N91-10461

VERTICAL VELOCITIES WITHIN A CIRRUS CLOUD FROM DOPPLER LIDAR AND AIRCRAFT MEASUREMENTS DURING FIRE: IMPLICATIONS FOR PARTICLE GROWTH

Ismail GULTEPE and Andrew HEYMSFIELD
National Center for Atmospheric Research[1]
P.O. Box 3000
Boulder, Colorado 80307

1. INTRODUCTION

This paper uses a large and comprehensive data set taken by the NOAA CO_2 Doppler lidar, the NCAR King Air, and rawinsondes on 31 October 1986 during the FIRE (First International Regional Experiment) field program which took place in Wisconsin. Vertical velocities are determined from the Doppler lidar data, and are compared with velocities derived from the aircraft microphysical data. The data will be used for discussion of particle growth and dynamical processes operative within the cloud.

2. SYNOPTIC DISCUSSIONS

There was no large scale disturbances over the experimental area on 31 October 1986. The 1800 GMT surface map showed that there was a cold front 600 km to the west of the experimental area. At 1200 GMT, there was a weak upper level trough at the 200 mb level. The jet stream, with maximum wind speeds of about 45 m s^{-1}, was situated north of Wisconsin. Cirrus cloud formation occurred to the south of the jet stream in a warm air zone. There was not a direct relationship between the cirrus cloud location and the jet stream. A sounding from Green Bay at 11 CST (Figure 1) shows a moisture increase at upper levels where later the cirrus cloud formed. The base of the moisture zone is at about 450 mb with an isothermal layer just under the base. The cloud studied extended over an area of 45×20 km.

3. DISCUSSION OF AIRCRAFT AND LIDAR MEASUREMENTS

The NCAR King Air collected data within the cirrus cloud using six horizontal penetrations from 7.6 km (−29.6°C), cloud base, to 9.2 km (−42.6°C), cloud top. The King Air sampling period for each penetration was about 5 minutes, corresponding to 30 km horizontal legs. The time for total sampling through cloud layer was approximately 30 minutes.

The principal equipment used for cloud particle spectra measurements were Particle Measuring System (PMS) 2D-C and 2D-P probes, although only the size spectra from the 2D-C probe were used. The 2D-C probe sized in the range 25 μm to 1400 μm.

The velocity azimuth display (VAD) technique is used to calculate vertical velocities from the Doppler lidar measurements. This technique was first proposed by LHERMITTE

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation

and ATLAS (1961), and later developed by BROWNING and WEXLER (1968). In the VAD scanning mode, the beam is scanned continously in azimuth angles while the zenith angle is held constant. Backscatter power and azimuth angle are digitized in real time and stored on magnetic tape. The radial velocities are measured at intervals of 300 m along the beam.

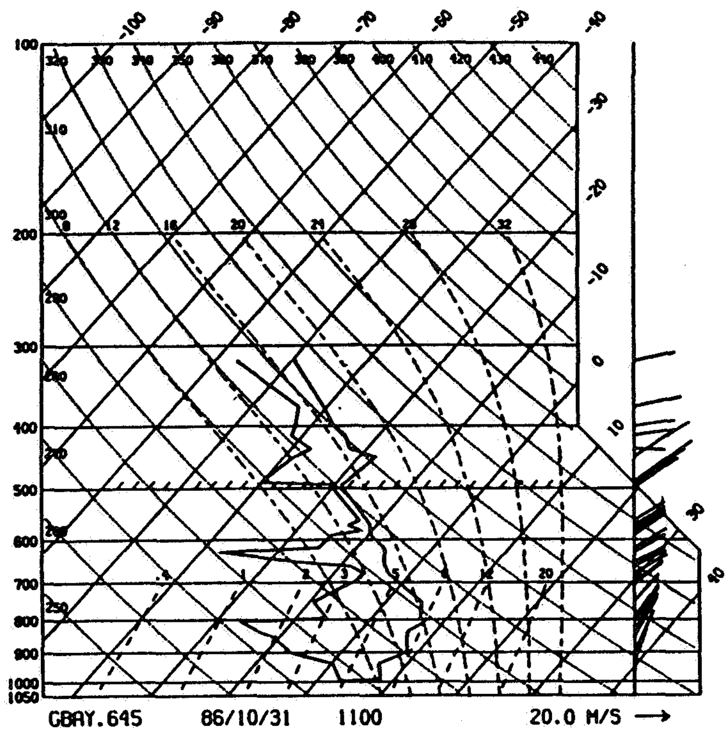

Figure 1: A skew T-log P diagram from Green Bay at 1100 CST on 31 October 1986. The moisture increase is seen approximately between 400 and 300 mb.

4. VERTICAL VELOCITY CALCULATIONS FROM AIRCRAFT MEASUREMENTS

In order to calculate vertical velocities from aircraft measurements, the precipitation rate, ice water content and terminal velocity were calculated from 2D-C probe size spectra measurements. HEYMSFIELD (1977) presented equations for calculations the above parameters. A mean size spectrum was obtained for each sampling pass. Particle habits observed in the 2D-C probe and from direct collections on oil coated slides were predominantly columns and bullet rosettes although some plates were detected (N. Knight, private communication). We then calculated the vertical velocity distribution with altitude.

4.1 STEADY-STATE TECHNIQUE

The basis of this technique is the conservation equation for total vapor, liquid and solid substances in a rising parcel of air (HEYMSFIELD, 1975). The assumption is made that ice supersaturation (S_i) remains constant with time (t) at any given level. Thus, the crystal growth and resulting depletion of vapor are balanced due to the updraft. The vertical air velocity is then derived from

$$U_A = \frac{\phi_2}{\phi_1}\frac{dw_i}{dt} , \tag{1}$$

where U_A is the air velocity, and ϕ_1, ϕ_2 are coefficients (HEYMSFIELD, 1977). $\frac{dw_i}{dt}$, the cumulative growth rate of the particle size spectrum, is not known until the supersaturation with respect to ice (S_i) is obtained (see discussion below).

4.2 FLUX TECHNIQUE

The second technique employed in calculating the vertical air velocity from the size spectra measurements is the flux method (HEYMSFIELD, 1977). In this technique, the vertical velocity was calculated by equating the decrease in moisture between a lower and upper sampling levels to the increase in the precipitation rate between the same levels. The velocity is calculated from

$$U_A = \frac{\Delta R}{\Delta IWC + \frac{RH}{100}\Delta\rho_s} \tag{2}$$

where ΔR is precipitation rate difference between level 1 and 2, ΔIWC is ice water content difference between the two levels, RH is the mean relative humidity, and $\Delta\rho_s$ is the vapor difference between level 2 and 1. Equations (1) and (2) can be solved simultaneously to yield U_A, RH and S_i (HEYMSFIELD, 1977).

5. VERTICAL VELOCITY CALCULATIONS FROM DOPPLER LIDAR MEASUREMENTS

Conically scanning Doppler lidar measurements were used to compute the mean divergence field, the horizontal wind speed, and direction. The VAD technique is based on a least squares technique for obtaining Fourier coefficients. Using the anelastic continuity equation, the vertical velocities are calculated at different altitudes through the cloud layer. Assuming that the particle velocity is equal to the terminal velocity, the zeroth order Fourier coefficient is given as (SRIVASTAVA *et al.*, 1986)

$$a_o = \overline{DIV}\frac{r\cos\alpha}{2} - \overline{V_t}\sin\alpha . \tag{3}$$

$\overline{DIV}$ is mean divergence, r is the horizontal range, $\overline{V_t}$ is mean backscatter-weighted terminal velocity, and α is the elevation angle. The mean horizontal divergence can be calculated from a_o, $\overline{V_t}$, r and α. According to BROWNING and WEXLER (1968), inhomegeneities in the particle fall speed is a primary source of error for the divergence calculation. From concurrent DMSP satellite infrared images, it is reasonable to assume that the cirrus cloud had formed a homogenous structure.

Mean backscatter-weighted terminal velocities ($\overline{V_t}$) are estimated from the particle size spectrum. $\overline{V_t}$ is found from:

$$\overline{V_t} = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} N_{i,j} D_{eq_{i,j}}^2 V_{t_{i,j}} \Delta D}{\sum_{j=1}^{m}\sum_{i=1}^{n} N_{i,j} D_{eq_{i,j}}^2 \Delta D} \tag{4}$$

where $N_{i,j}$ is number concentration in size class i with habit j. The physical diameter (D), which is used to calculate V_t, is converted to an equivalent diameter (D_{eq}) (HEYMSFIELD, 1972; 1975). Then, using the anelastic continuity equation and assuming vertical air velocities are zero at cloud top and base, the vertical air velocities are calculated. A variational adjustment technique is used to correct the divergence field. Vertical air velocity corrections are made following LIN *et al.* (1986).

6. RESULTS AND CONCLUSIONS

The aircraft vertical velocity and temperature measurements showed that the cirrus cloud formed in considerably stable atmospheric conditions on 31 October 1986. Maximum vertical shear of the horizontal wind was only 1.5×10^{-2} s^{-1} (at about 8.8 km). The cirrus cloud may be formed because of a weak wave pattern or large scale lifting.

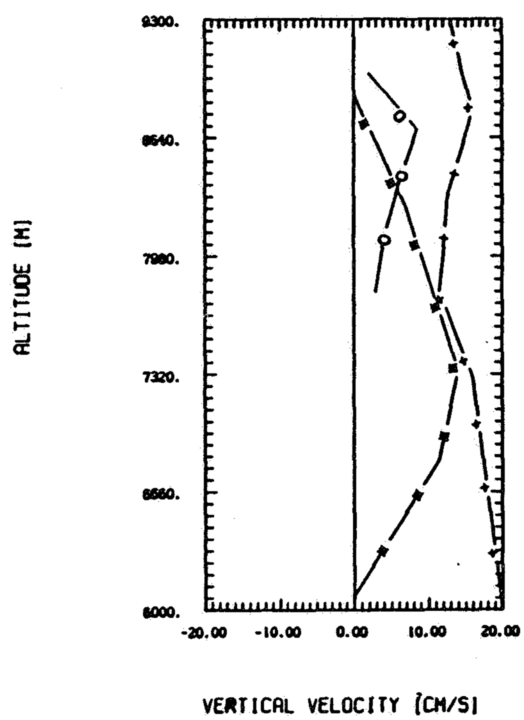

Figure 2: The calculated vertical air velocities from aircraft (o), rawinsonde (+) and lidar (*) measurements on 31 October 1986.

The ice crystal habits were predominantly columns and bullet rosettes at altitudes between 7.6 (−29.6°C) and 9.2 (−42.6°C) km. The total ice crystal concentration changed from 5.5 l^{-1} (7.6 km) to a maximum of 22.5 l^{-1} (8.8 km) where peak vertical velocities are found from the calculations based on aircraft and rawinsonde measurements. The ice water content values of 10^{-3} to 10^{-2} g m^{-3} through the cloud layer are significantly lower than found in convective cirrus, obviously as a result of weaker vertical motions.

The peak velocity from the VAD technique with 60 degree elevation angle was about 34 cm s^{-1} at about 7.4 km but with 30 and 40 degree elevation angles was only about 14 cm s^{-1} at 7.3 km ASL (see Figure 2) while vertical velocities changed from 9 cm s^{-1} at the cloud base to 0 cm s^{-1} at the cloud top. The calculated air velocities from the aircraft in-situ measurements showed a peak (10 cm s^{-1}) at about 8.8 km where the highest calculated ice crystal growth rates (about 0.2×10^{-4} g m^{-3} s^{-1}), ice supersaturation 42% and relative humidity with respect to water of 94% were found. The calculated vertical velocities are similar to that are found by HEYMSFIELD (1975), in thin ice clouds, ranging from 2–10 cm s^{-1} in frontal overrunning systems to 25–50 cm s^{-1} in clouds associated with closed lows aloft, longitudinal rolls and isolated convective cells. Maximum vertical air velocity derived from the triangle technique (BELLAMY, 1949) using three rawinsondes along baselines of approximately 200 km was found of about 15 cm s^{-1} (at 8.8 km) in the cirrus cloud layer (see Figure 2). Differences in derived vertical velocities between the triangle, Doppler lidar, and aircraft techniques can be attributed to scale effects.

REFERENCES

BELLAMY, J.C., : Objective calculations of divergence, vertical velocity and vorticity. *Bull. Amer. Meteor. Soc.*, **30** (1949) 45–49.

BROWNING, K.A., and WEXLER, R.: The determination of kinematic properties of a wind field using Doppler radar. *J. Atmos. Sci.*, **7** (1968) 105–113.

HEYMSFIELD, A.J.: Ice crystal terminal velocities. *J. Atmos. Sci.* **29** (1972) 1348–1357.

HEYMSFIELD, A.J.: Cirrus uncinus generating cells and the evolution of cirriform clouds. Part I: Aircraft measurements of the growth of the ice phase. *J. Atmos. Sci.* **32** (1975) 789–808.

HEYMSFIELD, A.J.: Precipitation development in stratiform ice clouds: A microphysical and dynamical study. *J. Atmos. Sci.* **34** (1977) 367–381.

LHERMITTE, R.M., and D. ATLAS: Precipitation motion by pulse Doppler. *Proc. Ninth Weather Radar Conf.*, Boston, Amer. Meteor. Soc. (1961) 43, 2302–2327.

LIN, *et al.*: Pressure and temperature perturbations within a squall line thunderstorm derived from SESAME Dual-Doppler radar data., *J. Atmos. Sci.*, **43, 21** (1986) 2302–2327.

SRIVASTAVA, R.C., T.J. MATEJKA, and T.J. LORELLO: Doppler radar study of the trailing anvil region associated with a squall line. *J. Atmos. Sci.*, **43** (1986) 356–377.