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MARINE METEOROLOGY

On the Formation and Structure of Downdrafts in Cumulus Clouds

By

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Director

Downdrafts, exhibiting speeds and mass transports comparable to those of the main updrafts, are a common feature of the cumulus clouds studied by the Woods Hole Oceanographic Institution's PBY aircraft in the trade-wind region. These downdrafts are observed to be most pronounced at the extreme downshear edge of the visible cloud and are generally stronger the greater the age of the cloud tower, although they are normally present at the edge of even rapidly growing turrets.

The cloud data obtained by the PBY on the 1952 Caribbean trip (reported on by Malkus, 1954, in a paper hereinafter referred to as I) suggested that these downdrafts mixed primarily with the air of the adjacent updraft, rather than with the drier air of the clear environment. This is plausible in view of the hypothesis voiced by the writer (1949, 1952) that air is moving through an updraft in the direction pointed by the shear vector; that is, an updraft entrains air mainly on the upshear side and sheds air mainly from its downshear side. Regarding a cumulus draft in terms of the bubble-like elements which compose it (see Malkus and Scorer, 1955), the same conclusion is reached when we consider that in a shearing wind field, the wake region is found downshear of the ascending buoyant elements.

The data available from the March-April 1953 trade-wind cloud flights now make it possible to set up a tentative physical theory concerning the origin and structure of these downdrafts at the edge of the clouds. It is suggested and made plausible by the calculations to follow that the downdraft originates at the top of the cloud from air which has recently been part of the updraft. Air shed from the updraft at cloud top may, because of slight dilution by the surroundings and evaporation of roughly 10% of its liquid water content, acquire sufficient negative buoyancy to begin a rapid downward acceleration, once given a small initial downward velocity of the order of magnitude observed in the turbulent fluctuations at cloud boundaries. In fact, the low stability of the common trade cumulus environment would permit extreme downward velocities to develop were there not constant braking due to entrainment of air with upward momentum, as will be illustrated.

The set of cloud traverses discussed here (through a single cloud observed on April 7, 1953) were made in a manner identical to those described in I, except that the vertical draft records are considerably more accurate, so that one-fifth second averages of w (draft values over about 10-12 m horizontal distance) may be relied on to better than 15% (see Bunker, 1954). This improvement is due primarily to the fact that in integrating the accelerometer records, accurate corrections to the aircraft's sinking speed caused by airspeed and attitude variations are now incorporated, rather than assumed to be negligible as in I.

The calculations from this set of traverses are based upon the steady-state model of an entraining cumulus draft described in I. In that paper, the relations between parameters prescribed by the steady-state model were shown to hold fairly adequately even when the cloud visibly departed from steady conditions (see Cloud II, loc. cit.) and for two separate clouds in widely differing phases of their life cycles. It is therefore contended that the development and decay of a single cloud may be approximated by a series of quasi-steady states.

Under steady conditions, the equation for conservation of vertical momentum (equation 8 in I) states that

$$\frac{1}{w_{do} - w_E} \frac{dw_d}{dz} = - \frac{1}{M} \frac{dM_1}{dz} + \frac{\bar{\alpha}}{w_{do} (w_{do} - w_E)} \qquad (1)$$

where the z-axis points upward and a small height interval between z and z + dz is considered. Vertical velocities are denoted by w, where w_d is the average velocity across the draft at z + dz; w_{do} is the corresponding value at z, and w_E is the average vertical motion of the nearby environment (actually of the entrained air). M is the average mass flux across the draft, so that $1/M \; dM_1/dz$ is the gross entrainment between z and z + dz calculated by Stommel's method, M_1 being the total mass flux entrained in the height interval. The buoyancy acceleration, α , is defined as $g(T_v - T_v')/T_v'$ where g is the acceleration of gravity; T_v is the mean virtual temperature of the draft air; and T_v' is the virtual temperature of the environment. The value $\bar{\alpha}$ denotes an averaging of the mean draft buoyancy between z and z + dz. Equation (1) is exact (under the assumed conditions) except for the omission of an additional drag term due to form drag and weight of suspended hydrometeors, which omission was justified by the previous observations. A further approximation to equation (1) was introduced in I since it was felt that the 1952 draft measurements were not sufficiently accurate to estimate w_E. This approximation has now been dropped and the observations are used directly in equation (1) as follows: the draft boundaries are defined at the point where the vertical velocity becomes zero. The major up- and downdrafts so defined are readily traceable from one level to the next on the reconstructed cloud cross section (draft profile presented in Figure 1). The average values across draft boundaries of w, T (actual temperature), T_v, q (mixing ratio), etc. are then made graphically at each level traversed from plotted diagrams similar to Figures 4-9 of I. The main updraft in the cloud (marked on Figure 1) is first considered. The gross entrainment between each two successive observed levels of this draft is calculated and the results are presented in Table 1 and Figure 2.

Table 1

Gross entrainment in the updraft

Level m	$\overline{T}$ (draft) deg C	$\overline{q}$ (draft) g/kg	T (env.) deg C	q (env.) g/kg	$\frac{1}{M}\frac{dM_i}{dz} \times 10^{-5}$ cm^{-1}	Increment liquid water g/kg	Wind shear m sec^{-1} km^{-1}
575	19.9	14.8	20.0	14.4			
					2.6	0.3	+0.9
793	18.6	14.2	18.4	13.7			
					3.7	0.4	+0.3
1100	16.4	12.8	16.0	12.2			
					2.4	0.4	-2.2
1420	13.9	11.5	14.15	10.0			
					2.4	0.35	
(1560)	13.0	10.8	13.85	8.5			
						$\sum = 1.45$	

Next the draft profile in the updraft is calculated using equation (1) and the horizontal traverses, similarly to the procedure in I. The first step is made by taking for w_{do} in the equation the observed average updraft at 575 m, calculating dw_d/dz from there up to 793 m, etc. The results are presented in Table 2, in which the last two columns give side-by-side the calculated w at each height compared to the value arrived at by a graphical averaging across the draft of the observed values shown in Figure 1.

Table 2

Draft calculation for the updraft

Level m	T_v deg K	T'_v deg K	$\bar{q}$ cm/sec^2	w_{do} cm/sec	w_E cm/sec	Δw cm/sec	w_d (calc) cm/sec	w_d (obs.) cm/sec
575	22.50	22.50		150				
			0.50		-20	- 24		
793	21.10	20.80		126			126	110
			1.35		-60	+114		
1100	18.60	18.10		240			240	220
			0.85		-50	-110		
1420	15.90	15.90		130			130	140
			-0.78		0	-128		
(1560)	14.85	15.30					2	~ 0

The highest level at which measurements were made within the cloud was at 1420 m or 4500 ft. The highest traverse made by the airplane was at 5400 ft, which however passed above the cloud top by about 300 ft. In order to discuss the formation of the downdraft, the updraft has been constructed upward from the 1420 m traverse to 1560 m (~ 5000 ft). This was done by assuming that rate of entrainment (comparable to values measured in nearby levels) which will give cloud properties at 1560 m such that the updraft is reduced to approximately zero velocity there. This could be used as a criterion since the tower top was observed to be rising no longer. These calculated values are the ones presented for the 1560 m level in Tables 1 and 2. A hypothesis concerning the manner in which the downdraft formed near the downshear edge of the visible cloud at this height will now be tested. It will be determined whether air with these calculated properties, after a slight dilution with outside environment air of known properties, could show up at the successively lower levels with the observed properties of the downdraft actually studied and marked in Figure 1. If the cloud is not precipitating (this cloud never did) and if the major fraction of its liquid water lies in drops of low fall velocity ($\leq$ 1 mm), the liquid water content at the cloud top will be approximately the sum of the increments in column seven of Table 1, namely 1.45 g/kg. If, at the upper cloud edge, after the updraft has gone to nearly zero, we make a mixture consisting of 84% updraft air and 16% outside clear air, and if we evaporate 0.15 g/kg liquid water, we obtain air of T = 12.8C and q = 10.6 g/kg water vapor, which is close to saturation and possessing a strong negative buoyancy. If such air is given a slight downward push, it should accelerate downward very rapidly due to the instability of the environment. In fact, the braking action of entrainment must come into play or the downdraft would possess magnitudes far greater than observed.

We are, however, considering a quasi-steady situation. The question to ask is whether air starting at 1560 m with the above properties can sink to 1420 m, and by reasonable amounts of mixing with the surroundings, appear at the latter level with the observed properties of the downdraft. We shall assume here that the downdraft air is mixing only with air from the adjacent updraft and but negligibly thenceforth with the clear air. This is quite a different hypothesis from that used in the work of the Thunderstorm Project (see Byers and Braham, 1949, Fig. 33 and p. 38) and requires some explanation. It was suggested by the downdraft calculations for the 1952 clouds (see Table 6 of I) that the downdraft obtained most of its air from the updraft. If in the present calculation, significant entrainment from the clear is assumed, the downdraft calculation becomes quite absurd and no possible admixture is found which gives the downdraft the observed properties from one level to the next.

Figure 3 shows the entrainment calculation for the downdraft marked on Figure 1. Point A is obtained for the downdraft at 1560 m, as indicated above, by first mixing 84% updraft air (curve U) with 16% clear air (curve CL) and then evaporating 0.15 g/kg liquid water. To arrive at point B, the observed downdraft properties at 1420 m, air with properties A ($T = 12.8C$; $q = 10.6$ g/kg; liquid water = 1.45 - 0.15 = 1.3 g/kg) must entrain from the updraft at a rate 2.0×10^{-5} cm^{-1} and evaporate 0.15 g/kg additional liquid water. From 1420 to 1100 m (the lowest level to which this downdraft penetrated vigorously on the cross section), in order to arrive with the observed properties C, the entrainment rate from the updraft must have stayed nearly the same and an additional 0.47 g/kg liquid water must have been evaporated. If the downdraft were entraining any significant amounts of air from the clear surroundings, the entrainment rate calculated from our data becomes absurdly large. This situation is physically visualized as follows: the more that the air entrained by the downdraft contains air from the clear, the drier is the entrained air. As the properties of the entrained air approach those of the air observed in the downdraft, the higher is the calculated entrainment rate, up to that point where the average properties of the entrained air become drier than the draft, when the calculated proportion entrained decreases again. However, Figure 3 shows that reasonable entrainment rates of drier air than that in the downdraft would give draft air far drier than actually observed. Thus it must be concluded that at this stage of this cloud, the observed downdraft is composed almost entirely of air originally in the updraft. This gives rise to a downdraft in which the temperature lapse rate is steeper than moist adiabatic, rather than more stable than moist adiabatic as in Figure 33 of the Thunderstorm Report (loc. cit.) in which the downdraft is entraining clear air.

The entrainment calculation for the downdraft is presented in Table 3.

Table 3

Gross entrainment in the downdraft

Level m	$\overline{T}$ (downdraft) deg C	$\overline{q}$ (downdraft) g/kg	T (updraft) deg C	q (updraft) g/kg	T (clear) deg C	q (clear) g/kg	$\frac{1}{M}\frac{dM_1}{dz} \times 10^5$ cm^{-1}	Evap. g/kg
(1560)	12.8	10.6	13.0	10.8	13.65	8.5		
							2.0	0.15
1420	13.75	10.9	13.8	11.5	14.4	9.5		
							1.9	0.47
1100	15.7	11.8	16.2	12.1	16.0	11.3		
							4.7	0.48
793	18.2	13.5	18.6	14.2	18.5	12.0		

The resulting entrainment rates are now comparable to those of the updraft, similar to the 1952 clouds. The total evaporation of liquid water by the time the 1100 m level is reached is the sum of the figures in the last column of Table 3 plus the original 0.15 g/kg hypothesized evaporated at 1560 m, namely a total of 0.77 g/kg. By 793 m it is seen that this downdraft must have essentially disappeared. The entrainment rate becomes large, and 1.25 out of the maximum possible 1.45 g/kg liquid water content has been evaporated. The disappearance of the downdraft by 793 m is even better illustrated in Table 4, which gives the draft calculation for the downdraft. Table 4 may be regarded as a check upon the previous assumptions and calculations, since it is possible to compare the velocity profile arrived at using the temperatures, mixing ratios, and entrainment rates obtained and the actually measured velocity profile of the downdraft. This comparison is made in the last two columns of the table.

Table 4

Draft calculation for the downdraft

Level m	T_v deg K	T'_v deg K	$\bar{\alpha}$ cm/sec^2	w_{do} cm/sec	w_E cm/sec	Δw cm/sec	w_d (calc.) cm/sec	w_d (obs.) cm/sec
(1560)	14.6	14.95		- 60				
			-1.20		+100	-230		
1420	15.65	16.0		-290			-290	-250
			-1.65		+100	+ 50		
1100	17.70	18.3		-240			-240	-230
			-1.96		+100	+230		
793	20.55	21.1					- 10	- 30

The virtual temperature of the downdraft air at 1560 m was taken as that of air at 12.8C, 10.6 g/kg water vapor. The virtual temperature of its environment was found from the average figures for updraft and environment given in Table 3. The initial downward velocity, w_{do}, at 1560 m was taken simply from the magnitude of turbulent fluctuations in w near the cloud boundaries at that height. The remaining figures were obtained from the cloud traverses in the same manner as in I.

The disappearance of the downdraft at 793 m is also plausible in view of the fact that below this level the wind shear is reversed in sign, being positive, so that a downdraft should appear thenceforth on the opposite, i.e. downwind, side of the cloud. The observational evidence on this point is in the present case inconclusive. It is pertinent to note, however, that the normal situation in the trade-wind cloud layer is a reversal of wind shear, from positive up to about 1100 m to negative above that. If the present hypothesis concerning the origin and structure of cumulus downdrafts is correct, this reversal of shear should make it difficult for the main downdraft, which starts near the top of the cloud on the upwind side, to penetrate downward to cloud base or lower before exhausting its liquid water. Exceptions might be found in the cases of very large cumulonimbus clouds, such as those studied by Malkus and Ronne (1954) which reached great heights and possessed undilute cores with presumably high liquid water contents.

It may be seen by reference to Figure 3 that although the observations in this particular case preclude significant entrainment of clear air by the downdraft, such a situation (as described by Byers and Braham, 1949, p. 38) is by no means physically proscribed. If the downdraft entrained outside air, it could maintain the same or even greater negative buoyancy merely by evaporating liquid water at a faster rate. It would, of necessity, have to do this if mixing with clear air, because so long as any liquid water remains it will evaporate until the draft air is nearly saturated.

In fact, this situation may be quite pertinent to a still later stage in the life cycle of the cloud tower. As the tower ages, its updraft weakens and the air in the updraft becomes closer in its properties to the air of the clear environment with which it is mixing. The downdraft, thus, receiving the majority of its air from the updraft, will be entraining air of properties somewhat closer to curve CL in Figure 3 than is curve U, i.e., drier and colder. In order to remain saturated, the downdraft then must evaporate its liquid water faster. If such water is available in large enough quantities, it may be shown by a calculation similar to those foregoing that the downdraft then will exhibit negative buoyancy equal to or greater than that calculated in Table 4. With the weakened braking effect of the updraft, w_E will be smaller, and it may be shown for the environment studied here and reasonable values of the updraft parameters, that the downdraft may reach 1420 m and 1100 m increased in intensity by 1 mps or more. As the updraft dies completely and the cloud top begins to evaporate, the downdraft, too, cannot last much longer, as its source of cooling, namely evaporation of liquid water, will soon give out.

Conversely, it may be shown that in an earlier stage of the updraft, although the downdraft is enabled to be more economical with its liquid water, the larger braking effect of the adjacent updraft will, under reasonable assumptions, restrain the downdraft magnitudes below the values given in Table 4.

It is thus possible to describe the structure of the cumulus downdraft in one stage of its development quantitatively in terms of a steady-state model. It is plausible in view of these calculations to believe that most of the air composing the downdraft was originally entrained from the updraft and that the primary source of the downward acceleration is due to the evaporation of liquid water. It does not appear to be necessary to call upon the weight of nor the drag exerted by the liquid drops to assure the needed downward force. It further seems possible, by regarding a series of quasi-steady states, to project the downdraft both backward and forward in its life cycle and to see how its time-dependent behavior is related to that of the updraft upshear of it. It seems evident from this work that the behavior of the downdraft is intimately dependent upon that of the updraft which, in this paper, was measured or extrapolated from measurements. The time-dependent behavior of the updraft itself has not been analyzed herein, although it may be suggested in conclusion that a similar approach might be applied to that more fundamental problem.

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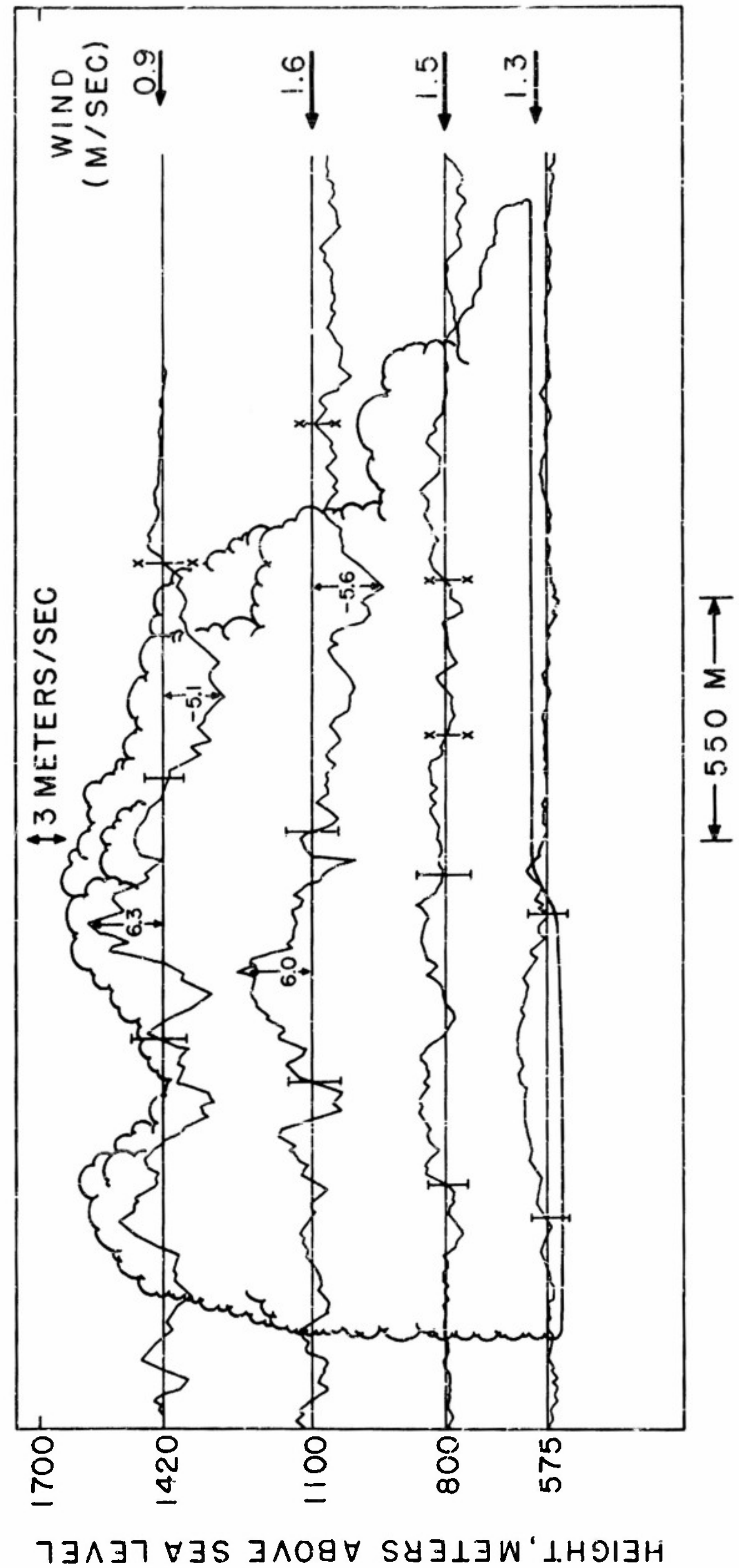
Fig. 1. Reconstructed cross section of the cloud studied by the PBY on April 7, 1953, showing the measured vertical draft profile. The cloud formed over open ocean about 100 miles northeast of San Juan, Puerto Rico. The airplane passes were made, from the top downward, in alternate directions approximately up- and downwind. The wind component along the section flown is given at the right. The major up- and downdraft used in the calculations are denoted by the vertical lines drawn at each level. Peak draft velocities in m sec^{-1} are indicated. Averages across the drafts are presented in the text.

Fig. 2. Entrainment calculation for the major updraft in the cloud shown in Fig. 1, using Stommel's method. The vertical coordinate is temperature in degrees Centigrade, while the horizontal coordinate is mixing ratio in g/kg. The curve E gives the properties of the nearby environment of the draft observed at each of the levels indicated (meters above sea level), while curve U gives the corresponding properties of the draft observed at all levels except 1560 m, which value was obtained by a calculation described in the text. The vertical lines downward from each point represent dry adiabatic cooling. The line joining the end of the vertical line to the corresponding environment point is the mixing line, and the final slanting line to the draft point represents condensation of liquid water. The ratio of entrained air (mass flux) to mass flux already in the draft between successive levels is thus the ratio of the right-hand to the left-hand portion of the mixing line intercepted by the condensation line.

Fig. 3. Entrainment calculation for the major downdraft in the cloud shown in Fig. 1. Exactly the same procedure was followed as illustrated in Fig. 2, except that the processes are in reverse, as described in the text. Curve CL gives the observed points for the clear air environment of the downdraft; curve U gives the observed or calculated nearby updraft properties; and curve D gives the observed downdraft properties, except for point A, which was calculated. The updraft curve, U, is not everywhere quite the same as the U curve in Fig. 2, since here that portion of the updraft nearest the downdraft was considered, while Fig. 2 gives the average properties across the entire updraft.


3 METERS/SEC
WIND
(M/SEC)
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6.3
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HEIGHT, METERS ABOVE SEA LEVEL

FIG. 1

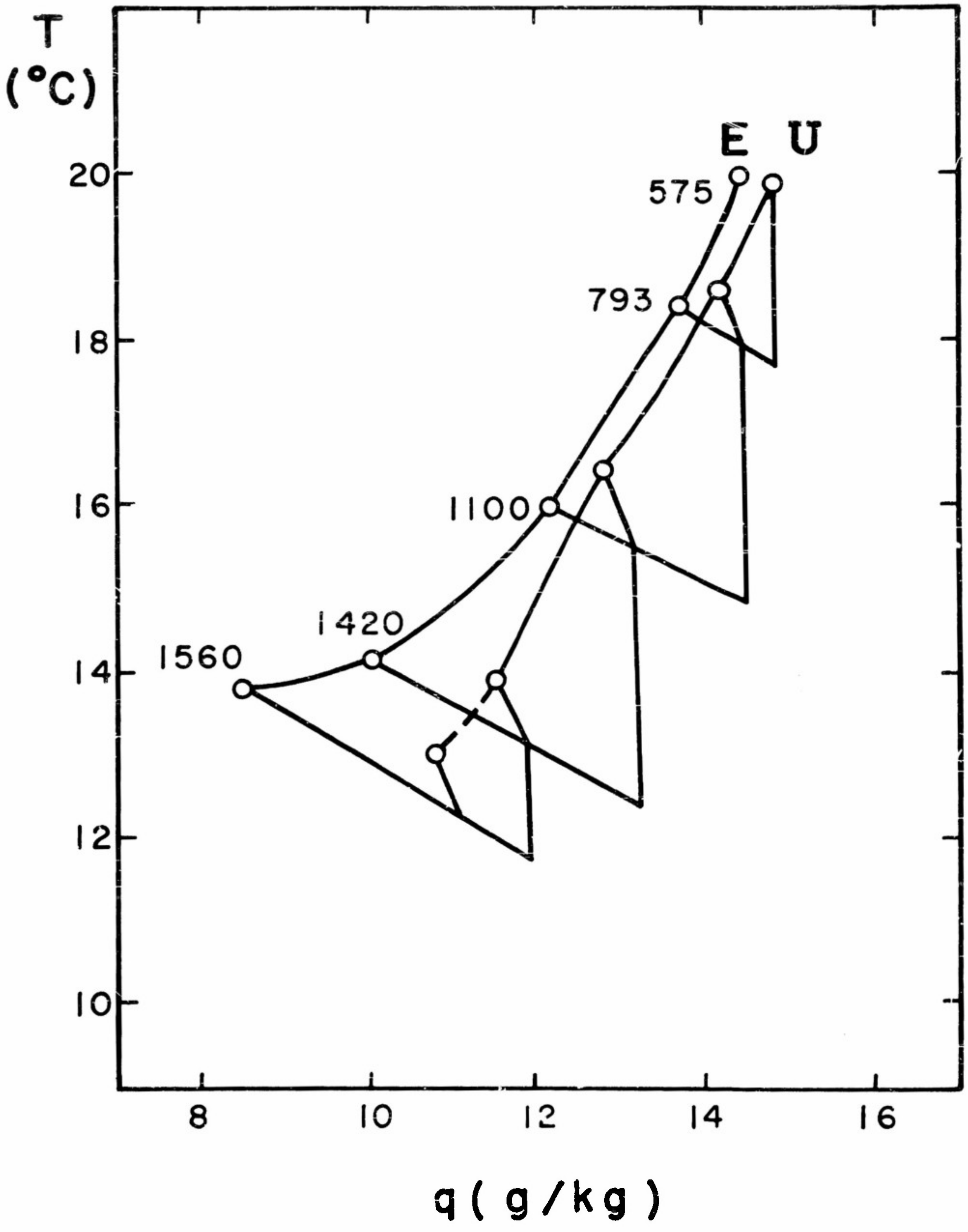
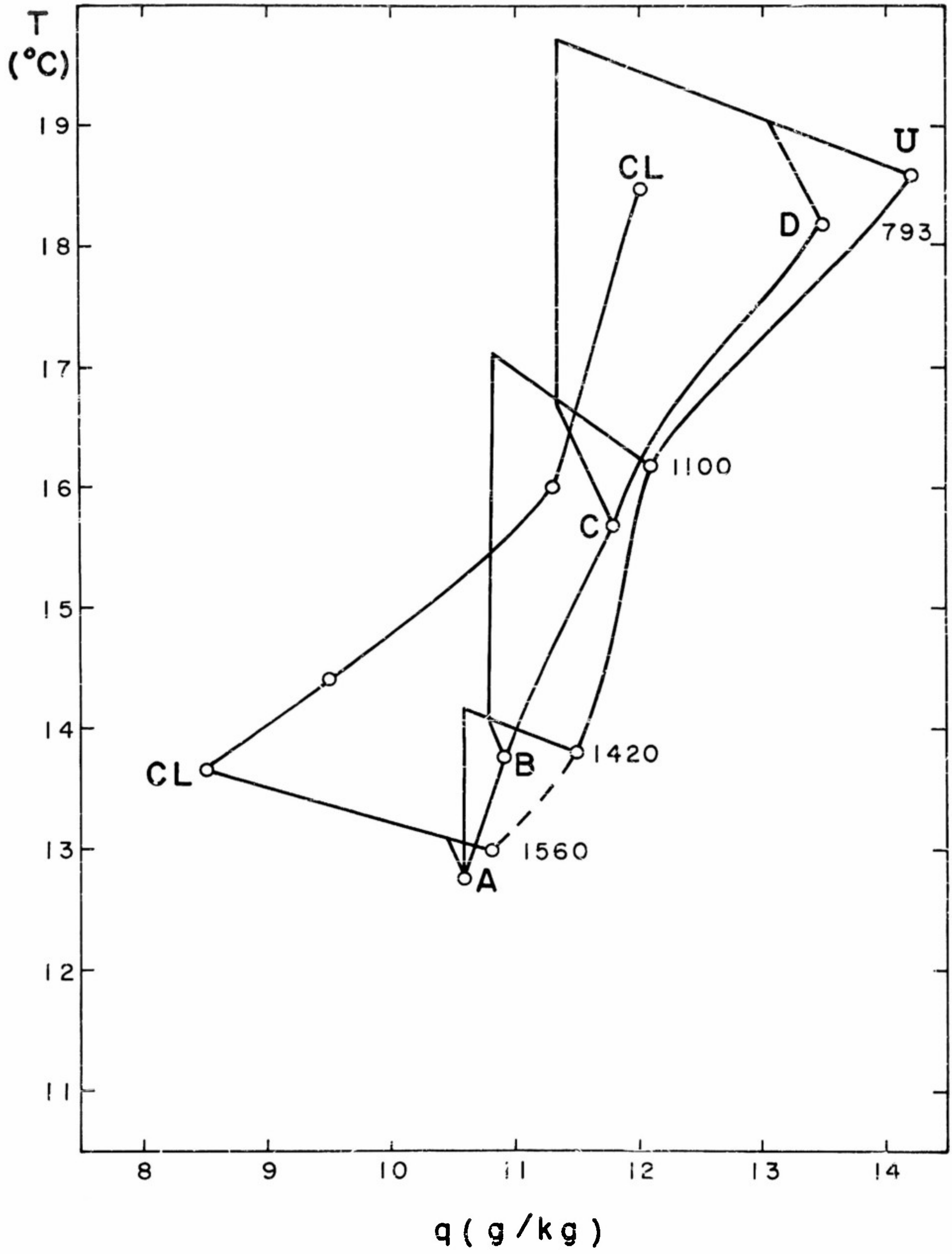


FIG. 2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CL
D
793
1100
C
B
1420
CL
1560
A

FIG. 3

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