3.1 LIDAR APPLIED TO CIRRUS CLOUD RESEARCH

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1. Introduction

To lessen climate change prediction uncertainties, it is necessary to better comprehend the processes governing the current state of climate, and the potential feedbacks that respond (positively or negatively) to greenhouse gas global warming. In both these areas, the role of cirrus clouds on climate is poorly known (Liou 1986). Lidar has been and will continue to be a vital component in the study of cirrus clouds.

Cirrus clouds are by definition icy, optically thin, and remote (Lynch et al. 2002). Although these features make them difficult or costly to study using aircraft probes, microwave radars, and satellites, lidar systems are uniquely suited to detect and characterize them via a number of optical techniques. These techniques are: simple backscatter lidar, which determines cloud boundaries and reveals internal cloud structures; scanning polarization diversity lidar, which provides information on cloud particle phase, shape, and orientation, as well as any associated aerosol; Raman or High Spectral Resolution Lidar (HSRL), which provides intrinsically calibrated optical attenuation coefficient and optical depth data; and Differential Absorption Lidar (DIAL), which characterizes particle backscattering and the water vapor density/relative humidity of the cirrus cloud environment.

Moreover, a number of multiple remote sensor methods have been developed that combine lidar with millimeter-wave radar or radiometer measurements to derive quantitative data quantities like visible and infrared optical depths. The most popular of these hybrid techniques is the combined lidar and midinfrared radiometer (LIRAD) method (Platt 1973; Platt et al. 1987; Comstock and Sassen 2001), and combined lidar-radar-radiometer methods, which have also shown utility in characterizing basic cloud type (Wang and Sassen 2001). The LIRAD method uses the downwelling atmospheric window radiation (after corrections for propagation losses and gaseous emissions), lidar cloud heights, and integrated backscattering to derive infrared emittance and improved estimates of visible cloud optical depth. In essence, the multiple remote sensing methods attempt to improve the data inversion on the basis of the different sensitivities of each sensor to the width of the ice particle size distribution.

Here we review recent developments in lidar studies of cirrus clouds, emphasizing findings between 1987 and 2002 from the Facility for Atmospheric Remote Sensing (FARS) in Salt Lake City, UT. Because of the unprecedented length of these observations dedicated to cirrus clouds, it is possible to draw climatologically representative findings from this extended polarization lidar and multiple remote sensor dataset.

2. FARS Data Collection

The (former) FARS was established in 1987 on the edge of the University of Utah campus (40° 49′ 00″ N, 111° 49′ 38″ E) overlooking Salt Lake City in northern Utah. An observational program emphasizing the study of midlatitude cirrus clouds lasted until April 2002 in support of the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE) Extended Time Observations component (Cox et al. 1987). Over this 15-year period polarization lidar and passive radiometric data were routinely collected from high clouds during times of GOES and polar orbiting satellite local imagery. The main source (~3,300-h) of data involved the ruby (0.694 μm) Cloud Polarization Lidar (CPL), although a number of radiometers and more advanced lidar and Doppler W-band radar systems also contributed (see Sassen et al. 2001). The

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high-power (1.5 J) CPL system has a 0.1 Hz PRF, and data is digitized at 8-bit resolution with 7.5 m range gates.

The FARS ETO data collection goals emphasized the afternoon and evening hours, corresponding to the local polar orbiting satellite. Most FARS observations periods are of ~3-h duration. They were designed to encompass multiple satellite overpasses, and obtain records corresponding to the passage of mesoscale features of advecting cirrus cloud systems.

3. FARS Midlatitude Cirrus Cloud Results

Researching the FARS high cloud dataset, we have reported previously on the macrophysical and synoptic (Sassen and Campbell 2001), microphysical (Sassen and Benson 2001), radiative (Sassen and Comstock 2001), and halo-producing properties (Sassen et al. 2003) of the cirrus clouds over northern Utah. We will briefly review these findings to showcase lidar cloud research capabilities, and also discuss more recent results dealing with cirrus cloud structural features (Wang 2004).

3.1 Simple (one-channel) lidar research

Although cirrus clouds are remote in the upper troposphere and can be optically thin to the point of being subvisual, in the absence of lower obstructing clouds, proper lidars are uniquely effective in detecting and characterizing the macrophysical properties (e.g., heights and corresponding temperatures using sounding profiles) of cirrus. (In situ observations have limited coverage, and even the most sensitive millimeter-wave radar measurements currently do not detect the coldest cirrus that contain the smallest ice particles.) Lidars capable of detecting mid-tropospheric molecular returns will detect subvisual cirrus, and visual cirrus are normally transparent to lidar probing. However, when the optical depth of thickening cirrostratus increases to ~3.0, backscattered lidar signals can attenuate out before reaching cloud top depending on the overall unit sensitivity and signal processing (analog-versus-photon counting) method. Fortunately, such optical depths typically correspond to the point where the solar disk begins to become obscure, the criterion applied to visually separate cirrostratus from the thicker and lower altostratus cloud type (Sassen 2002).

Because even the basic properties of cirrus clouds, and how these vary with geographical location, are not well known, lidar climatological studies are important in the testing and improvement of satellite cloud algorithms and weather/climate model predictions, for example. The most comprehensive lidar climatology to date reported in Sassen and Campbell (2001) reveals the mean monthly macrophysical properties of cirrus from a particular midlatitude site, and how these properties depend on weather processes and local atmospheric structure. It is important, though, to properly identify the type of cloud being probed to obtain a sample consistent with other approaches, or at least clearly state your criteria and limitations.

More recent analysis of the FARS lidar dataset addresses the characterization of the structural inhomogeneities present in cirrus Quante and Starr 2002). Clouds are treated as horizontally-homogeneous, plane-parallel layers in large-scale models, but it is recognized that this simplification can create significant errors in the transfer of visible and infrared radiation through the atmosphere (Carlin et al. 2002; Fu et al. 2000). Wang (2004) used various statistical approaches to analyze the spatial variations in cirrus backscattering as a function of height to search for periodic cloud- and meso-scale structures. Applying wavelet analysis (Demoz et al. 1998) reveals that only ~8% of the cirrus time-height cross sections contain periodic structures (between ~1 – 100 km wavelength) with a high (95%) confidence level. The structures consist of cirrus mammatus at cloud base, cirrus uncinus cells near cloud top, embedded Kelvin-Helmholtz waves, and inhomogeneities on the mesoscale attributable to gravity waves or other causes. However, the relative occurrence of such cirrus cloud structures increases significantly with decreasing confidence level, suggesting that they tend to be quasi-periodic. Moreover, the standard deviations of the mean integrated signals show that *homogeneous* cirrus are rare and restricted to the physically and optically thinnest clouds. Autocorrelation analysis also suggests that cloud-scale structures dominate and that there are no preferred wavelengths for mesoscale waves.

3.2 Polarization lidar for cirrus cloud microphysical research

The laser backscatter depolarization technique was one of the first to be tested in the atmosphere (Schotland et al. 1971), and remains the only remote sensing tool that can unambiguously discriminate between water and ice clouds through its ability to sense particle shape and orientation (Sassen 2000, 2004). Theoretical ray-tracing simulations indicate that the laser backscatter linear depolarization ratio δ is a function of ice crystal habit and exact particle shape, including inclusions and crystal defects (Takano and Liou 1995). Ice crystals of certain sizes and shapes tend to uniformly orient in space during fall, which theory and scanning lidar measurements show can drastically effect backscattering and depolarization (Noel and Sassen 2005). Particle size exerts an affect only when the dimensions are similar or smaller than the incident laser wavelength (Mishchenko and Sassen 1998).

The climatological polarization lidar findings from FARS reported in Sassen and Benson (2001) reveal that δ steadily decreases with increasing height or decreasing temperature in cirrus clouds, which is in qualitative agreement with studies from other locations. This finding must reflect a gradual change in basic ice crystal shape, from plates to columns, with decreasing temperature, along with such other factors as solid versus hollow particle effects and changes in their ability to orient in the horizontal plane. The depolarization data also show that the presence of supercooled water droplets in cirrus is uncommon, mainly restricted to transient patches near relatively warm cirrus cloud bottoms, or, occasionally, sporadically at the tops of cirrostratus altocumulogenitus (Sassen 2002). It has also been pointed out in Sassen et al. (2003) that those cirrus clouds producing brilliant halos characteristically generate relatively low δ indicative of pristine plate crystals, both randomly and horizontally oriented.

3.3 Advanced lidar methods for radiative properties

Although simple lidars can provide estimates (generally good to a factor of ~2) of cirrus cloud optical depth τ using clear-air backscattering assumptions and assigned cirrus particle backscatter-to-extinction ratios, spectroscopic lidar techniques can do this with significantly greater certitude. HSRL (Grund and Eloranta (1990) and Raman lidars (Weitkamp 2004) use separated molecular returns to determine the extinction coefficients and τ due to the cirrus cloud particles. Cirrus cloud climatological studies of extinction coefficients and τ using Raman lidar have recently been reported (Wang and Sassen 2002). The water vapor fields in and surrounding cirrus have also been described using Raman techniques, revealing basic information on cirrus ice crystal nucleation processes (Comstock et al. 2004).

Alternatively, multiple remote sensor approaches based on lidar and other probes can provide information on the radiative properties of cirrus clouds. With the LIRAD method, combined lidar and coailgned midinfrared radiometer measurements allow for the derivation of infrared emittance and improved visible optical depths. Only path-integrated data quantities can be obtained, however. Sassen and Comstock (2001) presented a climatology of LIRAD results from FARS cirrus clouds broken down by midcloud temperature and cirrus cloud type.

4. Conclusion and Outlook

The various lidar atmospheric probing techniques have proven themselves highly suited for researching aerosols and many cloud types. Cirrus clouds and lidar appear ideally suited for each other because of the favorable interaction of light with the microphysical contents of these high clouds. Over my extended period of lidar observations of cirrus clouds, I have yet to see two clouds with similar linear depolarization displays: each cloud in unique!

We look forward to the view from space being promised by the upcoming launch of the polarization lidar satellite, CALIPSO (Winker et al. 2002). From Earth orbit cirrus clouds will be especially prominent targets and our understanding of their distribution and properties will take a great leap forward.

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