large, horizontally-oriented flat faces. The presence of these sporadic, localized regions of specular reflection indicates the heterogeneous nature of ice crystal scattering properties within the cloud.

5. STRUCTURE OF CIRRUS CLOUDS

Preliminary examination of data acquired with the new UW Nd:Yag lidar has revealed organized cirrus cloud structure on scales ranging from our minimum resolution of 10 meters to the largest scales thus far observed of 50 km.

Casual 'eyeball' observations reveal that cirrus clouds frequently have complex three dimensional shapes. With conventional instruments it is difficult to map this structure. Even with a high repetition rate lidar, it is difficult to scan a sufficiently large volume in a short enough time to produce 3-D images which incorporate the large range of spatial scales represented by the clouds. The time available to generate an image is limited by the rapid motion and temporal evolution of the clouds.

Using the new UW Nd:Yag lidar we have begun studies of the 3-dimensional structure of cirrus clouds. In one type of observation, the lidar scans two orthogonal planes which cross at the zenith. One plane is approximately aligned with the mean motion of the cirrus and the other is perpendicular to the motion. This scan pattern allows construction of three dimensional pictures of cirrus clouds. the high repetition rate of this lidar allows a pair of scan planes to be completed in 30 seconds, with each plane showing a segment 8 km long at the cloud altitude. Height resolution of 15 meters is coupled with horizontal resolutions on the order of 20 meters. To observe larger spatial scales, a 60 km long section of cloud can be scanned in approximately 30 seconds, with only minor degradation in resolution. Space-time correlations can be used to provide the vertical profiles of the horizontal wind in the clouds as well as to investigate the scale sizes of the cloud structure. In the simplest 3-D display mode the two intersecting scan planes can be combined in perspective views and successive image pairs displayed to provide a time lapse movie of the cirrus structures. A display of this type will be included in our

presentation. At our laboratory we have also combined these images into true 3-D displays using cross polarized images for left and right eyes coupled with eyeglass filters. Additional 3-D depictions are planned using the cross-wind pictures and the measured wind speed to build 3-D volume filling images.

Observations of the cirrus clouds with our Nd:Yag lidar show considerable variability in the spatial structure of the clouds. Since this lidar is new, beginning operations in June of 1987, our data sample is rather small; it appears, however, that the cirrus clouds resulting from cumulonimbus formations tend to be different from clouds formed as a result of other processes. Many of the 'anvil cirrus' clouds are strongly layered with thin stable layers interspaced with thin apparently turbulent layers. The air mass cirrus developments observed during the Wisconsin fall often have much greater vertical extent with individual vertically developed structures embedded in the layer. These clouds often have thicknesses of several kilometers. These differences may be due to the fact that the vertical growth of cumulonimbus clouds is only halted by very stable air above the tropopause. The cirrus clouds are thus injected into a very stable regime often characterized by large wind shear; this stability coupled with the shear then produces the interspaced turbulent and stable layers. It seems likely that the air mass cirrus are produced in layers which are convectively unstable thus producing the greater vertical development.

6. ACKNOWLEDGMENTS

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