Paper No. 2

THUNDERSTORM VERTICAL VELOCITIES AND MASS FLUX ESTIMATED FROM SATELLITE DATA

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ABSTRACT

Infrared geosynchronous satellite data with an interval of five minutes between images are used to estimate thunderstorm top ascent rates on two case study days. A mean vertical velocity of 3.5 ms^{-1} for 19 clouds is calculated at a height of 8.7km. This upward motion is representative of an area of approximately 10km on a side. Thunderstorm mass flux of approximately 2×10^{11} gs^{-1} is calculated, which compares favorably with previous estimates. There is a significant difference in the mean calculated vertical velocity between elements associated with severe weather reports ($\bar{w}$= 4.6 ms^{-1}) and those with no such reports (2.5 ms^{-1}).

Calculations were made using a velocity profile for an axially symmetric jet to estimate the peak updraft velocity. For the largest observed w value of 7.8 ms^{-1} the calculation indicates a peak updraft of approximately 50 ms^{-1}.

1. INTRODUCTION

In the current paper we present the results of using a simple method to estimate thunderstorm cloud-top vertical velocity from SMS/GOES rapid-scan (5 minute interval) window channel infrared (IR) data. Time rate of change of cloud-top minimum equivalent blackbody temperature (T_{BB}) is converted to vertical velocity w by

$$w = \left(\frac{\partial T}{\partial z} \right)^{-1} \frac{dT_{BB}}{dt}, \quad (1)$$

where the lapse rate is determined from rawinsonde data. In the following sections the calculated vertical velocities are compared for clouds with associated severe weather reports and for those with no such reports, and the computed values are also compared with previous estimates of thunderstorm vertical velocities.

2. DESCRIPTION OF ANALYSIS TECHNIQUE

The analysis of the digital satellite data was performed on the Atmospheric and Oceanic Information Processing System (AOIPS), an interactive image analysis system described by Billingsley (1976). Sequences of images are enhanced, elements are isolated and identified, and their maximum gray level (minimum T_{BB}) recorded. The analysis of the thunderstorms used in this study (on April 24, 1975 and May 6, 1975) was part of a larger effort (see Adler and Fenn, 1978). On each of these study days an area of convection was monitored during a set period of time (approximately 4 hours). Thunderstorm elements were defined by the technique described by Adler and Fenn (1976, 1978) and time histories of each element were determined.

It should be emphasized here that not all thunderstorms can be observed at middle tropospheric heights. This is because they are often hidden by dense cirrus clouds produced by previous convection. In the two case studies that will be described here, of the thunderstorm elements defined above 10km (T_{BB} = 226K), only about 25-30% could be detected at lower heights.

3. VERTICAL VELOCITY ESTIMATES

a. Sources of Error

The vertical velocity estimates presented in this paper are subject to error because of errors in the satellite radiance measurements and possible unrepresentativeness of the data. A possible source of error is in the cloud emissivity. For thick water clouds such as we are dealing with, the emissivity (ϵ) is very close to unity. In order to use T_{BB} in place of T in Equation (1), $\epsilon = 1$ must be assumed. For ice clouds, especially thin cirrus clouds, emissivity can be substantially less than 1.0. As the thunderstorm top glaciates, the change from water to ice may reduce the cloud top emissivity and T_{BB} will be larger than T, the cloud top temperature. This effect, however, appears to be small and will not affect the vertical velocity calculations. This conclusion is based on calculations made with the help of tables presented by Hunt (1973) and on results presented by Cox (1977).

The most serious source of error stems from the satellite data itself. The IR channel has an instantaneous field of view (IFOV) of 8km on a side at the subsatellite point and approximately 10km at 40N. As noted by Negri, et al., (1976) the use of SMS/GOES IR temperatures to determine thunderstorm height results in underestimates, especially for small elements. In comparison with radar measurement of thunderstorm tops, the satellite underestimation is approximately 2km. This effect is related to two factors. First, the satellite, because of its rather large IFOV, is averaging over an area approximately 100km^2 compared with the radar observation, which is applicable to an area closer to 1km^2. Thus the radar will be identifying smaller, higher features, because of its better resolution. The second factor is inadequate sensor response when going from a warm (low) to a cold (high) target (Negri, et al., 1976). In general, the bias in the estimation of storm height will not affect the vertical velocity calculation. However, it may affect the height to which the velocities are assigned.

Other errors might arise from the use of inaccurate lapse rates in Equation (1). In the calculations to follow we use a smooth profile which is a mean of the ambient and the moist adiabatic lapse rate. The calculations can be shown to be rather insensitive to variations in the lapse rate. Using either the moist adiabatic or the ambient lapse rate instead of the average of the two produces only 10% differences in the calculated velocities. The final validation of the calculated vertical velocities must come through a careful comparison with radar, aircraft or satellite stereo observations.

b. Vertical Velocity Results

Fourteen elements on May 6, 1975 and ten on April 24, 1975 were analyzed. Minimum T_{BB} as a function of time for each element was plotted and dT_{BB}/dt

values were calculated. The warmest or lowest of the monitored elements was at T_{BB} = 260K (about 6km). Not all thunderstorms could be observed from that point upward through the remainder of the troposphere. Some elements were blocked out by other storms; other elements were not detected until they penetrated middle level cloud fields.

Vertical velocities were calculated every 5K in the vertical for each cloud element or thunderstorm using Equation (1) and a lapse rate halfway between ambient and moist adiabatic. The mean w was then calculated for various categories of clouds to produce composite profiles. The results for the May 6 case are shown in Figure 1. Profiles are shown for thunderstorms associated with severe weather reports (based on National Severe Storms Forecast Center logs) and those with no accompanying reports. The numbers in parentheses indicate the number of cases constituting each mean or composite vertical velocity. The mean profile of all cases is also shown.

The vertical velocities in Figure 1 and the calculated divergence noted above are applicable to an area of about 10km on a side. The calculated vertical velocities do not represent updraft core velocities, which could be an order of magnitude larger when measured on a horizontal scale of 1 km (see Section 5).

A similar diagram for April 24, 1975 case is given in Figure 2. The convection of interest on this day was centered in southwestern Missouri. The composite w profiles for three categories are displayed. The additional category is for weak elements which did not reach a height of 10km (as determined by the T_{BB} values). In the layer from 7 to 9km the average w is approximately 1.5ms^{-1} for those storms. This is significantly lower than the composite for "non-severe" elements in either Figure 1 or 2.

The 235-240K level (~8.7km) is representative of the layer of relatively large vertical velocities on both days. Figure 3 shows the frequency distribution of the 19 elements or clouds for these two days. The hatched portion of the histogram contains the values for the severe weather elements. The average w for all 19 cases is 3.5ms^{-1}. The severe and non-severe elements have average values of 4.6 and 2.5ms^{-1}, respectively. The severe thunderstorms dominate the high end of the distribution where six out of seven cases with $w > 4ms^{-1}$ are associated with severe weather reports.

c. Mass Flux Calculation

Because of the values of w calculated in the last section are representative of an area larger than a typical thunderstorm updraft, vertical volume or mass flux calculations can be simply made through the formula,

$$F_m = \rho A w, \qquad (2)$$

where F_m is the vertical mass flux, ρ is the density, and A is the area. For the 235-240K layer (~8.7km) ρ is assumed to be $5 \times 10^{-4} gcm^{-3}$, and A is assigned a value of 100km^2 for the area of the satellite IFOV.

With the given values for ρ and A the mean w for all storms of 3.5ms^{-1} is converted to a mass flux of $1.8 \times 10^{11} gs^{-1}$. The mean w of severe elements (4.6ms^{-1}) is equivalent to a mass flux of $2.3 \times 10^{11} gs^{-1}$. These magnitudes are for the mass flux through a given layer associated with a growing thunderstorm top. The calculated values compare favorably with results presented by other investigators. Kropfli and Miller (1976) calculate a value of $1.9\text{-}2.0 \times 10^{11} gs^{-1}$ between 8-9km for a northeast Colorado storm calculated using vertical velocity inferred from dual-Doppler radar data. Auer and Marwitz (1968) present results of the cloud base mass flux into 18 hailstorms on the high plains deduced from aircraft measurements. Their average value is $2.3 \times 10^{11} gs^{-1}$. Therefore, it appears that the upward flow deduced from the satellite observations is of a reasonable magnitude when compared to calculations and observations on approximately the same scale. Inferences about the magnitude of the maximum updraft are presented in Section 5.

4. EXAMPLE OF INTENSE THUNDERSTORM

On April 24, 1975 a severe thunderstorm complex developed over extreme northeastern Oklahoma in the late afternoon and moved into southwestern Missouri around sunset. The most significant severe weather associated with the system was the Neosho, Mo. tornado which touched down at approximately 0040 GMT, April 25. By following the evolution of the storm system backwards in time, the initial intense convection can be detected and its associated rapid cloud top growth calculated.

The Neosho cloud system was designated cloud 18 as part of a larger study of this day. Figure 4 exhibits minimum cloud top T_{BB} as a function of time for cloud 18 in its early stages. The temperature drops precipitously between 2200 and 2220GMT with a maximum calculated rate of $4K\ min^{-1}$. The drop in temperature between 260K and 220K takes only a little more than 15 minutes. This type of rapid change emphasizes the importance of short interval data to study and monitor thunderstorm activity.

Using a lapse rate varying from $7.8 km^{-1}$ at 260K, to $8.6 K km^{-1}$ at 240K, to $8.0 K km^{-1}$ at 215K the vertical velocity was calculated using Equation (1). The maximum calculated w is $7.8 ms^{-1}$ at about 9km.

5. INTERPRETATION OF CALCULATED VERTICAL VELOCITIES IN TERMS OF MAXIMUM UPDRAFT

The vertical velocities presented in the previous sections of this paper are mean velocities over an area equivalent to the satellite instantaneous field of view (IFOV), which in this case is approximately $100 km^2$. In the temperature range 235-240K (~8.7km) the 19 observed w's based on the satellite data ranged from 1.2 to 7.8 ms^{-1}, with a mean of $3.5 ms^{-1}$. Although these are very large values when compared to typical synoptic-scale w's, they are small when compared to maximum thunderstorm updraft magnitudes. Thunderstorm updrafts can reach magnitudes of $10 ms^{-1}$ very easily and are typically $30 ms^{-1}$ in supercell thunderstorms (Browning, 1977; Davies-Jones, 1974). These large updraft values are probably representative of an area approximately $1 km^2$. Thus there are two orders of magnitude difference in the area covered by the estimated w's obtained from the satellite data in this study and the area covered by the peak updraft velocity.

Assuming axial symmetry and a knowledge of the shape and size of the radial profile of vertical velocity, one can make an estimate of the maximum updraft magnitude. The formula chosen in this study, based on Kyle et al., (1976) and Schlichting (1978) is

$$w = w_o\, e^{-a(r/R)^2}, \tag{3}$$

where w_o is the peak w, r is the radial distance, R is the radius of the updraft, and the constant a = 2.3.

Integrating Equation (3) over a circular area of radius r_1, and dividing the result by the area of the integration produces an expression for the mean w over the area, i.e.,

$$\bar{w} = \frac{w_0}{a} \left(\frac{R}{r_1}\right)^2 [1 - e^{-a(r_1/R)^2}]. \quad (4)$$

The size of thunderstorm updrafts is highly variable (Browning, 1977). Based on the discussion of updraft sizes by Browning (1977) and an examination of cross-sections by Kropfli and Miller (1976) and Ray (1976) of thunderstorm vertical motions deduced from Doppler radar data, an updraft radius of 3km is reasonable.

For an area of 100km² (approximately equal to the IFOV), the equivalent radius of integration is 5.6km. Thus with R = 3km and r_1 = 5.6km,

$$\bar{w} = 0.12\ w_0. \quad (5)$$

Thus, with all the assumptions as to profile shape and updraft size, Equation (5) indicates that the mean $\bar{w}$ of 3.5 ms^{-1} is equivalent to a w_0 of 29 ms^{-1} and the 7.8 ms^{-1} value from the Neosho storm (Section 4) is equivalent to a w_0 of 65 ms^{-1}.

For an R of 3.5km, instead of 3km, the 65 ms^{-1} value in the largest paragraph would drop to 46 ms^{-1}. It is obvious that the calculated w_0 is sensitive to the size of the updraft.

Despite the variability and sensitivity of the w_0 calculations, it is evident that the satellite observations on a scale of 10km are producing $\bar{w}$ of up to approximately 8 ms^{-1}, and this can be interpreted as being roughly equivalent to a maximum updraft of 50 ms^{-1} in intense thunderstorms.

6. SUMMARY

Rapid-scan (5 minute interval) SMS/GOES IR data have been used to estimate thunderstorm top ascent rates for severe and non-severe thunderstorms on two case study days. On both days examined (May 6 and April 24, 1975) the thunderstorm elements with associated severe weather reports have larger average w's. The severe and non-severe elements had mean w's of 4.6 and 2.5 ms^{-1}. Intensity of convection appears to be correlated with the occurrence of severe weather, and the satellite data appear to be capable of quantifying the convection intensity.

The calculated vertical velocities are representative of an area (100 km²) roughly equivalent to the satellite instantaneous field of view (IFOV). Mass flux estimates of approximately 2 x $10^{11} gs^{-1}$ are calculated, which are reasonable in comparison with other estimates.

Calculations were performed to estimate the peak updraft velocity from the satellite based values (averages over 100 km² areas). With a reasonable value of R (3-3.5km), the $\bar{w}$ of 7.8 ms^{-1} for the Neosho storm produces an estimate of approximately 50 ms^{-1} for w_0.

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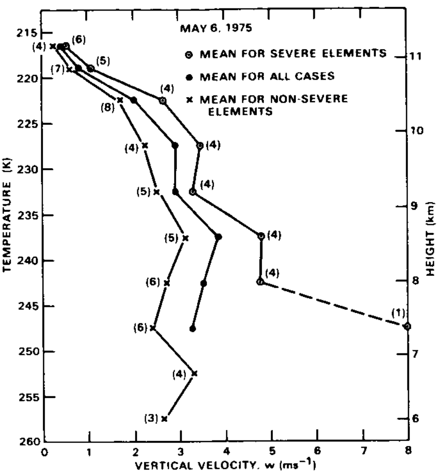

Fig. 1–Composite vertical velocity profiles for May 6, 1975. Numbers in parentheses are the number of cases.

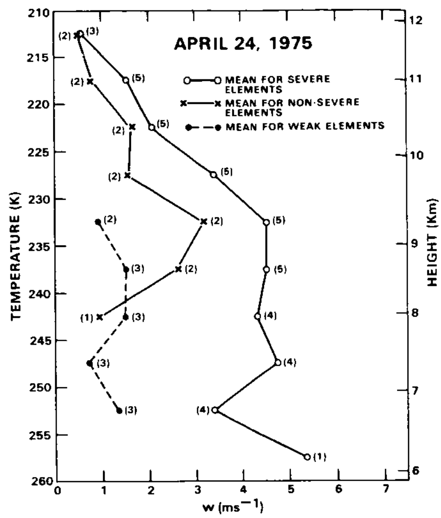

Fig. 2–Composite vertical velocity profiles for April 24, 1975.

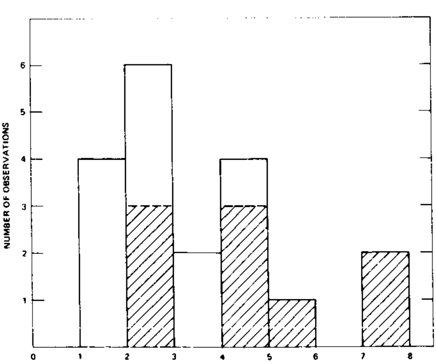

Fig. 3–Frequency distributions of estimated vertical velocities at 8.7 km for clouds on April 24 and May 6, 1975. Hatched portion of histogram indicates thunderstorms with accompanying severe weather reports.

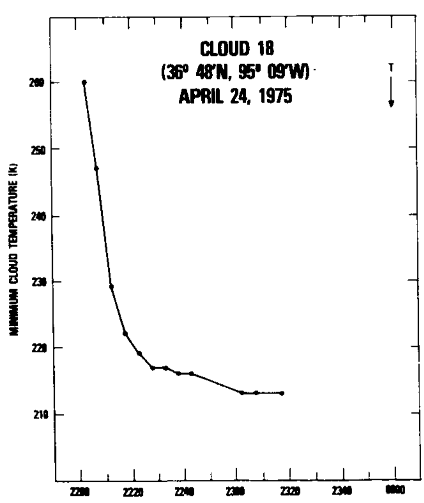

Fig. 4–Minimum equivalent blackbody temperature (T_{BB}) as a function of time for cloud 18 on April 24, 1975.