M.O. 420p AIR MINISTRY

METEOROLOGICAL OFFICE

PROFESSIONAL NOTES NO. 96

(Sixteenth Number of Volume VI)

COOLING OF AIR BY RAIN AS A FACTOR IN CONVECTION

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LONDON
HIS MAJESTY'S STATIONERY OFFICE

1949

Decimal Index
551.511 : 551.577

THREEPENCE NET

Prof. Notes Met. Off.
London, 6, No. 96, 1949

COOLING OF AIR BY RAIN AS A FACTOR IN CONVECTION

By J. S. Sawyer, M.A.

Preliminary note.—This paper is intended to set out certain facts which, although common knowledge to some forecasters, have not, it is believed, been concisely presented in a readily available form.

Introduction.—A theoretical treatment of the process of convection by which cumulus cloud and precipitation are formed is given in standard text-books (see Petterssen[1*] and Brunt[2]). However no discussion is usually included of the changes in air temperature which may result if precipitation produced in upward convection currents falls into a region of unsaturated air, nor of the effect of such cooling on the convection process. The problem was fully considered by Humphreys[3] in the "Physics of the air", first published in 1920, and the present paper is on the same general lines as his discussion, although references to more recent work in this field are incorporated.

Following up a suggestion in his own paper of 1921[4], Normand showed in 1937[5] that, if the evaporation of rain took place into a descending mass of air adjoining an upward convection current, the energy realisable from instability, under ideal circumstances, might be more than twice that assessed on the assumption that no evaporation of rain took place.

Previous observations in India had indicated that the cool air, which followed the violent squalls of the early summer thunderstorms of Bengal, must originate from levels of the atmosphere 10,000 ft. or more above the surface, and must be maintained in an almost saturated condition during the descent.

It was thus realised that, in India at least, the cooling of air by the evaporation of rain formed an important part of the convective process. This has since been found to be true in other parts of the world, notably west Africa, but also probably in east Africa and South America. The degree of importance to be attached to the process depends on the amount of cooling that can be produced; and this in turn depends on the initial dryness of the air. Thus it is in tropical latitudes, particularly on the fringes of the continental areas where steep lapse rates and low humidities occur, that the evaporation of rain plays the greatest part in the convective process. It is in the tropics also that topography is most effective in canalising the flow of evaporatively cooled air, and thus influencing the movement and development of convectional storms as discussed on p. 10, in the section on the effect of topography on convectional storms.

The origin of the surface air behind a convectional squall.—During the months of March and April violent convective storms (known as nor'westers) occur frequently over north-east India, and the squalls associated with them are often responsible for much damage to property and sometimes loss of life. For this reason they have been the subject of several investigations; a brief summary of the results of the most recent being published by the India Meteorological Department in 1944[6].

During the "nor'wester" season a shallow layer of moist air from the Bay of Bengal often covers north-east India, and above it lies relatively cold dry air of continental origin. The air column is convectively unstable and

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* The index figures refer to the bibliography on p. 11.

the wet-bulb potential temperature falls off upwards from about 81°F. at the surface to 66°F. at about 15,000 ft. True or latent instability is also sometimes present.

The interesting feature of nor'westers in the present discussion lies in the fact that the squall, besides being associated with a fall of temperature (commonly about 6°F. but sometimes 20°F.), is also accompanied by a fall of wet-bulb temperature to a value which is usually about 70°F. It will be recalled (see Brunt[2]) that the wet-bulb potential temperature is changed neither by the evaporation of water into an air mass nor by vertical motion under adiabatic conditions. The temperature of the air is, however, lowered by evaporation. Thus it follows that the air found on the surface after a nor'wester cannot be the same air that was there before, since its wet-bulb temperature is some 10°F. lower.* It must have originated from some level where the initial wet-bulb potential temperature was of the order of 70°F. Such a level is usually not found below 4,000 or 5,000 ft. at this season, and cases have been observed in which air must have descended to the surface from 15,000 ft. In fact it is likely that descents on the latter scale are the rule.

Here then we have a demonstration that, in these Indian storms at least, air descends to the surface from higher levels of the atmosphere, arriving on the ground as a cool wind indicating that evaporation of rain into the descending air has taken place. A very similar origin has been attributed to the air behind west African squall lines by Hamilton and Archbold[7]. C. K. M. Douglas has also pointed out that, in the middle of the continuous rain of the widespread thunderstorms over England in July 1945, violent SW. squalls occurred immediately followed by northerly winds. These undoubtedly came down from just below the freezing level of 12,000 ft.

Further examples of the evaporation of rain during its descent are the duststorms of northern India and certain other parts of the world. These can be accompanied by cumulonimbus cloud and thunder indicating the presence of raindrops aloft of which few, if any, reach the ground through the dry intermediate layers. A squall of cool air is, however, a feature of these storms and can only have been produced by the cooling effect of rain.

It is noteworthy in this connexion that Gold[8] has estimated the rate of change of the difference between the dry- and wet-bulb temperatures of the air as a result of the evaporation of rain into air without vertical motion; he considers that a reduction to about one-third the initial value of the difference can be expected in a period of the order of 10 minutes. A fuller treatment of the problem has recently been given by Dolezel[9].

The simpler treatment due to Gold can be extended in an approximate manner to the problem of the evaporation of rain into a descending air current. Calculation shows that, provided the rate of descent does not exceed about 200 ft./min., sufficient evaporation can take place for the temperature of the descending air to be nearer to the appropriate saturated adiabatic than the dry adiabatic.† With rates of descent in excess of about 200 ft./min. the air reaches the ground only slightly cooler than it would in the absence of rain.

* Cooling by conduction of heat to cold raindrops could be responsible for a lowering of wet-bulb temperature, but Humphreys has shown that this effect is too small to account for the observed lowering of the wet bulb.

† The appropriate adiabatics are those which pass through the point of the characteristic diagram which represents the state of the air before it commences to descend.

As an example the following figures are quoted for air descending from 10,000 ft. with heavy rain falling at a rate of 50 mm./hr. and drops of 2-mm. diameter. It will be recalled that the air reaches the ground with approximately the same wet-bulb temperature to whatever extent evaporation takes place.

(*a*) If the air is initially saturated and descends at 50 ft./min., it reaches the ground with a temperature about 8°F. above its wet-bulb temperature, instead of 32°F. above if the descent were dry adiabatic—an effective cooling of 24°F.

(*b*) If the air descends at a rate of 200 ft./min., it reaches the ground with a temperature about 15°F. above its wet-bulb—an effective cooling of 17°F., only just over half the possible amount.

(*c*) If the air descends at a rate of 1,000 ft./min., it reaches the ground with a temperature some 26°F. above its wet-bulb temperature, and only 6°F. below the temperature it would have attained dry adiabatically—effective cooling about 6°F.

An increase in the rate of rainfall increases the cooling, but an increase in the size of the drops with the same rainfall results in a decrease of cooling, because of the reduction of the area of the drops. Rain at the rate of 100 mm./hr. with drops of 5-mm. size causes less cooling than in the example quoted above.

The heat abstracted from the air in the melting of frozen precipitation is another factor assisting in cooling air, and may be important in certain circumstances.

The energy available as a result of cooling air by evaporation.—To demonstrate the possibility of the release of considerable energy by the cooling of air by rain, consider the development of instability in an air column represented in the tephigram of Fig. 1. This example is quoted from Normand's paper.

The initial lapse rate is represented by the dry adiabatic from the surface (1000 mb.) to 400 mb. (AB) and is surmounted by an inversion sufficient to limit convection at this level (BV). The initial wet-bulb curve is taken to be DEFB, corresponding to a constant wet-bulb potential temperature of 75°F. from the surface to 800 mb., and a constant wet-bulb potential temperature of 54°F. thence to 400 mb, the air being saturated at the highest level.

As is shown in the standard text-books the energy realised by the ascent of a " parcel " from the surface under conditions represented by the line AOK is given by the area BKO ; the replacement of this " parcel " by another descending dry-adiabatically from B to A involves no release or absorption of energy. The upward movement of another " parcel " of the lower moist layer from P to S and its replacement by the descent of the corresponding upper " parcel " from T to P releases energy represented by the area TSO ; and the energy released by the upward motion of the uppermost " parcel " of the moist layer and its replacement is HGO.

Thus on the assumption that the descending air moves downward under dry-adiabatic conditions, the total energy released for each unit mass moving upward during the overturning process is represented by the mean of the areas BKO, TSO, HGO, etc., i.e. approximately by the triangle TSO. It may be noted here that in the example chosen the same estimate of the available energy is obtained whether the problem is treated by the " parcel " or the " slice " method[1]. This is a consequence of the initial dry adiabatic lapse rate.

We now proceed to derive the maximum additional energy which can be made available if the excess moisture condensed in the ascending air can be evaporated into the descending air under ideal circumstances. It is not suggested that in the circumstances prevailing in the atmosphere all the possible energy will be released in this way, but an estimate of the maximum available energy is of interest for an understanding of the importance of the effect.

It can easily be verified from the tephigram that the water condensed during the ascent of the " parcel " initially at A along the path OK (Fig. 1) is sufficient to maintain saturation during the descent of the corresponding " parcel " from B, which will now follow the saturated adiabatic BC. The

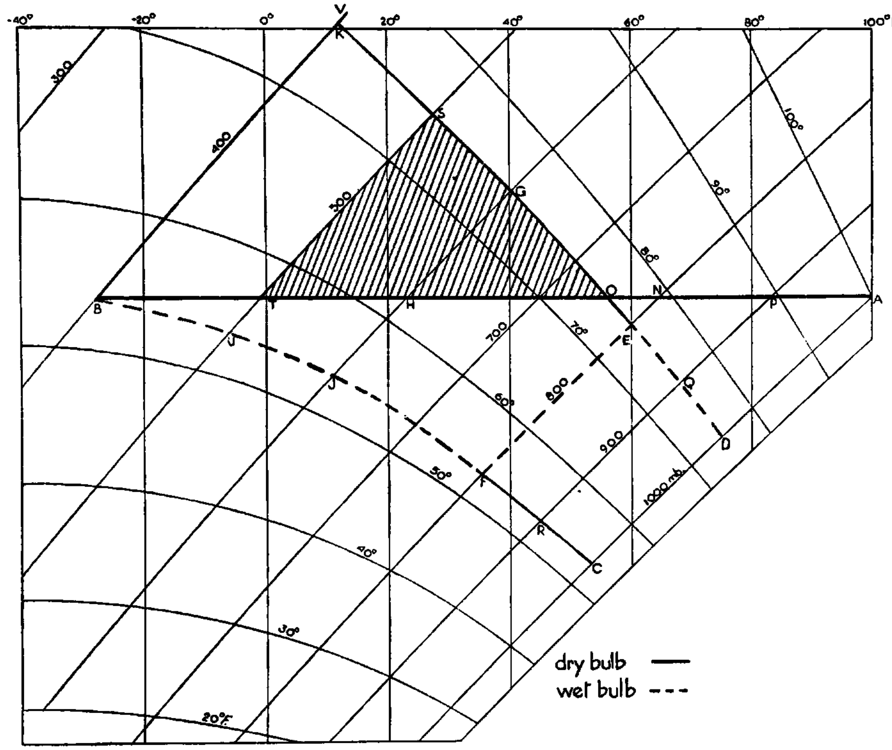

FIG. 1.—SCHEMATIC AEROLOGICAL SOUNDING

energy so released is represented by the area BCA. The heat content of the liquid water is ignored here, but its inclusion would make very little difference to the estimate of available energy.

Similarly it can be shown that the energy released during the saturation and descent of air initially at T and H is given by the areas TURP and HJFN respectively and the total energy per unit mass of descending air for the whole column is given approximately by the area TURP. The water condensed during the ascent of a " parcel " from N to G is not quite sufficient to saturate the corresponding parcel throughout its descent from J to F, but in the ideal case this can be supposed made good by an excess of water condensed during the ascent of the " parcel " from A over that required to maintain saturation in the corresponding "parcel" descending from B.

Thus we see that under the most efficient circumstances which can be envisaged in which the descending air absorbs the condensed water, the energy released during the overturning of the air column illustrated in Fig. 1 is represented by the area TURPOST. This is more than double that which would be obtained if the descending air was not moistened, viz. the area TSO.

It is interesting to note Normand's calculation that if the total energy released could be utilised to give kinetic energy to the whole air column, the velocity attained would be 80 kt.

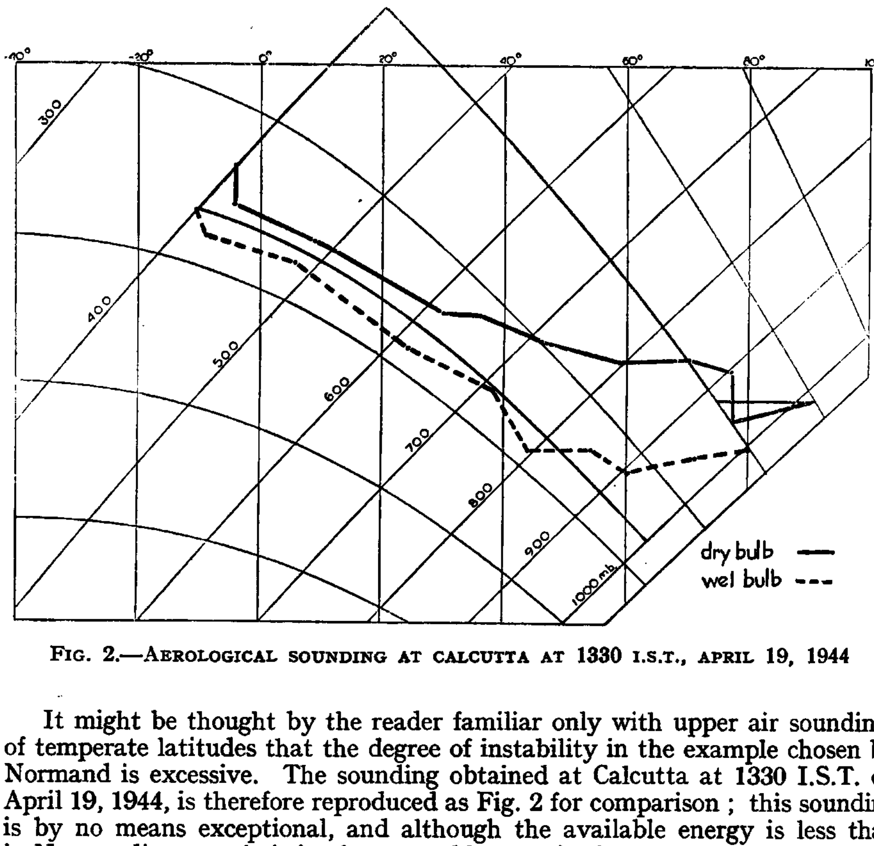

Fig. 2.—Aerological sounding at Calcutta at 1330 I.S.T., April 19, 1944

It might be thought by the reader familiar only with upper air soundings of temperate latitudes that the degree of instability in the example chosen by Normand is excessive. The sounding obtained at Calcutta at 1330 I.S.T. on April 19, 1944, is therefore reproduced as Fig. 2 for comparison ; this sounding is by no means exceptional, and although the available energy is less than in Normand's example it is of comparable magnitude.

It is to be realised that the transfer of liquid water from the ascending to the descending air current cannot take place in the ideal manner envisaged by Normand. It is, however, a common experience to see precipitation falling from the upper parts of a cumulonimbus cloud through a region of cloud-free and presumably descending air (see Fig. 3). It thus seems likely that part of the water condensed in the ascending current is evaporated into descending air.

Another situation which arises and can give rise to rain falling into relatively dry air occurs behind a cold front where rain from the overlying warm air mass falls through a cold air mass dried and warmed by subsidence. As will be seen in the example quoted in the following section, the effect of cooling by rain may be pronounced under these circumstances, particularly if the rain falls unevenly along the front because of instability in the warm air.

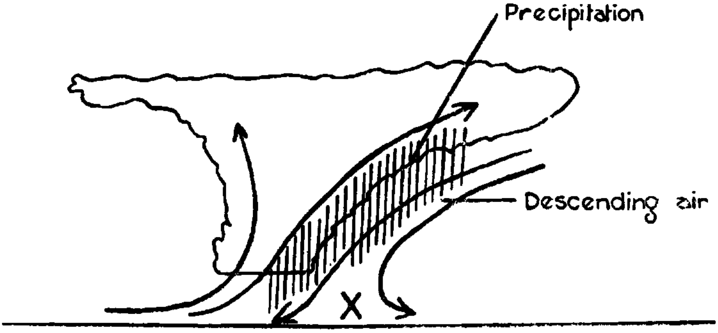

FIG. 3.—CONVECTIONAL STORM

Surface pressure changes resulting from the cooling of air by rain.—An immediate effect of cooling an air column by rain is to cause it to contract vertically. This causes a fall of pressure aloft and an inflow of air at the higher levels into the new low-pressure centre. The increase of mass of the air in the column is reflected in an increase of surface pressure, and although the air at the surface tends to flow out from the new "high" it is prevented by friction from balancing the inflow aloft. Thus we can expect cooling by rain to be accompanied by a rise of surface pressure.

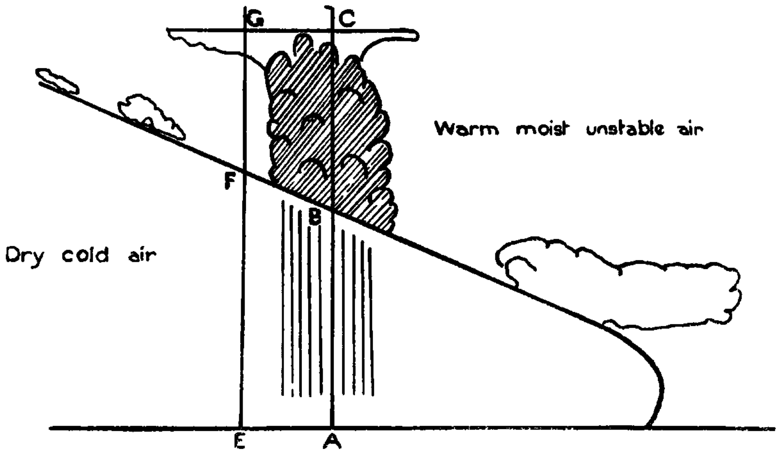

FIG. 4.—CROSS-SECTION THROUGH A COLD FRONT

It would be difficult to assess the magnitude to be expected in a convectional storm of such a pressure rise because of the complex nature of the storm and the uncertainty as to its kinematic structure. However in the following paragraphs an estimate has been derived of the pressure rise to be expected in the simpler problem of rain falling from an unstable warm air mass above a cold front surface.

Fig. 4 represents a cross-section through a cold front between a dry, cold air mass and a warm, moist, unstable air mass. Fig. 5 represents a schematic aerological sounding along the vertical ABC or EFG of Fig. 4 before precipitation commences from the convection cloud BC which is supposed to exist in the warm air above the frontal surface.

The lapse rate is taken to be dry adiabatic in the cold air mass from the ground to the frontal surface at 700 mb. (A′B′, Fig. 5) ; a sharp inversion is assumed at the frontal surface with a lapse slightly in excess of the saturated adiabatic above it (B″C′). The wet-bulb curve in the cold air mass is taken as along the saturated adiabatic A″B′. Although some features of the

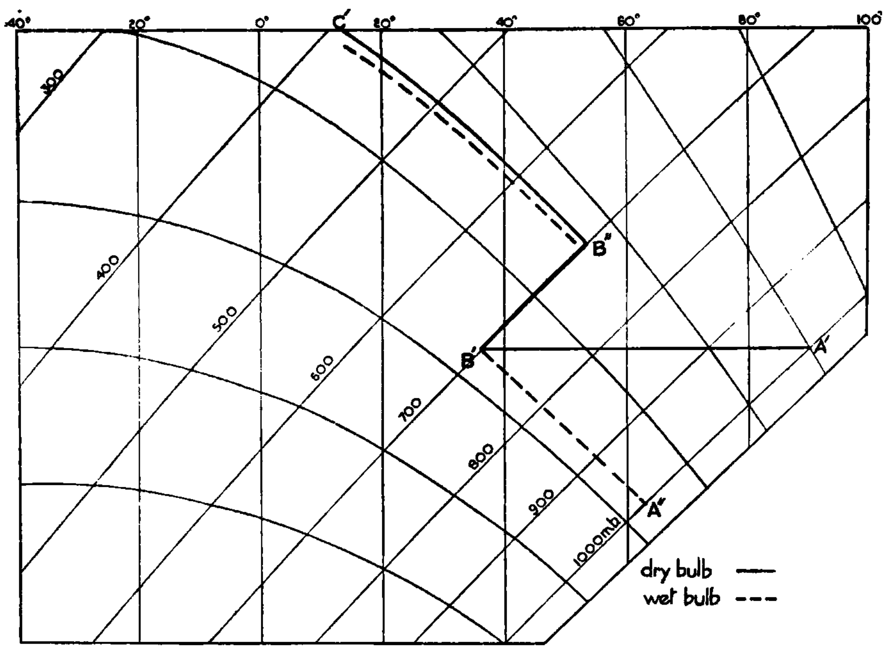

FIG. 5.—SCHEMATIC AEROLOGICAL SOUNDING ALONG ABC OR EFG OF FIG. 4

schematic sounding are exaggerated in Fig. 5 so as to simplify the discussion, little change in the magnitude of the effects would result from the substitution of a lapse rate more in accordance with observation.

We now consider the effect of rain falling from the cloud BC and evaporating into the air column AB. If the process could be carried out ideally the air column AB would be cooled to its wet-bulb temperature and its lapse rate would be represented by A″B′ (Fig. 5) while the lapse rate in the column EF outside the precipitation area would remain along A′B′.

It is easily verified from a tephigram that the thickness of an air column from 1000 to 700 mb. with the initial lapse rate A′B′ is 9,930 ft., but when cooled by evaporation to the saturated adiabatic A″B′ the column contracts to 9,680 ft. Thus if there were no horizontal movement of air, the effect of

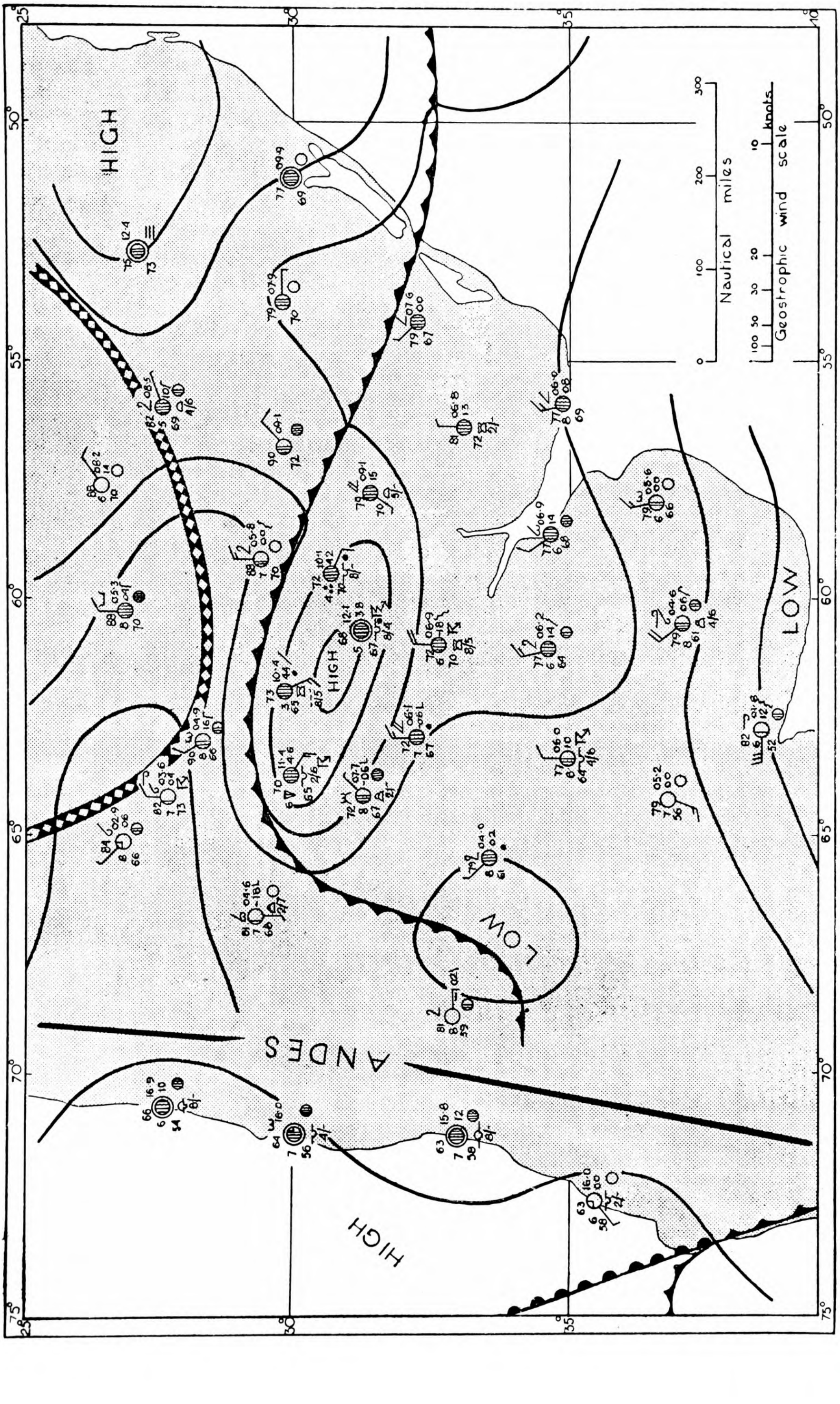

FIG. 6.—SYNOPTIC CHART FOR NORTHERN ARGENTINE AREA, 1200 G.M.T., JANUARY 12, 1942

the cooling of the air column AB would be to lower the isobaric surfaces at B and upwards by 250 ft., while at neighbouring points (e.g. F) outside the rain area there would be no such change in height. Clearly this will result in an inflow of air towards the air column AC which will destroy the low-pressure centre formed aloft, and if we imagine this to occur while the outflow of air at the surface is prevented by friction, sufficient air must flow in to raise the surface pressure until the 1000-mb. surface rises from the ground to 250 ft. This involves a rise of surface pressure of 9 mb.

In practice, in the atmosphere, outflow will take place at the surface as the pressure rises, although friction will prevent it from being as rapid as the inflow aloft. Thus the full rise of pressure computed above may not be realised; however the computation indicates the possible magnitude of the effect under favourable circumstances, and it is seen to be quite sufficient to account for the pressure rise observed during convectional squalls.

Part of a synoptic chart of South America is reproduced as Fig. 6. It shows a remarkable high-pressure centre believed to be the result of the process outlined above. The rise in pressure at the centre is about 6 mb., and it will be noticed that the surface winds are blowing outward from the centre. The pressure gradient is far too intense to be balanced by geostrophic winds; the gradient on the south side corresponds to a wind of 45 kt. even when the curvature of the isobars is ignored.

The effect of topography on convectional storms.—It has been seen in the preceding section how the effect of rain in cooling air may be to cause a rise of surface pressure by several millibars, and how this results in an outflow of surface air from the region in which the cooling has taken place, such as the edge of a convectional storm (X in Fig. 3). If however the ground surface is not flat, but includes ranges of hills, the outflow of the cooled air may be prevented from following certain directions by the contour of the ground. The strength of the outflow in other directions will thus be increased.

Fig. 7 shows the development which may take place when a convectional storm forms in the neighbourhood of a range of hills. The outflow of air from the region X is now forced to take place towards the storm itself, under-

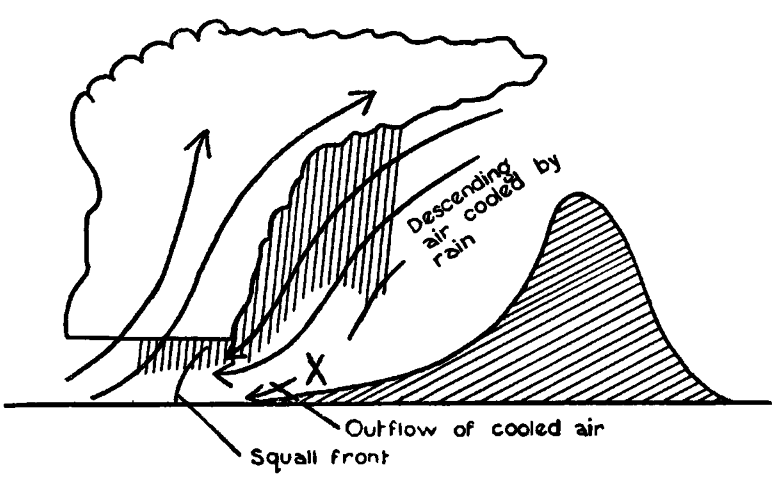

FIG. 7.—CONVECTIONAL STORM NEAR A RANGE OF HILLS

cutting and lifting the unstable air which is entering the storm. The vigour of the storm is thus increased, the cooling of the descending air continues, and the cooled air is forced to flow further and further from the hills, lifting the unstable air as it goes and causing the storm centre to be displaced away from the line of the hills irrespective of the pre-existing wind direction.

Such briefly is the structure of the "nor'westers" of Bengal which form along the hills to the west, north or east of Bengal and move away in a direction more or less at right angles to the line of hills on which they form; the squall line is more or less parallel to the hills. This type of storm is not confined to India; the sumatras of the Straits of Malacca have a similar structure, and a motion of storms from the hills towards the plain has also been observed in east Africa. Hamilton and Archbold[7] have recently suggested that the north-south orientation of the squall lines of the west African "tornadoes" is due to the orientation of the hills on which they form.

Conclusion.—It will be seen from the above discussion that under favourable circumstances the cooling of air by rain can form an important part of the process of convection; it may be responsible for the release of as much energy as is due to the buoyancy of the upward currents, and downward currents of cooled air deflected by the hills may determine the later development and movement of a storm. The rise of pressure caused by the cooling of air by rain may be several millibars.

The most favourable conditions for the development of the phenomena occur in tropical regions on the borders of the continents, but cooling by rain will produce similar effects, although to a less degree, in higher latitudes.

Acknowledgement.—Acknowledgement is due to Mr. C. K. M. Douglas who read the paper in draft form, and made some suggestions which have since been incorporated.

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(85795) Wt. 3271/M1028 3/49 Hw. PRINTED IN GREAT BRITAIN

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