On the analysis of Thermodynamic diagrams for Instability

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ABSTRACT. In this paper a modified parcel method of analysis of tephigrams is discussed. The method takes account of the entrainment of environmental air by the cloud air and the integrated effect of lifting air parcels from all levels in the "layer of instability". An attempt has also been made in the modified parcel method to take account of a few other factors, *viz.*, freezing level and shear vector. Some worked out examples by the use of the modified parcel method have been examined for Indian conditions and it has been shown that a fair degree of success can be obtained by this method, if judiciously applied.

1. Parcel Method *versus* Slice Method

Two methods are generally used in the routine analysis of thermodynamic diagrams for instability. One is the "Parcel method" which owes its origin primarily to Normand[1] and has been in use for a long time. In this method a rising cloud parcel is assumed to pass through the environment without disturbing it. The method lends itself to easy graphical treatment and has proved very popular, particularly in India, inspite of the fact that the validity of this method of treatment has been questioned by J. Bjerknes[2]. In 1938, J. Bjerknes formulated his method of treatment, known as the "Slice method", in which saturated cloud air is assumed to ascend through a dry adiabatically descending environment. The slice method received considerable attention in the hands of Petterssen[3]. Later, Norman Beers[4] extended the slice method to obtain an estimate of "total instability" by applying the circulation theorem of V. Bjerknes. The slice method as applied by Norman Beers is not a simple graphical method ; it involves a calculation of circulation acceleration for each significant layer and the summing up algebraically of the circulation acceleration corresponding to each such layer. A number of examples have been worked out by Norman Beers to prove the superiority of this method of treatment over the parcel method. A point to note, however, is that the slice method as extended and applied by Norman Beers takes account of total instability realisable from all layers, whereas the parcel method is applied in the usual way without an attempt to obtain an estimate of total instability. The two are, therefore, not strictly comparable.

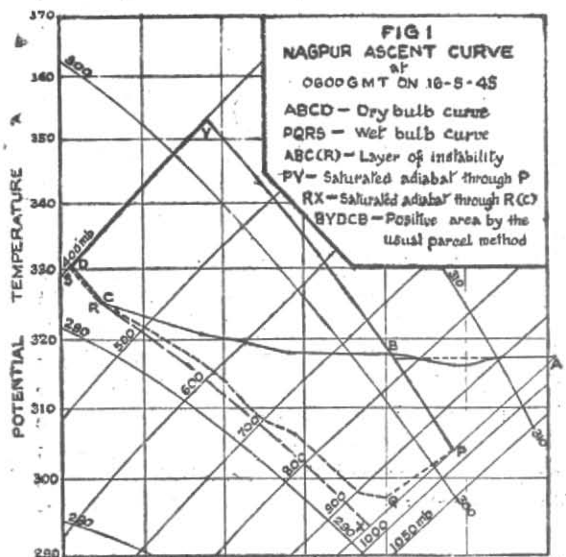
It has been claimed of the slice method that it gives a more realistic picture of the process as actually realised in nature. Recent work of Stommel[5] and Byers and Braham[6] has, however, shown that there is no descending current at the "growth stage" of the cumulus cell. There is, of course, a down current at the "mature" and "dissipating" stages of cumulus cell, but these down currents have an altogether different history of origin and are not in the nature of a direct compensatory down current which is the basis of the slice method. Work of Stommel[5], Austin[7] and Byers and Braham[6] has proved conclusively that what we have in the environment to preserve mass continuity is a gentle subsidence. Much more important than the gentle subsidence in the environment is the fact that the rising cloud air pulls in air from the environment and mixes with it. This entrainment and mixing of environmental air, which has usually a much lower wet bulb temperature than the cloud air, modifies the cloud lapse rate considerably. It would thus appear that in the daily analysis of instability, no appreciable error is likely to be caused by the neglect of the gentle subsidence in the environment but considerable error is introduced if one omits to take account of the entrainment of environmental air.

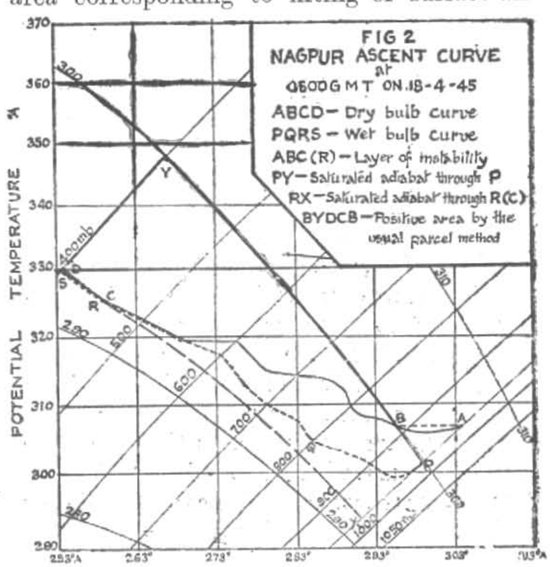
2. Modified Parcel Method and total Positive Area

How the lapse rate of cloud air gets modified by the entrainment of environmental air has been discussed by Austin and Byers and Braham (*loc. cit*). The most important fact to remember in this connection is that, due to entrainment of environmental air, the cloud lapse rate curve becomes steeper than the saturated adiabatic and approaches the environment curve so that, the positive area obtained by the traditional parcel method is considerably reduced, the more so, the drier the environment. It has long been known that a dry environment inhibits the growth of thunderstorms but the usual parcel method does not allow for this important factor.

In a note published previously, the author[8] has illustrated how considerable the effect of entrainment of environmental air can be in reducing the positive area, particularly when the environment is dry. The illustrative diagrams in that note were idealised ones and were introduced in order to avoid an overlapping of the "layer of instability" and the "environment of instability". In Figs. 1 and 2 of the present paper are shown two actual ascents of Nagpur, in both of which the "thickness of layer of instability" is the same (about 550 mb). In both the figures, ABCD represents the dry bulb curve, PQRS the wet bulb curve and ABC(R) the layer of instability. It will be seen that the positive area given by BYDCB is much greater in the case of Fig. 1 than in the case of Fig. 2, but one would not expect appreciable cumulus growth, not to speak of thunderstorm, in the case of the situation depicted in Fig. 1, whereas, in the case of the situation depicted in Fig. 2, one has to analyse the situation carefully for convective phenomena. Actually, the situation depicted in Fig. 2 gave a thunderstorm with $\frac{1}{2}''$ of rain, whereas in the case of Fig. 1, very little cloud developed. The point to note, however, is that, by the usual parcel method, the positive area corresponding to the surface air parcel is greater in the case of Fig. 1 than in the case of Fig. 2 and that the thickness of layer of instability is the same in both the cases.

It has been pointed out in the previous section that the extended slice method introduced by Norman Beers (*loc. cit.*) makes an estimate of the total instability. Attempts at obtaining total instability (or total realisable energy) have also been made by Rossby[9], Littwin[10] & Normand[11,12,13]. These are, however, all rather unsuitable for adoption in routine daily analysis, for which the method of analysis as advocated by Normand and as commonly practised in India to this day, takes account of the positive area corresponding to lifting of surface air





parcel only, together with the thickness of layer of instability. How misleading such an analysis can sometimes be is well illustrated by Figs. 1 and 2. If, however, the positive area is determined by using the lapse rate as obtained by taking entrainment into account, with entrainment rate 25 per cent in 50 mb and the integrated effect of lifting air parcels from all levels in the layer of instability is computed, then we obtain an estimate of the total instability which is about 3 times more in the case of Fig. 2 than in the case of Fig. 1. The method by which the integrated effect of lifting air parcels from all levels can be obtained is explained in the next section. It may, however, be noted here that in obtaining both the modified lapse rate and the integrated effect of lifting air parcels from all levels, we have retained the essential features of the parcel method, *viz.*, it is the energy realisable by the lifting of a unit element of air parcel through an environment at rest that is examined. We will call this the "modified parcel method".

3. Estimation of Total Instability

(a) Direct Method

A most straightforward method of obtaining the integrated effect of lifting air parcel from each significant level would be as follows—

Let p_0, p_1, p_2, p_3, etc. be the pressures at the surface and the first, second, third etc. levels above the surface, and A, B, C, D, etc. represent the positive areas given by the lifting of air parcels from the levels p_0, p_1, p_2, p_3 etc. respectively, then the integrated effect of lifting air parcels from all levels in the layer of instability may be represented by—

$$\tfrac{1}{2}\, Ah_1 + \tfrac{1}{2}B\,(h_1+h_2) + \tfrac{1}{2}\, C\,(h_2+h_3) + \ldots$$

where $p_0 - p_1 = h_1$, $p_1 - p_2 = h_2$, $p_2 - p_3 = h_3$ etc.

This may be called the "total positive area" of the modified parcel method. The unit of pressure may be taken as 10 mb, in which case the total positive area obtained will represent the sum of energy realisable by the lifting of a unit air parcel from each 10 mb level. If desired, the total positive area may be converted into joules per kilogram of dry air by reference to the scale of the tephigram paper used and defined as "total instability" of the modified parcel method.

The total negative area could also be obtained in a similar manner, or alternatively, the negative area for each level could be subtracted from the positive area for that level to obtain the net positive area, which may then represent A, B, C etc. in the above formula. The circumstances under which it may be permissible to subtract the negative area from the positive area have been discussed later.

The method of estimating the total positive area described in the above paragraphs will take about 10 minutes, if the simplified technique for obtaining lapse rate described by the author[14] is used. It will now be shown that on certain simplifying assumptions and approximations, a rough estimate of the total positive area can be obtained in much shorter time. The rough estimates obtained by any of the two methods described below will give values correct to within about 25 per cent* and such rough estimates by themselves will be sufficient in many cases to assess the liability or otherwise to convective phenomenon. In cases of doubt, *i.e.*, in border cases, the direct method described above can be used.

(b) Indirect Methods

(i) Approximate Method 1. In Fig. 3, ABCD represents the dry bulb curve and PQ_1 (Q'_1) Q_2 $(Q'_2)RS$ represents the wet bulb curve of an ascent. B is the condensation level corresponding to the surface air parcel. Let the pressure interval between P and Q_1 (Q'_1) be h_1 and that between Q'_1 and Q_2 be h_2. The wet bulb curves between P and Q_1 and Q'_1 and Q_2 follow the saturated adiabat, so that, the positive area given by the lifting of air parcel from any level between P and Q_1 is the same; let it be a; similarly, the positive area given by the lifting of air parcel from any level between Q'_1 and Q_2 is the same; let it be b. As Q_2 marks the limit

*The rough estimates obtained by either of the two methods described here were compared with the "total positive area" obtained by the direct method described above in a large number of cases. The comparative figures are not reproduced.

of the layer of instability the total positive area is given by

$$ah_1 + bh_2$$

The wet bulb curve will, of course, in general, not take the shape represented above but a curve of this type can be fitted into the actual wet bulb curve. If necessary, more points Q_3, Q_4 etc. can be introduced to get a better fit, in which case, the total positive area will be given by

$$ah_1 + bh_2 + ch_3 + \ldots .$$

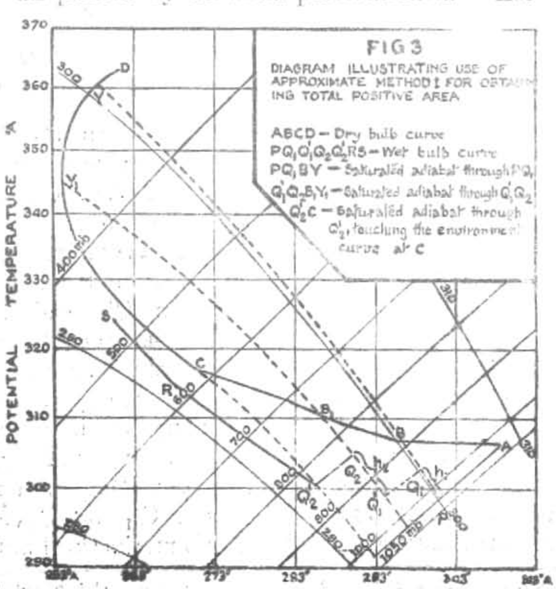
where c and h_3 represent the positive area and height interval corresponding to Q_3 and so on. If, however, more than three points have to be introduced to get a satisfactory fit, one might as well use the direct method described before. This method is particularly useful when complete mixing in the turbulent layer is assumed, so that, θ_{sw} = constant, in the whole of the turbulent layer (vide Section 4).

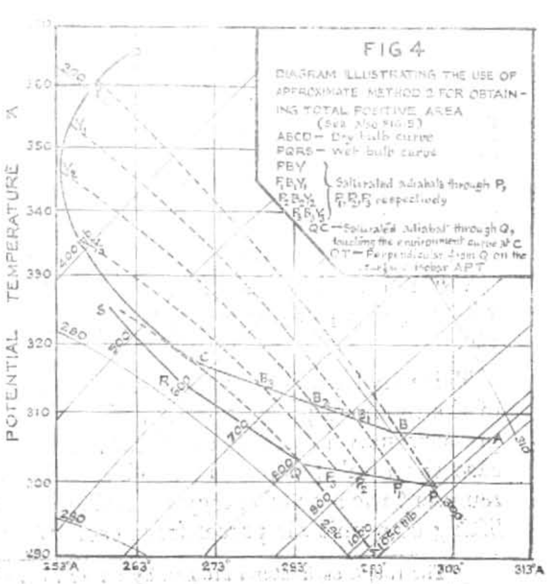
(*ii*) *Approximate method 2.* In Fig. 4, ABCD is the environment (dry bulb) curve and PQRS the wet bulb curve. PBY is the saturated adiabat through the surface wet bulb temperature, P and B the points where it intersects the environment curve. BCYB thus represents the positive area corresponding to the lifting of a surface air particle by the usual parcel method. Let this area be A. Q is the point on the wet bulb curve which marks the limit of the layer of instability and C the point on the dry bulb curve where the saturated adiabat through Q touches the dry bulb curve. The portion PQ of the wet bulb curve and the portion BC of the dry bulb curve are for the present taken as straight lines. QT is the perpendicular from Q on the surface isobar TP.

If a particle is lifted from any other level represented by the point P_1 on the wet bulb curve, the positive area corresponding to the lifting is $B_1Y_1CB_1$, where B_1 is the point where the saturated adiabat through P_1 intersects the environment curve. Similarly, the positive area corresponding to a point P_2 in the wet bulb curve is $B_2Y_2CB_2$ and so on, until the point Q is reached, the positive area corresponding to Q being zero. If now the saturated adiabats intersecting PQ and BC, *i.e.*, PB, P_1B_1, P_2B_2 etc. are taken as parallel, we can regard the positive areas as built up on a uniformly varying base BC, of length, say L. If the area a built on the variable base retains the same shape as it diminishes from A to zero, we can put

$$a = K_1L^2, \text{ where } K_1 \text{ is a constant} \ldots . (1)$$

By virtue of the assumed parallelism of the saturated adiabats intersecting PQ and BC, L will be further proportional to l, where l





represents the length QP when P is a moving point on the line QP. Finally, if h represents the length of QT, where QT is the projection of QP on QT, we can put

$$a = Kh^2, \text{ where } K \text{ is a constant.} \quad (2)$$

The value of the constant K in (2) above is easily determined by putting $a = A$, when $h = H$, where A is the positive area corresponding to the lifting of a surface air parcel P and H is the perpendicular distance on any linear scale between Q and P. Thus,

$$K = \frac{A}{H^2}$$

$$\text{and } a = \frac{A}{H^2} \cdot h^2 \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

Integrating a between Q and P, we have,

$$\int_0^H \frac{A}{H^2} \cdot h^2 \cdot dh = \frac{AH}{3} \quad \ldots \quad \ldots \quad (4)$$

The total positive area can thus be obtained from the positive area corresponding to the lifting of surface air parcel, by multiplying it by the "thickness of layer of instability" and dividing by 3, provided the following assumptions which have been made in deriving (4) are true :

(1) PQ is a straight line
(2) BC is a straight line
(3) The saturated adiabats intersecting PQ and BC are parallel and
(4) The positive area built on the variable base BC retains the same shape as it diminishes from A to zero.

The assumptions (2) to (4) are justified when it is remembered that only a rough estimate is aimed at and that the effect of variation from the assumed conditions is not generally large. Although, for simplicity, the positive area considered in the illustration is the positive area by the usual parcel method, the method will be equally applicable when entrainment is allowed for, as the assumption in regard to the positive area, *viz.*, that the area retains the same shape as it diminishes from A to zero, is roughly true in this case also.

The assumption (1) will, however, not be justified in most cases, as any appreciable deviation from the assumed condition will in this case effect a large variation in the total positive area. Any deviation from the straight line of the portion of the wet bulb curve represented by PQ can, however, be allowed for by multiplying the total positive area given by $AH/3$, by a suitable factor which can be determined by inspection, from the following considerations.

In Fig. 5, the dry bulb curve and the portion of the wet bulb curve represented by QRS are the same as in Fig. 4. Let the portion PQ of the wet bulb curve be represented now by PQ_1Q. As the curve PQ_1Q lies wholly to the left of the straight line PQ, the total positive area corresponding to this wet bulb curve will be obviously $< AH/3$. It should also be noted that if the wet bulb curve had taken the shape $PQ'Q$, QQ' being the saturated adiabat through Q, then the total positive area would tend to 0. For a wet bulb curve PQ_1Q, the total positive area would thus be $< AH/3$, being nearer $AH/3$ when it lies nearer to PQ and being nearer 0 when it lies nearer to $Q'Q$. In the case of the wet bulb curve PQ_1Q represented in Fig. 5, the total positive area would be very near to $\frac{1}{2}$ of $AH/3$. Again, if the wet bulb curve had taken the shape PQ_2Q, the total positive area would be $> AH/3$. The upper limit of the total positive area is set by the fact that the total positive area corresponding to a wet bulb curve $PBQ''Q$ is $< AH$, for, the total positive area

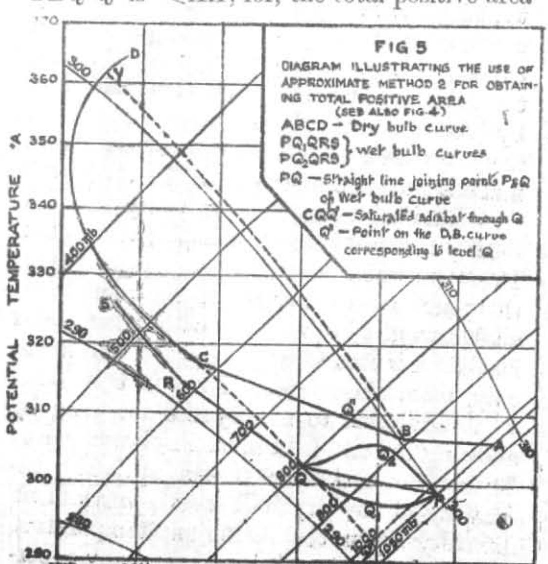


FIG 5
DIAGRAM ILLUSTRATING THE USE OF APPROXIMATE METHOD 2 FOR OBTAINING TOTAL POSITIVE AREA
(SEE ALSO FIG 4)

corresponding to the portion PB is AH_1 and that corresponding to the portion BQ″Q $<AH_2$. Thus, when the wet bulb curve lies to the right of PQ, the multiplying factor would be between 1 and 3; in the case of the curve PQ_2Q shown in the figure it would probably be very much nearer to 2, *i.e.*, the total positive area corresponding to PQ_2Q would be roughly $2\times AH/3$.

In all the three methods, the direct method as well as the approximate methods 1 and 2, the convenient pressure unit to use is centibar *i.e.*, 10 mb. If it is desired to obtain the total negative area also, the approximate methods 1 and 2 may not be suitable.

4. Application of the "Modified Parcel Method"

In the analysis of thermodynamic diagrams, certain assumptions have to be made. Some of the assumptions usually made are (cf. Beers; *loc. cit.*)—

1. Horizontal motion does not maintain any net inflow or outflow from any stratum determined by the air between significant levels.

2. Conditions are barotropic initially.

3. All motions are adiabatic above the surface layers.

The above assumptions are generally valid in circumstances where cumulus activity is due to surface heating alone and the so-called heat thunderstorms thus present the simplest cases for analysis. In analysing cases where frontal or orographic lifting is expected, it will be necessary first to modify the sounding by raising each significant level by the amount of expected lifting. If, from synoptic situation, the forecaster can make a proper assessment of the changes in the sounding during the forecast period and modify the sounding accordingly, assumption 1 need not be made. In the present paper, the practical application of the method of analysis will be confined to cases where solar insolation serves as the "trigger" and is the only modifying factor. Even in this case, it is advisable to modify the sounding by allowing for the maximum insolation effect before the analysis is taken up. The redrawing of the dry bulb curve presents no difficulty when the maximum temperature likely to be attained is known and any super-adiabatic lapse rate that may develop at lower levels is ignored. The dry adiabat through the surface maximum temperature is then drawn to meet the environment curve and this dry adiabatic line represents the modified environment curve. As regards the wet bulb curve, certain assumptions have to be made. We may assume that no addition of moisture takes place and also that there is no transport of moisture upwards due to turbulence. In this case, the humidity mixing ratio in each level remains unaltered and the wet bulb curve can be redrawn by graphical interpolation with the help of Normand's theorem[15]. We may, on the other hand, assume a thorough mixing due to turbulence, with or without the addition of extra moisture. In this case the pseudo wet bulb potential temperature, θ_{sw}, is constant in the whole of the turbulent layer, the limit of which may be defined as the level where the dry adiabatic line through the surface maximum temperature intersects the sounding. In the analyses made by Beers by the slice method (*loc. cit.*) a 2-gram increase in the mixing ratio has been allowed. The redrawal of the wet bulb curve when there is complete turbulent mixing will necessitate the determination of the mean mixing ratio for the whole of the turbulent layer and this cannot be done graphically. But once the mean mixing ratio is determined, the estimation of the total positive area becomes very easy, as, θ_{sw} being constant, the positive area corresponding to any level in the turbulent layer is the same and as such, the total positive area corresponding to the whole of the turbulent layer is simply AH, where A is the positive area corresponding to any level and H, the height of the turbulent layer (c.f. Approximate method 1). In the present method of analysis, we are concerned not with the absolute size of the positive area but its relative size on different occasions. The relative size of the positive area is not likely to differ much whichever of the above assumptions we make. I have found it more convenient to use the first assumption, *viz.*, that there is no addition of moisture and also that there is no transport of moisture upwards due to turbulent mixing.

A note of explanation in regard to the rate of entrainment to be used in the analysis is necessary. From aircraft data in American experiments under Byers (*loc. cit.*), a 25 per cent entrainment in 50 mb was observed in well developed cells, although the computation of lateral convergence in the vicinity of bulging cumulus by means of radiosonde ascents gave a much lower rate of entrainment. We have no data for Indian conditions, but it is reasonable to assume that the rate is not likely to differ very much from what was observed in American experiments. I have used the rate obtained in American experiments from aircraft data in my analysis of Nagpur tephigrams in Section 6. As the object is to find the liability to thunderstorm and as the only effect of entrainment in the present analysis is to reduce the positive area, the rate of entrainment in well developed clouds is what matters. Further, as already pointed out, the object of the analysis is not to obtain the absolute size of the positive area but only its relative size on different occasions. The relative size of the positive area will not differ much by the use of somewhat higher or lower rate of entrainment, provided the rate of entrainment does not differ widely from one occasion to another.

5. Other Factors

(*a*) *Freezing level.* Although it is now known that in the tropics heavy showers may occur without the cloud reaching the freezing level, it would appear doubtful whether a thunderstorm can occur without the clouds reaching the freezing level. The typical anvil of the cumulonimbus is a pointer. If, therefore, the ascensional movements do not reach the freezing level, the instability phenomenon may not culminate in a full thunderstorm. Hence, the cases where the modified lapse rate curve cuts the environmental curve much below the freezing level, thereby preventing the cloud tops reaching the freezing level in spite of their momentum, may have to be ruled out, even when they exhibit large positive areas. However, for the cases examined by me in Section 6, whenever the positive areas were large, the cloud lapse rate curve cut the environment curve much above the freezing level ; and whenever the point of intersection was much below the freezing level, the positive areas were small. Hence it was not necessary to give any special weightage to the freezing level, so far as the present analysis is concerned.

(*b*) *Vertical Shear.* Byers and Battan[16] have discussed the effect of vertical shear in inhibiting thunderstorms. If there is any appreciable vertical shear, the tops of the clouds may be severed from their energy source. Further, the vertical shear may initiate premature downdrafts, which may interfere with the updrafts. The inhibition due to vertical shear will depend on several factors, *viz.*,

(*i*) The shear vector,

(*ii*) The horizontal extent of the updrafts and (*iii*) The velocity of the updrafts.

If, however, the horizontal extent and the velocity of updrafts are assumed to be proportional to the positive area, shear vector itself may be taken as a measure of the inhibition. As pointed out in (*a*) above, growth of cumulus beyond freezing level appears necessary for the realisation of a thunderstorm and as such, the shear vector between the friction free surface air, say wind at 500 metres and the freezing level may give an idea of the inhibition due to vertical shear.

6. Examination of Nagpur Tephigrams for April and May, 1945

Tephigrams for Nagpur for April and May 1945 were examined to find out how far the method of analysis discussed in this paper is likely to succeed. As the so called heat thunderstorms present the simplest cases for analysis, the choice was made of a place where the upper air regime is likely to be least affected during the forecast period. The central parts of the country provide such a region, where it is known that air masses have a tendency to stagnate for a reasonable period. Northeast India and northwest India are obviously unsuitable for reasons well known and similarly, the Peninsula also is unsuitable, due to its proximity to both the Arabian Sea and the Bay of Bengal.

The results of analysis are shown in Tables 1 and 2. The total positive area has been converted into joules per kgm of dry air and shown in the tables in column 3 as total instability, representing the sum of energy realisable by the lifting of an air parcel

TABLE 1

Analysis of Nagpur T-ϕ grams (April 1945)

Date	Time of ascent (GMT)	Total instability upto 400 mb level (in kilo joules)	Shear vector (mps)	Instability phenomena between 0230 GMT of the day and 0230 GMT of the following day
1	0600	1·2	—	—
2	0600	3·1	—	—
3	0600	1·8	—	—
4	0600	5·3	16	—
5	0600	1·0	—	—
6	0600	0·4	—	—
7	0600	0·4	—	—
8	0600	2·5	—	—
9	0600	2·8	—	—
10	0600	2·7	—	—
11	0600	0·4	—	—
12	0600	0·7	—	—
13	0600	2·9	12	Thunderstorm with 0·01″ of rain
14	0100 0600	9·4 11·7	16	Thunderstorm without rain
15	0600	3·7	—	—
16	0100 0600	6·1 7·7*	13	Thunder rain 0·13″
17	0100 0600	6·7 8·1*	10	Thunder rain 0·29″
18	0600	5·4	13	Thunder rain 0·48″
19	0600	5·7	9	Thunder rain 0·72″
20	0600	2·9	—	—
21	0600	1·6	—	—
22	0600	5·4	9	Thunderstorm without rain
23	0600	4·7	11	—
24	0600	2·4	—	—
25	0600	7·9	9	Thunderstorm without rain
26	0600	4·8	7	—
27	0600	2·9	—	—
28	0600	3·2	—	—
29	0600	5·0	7	—
30	0600	2·0	—	—

*These are interpolated values. 0600 GMT ascents were not available on these days

TABLE 2

Analysis of Nagpur T-ϕ grams (May 1945)

Date	Time of ascent (GMT)	Total instability upto 400 mb level (in kilo joules)	Shear vector (mps)	Instability phenomena between 0230 GMT of the day and 0230 GMT of the following day
1	0600	2·5	—	—
2	0600	5·0	—	—
3	0600	1·7	—	—
4	0600	1·2	—	—
5	0600	0·9	—	—
6	0600	0·6	—	—
7	0600	1·5	—	—
8		No ascent		
9		No ascent		
10	0600	1·1	—	—
11	0600	2·5	—	—
12	0600	2·4	—	—
13	0600	4·7	—	—
14	0600	2·5	—	—
15	0600	0·6	—	—
16	0600	2·0	—	—
17	0600	2·9	—	—
18	0600	7·7	5	Thunder rain 0·04″
19	0600	6·1	7	Thunder rain 0·08″
20	0600	5·4	6	Showers
21	0600	4·6	—	—
22	0600	3·7	—	—
23	0600	3·6	—	—
24	0600	5·0	5	—
25	0600	3·0	—	—
26	0600	3·6	—	—
27	0600	3·6	—	—
28	0600	3·7	—	—
29	0600	7·3	5	Showers
30	0600	2·5	—	—
31		No ascent		

to 400 mb* level from each 10 mb level from surface upto 400 mb*. It has been derived by the direct method described in Section 2. The ascents used are those of 0600 GMT. On 16 and 17 April, 0600 GMT ascents were not available. Hence, on these two days, 0100 GMT ascents have been used and the positive areas obtained from these ascents have been increased by 25 per cent to allow for the normal increase between 0100 and 0600 GMT. The increase by 25 per cent between 0100 and 0600 GMT is based on the average increase observed on days when both 0100 and 0600 GMT observations were available. However, even without this increase by 25 per cent, the positive area obtained on the morning ascent itself is large enough to warrant a thunderstorm forecast on each of these days. Before taking up the analysis, both the dry bulb and wet bulb curves have been redrawn to allow for the maximum temperature attained on the day, on the assumption that there is no superadiabatic lapse rate at any level and that there is no turbulent mixing and addition of moisture (*vide* Section 4). As the direct method of determining the total positive area has been used, it has been possible to allow for the negative area. The negative area, if any, corresponding to each significant level, has been subtracted from the positive area for that level, to give the net positive area. On all the occasions examined, the dry adiabatic through the surface maximum temperature cut the environment curve above the convective condensation level, so that, there was no negative area corresponding to air parcels from the surface and lower levels. The negative area due to lifting of air parcels from higher levels was also usually small, so that, no appreciable error would have arisen if this negative area was neglected. It may be questioned whether subtracting the negative area from the positive area is the best way of allowing for the negative area. When, however, there is no negative area corresponding to the lifting of air parcels from the surface and lower levels, any negative area corresponding to lifting of air parcels from higher levels is by itself not likely to inhibit a thunderstorm. In the circumstances, it was considered that the negative area corresponding to higher levels could best be allowed for by subtracting from the positive area. As already stated, negative area being small, no serious error would have arisen even if the negative area was neglected.

The shear vector given in column 4 of Tables 1 and 2 is that between the levels of 0·6 km and 4·5 km above sea level. The height of the station being 0·31 km, the lower height corresponds to 0·29 km instead of 0·5 km above ground. The winds at 0·29 km above ground have been used, as winds for 0·5 km above ground were not readily available. On many critical days, winds for 4·5 km above sea level were not available and on such days, they were obtained by extrapolation from stream lines on the 4·5 km upper wind chart. As the total positive area given in column 3 has been obtained after allowing for the maximum solar insolation of the day, the shear vector on the morning of the day has not been considered. The shear vector shown in column 4 is the mean of the shear vectors in the afternoon (1100 GMT approx.) of the day and on the morning (0300 GMT approx.) of the following day, the latter being taken into account in order to allow for any change in the shear vector between the afternoon of the day and the morning of the following day, the period during which the instability phenomena usually occurred. The shear vector has not been worked out for days when the positive area is too small. The instability phenomena shown in column 5 have been taken from the data published in the Indian Daily Weather Reports, supplemented in cases of doubt by reference to the Monthly Meteorological Register of the station. As rain during the season is usually associated with thunderstorm, any reportable rainfall has been taken as thunder rain, irrespective of whether thunder has been reported or not.

A reference to Tables 1 and 2 shows that, except for 4 April, instability phenomenon occurred on all days in April and May 1945 when the " total instability " according to the modified parcel method exceeded 5 kilo joules. On 4 April, the shear vector was as high as 16 mps while the total instability was only slightly above the critical value of 5 kilo joules, so that, taking account of the shear vector, one would not normally

* The ascents were made only upto 400 mb

expect a thunderstorm to occur. On 14 April, when the total instability was as high as 11·7 kilo joules, there was no measurable precipitation, although a thunderstorm occurred. This can also probably be ascribed to large shear (16 mps). On 19 April, the total instability, although sufficiently above the critical value, is not very large and the comparatively large rainfall on this day can perhaps again be ascribed to smaller vertical shear on this day. On 25 April, when the total instability was fairly high and the shear small, one would have expected a substantial amount of precipitation, which, however, did not occur and to that extent the method does not succeed. On 13 April, a thunderstorm occurred, although the total instability was only 2·9 kilo joules. An examination of the tephigram of the next morning, however, shows that there had been a rather rapid increase of moisture in the lower levels after the 0600 GMT ascent of the 13th, so that, if proper allowance is made of the increase in the positive area due to addition of moisture at lower levels, a thunderstorm is indicated. It should be noted that on the next day, *i.e.*, on the 14th, the total instability increased to over 11·7 kilo joules.

The analysis in the Tables 1 and 2 thus shows that reasonable success can be attained by the application of the method discussed in this paper, although more examples are required to be worked out before a proper assessment can be made of the degree of success attainable by this method. A note of caution appears necessary here. The critical value of 5 kilo joules for total instability found in the present analysis should not necessarily apply to other seasons and to other stations. For each month at each station a critical value has to be obtained by trial. Moreover, owing to the many assumptions and approximations involved in the method, the critical value obtained has to be regarded only as a rough guide. Again, the method has to be used with caution and due allowance must be made for changes in the ascent curves, when it is used for occasions when rapid changes in air masses are taking place and when frontal effect or convergence is superposed.

Finally, both the present method as well as the usual parcel method of analysis for latent instability assume that the kinetic energy of the updraft is a direct measure of the liability to thunderstorm. The work of Byers and Braham (*loc. cit.*) has, however, shown that the mature stage of a thunderstorm is characterised by downdraft in addition to updraft and that the downdraft is initiated by precipitation. As the occurrence of precipitation is not necessarily determined by the kinetic energy of the updraft, *i.e.*, by the size of the positive area shown in the tephigram, a doubt arises as to how far the size of the positive area by itself can be taken as a criterion for forecasting thunderstorm, and what weight, if any, should be given to the liquid water content of the cloud and other factors that determine precipitation. This question is under examination.

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