THUNDERSTORM GUSTS COMPARED WITH COMPUTED DOWNDRAFT SPEEDS

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ABSTRACT

The buoyancy equation is integrated to find the downward speed of a parcel of air that becomes cooler than its environment and sinks to the ground, such as a downdraft in a thunderstorm. This downdraft speed is related to a positive energy area on a thermodynamic diagram. From a sample of one hundred soundings taken just prior to thunderstorm occurrences a correlation coefficient of 0.50 is obtained for the computed downdraft and measured wind gusts. Taking the upper wind speed into account fails to improve significantly the correlation coefficient. A correlation coefficient of only 0.22 is obtained for the direction of the surface wind gust and the wind direction in the 700-500-mb. layer.

1. INTRODUCTION

Several authors have developed aids to forecasting maximum wind gusts expected to accompany thunderstorm activity. Two of the more widely known methods are those of Brancato [1] and Fawbush and Miller [2]. In general, these methods relate wind gust intensity to the temperature difference between the downdraft air in a thunderstorm and the environmental air. In addition either the speed of the thunderstorm or some upper wind speed is added to arrive at a wind gust forecast.

This study pursues the problem along the same line, but incorporates certain refinements which are broken down into parts and tested sufficiently to evaluate their effectiveness. It is proposed that the wind gust accompanying a thunderstorm evolves largely from a downdraft resulting from the negative buoyancy force acting on a parcel of air entrained into a thunderstorm at some upper level and cooled by evaporation until it becomes cooler than its environment and descends to the ground.

2. THEORETICAL DOWNDRAFT SPEED

The vertical acceleration $\dot{w}$ due to the buoyancy force acting on a parcel having a temperature T' in an environment with temperature T is expressed by the equation (c. f. [3]):

$$\dot{w}=g\left(\frac{T'-T}{T}\right)=g\frac{\Delta T}{T} \tag{1}$$

where g is the acceleration of gravity. If steady state conditions and negligible horizontal advection of the vertical velocity w are assumed, (1) becomes

$$w\frac{dw}{dz}=g\frac{\Delta T}{T} \tag{2}$$

where z is height above the ground. For the integrati of equation (2) an expression for the vertical distributi of T is obtained by assuming that between the surfa and the level where $\Delta T=0$ the energy area on a therm dynamic diagram of the descending parcel is well appro mated by a triangle (for example, see fig. 2). The thr sides of the triangle correspond to: (1) the moist adiab traced by the descending parcel which is assumed to r main saturated during its descent to the ground, (2) t temperature curve with lapse rate that is the mean lap rate of the environmental temperature in the layer b tween the ground and the level where $\Delta T=0$, and (the surface isobar. For this triangle,

$$\Delta T=\Delta T_0(1-z/Z)$$

where ΔT_0 is the surface value of ΔT and Z is the heig above ground of the level where the descending parc and the environment have equal temperatures ($\Delta T=$ or the "level of free sinking." Let $w=0$ at $z=Z$ a $w=w_0$ at $z=0$. Then, with the approximation $T=T_m$ mean temperature of the parcel in descent, equation (may be integrated from the ground to the level of fr sinking:

$$\int_{w_0}^{0} w\,dw=\frac{g\Delta T_0}{T_m}\int_{0}^{Z}(1-z/Z)\,dz \tag{3}$$

this gives

$$w_0^2=-\frac{gZ\Delta T_0}{T_m}$$

or

$$w_0=-\left(-\frac{gZ\Delta T_0}{T_m}\right)^{1/2} \tag{4}$$

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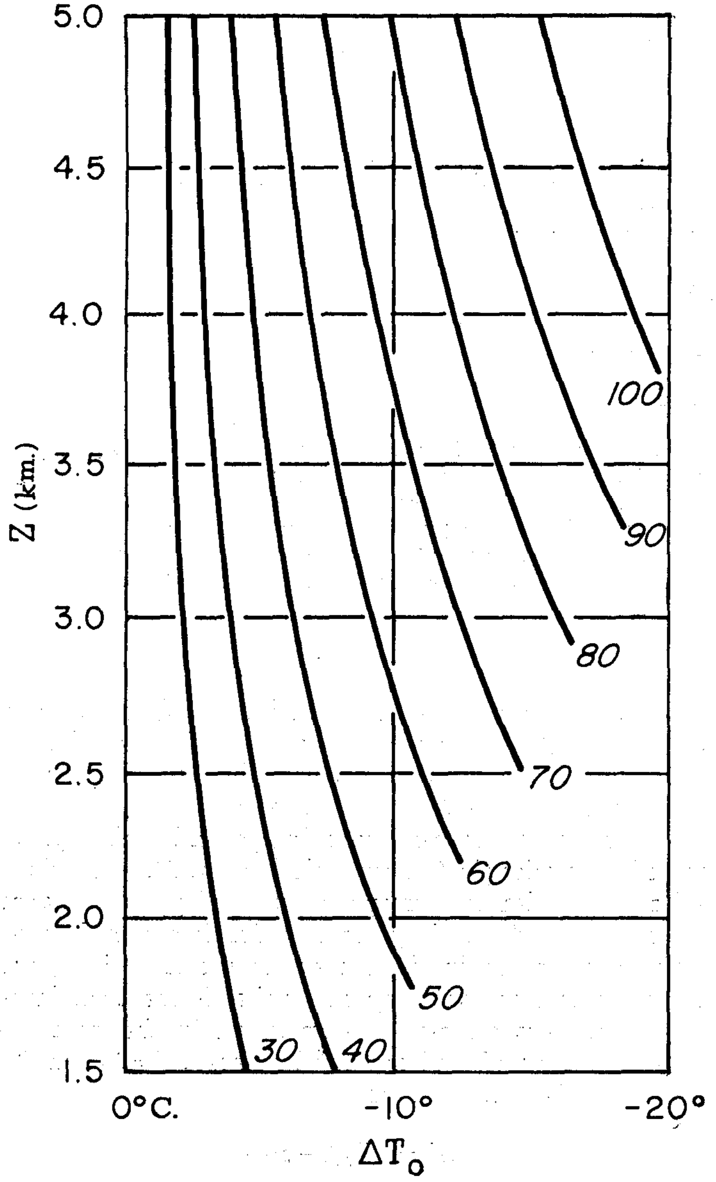

FIGURE 1.—Curved lines are computed downdraft speed in knots of a parcel falling through a positive area of dimensions Z and ΔT_0. (Made as an overlay for WB Form 770-9.)

where the negative radical was chosen in keeping with the convention for the sign of downward motion. Note that by definition, ΔT_0 is negative for the problem considered here so that the term under the radical is positive.

Figure 1 is a graphical solution of equation (4) with $T_m=286°$ A. The graph was constructed as an overlay for the particular pseudoadiabatic chart used routinely in the Weather Bureau (WB Form 770-9), but it can be readily adapted for use on any Stüve diagram by adjusting the vertical and horizontal scales. Although the pseudoadiabatic chart is not a true energy diagram, the error involved in its use here is small enough to be neglected.

3. DOWNDRAFT SPEED RELATED TO UPPER AIR SOUNDING

Temperature and height chosen for the level of free sinking are the two unknowns that must be determined before the graph (fig. 1) can be applied. This problem of finding these unknowns was attacked empirically. Observations from radiosondes that were released prior to thunderstorm occurrences (but not more than 4 hours prior) were collected, and for each observation an accompanying wind gust speed measured at or within 60 miles of the radiosonde station was obtained from information reported currently by a weather station or recorded in climatological records. Only the period 1952 through 1955 and the area of the United States from the Rocky Mountains to the Atlantic Coast were considered. These data were sorted (by reference to synoptic charts) to eliminate any case where thunderstorms were not in the same airmass as the sounding. There were 100 remaining cases.

It was possible in 72 out of the 100 cases to obtain surface temperatures and dewpoints in the thunderstorm. In these cases the lowest values observed were recorded. All of these cases were squall line cases where surface temperatures recovered appreciably after the thunderstorm passed. From the surface temperature and dewpoint, the surface wet bulb temperature was obtained. The moist adiabat through this point was taken to be that followed by the downdraft parcel. Examination of a few cases revealed that this moist adiabat approximated the average of the computed moist adiabat of the updraft and the mean moist adiabat of the environment in the intermediate levels of the troposphere.

The computed updraft moist adiabat is found as in the hail-size forecasting technique of Foster and Bates [4] and the Severe Local Storm Center method of finding the 500-mb. "Lifted Index" [5]. Briefly, this procedure is as follows: First, the mean mixing ratio and mean potential temperature expected in the lower 3,000 feet above the ground in the thunderstorm area are obtained. Then corresponding isopleths are extended upward on a thermodynamic diagram to their intersection, thus determining the condensation pressure. The moist adiabat through this point of intersection is taken as that of the core of the updraft. This moist adiabat is assumed to represent actual conditions in the core of the updraft, on the presumption of no entrainment into the core.

The mean moist adiabat of the environment in the intermediate levels was taken as the moist adiabat which passed through the mean wet bulb potential temperature in the layer between 700 and 500 mb., averaged with respect to height.

A mid-way moist adiabat, to be computed from a sounding, was then defined as the one along which the wet bulb potential temperature was the mean of the wet bulb potential temperatures of the updraft moist adiabat and the moist adiabat of the intermediate level environ-

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ment. This definition was for the purpose of making a comparison between the wet bulb potential temperature of the mid-way moist adiabat and the wet bulb potential temperature of the surface air in the thunderstorm, and to determine whether such an adiabat could reasonably be presumed to represent conditions in the thunderstorm downdraft. Correctness of this assumption would suggest that the downdraft air is a mixture of updraft air and the environmental air of middle levels produced by entrainment [6]; however, the purpose was only to establish a working relationship rather than to determine the physical processes.

For a test, the mid-way moist adiabat in the layer between 700 mb. and 500 mb. was found and projected to the surface pressure for the 72 cases for which the surface wet bulb temperatures were available. The correlation coefficient for the measured surface wet bulb temperature in the thunderstorm and the surface wet bulb temperature of the mid-way moist adiabat was 0.91, sufficient evidence that this mid-way moist adiabat is close enough for practical purposes to represent the downdraft temperature.

In the majority of the 100 cases, the mid-way moist adiabat intersected the actual temperature curve at some fairly high level and was colder at all lower levels. This intersection defines the level of free sinking. In the remaining cases the mid-way moist adiabat did not intersect the curve of actual temperature, and was therefore everywhere colder than the actual temperature. For these cases level Z was arbitrarily chosen at 5 kilometers above the ground. At higher levels, in all these cases, the difference between the mid-way moist adiabat and the actual temperatures was very small, and was therefore considered negligible. Figure 2 illustrates the analysis of one of the soundings.

4. GUST SPEED RELATED TO DOWNDRAFT SPEED

Downdraft speeds were computed for the 100 soundings using the graph in figure 1. The average computed downdraft was 78 knots, yet the average measured gust was only 61 knots. It is reasonable to believe that the computed value of the downdraft may be stronger than the measured gusts. In the first place, it is not known for sure that the measured gust was the strongest that occurred in each case. In the second place, in defining the positive area triangle, the downdraft parcel was assumed to be saturated all the way to the ground. This would mean 100 percent relative humidity at the ground during a thunderstorm. Records of the Thunderstorm Project [6] show that relative humidities during thunderstorms vary all the way from 100 percent to less than 50 percent. A relative humidity less than 100 percent would mean that the temperature of a sinking parcel would be higher than assumed, and therefore that the computed downdraft would be too large. In addition there must be frictional forces involved that act to retard the computed downdraft, and pressure gradient forces that may either increase or decrease the resulting surface gust. Also, wind measurements are subject to differences in local exposure of the anemometer. Inability to take into account the various modifying factors will of course affect the results of the procedure. However, a qualitative correction may be made in the case of dry air in the layer near the ground. See Krumm [7] on downdrafts from thunderstorms over the Plateau area of the United States.

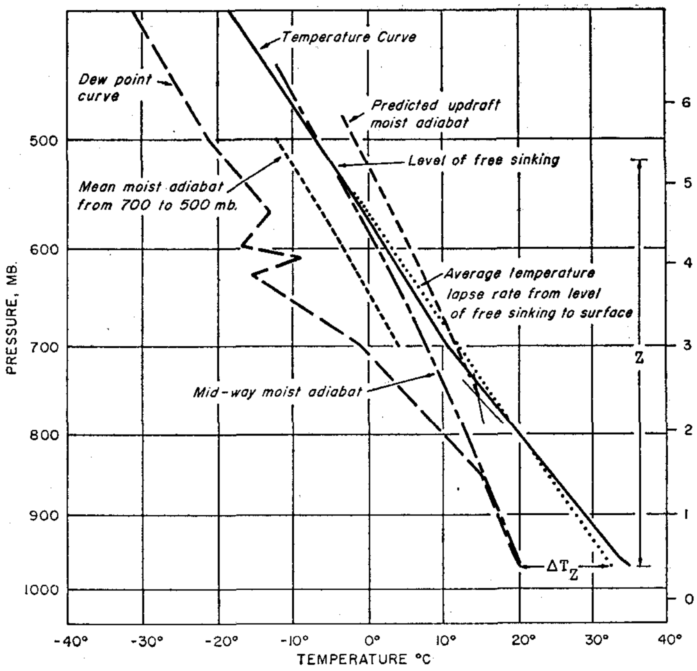

FIGURE 2.—Sounding for Huron, S. Dak., 1500 CST, July 12, 1955. Predicted downdraft temperature at surface is 20° C. Temperature and dewpoint at 1800 CST following thunderstorm were 75° and 66° F, which gives a wet bulb temperature of 20° C. Huron had gusts to 60 knots at 1639 CST and Aberdeen, S. Dak. had gusts to 73 knots at 1500 CST.

Figure 3 shows the computed downdrafts plotted against the actual measured gusts. The linear regression line appears to fit the data as well as more complicated curves. It means, for example, that given a computed downdraft of 72 knots the best forecast would be for a wind gust of 57 knots. The scatter of data is considerable and the correlation coefficient for the 100 cases is only 0.50. Though the correlation coefficient is low, it is statistically significant beyond the 1 percent level. The technique of Fawbush and Miller [2], when applied to the 100 cases used here, yielded a correlation coefficient of only 0.17. This poor result as compared with the correlation coefficient of 0.86 given in [2] is not completely understood. While a partial explanation, no doubt, is the difference in using dependent and independent data, this hardly seems to account for such a large difference. Another possibility might be in the method of selection of cases.

There is some reason to believe that surface gusts may be influenced by the speed of the thunderstorm. Also, according to radar studies of thunderstorms during the Thunderstorm Project [6], thunderstorm cells do not move

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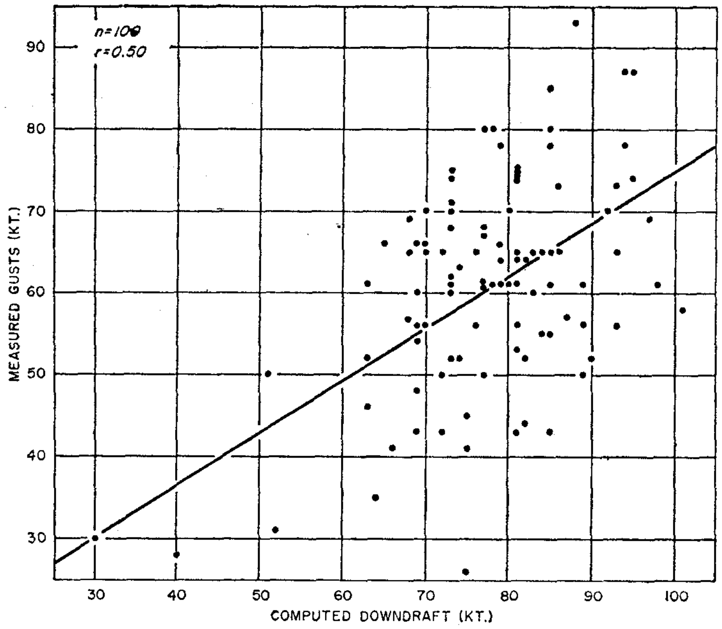

FIGURE 3.—Measured wind gusts plotted against computed downdraft speeds.

as fast as the measured winds aloft. As Newton [8] pointed out, in his discussion of the propagation of the squall line, an air parcel tends to conserve its horizontal momentum as it ascends or descends in the thunderstorm cell. As a result, a parcel of air moving in a strong flow in the middle troposphere may enter a thunderstorm cell and be carried to the ground in a downdraft, maintaining much of its horizontal momentum. This factor could contribute to, and in general increase, the wind gust.

To test the possible effect of downdraft transport of horizontal momentum for the 100 cases, the average wind speeds at 700 and 500 mb. were obtained for each case and the resulting speed added to the computed downdraft speed. The correlation of the results with the reported gust speeds was 0.51, not significantly different from the coefficient of 0.50 between computed downdraft speeds and reported gusts. (See fig. 4.) However, this failure to improve the correlation is no indication that the hypothesis is invalid.

5. GUST DIRECTION RELATED TO UPPER WIND DIRECTION

A test was made of whether the direction of the surface gust can be determined by the winds aloft. The average winds between 700 and 500 mb. were tabulated, using only those cases for which the resulting average speed was over 20 knots. There were 50 such cases. The arithmetical average of the wind directions was 240° and the arithmetical average of the direction of the surface gusts was 250°. However, because the deviations in individual cases were so large, the correlation coefficient was only 0.22, which is not statistically significant even at the 10 percent level.

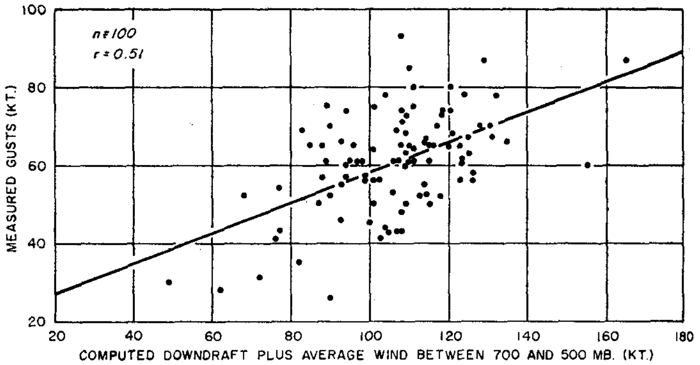

FIGURE 4.—Measured wind gusts plotted against computed downdraft speeds plus average wind speed between 700 and 500 mb.

6. SUMMARY

In summary, an analysis of 100 upper air soundings, taken close to and prior to thunderstorm activity, shows that a surface wet bulb temperature within thunderstorms can be estimated with a high degree of success. From this wet bulb temperature, it is possible to compute the approximate energy released by a pseudoadiabatically descending air parcel. The speed of the computed downdraft appears to be related to the gust velocity accompanying the thunderstorms. The correlation coefficient, although not high, is statistically significant. Adding the wind speed at upper levels does not improve significantly the correlation coefficient. An attempted correlation of surface wind gust direction with the direction of the wind in intermediate levels failed to give a significant result.

Although the results may not be as good as desired, the downdraft graph (fig. 1) may be useful as a guide to forecasting wind gusts accompanying thunderstorms.

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