

# Influence of orography on the upper winds over Mussooree

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**ABSTRACT.** The influence of the orographic features at Mussooree on the upper winds in the lower levels of the atmosphere has been examined in this paper, analysing the data of 561 pilot balloon ascents during the period, May 1950 to June 1955. It has been found that the influence of orography on the upper winds at Mussooree extends to about 30,000 ft a.s.l. resulting in appreciable reduction of the wind speed on a large number of occasions. The frequencies of appreciable velocity reduction at various levels for winds blowing from different directions are presented and discussed. The data studied in this paper support the present theoretical concepts regarding some of the features of "standing waves".

## 1. Introduction

A pilot balloon observatory functioned at Mussooree Lat.  $30^{\circ}27' N$ , Long.  $78^{\circ}05' E$  occasionally since 1950 to observe the upper winds for issuing special weather forecasts for various Himalayan expeditions including the famous British Mt. Everest Expedition of 1953. The upper wind data collected showed a very high frequency of occasions of velocity reduction at some intermediate levels of the atmosphere upto 3 Km. This anomaly was seen in the shape of a sudden dip in the velocity curve in the lower levels after an initial increase, as illustrated by the typical height-velocity curves reproduced in Fig. 1. This peculiarity could not be ascribed to non-uniformity in the rate of vertical ascent of the balloon as this rate is a function of the buoyancy of the balloon due to density contrast. It, therefore, appeared that this anomalous distribution of the wind velocity is due to the orography of the place. An attempt is made in this paper to present an analysis of the data and to advance arguments in favour of the orography being responsible for this peculiarity.

## 2. Topography

In Fig. 2 is shown a contour map of Mussooree and its neighbourhood. As will be clear from it, a long range of hills stretching north-south between the gorges of the Jumna on the west and the Ganges on the east flattens out towards the great low land

plain of Hindustan. Bordering this great plain is situated the Mussooree range with an average elevation of about 6000 ft running practically east-west. To the east adjoining the Mussooree is the Landour range lying north-west to south-east with an average elevation of about 7000 ft. At a distance of about  $1\frac{1}{2}$  miles away from the foot of a hillock lying east-west is situated the Mussooree pilot balloon observatory (elevation 6724 ft corresponding to 2.05 km). Looking from the Jumna the Mussooree range resembles a small plateau with its flat top approximately 10 miles long and 3 miles broad. The flat surface drops 2000 ft in about  $1\frac{1}{2}$  miles to Happy Valley on the north and 3000 ft in about 3 miles to Dehra Dun valley on the south, both lying almost parallel to the Mussooree range. Happy Valley is about 2 miles broad increasing in elevation towards the Nagtibba hills on the north. Dehra Dun valley is of an average elevation of about 2500 ft for about 8 miles to the south with a further drop of about 500 ft at the Reserved Forest situated at the foot of the Shivalik range. The western end of the Mussooree range drops 4000 ft in about 5 to 6 miles to form the plains on the west. The West Plain is about 1500 ft in elevation extending for more than 15 miles east-west.

## 3. Analysis of data

The observational data relate to the months of April (1953 and 1955), May, June (1950, 1953 and 1955), September (1954) and

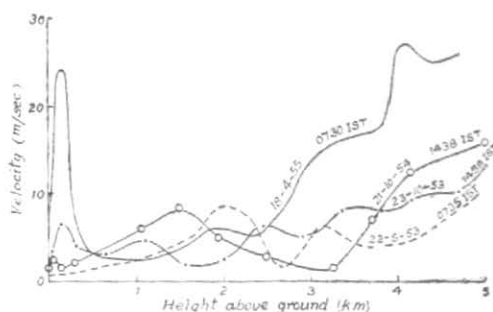


Fig. 1. Typical curves of the velocity distribution in the lower levels of the atmosphere over Mussoorie

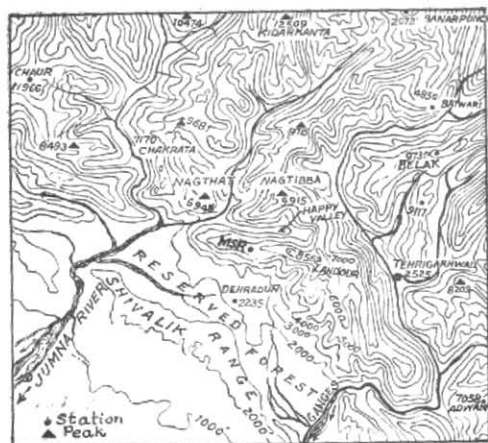


Fig. 2. Topographic map of Mussoorie (MSR)  
(Scale : 1 inch = 32 miles)

October, November (1953 and 1954). There were altogether 561 useful ascents including those for the forenoons and afternoons. Data in respect of (1) wind direction at the height prior to the velocity fall, (2) its velocity and (3) the height at which the maximum fall of velocity takes place were collected from the flight sheets of these ascents. The magnitude by which the reduction in the velocity occurred was then worked out. The ratio of the minimum wind velocity reached to the maximum velocity just before its fall has been worked out as a percentage on each of the 561 occasions corresponding to the ranges of the angle subtended by the principal orographic features intervening between them at the place of observation. In Table 1

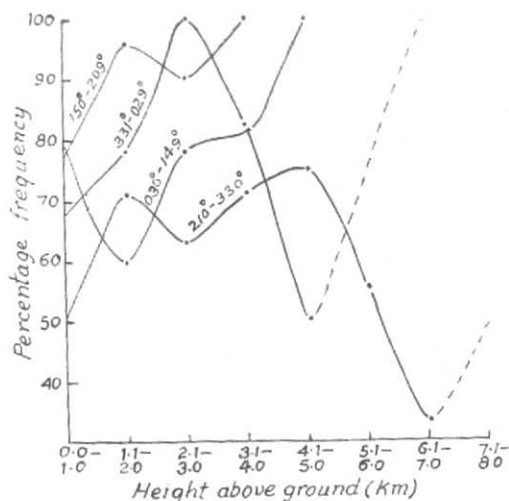


Fig. 3. Frequency of occasions of velocity reduction by more than 40 per cent at different heights for different sectors

are given the frequencies of velocity reductions for less than 40 per cent and more than 40 per cent in respect of winds blowing from Mussoorie towards the surrounding hills and low lands. For the purpose of this study velocity fall by more than 40 per cent has been considered as "appreciable".

The ratio of the number of occasions of appreciable fall of velocity to the total number of occasions of velocity falls worked out as a percentage for each level in the range of 0 to 1.0, 1.1 to 2.0, 2.1 to 3.0 km etc separately for different sectors is graphically represented in Fig. 3 in order to facilitate the study of appreciable velocity falls for different heights. The dotted lines show that

TABLE 1

Wind sector from Mussooree	Towards	No. of occasions of velocity reduction	
		<40%	>40%
030—149°	West Plain	25 (21)	97 (79)
150—209°	Happy Valley	18 (16)	93 (84)
210—330°	Landour Hills	98 (37)	167 (63)
331—029°	Dehra Dun Valley	17 (27)	46 (73)

Note—Figures within brackets are the actual percentages of total number of observations

the appreciable fall of velocity was on one occasion. Fig. 4 shows the pattern of air flow with the standing waves in the wake of a hill closely resembling the hill of Mussooree in its different orientations to airflow from different sectors.

4. Discussion

It is seen from Table 1 that when the wind is blowing towards the West Plain and Happy Valley of the Mussooree range there are respectively 79 and 84 per cent of occasions of sensible reduction of the initial velocity of more than 40 per cent. Again, when the winds blow towards the Landour hills and Dehra Dun valley there are 63 and 73 per cents of occasions respectively of sensible velocity fall.

Queney (1948) and Scorer (1949) have discussed in detail the problem of air motion in the lee of hills. They have shown theoretically that when winds blow across a ridge, a train of waves known as "lee waves" or "standing waves" form downstream. In the vicinity of the crests and troughs of lee waves rising and falling currents respectively may occur as shown by Laird (1952) in his study on the standing waves at Aberporth. Accounts given by Yates (1949) and Turner (1951) of the experiences of aviators show that such lee waves can result in considerable reduction in the wind speed. When the winds blow from 030—149° the balloon released at Mussooree would be carried by winds on to

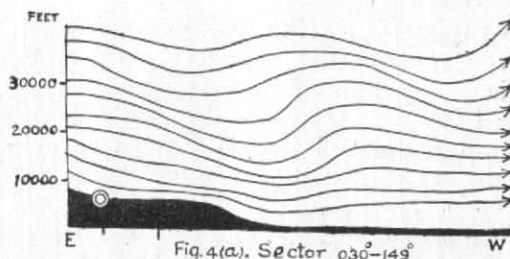


Fig. 4(a). Sector 030°-149°

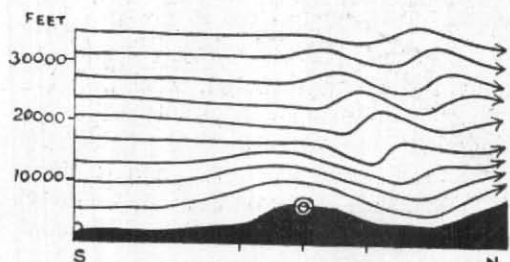


Fig. 4(b). Sector 150°-209°

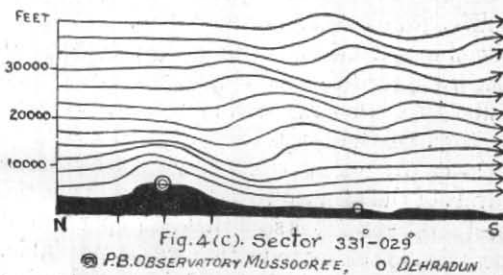


Fig. 4(c). Sector 331°-029°

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Fig. 4. Vertical projection of the streamline flow of winds from different sectors in the lee of the Mussooree range

the West Plain where lee waves apparently prevail—Fig.4(a). The entanglement of the released balloon within the lee waves thus appears to be the main factor for the anomalous distribution of velocity of the winds blowing from  $030-149^\circ$  in the lower levels of the upper winds over Mussooree. In the case of the winds blowing from  $150-209^\circ$  and  $331-029^\circ$  the balloon would proceed towards Happy Valley and Dehra Dun Valley—Figs. 4(b) and (c)—respectively and we should expect a high percentage of occasions of reduction of velocity. It is in fact so because on 84 and 73 per cents of all occasions of the winds blowing from  $150-209^\circ$  and  $331-029^\circ$  respectively, the reduction of velocity was by more than 40 per cent.

Banerji (1930) has shown that when winds blow against a natural barrier the motion of the air on the windward side of the barrier becomes turbulent in character resulting in reduction of wind speed. Such frictional effects can result in considerable reduction in the wind speed even upto thrice the height of the hills as shown by Rao and Raghavan (1950) in their study on the influence of the hills at the Visakhapatnam airfield on the upper winds in the lower levels there. When the winds blow from  $210-330^\circ$  the released balloon would be carried by the winds towards the Landour hills. The discontinuity of velocity for the winds blowing from  $210-330^\circ$  thus seems to arise mainly from the prevalence of eddies on the windward side of the Landour hills.

The graphs in Fig. 3 show the frequency of sizeable reduction of velocity (more than 40 per cent) at different heights where velocity fall occurs when winds blow from different sectors. Of the total number of occasions of velocity reduction occurring in the lower levels of the atmosphere upto 1.0 km for the sector  $030-149^\circ$  it is seen that on 79 per cent of occasions velocity reduction was appreciable. It is a curious fact that such large reduction of velocity occurs so frequently before the released balloon would hardly reach the lee of the Mussooree range. It is likely that the eddies forming at the crest of the Landour

range migrate to its lee side (Ramakrishnan 1929) and affect the winds close to the ground. It is interesting that after the critical height of about 1.0 km the effect of eddies decreases with increasing height upto about 2.0 km whereafter, apparently as the balloon enters the West Plain, the lee effect is predominant because the frequency is found to increase rapidly from 60 per cent at 2.0 km to 78 per cent at 3.0 km. Between 3.0 and 4.0 km the lee effect appears to be almost constant because the increase in frequency is only 3 per cent from 3.0 to 4.0 km. Since the data analysed include more number of occasions of the winds above 2.0 km blowing from near about the southeast during the months of May and June probably the discontinuity in the variation of frequency of appreciable velocity fall between 3.0 and 4.0 km is due to the frequent deflection of the released balloon above 2.0 km towards the lee to the northwest of the Mussooree range where the lee waves may be comparatively smaller as the lee side there is less expansive (Scorer 1951) than the rest of the sides facing the West Plain. The phenomenal increase of frequency from 81 per cent at 4.0 km to 100 per cent at 5.0 km seems to occur mainly due to the frictional effect of the hills lying to the northwest of the Mussooree range.

For the sector  $150-209^\circ$  and  $331-029^\circ$  there are 78 and 68 per cent respectively of appreciable velocity fall in the lower levels upto 1.0 km. Such frequent sensible reduction of the wind velocity close to the ground is questionable in view of the distance from the place of release of balloon to the lee sides of the Mussooree range corresponding to the sectors  $150-209^\circ$  and  $331-029^\circ$ . It may be called into account that the Shivalik range and the Nagtibba lie almost parallel to Dehra Dun Valley and Happy Valley respectively. Possibly the standing waves forming in the lee of the Shivalik range and the Nagtibba when the winds blow from  $150-209^\circ$  and  $331-029^\circ$  respectively advance towards the top of the Mussooree range where ascending and descending currents are set up resulting in fall of velocity of the winds close to the

ground there (Roper 1952). The place of release of balloon being more distant from the Shivalik range than from the Nagtibba one should expect proportionately less effects of the lee waves of the Shivalik range on the velocity of the winds upto 1.0 km over Mussooree. But contrary to this we find that the lee waves of the Shivalik range affect the winds more frequently than the lee waves of the Nagtibba. This may be explained by the fact that the lee side of the Shivalik range is more expansive than that of the Nagtibba thus helping to form correspondingly larger lee waves. The frequency of sizeable reduction of velocity for the sector 150—209° further increases from 78 per cent at 1.0 km to 96 per cent at 2.0 km which seems to be the critical height of the influence of the lee waves at Happy Valley because beyond 2.0 km the frequency decreases to 90 per cent at 3.0 km. Later the frequency instead of decreasing proportionate to the increasing height increases to 100 per cent at 4.0 km thereby suggesting that certain additional orographic effect causing velocity reduction is predominant above 3.0 km. It appears that as the lee waves approach Nagtibba hills to the north of Happy Valley the waves turn into eddies. The increase in frequency of appreciable velocity fall above 3.0 km thus appears to occur mainly due to the turbulence prevailing at the Nagtibba.

In the case of the winds blowing from the sector 331—029° the frequency increases steadily upto 100 per cent at the critical height of about 3.0 km whereafter it decreases to 50 per cent at 5.0 km. It is worthy of note that appreciable effect of the lee waves developing in Dehra Dun valley when the winds blow from 331—029° is significant upto about 5.0 km which works out to about 10 times the average elevation of Dehra Dun valley. This proportion can be favourably compared with that indicated by the observations of Manley (1945) on the lee waves at Crossfell, and that shown by the record-breaking (British) soaring by Wills (1955) in the lee waves at New Zealand.

It is interesting that the maximum frequency of appreciable effect of the lee waves in Dehra Dun valley is 100 per cent while it is only 96 per cent for those forming in Happy Valley which is comparatively narrow.

Finally for the sector 210—330° the frequency increases rapidly from 51 per cent at the lowest levels to 71 per cent at 2.0 km whereafter it decreases to 63 per cent at 3.0 km. This decrease in frequency of appreciable velocity fall at 3.0 km is probably because the number of occasions of winds at about 2.0 km blowing towards the Landour is less during October and November when the winds are generally from the northwest. It is interesting that after the critical height of about 5.0 km where the frequency of frictional effect is 75 per cent the frictional effect decreases with increasing height to 33 per cent at 7.0 km.

#### 5. Conclusion

The present study shows that turbulence induced by the orographic irregularities of Mussooree and its neighbourhood is almost a permanent feature and extends to about 23,000 ft a.s.l. over Mussooree for the northerly and easterly winds and upto about 20,000 and 30,000 ft a.s.l. for the southerly and westerly winds respectively. The turbulence is particularly marked for the southerly winds. Low flying in the area in powered aircraft will, therefore, be hazardous. The results of the study further suggest that the effects of the lee waves for the northerly winds should be still discernible at heights of twelve or more times that of Dehra Dun valley. Considering along with this the inversion prevalent in the area during the winter and also the contiguity of the vast expanse of plain land to the south of Dehra Dun, it should be encouraging for the glider pilots in the country to attempt a record breaking flight (absolute altitude world record 44,500 ft by Edger and Klieforth in the lee of the Sierra Nevada in California on 29 March 1952) by taking advantage of the waves forming in the lee of the Mussooree

range. The results indicate also that the upper wind observations taken at a pilot balloon station in the Himalayan region may hardly represent the velocities of the winds in the lower levels of the atmosphere beyond a radius of about 5 to 6 miles due to the striking diversities of the relief of the terrain at short distance.

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