On the Sub-tropical Jet Stream and its Role in the Development of Large-scale Convection

By C. RAMASWAMY, International Meteorological Institute in Stockholm[1]

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Abstract

This paper contains mainly the results of a synoptic and climatological study of the large-scale convection in northern India and Pakistan during the three months preceding the onset of the southwest monsoon. It has been shown that the sea-level and lower tropospheric charts give little clue to the development of the large-scale convection and that the latter is overwhelmingly determined by the divergence in the waves in the sub-tropical jet-stream. It has further been shown from detailed synoptic evidence that nor'westers, andhis and the majority of the thunderstorms without squalls in northern India and Pakistan in the pre-monsoon period are fundamentally the same phenomenon. The role of cold-air advection in the middle and upper troposphere in the development of large-scale convection has also been discussed. This study has further revealed that the regions of upper-divergence and convergence can be qualitatively located by identifying certain typical patterns on the high-level maps more than 12 hours before the usual time of commencement of convection and that, consequently, these maps can be used as effective tools in the issue of area-warnings against thunder in general and nor'westers and andhis in particular.

A general study has also been made of the large-scale convection in southeast Australia, Union of South Africa, Bechuanaland, Southern Rhodesia, northeast Argentina, Uruguay, southeast Brazil and southeast United States and the similarities between the large-scale convection in these countries and in Indo-Pakistan have been brought out. On the basis of these studies, it has been suggested that the jet stream plays the very important role of producing large-scale convection in the subtropics all over the world wherever it over-runs on its equatorward side, moist air possessing a high degree of latent instability.

1. The nor'wester and andhi problems of Northern India and Pakistan.

From the middle of March to the time of establishment of the southwest monsoon, northern India (defined broadly, for purpose of this paper, as India north of latitude 20° N) and Pakistan experience thundersqualls or convective duststorms which are occasionally of great severity and cause heavy destruction of life and property. The thundersqualls which occur in Northeast India and East Pakistan, i.e. roughly between 83° E and 95° E and between 20° N and the foot of the Eastern Himalayas are popularly known as *nor'westers*. They are often accompanied by very heavy rain and sometimes by hailstorms and they occur generally late in the afternoon or in the evening in the plains and late in the night or early in the morning in the valleys of Assam and along the foot of the Eastern Himalayas. Nor'-westers are, however, not uncommon over these regions in other parts of the day or night. The convective duststorms over the rest of northern India and over West Pakistan are popularly known as *andhis*. They are characterized by dustwalls and are invariably accompanied by cumulonimbus clouds. Thunder is

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[1] The author belongs to the Indian Meteorological Service. He took part in the meteorological research activities at Stockholm when he was on ex-India leave.

also frequently heard during such storms, but the rainfall associated with them is usually small or negligible. They occur generally late in the afternoon or in the evening in the plains, but are not uncommon in those regions at other times of the day or night. Tornado clouds with the typical funnel shape have also sometimes been observed with the nor'-wester as well as the andhi. Squalls of 100 mph have been recorded in association with these phenomena.

Calcutta and Delhi, two of the great cities in India, experience the typical nor'wester and the andhi respectively. The following statistics of squalls of 40 mph or more at Calcutta and Delhi (K. P. RAMAKRISHNAN and B. GOPINATH RAO 1954) is of interest.

Station	Number of squalls per month						Usual date of onset of southwest monsoon
	March	April	May	June	July	August	
Calcutta (Alipore 22° 30′ N 88° 30′ E)	2.6	3.6	5.2	2.4	0.2	—	First week of June
Delhi (New Delhi 28° 35′ N 77° 12′ E)	0.6	2.8	7.0	4.2	2.0	0.4	End of June

N.B. When several distinct squalls occurred on the same day, a maximum of two have been counted with a view to avoid a large contribution to the average by exceptional days.

For purposes of comparison, the periods during June when the southwest monsoon usually sets in at Calcutta and New Delhi have been given by the present writer in the above table. These are based on the curves showing the normal dates of onset of the southwest monsoon published by the Government of India Meteorological Department in the *Climatological Atlas for Airmen* (1943 edition, p. 3). As the date of establishment of the monsoon in any individual year can differ considerably from the normal date as given in the Atlas, it will be obvious from the above table that large-scale convection in northern India and Pakistan, as manifested in the nor'-wester and the andhi, markedly decreases with the establishment of the southwest monsoon.

2. Normal climatological features over Northern India and Pakistan in the pre-monsoon period[1]

The normal sea-level pattern over this region in May which is a typical month of large-scale convection is shown in Figure 1. It has been reproduced from the *Climatological Atlas for Airmen* (1943 edition, page 7) referred to above. The isobars in this diagram refer to the mean pressure during the day. On this normal map, the present writer has superposed isopleths of normal dewpoints at 03 G.M.T. (i.e. 0830 hrs Indian Standard Time[2]) based on the data of about 200 stations. The trough lines based on the published isobars and surface winds have been drawn by the present writer. An examination of this sea-level map shows the following:

(a) In association with the low-pressure area over West Pakistan and northern India, there is a normal incursion of moist air from the Bay of Bengal into Northeast India and East Pakistan (i.e. east of 83° E north of 20° N) the moisture, as revealed by the dewpoints being a maximum in the coastal districts and gradually decreasing northwards in the interior.

(b) In association with the same sea-level pressure-system, relatively very much drier air sweeps over the rest of northern India and over West Pakistan.

(c) There are, broadly speaking, three air-streams over northern India and Pakistan at sea-level namely (1) westerlies or northwesterlies (2) southwesterlies or southerlies (3) easterlies. The southwesterlies or southerlies and the easterlies are both moist while the westerlies and northwesterlies are relatively very much drier. These three air-streams show a certain amount of velocity—convergence along the trough lines marked UC, CA and CM.

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[1] For the Indo-Pakistan *sub-continent as a whole*, the following may be taken as the four seasons of the year:
The cold weather period—December to February.
The pre-monsoon or hot weather period—March to May.
The monsoon period—June to September.
The post-monsoon period—October and November.
Unless otherwise specifically stated, the word "monsoon" as used in this paper refers to the southwest monsoon.

[2] The Indian Standard Time (I.S.T.) is $5^1/_2$ hours ahead of Greenwich Mean Time.

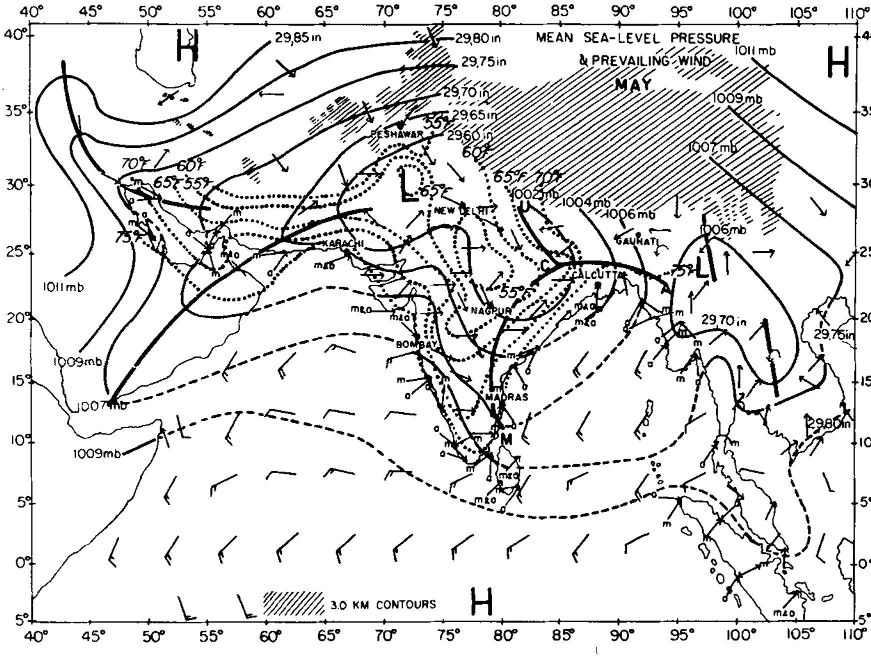

Fig. 1. This map has been reproduced from the *Climatological Atlas for Airmen* (Government of India Publication, 1943 edition) and has been plotted according to the conventions in vogue at the time of its publication. On this map, the present author has drawn the trough lines and superposed isopleths (dotted lines) of the normal surface dewpoints at 03 G.M.T.

(d) The normal west to east pressure gradient across West Bengal and East Pakistan is only about 4 millibars.

The normal 09 G.M.T. stream lines and trough lines at 3,000 and 5,000 feet in May, which have not been reproduced here, show the following:

(a) The easterlies and the trough-line CA seen on the normal sea-level chart, are not seen at 3,000 and 5,000 feet.

(b) The line UCM seen at sea-level and which more or less separates the very dry from the moist stream is persisting at the 3,000 and 5,000 feet levels, but it shifts eastwards with increase in height.

(c) The normal winds are only 5 to 13 knots even at 5,000 feet.

Above 5,000 feet, the dry westerlies dominate the scene and steadily increase in speed with height up to the tropopause, the increase becoming marked above 10,000 feet. The normal contour-pattern at the 300 mb level in May is shown in Fig. 2. Almost all the winds on this map are 09 G.M.T. (1430 I.S.T.) wind normals[1] of resultant wind-direction and *resultant* velocity (i.e. taking into account directions) computed by the India Meteorological Department and based on all observations available upto 1950 in the case of Indian stations and upto 1947 in the case of Pakistan stations. The normals of the height of the 300 mb isobaric surface and of the partial thickness of the 500~300 mb layer were computed by the present author from the daily radiosonde observations at 15 G.M.T. for the years 1951—55 published in the Indian Daily Weather Reports. The normals for Shillong are based on the data for the years 1953—55 only.

The 300 mb contour map clearly shows that there is a maximum of speed of the westerlies near about the latitude of New Delhi. This observational fact is consistent with the findings of KOTESWARAM and PARTHASARATHY (1954) about the mean position

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[1] Normals based on less than 10 individual observations have not been included in the map.

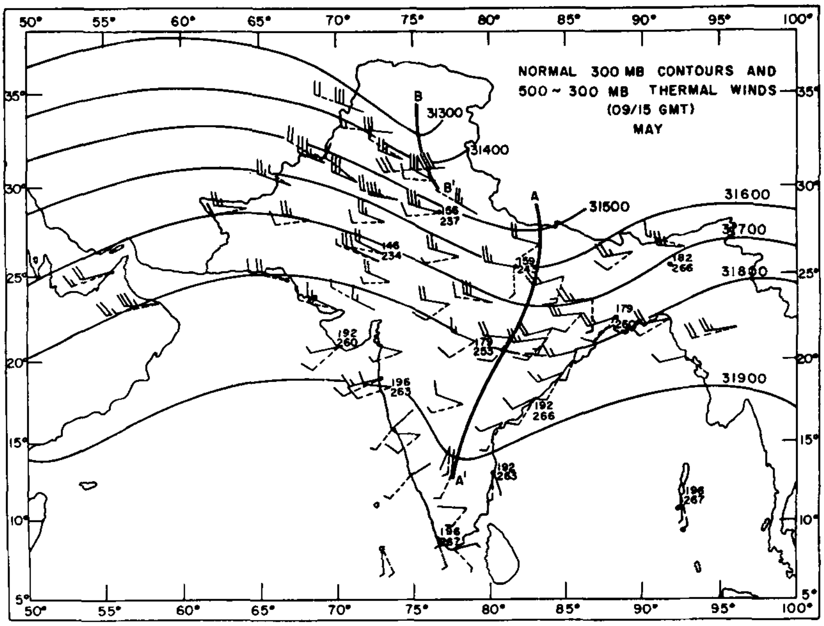

Fig. 2. The figures against some of the stations are the normal heights of the 300 mb surface (upper figures) and the normal partial thicknesses of the 500 ~ 300 layer (lower figures) at 15 G.M.T. correct to the nearest tens of geopotential feet. The figure in the ten thousandth place has been omitted in the upper as well as the lower figures. For example, 179 and 260 against Calcutta indicate that the height of the 300 mb surface is 31,790 geopotential feet and that the partial thickness of the 500~300 mb layer is 12,600 geopotential feet. The contours have been drawn for every hundred geopotential feet.

of the axis of the jet stream over India during the period April—May.

In the pre-monsoon period, the highly moist air from the Bay of Bengal which is continuously invading Northeast India and East Pakistan possesses a high degree of latent instability (Normand, 1938. S. Petterssen, 1940). This instability cannot however be realized on account of an inversion which separates the moist layer from the superincumbent dry westerlies. On the other hand, over Northwest India and West Pakistan, the lower tropospheric air is normally very dry and the lapse-rate in this air is very nearly dry adiabatic. The studies made by earlier workers on convective duststorms show that, prior to the development of these storms, there is an injection of moisture in the lower troposphere mainly as a result of movement of extra-tropical type of cyclonic circulations known in Indian meteorological literature as western disturbances (Riehl 1954, p. 269). This "semi-moist" air has a high degree of latent instability, the energy from which can be released only by a trigger of sufficient intensity.

3. Present ideas about the mechanism of the nor'wester and the andhi

The following is a very brief summary of the present ideas about the mechanism of the nor'wester and the andhi:

The *nor'wester*—Almost the entire work on this subject has been confined to the study of the nor'westers over West Bengal[1] and East Pakistan.[1] In 1938, K. R. Ramanathan and K. P. Ramakrishnan put forward the view that the development of the nor'wester is primarily determined by cold-air advection above 6 km. The authors based their conclusion on the

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[1] The region referred to as West Bengal and East Pakistan in this paper was politically known as "Bengal" before 15 August 1947. Hence the expression "nor'westers of Bengal" has gained currency in scientific literature. Destructive nor'westers, however, occur in the State of Assam and also occasionally in other States in and near Northeast India.

monthly mean upper-air temperatures computed from the change of the monthly mean winds with height. Surprisingly enough, their view about the mechanism receded into the back-ground and in spite of an attempt by S. L. MALURKHAR (1948, 1949) to bring it again to the forefront, the nor'wester is considered today as an essentially lower tropospheric phenomenon. The workers have been seeking for the cause of this phenomenon in the accentuation of the west to east pressure-gradient across "Bengal", in insolation, the "convergence-front" between moist air and dry air in the lower troposphere, cold fronts of the middle-latitude type associated with western disturbances, cold air from a neighbouring thunderstorm, katabatic winds from the hills, and so on (A. K. ROY 1949, 1950, B. N. DESAI 1950).

The *andhi*—This phenomenon has been studied at only two or three individual stations (P. R. KRISHNA RAO 1938, SREENIVASAIAH and SUR 1939, DESAI and MAL 1940, K. L. SINHA 1952). According to these workers, the andhis are associated with the release of the latent instability energy in the moist air brought by the western disturbances, the trigger for the release being insolation or cold-fronts of western disturbances or lower tropospheric convergence near a discontinuity.

At this stage, it would not perhaps be irrelevant to mention that the present writer and B. L. Bose, on the basis of a study of the mean isotherms for the 700 ~ 500 mb and 500 ~ 300 mb layers for daily situations, had tentatively suggested (C. RAMASWAMY and B. L. BOSE 1954) that the development of the nor'westers was determined by (1) the dynamics of the middle and upper tropospheric west-wind belt (2) the thermal advective processes as observed from the change of wind with height, in the 700 ~ 500 mb and 500 ~ 300 mb layers. The authors had also made a general suggestion that similar processes were probably responsible for the convective dust-storms of Northwest India and West Pakistan.

4. Technique of analysis in the present investigation

The investigation reported in this paper is an examination of the *entire problem de novo* without any reference to the previous work of the author and is based on charts prepared and analysed by the author in the International Meteorological Institute, Stockholm, Sweden. The technique adopted consisted, broadly speaking, of analyses of (1) sea-level and upper-air maps for 80 daily situations (2) vertical time-sections of representative stations (3) mean upper-air maps for one unusually long spell of large-scale convection and (4) normal sea-level and upper-air maps for March, April and May in relation to the normal number of days of thunder and normal number of squalls per month.

The daily situations for the following 80 days were studied. The dates[1] given below refer to the 500 and 300 mb charts. The corresponding sea-level and lower tropospheric upper-air maps refer to the next morning.

Daily situations

1. 12 to 15 April 1952 and 17 April 1952.
2. 28 and 29 April 1952.
3. 4 and 5 June 1952.
4. 6 to 12 March 1953.
5. 17, 18 and 19 April 1953.
6. 26 April 1953 (vertical time-sections were prepared for the period 24 April to 2 May 1953 besides those for other periods).
7. 1 to 31 May 1953.
8. 27 March to 14 April 1954.
9. 27 April to 6 May 1954.

In addition to the above 80 days, the sea-level and 500 and 300 mb maps which corresponded to the record squall of 101 mph at Allahabad (25° 27′, N 81° 44′ E) on 21 March 1950 were also examined.

The above days were selected mainly with reference to the weather developments east of 83° E: they included many severe and destructive squalls, a number of which constituted records for the stations concerned. They also included a large number of cases of severe convection between 70° E and 83° E.

For the majority of these situations, the sea-level maps for 03 G.M.T. (i.e. for 0830 hours Indian Standard Time) published in the Indian Daily Weather Reports, which are based on a very large amount of data were utilized. The upper-air maps were prepared mainly from the data published in the Indian

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[1] Unless otherwise explicitly stated, all dates in this paper refer to the 500 and 300 mb charts and not to the sea-level or lower tropospheric charts or the weather developments.

Daily Weather Reports. These reports were very kindly placed at the disposal of the author by the Director, Swedish Meteorological and Hydrological Institute, Stockholm, Sweden.

On the sea-level maps, trough lines including those corresponding to CA, CM, CU in Fig. 1 were marked. Trough lines and stream lines were also drawn on the lower tropospheric maps in the simple manner suggested by RIEHL (1954, p. 189). On all the sea-level (03 G.M.T.) and lower tropospheric maps (02 G.M.T.) were superposed the thunderstorms (including "thunder heard", ww = 17), convective duststorms and squalls which developed between 03 G.M.T. of *that day* and 03 G.M.T. of the *following day*. These data for northern India and Pakistan were specially obtained from the India Meteorological Department so that they may be as complete and reliable as possible. Similar data for southern India and Burma (the discussion of the weather in these regions is outside the scope of the present paper) were taken from the Indian Daily Weather Reports. The Pakistan data are not complete. They may not also be free from accidental errors, such as mutilations, as they were received in India through the usual telecommunication channels.

The 500 and 300 mb[1] maps contained Pilot Balloon observations at 09 G.M.T. and Radiowind and Radiosonde observations at 15 G.M.T. This difference in time between the two sets of observations was unavoidable as there was no other way of getting a reasonably complete picture of the flow patterns in the upper atmosphere. The mean hour of these composite maps corresponded to 12 G.M.T. (i.e. 1730 Indian Standard Time). Wind-data for 18,000 feet were obtained from the India Meteorological Department and utilized for the 500 mb level for stations at which the balloons did not reach 20,000 feet. Similarly wind-data for 25,000 feet were utilized for the 300 mb level when the balloons did not reach 30,000 feet. Data in the Indian Daily Weather Reports which appeared doubtful due to printing or other mistakes were referred to the India Meteorological Department and corrected on the basis of information supplied by that department.

On these maps, the partial thermal winds and partial thickness values for the 700 ~ 500 mb and 500 ~ 300 mb layers were plotted. The thunderstorms (including "thunder heard" ww = 17), convective duststorms and squalls which developed between 03 G.M.T. of the *next day* and 03 G.M.T. of the *following day* (i.e. the same weather developments as plotted on the sea-level and lower tropospheric maps for the next morning) were superposed on these maps). The main reason for adopting this procedure was that the 09 G.M.T. Pilot Balloon data on this chart cannot normally be available for analysis before 13 G.M.T. (1830 I.S.T.) by which time the afternoon convection in the plains would have started. And what is more important, the Rawin and Radiosonde data of 15 G.M.T. cannot be available for analysis before 18 G.M.T. (2330 I.S.T.) by which time, the convection would be over or be in the dying phase. Consequently, the composite chart of 09/15 G.M.T. which is the best one available at present for *high level analysis* can be used for forecasting convection in the plains only on the following day.

As regards the choice of the period 03 G.M.T. to 03 G.M.T. for the plotting of convection-data, it may be mentioned that the hour 03 G.M.T. is in many respects, the most important synoptic hour in the Indian region and, as such, is a convenient hour of reference in discussions on forecasting. It is also the nearest principal synoptic hour before convection begins to develop in the plains.

In the analysis of the 500 and 300 mb contours, considerable attention was given to the principle of continuity. Much greater weight was also given to the winds than to radiosonde data in view of (1) the reasons pointed out by Riehl (1954, p. 183) about tropical radiosonde data and (2) of the general consensus of opinion among experienced analysts of Indian data (A. K. ROY and N. C. RAISARCAR, 1955) that, in the Indian region, at present, pilot balloon data are "very much more dependable" than radiosonde data.

It was often found difficult to make the spacing of the contours on the basis of radiosonde data at 15 *G.M.T.* consistent with the pilot balloon winds at 09 G.M.T. or the radio winds at 15 *G.M.T.* This difficulty which was

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[1] 250 mb charts were also prepared for days on which the data for this level were adequate enough to be a useful supplement to the 300 mb charts.

particularly felt at the 300 mb level is perhaps partly due to errors in the radiosonde data. The exact reasons for these "inconsistencies" are, however, not clear and should be thoroughly investigated as a separate problem (RIEHL, 1953, p. 193). In view of these unknown factors, it was felt that no special advantage would be gained by spacing the lines with a geostrophic wind-scale. This slightly increased the subjectivity in the analysis which was unfortunate but unavoidable. However, as the purpose of this paper was merely to establish purely qualitative relationships between high level patterns and large-scale convection, this additional subjectivity in analysis did not in any way affect the general conclusions summarized in the later paragraphs.

5. Sea-level and lower tropospheric circulation patterns in relation to large-scale convection

The following is a brief summary of the sea-level and lower tropospheric analysis. The dates given in brackets against some of the paragraphs, refer to *the dates of the sea-level and lower tropospheric charts*. The instances cited are not the only ones to illustrate each type of situation: many others could also be given.

1. *East of 83° E. north of 20° N.*

Sea-level pressure and wind systems.

(a) The sea-level west to east pressure-gradient had no significant association with the development of large-scale convection. Very weak east to west pressure-gradients were sometimes found to be associated with widespread thunderstorms and severe squalls (14, 16 and 18 April 1952 and 19 and 20 April 1953) in parts of Northeast India and East Pakistan while pressure-gradients in excess of the normal for the month were a number of times associated with only isolated thunderstorms or fair weather west of 90° E south of 25° N (9 March 1953, 6 April 1954).

(b) Sometimes, the seasonal trough of low pressure appeared as a closed low (isobars drawn at 2 mb intervals). No significance could be attached to the appearance of this closed low or its position or intensity so far as the subsequent convective developments were concerned. Extensive squalls, a few of which caused very heavy destruction, developed over Northeast India and the adjoining districts o East Pakistan without any closed low at sea level (27 April 1953) while fair weather prevailed over West Bengal and the adjoining parts of East Pakistan in spite of closed lows over or near these areas (8 March 1953, 9, March 1953, 7 May 1953, 5 April 1954, 13 April 1954). Squalls, widespread thunderstorms and moderate convective rain also sometimes developed over the State of Assam and the contiguous districts of East Pakistan with a ridge extending from the Tibetan or upper Burman border into East Pakistan through Assam (14 April 1954, 5 May 1954).

(c) The trough lines CU and CM had no association with convective developments beyond what may be expected by mere chance. The trough line CA was, however, slightly better associated with the developments. The association was, however, far too poor to consider it as the determining factor.

No front of the middle-latitude type or tropical cyclone or depression moved across the region under discussion.

Lower tropospheric flow-patterns

(a) The streamlines at the 3,000 and 5,000 feet levels showed that the convective weather developed mostly in the southwesterlies or southerlies or in the easterlies, i.e. in the moisture-laden air.

(b) The trough-lines CU and CM did not have any association with the thunderstorm field. The number of thunderstorms and squalls which developed along and near the CA trough line was only a small percentage of the total number of thunderstorms, and squalls. Severe convective developments took place even where the streamlines were *anticyclonically* curving at 5,000 feet. A good instance of this type was on the 19 April 1953 near Gaya and Allahabad. These stations, in spite of the anticyclonic curl of the stream-lines near their vicinity, experienced heavy squalls on the same afternoon. Gaya (24° 45′ N, 84° 57′ E) experienced a record squall of 100 mph and Allahabad (25° 27′ N, 81° 44′ E) a squall of 60 mph.

(c) There were one or two occasions when feeble western disturbances seemed to have moved across Northeast India and East Pakistan in the lower troposphere. Also, on some days, cyclonic circulations appeared in certain parts of Northeast India in the lower troposphere. But they died *in situ* within 24 or 48 hours. Neither the western disturbances as they appeared at the 5,000 feet level nor the locally-developed cyclonic circulations had *any direct connection* with the convective developments.

Figures 3, 4 and 5 show the sea-level isobars and trough lines CA, CM, CU (compare Fig. 1), the 24 hours isallobars and the 3,000 and 5,000 feet streamlines at 02/03 G.M.T. on 14 May 1953. The upper winds at 06 G.M.T. have been plotted with broken arrows. The hatched areas in Fig. 3 show the region where the thunderstorms developed and the cross-hatched areas[1] show the region where thundersqualls or convective duststorms developed between 03 G.M.T. of 14 and 03 G.M.T. of 15 May 1953. According to Press Reports, the squalls caused damage to property, interruption in communications and loss of several human lives in Gangetic West Bengal. Calcutta itself experienced two squalls, well-separated from each other,—a rather unusual development.

Figures 6, 7 and 8 show the corresponding charts on 28 May 1953 and the convective developments during the subsequent 24 hours. It will be seen that the convective developments took place only in Assam and the contiguous districts of East Pakistan and that fair weather prevailed practically over the entire region to the west of 90° E.

These two sets of charts illustrate some of the conclusions summarized above regarding regions east of 83° E. The charts look so alike and yet were associated with such different weather developments. Indeed, in some respects e.g., the positions of the trough lines, the depth of the moist air, the speed of the winds in the moist stream and the 24 hours isallobars, the charts for 28 May might, according to the conventional ideas, be considered as more favourable than those for 14 May 1953 for the development of thundersqualls in and around Gangetic West Bengal (i.e. between 21° N and 25° N and 85° E and 89° E). It may also be noted that the east to west sea-level pressure-gradients over West Bengal and East Pakistan on these two days did not differ significantly from the normal gradient for the month as seen in Fig. 1.

II. *West of 83° E, north of 20° N*

Sea-level pressure and wind-systems.

The extensive seasonal low-pressure area to the west of 83° E vide Fig. 1, had only one closed low at sea-level (isobars drawn at 2 mb intervals) on about 43 % of the daily situations, the closed isobar lying mainly to the west of 74° E. On about 9 % of the days, the low pressure area had two closed lows west of 83° E and on 6 % of the days only, any of the lows had more than one closed isobar. In the preparation of this statistics, the closed lows in Northeast India, which sometimes extended to the west of 83° E have not been taken into account. The formation, movement and disappearance of the lows with only one closed isobar were often erratic (15 to 17 May 1953, 21 to 23 May 1953 and 2 to 7 May 1954). And neither the lows with one closed isobar nor even those with more than one nor the trough-lines associated with these sea-level systems had any significant connection with large-scale convection (18 and 30 April 1952, 18 and 19 April 1953, 17, 18 and 21 May 1953).

Lower tropospheric flow-patterns

(a) The thunderstorms, convective duststorms and squalls developed, broadly speaking, in the following three sectors of the wind-field at the 5,000 feet level: SSW/WSW, E/SE and WNW/NNW. For facility of easy reference, these will be referred to in the following discussion as the southwesterlies, the eastsoutheasterlies, and the northwesterlies. The southwesterlies and the eastsoutheasterlies are, as is well-known, drawn into the region by the western disturbances. Of the total number of thunderstorms, convective duststorms and squalls which developed over the plain stations west of 83° E north of 20° N, 39 % developed in the southwesterlies, 16 % in the eastsoutheasterlies and 45 % in the northwesterlies at the 5000 feet level. This statistics is of course rough and no undue importance should be attached to the actual percentages. Nevertheless, the *relative values of the figures do reveal that large-scale convec-*

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[1] The hatched and cross-hatched areas show only the general distribution of the storms and squalls. They do not imply that each and every observatory in those areas reported the phenomena concerned.

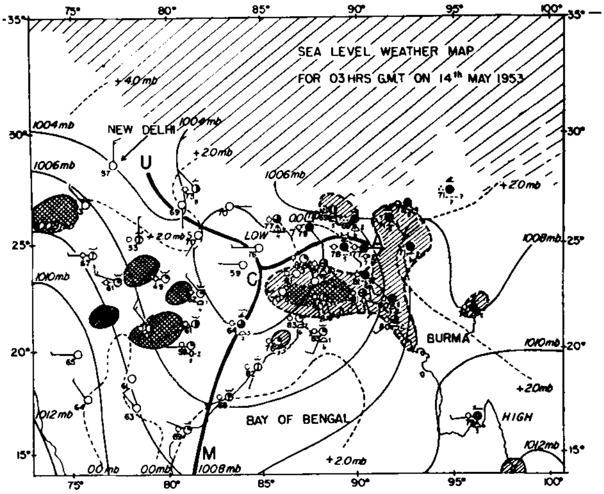
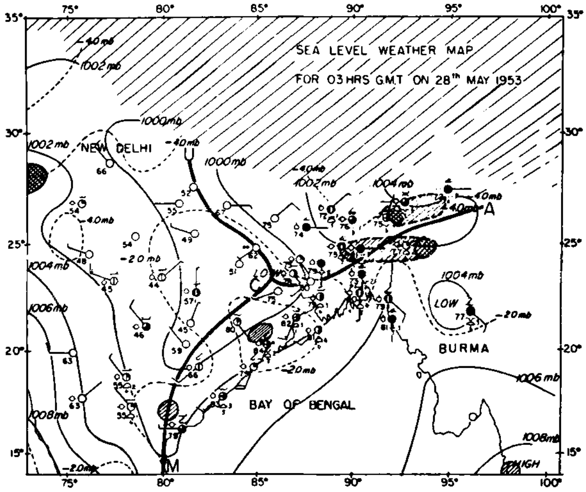


Fig. 3.



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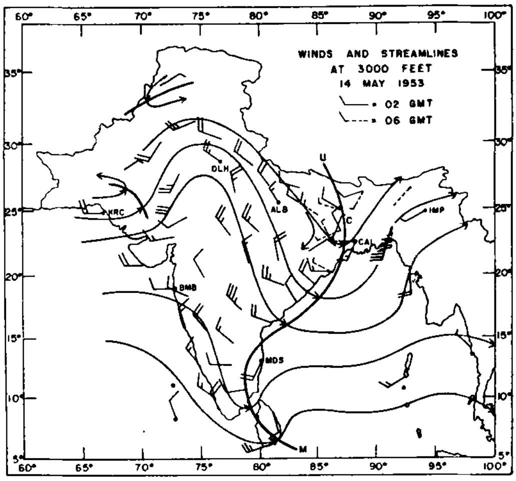

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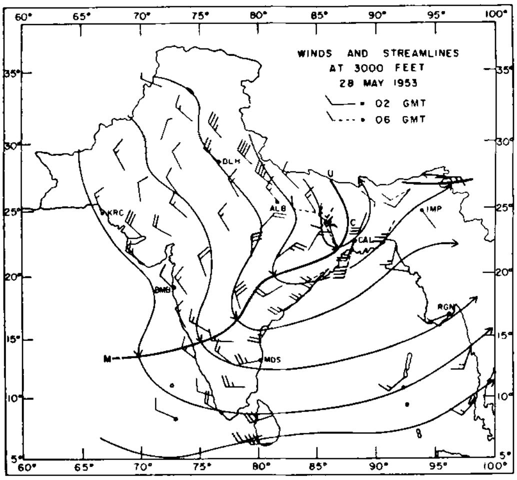

Fig. 7.

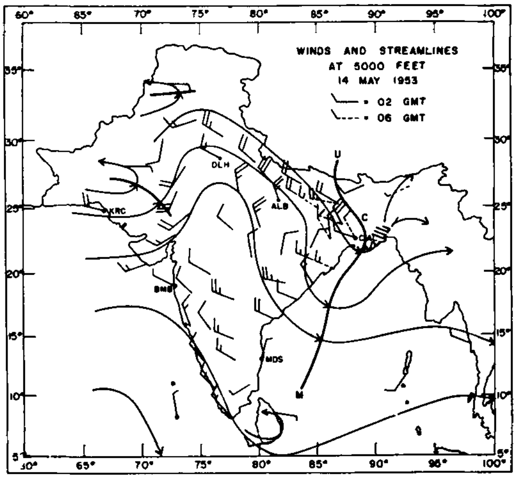

Fig. 5.

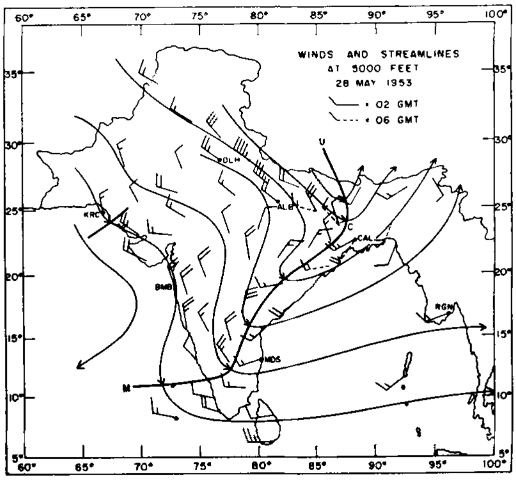

Fig. 8.

tion develops in the northwesterlies much more frequently than it is generally believed: it probably develops in this stream as frequently as in the southwesterlies. The importance of this fact will become obvious in the light of the discussion in sub-paragraphs (c) and (d) below.

(b) The large-scale convection developed in the three streams mentioned above, most often within the body of each of these streams and quite far away from the trough-lines associated with these systems and *very often in anticyclonically curving stream-lines* (15 and 30 April 1952 and 6 June 1952, 18 and 19 April 1953, 15, 16 and 17 May 1953).

(c) Of the storms and squalls which developed in the northwesterlies, *the majority developed in advance of the ridge* associated with the incursion of the "semi-moist" southwesterlies from the north Arabian Sea. In these northwesterlies, there was obviously no agency for convergence. The rest of the storms and squalls in this stream developed in a more or less straight current in which it was not possible to find any significant convergence. Among the cases studied in this paper, the most spectacular case of large-scale convection in northwesterlies, occurred on 30 April 1952 when extensive andhis and/or thunderstorms developed over an area of about 88,000 sq. miles with Delhi near about the centre of this area. This case deserves special study not only because it is meteorologically of great interest but also because, according to Press reports, a Dakota aircraft of a scheduled passenger service crashed a few miles from Delhi just before landing when that station was in the grip of the andhi and the aircraft and all the passengers and the aircrew were lost. Other good instances of thunderstorms, convective duststorms and squalls in northwesterlies were on 10, 16, 17, 18 and 20 May 1953 and 6 May 1954.

(d) In any discussion on large-scale convection in the northwesterlies, it is necessary to remember that the very dry stream over this region on a large number of days in this season is also a northwesterly current and that it is characterized by clear or partly clouded skies (A. K. Roy, 1946). In view of this and also of the statistics and other conclusions presented in sub-paragraphs (a) and (c) above, it would appear that the forecaster who draws his conclusions only from the lower tropospheric charts and proceeds on the assumption that no deviation from the average (Riehl 1954, p. 178) in the *lower* tropospheric flow-patterns necessarily indicates fair weather, runs the risk of making incorrect prognoses on a large number of occasions of large-scale convection west of 83° E.

(e) No cold-front of the middle-latitude type (Riehl 1954, page 237) caused large-scale convection in the region under discussion.

Considerations of space and the need for restricting the number of diagrams prevent us from reproducing in this paper, the sea-level or lower tropospheric charts for any of the days mentioned above. However, Figs. 3 to 8 which had been selected for illustrating weather situations east of 83° E also incidentally illustrate some of the conclusions regarding regions west of 83° E. It will be seen from Figs. 3, 4 and 5 that the cross-hatched areas west of 83° E where there were convective duststorms and some thunderstorms (there were also showers between and around these areas) lay in a region of *rising sea-level pressures* and in a region in which there were no cyclonic wind-shifts. In particular, it may be noted that the large-scale convection between 75° E and 80° E and between 20° N and 25° N *developed in a northwesterly*

Fig. 3. The thick continuous lines are trough lines UC, CA, CM and the thin dotted lines are isopleths of 24 hrs pressure-changes at 03 G.M.T. drawn at 2 mb intervals. The two figures to the left rear of each station circle are dew-points at 03 G.M.T. Compare with Figure 6 especially with the areas of thunderstorms (hatched) and of thundersqualls or convective duststorms (cross-hatched).

Fig. 4. The streamlines have been drawn for the 02 G.M.T. winds. Compare with Fig. 7 and with the areas of convective developments in Fig. 3.

Fig. 5. The streamlines have been drawn for the 02 G.M.T. winds. Compare with Fig. 8 and with the areas of convective developments in Fig. 3.

Fig. 6. Same convention in plotting as in Fig. 3. Compare with Fig. 3 especially with the areas of convective developments.

Fig. 7. The streamlines have been drawn for the 02 G. M.T. winds. Compare with Fig. 4 and with the areas of convective developments in Fig. 6.

Fig. 8. The stream-lines have been drawn for the 02 G.M.T. winds. Compare with Fig. 5 and with the areas of convective developments in Fig. 6.

stream in advance of a sea-level and lower tropospheric ridge. In contrast to this, fair weather prevailed over the same region in association with northwesterlies and with *falling sea-level pressures* vide Figures 6 to 8.

6. Analysis of 500 and 300 mb patterns on individual days

Unfortunately, adequate *wind*-data were not available on quite a large number of days to fix the 300 mb patterns with reasonable certainty. Nevertheless sufficient number of situations was available in which the data on the 500 and 300 mb levels taken together could enable the author to draw the following *purely qualitative* conclusions:

(a) The convective developments (i.e. convective duststorms and thunderstorms with or *without* squalls) over every part of northern India and Pakistan had far better association with the 500 and 300 mb vorticity patterns than with the sea-level maps and lower tropospheric flow patterns.

(b) The convective developments took place mostly in *advance* of a trough or in the *rear* of a ridge at the 300 mb level. This conclusion was also true in a large number of cases, for the 500 mb level. However, as the wave-patterns sloped westwards with height, more thunderstorms were found in the rear of the trough line at the 500 mb level than at the 300 mb level. In a number of cases, the association with the 500 mb patterns was poor but was quite satisfactory at the 300 mb level.

(c) Other conditions being the same, the greater the general intensity of the jet stream, the more extensive were the thunderstorms and the more severe in general were the squalls. It is interesting to note that the record squalls were associated with high-speed jets.

(d) Quite stable weather prevailed on a large number of occasions in the rear of a trough and in advance of a ridge although there was a steady incursion of latently unstable moist air in the lower troposphere over those regions.

(e) Unusual fair weather also prevailed over the major part of Northeast India and East Pakistan when the winds over that region were exceptionally light in the upper troposphere. This situation arose when the axis of the jet stream was oriented from southwest to northeast and had shifted far to the west and northwest of the region of light winds.

(f) As should be expected from the kinematic and hydrostatic properties of waves in the westerlies (ROSSBY 1946), the partial thickness lines for the 700 ∼ 500 mb and 500 ∼ 300 mb layers showed, *in general*, the wave patterns in the jet-stream *more conspicuously* than the 500 mb and 300 mb contour-patterns respectively. *In a large number of cases*, the partial thermal winds for these layers also indicated that the actual winds were backing with height in the regions in which there was subsequent development of large-scale convection.

The high-level contour patterns associated with the convective developments have been schematically classified into the following 5 types and shown in Figures 9 (a) to 9 (e). For facility of easy reference, the various types have been designated by suitable abbreviations shown against each type.

Serial No.	Schematic Pattern	Abbrevation
1	Uniform shear and sinusoidal variation in curvature.	S_U-Sin
2	Uniform shear and rapid decrease of curvature ahead of trough-line.	S_U-T
3	Uniform shear and rapid increase of curvature in the rear of ridge-line.	S_U-R
4	Varying shear and rapidly diverging contours mainly ahead of trough-line.	S_V-T
5	Varying shear and rapidly converging contours mainly in rear of ridge-line	S_V-R

In this connection the following points should be emphasized

(i) The schematic patterns pre-suppose the existence of latently unstable moist air in the lower troposphere over the region covered by the respective patterns.

(ii) The schematic patterns are purely tentative. In particular, it may be mentioned that clear-cut cases of S_U-T could not be found during this study as it was difficult with the usual positions of the troughs and the ridges and the available number of observations at the 500 and 300 mb levels to state categorically that they were different from those represented by S_U-Sin.

(iii) The schematic patterns by no means exhaust the possible types of patterns which can lead to large-scale convection.

(iv) The patterns are strictly true only for the 300 mb level. However, in the absence of observations at the 300 mb level, they may be taken as *very roughly* true of the 500 mb level also bearing in mind that the convective developments will generally be nearer the trough-line and further away from the ridge-line at this level.

Figures 10 and 11 show the 500 and 300 mb contour-patterns at 09/15 G.M.T. on 18 April 1953 and the convective phenomena which developed between 03 G.M.T. of

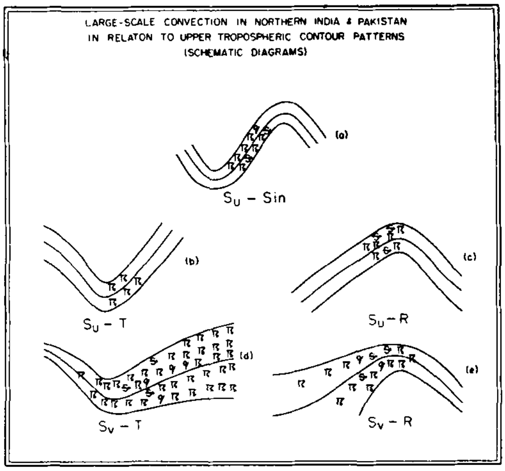

Fig. 9. The relative positions of the thunderstorms, duststorms or squalls (symbol q) or their actual number as shown in the schematic patterns have no special significance.

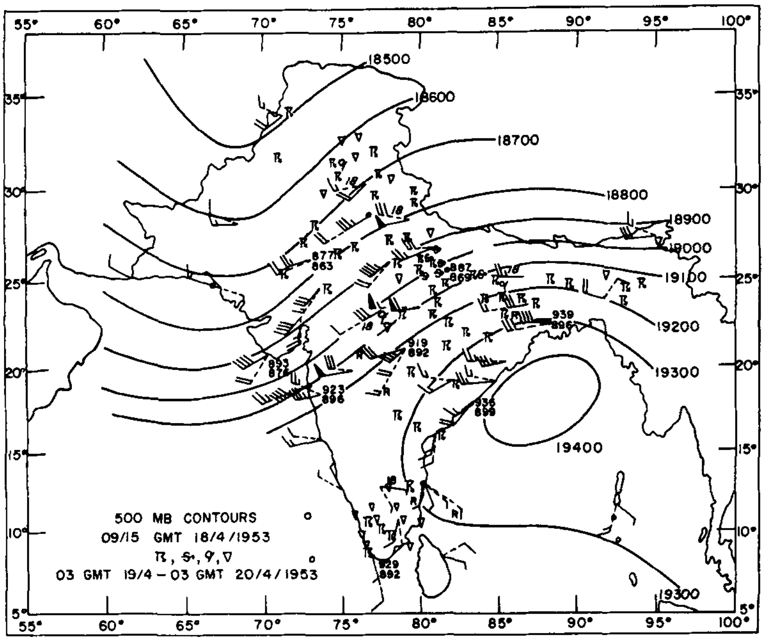

Fig. 10. Arrows indicated by continuous lines are actual winds while arrows indicated by broken lines are the partial thermal winds. The letter R indicates that data are based on Rawin observations. The figure 18 by the side of some of the wind-arrows indicates that the winds are for 18.000 feet level. The radiosonde heights and the partial thicknesses have been plotted and the contours have been drawn according to the same convention as in Fig. 2. The symbol q indicates squalls. The convective phenomena at some of the stations have been plotted in slightly altered positions, for lack of space. The phenomena south of Lat. 20° N have also been shown for the sake of completeness but are outside the scope of discussion in the present paper.

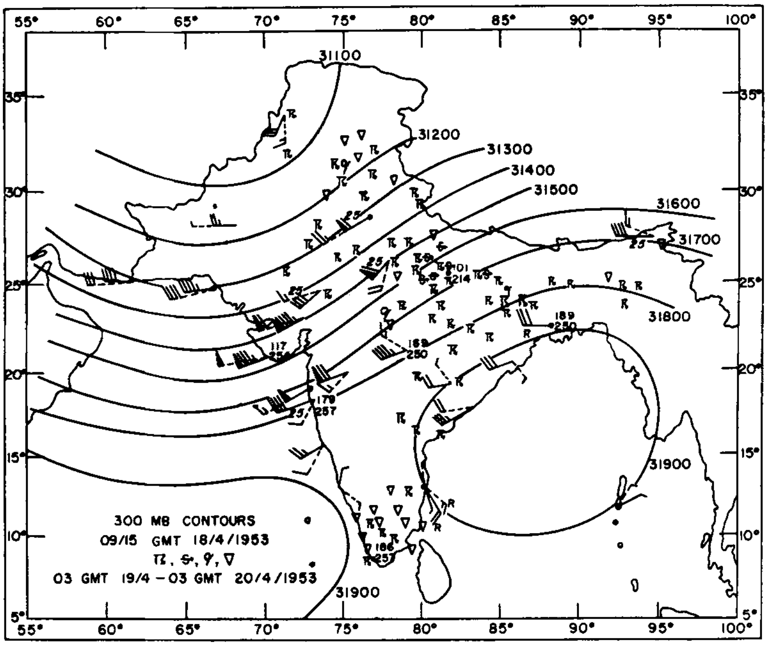

Fig. 11. The figure 25 by the side of some of the wind-arrows indicates that the winds are for the 25,000 feet level. Other conventions in plotting are the same as in Fig. 10.

19 April and 03 G.M.T. of 20 April 1953. As convection mostly develops along the foot of the Himalayas and in the valleys of Assam in the night or very early in the morning when observers maintain watch only at a very small number of stations, the thunderstorms etc. plotted on the maps in these regions do not give a complete picture of the actual convective developments. In order to make up this deficiency, the symbol for showers has been plotted at stations which did *not* report a thunderstorm or squall or convective duststorm *but* which reported rainfall during the past 24 hours in their next morning's routine weather message (i.e. at 0830 I.S.T. or 0300 G.M.T. on 20 April 1953). Similar procedure was also followed in respect of the other cases studied in this paper. The patterns seen on the 500 and 300 mb maps of 18 April 1953 are of the S_U-Sin type. Among the numerous andhis and nor'westers seen in the diagrams, the reader's attention is specially invited to the record nor'wester squall of 100 mph (English miles) at Gaya (24° 45′ N, 84° 57′ E) and a 60 mph andhi at Allahabad (25° 27′ N, 81° 44′ E). These stations lie in a region, which is normally not susceptible to large-scale convection, vide section 8. The sea-level and the 5,000 feet patterns for this case have already been discussed in section 5.

Figures 12 and 13 show the 500 and 300 mb patterns at 09/15 G.M.T. on 7 March 1953 and the convective developments between 03 G.M.T. of 8 March 1953 and 03 G.M.T. of 9 March 1953. The patterns over Northeast India and East Pakistan are of S_V-T type. The thunderstorms (and showers) mainly lie ahead of the trough-line at the 300 mb level but some lie behind the trough-line also in regions where the contours are diverging and the winds are comparatively stronger. The day illustrated is one during the spell 6 to 12 March 1953 when there was extensive convection in and around the State of Assam. It may be of interest to observe that the jet stream strengthened after 7 March; on 12 March, it was intense and was responsible for very severe squalls at some places in the area of thunderstorms in the above maps, east of 85° E. Unfortunately, on account of the per-

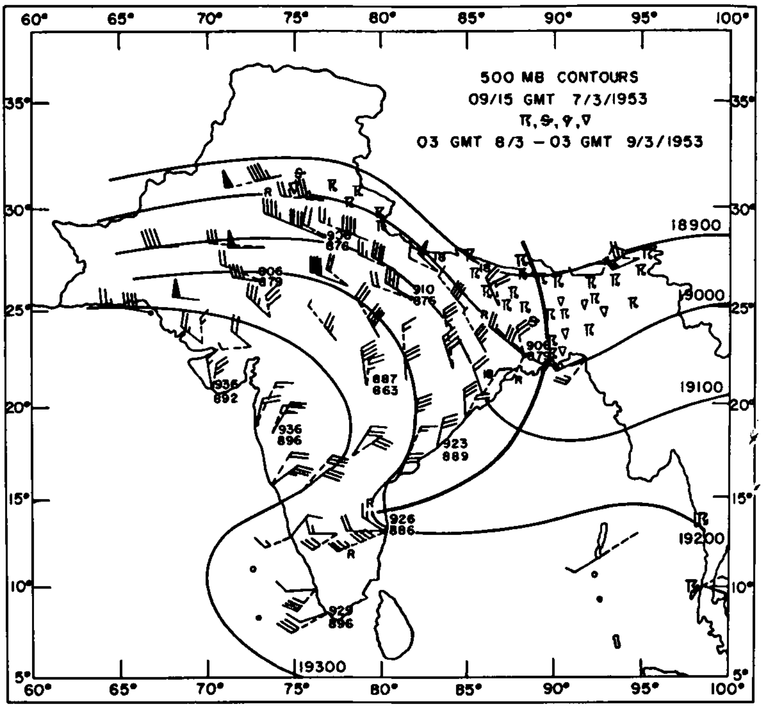

Fig. 12. Same conventions in plotting and drawing of contours as in Fig. 10.

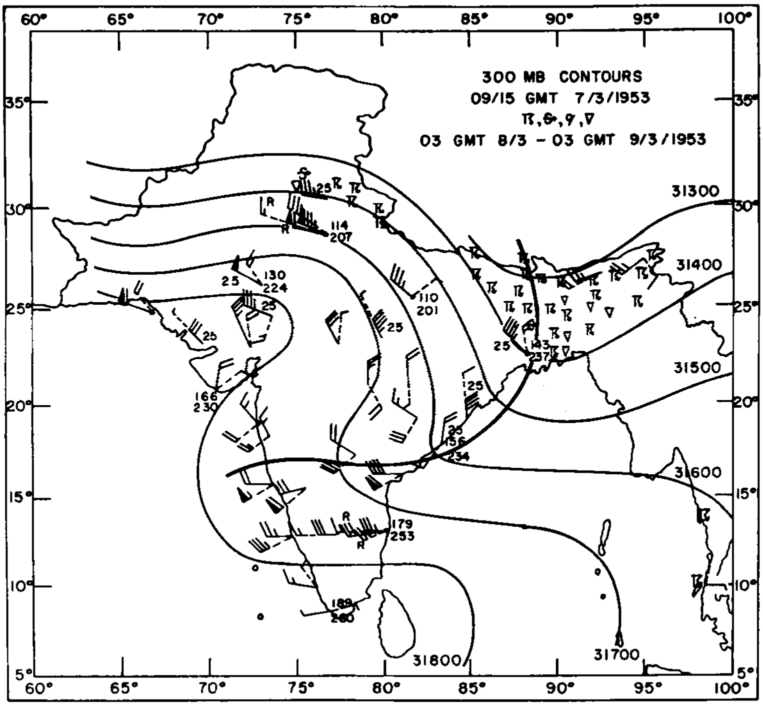

Fig. 13. Same conventions in plotting and drawing of contours as in Fig. 11.

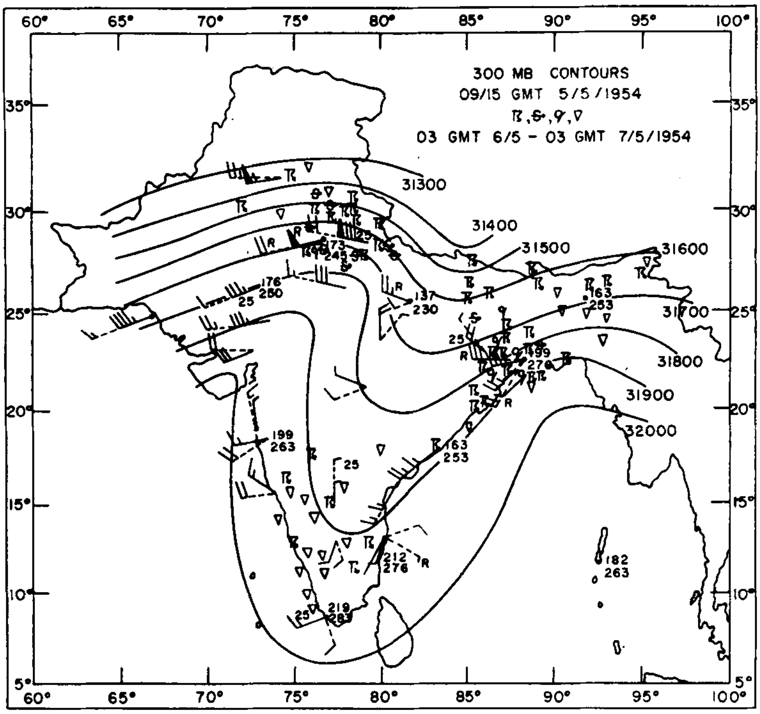

Fig. 14. Same conventions in plotting and drawing of contours as in Fig. 11.

sistent low clouds, no pilot balloon observations were available east of Calcutta on this day (radiosonde observations of Shillong were not available for this spell). Hence the vorticity-patterns in the region of convection on this remarkable day can only be inferred from the patterns west of 89° E and from their similarity with those for other days when observations were available east of 89° E during this spell and the similar Sv-T spell between 27 March 1954 and 14 April 1954.

It may be incidentally mentioned that the region under discussion consists largely of valleys and hills and as such, there can be no doubt that orography plays some part in producing convection in this region. However, it has to be noted that similar weather did not develop on days on which the lower tropospheric flow patterns were far more favourable for orographic developments. Further, an examination of a relief map of India shows that the hills in and around Assam are so situated that any convective clouds which develop over them due to orography would not drift into the two important valleys in that State (with which we are mainly concerned) but would move along the hills on account of the middle and upper tropospheric flow patterns. The discussions and the diagrams in Section 7 of this paper are also quite relevant in this connection. In the circumstances, there cannot be any doubt that, in the large number of cases of convection in and around Assam studied in this paper, the contribution by orography was much less than that by the jet-stream waves. Incidentally, these remarks are equally true of large-scale convection along the foot of the western Himalayas.

The convective phenomena between 75° and 80° E, north of 30° N in Figs 12 and 13 have partly occurred in the hill-stations in the western Himalayas and partly in the submontane districts. While orography has obviously played a part in the development, the Su-R patterns seen in that region (see particularly the winds on the 500 mb chart in Fig. 12) have also contributed to the development, especially in the submontane districts.

Fig. 14 shows the 300 mb pattern at 09/15 G. M.T. on 5 May 1954 and the convective developments between 03 G.M.T. of 6 May 1954 and 03 G.M.T. of 7 May 1954. It is a typical instance to show *how convective developments in very distant regions which may appear on the sea-level and lower tropospheric charts as quite disconnected and even random developments* (see Section 5) *may appear as well-connected and orderly developments on the vorticity pattern at the 300 mb level.* It also illustrates the paradox that under suitable conditions severe weather can develop "at a ridge". The convective developments in extreme northwest India are of type S_U-R while those in and around Gangetic West Bengal are of type S_V-R. The weak SSW or SW winds at Visakhapatnam and Masulipatam which are in lower latitudes and the strong W winds at Calcutta which is in a higher latitude, indicate converging contours in the rear of a ridge. With regard to the northwesterly wind at Jamshedpur (west of Calcutta) which does not fit in with the contours, it may be mentioned that the wind refers to 25,000 feet and that the winds over Calcutta also, on this day at 09 G.M.T., were 320 degrees at 25,000 feet but backed with height and became 260 degrees at 30,000 feet (300 mb-level).

Among the cases studied in this paper, those relating to 13 and 29 April 1952, 26 April 1953, 8, 13, 20, 24, 27 and 31 May 1953, 28 March 1954, 5 and 28 April 1954 and 2 May 1954 are of great interest[1], as the upper tropospheric patterns on these days led to "sudden" and/or severe convective developments (andhis and/or nor'westers) or to the development of thundersqualls after a long break or to exceptional fair weather. Considerations of space do not permit us to go into these cases here. We would, however, like to describe below at least in a few sentences what was perhaps the most unique case in the above list.

26 April 1953.—This led to the most extensive development of squalls in Northeast India studied during the present investigation and caused very heavy destruction at Barrackpore, a suburb of Calcutta. The 300 and 250 mb charts show a S_U-Sin pattern. *The velocity-profile on this day at the 250 mb level along the meridian 80° E shows a remarkably sharp "knife-edged" jet.* The lower tropospheric situation on the morning of 27 April 1953 has already been referred to in Section 5. The vertical time-section over Calcutta on this day may be seen in Fig. 15.

Figures 15, 16 and 17 show the vertical time-sections over Calcutta during three typical spells. Fig. 15 represents a spell in which a trough lay with its axis to the west of Calcutta at the 250 mb level with varying intensities and slightly different positions. Fig. 16 represents the situation during a part of the spell of vigorous convection in and around the state of Assam between 27 March 1954 and 14 April 1954 (vide section 7) when the trough at the 500 mb level and higher levels lay with its axis to the east of Calcutta. Fig. 17 shows a spell characterized by weak vertical wind shear. In studying these three diagrams, the convective developments *on each day* have to be compared with the upper winds, mixing ratios and 24 hours pressure changes of *the previous evening* and also with the 24 hours pressure-changes at 03 G.M.T. *on the day* of the development. The winds, mixing ratios, etc. *in each spell* should also be compared with the corresponding elements in the *two other spells* with a view to assess their importance in the development of convection. It will be observed that.

(a) The upper winds in the middle and upper troposphere had by far better association with the convective developments than the winds in the lower troposphere or the mixing ratios or the 24 hours pressure-changes.

(b) In Fig. 15, there was a general tendency for the convective activity to increase with the strengthening of the southwesterlies or westerlies at the 300 mb level and aloft. Likewise, there was a decrease in the convective activity with a marked decrease in the strength of the southwesterlies and westerlies in the upper troposphere.

Fig. 18 shows the vertical time-section over Delhi during the passage of a jet-stream wave. It will be observed that the general conclusions stated in the above cases for Calcutta with regard to the wind, mixing ratios and pressure changes, are true in this case also. The moisture-content of the air was, however, less than that over Calcutta even during the period

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[1] The sea-level and the lower tropospheric situations for a number of these cases have been very briefly referred to in section 5.

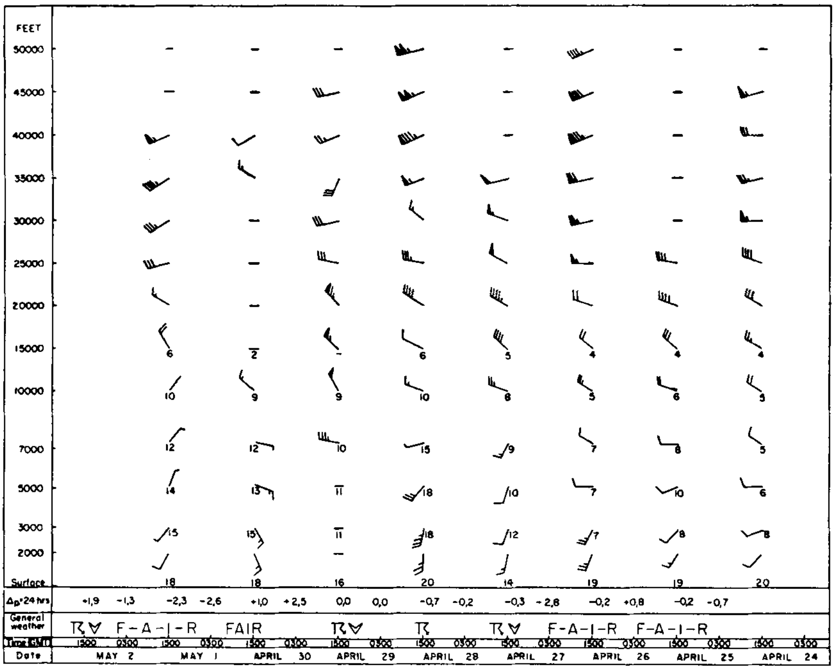
CALCUTTA IN ADVANCE OF A JET STREAM TROUGH
24 APRIL — 2 MAY 1953

Fig. 15. The figures near the wind-arrows and near the base-line below the 2,000 feet winds are mixing ratios. The vertical section below 10,000 feet has been drawn on an enlarged scale. The 24 hrs pressure changes refer to 03 and 12 G.M.T. respectively. Compare particularly the upper tropospheric winds on each day with the convective developments on the following day.

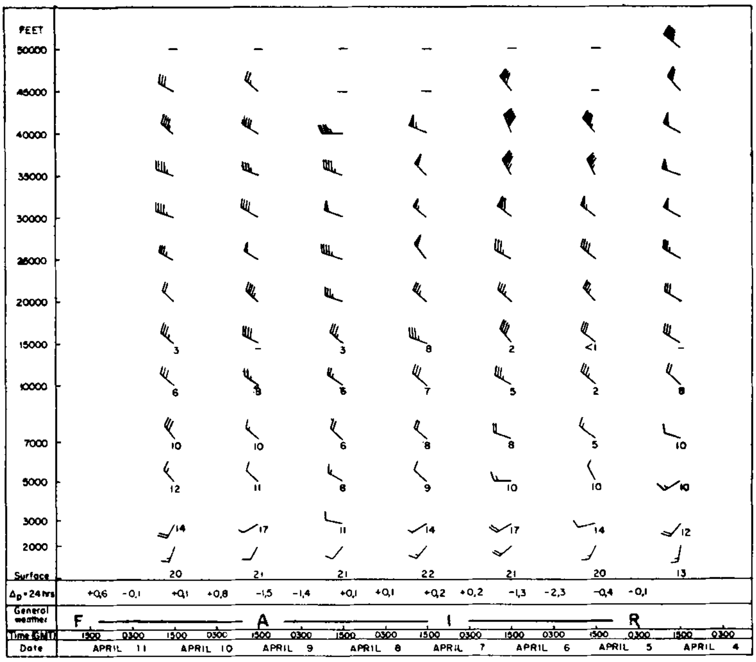
CALCUTTA IN THE REAR OF A JET STREAM TROUGH
4 APRIL — 11 APRIL 1954

Fig. 16. Same conventions in plotting as in Fig. 15. Compare particularly the lower and upper tropospheric wind systems and lower tropospheric mixing ratios with the corresponding elements in Fig. 15.

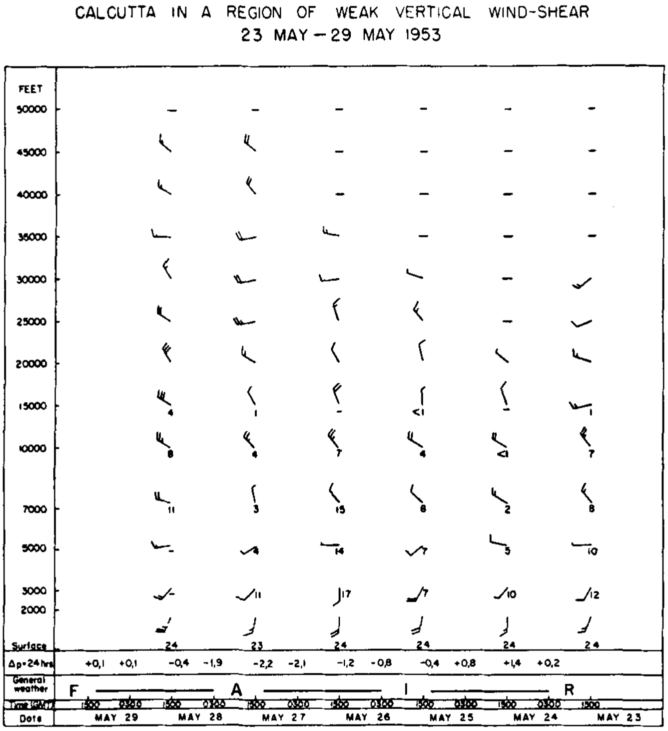

Fig. 17. Same conventions in plotting as in Fig. 15. Compare particularly the lower and upper tropospheric wind systems and lower tropospheric mixing ratios with the corresponding elements in Fig. 15.

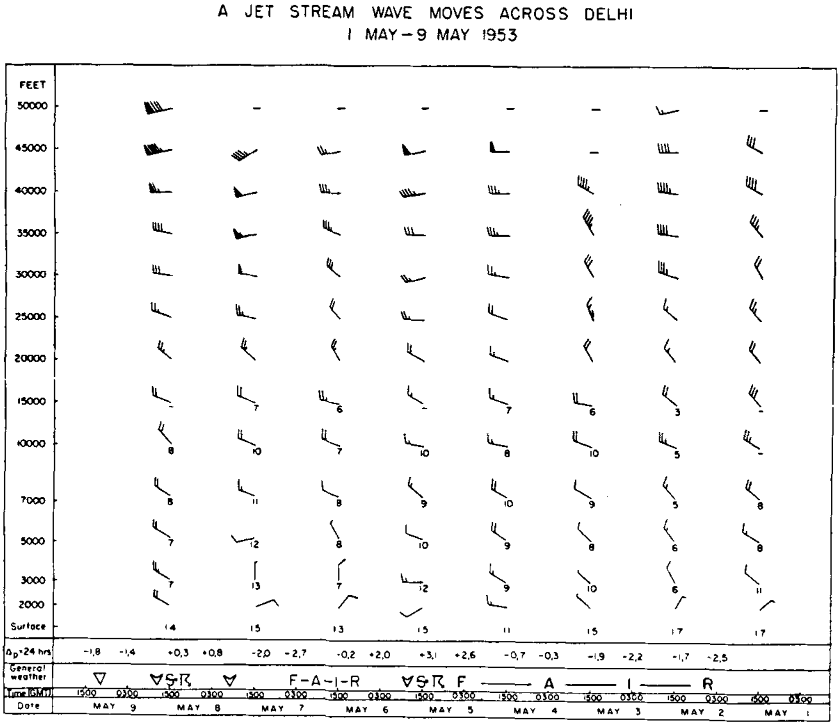

Fig. 18. Same conventions in plotting as in Fig. 15. Compare particularly the general values of the mixing ratios with those in Figs 15, 16 and 17.

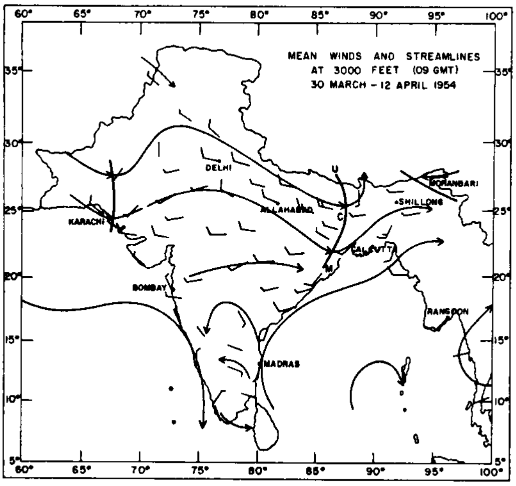

Fig. 19. Mean pattern at 3,000 feet during the spell of large-scale convection in and near the State of Assam (i.e. roughly north of 23° N between 90° and 95° E). Compare with the normal pattern in Fig. 23.

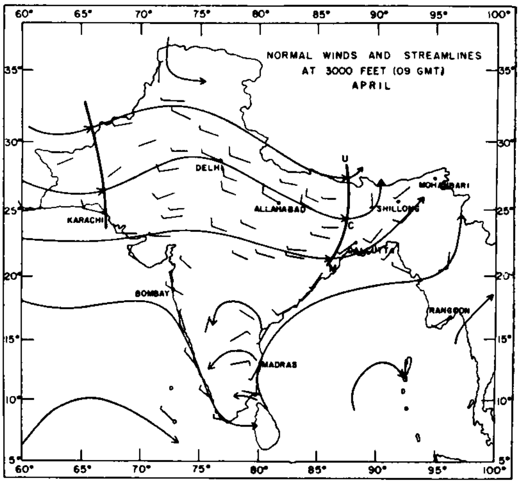

Fig. 23. Normal pattern at 3,000 feet in April. Compare with Fig. 19.

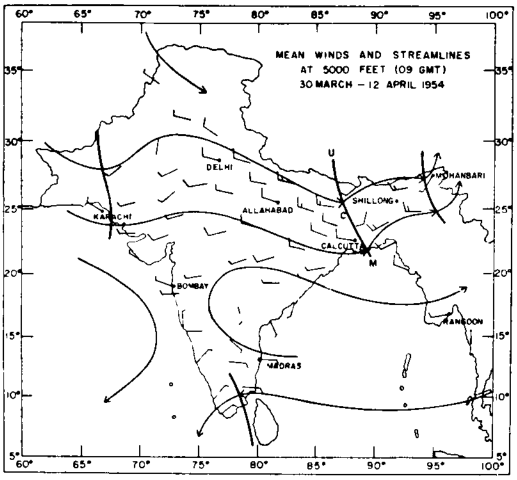

Fig. 20. Mean pattern at 5.000 feet during the spell of large-scale convection in and near the State of Assam. Compare with the normal pattern in Fig. 24.

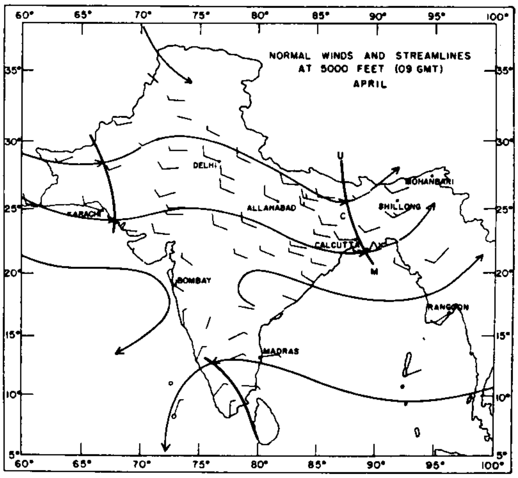

Fig. 24. Normal pattern at 5,000 feet in April. Compare with Fig. 20.

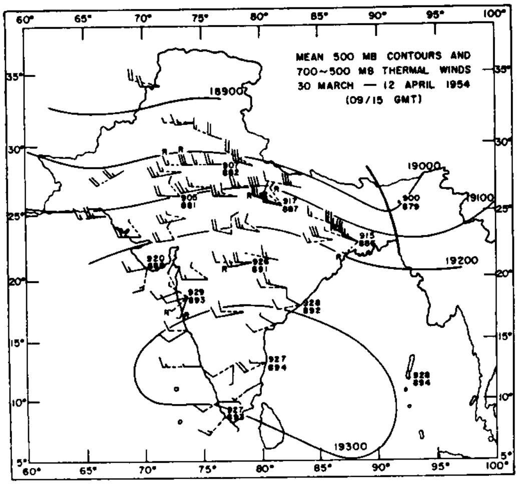

Fig. 21.

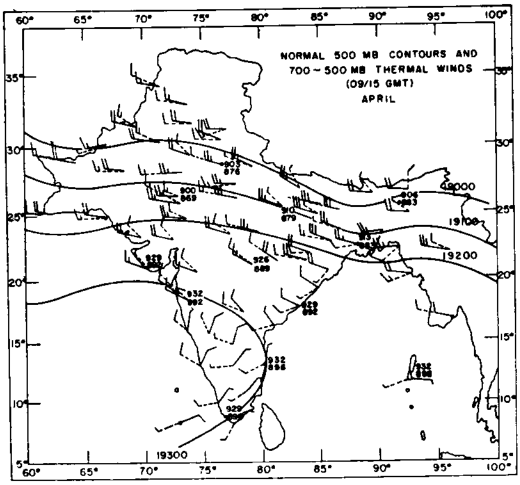

Fig. 25.

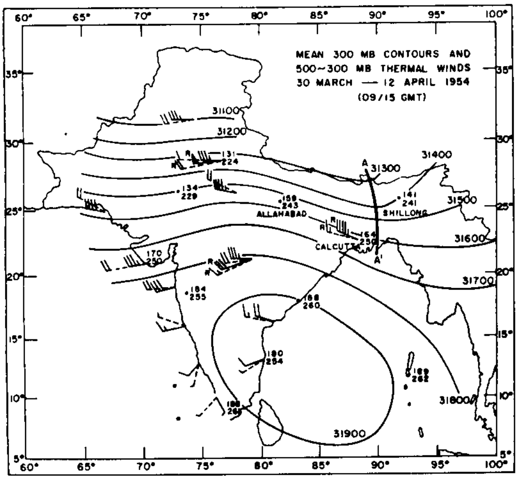

Fig. 22.

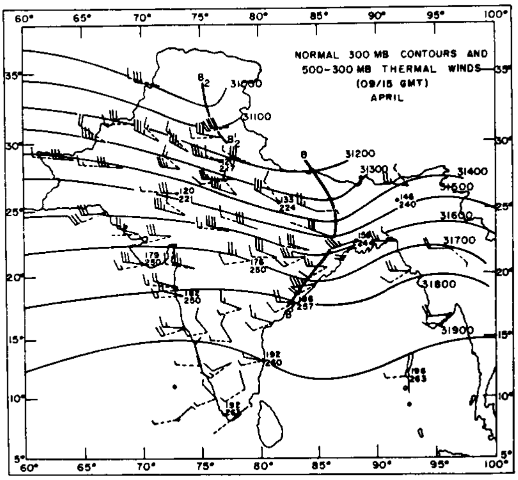

Fig. 26.

Fig. 21. Mean pattern at 500 mb level during the spell of large-scale convection in and near the State of Assam. Same convention in plotting as in Fig. 10. Compare with Fig. 25.

Fig. 22. Mean pattern at 300 mb level during the spell of large-scale convection in and near the State of Assam. Same convention in plotting as in Fig. 2. Compare with Fig. 26 especially with the speeds of the actual winds and the horizontal and vertical wind-shear west of 90° E.

Fig. 25. Normal pattern at 500 mb level in April. Compare with Fig. 21.

Fig. 26. Normal pattern at 300 mb level in April. Compare with Fig. 22.

Fig. 27. The rainfall figures refer to the *plain-stations*. The numerator in each figure refers to the actual rainfall (in inches and correct to one place of decimals) while the denominator refers to normal rainfall over the same area. AA' is the axis of the jet stream trough at 300 mb level *during the spell*. BB' is the *normal* position of the axis of the trough in April vide Fig. 26.

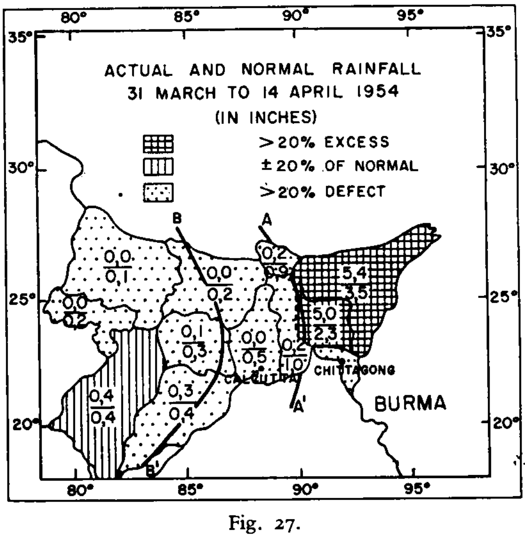

Fig. 27.

of intense convection. The discussion in section 2 is relevant in this connection.

7. Mean patterns during an unusually long spell of large-scale convection

As already mentioned in section 6, the State of Assam and the contiguous districts of East Pakistan (i.e. roughly east of 90° E and north of 23° N) experienced in association with S_V-T situations, an abnormal spell of widespread thunderstorms, frequent squalls and heavy convective rainfall during the period 27 March 1954 to 14 April 1954[1] (dates refer to the 500 and 300 mb charts). Figures 19, 20, 21, and 22 show the mean streamline pattern at 3,000 and 5,000 feet at 09 G.M.T. and the mean contour-patterns at the 500 and 300 mb levels and the partial thermal winds for the 700 ~ 500 mb and 500 ~ 300 mb levels at 09/15 G.M.T. during the period 30 March to 12 April 1954.

In order to make the charts as representative of the mean conditions as possible, no station with less than 6 days' daily data (out of the total number of 14 days) was used in the computations. This unfortunately resulted in no mean wind-data for the region east of 90° E at the 500 and 300 mb levels. However, the radiosonde-data of Shillong were available for all the 14 days of the spell. These and also the radiosonde data for all the other Indian stations for the same period taken from the Indian Daily Weather Reports were specially checked by reference to the India Meteorological Department. No data for any station were corrected by the present writer from synoptic considerations.

A comparison of these mean patterns with the corresponding normal patterns for April,[2] vide Fig. 23, 24, 25, and 26 shows the following:

(a) With regard to convergence, it is very difficult to find any significant difference between the mean streamline patterns for the spell and the corresponding normal[3] streamline patterns for the 3,000 and 5,000 feet levels in the region of large-scale convection. If at all—contrary to the conventional ideas—the streamlines in the mean patterns for the spell show an anticyclonic instead of cyclonic curving in the region between 90° E and 94° E and between 23° N and 26° N where convection was most vigorous. It may be added that the mean pattern for 5,000 feet level, for 02 G.M.T. is also very similar to the normal pattern for that hour. These have, however, not been reproduced here.

(b) In contrast to the above, there is pronounced difference between the mean patterns for the spell and normal[4] patterns for the 500 and 300 mb levels. In particular it may be noted that in the 300 mb level

(i) the mean jet stream during the spell is more concentrated than the normal jet: the increase in the horizontal as well as vertical shear and the strengthening of the wind at every station along and to the south of the jet axis may be particularly noted. A rough computation shows that there has been an increase of more than 35 % in the general wind-speed, irrespective of direction, north of lat. 20° N. As will be shown in section 9, this increase in wind-speed is equivalent to an increase in upper convergence (in the rear of the trough line) and increase in upper divergence (ahead of the trough line) of about 80 %, provided *other conditions are the same.*

(ii) The jet stream trough whose axis is near 86° E on the normal chart (see Fig. 26: the partial thermal winds show the trough a little more clearly) is much more pronounced in the mean pattern for the spell and has shifted eastwards. The mean upper winds over Calcutta and the mean heights of the 300 mb surface over Shillong, Calcutta and Allahabad (see Fig. 22) show that *the region of large-scale convection lay in a trough and that the trough-line of this*

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[1] The spell continued beyond this date. The present study, however, has been confined up to 14 April 1954 only.

[2] These are based on 09 G.M.T. normal pilot balloon winds and 15 G.M.T. normal radiosonde heights as in the case of May, vide Section 2.

[3] No normals are available for Mohanbari (27° 29′ N 95° 01′ E) in the extreme northeast of Assam. It is therefore not known whether there is also not a trough-line near that station at 3,000 feet and 5,000 feet, in the normal pattern, as in the mean pattern for the spell. Incidentally, the very low speeds of the winds at Mohanbari at 3,000 feet (01 knot) and 5,000 feet (04 knots) in the mean pattern Figs. 19 and 20 may be noted.

[4] The pilot balloon ascents at Delhi did not reach the 300 mb level on a number of days on which high winds were recorded by the radar. The latter observations were available on all the 14 days and, as such, may be considered as more representative of the mean conditions.

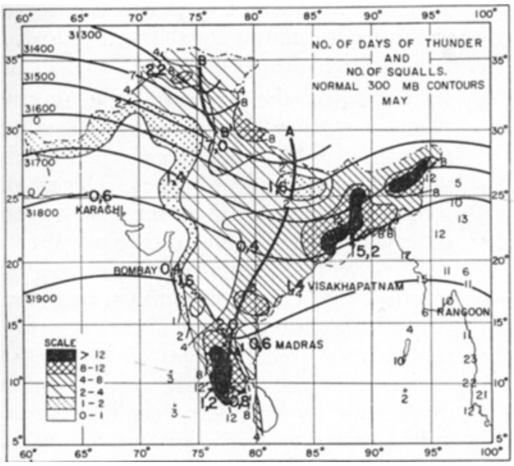

Fig. 28. Normal 300 mb contours in relation to normal large-scale convection in May. The figures in *thin* type over Burma and the Bay and Arabian Sea Islands are the number of days of thunder at individual stations. Over India and Pakistan, lines of equal frequencies of thunder have been drawn. The figures in *thick* type are the average number of squalls *per month* at individual stations.

> *system lay to the east of Calcutta. There cannot be any doubt on these two points no matter how the contours are drawn.* And it would perhaps be justifiable to place the trough-line somewhere near 89° E or 90° E as has been done in Fig. 22. It therefore follows that the unusually long spell of large-scale convection in and near Assam was associated with an unusual strengthening of the jet stream and the shifting of the trough to an unusual position and its remaining there in a quasi-stationary state during a whole fortnight.

Fig. 27 shows the actual and normal rainfall at *plain stations* in various parts of Northeast India and East Pakistan between 03 G.M.T. of 31 March 1954 and 03 G.M.T. of 14 April 1954. This period of rainfall corresponds exactly to the period of the mean 500 mb and 300 mb patterns on the basis of the convention adopted earlier in this paper for comparing the high level patterns with the subsequent weather developments. For facility of discussion the trough-line AA′ in the 300 mb mean pattern for the spell (Fig. 22) and the trough-line BB′ in the normal pattern (Fig. 26) have been reproduced on the rainfall chart. It is obvious from the chart that

(i) the region of abnormal excess of rainfall lay ahead of the trough-line that is, in a region of pronounced upper divergence (vide Section 9).

(ii) the region of abnormally deficient or no rainfall lay in the rear of the trough-line, which is normally a region of pronounced upper convergence (vide Section 9).

Thus the above study brings out the importance of upper divergence and convergence in the production of convective rainfall which in a State like Assam can produce floods even before the monsoon sets in.

8. Normal 300 mb flow-patterns in relation to normal convective activity

Fig. 28 shows the normal number of days of thunder in May reproduced from the India Meteorological Department publication *Climatological Atlas for Airmen* (1943 edition, page 25). On this map have been superposed

(a) the normal contour-patterns at 300 mb level in May shown in Fig. 2.

(b) the normal number of squalls of 40 mph or more in May at different stations in India and Pakistan as published by various workers (P. R. KRISHNA RAO 1938, C. RAMASWAMY and K. C. MAJUMDAR 1950, K. P. RAMAKRISHNAN and B. GOPINATH RAO 1954).

An examination of this composite diagram for regions north of latitude 15° N, i.e. for regions under the influence of the westerlies, leads us to the following conclusions:[1]

(a) The area east of 83° E which experiences more than 8 days of thunder, more or less coincides with the area in which there is decreasing cyclonic and increasing anticyclonic vorticity. The maxima of thunder of more than 8 days in the State of Assam may to some extent be due to orographic effects in that area, but nevertheless the pattern does suggest that the vorticity variations contribute very significantly to the development of convection.

(b) There is a remarkable decrease in convective activity west of the trough-line AA′ which is a region of increasing cyclonic vorticity. It is very interesting to see

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[1] In normal patterns, the shear variations are less than in the daily patterns. The effect of variation in the shear on vorticity has, therefore, been neglected in this discussion, for the sake of simplicity.

that Allahabad (25° 08′ N, 79° 07′ E) and Nagpur (21° 09′ N, 79°07′ E) which lie close to the trough-line AA′ but in its rear experience 1.6 and 0.4 squalls respectively, while Calcutta which lies ahead of this trough-line experiences 5.2 squalls.

(c) There is a marked decrease in the number of squalls as we proceed from Calcutta to Madras along the coast: Calcutta has 5.2 squalls, Visakhapatnam 1.4 and Madras 0.6. This decrease occurs in spite of the fact that the entire coastal region is swept by moist air in the lower troposphere and the depth of the moist air is greater over Madras than over Calcutta. The reason for this is that as we proceed further and further to the south, the wind decreases considerably in speed. As will be shown in the next section, a pronounced increase of the westerly wind with height is one of the essential conditions for the development of upper divergence upon which depends large-scale convection. And secondly the upper divergence is proportional to the square of the wind-speed in jet-stream zones. Both these conditions are, in the mean, less and less fulfilled as we proceed from Calcutta to Madras along the coast. Consequently large-scale convection as manifested in squalls becomes progressively less as we proceed towards the south from Calcutta.

(d) There is a secondary maximum of thunderstorms between 77° E and 80° E north of 27° N. This region falls east of the trough-line BB′, i.e. in a region of decreasing cyclonic vorticity.

Although the association between the number of days of thunder and the normal contour pattern is not satisfactory to the west of 75° E, the phenomenon of thunder in this region shows in general a decrease as we proceed from 34° N to 20° N. This seems to be for the same reason as the decrease in the number of squalls as we proceed from Calcutta to Madras namely that we are proceeding from a region of strong winds to a region of lighter winds in the upper troposphere. It may be incidentally noted that New Delhi which is very near the axis of the mean jet experiences the maximum number of squalls (7.0) in Northern India during this month.

With regard to the unsatisfactory association between the number of days of thunder and the contour-pattern *west* of 75° E, the following tentative explanation is offered:

(a) In this region, the predominant convective phenomenon is the duststorm in which thunder is often not heard due to the noise of the violent winds. Hence the frequency of thunder as reported by the observers cannot give a true picture of the convective acitivity in this region: frequency of convective duststorms alone will give a correct picture. Unfortunately no statistics of convective duststorms are available as the phenomena reported as duststorms by the observers include not only the convective duststorms but also those[1] caused by steep pressure gradients which are not determined by convective processes.

(b) From the study of the individual cases, one gets the impression that, in this region, there is a greater variability of wave-patterns than to the east of 75° E or 80° E. Consequently, perhaps, no pattern typical of convective situations emerges as the normal for the month of May.

The 300 mb contours for March and April have also been similarly studied with reference to the normal number of days of thunder and of squalls. They also show similar characteristics but the wave-pattern east of 80° E is less marked in these two months.

A discussion about the maximum of thunder in the extreme south of peninsular India is outside the scope of the present paper as it occurs outside the normal sphere of influence of the sub-tropical jet stream. However, it may be noted that the relative proportion between the number of squalls and the number of days of thunder in this region is very different from that in Northeast India where also the number of days of thunder is large. This would suggest that the mechanism of thunder in the southern tip of the peninsula is very different from that in the region of influence of the sub-tropical jet and that the phenom-

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[1] These are common in this region and are referred to in Indian synoptic literature as dust-raising winds. They are popularly known as the *loo*. It is quite easy to distinguish them from convective duststorms on the synoptic charts. It need hardly be added that only convective duststorms have been plotted on the synoptic charts and diagrams in this paper.

enon is probably of a much milder type, resembling the thunder in Northeast India during the southwest monsoon period.

9. Mechanism of large-scale convection over northern India and Pakistan

It is well-known that the horizontal divergence in a zonal wave moving without change of shape in a broad current is given by the equation

$$\operatorname{div}_H \mathbf{v} = -\frac{(u-c)\cdot\frac{\partial \xi}{\partial x}}{\xi + f} \qquad (1)$$

where u is the zonal wind-speed
c is the speed of the zonal wave
ξ is the relative vorticity
f is the coriolis parameter

and x and y are the rectangular coordinates measured in the west to east and south to north directions respectively. In the derivation of this equation, the w component of the wind-speed and the north to south variation of the absolute vorticity have been neglected.

Synoptic experience indicates that the wave-patterns in the westerlies over India and Pakistan move very slowly in comparison even with the wind at the 700 mb level. And, as we have already seen, the westerlies markedly increase with height above the 700 mb level in the pre-monsoon period. Hence $u - c$ in the above equation is generally positive above the 700 mb level and increases with height at higher levels. Now let us assume that the level of non-divergence over Indo-Pakistan is near about the 700 mb[1] level. Let us also assume, as is implied in the above equation, that the contribution to the variation in the vorticity is mainly due to the curvature term. It then follows from the above equation that in the eastern half of the trough and the western half of the ridge where $\frac{\partial \xi}{\partial x}$ is negative, there is a steady increase of divergence with height above the 700 mb level, the divergence reaching a maximum at the tropopause which lies near the 200 mb level over Indo-Pakistan in the pre-monsoon period. Likewise, in the western half of the trough and the eastern half of the ridge where $\frac{\partial \xi}{\partial x}$ is positive, there must be convergence above the 700 mb level which would steadily increase with height and reach a maximum at the tropopause. This upper divergence and convergence in the different parts of the zonal wave must result in a corresponding compensation convergence and divergence below the 700 mb level according to the Dines model and such a compensation over Indo-Pakistan must be even more complete than in middle latitudes in view of the well-known fact that the pressure-changes at sea-level in the subtropics in the absence of tropical cyclones is much less than the pressure changes in middle-latitudes.

As a result of this upper divergence and lower convergence, there would be, in the eastern half of the trough or the western half of the ridge

(i) strong upward motion *at all heights* in the troposphere
(ii) lateral contraction and vertical stretching of the air *below* the level of non-divergence
(iii) lateral spreading and vertical shrinking of the air *above* the level of non-divergence.

Now let us confine ourselves for the time-being to the synoptic situations in Northeast India and East Pakistan where warm, latently unstable air is separated from the upper dry westerlies by an inversion. As a result of (i) and (ii) above, the latently unstable moist air below the inversion will be vigorously forced upwards. In this process, it will break the inversion lid and shoot up to the levels where the energy from latent instability can be released. Such a process would obviously manifest itself in a rapid development of a vigorous squall-producing thunderstorm cell. It may be added that the process as visualized above is fully supported by observations of the actual development of the nor'wester.

Per contra, in the western half of a trough and the eastern half of a ridge where there would be upper convergence and lower divergence, there would be

(i) strong downward motion *at all heights* in the troposphere

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[1] In middle latitudes, this level has been assumed to be near about the 600 mb level but we are justified in assuming a slightly lower level over Indo-Pakistan in view of the variation of wind with height observed in tropical cyclones. However, it is not important from the point of view of the later discussion in this paper, whether the level of non-divergence is nearer 600 or 700 mb.

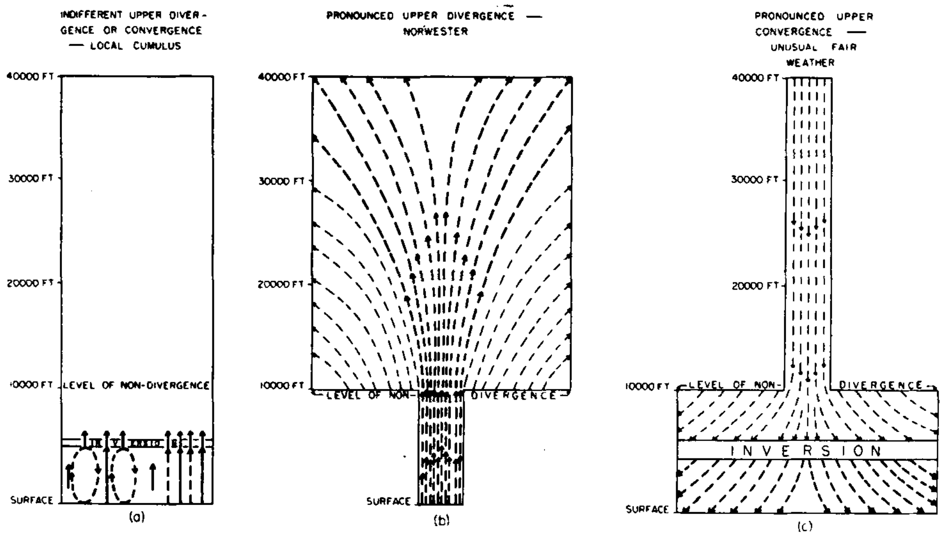

Fig. 29. Schematic representation of dynamical processes in Northeast India and East Pakistan in the pre-monsoon period. Thick arrows indicate air movement in moist air and thin arrows air movement in dry air. Below and very near the inversion in Fig. 29 (a), short continuous arrows indicate forced lifting due to orography and long continuous arrows, velocity-convergence in lower troposphere in association with trough-lines etc. Broken ellipses indicate local convection due to insolation and long broken arrows indicate nocturnal Bleeker-Andre convergence in the valleys of Assam and along the foot of the Himalayas. Note particularly the magnitude of the dynamical effects associated with insolation, lower-tropospheric trough-lines etc. in (Fig. 29 (a) in comparison with the dynamical effects associated with upper divergence. Note the absence of the inversion in Fig. 29 (b). This schematic diagram also holds good with minor modifications, for the andhis in Northwest India and West Pakistan (see text).

(ii) lateral spreading and vertical shrinking of the air *below* the level of non-divergence

(iii) lateral contraction and vertical stretching of the air *above* the level of non-divergence.

In such a development in Northeast India and East Pakistan, the moist air below the inversion will shrink and spread under the inversion. The inversion itself would also probably intensify and lower as a result of the strong downward motion above it. Consequently quite stable, fair weather will prevail. These fair weather conditions have been repeatedly observed in Northeast India in the rear of troughs, vide discussion in Section 6.

The dynamical processes discussed in the above paragraphs have been schematically depicted in Figures 29 (a), 29 (b), and 29 (c). The effect of surface-heating and of the other lower tropospheric agencies such as convergence associated with the trough-lines or with the nocturnal sinking of isobaric surfaces in valleys (Bleeker and Andre 1951) are also shown schematically below the inversion. These agencies which are of minor importance in comparison with upper divergence and convergence are discussed in greater detail in the later part of this section.

The above discussions are equally valid for the rest of northern India and West Pakistan also (i.e. west of 83° E, north of 20° N) if only we take into account one additional factor, namely a prior injection of moisture below the region of upper divergence. This injection usually takes place, as pointed out by the earlier workers, by the western disturbances. The inversion which we have mentioned in the case of Northeast India and East Pakistan does not exist in Northwest India or West Pakistan, presumably because the incursion of moist air below the dry upper westerlies is a temporary phenomenon and as such there is not sufficient time for the development of the inversion. Nevertheless, latent instability develops in this semi-moist air which means that the moist air is subject to resistance to lifting. And this resistance is overcome by the vertical stretching and the strong upward motion induced by upper divergence. In the circumstances the schematic diagrams in Fig. 29 (a), (b) and (c) can, in a sense, be also taken as valid for the development of large-scale convection over any part of northern India and Pakistan.

It should be specially stressed that the schematic diagrams are only crude representations of the actual dynamical processes and that they are not intended to give any quantitative estimate of the vertical stretching, lateral spreading etc. The author's purpose in presenting them is mainly to show graphically that the dynamical effects produced by upper divergence and convergence are much more pronounced than those produced by the lower tropospheric agencies shown in Fig. 29 (a).

If the zonal wave described above is of the sinusoidal type, the upper divergence would be a maximum not immediately to the east of the trough-line (or to the west of the ridge-line) but somewhat downstream in the case of the trough and upstream in the case of the ridge where $\frac{\partial \xi}{\partial x}$ is a maximum. Hence large-scale convection would tend to be a maximum in such regions. This has been actually observed on quite a number of occasions in our studies and has been schematically shown as S_U-Sin in Fig. 9 (a).

Expressing the above in more general terms, if the wave-pattern is of any other type, large-scale convection would tend to be a maximum in the region where the rate of change in curvature of the contours is a maximum. Two simple cases of this type are shown in schematic patterns S_U-T and S_U-R in Figures 9 (b) and 9 (c). In S_U-T, there is an abrupt decrease in cyclonic vorticity just to the east of the trough-line with little or no change in vorticity further downstream. Consequently, large-scale convection would be practically confined to the area shown in that pattern. Likewise in the case of S_U-R type, there is little or no change in vorticity followed by an abrupt increase in anticyclonic vorticity downstream in the rear of the ridge-line. Consequently, large-scale convection will be practically confined to the area shown in that pattern. It is interesting to note that a large number of cases of S_U-R type have been found in our studies confirming the conclusions arrived at here purely from theoretical considerations.

In the above discussions, it had been assumed that the contribution to the change in the vorticity by the shear-term was negligible. However, this assumption would not always be justified. S. PETTERSSEN, DUNN and MEANS (1955) have, recently, in another connection solved this difficulty, so far as jet stream zones are concerned. They have pointed out that in the jet-stream zones, the vorticity-advection A can be written as equal to

$$-V^2\left(\frac{\partial K_s}{\partial x}+K_sK_n\right) \qquad (2)$$

where K_s is the curvature of the contour K_n is the orthogonal curvature of the contour and V is the wind-speed.

Now let us see the implications of the above equation with reference to the schematic patterns S_V-T and S_V-R in Figures 9 (d) and 9 (e).

In the pattern S_V-T, the term $\frac{\partial K_s}{\partial x}$ as well as K_sK_n will be negative and, therefore, the vorticity-advection A will be positive and large. As positive vorticity-advection is an indication of upper divergence, it follows that there will be pronounced upper divergence and consequent vigorous convection ahead of the trough line. In the rear of the trough-line, $\frac{\partial K_s}{\partial x}$ will be positive but K_sK_n will be negative since the contours are diverging. Hence the vorticity advection A will be positive or negative depending upon the algebraic sum of $\frac{\partial K_s}{\partial x}$ and K_sK_n. It is, therefore, quite reasonable to expect positive values of vorticity-advection in the rear of the trough-line if the contours are markedly diffluent. And since the speed of the wind enters as a second power term in the above equation, it will be readily seen that, with high-speed jets, there can be appreciable upper divergence in the rear of the trough-line also. Further, along and near the trough-line, the temperatures would be lowest and this would further contribute to the development of instability. Consequently, there could be development of large-scale convection in the rear of the trough-line, the severity of the convection decreasing as we proceed further and further away from the trough-line. This is exactly what we find in weather situations of the S_V-T type, *the westward extension of the large-scale convection in the rear of the trough-line depending upon the extent of fanning of the contours and the wind-speed in the jet stream in that region.*

Arguing on the same lines, it can be seen that in the case of the S_V-R pattern, the upper divergence would be pronounced in the rear of the ridge-line but could also be appreciable ahead of the ridge-line, the eastward extension of the divergence area ahead of the ridge-line depending upon the confluence of the contours and the wind-speed. In this case, however, the higher temperatures along and near the ridge-line may slightly counteract the development of instability. These conclusions are fully supported by the schematic pattern shown as S_V-R in Fig. 9 (e).

During the course of our investigation, we have found that thunderstorms occasionally occur ahead of the trough-line in regions where the contours show a certain amount of confluence. In this case $\frac{\partial K_s}{\partial x}$ is negative and $K_s K_n$ is positive but the vorticity advection may still be positive if the algebraic sum of these two quantities is negative. And if the wind-speeds in such a region are high, the net positive vorticity-advection, i.e. net upper divergence, may be quite large and lead to violent convection in spite of the confluent contours.

The effect of the curvature and orthogonal curvature of the contours has been discussed above on a purely qualitative basis. A quantitative estimation of vorticity advection alone can make it absolutely certain in any individual case whether the net vorticity advection is positive or not, i.e. whether there is net upper divergence or not. Such quantitative estimation of upper divergence should preferably be made at the 250 mb level in view of the height of the tropical tropopause but this can perhaps be attempted with confidence only when more radio-wind observations become available over Indo-Pakistan.

It may be specially emphasized that equation (2) above is of general applicability and as such holds equally good for all the schematic patterns in Fig. 9. This implies that, *other conditions being the same, the severity of the large-scale convection would depend greatly on the wind-speed in the upper troposphere.* As this conclusion has a direct bearing on the problem of area-warnings for squalls it will be referred to again in section 10.

It can also be readily seen from equation (2) that there can be numerous combinations in the values of V^2, $\frac{\partial K_s}{\partial x}$ and $K_s K_n$ which can correspond to a specified positive value of vorticity-advection i.e. very roughly to a specified degree of large-scale convection. It would therefore appear that the schematic patterns in Fig. 9 which represent the types actually observed by us on the upper air maps are only some of the various possible patterns which can lead to large-scale convection. These other patterns may come to light as a result of further investigations based on more observations.

In the above discussions, we have made a fundamental assumption that there is a steady increase of the westerly wind with height. When, however, this condition is not satisfied, there may not be upper divergence and there may even be upper convergence if u becomes less than c in equation (1). In such situations, there would obviously be no convective developments. We have met with such situations (which, however, seem to be rather rare). Vide Fig. 17 and discussion in section 6.

With regard to the general magnitude of upper divergence or convergence, it may be mentioned that Petterson and his collaborators (1955) have recently pointed out that vorticity maxima in the range of 2×10^{-4} sec^{-1} to 5×10^{-4} sec^{-1} are *regularly* found at the trough-lines in the jet stream over the U.S.A. at the 300 mb level. Since the troughs in the sub-tropical jet are usually less pronounced than those in the polar-front jet, we cannot expect such high values of vorticity maxima as 2×10^{-4} sec^{-1} to 5×10^{-4} sec^{-1} at the trough-lines over Indo-Pakistan. However, RIEHL (1954, p. 204) has shown that a convergence of only 1×10^{-5} sec^{-1} in moist air can produce much bad weather when lasting for several hours. These figures, apart from the evidence we have already adduced, lead us to think that we have in upper divergence and convergence over Indo-Pakistan a factor much more potent and of a higher order of magnitude than lower tropospheric convergence in winds which are often light even at 5,000 feet in the pre-monsoon period.

Palmén (unpublished[1]) has shown that the ageostrophic wind-component across the contours is approximately given by the following expression

$$v_{na}= -\frac{g}{f\left(f-\frac{\partial v_s}{\partial n}\right)}\cdot\left[\underbrace{\frac{\partial}{\partial n}\left(\frac{\partial h}{\partial t}\right)}_{\substack{\text{Brunt-}\\\text{Douglas}\\\text{term}}}+\underbrace{v_s\frac{\partial}{\partial s}\left(\frac{\partial h}{\partial n}\right)}_{\substack{\text{Confluence-}\\\text{Diffluence}\\\text{term}}}+\underbrace{\frac{w}{T}\frac{\partial T}{\partial n}}_{\substack{\text{Thermal}\\\text{wind}\\\text{term}}}\right]$$

where g is the acceleration of gravity
f is the coriolis parameter
v_s is the speed of the wind along the contour
v_{na} is the ageostrophic component perpendicular to the contour
h is the height of the isobaric surface
w is the vertical velocity
$\frac{\partial T}{\partial n}$ is the temperature gradient on the isobaric surface
s is the direction along the contour.
n is the direction normal to the contour.

The above equation has been derived from the equation of motion $\frac{dv_s}{dt}-fv_{na}=-\frac{1}{\varrho}\frac{\partial p}{\partial s}$ in natural coordinates, using the thermal wind equation to evaluate $\frac{\partial v_s}{\partial z}$ and the geostrophic approximation to evaluate the terms $\frac{\partial v_s}{\partial t}$ and $\frac{\partial v_s}{\partial s}$.

In the jet-stream zone to the south of the jet axis, $\frac{\partial v_s}{\partial n}$ is large and therefore $f-\frac{\partial v_s}{\partial n}$ is small. And consequently v_{na} is large. Further, f is progressively less and less in lower latitudes. Hence the ageostrophic motion represented by v_{na} is greater in the sub-tropical jet than in the polar-front jet and greater to the *south* of the subtropical jet than to the north of it. As ageostrophic motion is an indication of divergence and convergence and as the axis of the subtropical jet is situated over Indo-Pakistan near lat. 29° N in the typical large-scale convection months April and May and tends to shift to near about 35° N in June before it eventually shifts to the north of the sub-continent (with the establishment of the monsoon), it will be seen that northern India and Pakistan lie on the equatorward side of the jet stream and close to the jet axis during the large-scale convection period. Conditions are, therefore, most favourable in these regions for pronounced upper divergence and convergence and for the consequent pronounced dynamical reactions on the lower troposphere as already discussed in the preceding paragraphs.

We have so far considered only compensation-convergence in the moist air. Besides this, there may be velocity-convergence in this air, as for instance along the trough-line CA in Fig. 1. The moist air may also be subject to upward impulses due to insolation or forced lifting due to orography. In the valleys of Assam and along the foot of the Himalayas, the nocturnal sinking of the isobaric surfaces (Bleeker and Andre, 1951) may lead to low-level convergence in the moist air late in the night and very early in the morning. This type of convergence is of a higher order of magnitude than that due to katabatic winds and as such is a more important factor in the development of nocturnal thunderstorms in the valleys and along the foot of the Himalayas. All these lower tropospheric processes undoubtedly contribute to the development of large-scale convection. But they are either invariably present, as for instance, orography or are very often present in fair weather as well as convective weather as, for instance, insolation[1] and Bleeker-Andre valley convergence or show only slight association with convective developments as, for instance, velocity-convergence. On the other hand,

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[1] The author is specially indebted to Professor E. Palmén for drawing his attention to this equation which has not yet been published.

[1] The normal time of development of the large-scale convection in the plains (P. R. Krishna Rao 1938, India Met. Dept. 1944, C. Ramaswamy and K. C. Majumdar 1950, Y. P. R. Bhalotra 1954) cannot be explained on the basis of insolation alone as vigorous convection develops rather too long after the time of maximum temperature. Some other *local* destabilizing factor, which is at present unknown, seems to come into play and determine the *time* of development.

we have seen that in regions where latently unstable, moist air is present in the lower troposphere, large-scale convection seems to be invariably connected with upper divergence while persistent fair weather is connected with upper convergence. We have also seen that this upper divergence or convergence is of a higher order of magnitude than lower-tropospheric velocity-convergence. We have, therefore, to conclude that among the various triggers so far discussed for the release of the latent instability energy, upper divergence is the most important one.

With regard to the role of cold fronts of the middle-latitude type, we would mention that among the 80 cases distributed over three years which we have studied and in which there were destructive squalls of record intensity, we have not seen any case which could be attributed to a cold-front of the middle-latitude type. It may also be noted that meteorologists who have investigated into tropical conditions in other parts of the world (Riehl 1954, p. 237) have, on the basis of other evidence, seriously questioned the existence of fronts in the tropics—fronts as this term is commonly understood. And we would add that, in the case of Indo-Pakistan, the great Himalayan range to the north and the Karakoram and Hindukush ranges to the northwest form a mighty barrier against surges of polar air reaching the plains of this sub-continent. It therefore seems a priori very unlikely that in the pre-monsoon period, especially in April, May and early in June, polar air even of the modified type could reach the plains of northern India and Pakistan in *sufficient depth* as to retain its characteristics in spite of the strong surface-heating and produce a middle-latitude type of frontal effects. And even if such a cold-front were found, it would be worth while to see whether the upper divergence associated with the 300 mb trough of the western disturbance does not have a more direct connection with the convective developments than with the cold-front at the ground. For the present, therefore, we shall proceed on the assumption that such cold-fronts are *very rare* and, as such, need not enter into a general discussion on large-scale convection in northern India and Pakistan.

The thermal advective processes as seen in the backing of winds with height between the 700 and 300 mb layers referred to in Section 6 should now be discussed in relation to the mechanism of large-scale convection. In middle latitudes, such a backing of winds could automatically be taken as evidence of cold-air advection whether or not[1] it caused a drop in temperature at a particular station. However, in view of the following reasons, it was difficult to proceed strictly on the same basis in our present studies:

(i) The winds were probably ageostrophic to some extent over Northern India and Pakistan.

(ii) The cold troughs and warm ridges over Indo-Pakistan were less deep than similar troughs and ridges in middle latitudes. Consequently, the local temperature-changes in association with these systems would be less pronounced than in middle latitudes and at times may even be less than the errors in tropical radiosonde-data at these high levels.

In view of the above and also of the fact that the region of maximum convective activity in trough-areas lay ahead of the trough-lines at the 300 mb level and not in the neighbourhood of these lines themselves where the temperatures would be lowest, it has to be concluded that although cold-air advection (as inferred from wind-observations) does occur in a large number of cases and as such, is important,[2] *the dynamical effect discussed in the earlier paragraphs is very much more important.*

It will, thus, be evident that large-scale convection over northern India and Pakistan in the pre-monsoon period *is overwhelmingly determined by upper-divergence, i.e. by a dynamical process which begins to operate above 10,000 feet and attains a maximum at the level o the tropopause*, namely, near about the 200 mb level.

It would also appear from this study that

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[1] That cold-air advection does not necessarily imply a drop in temperature at a station can be seen from the equation for the "individual change" of the potential temperature of a moving air-parcel. The vertical component of the wind can be such that the "*local change*" of potential temperature is zero $\left(\frac{\partial\Theta}{\partial t} = 0\right)$.

[2] The importance of cold-air advection in the upper levels in the development of instability in the sub-tropics has also been stressed by Riehl (1947) in his studies of the thunderstroms in sub-tropical U.S.A. in summer.

andhis, nor'westers and the majority of the thunderstorms without squalls in northern India and Pakistan during the pre-monsoon period are fundamentally the same[1] *phenomenon,* the difference between the first two being merely due to a difference in the moisture-content of the air in the lower troposphere and the difference between the last two being due to different degrees of convection produced by one and the same mechanism.

It is of interest to know the genesis of the et-stream waves which so profoundly control the large-scale convection over northern India and Pakistan. This has, however, to be taken up as a separate problem. Nevertheless the author would like to record here his general impression that there is probably a stationary (or quasi-stationary) wave-pattern in the jet over Indo-Pakistan with a wave-length of 3,000 to 4,000 kilometres and with the axis of the trough in this pattern somewhere between 82° E and 87° E (see Fig. 2). In addition, a series of waves seem to move across the sub-continent producing, as a result, varying vorticity patterns over the northern half of the sub-continent. That there can be two such wave-patterns superposed over the same region has already been recognized by the earlier workers on the polar-front jet (AROWA-PROJECT 1953). It may be further added that the stationary (or quasi-stationary) wave referred to above does not appear to be merely an effect of the contour of the Himalayas. The normal contours at the 300 mb level in May and April (Figs. 2 and 26) may be seen in this connection.

As mentioned in Section 1, large-scale convection in northern India and Pakistan as manifested in the nor'wester and the andhi markedly decreases with the establishment of the monsoon. The reason for this is that the sub-tropical jet-stream shifts to the north of the Himalayas with the establishment of the monsoon and consequently the upper divergence associated with the waves in the jet-stream which are so essential for large-scale convection is absent in northern India and Pakistan[1] during the monsoon-period. With the withdrawal of the monsoon, the sub-tropical jet-stream returns to the south of the Himalayas (KOTESWARAM 1954) and there is a revival of the convective activity over the sub-continent. (A. K. ROY 1949, K. P. RAMAKRISHNAN and B. GOPINATH RAO 1954). However, on account of the highly monsoonal character of the weather systems over Indo-Pakistan, the sea-level isobars and the lower tropospheric flow patterns in the post-monsoon and cold-weather periods are such that most of the sub-continent is invaded by a very dry air stream of land origin and there are only very occasional incursions of moist air from the Bay of Bengal and the Arabian sea into the country in association with moving pressure-systems. And the moist air which thus penetrates into the country has increasingly stable characteristics with the advance of the year. Consequently large-scale convection over northern India and Pakistan is much less frequent in the post-monsoon period than in the pre-monsoon period and virtually ceases in the cold-weather period.

10. The 500 and 300 mb patterns as tools in forecasting large-scale convection in the pre-monsoon period

The 500 and 300 mb vorticity patterns over northern India and Pakistan (as judged from the contour-patterns) are persistent: they move very slowly and undergo only moderate variations in their configuration during a 24-hour period. The 300 mb charts for the period 28 April 1954 to 6 May 1954 when there were fairly adequate *wind-data* for this level for a *continuous* period of 9 days may be cited as an example. The upper tropospheric charts also show a high degree of consistency with the later convective developments, which is supported by the theoretical reasoning outlined in the preceding section. In this

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[1] In an article on unusually dusty weather at Delhi in 1952 and 1953, (S. C. ROY, 1954) has also mentioned that the andhi and the norwester are essentially of the same origin. His article does not however contain any specific synoptic evidence in support of this statement. And, further, it is clear from his later statement in the same article that, in his opinion, the determining factor in the development of the andhi is in the lower troposphere.

[1] The Northwest Frontier Province of West Pakistan and the adjoining areas (regions near about 34° N and to the north of this latitude) are an exception: they continue to be predominantly under the influence of the westerlies in the middle and upper troposphere throughout the monsoon period (S. P. VENKITESWARAN 1950) and consequently continue to experience squalls throughout this period (C. RAMASWAMY and K. C. MAJUMDAR 1950).

connection it may be recalled that the 500 and 300 mb charts refer to 09/15 G.M.T. and that the convective developments superposed on these charts refer to the period 03 G.M.T. of the next day to 03 G.M.T. of the following day. The analysis of the high-level charts in the qualitative manner done in this paper can be easily completed by 20 G.M.T., i.e. long before convection begins to develop in the plains. And it is to be remembered that convection usually reaches a vigorous stage only after 09 G.M.T. and at a large number of places only after 12 G.M.T. Thus the persistency of the middle and upper tropospheric vorticity patterns and the comparatively late development of convection, have placed at our disposal *an effective tool for forecasting more than 12 hours ahead, the broad regions in which thunder in general and thundersqualls and convective duststorms in particular would develop*. Obviously, this new technique is still only in its first stage of development and can be used in its present form only for area-warnings. It should be improved further when more radio-wind observations become available and further researches are carried out on small-scale motions in the middle and upper troposphere. It need hardly be added that the success of the technique with the present net-work of stations will depend upon the number of high-level wind observations available on any individual day and upon the judicious use of high-level radiosonde data in regions in which wind-observations are inadequate.

The new technique would, broadly speaking, be to identify first the regions where the existing supply of moist air is likely to continue or a fresh supply is likely to be made available on the next day as a result of changes in the lower tropospheric flow patterns. Then the regions of upper divergence and convergence have to be identified. This can be done very qualitatively on the basis of the schematic patterns presented in this paper, keeping in mind that, *other conditions being the same, the speed of the wind is a factor of major importance* and that the maximum upper convergence or divergence occurs *in general* in regions where the contours undergo the most rapid changes in curvature. The 300 mb chart is the one where these factors are to be specifically looked for but in the absence of adequate data at this level, the 500 mb chart can be used as the next best, keeping in mind the westward tilt of the wave-patterns with height. The vertical wind-shear between the 700 and 500 mb and between the 500 and 300 mb layers (strength and direction of the relative topography winds) is another important factor to be considered by the forecaster. The contribution by the lower tropospheric velocity-convergence as for instance along the CA trough-line (see Fig. 1) may also be taken into account but *very much less weight* should be given to it than to upper divergence and convergence. The time of development of the convection has to be forecast on the basis of the additional agencies known at present, such as insolation in the plains and nocturnal low-level convergence in the valleys, which would help the upper divergence field to overcome the resistance to lifting of the moist air. And having thus decided upon his prognosis, the forecaster should continuously be on guard in regions of upper divergence even if the lower tropospheric analysis does not clearly reveal moist air supply *because it is in these regions of upper divergence that there can be "sudden" and violent convective developments*, as there actually were, for instance, with the upper divergence situations on 13 April 1952 (nor'westers) and 29 April 1952 (andhis).

11. Large-scale convection in the sub-tropics in other parts of the world

An examination of the mean streamlines and isobars (Riehl 1954, p. 9 and 10) and daily and mean upper air soundings (Serra 1943, Loew 1943, 1945, Roux 1954, Walter Georgii 1952, Kendrews 1953, pp. 123, 394, 398) of the sub-tropics in other parts of the world shows that the equatorward side of the jetstream lies above latently unstable, moist air (Normand, 1938, Petterssen, 1940) in the following regions in the summer half of the year.

(1) Southeast United States
(2) New South Wales and Southern Queensland in Australia
(3) Union of South Africa outside West Cape Province, southeast Bechuanaland and South Rhodesia south of 20° S in Africa and
(4) Southeast Brazil (south of 21° S), Uruguay and northeast Argentina in South Africa.

It is also seen that, in many of the regions listed above, the moist air in the lower levels is separated from the upper dry westerlies by an inversion (or a minimum of lapse-rates) as in Northeast India and East Pakistan.

It is clear from the available literature that all the above regions experience large-scale convection during the summer half of the year (EDWARD BROOKS 1951, GRIFFITH TAYLOR 1917, LOEW 1943, KENDREW 1953, pp. 118, 127, 511, 512, CARVALHO 1913, LE ROUX 1953, UNION OF SOUTH AFRICA WEATHER BUREAU 1949, COMMONWEALTH METEOROLOGICAL SERVICES 1951, SERRA 1938).

From the mean positions of the equatorial trough as given by RIEHL (1954, page 13) we can presume that the convergence in this trough does not contribute materially even at the sea-level to the development of large-scale convection in the above regions. We may, therefore, leave out the equatorial trough in our further discussions.

Southeast United States—We shall consider here only the tornadoes. An examination of the climatic Atlas of U.S.A. by STEPHENS VISHER (1954) shows that March, April and May are the months in which the States east of 110° W and south of 35° N get the maximum number of tornadoes. It is interesting to note that these are the very months in which northern India and Pakistan also experience severe thundersqualls or convective duststorms. It is also seen from Visher's Atlas that the States in more northerly latitudes in U.S.A. experience the maximum number of tornadoes progressively later in the year compared to the States in more southerly latitudes, suggesting their association with the progressive northward shift of the mean jet-stream (Arowa Project, 1953).

It is of course well-known that the upper or surface cold-front is of great importance in the development of tornadoes and that 80 % of the tornadoes occur in association with a well-developed parent low at the surface. Nevertheless the fact that even 20 % of them develop without a surface low or a front or even in a region of surface high-pressure (EDWARD BROOKS 1951) would suggest that upper divergence associated with vorticity variations in the upper troposphere might be contributing to the development of the tornadoes.

New South Wales and Central Queensland—We shall discuss the convective developments in this region only south of 20° S and east of 140° E.

The axis of the mean jet-stream over Australia at the 200 mb-level is slightly to the north of 30° S in winter and slightly to the south of 30° S in summer (GIBBS 1953). It is, therefore, justifiable to assume that the mean position of the jet for the year as a whole is along 30° S. An examination of the isobronts of annual number of days of thunder published by H. BARKHLEY (1934) shows that there is a pronounced maximum of thunderstorms in Southeast Queensland (i.e. roughly between 25° S and 30° S). According to Barkhley, *this region of maximum number of thunderstorms is traversed by squall-lines.*

Among the line-squalls which affect Southeast Australia, the spectacular southerly bursters deserve special mention. The city of Sydney (33° 52′ S, 151° 12′ E) experiences the typical southerly burster. Fig. 30 shows the normal monthly distribution of this line-squall at Sydney based on 32 years' data. (GRIFFITHS 1917). On the same diagram has been superposed the monthly distribution of the squalls (andhis) at Peshawar (34° 01′ N, 71° 35′ E). These are based on Dines P.T. Anemograph-data for 17 years (C. RAMASWAMY and K. C. MAJUMDAR 1950). As the northern hemispheric summer corresponds to the southern hemispheric winter, the abscissa for the curve starts from July in the case of Sydney and from January in the case of Peshawar. As the specifications of wind-speed defining an andhi and a southerly burster are not the same,

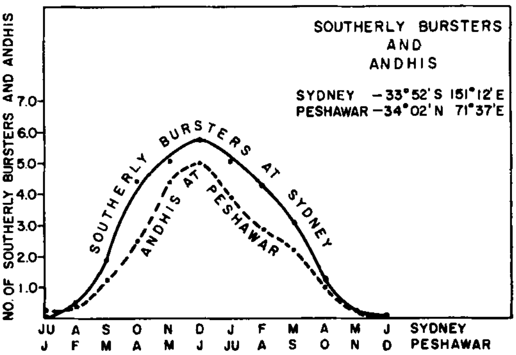

Fig. 30. The ordinates represent the normal number of southerly bursters at Sydney and andhis at Peshawar in each of the months of the year.

the absolute number of squalls at the two stations are not comparable. However, the *similarity in the monthly trends* at the two stations is of great interest. These two stations have nothing in common except that they are at about the same latitude (although in different hemispheres) and that they are in the vicinity of the jet stream in the upper troposphere. In the circumstances, the observed similarity in the monthly variation of the squall-frequencies does, in the light of the detailed evidence already adduced in the case of Indo-Pakistan, lend support to the view that *the jet stream may be the common and the most important factor in the development of large-scale convection in the sub-tropics in both the hemispheres.*

Union of South Africa and the neighbouring regions—According to Gibbs (1953) the mean position of the jet stream over Australia may also be taken as true of the rest of the southern hemisphere. Gibbs has also shown that the mean position of the jet stream in the spring is slightly more towards the equator than in the autumn. From Gibbs' paper as well as from the later analysis of the radar winds over Pretoria (25° 46′ S, 28° 14′ E) and over Maun (19° 59′ S, 23° 25′ E) by HOFMEYER (1953, 1954) it is quite clear that even southeast Bechuanaland and southern Rhodesia are dominated by the jet stream throughout the summer.

The seasonal and annual distribution of the thunderstorms over these countries as presented by J. J. LE ROUX (1953) *shows a close association with the mean positions of the jet stream in the different seasons* as given by Gibbs. Most of the thunderstorms occur on the equatorward side of the jet in all the cases. And when we remember that these thunderstorms are large in number during the period October to April and are accompanied by severe squalls especially in the summer months, when latently unstable moist air is most available in the lower troposphere, the association between the jet stream and large-scale convection over subtropical South Africa becomes even more evident.

Southeast Brazil, Uruguay and Northeast Argentina—The well-known Pamperos in these regions occur on the equatorward side of the jet stream mostly in spring and summer (KENDREW 1953, pp. 511 and 512).

The appearance of the approaching Pampero and the meteorological changes it causes as it passes over a station (U.S. NAVY DEPARTMENT WEATHER SUMMARY OF SOUTH AMERICA, 1945) bear a strong resemblance to those associated with the Indo-Pakistan nor'wester. The Pampero like its Australian counterpart, the southerly burster (GRIFFITHS 1917) is supposed to be caused by cold-fronts. WALTER GEORGII (1952) has, however, recently shown that the cold-fronts which cause the Pampero are different from the cold-fronts of middle-latitudes and that they pass over a station 1—3 hours *before* the development of the Pampero. As the 300 mb trough in such cases would obviously be tilted westwards with respect to the surface-front, it would be interesting to see whether the Pamperos (and also the southerly bursters) do not show a more direct connection with the vorticity variations at the 300 mb level (i.e. with upper divergence) than with the cold-fronts at the surface.

GENERAL. It will be seen from the above that the jet stream is in the right position to cause the large-scale convection in the above mentioned countries as in Indo-Pakistan. The only important difference between these countries and Indo-Pakistan is that, in the case of the former, the large-scale convection continues throughout the summer while in the case of the latter (i.e. Indo-Pakistan) the large-scale convection abruptly decreases with the establishment of the monsoon. And for the reasons already fully discussed in Section 9 this difference is due to the fact that the jet stream itself moves away from Indo-Pakistan during the monsoon. And we have further shown that in the case of Peshawar in the extreme northwest of Pakistan, which is more or less continuously under the influence of the jet stream even during the monsoon period, the monthly variation of andhis bears a striking resemblance to the monthly variation of the southerly bursters at Sydney, which is at the same latitude in the southern hemisphere. It would thus appear that the sub-tropical jet stream does not produce large-scale convection only in Indo-Pakistan: it seems to produce similar convection in the sub-tropics *all over the world*, wherever it overruns on its equatorward side, moist air with pronounced latent instability.

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