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# RAINFALL IN EAST SCOTLAND IN RELATION TO THE SYNOPTIC SITUATION

By R. F. M. HAY, M.A.



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# RAINFALL IN EAST SCOTLAND IN RELATION TO THE SYNOPTIC SITUATION

By R. F. M. HAY, M.A.

*Publication of this note, which was written before 1939, has been delayed owing to the war.*

**Introduction.**—This paper attempts to relate the incidence and magnitude of falls of rain in east Scotland with the synoptic situations in which they occur. This district was suggested as a suitable one on which to carry out an investigation of this nature, partly on account of its geographical position (in the shelter of the Grampians) and also because the circumstances under which falls of rain occur there do not seem to have been examined previously in much detail. It was also anticipated that falls of " orographical " and " instability " types (which have already received much attention from different workers) would be infrequent in this area, and this expectation was to a large extent verified in the course of the work.

A station was wanted for which hourly values of rainfall were available, and it was decided to base the work upon an examination of the data for Aberdeen Observatory published in the *Observatories' Year Book* ; most of the conclusions have been reached as the result of a detailed examination of the records of this station for the five years 1926–30 together with the charts for the same period in the British and International Sections of the *Daily Weather Report.*

The movements of the depressions are discussed in relation to the falls of rain for which they were considered to be responsible under three separate headings " heavy falls ", " moderate and heavy falls " and " falls in relation to fronts and occlusions ".

**Heavy falls.**—Occasions on which falls of 25 mm. (1 in.) or more occurred within any consecutive 24 tabular hours were considered under this heading, and records were examined over a period of ten years, 1926–35, so as to include an adequate number of these falls. The paths followed by the centres of the systems responsible for the 38 heavy falls, which were found to occur in this period, were plotted on a map which showed that these paths converged to a striking degree upon an area just to the south of Aberdeen.

Thirty-five of the systems moved on tracks passing to the south of Aberdeen, and the greater number of them had formed over the Atlantic to the west and south of a line joining Blacksod Point to Ushant. In about half the cases the direction of motion of the centre, at the time when it was distant some 700 miles from Aberdeen, made an angle of approximately 20° with the line joining it to Aberdeen (in a clockwise sense), and this was true for systems approaching from all directions within a sector of radius 700 miles and defined by lines running west-south-west and south-east from Aberdeen. The largest falls of rain are thus mainly associated with systems which, from their direction of approach, would appear to give longest warning of their arrival. Only three of the thirty-eight falls were accompanied by thunder, justifying the selection of Aberdeen as a station free from " instability " falls of this nature. Autumn (September, October, November) with 18 out of the 38 cases had the greatest number of these large falls, followed by Spring (March, April, May) with 8, and Summer (June, July, August) and Winter (December, January, February) with 7 and 5 respectively.

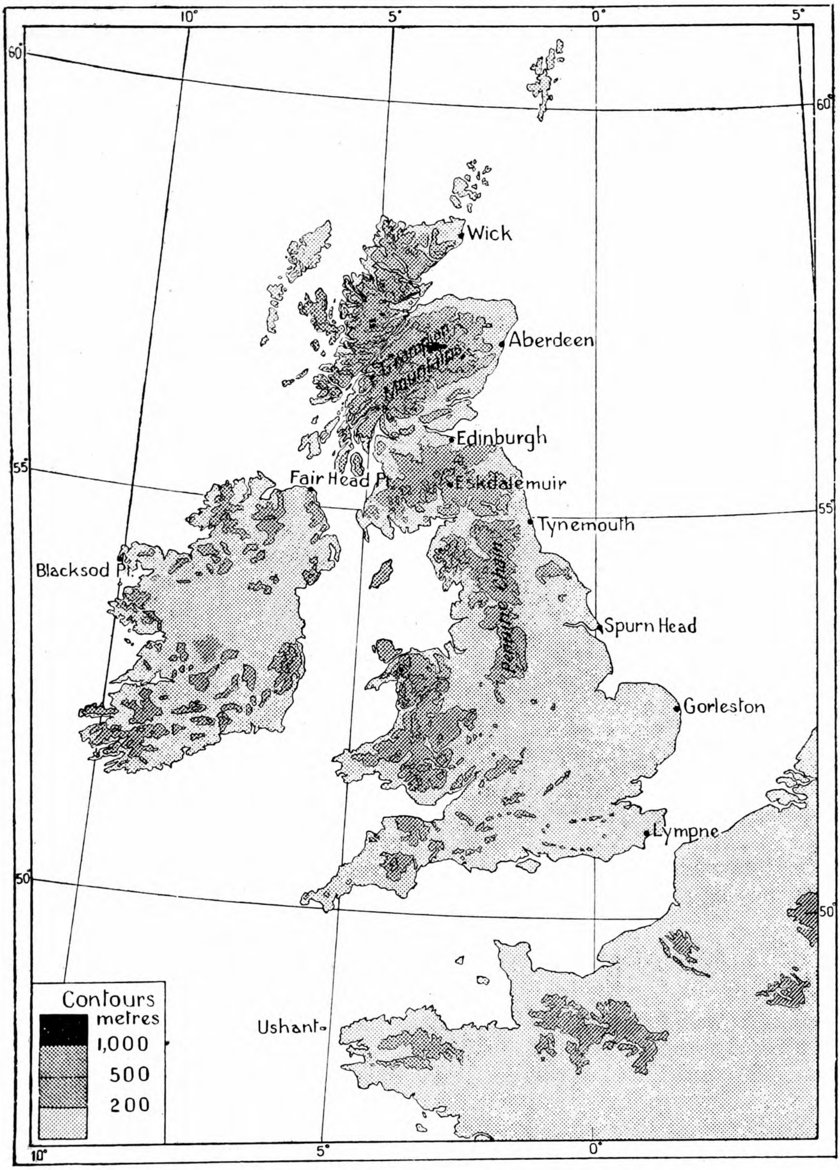


FIG. 1.—OROGRAPHICAL MAP OF THE BRITISH ISLES

**Moderate and heavy falls.**—*Classification of tracks.*—The paths followed by all low-pressure systems yielding **3** mm. of rain or more in the five years **1926–30** (including those yielding **25** mm. or more during the same period) were examined, and each path was assigned to a simplified " track ", which most closely agreed with the true track in accordance with a classification of " tracks " devised for the purpose, and shown in Fig. 2. The " tracks " are represented as straight lines but each is to be regarded rather as a sheaf of lines tied together in the middle. These simplified tracks were listed together with the amounts of rain yielded by the systems from data given in the *Observatories'*

*Year Book, Daily Weather Report* and *Monthly Weather Report* as before. No reference was made to frontal developments at this stage. The classification of secondaries and secondary troughs presented some difficulty so that in the tables the tracks were assigned (*a*) to the primary depression where there was no definite evidence that a secondary or trough was responsible for the rain, and (*b*) to the secondary or trough when the case was clear, the path of the primary in this case being merely noted.

In the notation used below the figure 1 denotes a primary depression, and 2 a secondary depression with closed isobars. The capital letter attached refers to the track followed by the systems ; brackets round the letter denote a secondary with open isobars moving on the track in question. Thus

1 A denotes a primary depression moving on track A.
2 B denotes a secondary with closed isobars moving on track B.
2 ($C_1$) denotes a secondary with open isobars moving on track $C_1$.

No large falls were occasioned by primary depressions moving on track E, and in compiling these lists any falls occurring when deep primary depressions were centred off west Scotland were credited with certainty to secondaries moving on another track.

In totalling the number of systems moving on each track, the path of the secondary has been the track used in all cases where both primary and associated secondary tracks were listed together. There were a certain number of doubtful cases, where the system or the track followed by the system responsible for the rainfall could not be allotted with any degree of certainty, and an estimate of the number of these systems, together with the percentage of the rainfall of the five years which was unaccounted for as a result, is given later.

*Seasonal distribution of frequency of systems on selected tracks.*—The number of systems following the various tracks is given for the seasons of the period 1926–30 in Table I. The tracks of some secondary troughs have been omitted from the table, and the data given there do not represent the frequencies of all systems following these tracks in every case. In particular, a number of troughs moving on track $C_2$ have been omitted.

It was possible to assign tracks to 411 systems. Thunderstorms were associated with only 9 of these systems so that the results in Table I would not be affected in any systematic manner by the exclusion of these 9 cases.

Track A was followed by the largest number of rain-yielding systems, namely 76, B was followed by 67 systems, $C_2$ by 63, and F by 56. Neglecting the tracks $B_1$ and I, 244 of these systems passed south of Aberdeen and 125 to the north. Fewer primary systems on track A were responsible for falls than on track B, while the number of secondary systems following track A was strikingly large. Although secondary systems which produced rain were more numerous on track $C_2$ passing just to the north of Aberdeen than on track $C_1$ which passes just to the south, the systems in the former group yielded much smaller amounts of rain.

As was expected, the rain-bearing systems on tracks A and B, having their origin over the warm waters of the Atlantic to the west of the British Isles, are most frequent in autumn and winter. A large number of secondaries also follow track A, notably in winter, and spring is the only season when their occurrence is relatively infrequent. A similar seasonal distribution is also found for the systems following track $C_2$. On the other hand, rain-bearing secondaries on track $C_1$ are most common in spring and summer. Systems following track F are nearly as numerous as those on A and B in spring and autumn but are

TABLE I—NUMBER OF SYSTEMS FOLLOWING GIVEN TRACKS DURING THE FIVE YEARS 1926–30

| | 1A 2A 2(A) | 1B 2B 2(B) | $1B_1 2B_1 2(B_1)$ | $1C_1 2C_1 2(C_1)$ | $1C_2 2C_2 2(C_2)$ | 1D 2D 2(D) | 1F 2F 2(F) | $1F_1 2F_1 2(F_1)$ | 2G 2(G) | 1H 2H 2(H) | 1I 2I |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Spring | ... 3 8 | 3 4 1 | 2 4 ... | 1 6 2 | ... 6 6 | 1 3 ... | 2 9 9 | ... 2 1 | 3 6 | 2 4 1 | 1 ... |
| Summer | 2 6 11 | 8 5 6 | 2 3 1 | 1 6 4 | 1 7 9 | ... 4 2 | ... 4 3 | ... 1 ... | 5 4 | 1 3 1 | ... ... |
| Autumn | 3 11 8 | 6 11 3 | 2 8 1 | 1 4 1 | ... 8 6 | 2 2 ... | 3 9 15 | ... ... ... | 4 3 | 3 4 ... | 2 ... |
| Winter | 1 7 16 | 4 8 8 | 3 8 3 | 1 2 3 | 5 6 9 | ... 1 1 | ... 2 ... | 1 1 ... | 2 3 | ... 4 1 | 1 1 |
| Total | 6 27 43 | 21 28 18 | 9 23 5 | 4 18 10 | 6 27 30 | 3 10 3 | 5 24 27 | 1 4 1 | 14 16 | 6 15 3 | 4 1 |

TABLE II—NUMBER OF SYSTEMS YIELDING FALLS OF A CERTAIN MAGNITUDE

| (*a*) Systems with closed isobars | | | | | | (*b*) All systems | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tracks | Total number tabulated | Number yielding | | | | Tracks | Total number tabulated | Number yielding | | | |
| | | <3 mm. | 3 mm.–7 mm. | 7 mm.–10 mm. | >10 mm. | | | <3 mm. | 3 mm.–7 mm. | 7 mm.–10 mm. | >10 mm. |
| 1A + 2A | 33 | 8 | 5 | 6 | *14* | A | 76 | 11 | 23 | 10 | *32* |
| 1B + 2B | 49 | 16 | 9 | 4 | *20* | B | 67 | *26* | 11 | 7 | *23* |
| $1B_1 + 2B_1$ | 32 | *24* | 4 | 2 | 2 | $B_1$ | 37 | *29* | 4 | 2 | 2 |
| $1C_1 + 2C_1$ | 22 | *8* | 3 | 4 | 7 | $C_1$ | 32 | 10 | 9 | 5 | 8 |
| $1C_2 + 2C_2$ | 33 | 7 | *12* | 9 | 5 | $C_2$ | 63 | 13 | *31* | 13 | 6 |
| 1D + 2D | 13 | *5* | 3 | 0 | *5* | D | 16 | *6* | 4 | 0 | *6* |
| 1F + 2F | 29 | 7 | *15* | 5 | 2 | F | 56 | 8 | *34* | 9 | 5 |
| $1F_1 + 2F_1$ | 5 | ... | 3 | 0 | 2 | $F_1$ | 6 | ... | 4 | 0 | 2 |
| 2G | 14 | *5* | 2 | 2 | *5* | G | 30 | *11* | 6 | 4 | 9 |
| 1H + 2H | 21 | *13* | 4 | 2 | 2 | H | 24 | *14* | 6 | 2 | 2 |
| 1I + 2I | 5 | 2 | 2 | 0 | 1 | I | 5 | 2 | 2 | 0 | 1 |

Numbers which are equivalent to one third or more of the total number of cases and also not less than five are in italics.

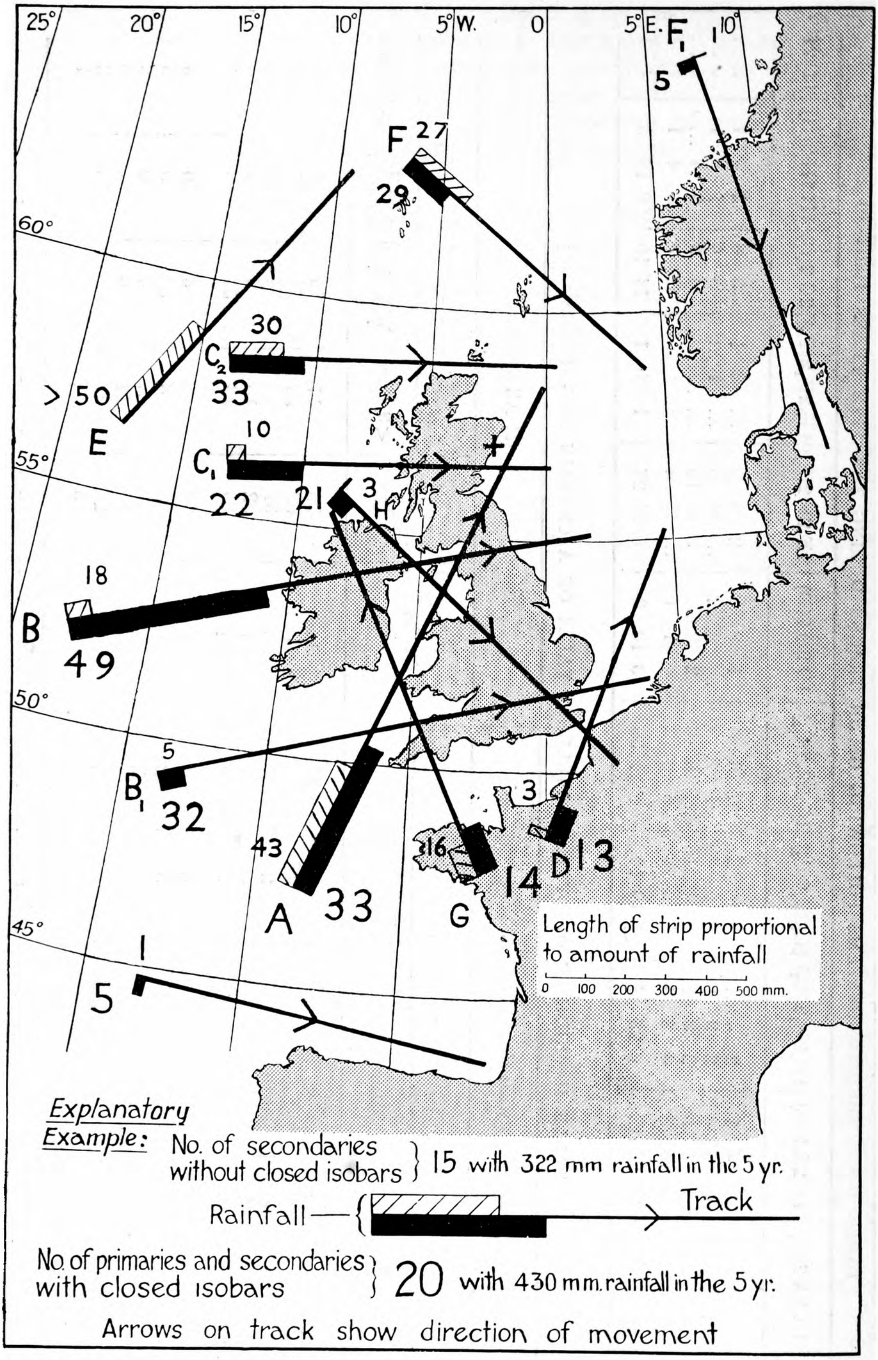


FIG. 2.—CLASSIFICATION OF TRACKS TOGETHER WITH RAINFALL AMOUNTS YIELDED AT ABERDEEN BY DEPRESSIONS FOLLOWING THE TRACKS SHOWN, AND NUMBER OF DEPRESSIONS FOLLOWING EACH TRACK DURING THE FIVE YEARS 1926–30.

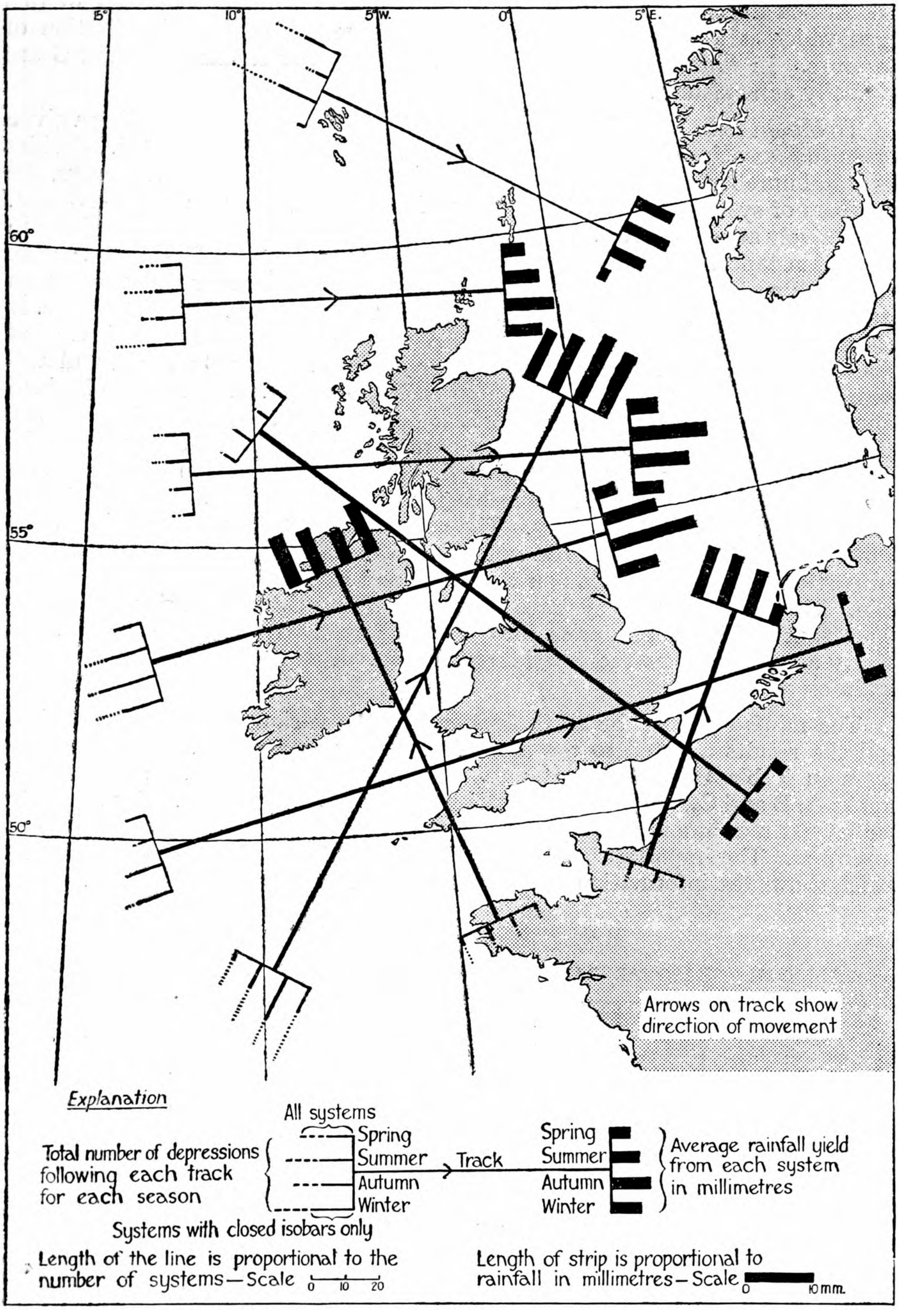


FIG. 3.—TOTAL NUMBER OF DEPRESSIONS FOLLOWING EACH TRACK DURING THE SEASONS OF THE FIVE YEARS 1926–30 AND AVERAGE SEASONAL RAINFALL YIELD FOR EACH SYSTEM.

uncommon in summer and winter, showing the equinoctial character of this type which is associated with major changes in the general distribution of pressure. In winter, systems moving on the irregular tracks D, F and G are virtually non-existent.

To obtain some idea of the relative frequency of heavy falls exceeding a given magnitude associated with the various tracks, Table II was constructed. Besides the total number of systems giving falls on each track in the five years, the numbers of systems which yielded falls of >10 mm., >7 mm., and < 3 mm. respectively are also shown. Systems with closed isobars only are considered in the first instance. The table shows that a good chance of a fall of >10 mm. occurs only with systems following tracks A and B, two out of every five systems on track B yielding >10 mm. of rain. The best chance of a fall of >7 mm. is afforded by a system moving on track A (two in three), and there is a good chance of a fall of >7 mm. with systems moving on tracks B and $C_1$, and also with those following the less frequented tracks D and G. The figures obtained when all systems are included—Table II (*b*)—show that the chance of occurrence of a rainfall amount of >7 mm. becomes rather smaller for all the tracks while their distribution is not greatly affected. The high proportion of systems on tracks $C_2$ and F which are responsible for yielding rainfall amounts between 3 and 7 mm. is also noteworthy. The column giving the number of systems moving on each track which did not yield >3 mm. of rain, shows that a large proportion of systems moving on tracks $B_1$ and H do not yield this amount of rain. The figures for the systems on tracks B and $C_1$ are of interest as they show that (taking secondaries into account) systems yielding < 3 mm. are nearly as numerous as those yielding >7 mm. This point will be referred to again on p. 14.

The rainfall yielded by all the systems on the various tracks was totalled, and the results allotted to the seasons and year as a whole. These results, given in Table III, show that autumn yields the largest rain amounts for tracks A, B and $C_2$, and spring the largest for tracks D, F and G. For track $C_1$, the largest rain amounts are yielded in summer, winter showing a pronounced minimum. The importance of tracks A, B, $C_1$ and $C_2$ is brought out in Fig. 2 which shows the information for the year contained in Tables I and III.

TABLE III—SEASONAL RAINFALL TABLE FOR THE FIVE YEARS 1926–30

| Systems with closed isobars following tracks | Spring | Summer | Autumn | Winter | All systems following tracks | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|---|---|---|---|---|
| | *millimetres* | | | | | *millimetres* | | | |
| 1A + 2A | 25 | 106 | 141 | 127 | A | 88 | 174 | 232 | 240 |
| 1B + 2B | 20 | 130 | 255 | 96 | B | 27 | 145 | 267 | 118 |
| $1B_1 + 2B_1$ | 8 | ... | 9 | 46 | $B_1$ | 8 | ... | 9 | 46 |
| $1C_1 + 2C_1$ | 25 | 104 | 44 | 14 | $C_1$ | 35 | 123 | 49 | 22 |
| $1C_2 + 2C_2$ | 14 | 39 | 65 | 65 | $C_2$ | 36 | 83 | 100 | 99 |
| 1D + 2D | 32 | 28 | 27 | 3 | D | 32 | 45 | 27 | 6 |
| 1F + 2F | 49 | 38 | 40 | 3 | F | 127 | 49 | 126 | 3 |
| $1F_1 + 2F_1$ | 4 | 6 | ... | 16 | $F_1$ | 7 | 6 | ... | 16 |
| 2G | 38 | 21 | 26 | 34 | G | 75 | 41 | 46 | 42 |
| 1H + 2H | 15 | 3 | 21 | 10 | H | 15 | 7 | 21 | 10 |
| 1I + 2I | 20 | ... | ... | 6 | I | 20 | ... | ... | 6 |

The seasonal rainfall totals clearly depend to some extent upon the seasonal number of systems frequenting the given tracks. If the seasonal rainfall totals for each track are divided by the seasonal number of systems following the track, the quotients should give the average rainfall yielded by each system at Aberdeen during the seasons. The results are shown in Table IV and set out diagrammatically in Fig. 3. All the systems listed were taken into account, including those with rainfall entered as " Nil " because it was less than 3 mm.

TABLE IV—AVERAGE RAINFALL YIELD IN EACH SEASON FOR ANY SYSTEM FOLLOWING THE GIVEN TRACK

Figures are obtained from the quotient :—

$$\frac{\text{Rainfall yield from all assignable systems in track}}{\text{Total number of systems assigned to track}}$$

When the number of systems is too few for the figures to be reliable they are inserted in brackets.

| Track | Spring | Summer | Autumn | Winter | Track | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|---|---|---|---|---|
| | *millimetres* | | | | | *millimetres* | | | |
| A | 8 | 9 | 11 | 10 | D | 8 | 8 | 7 | 3 |
| B | 3 | 8 | 13 | 6 | F | 6 | 7 | 5 | 1 |
| $B_1$ | 1 | 0 | 1 | 3 | $F_1$ | [2 | 6 | ... | 8] |
| $C_1$ | 4 | 11 | 8 | 4 | G | 8 | 5 | 7 | 8 |
| $C_2$ | 3 | 5 | 7 | 5 | H | 2 | 1 | 3 | 2 |
| | | | | | I | [20 | ... | 0 | 3] |

The table shows that as much as 13 mm. falls on the average from any system following track B in autumn, the amounts being a little smaller from track A in autumn and winter and $C_1$ in summer. The largest average yield occurs in autumn for systems on tracks B and $C_2$, and in summer for $C_1$ ; for A it is large at all seasons. The smallest average rain yield occurs in spring for tracks A, B and $C_1$, and in winter for D and F. From a study of a number of the occasions when falls occurred with systems moving on track $C_1$ it appears that the contrast between the average rain amounts yielded in summer (11 mm. per system) and in winter (4 mm. per system) is probably due to the greater degree of atmospheric instability present in summer, the higher figure at that season being due to the incidence of showers or cold-front rain[1*] at Aberdeen. The higher temperature of the sea off the west coast is also likely to exercise a similar influence in the figure for the summer yield at west-coast stations.

As it was not found possible to assign tracks to all the systems yielding rain in the period 1926–30 under review, an examination of the data was made to determine what percentage of the rainfall was unassigned, and the results are set out in Table V.

Systems whose directions of motion were so irregular that they could not fairly be considered to follow any of the tracks used in this classification contributed 9 per cent. of the total rainfall of the five years, while a further 19 per cent. of the rainfall has not been included in the tables as it occurred in individual falls of < 3 mm. which it was decided to omit from the discussion.

*Rainfall on the east coast of Great Britain in relation to selected tracks.*—The largest number of moderate and heavy falls on the east coast of Scotland is yielded by systems moving on tracks A and B (on p. 11 evidence is adduced

* The index figures refer to the bibliography on p. 17.

TABLE V—RAINFALL TOTALS FOR THE FIVE YEARS 1926–30 AT ABERDEEN YIELDED BY (*a*) ALL ASSIGNABLE SYSTEMS, (*b*) UNASSIGNABLE SYSTEMS AND (*c*) INDIVIDUAL FALLS OF <3MM. EXCLUDED FROM THE DISCUSSION

(*a*) All assignable systems

| Track. | A | B | $B_1$ | $C_1$ | $C_2$ | D | F | $F_1$ | G | H | I | E | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total rainfall yielded (mm). | 734 | 557 | 63 | 229 | 318 | 110 | 305 | 29 | 204 | 53 | 26 | 309 | 2,937 |

(*b*) Unassignable systems

| | mm. |
|---|---|
| Total rainfall yielded in individual falls of > 3 mm. and < 25 mm. ... ... | 225 |
| Total rainfall yielded in individual falls of > 25 mm. ... ... ... ... | 140 |
| Total ... ... ... ... ... ... ... | 365 |

(*c*) Individual falls

| | mm. |
|---|---|
| Total rainfall occurring in individual falls of < 3 mm. excluded from discussion | 799 |

| | mm. | Percentage of total rainfall |
|---|---|---|
| Total rainfall used in discussion ... ... ... ... ... | 2,937 | 72 |
| Total rainfall from all unassignable systems ... ... ... ... | 365 | 9 |
| Total rainfall occurring in individual falls of < 3 mm. ... ... | 799 | 19 |
| Total rainfall for 5 years 1926–30 ... | 4,101 | 100 |

for the belief that, with one exception, the rainfall régime at Aberdeen is sufficiently representative of that of the east coast of Scotland to justify this statement). The east coast districts of England might correspondingly be expected to derive a large number of their moderate and heavy falls of rain from systems moving on tracks D and $B_1$.

This supposition was tested by separately totalling the amounts of rain received from all systems following tracks D and $B_1$ for the years 1926–30 at the five stations Wick, Tynemouth, Spurn Head, Gorleston and Lympne, using data from the *Daily Weather Report.* On some occasions it happened, especially at Wick, that the rain was obviously yielded by a separate system (following a more northerly track) and in this case the rain was excluded from the discussion.

The totals were expressed as percentages of the individual total rainfall at each station for the five years 1926–30.

| | Wick | Aberdeen | Tynemouth | Spurn Head | Gorleston | Lympne |
|---|---|---|---|---|---|---|
| Track $B_1$ .. | 0·9 | 1·5 | 7·4 | 10·0 | 9·7 | 8·3 |
| Track D .. | 1·8 | 2·7 | 3·8 | 5·4 | 3·8 | 3·3 |

As was anticipated the maximum yield from systems on tracks $B_1$ and D is along the coast of north-east England. The figures show a roughly uniform decrease to north and south from Spurn Head. The rainfall from systems on track $B_1$ is about twice as great as from track D while the region of maximum fall from $B_1$ appears to lie correspondingly further south.

From a geographical standpoint a close similarity between the figures for the percentage of the total fall yielded by systems moving on track B at Aberdeen (13·6 per cent.), and on track $B_1$ at Spurn Head (10·0 per cent.) is to be expected. At first sight it seems that the analogy for the case of the tracks having a more southerly origin does not hold, as track A at Aberdeen yields 17·9 per cent, while track D at Spurn Head yields only 5·4 per cent. of the total. If comparison be made between the figures for the mean rainfall per system (B at Aberdeen 7 mm., $B_1$ at Spurn Head 8 mm., A at Aberdeen 10 mm., D at Spurn Head 10 mm.) the agreement is at once apparent. Thus, systems following track $B_1$ yield as much rain in north-east England as those systems which follow track B yield at Aberdeen, but the similar relationship holding for tracks D and A in north-east England and north-east Scotland respectively does not show up until account is taken of the much smaller number of systems which follow track D.

The paths of the systems following track $B_1$ during the period under review were separately plotted on a map. No dependence of the tracks upon any geographical features was apparent, all the systems moved in simple and nearly straight paths in a direction between east and east-north-east and crossed England south of the Pennines. The map which was also drawn to show the paths of the systems allotted to track D is reproduced in Fig. 4. The paths of nearly all the systems converge to pass near or through the Straits of Dover, and some of the systems move in a north-westerly direction or very erratically thereafter. The movements of systems following this particular track would, therefore, appear to be influenced by the physical configuration of the western European seaboard, where, especially in winter, the warm surface of the seas facilitates the upward movement of air near the centre of a depression whose life is thereby prolonged when its centre follows a track which lies over the sea. The temperature contrasts between the surface waters of the North Sea and English Channel may also affect the movement of these depressions to some extent.

**Falls in relation to fronts and occlusions.**—The synoptic situations of some fifty occasions when rainfall amounts were moderate or large (and including a few cases when they were unexpectedly small) at Aberdeen, were examined with the aid of the Meteorological Office working charts, supplemented on some of the occasions by autographic records for Aberdeen and Eskdalemuir. From these cases it appears that the majority of heavy or moderate falls of rain at Aberdeen are associated with the movement of warm occlusions in a direction between east-north-east and north over the British Isles. In many cases a characteristic anti-clockwise rotation of the front in relation to the low-pressure area to the west is observed, and the front frequently runs nearly due west to east by the time the rain belt has reached Aberdeen. In many of the situations where the heaviest falls occur, the isobars in the cold air preceding the front run nearly parallel to it, giving a gradient for strong SE. winds. Generally the isobars behind the front are more nearly perpendicular to the front and the pressure gradient is weaker.

*Autumn and winter falls.*—An area of low pressure is most commonly established over the north-east Atlantic near Iceland in autumn and winter, and this distribution of pressure is favourable for the passage of secondaries across the British Isles in a north-easterly direction. The air in the warm sectors of these systems usually moves from south-west or south-south-west, confirmation of this fact being afforded by a scrutiny of the nephoscope observations which were available for a number of the cases examined, and most of the moderate (5–25 mm.) and some of the heavy falls of rain at Aberdeen occur during the approach of secondaries (on track A) associated with warm occlusions as described above. The eastward movement of a trough of low pressure is sometimes hindered by an anticyclone centred over Scandinavia, and, in these circumstances, heavy falls of rain tend to occur in east Scotland.

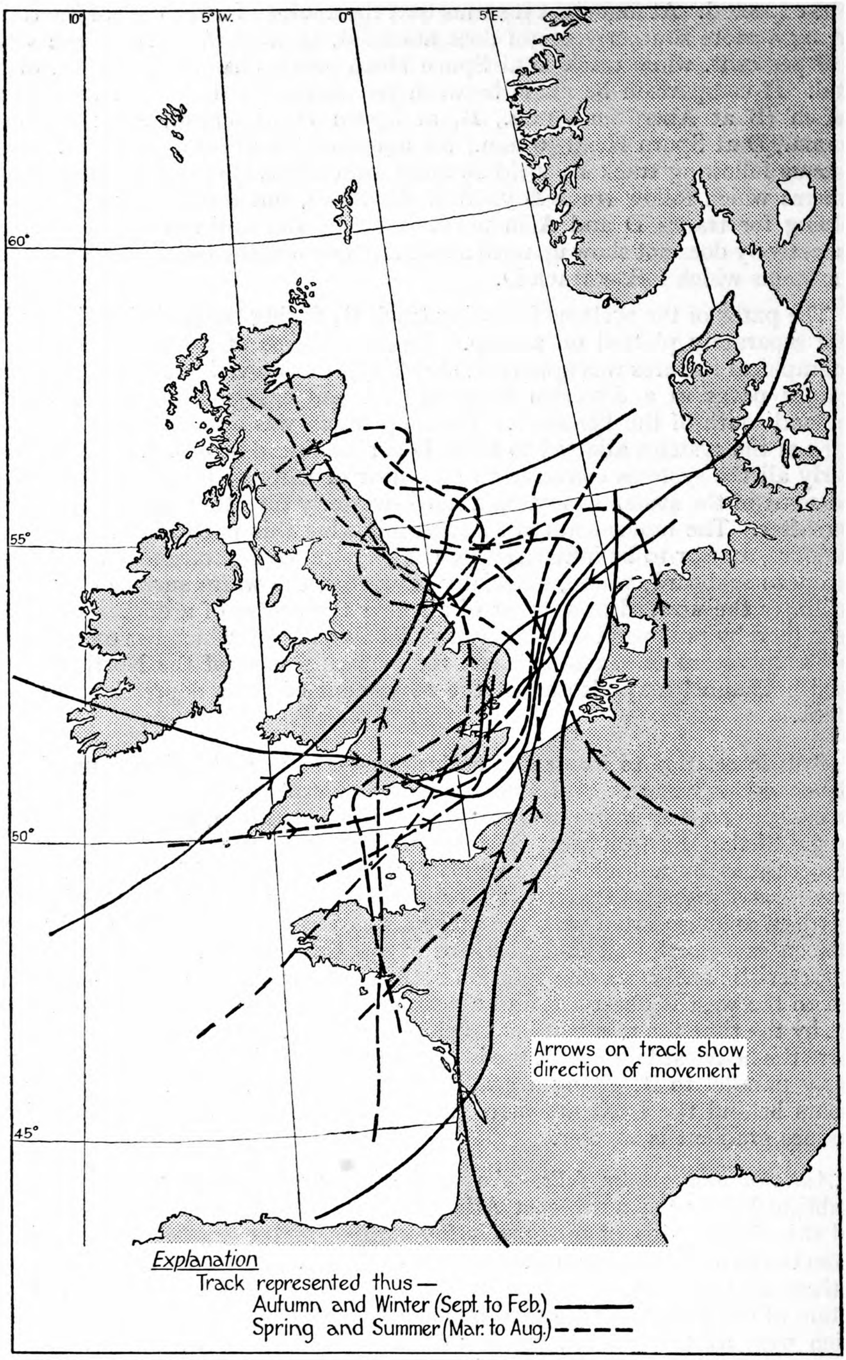


FIG. 4.—MOVEMENTS OF CENTRES OF ALL SYSTEMS ALLOTED TO TRACK D 1926–30

The pressure gradient, in these and other cases when large falls occurred, is often favourable for strong steady SE. winds which begin to blow up to twelve hours before the commencement of the rain and last through most of the period of the fall. At Aberdeen they are on-shore winds, and the falls appear to be local to some extent. To eliminate local effects, the rainfall record at Edinburgh (Royal Observatory) together with the Aberdeen record have been examined on all occasions of moderate or heavy rain at the latter station during the period under review. For these occasions of prolonged SE. wind yielding large falls at Aberdeen it was found that the falls at Edinburgh were generally small. Apart from these cases, there is good agreement between the amounts of rainfall at Edinburgh and Aberdeen, on occasions of moderate and heavy falls at the latter station, during the approach of low-pressure systems with associated warm occlusions from the south-west.

Most of the occasions when rainfall was moderate at Edinburgh but negligible at Aberdeen in autumn and winter were due to the eastward movement of a depression on track $B_1$ (or sometimes B), in which the counter-clockwise rotation of the warm front did not carry it far enough to the north for the rain belt to reach Aberdeen, but in a few of these cases the rain area reached south Scotland and died out before extending further to the north-east. The depressions responsible for these falls were found to be nearly filled up, the fronts no longer being marked on the charts.

Few cases of moderate falls due to the passage of cold fronts occurred during the period under review. Cold occlusions, when associated with a system moving on tracks $C_2$ or F (*i.e.* in an east or east-south-east direction to the north of Scotland) appear to yield only trifling or moderate amounts of rain in brief showers. Cold fronts running approximately north to south, and associated with a trough or considerable shear in the isobars are sometimes responsible for moderate and even considerable falls, as are also intensifying fronts accompanied by a pronounced southward movement of polar air.

*Spring falls.*—The on-shore winds from E. and NE. associated with depressions moving on tracks F and $F_1$ in spring and early summer generally yield heavy falls of rain. These falls are associated with instability in air which has moved to the North Sea from high latitudes and may also be assisted by the configuration of the high ground in east Scotland.

*Summer falls.*—In summer large falls of rain sometime occur at Edinburgh and Aberdeen near the centres of shallow slow-moving depressions which appear to be already completely occluded. These falls are not always associated with thunder and would appear to be due to interaction on the south side of the centre between air masses of continental and Atlantic origin at a trough which sometimes forms at a later stage, or else to frontogenesis and regeneration of the depression due to the arrival of colder polar air in the west flank of the system. Other moderate and heavy falls in summer are due to the approach of warm occlusions from the south-west as already described, though the proportion of these falls that occur in this season is much smaller than in autumn and winter.

Occasionally large rainfall totals are experienced on several successive days even in east Scotland. Such a run of wet days occurred in Edinburgh in the period July 3–9, 1937, and was one reason which prompted this investigation. During this week 118 mm. of rain fell at the Royal Observatory. The forecasts of rainfall amount were correct on two days, underestimated on three days, overestimated on one day and badly underestimated on one day. In two of the cases of underestimated rainfall and in one where it was overestimated the actual amounts of rain experienced accord quite well with the results found earlier in this work. In one of the cases where the rainfall was correctly forecast, the same result is indicated in this work, but unfortunately little or no help is afforded in dealing with the synoptic situation on July 7 when the one case of serious underestimation of rainfall occurred.

*Cases of negligible falls.*—When secondary centres are smaller or less pronounced on the chart they are sometimes developed among straight isobars (*i.e.* in a broader air flow), or another centre may lie a short distance to north-west or north of them. The former situation not infrequently occurs during spells of " westerly " weather in winter, the latter is characteristic of cyclonic conditions during summer, and in both cases the vigorous convergence observed in the secondary troughs in autumn and winter is to a large degree absent. Rainfall, in these cases, though liable to be heavy in the immediate vicinity of the track of the secondary centre shows a rapid decrease to north of it, and this may be related to the absence of a fully developed circulation on the north side of the centre and the presence of a westerly current within a short distance of it. A number of the cases of rainfall $< 3$ mm. noted with systems moving on tracks B and $C_1$, and referred to on p. 8, were associated with secondaries of the types just described.

*Practical applications.*—During the period under review (1926–30) the interval which elapsed between the certain identification of the warm front on the map by the forecaster and the commencement of the rain at Aberdeen in a number of cases was found to be seldom more than six hours and only once as great as 24 hours. Subsequently the International Charts of the *Daily Weather Report* for the years 1935 and 1936 were examined. For the 18 cases which lent themselves to treatment on these lines it was found that the mean interval between the establishment of the front on the chart and the commencement of the rain at Aberdeen was 27 hours. Once rain actually commenced one hour before the front was established, while in another, 53 hours elapsed after the front had been established before the associated rain belt reached Aberdeen.

As a warm front approaches the west coast of Ireland its direction of motion can be determined more accurately. For the same cases the mean interval that elapsed after the warm fronts had crossed the arbitrarily selected point 50° N. 15° W. on the Atlantic until rain began at Aberdeen was found to be 15 hours. This corresponds to a mean component of velocity of 43 m.p.h. over the distance of 500 miles between 50° N. 15° W. and Fair Head (Northern Ireland) along the line joining these two points. The rain belt associated with the fronts frequently reached Aberdeen (distant 200 miles) at the same time as the fronts were crossing Fair Head, so that in these cases the width of the rain belt was commonly about 200 miles. The mean component of velocity of the fronts between Fair Head and Aberdeen was similarly found to be 33 m.p.h.*

In general the warning of the approach of the fronts is longer in summer than in winter. In the former season systems sometimes move very slowly ; in fact, they spread rather than travel and the direction of their motion is less constant. Winter systems, for weeks at a time, have more definite tracks, which in itself might assist in the practical application of some of the results mentioned earlier. In the case of systems approaching Scotland from west and south-west on tracks B and $C_1$ the interval between the drawing of the system on the chart and the commencement of the rain must be rather shorter owing to the smaller distance through which the movement of the system can be followed over land stations.

* The point 50° N. 15° W. was selected solely because it lay at one end of an imaginary base line along which frontal velocities near the western seaboard could conveniently be measured, and has no connexion with amounts of rain yielded at Aberdeen. Many depressions which pass this point subsequently yield little or no rain at Aberdeen.

Negligible rainfall amounts are contributed by individual primary depressions moving in a north-easterly direction off west Scotland, and the amounts of rain from secondaries which follow track E seldom exceed 5 mm. When the main area of low pressure lies further to south and east of its normal position and the isobars in the warm sector of the approaching secondary run from west to east, the system generally follows a track between B and $B_1$ and no rain falls at Aberdeen.

*Theoretical applications.*—The asymmetrical distribution of rainfall along the track of a depression was first pointed out by Dr. Mill in 1904. In his paper, he stated that "the belt of cyclonic rains is much wider on the left of the path than on the right, and the heaviest falls occur in advance of the centre."[2] The results already found here show that depressions of which centres pass some distance to southward of Aberdeen yield the heaviest falls of rain there. The centres of most of these systems eventually pass from 60 to 190 miles south-east of Aberdeen, though they are often situated considerably further south during the period when it is raining most heavily at Aberdeen. There appears to be a tendency for the centres of the systems yielding the heaviest falls ($>$25 mm.) to keep roughly more than 60 miles to southward while the centres of systems which yield smaller rain totals pass quite close to Aberdeen. An explanation of these facts is afforded by the work of those authors who have succeeded in establishing that the tropical air in a depression at higher levels penetrates to north and north-east of the ground-level centre. In reference to a sounding made at Benson on December 20, 1922, near the centre of a deep depression at the time of its maximum intensity, Douglas[3] stated, "There was apparently a layer of tropical air with colder air above and below it." Rainfall was very heavy a short distance to the north of the path of the centre in this example. In several of the depressions considered in this paper nephoscope observations confirmed the existence of a SSW. current at the cirrus and altocumulus levels in the tropical air to the south of the centre. The cirrus-level diagrams given by Goldie[4] (Figs. 7, 8, 9 of *Geophysical Memoirs* No. 79) for air motion above depressions show in greater detail what occurs. The diagrams in fact show that the centre at the cirrus level is on the average 160 to 190 miles (250 to 300 Km.) further north than the surface centre. The penetration of the warm air to north and north-east of the surface centre of lowest pressure involves vertical convergence (together with simultaneous horizontal divergence or increased horizontal velocity if the warm air is to be disposed of in fulfilment of the equation of continuity) and Hewson has recently shown[5] that this is of frequent occurrence in the warm air of developing cyclones. The region of heaviest rainfall will be in the neighbourhood of the zone of maximum uplift of the tropical air. The approximate lines of flow of the tropical air in the warm sector at the slopes of the polar front surface have been drawn for a single depression by Bjerknes and Palmén[6] and the manner in which the tropical air circulation existed north of the ground-level centre was sketched. For the same depression the authors also showed that the region of maximum uplift of the tropical air, where the whole component of its velocity was at right angles to the frontal surfaces up to a height of some miles lay just to north-east of the ground-level centre. The simultaneous translational and rotational movements of curved warm and cold fronts might be expected to result in a zone of maximum uplift of the warm air in every developing depression, adjacent to the point where the cold front leaves the ground and lies against the warm-front surface. In districts relatively free from orographic influence such as the east coast of Great Britain, the area of heaviest rainfall would lie on the path of this zone, which shares in the movement of the depression.

Rainfall near the centre of a depression will also be influenced by the amount and distribution of the moisture content of the air through the vertical, which considerably affects the amount of " latent instability " available for raising the moist air layers above the saturation level.[7] Tephigrams for the Duxford ascents on some of the occasions of moderate and heavy falls of rain at Aberdeen were drawn. In the majority of these cases " latent instability " was present through a considerable thickness of the lowest 5,000 ft. of the atmosphere and the maximum humidities were often also in the same layer. The development of " latent instability " was sometimes possible at higher levels, *i.e.* within the tropical air, though this occurs infrequently and the tropical air is usually stable.

**Summary and conclusions.**—In the course of the work the following conclusions were reached.

1. A pronounced degree of convergence to a region a short distance (60 to 125 miles) south of Aberdeen is shown by the tracks of nearly all the depressions which yield more than 25 mm. (1 in.) of rain at Aberdeen.

2. During the period under review it was found that the largest number of rain-yielding systems were allotted to the tracks A and B in the classification adopted.

3. Only with systems moving on tracks A and B is there a good (40 per cent.) chance of the rainfall from a single system exceeding 10 mm.

4. For the majority of the tracks, including A and B, the average rainfall from a single depression is largest in autumn. The seasonal distribution for track $C_1$ shows a large difference between the average rain yield of individual depressions in summer (11 mm.) and winter (4 mm.), a greater degree of atmospheric instability probably accounting for the high summer figure.

5. The rainfall yield at Spurn Head from systems on track $B_1$ was found to correspond closely with that at Aberdeen from systems on track B. There is also a similar agreement at the two places for the rainfall from tracks D and A. Other evidence shows that certain of the results for Aberdeen can be generalised to apply to other parts of the east coast of Scotland and England.

6. On the other hand, a certain dependence upon the physical configuration of the west European seaboard is shown by the movements of the depressions on track D but not by those on track $B_1$.

7. The majority of heavy and moderate falls of rain at Aberdeen occur with the passage of warm occlusions in a north-easterly direction across the country, especially in autumn and winter.

8. Some of the results found are discussed in relation to conditions prevailing during an outstanding week of rain in Edinburgh.

9. Systems responsible for winter falls in general move faster and on more definite tracks than those that occur in summer. Some figures were found relating to the warning given by systems of their approach at different seasons and the rates of advance of fronts from the Atlantic.

10. Nephoscope observations showed that the direction of motion of the tropical air at cirrus and altocumulus levels was frequently from south-southwest in the systems discussed.

11. Tephigrams for several of the cases when heavy falls occurred showed that " latent instability " was present in the lowest layers of the atmosphere : the tropical air above was stable but usually not far removed from saturation.

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