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LOCAL FALLOUT OF RADIOACTIVE DEBRIS FROM NUCLEAR EXPLOSION IN A MONSOON ATMOSPHERE

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Abstract

For a hypothetical megaton-yield near-surface nuclear explosion, local fallout patterns with reference to four principal cities in India are computed using mean wind data over these cities during both winter and summer monsoon months when there is a reversal of wind direction with height over a large part of India. The mushroom-shaped debris cloud with a horizontal diameter of about 32 kms and vertical depth of about 10 kms is assumed to contain bulk of the fission radioactivity and stabilise at a mean altitude of about 21 kms a.s.l. and the fallout of particles of various sizes ranging from 500 μ to 40 μ is assumed to commence from this altitude approximately 10 minutes after the time of detonation. Time and space variations of mean wind in different layers are neglected and a horizontal eddy diffusivity co-efficient of $1.0 \times 10^4 \ m^2 s^{-1}$ is assumed for all particle sizes. Computed fallout patterns with activity at different distances downwind expressed as whole-body gamma dosage (roentgens/hr) are presented in map form for alternate months of the year. Regional and seasonal variations are discussed.

1. Introduction

On explosion at or near the earth's surface, a megaton-yield nuclear bomb produces an intense fireball with a cloud ring associated with it, which rises and expands rapidly to produce a huge mushroom-shaped debris cloud in the upper atmosphere. It is estimated that the debris cloud of a 1-megaton bomb stabilises at a mean altitude of about 21 kms with a horizontal diameter of about 32 kms and vertical extent of about 10 kms in a period of about 10 minutes from the time of detonation (Kellogg, Rapp, and Greenfield, 1957). Depending upon the bomb-yield, height of burst above surface, and terrain conditions, the content of the bomb and the earth material that is drawn into the fireball are pulverised under the intense heat released by the bomb and the particles inside the debris cloud are more or less homogeneously mixed and have sizes ranging from a few microns to a few millimeters in diameter. Largest and heaviest particles ($> 500\,\mu$ in diameter) would no doubt start falling under gravity even before the stage of stabilisation of the cloud but it may be assumed that particles smaller than this limiting size would commence descent only after the cloud has stabilised. Local fallout consists of particles which descend to the earth's surface within a period of about 24 hours from the time of detonation. Particles reaching the earth's surface later constitute global or worldwide fallout. It is estimated that the debris cloud of an average surface or near-surface burst contains about 90% of the total radio-activity resulting from the fission process (the remaining 10% being contained in the stem) and this radioactivity is distributed among the debris particles. However, there is little authentic information about the spectral distribution of radioactivity among particle sizes. An estimated percentage distribution, adapted from USAEC (1964) is shown in Fig.1. It may be seen that percentage radioactivity carried by very large and very small particles is smaller than that carried by particles in the size range, $40\mu - 80\mu$. However, since radioactivity is subject to time decay, larger particles despite their smaller percentage of initial radioactivity carry a larger amount of radioactivity to earth's surface than smaller particles which require longer time to reach the earth's surface and hence undergo greater decay.

2. Method of computation

During descent, the radioactive particles are affected by prevailing wind distribution and arrive at distances from ground-zero which depend upon the rates of fall through the different layers and the strength and direction of the horizontal wind. In falling through the different layers of the atmosphere, they may be affected by different winds but it is the vertically integrated resultant wind that determines the direction and distance of the fallout. If $W(h, r)$ is the mean fall velocity of a particle of radius r in a layer of thickness Δh and $\vec{V}(h)$ is the mean horizontal wind vector in the same layer, the horizontal vector displacement $\vec{D}(h_i, r)$ of the particle from ground-zero is given by

$$\vec{D}(h_i, r) = \sum_{h=0}^{h=h_i} \frac{\Delta h}{W(h, r)} \vec{V}(h) \qquad (1)$$

where h_i is the mean altitude of stabilisation of the debris cloud. Further, there is likely to be lateral diffusion of the particles during descent due to unsteadiness of wind that may be present in an actual case. A measure of the lateral dispersion may be given by the approximate relation $y^2 = 2Kt$, where y is radial gain, K is co-efficient of eddy diffusion and t is the total time of fall.

Equation (1) shows that the computation of horizontal displacement of falling particles from ground-zero involves a knowledge of the velocity of fall of particles and the horizontal winds in individual layers between the height of stabilisation of the debris cloud and the earth's surface. For particles of radii greater than 10 the terminal velocity of fall is given by the aerodynamical relation :

$$W = \left(\frac{4\, r g \rho'}{3 k \rho}\right)^{1/2} \qquad (2)$$

where W is fall velocity, r and ρ' are respectively radius and density of the particle, k is coefficient of aerodynamic resistance, ρ is air density and g is acceleration due to gravity. Equation (2) shows that the fall velocity is directly proportional to the square root of the radius of the particle and inversely proportional to the square root of air density. Kellogg, Rapp and Greenfield (1957) have computed values of fall velocities for different particle radii and air densities at different heights in the atmosphere and these were used in the present study. The computation is based on the following assumptions :-

(i) Each megaton of fission-yield produces 3×10^{11} curies of radioactive fission products, measured at 1 hr. The fission products decay at the rate of $t^{-1.2}$ (approx.), where t is time in hours measured from burst time.

(ii) The fallout consists of spherical particles with density 2.5 gm/c.c.

(iii) Particles of all sizes are homogenously mixed in the debris cloud.

(iv) The monthly mean resultant wind at a particular standard pressure level is constant in the layer between that level and the next lower level.

(v) A constant mean horizontal diffusivity of 10^4 m^2 s^{-1} is assumed for the whole atmosphere.

(vi) Vertical eddy diffusion is assumed to be small in comparison with horizontal diffusion.

(vii) There is no scavenging by rain.

(viii) The effect of topography is ignored.

3. Data and computation

The object of the present paper is to compute mean patterns of local fallout from hypothetical megaton-yield nuclear explosions at four selected Indian stations in different months of the year. The selected stations are Delhi and Calcutta in northern India and Bombay and Madras in southern India. There is no particular reason behind this choice of stations except that contrasting features of vertical wind distribution between northern and southern Indian stations in the matter of characteristic reversal of direction with height due to monsoons are, perhaps, well brought out by the choice, although Calcutta may often fail in this criterion.

Wind data in the form of mean monthly resultant winds upto about 16 km a.s.l. were taken from a publication by Raman and Dixit (1964) and monthly mean directions and velocities for levels 16.2 km and above from an unpublished manuscript of the India Meteorological Department. Fig.2 shows the vertical distribution of the zonal component of the mean resultant winds at the four selected stations during January and July, which are representative months of winter and summer monsoons respectively. It shows the typical reversal of wind direction with height in the monsoon atmosphere of southern India stations particularly during the summer monsoon. For lack of space, wind distributions for other months of the year are not presented. However, it may be stated that during the transition months between the main monsoon seasons, the horizontal winds become very light. Local fallout is computed in the present paper using the above wind data in the cases of particles of different sizes which leave the debris cloud at an altitude of 21 kms a.s.l. in a circular area of radius 16.2 kms, approximately 10 minutes after the time of detonation. Each circular area containing particles of a particular size is displaced horizontally by the prevailing winds as it falls and also undergoes slight horizontal expansion due to lateral diffusion before it reaches the earth's surface. Areas containing particles of different sizes thus arrive at different locations away from ground-zero. The envelope of these circular areas at the earth's surface constitutes the fallout patterns.

4. Results

Table I gives the computed details of local fallout in the case of a 1-megaton surface burst.

Fig. 3-8 show mean monthly fallout patterns for particles of different sizes computed for the four selected Indian stations during January, March, May, July, September and November in the case of 1 -mT fission-bomb explosion. The circular area for each class of particles in these diagrams marks the outer boundary of the fallout pattern for that class as given in Table-I. In all diagrams the Class-I particles with radius 40 μ form the outermost boundary arc and Class-IX particles with radius 500 μ the innermost boundary arc. The resultant pattern of fallout for particles of all the sizes is obtained by drawing the tangential envelope of all the circular arcs. The whole body gamma

Table I : Details of local fallout in the case of a 1-megation surface burst

($K = 10^4\ m^2\ s^{-1}$)

Class	Particle size (microns)	Time of fall (hours)	Fallout area ($10^8\ m^2$)	Whole body gamma dosage (Roentgens/hr)
IX	500	0.58	95	1500
VIII	400	0.72	121	
VII	300	0.88	137	
VI	200	1.28	196	
V	150	1.77	211	300
IV	100	2.95	416	100
III	80	3.90	531	80
II	60	6.25	835	40
I	40	11.77	1780	15

dosage, in Roentgens per day, associated with the fallout is given in the last column of Table-I. Such fallout patterns were computed for all the months of the year but for lack of space, those for alternate months only are presented. The monthly patterns would appear to show the following general features at the four stations :-

January

January marks the peak winter conditions over the Indian subcontinent. The fallout distances and patterns for New Delhi, Bombay and Calcutta appear to be largely determined by the strong westerly wind regime shown in Fig.2.

The debris particles of all sizes are rapidly displaced in a direction slightly north of east and the lightest particle of 40 μ size reach the surface at a distance of about 1400 km in the case of Delhi, 1500 kms in the case of Calcutta and 1200 kms in the case of Bombay. At Madras a shallow layer of light easterly wind is overlain by a slightly deeper layer of westerly wind. The resultant effect on the fallout pattern is that the particles are displaced to the east and the lightest particle of 40 μ size reach the surface at a distance of about 300 kms. The January fallout patterns appear to show that radioactive dosage reaching the earth's surface in size range smaller than about 200 μ are widely dispersed in the cases of Delhi, Calcutta and Bombay, whereas it remains rather concentrated near the point of explosion in the case of Madras.

March

The fallout patterns during March are very similar to those during January. However, the westerly wind regime is somewhat weaker, with the result that the eastward displacement of the debris particles is somewhat smaller at all the stations. The smallest particles of size 40 μ reach the earth's surface at a distance of 1000 kms from Delhi, 1300 kms from Calcutta, 1000 kms from Bombay and about 250 kms from Madras. There is considerable superposition of radioactivity in size ranges larger than 150 μ in the cases of Delhi, Calcutta and Bombay whereas in the case of Madras maximum concentration obtains near the station in all size ranges except the smallest 40 μ.

May

The fallout patterns show eastward displacement of particles, though to a much lesser extent than during January and March, in the cases of Delhi and

Calcutta. The pattern at Bombay shows displacement in a northeasterly direction. The pattern at Madras shows a westward displacement.

The May patterns show that radioactive dosage from local fallout is much more concentrated near the points of explosion in all size ranges except the smallest 40 μ than during the winter months.

July

July signifies the peak summer monsoon condition over the Indian subcontinent. There is dramatic change in the fallout pattern during this month in that the displacements are westward at all the stations. Maximum westward displacements are found at Calcutta and Bombay. Fig.2 shows that during July the vertical distribution of wind consists of a layer of westrly below and easterly above. Westerlies are strong and extend up to a height of about 6-8 kms at Madras and Bombay, whereas they are weak and have much smaller depth at Calcutta and Delhi. The easterlies aloft are strong with a mean maximum of about 40 m.p.s. at about 14 kms a.s.l. at Madras, Calcutta and Bombay but weak at Delhi. The July fallout patterns would seem to indicate a rather high concentration of radioactive dosage at and near the stations particularly at Delhi. At Bombay the pattern extends out to Arabian sea, the smallest particle of size 40 μ reaching a distance of about 700 kms from the station. At Madras the pattern extends towards Mangalore on the west coast. The pattern at Calcutta extends to a distance of about 700 kms in the direction of Bhopal.

September

The fallout patterns at Bombay, Calcutta and Madras during September are very similar to those during July in that displacements continue to be

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westward under the summer monsoon wind regime, although the actual displacements at Bombay and Calcutta are considerably less and at Madras somewhat more than during July. There is, however, a marked change in the fallout pattern at Delhi, the displacement being northeastward during September instead of westward during July. This change is due to the fact that there is a reversal of upper wind during September consequent upon the withdrawal of easterly monsoon from Delhi.

The radioactive does rates are high during September at and near all the stations due to considerable super-position of fallout particles of larger sizes.

November

November marks the transition between the summer and the winter monsoon seasons.

The fallout patterns are similar to those during May, although the eastward displacements at Delhi and Calcutta are much greater. The displacement at Bombay is greater and in a more easterly direction than during May. The displacement at Madras is somewhat less and slightly more north of west than during May. There is considerable superposition of radioactive dosage at Delhi and Calcutta in size ranges larger than 150 μ . The limit is brought down to 80 μ in the cases of both Bombay and Madras.

5. Discussion : Limitations and possibilities

There are several limitations of the present study which must be pointed out. These arise mostly from our ignorance of authentic information of explosion details especially the altitude and diameter of the debris cloud and the spectral distribution of fission radioactivity amongst the debris particles. The velocity of fall for particles of various sizes may be treated as very approximate and since the horizontal displacement of particles depends, inter alia, upon this parameter, the computed fallout distances must be looked upon as very rough estimates. The wind data used in the computation are mean values for a few years and may not obtain in an actual situation. The diffusion of particles during fall has been taken into account by using a constant diffusion coefficient of 10^4 m^2 s^{-1}. Although airborne measurements of atomic debris suggest a lateral diffusion coefficient of about 10^4 m^2 s^{-1} at km a.s.l. (Machta et al, 1957), it is possible that the diffusion coefficient may be different at different altitudes and speed ranges and between the westerlies and the easterlies. An accurate estimate of fallout distances and patterns is only possible when wind information at different heights during different stages of fall is available. Finally, the computed fallout dosage is based on the assumption that the debris particles commence falling from the mushroom cloud all at the same time approximately 10 minutes from the time of detonation. The actual times at which fallout commences may be quite different. Since local fallout encompasses fallout of all particles within the first 24 hours, it is probable that fallout occurs in different phases during the movement of the debris cloud by the prevailing winds. It is also highly probable that radioactive dosage brought down by fallout in areas of excessive monsoon rain may be quite different from what has been indicated in the present paper.

Despite the above mentioned limitations, the usefulness of a study of the kind here undertaken should also be indicated. It is well known that

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climatological winds are fairly steady over most regions of the monsoon. Hence computations carried out with these winds are likely to reflect the gross fallout features that may be anticipated in an actual situation. In fact, it was this point of view that inspired the present study. Accurate forecast of fallout in any eventuality will no doubt require accurate forecast of winds. But climatological winds may give us the first order approximation to the fallout patterns that may be expected. For purposes of civil defence against possible nuclear attacks, a knowledge of fallout patterns based on climatological wind information can, indeed, be of great help.

6. Conclusion

Based on assumptions that the debris cloud of a 1 megaton nuclear explosion stabilises at an altitude of about 21 km a.s.l. approximately 10 minutes after detonation and using climatological wind information the paper computes the local fallout patterns likely to be obtained at four principal cities in India during the monsoon seasons when there is reversal of wind with height at most of the Indian stations. It is concluded that although such fallout information is useful for purposes of planning of civil defences, fallout patterns likely to occur in an actual situation should be computed on the basis of accurate wind forecasts.

REFERENCES

Kellogg, W.W., Rapp, R.R. and Greenfield, S.M.	1957	Close-in fallout. J.Met., 14, pp.1-8
Machta, L. et al	1957	Airborne measurements of atomic debris. J.Met., 14, pp.165-175
Raman, C.R.V. and Dixit C.M.	1964	Analyses of monthly mean resultant winds for standard pressure levels over the Indian ocean and adjoining continental areas (part II). India Meteorological Dept. International Meteorological Center, Bombay
USAEC	1964	The effects of nuclear weapons (Ed. S.Glasstone). U.S.Dept. of Defence and U.S.Atomic Energy Commission, (Revised edition).

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IITM/ROMAYOR/SGG/1972.

Legends of diagrams

1. Percentage distribution of total fission-radioactivity among different particle sizes (microns).

2. Distribution of the Zonal component of monthly mean resultant winds with height at New Delhi, Bombay, Calcutta and Madras during January and July.

3. Local fallout patterns at the four selected stations during January. In each pattern, the small circular arcs marked I, II, III, etc. refer to outer boundaries of particles of different sizes (see Table I).

4. Same as Fig. 3, March.

5. Same as Fig. 3, May.

6. Same as Fig. 3, July.

7. Same as Fig. 3, September.

8. Same as Fig. 3, November.

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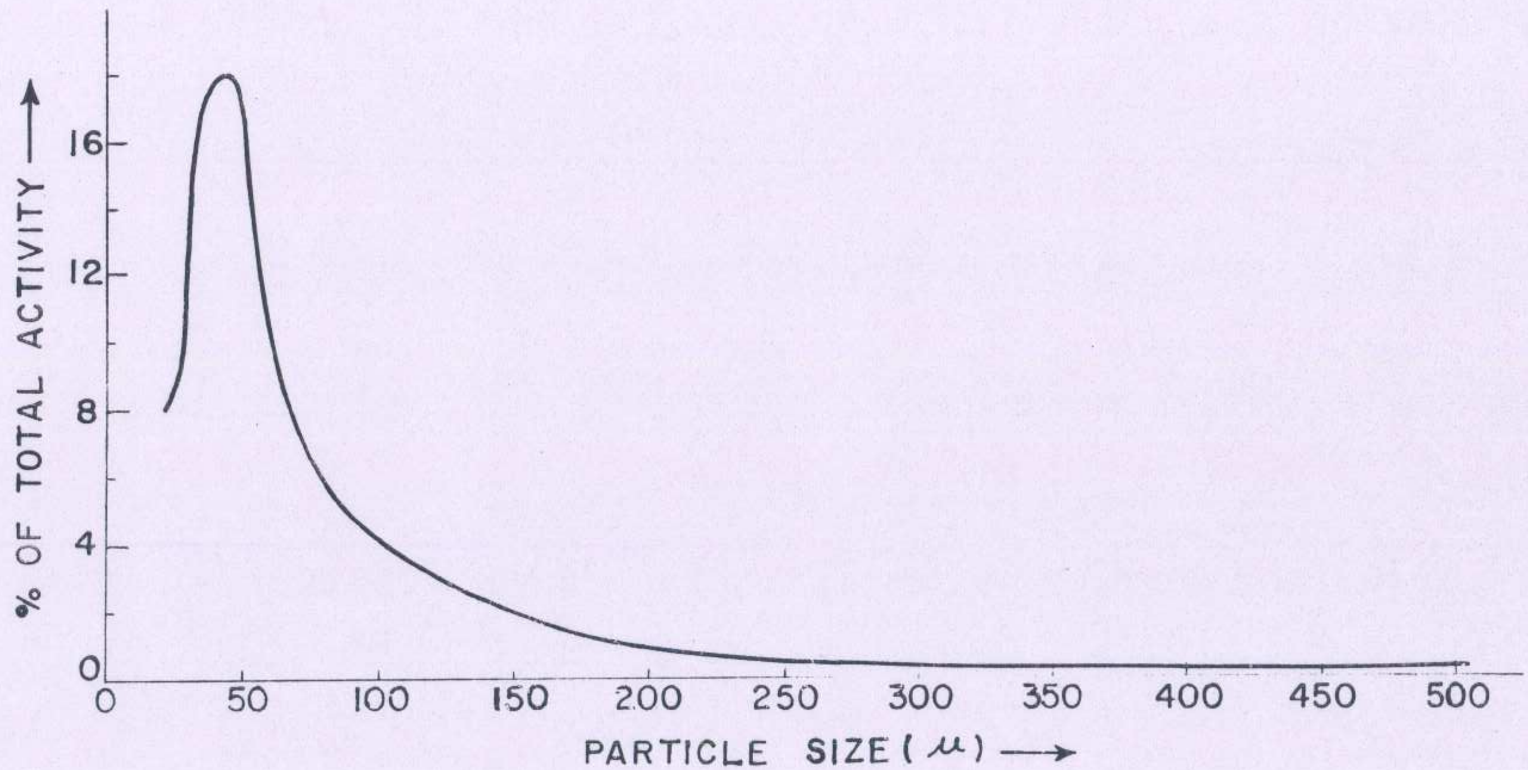

% OF TOTAL ACTIVITY
0
4
8
12
16
0
50
100
150
200
250
300
350
400
450
500
PARTICLE SIZE (μ)

FIG. I

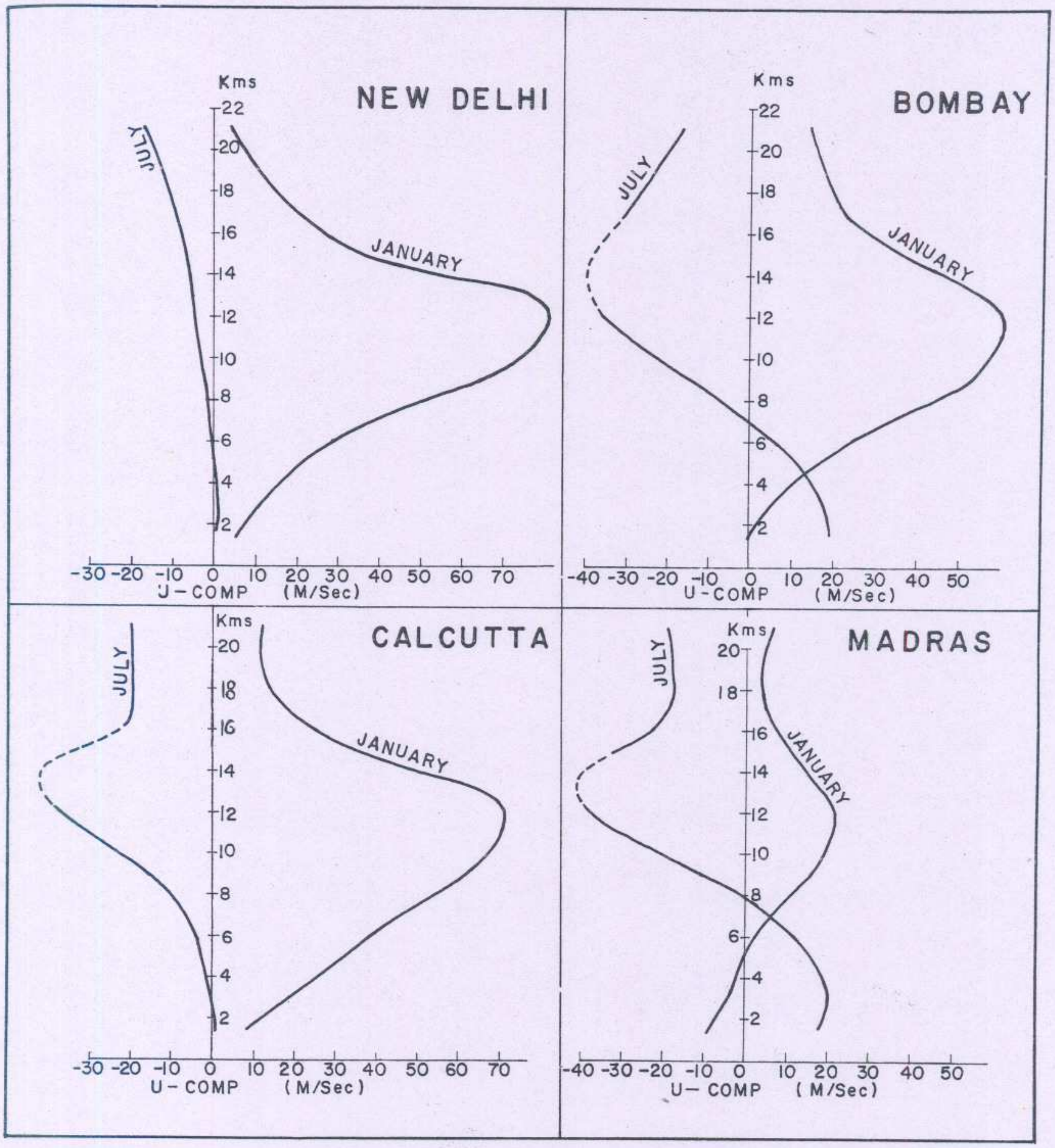

NEW DELHI
BOMBAY
CALCUTTA
MADRAS
Kms
JULY
JANUARY
U-COMP (M/Sec)

FIG. 2

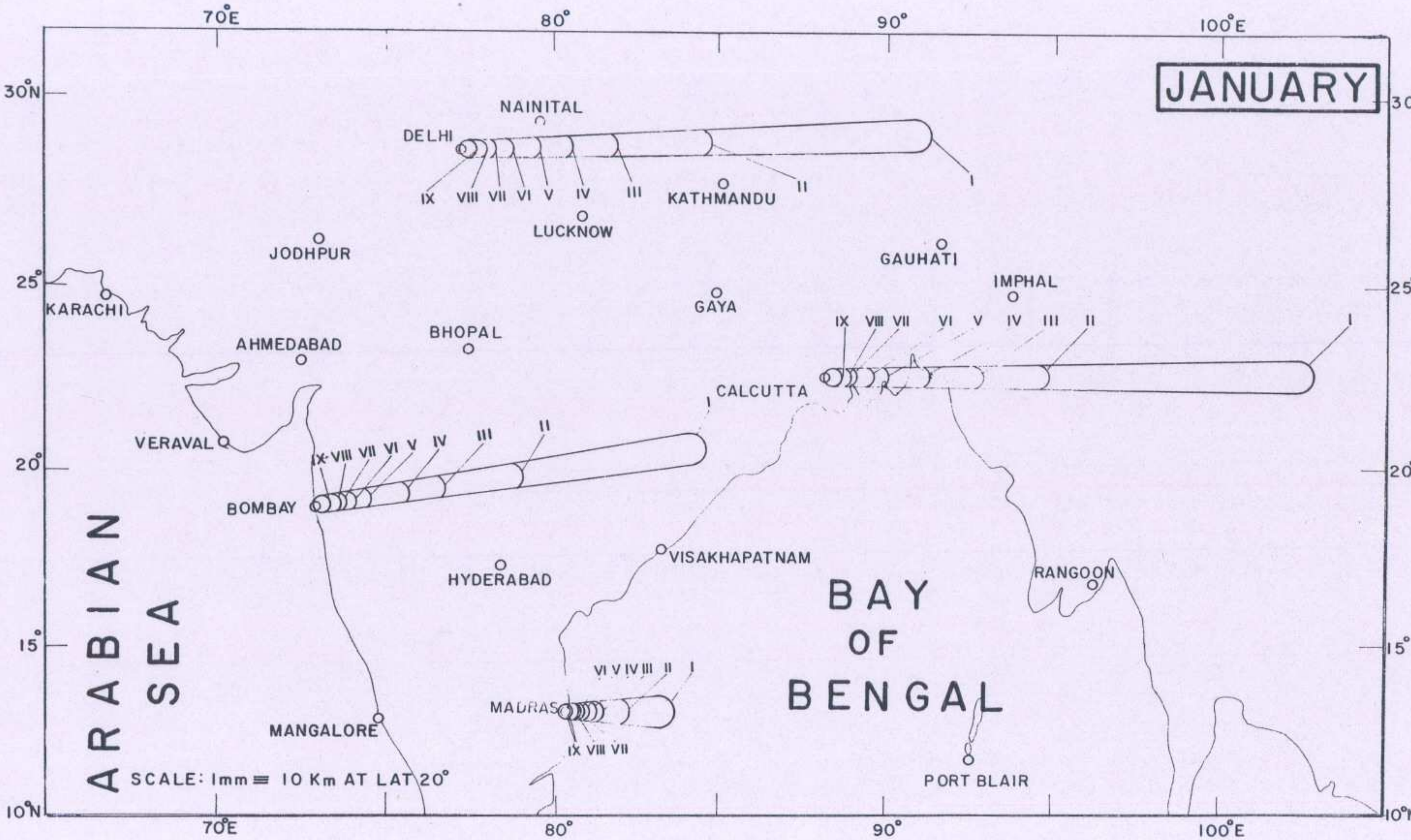

JANUARY
70°E
80°
90°
100°E
30°N
25°
20°
15°
10°N
NAINITAL
DELHI
IX VIII VII VI V IV III II I
KATHMANDU
LUCKNOW
JODHPUR
GAUHATI
IMPHAL
KARACHI
GAYA
AHMEDABAD
BHOPAL
CALCUTTA
VERAVAL
BOMBAY
VISAKHAPATNAM
HYDERABAD
RANGOON
BAY
OF
BENGAL
ARABIAN
SEA
MADRAS
MANGALORE
PORT BLAIR
SCALE: 1mm ≡ 10 Km AT LAT 20°

FIG. 3

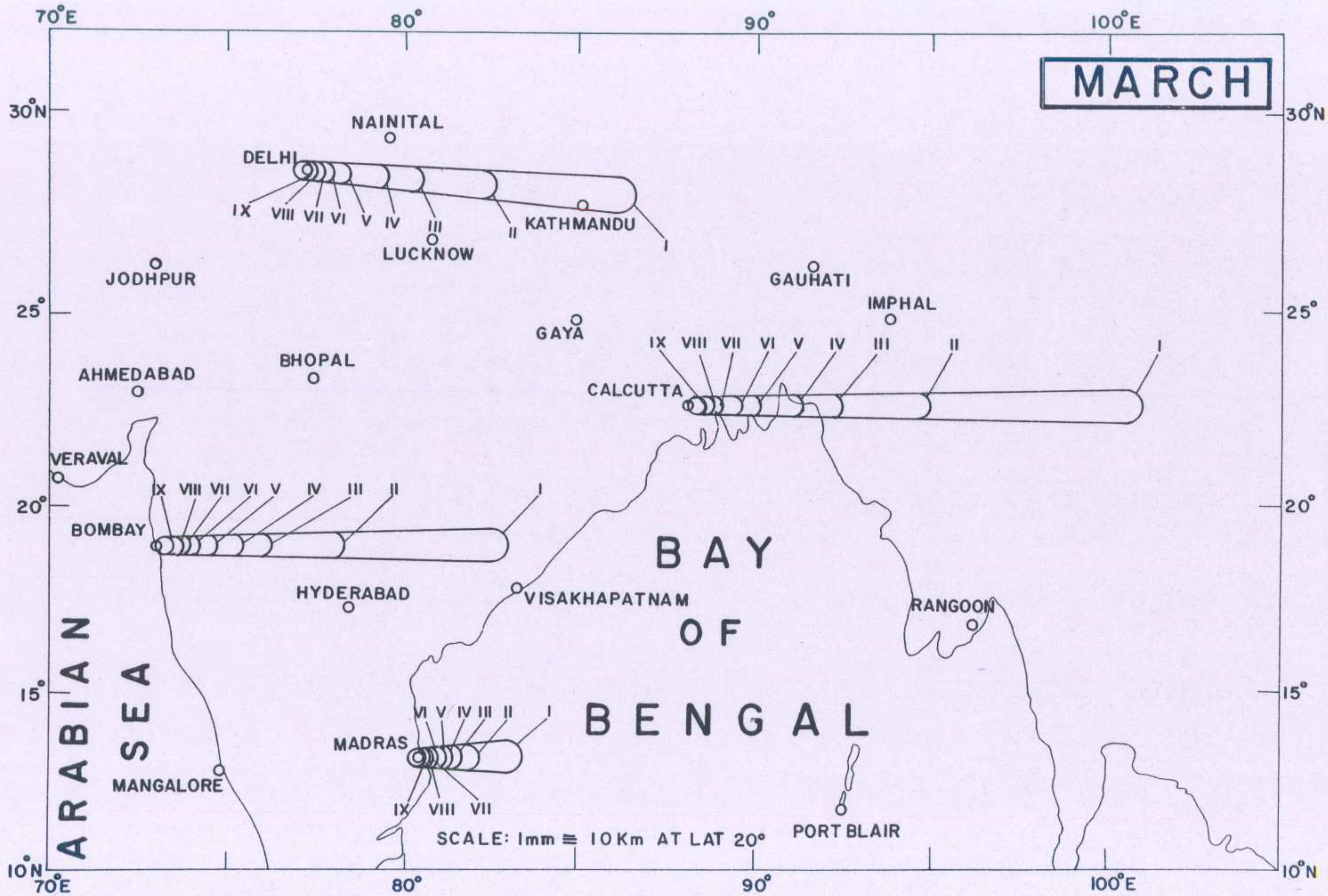

MARCH
70°E
80°
90°
100°E
30°N
25°
20°
15°
10°N
NAINITAL
DELHI
KATHMANDU
LUCKNOW
JODHPUR
GAUHATI
IMPHAL
GAYA
BHOPAL
AHMEDABAD
CALCUTTA
VERAVAL
BOMBAY
HYDERABAD
VISAKHAPATNAM
RANGOON
MADRAS
MANGALORE
PORT BLAIR
ARABIAN SEA
BAY OF BENGAL
I
II
III
IV
V
VI
VII
VIII
IX
SCALE: 1mm ≡ 10Km AT LAT 20°

FIG. 4

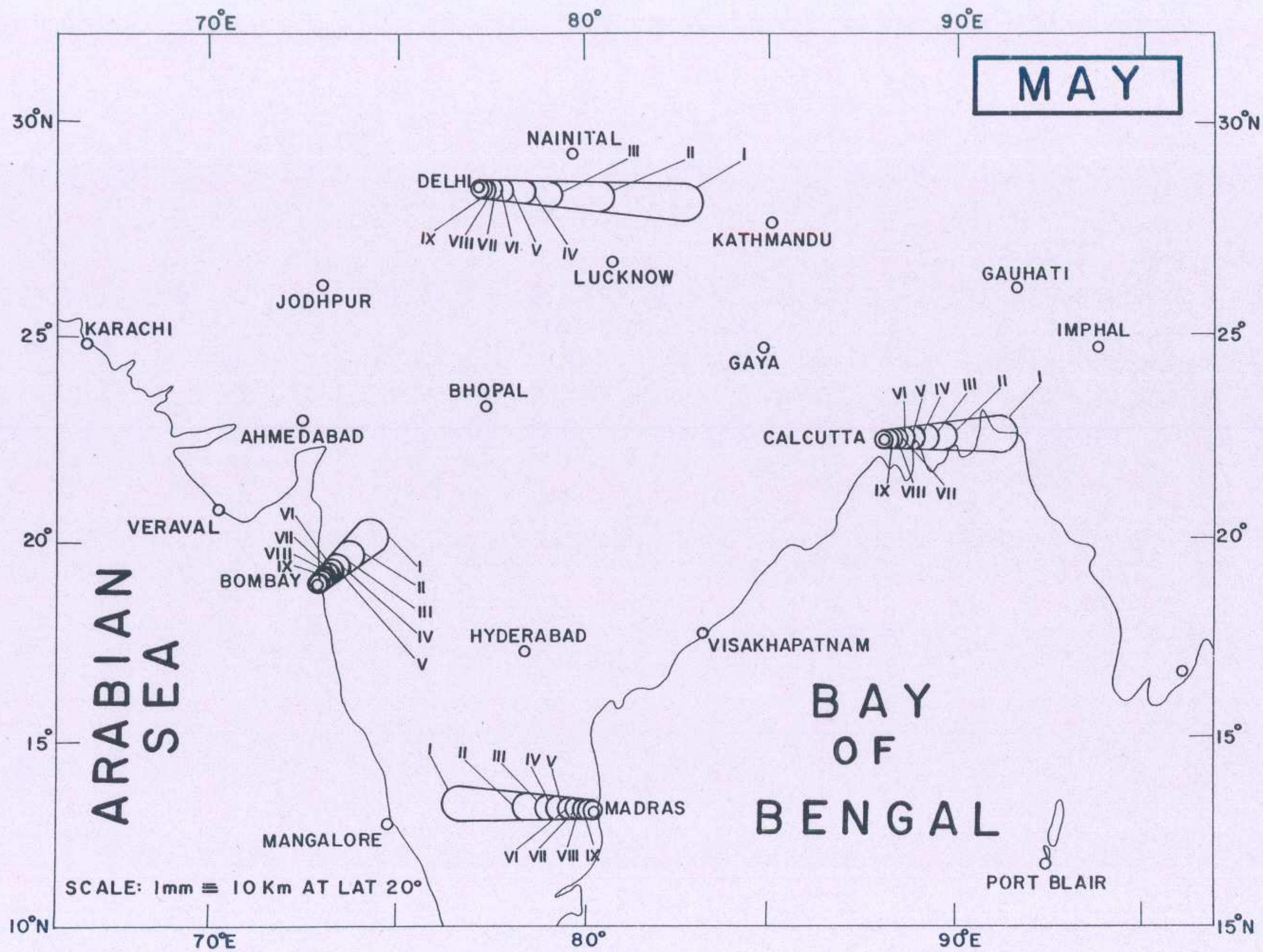
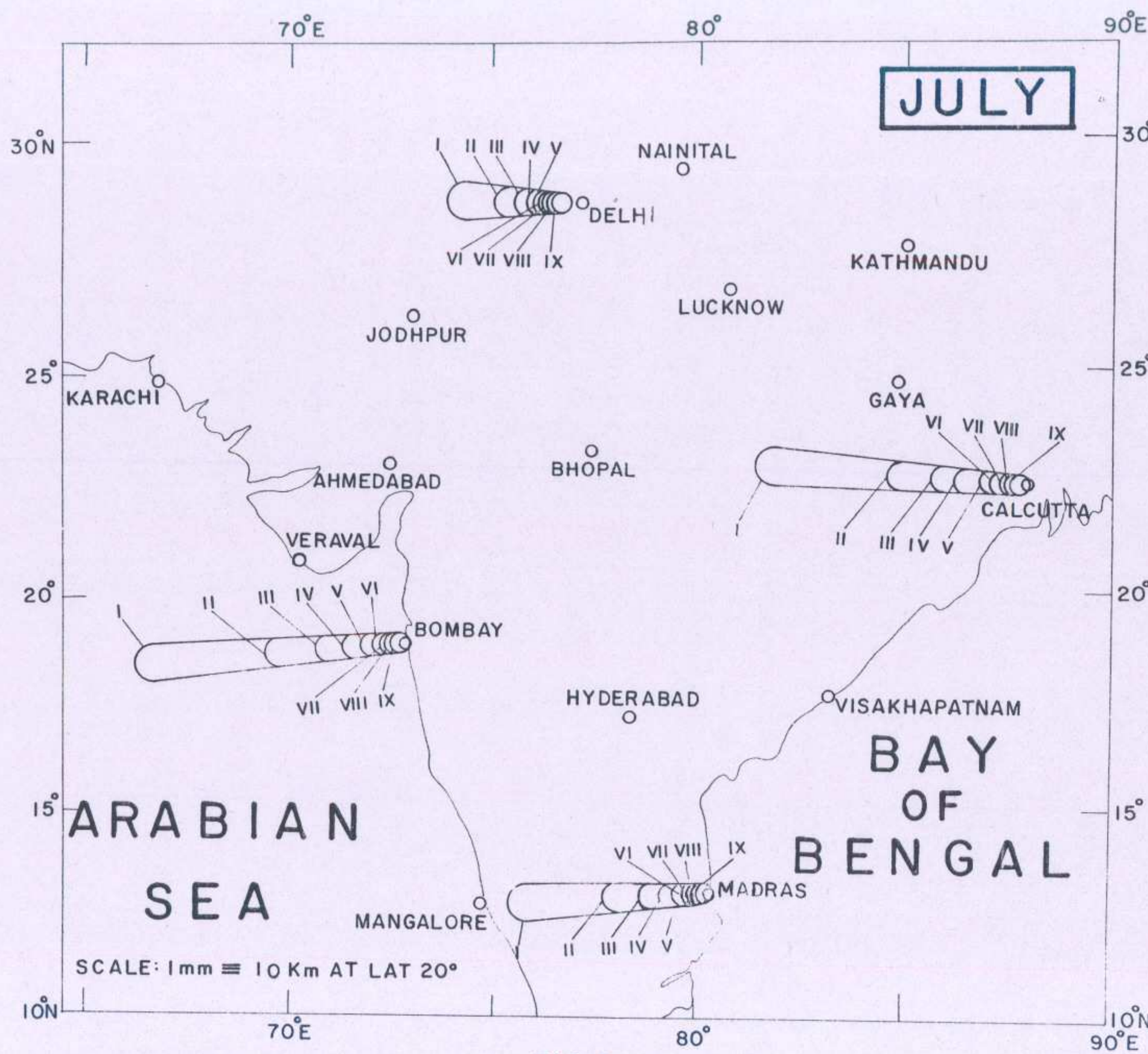

MAY
70°E
80°
90°E
30°N
25°
20°
15°
10°N
15°N
NAINITAL
DELHI
KATHMANDU
LUCKNOW
GAUHATI
JODHPUR
KARACHI
IMPHAL
GAYA
BHOPAL
CALCUTTA
AHMEDABAD
VERAVAL
BOMBAY
HYDERABAD
VISAKHAPATNAM
ARABIAN SEA
BAY OF BENGAL
MADRAS
MANGALORE
PORT BLAIR
SCALE: 1mm ≡ 10 Km AT LAT 20°

FIG. 5


JULY
70°E
80°
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25°
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NAINITAL
DELHI
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CALCUTTA
VERAVAL
BOMBAY
HYDERABAD
VISAKHAPATNAM
BAY
OF
BENGAL
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SEA
MADRAS
MANGALORE
I II III IV V VI VII VIII IX
SCALE: 1mm ≡ 10 Km AT LAT 20°

FIG. 6

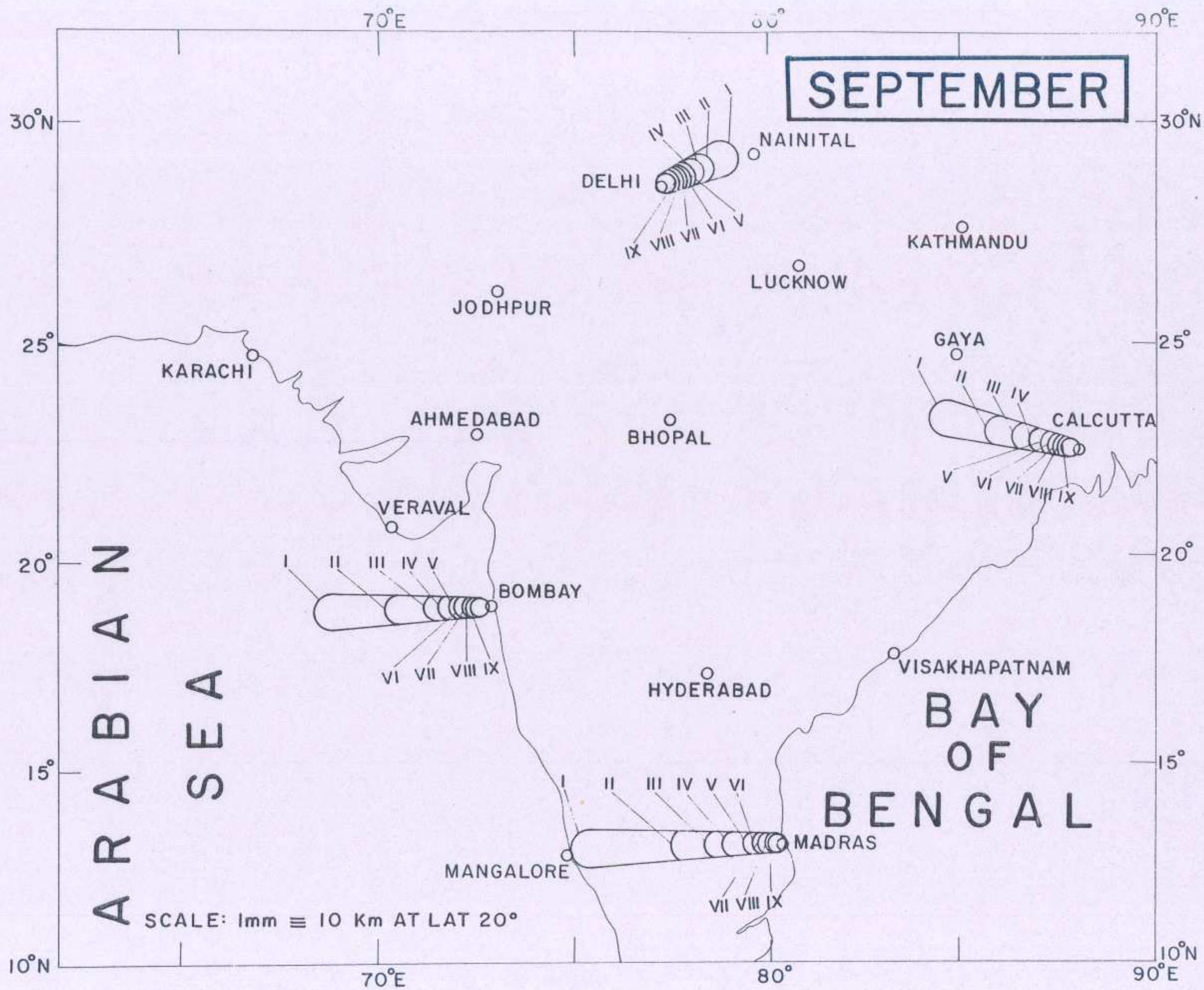
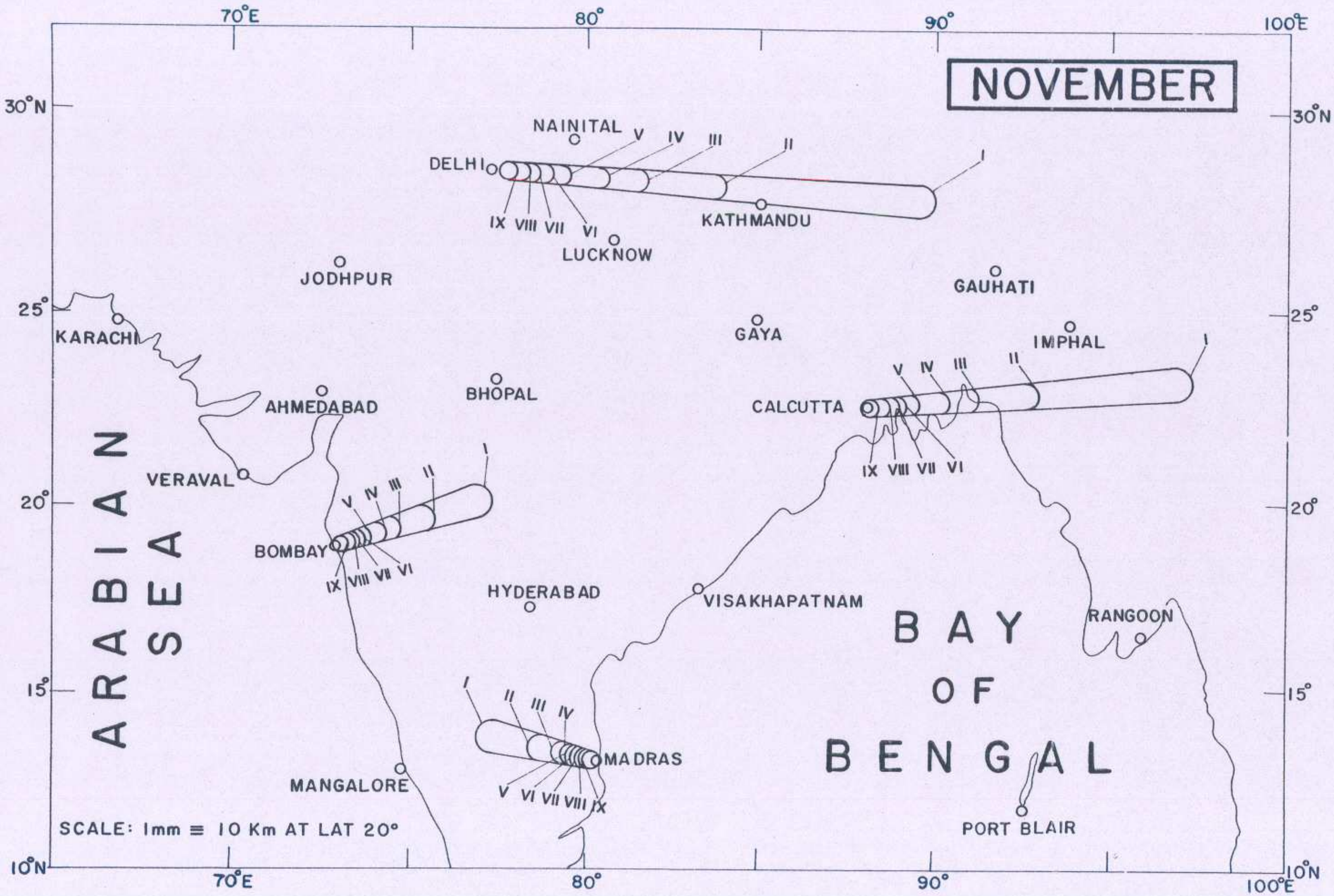

SEPTEMBER
70°E
80°
90°E
30°N
25°
20°
15°
10°N
NAINITAL
DELHI
KATHMANDU
LUCKNOW
JODHPUR
GAYA
KARACHI
AHMEDABAD
BHOPAL
CALCUTTA
VERAVAL
BOMBAY
VISAKHAPATNAM
HYDERABAD
MADRAS
MANGALORE
ARABIAN SEA
BAY OF BENGAL
I II III IV V VI VII VIII IX
SCALE: Imm ≡ 10 Km AT LAT 20°

FIG. 7


NOVEMBER
70°E
80°
90°
100°E
30°N
25°
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15°
10°N
NAINITAL
DELHI
KATHMANDU
LUCKNOW
JODHPUR
GAUHATI
GAYA
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AHMEDABAD
BHOPAL
CALCUTTA
VERAVAL
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HYDERABAD
VISAKHAPATNAM
RANGOON
MADRAS
MANGALORE
PORT BLAIR
ARABIAN SEA
BAY OF BENGAL
I II III IV V VI VII VIII IX
SCALE: 1mm ≡ 10 Km AT LAT 20°

FIG. 8