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## The vertical slope of the monsoon trough and its association with distribution of rainfall over India

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**ABSTRACT.** By evaluating the Margules' simplified equation for the slope of a surface of airmass discontinuity with relevant data and comparing the computed slope with observations, it has been suggested that, to a high degree of approximation, the monsoon trough over India may be regarded as a surface of airmass discontinuity separating the relatively warm easterly winds in the north from the cool westerly winds in the south and sloping southward with height. Rainfall associated with the normal southward slope of the trough appears to be distributed mainly to the south of the MSL position of the trough. However, both the slope of the trough as well as the distribution of rainfall associated with it are found to undergo major changes when synoptic disturbances such as the Bay of Bengal depressions or western disturbances affect India. Some main patterns of these changes are identified and discussed with reference to the possible role of the synoptic disturbances.

### 1. Introduction

During the southwest monsoon season in India (June-September), an extensive area of low pressure generally known as a heat 'low' lies centred over west Pakistan and adjoining north-western part of India. As part of this heat low, a well-marked trough of low pressure known as the monsoon trough extends at mean sea level from northwestern India to the head Bay of Bengal (*see* Fig. 1). The presence of this trough is also discernible in the isobaric height fields, upto about 500 mb. Normally the trough appears to slope southward with height, separating the warm easterly winds in the north from the cool westerly winds in the south (*see* Fig. 2) and thereby exhibit the characteristics of a surface of airmass discontinuity. It is well known that with the monsoon trough at the surface lying along the Gangetic valley, air temperature to the north of the trough from surface to about 500 mb is, on an average, at least 1 to 2 deg. C higher than that to the south (*see* Saha 1968; Ramage and Raman 1972). However, the slope appears to vary with variation in the intensity of the monsoon apparently caused by the moving distur-

bances, such as the Bay depressions or the western disturbances. It is generally known that the distribution of rainfall over India, barring orographic rainfall, has some relationship with the monsoon trough. It may be of special interest to inquire how the meridional distribution of rainfall varies with the slope as well as the location of the monsoon trough. The purpose of the present paper is to test the hypothesis that the monsoon trough in space may be regarded as a surface of airmass discontinuity by computing the theoretical slope of the trough and comparing it with observations, study the variation of the slope with intensity of monsoon and examine possible relationship between the vertical slope of the trough and the distribution of rainfall under different synoptic situations.

### 2. Data

During Monsoon-77, an experiment was conducted over the Indian Ocean region as a joint Indo-Soviet meteorological program and special efforts were made to collect as much data as possible over the Indian sub-continent as well as over the ocean. The period July and August 1977 was, therefore, selected for the proposed study.

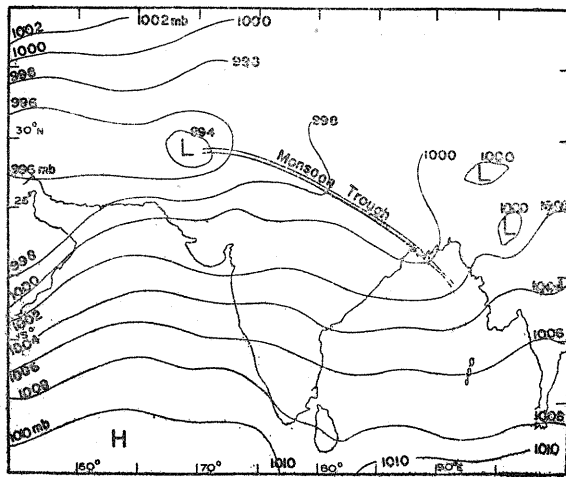


Fig. 1. Map showing normal MSL pressure distribution during July, as published by India Met. Dep. The double line shows the location of the monsoon trough.

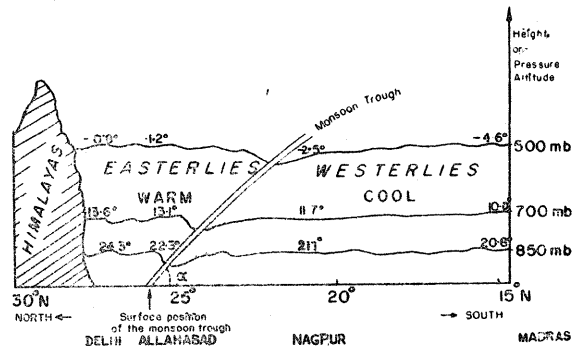


Fig. 2. Schematic diagrams showing the approximate location of the monsoon trough (indicated by a double line) in the vertical along meridian about 80° E, in a normal monsoon situation. The angle  $\alpha$  denotes the vertical slope of the monsoon trough. Long-term averages of air temperatures (°C) at 850, 700 and 500 mb over Delhi, Allahabad, Nagpur and Madras which lie close to meridian 80° E, taken from Ramage and Raman (1972) are included in the diagram to bring out the temperature differences to the north and the south of the monsoon trough

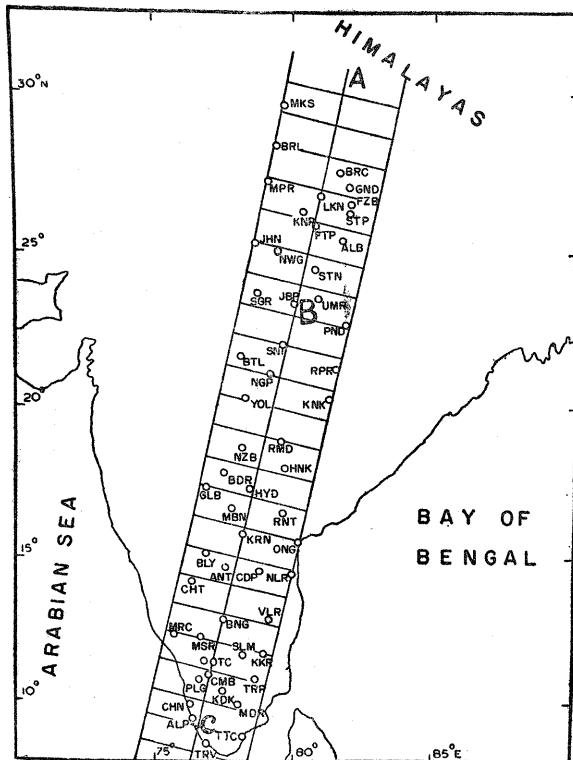


Fig. 3. Framework and grid used for recording data of the position of the monsoon trough at MSL and various isobaric surfaces and mean distribution of rainfall along the reference line ABC which makes an angle of about 12.5° with the meridian 80° E at Jabbalpur (point B),

For determining the observed slope of the monsoon trough and comparing it with the theoretical slope at various isobaric surfaces, a vertical section oriented at an angle of about 12.5 deg. to meridian 80 deg. E at Jabbalpur (23 deg. 10'N 79 deg. 57'E) which is more or less normal to the axis to the monsoon trough at MSL was used as a reference section for collecting data regarding the trough position as well as temperature and wind at MSL and at various isobaric surfaces upto 500 mb. A view of this section is shown by ABC in Fig. 3. Included in Fig. 3 is also a grid with spacing at about 200 km on either side of this reference section, which was used for collecting data of rainfall. Rainfall reporting stations shown in the framework of Fig. 3 were used to give the mean daily rainfall at intervals of roughly one degree of latitude along the reference line ABC. The available number of rainfall-reporting stations within each rectangular strip with the dimension of about 100 km along the reference line and 200 km across varied somewhat along the reference line and it is possible that this variation in the number of reporting stations may have introduced some degree of inhomogeneity in the distribution of rainfall used in the study. But the mean number of stations for each strip was three and this was considered to be fairly adequate to yield a correct representation of the rainfall state over the strip. Because of the presence of high mountains and lack of adequate number of upper-air as well as rainfall reporting stations to the north of the surface position of the monsoon trough, great

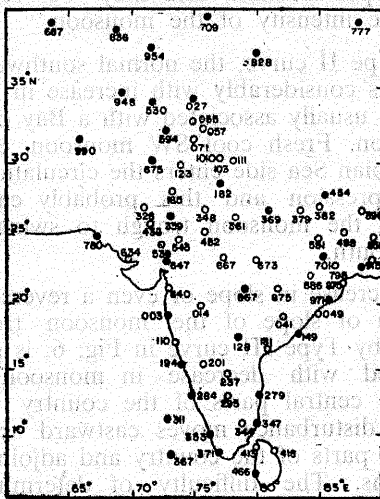


Fig. 4. Map showing pibal and radiosonde stations of India and neighbourhood available during 1977 and used in the study.

● : Radiosonde and ○ : Pibal stations

difficulty was encountered in correctly determining the positions of the trough at different isobaric surfaces as well as the distribution of rainfall over the mountainous region. Pilot balloon and radiosonde stations of India and neighbourhood which were available during July and August 1977 and used in the study are shown in Fig. 4.

3. Slope of the monsoon trough

Comparison of theory with observations

If it is assumed that the monsoon trough behaves like a quasi-stationary surface of discontinuity separating the fresh and cool southwesterly winds in the south from the deflected but somewhat warmer southeasterly winds in the north, the following well-known Margules' equation may be used for computing the approximate slope of the trough in the vertical (Brunt 1941) :

$$\tan \alpha = \frac{2\Omega \sin \phi}{g} \frac{(u_1 - u_2)}{(T_2 - T_1)} \bar{T}$$

where,

- α is the angle of slope of the trough above the ground level in the reference plane,
- Ω is the angular velocity of the earth,
- φ is latitude,
- g is acceleration due to gravity,
- u<sub>1</sub>, u<sub>2</sub> are the zonal components of the winds to the south and the north of the trough, respectively (positive for westerly winds)

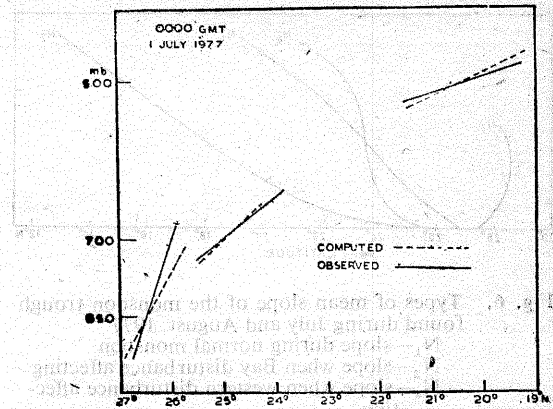


Fig. 5. Comparison of the computed slope with the observed slope of the monsoon trough (00 GMT of 1 July 1977)

T<sub>1</sub>, T<sub>2</sub> are the absolute temperatures to the south and the north of the trough respectively, and

$\bar{T}$  is the mean absolute temperature equal to  $[(T_1 + T_2)/2]$

The foregoing equation is based on the geostrophic balance which may be satisfied to a sufficient degree of approximation in the monsoon trough region. It was used by Sawyer (1947) for the computation of the slope of the intertropical front over NW India during the summer monsoon.

A knowledge of the values of winds and temperatures at stations lying on either side of the axis of the monsoon trough at various isobaric surfaces in the vertical along the reference plane enabled us to compute the daily values of the theoretical slope of the monsoon trough using the given equation. The theoretical slopes so computed were compared with the observed slopes derived from daily trough positions at various isobaric surfaces. The agreement between the two was found to be fairly close. An example of this comparison for the monsoon trough at 00 GMT on 1 July 1977 is shown in Fig. 5.

4. Types of slopes

The locations of the monsoon trough in the reference plane ABC at MSL and the standard isobaric surfaces 850, 700 and 500 mb were plotted on graphs. The cases in which the trough was found to be discontinuous or missing at any of the isobaric surfaces were left out. The plotted curves appeared to fall in a few distinctive groups, each group showing considerable similarity of slopes. For this reason, a mean slope was worked out for each group. These mean curves are designated by N<sub>1</sub>, N<sub>2</sub>, N<sub>3</sub>, and N<sub>4</sub> in Fig. 6. They appear to identify the following types of slopes:

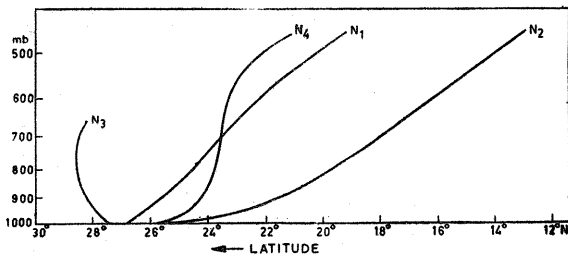


Fig. 6. Types of mean slope of the monsoon trough found during July and August 1977

- $N_1$ —slope during normal monsoon
- $N_2$ —slope when Bay disturbance affecting
- $N_3$ —slope when western disturbance affecting
- $N_4$ —slope under joint influence of a Bay disturbance and western disturbance

#### Type I (Curve $N_1$ )

It represents the normal southward slope of the monsoon trough. From a latitudinal position of about 27 deg. N at MSL, it attains a latitude of about 20 deg. N at 500 mb.

#### Type II (Curve $N_2$ )

In this type, the angle of normal southward slope of the monsoon trough is very much reduced. From a latitudinal position of about 26 deg. N at MSL, it attains a latitude of about 14 deg. N at 500 mb.

#### Type III (Curve $N_3$ )

The normal southward slope of the monsoon trough appears to have reversed towards the north with height in this type. From a latitudinal position of about 27 deg. C at MSL it appears to have attained a latitude of about 28.5 deg. N at 700 mb. As already mentioned, the presence of high mountains and lack of reporting stations of the north prevented determination of the slope at the higher levels.

#### Type IV (Curve $N_4$ )

This type appears to represent a combination between the southward slope of the monsoon trough as represented by the curve  $N_2$  and the northward slope of the monsoon trough as represented by the curve  $N_3$ .

### 5. Variation of slope with intensity of monsoon

In the actual, the slope of the monsoon trough appears to vary sometimes widely from day to day or over short intervals of a few days as the intensity of the monsoon over the central parts of the country varies. However, some standard patterns are noticeable as typified by the curves shown in Fig. 6.

The slope represented by the Type I relates to the case of normal monsoon, undisturbed by any

moving perturbation, and may be related to moderate intensity of the monsoon.

In Type II curve, the normal southward slope decreases considerably with increase in monsoon intensity usually associated with a Bay of Bengal depression. Fresh cool SW monsoon air from the Arabian Sea side enters the circulation of the Bay depression and this probably causes the slope of the monsoon trough to swing further to the south.

An increase in slope or even a reversal of the direction of slope of the monsoon trough as typified by Type III curve in Fig. 6, is generally associated with decrease in monsoon activity over the central parts of the country when a western disturbance moves eastward across the northern parts of the country and adjoining high mountains. The difficulty of determining the slope of the monsoon trough on such occasions with confidence has already been pointed out.

The slope of the monsoon trough appears to be complex when the monsoon activity over the country strengthens under the joint influence of of a Bay depression and a western disturbance. On such occasions, the slope may decrease in the lower layers and increase in the upper layers or *vice-versa*. This is quite apparent from the Curve IV presented in Fig. 6.

The variation in the slope of the monsoon trough with the intensity of the monsoon as found in the present investigation appears to be in general agreement with that found by Thiruvengadathan (1972) who stated: "The position of the axis of the monsoon trough at 3.0 km asl was, on 75 per cent of the strong monsoon conditions, south of Lat. 21 deg. N, while it was on 80 per cent of the weak monsoon conditions, north of Lat. 27 deg. N."

### 6. Relationship with rainfall

Distribution of mean rainfall along the reference plane ABC (see Fig. 3) corresponding to the situation represented by the mean slopes shown in Fig. 6 is presented in Fig. 7 (a)-(d) along with the different types of slopes of the monsoon trough discussed in Section 4. Fig. 7 (a) which shows the case of normal monsoon appears to bring out that with reference to the position of the trough at MSL at about 26.8 deg. N, appreciable amount of rainfall is distributed mainly to the south. Fig. 7(b) shows the distribution of rainfall when a Bay depression affects the central parts of the country. With reference to the position of the monsoon trough at MSL at Lat. 26.2 deg. N, rainfall is distributed further to the south and, to some extent, also to the north in this case than in Fig. 7(a). Fig. 7 (c) shows the distribution of rainfall in the case of a western disturbance when the monsoon trough appears to slope northward with height

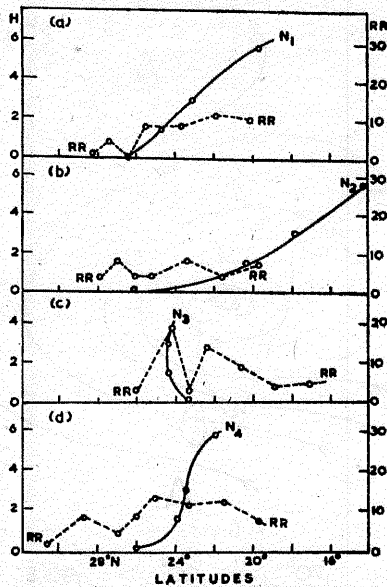


Fig. 7. Distribution of rainfall along ABC, associated with different types of mean slope of the monsoon trough (H is height in km above MSL and RR is rainfall in mm)

in the lower troposphere. With the trough position at MSL at about Lat. 27.5 deg. N, rainfall appears to have extended more to the northern parts of the country, although some amounts of monsoon rainfall continues in the south. Fig. 7 (d) shows the distribution of mean rainfall when the slope of the monsoon trough exhibits a complex structure under the joint influence of a Bay depression and a western disturbance. It is evident that rainfall is now equitably distributed both to the south and the north of the surface position of the trough.

#### 7. Synoptic Interpretation of findings

For proper interpretation of the patterns of slope of the monsoon trough and rainfall associated with them, found in the present investigation, it appears necessary to identify the specific type of synoptic situations which may give rise to them. This is all the more necessary in view of the fact that the monsoon trough over India frequently comes under the disturbing influences of the Bay of Bengal depressions in the south and the western disturbances in the north. When such a disturbance enters the Indian region, there is readjustment of the location of the trough leading to changes in its slope and rainfall associated with it. In the case of a Bay disturbance, the SW monsoon air that is drawn into its circulation from the Arabian Sea is fresh and cool with the result that the temperature of the airmass to the south of the monsoon trough drops, leading to a decrease in the slope of the trough and a southward extension

in the distribution of rainfall in this case. In the case of a western disturbance, warm and cold airmass sectors associated with it move successively from west to east across the northern parts of India and their effects on the slope of the monsoon trough may be visualised as follows:

When the warm sector associated with the western disturbance appears in the north, its net effect may be to increase the temperature of the airmass to the north of the monsoon trough and thereby cause a decrease in the normal southward slope of the trough and an extension of the rain-belt further to the south of the surface position of the trough. In the wake of the warm sector when the cold sector arrives, there is a marked drop in air temperature to the north of the monsoon trough (Ananthkrishnan 1950) which may cause, depending upon the relative value of this temperature in comparison with the air temperature to the south of the monsoon trough, either a sharp increase or a reversal of the slope of the monsoon trough. There are occasions when a Bay disturbance which may take the form of an upper-air cyclonic circulation or a surface low, depression or cyclonic storm and a western disturbance exist simultaneously over India. A basic question that may be asked is what happens to the monsoon trough on such occasions? Although in the mean, a complex single trough may be found in some cases, as shown in Fig. 6 (Curve  $N_3$ ), observations appear to show that two distinct troughs may often appear on such occasions, one in the north and the other in the south. However, further elucidation of this apparent splitting or displacement of the monsoon trough under the joint influence of a Bay disturbance and a western disturbance is at present well-nigh impossible in the absence of an adequate network of upper-air reporting stations especially in the north.

Mean flow patterns at about 700 mb relevant to the synoptic situations discussed above are presented schematically in Fig. 8 (a)-(d). These diagrams are self-explanatory.

The above interpretations of the different types of slopes of the mean monsoon trough in possible association with different types of synoptic situations must, however, be treated as somewhat speculative at present.

Much more surface and aerological data that are available today especially to the north of the trough are required for a more detailed examination of the problem.

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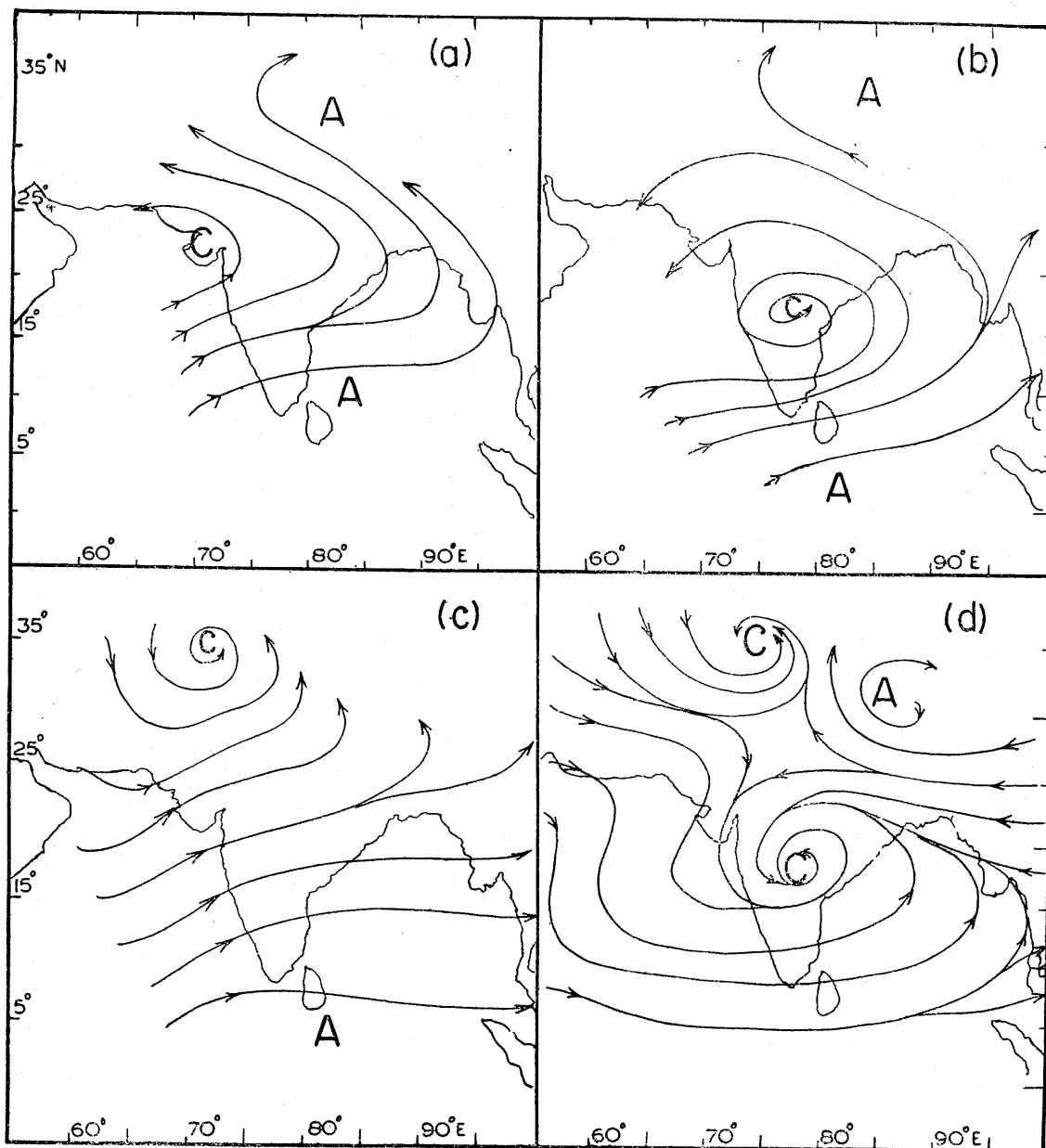


Fig. 8. Schematic diagrams showing approximate mean flow patterns at 700 mb associated with (a) a normal monsoon situation; (b) a Bay depression affecting central India; (c) a western disturbance affecting northern India and (d) a Bay depression and a western disturbance jointly affecting India. C—Cyclonic, A—Anticyclonic

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