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Satellite observations of mountain waves over northwest India and neighbouring regions and their theoretical verification

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सार — इस शोध-पत्र में उपग्रह के चित्रों की सहायता से भारतीय क्षेत्र में, विशेषरूप से पश्चिमी हिमालय में पर्वतीय तरंगों का प्रेक्षणीय प्रमाण प्रस्तुत किया गया है। उपलब्ध पवन और तापमान आंकड़ों की सहायता से उत्तर-पश्चिम और उत्तर-पूर्व भारत और निकटवर्ती क्षेत्रों में पर्वतीय तरंगों की तरंग-दैर्ध्यों का सैद्धान्तिक अभिकलन किया गया है। इन परिणामों की प्रेक्षणीय उपग्रह आंकड़ों से तुलना की गई है और ये आपस में समान पाए गये हैं। प्रेक्षित तरंग-दैर्ध्य 10 और 30 कि. मी. के मध्य परिवर्तित होते हैं।

ABSTRACT. The paper presents the observational evidence of mountain waves in the Indian region with particular reference to the Western Himalayas with the help of satellite pictures. Theoretical computations of the wavelengths of mountain waves have been made from the available wind and temperature data over northwest and northeast India and neighbouring regions. The results have been compared with the observational satellite data and have been found to agree well. The observed wavelengths vary between 10 and 30 km.

1. Introduction

Occurrence of mountain waves over uneven terrain is of considerable interest to aviation. Mountain waves, (Sarker 1974), constitute a major hazard to aviation. Thus, their detection and forecasting is of great operational importance. It is now well known that when wind blows across a mountain range, while thermal stability and wind flow are favourable, waves are formed on the leeward of the mountains. The orographic clouds are visible manifestation of the lee waves when sufficient moisture is available in the atmosphere. In satellite imageries these clouds are seen as grey to white bands of clouds which can extend up to hundreds of kilometres parallel to the wave producing mountain.

Since 1960, many authors have used satellite pictures to identify the lee waves and to measure the lee waves from the satellite pictures and compare them with lee wave length computed theoretically. Such observations have been reported from different parts of the world by Dōōs (1961, 1962), Conover (1964), Fritz (1965), Cohen *et al*. (1966, 1967), Wooldridge and Lester (1969), Sarker & Calheiros (1974), Cruette (1976) etc.

In India, De (1970, 1971) reported lee waves as evidenced by satellite cloud pictures over northeast India. Observed wavelengths were compared with the wavelength computed theoretically. Sinha Ray and De (1982) have reported that in the winter season the airstream over *northwest* India is predominantly stable and is suitable for the formation of wave perturbation provided the direction of the air flow has an appreciable component normal to orography. In this case an airstream moving northwestward, northward or northeastward (southeasterly, southerly or southwesterly winds), is favoured direction for the formation of lee waves. They have found out theoretically the wavelength of lee waves in 9 different cases and it has been noticed that in all these cases Scorer's criteria for existence of lee waves has been satisfied.

The Western Himalayas situated in the northwestern part of the country plays an equally important role on the weather in the northwest India. The aim of the present paper is to furnish observational evidence of mountain waves with particular reference to the Western Himalayas and to compare the observed wavelength of lee waves with that of theoretically computed lee wavelength.

2. Data and technique

The topography of the area is shown in Fig. 1(a) and Fig. 1(b). Satellite cloud pictures of NOAA-7, 8 and 9 for the period 1982-1985 have been considered for selecting the mountain waves over northwest India and over northeast India. From these catalogues the cases in which the mountain wave clouds were clearly discernible and could be identified were taken up for further work. The satellite photographs were already grided. Some typical satellite pictures of lee waves are shown in Figs. 2(a-d). The wavelength of the lee waves is measured as the distance between a group of waves, divided by the number of waves in the group. Several measurements are made along different lines parallel to the direction of waves in the wave

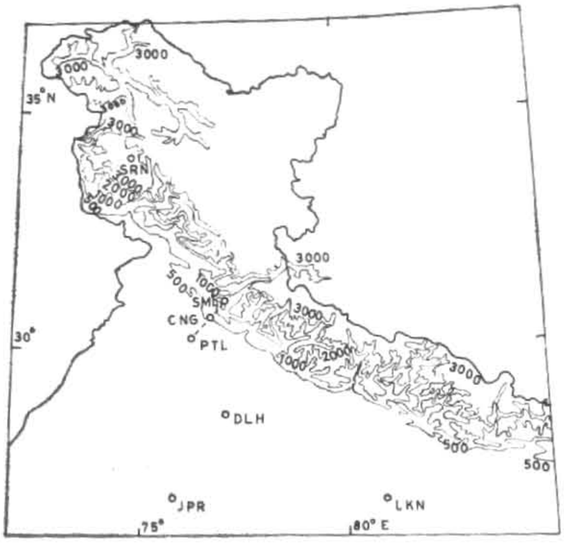


Fig. 1(a). Map of the northwest Himalayas indicating the region of investigation along the two dimensional section from Patiala

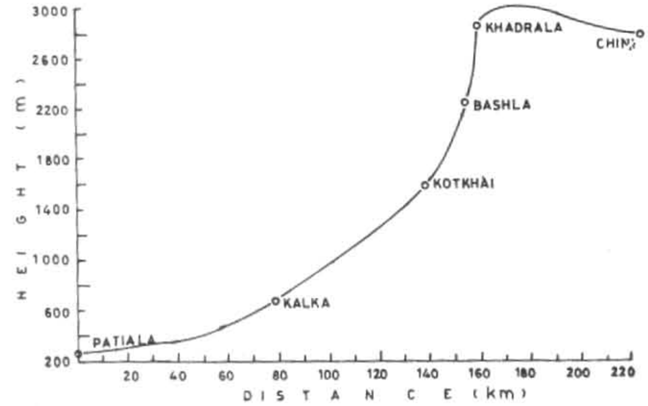


Fig. 1 (b). Two dimensional mountain profile from Patiala to Chini

TABLE 1

Wavelength of lee-waves from satellite imageries

Date	Time (GMT)	Location Lat. (°N)	Long. (°E)	Wave length (km)
9 Jul 82	0832	35-40	85-90	12.9
14 Jul 82	0913	32-35	77-80	16.5
16 Jul 82	0850	32-34	76-85	13.9
25 Jul 82	0843	35-37	76-80	10.1
27 Aug 82	0851	30-35	77-85	22.3
28 Aug 82	0830	33-35	80-85	17.1
30 Aug 82	0816	30-32	78-85	14.0
24 Sep 82	0819	27-33	85-90	12.3
25 Sep 82	2012	27-33	85-90	12.9
26 Nov 82	0906	23-25	76-79	10.5
8 Aug 83	0302	27-29	74-77	12.0
25 Sep 83	0228	29-34	81-93	14.4
26 Nov 83	0333	35-37	76-80	11.8
21 Dec 83	0848	27-31	85-95	10.2
25 Dec 83	0939	23-25	90-95	15.4
10 Jul 84	0919	30-32	80-90	10.9
9 Dec 84	0950	33-35	77-85	18.8
1 Sep 85	0841	34-37	73-80	16.0
5 Sep 85	0257	32-35	85-90	13.4
17 Sep 85	0911	32-34	81-83	14.8
13 Oct 85	0756	30-34	80-90	13.5
15 Oct 85	0736	30-32	83-91	13.1
22 Oct 85	0801	24-27	90-100	11.9

cloud and a mean is worked out. Döös (1962), De (1970) have used a similar method to estimate the wavelength. It is possible to compare the observed values of wavelength with those computed theoretically in order to verify the results.

In all 23 cases of mountain waves have been observed. Table 1 gives the observed wavelength of these waves along with its location. Broadly these regions of investigation have been classified into two groups as follows :

A : 28° N to 32° N and 76° E to 80° E

B : 33° N to 37° N and 75° E to 80° E

The radiosonde data of Patiala (30° 20′ N, 76° 28′ E) and Srinagar (34° 05′ N, 74° 50′ E) have been considered for verifying these cases of lee wave over northwest India. The regular radiosonde ascents were available for some of the cases to make the required computation. From the wind direction and speed, component of wind along 225° has been determined since this is the direction normal to the extension of the orography. The conditions that should be satisfied for the formation of lee waves are as follows :

(*i*) Wind should blow roughly perpendicular to the mountain ridge and the wind speed should increase with height.

(*ii*) The atmosphere should be stably stratified.

In order to verify the observed values of wavelengths of mountain waves a two-dimensional steady-state linear model similar to Sarker (1965, 1967) and Sawyer (1960) has been considered. A two-dimensional model of mountain wave in X-Z plane with X-axis pointing towards northeast direction and Z-axis vertical reckoned to be positive upwards, has been considered. The airstream which is southwesterly, therefore, blows

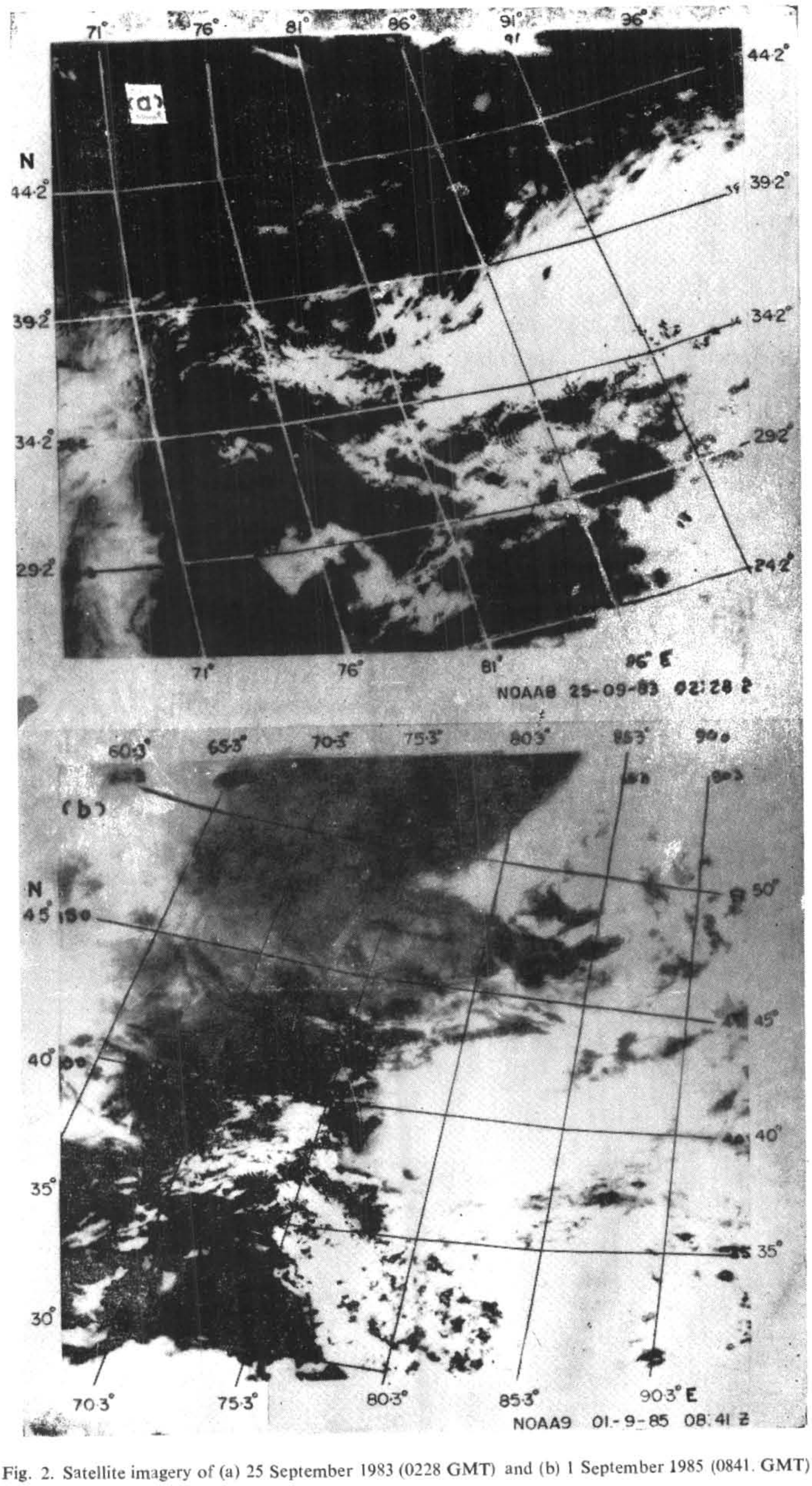
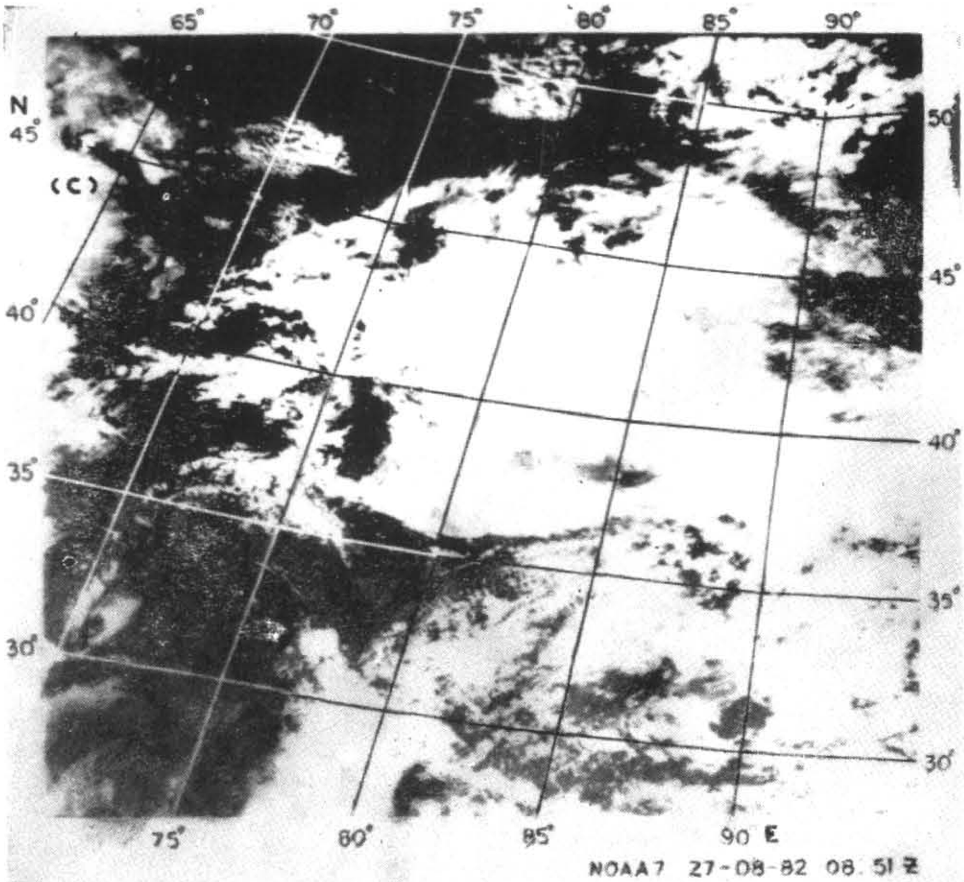


Fig. 2. Satellite imagery of (a) 25 September 1983 (0228 GMT) and (b) 1 September 1985 (0841 GMT)



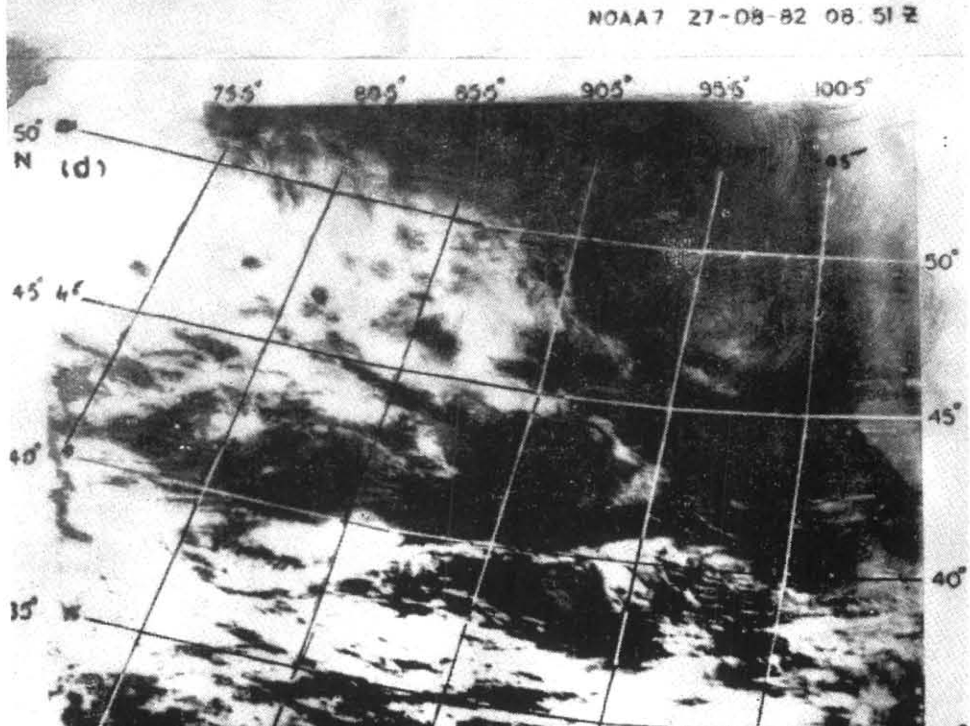


Fig. 2. Satellite imagery of (c) 27 August 1982 (0851 GMT) and (d) 21 December 1983 (0848 GMT)

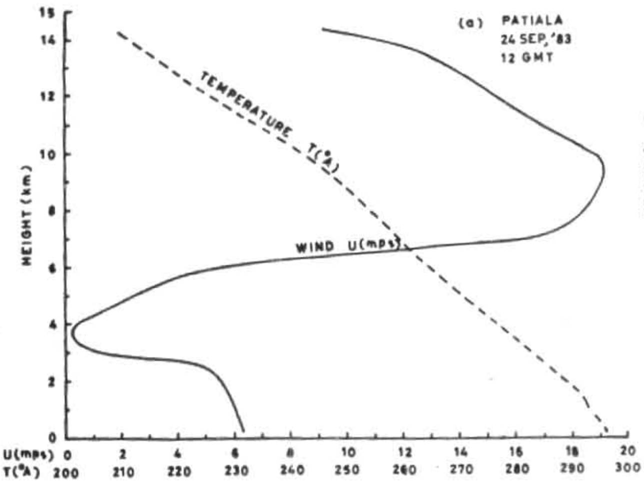


Fig. 3(a). Smoothed profiles showing wind component and vertical temperature distribution for Patiala, 24 September 1983 (12 GMT)

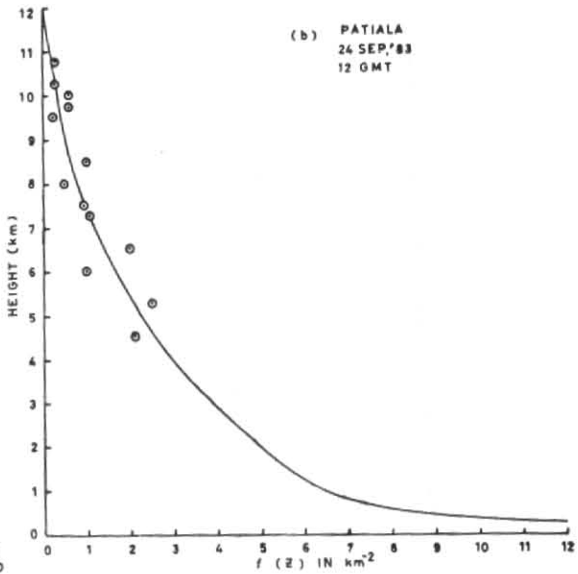


Fig. 3(b). Vertical distribution of $f(z)$ for Patiala, 24 September 1983 (12 GMT)

perpendicular to the ridge which has a NW to SE extension. Using perturbation technique, the perturbation vertical velocity for a steady frictionless adiabatic flow in X-Z plane is obtained as

$$\frac{\partial^2 w_1}{\partial x^2} + \frac{\partial^2 w_1}{\partial z^2} + f(z)\, w_1 = 0 \qquad (1)$$

where,

$$w = w_1 \exp\left(\frac{g - R\gamma}{2R\bar{T}}\, z\right)$$

$$f(z) = \frac{g(\gamma^* - \gamma)}{\bar{U}^2\, \bar{T}} - \frac{1}{\bar{U}}\frac{d^2\bar{U}}{dz^2} + \left(\frac{\gamma^* - \gamma}{\bar{T}} - \frac{g}{\chi R \bar{T}}\right)\frac{1}{\bar{U}}\frac{d\bar{U}}{dz} - \frac{2}{\chi R \bar{T}}\left(\frac{d\bar{U}}{dz}\right)^2 - \left(\frac{g - R\gamma}{2R\bar{T}}\right)^2$$

$\bar{U}$ and $\bar{T}$ represent wind speed and temperature in the undisturbed airflow which is a function of z only,

γ^* is the dry adiabatic lapse rate

γ is the actual lapse rate

$\chi = c_p/c_v = 1.4$

$f(z)$ is a function of wind speed, wind shear and stability.

The first two terms of $f(z)$ correspond to l^2 parameter of Scorer (1949). The values of $f(z)$ are computed using the temperature data and smoothed wind data from 00 & 12 GMT radiosonde ascents of the day or that of previous day of Patiala and Srinagar. The values of $f(z)$ are plotted against the corresponding values of z to give a vertical profile of $f(z)$. The profiles of $f(z)$ along with vertical distribution profile of wind and temperature are examined with a view to find out meteorological conditions relating to the occurrence of mountain waves in this region. Four typical examples are discussed here :

Case I — 25 *September* 1983

The wind and temperature distribution are given in Fig. 3(a) and the corresponding $f(z)$ profile in Fig. 3(b). The wind and temperature distribution represent values from radiosonde ascent of Patiala (24 Sep 1983, 12 GMT). The wind speed decreases from 6.0 mps at the surface to 0.2 mps at 3.5 km and then increases reaching a maximum value of 19.5 mps at 10.5 km height, then decrease to 9.0 mps at a height of 14 km. Wind is southwesterly. The temperature values fall from 296.5° K at surface to 212° K at 14 km. The lapse rate of the individual layer varies between 5° & 9° / km and is quite stable favouring the formation of lee waves. The $f(z)$ values decrease rapidly from 12.0 km^{-2} at 0.25 km level to 5.0 km^{-2} at 2.0 km level and then it decreases more gradually. The vertical distribution of $f(z)$ appears favourable for the growth of lee waves.

Case II — 1 *September* 1985

The wind and temperature distribution are given in Fig. 4(a) and the corresponding $f(z)$ profile in Fig. 4(b). The wind and temperature profile represent the values from 1 September 1985 (12 GMT) radiosonde ascent of Patiala. The wind speed increases from 1.0 mps at the surface to 13.0 mps at 13.25 km height. The temperature decreases from 298° K at 0.25 km to 210° K at 14 km. The wind is having substantial component from the southwesterly direction. The atmosphere is stable, the lapse rate varying between 4° & 9°/ km. The $f(z)$ values decrease from 98.5 km^{-2} at 0.25 km to 61.5 km^{-2} at 2 km and then more gradually to 0.2

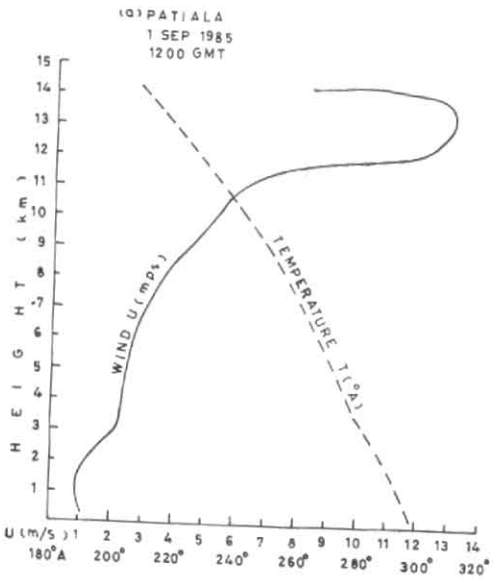


Fig. 4(a). Smooted profiles showing wind component and vertical temperature distribution for Patiala, 1 September 1985 (12 GMT)

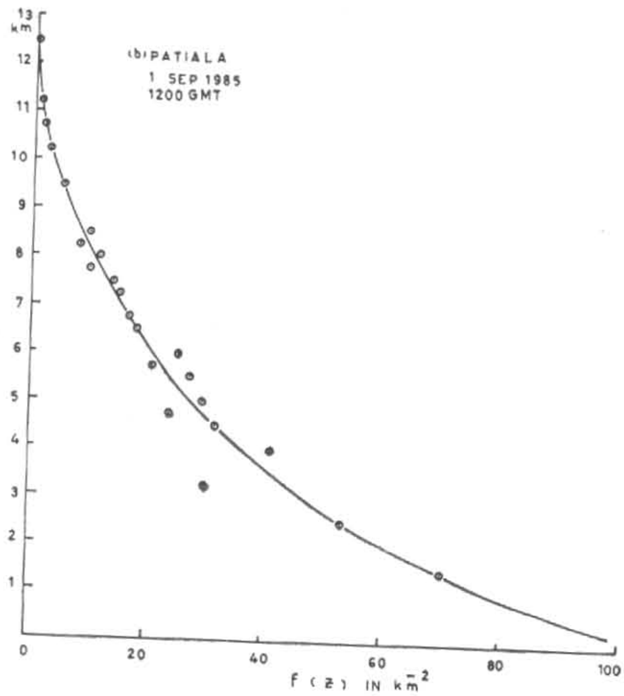


Fig. 4(b). Vertical distribution of $f(z)$ for Patiala, 1 September 1985 (12 GMT)

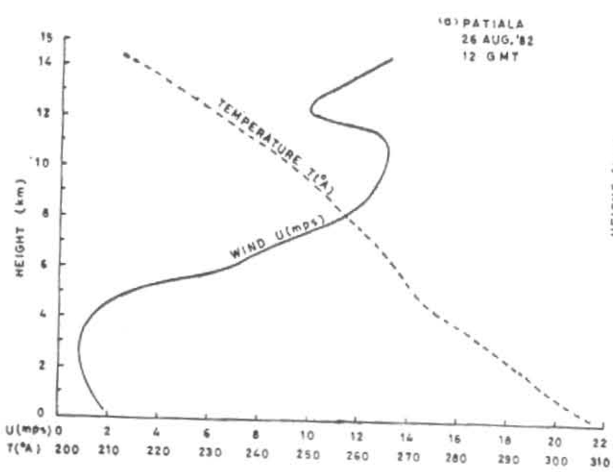


Fig. 5(a). Smoothed profiles showing wind component and vertical temperature distribution for Patiala, 26 August 1982 (12 GMT)

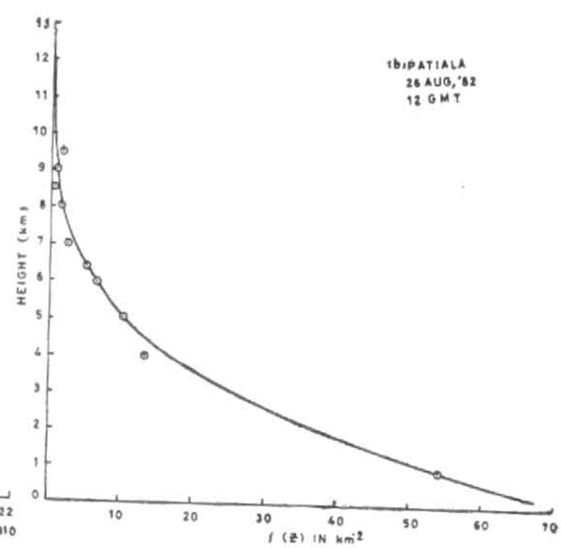


Fig. 5(b). Vertical distribution of $f(z)$ for Patiala, 26 August 1982 (12 GMT)

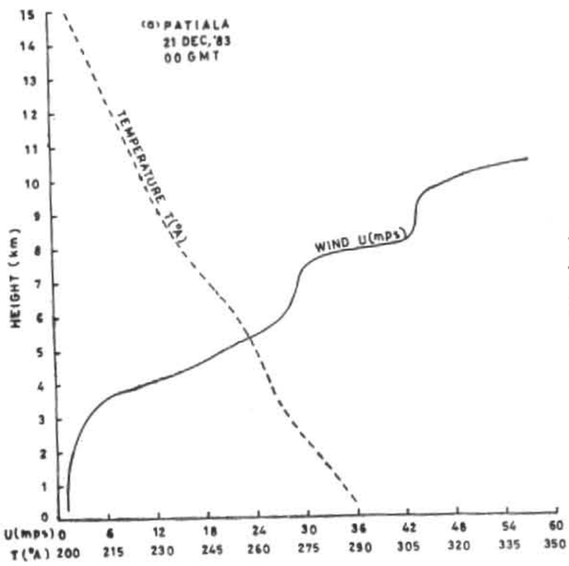


Fig. 6(a). Smoothed profiles showing wind component and vertical temperature distribution for Patiala, 21 December 1983 (00 GMT)

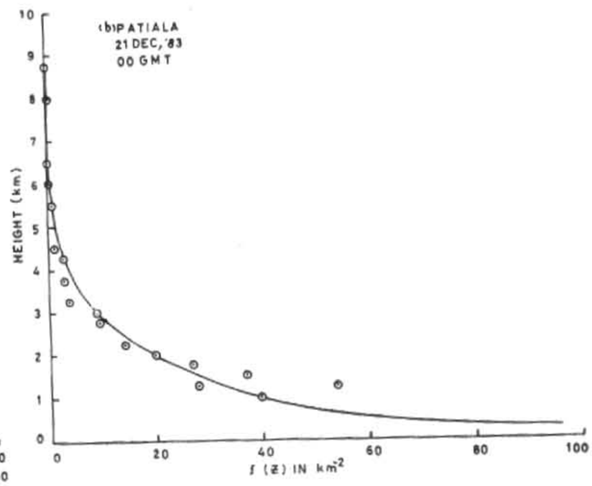


Fig. 6(b). Vertical distribution of $f(z)$ for Patiala, 21 December1983 (00 GMT)

km^{-2} at 11.5 km. The distribution of $f(z)$ with height appears favourable for the formation of mountain wave.

Case III — 27 *August* 1982

The wind and temperature profile has been shown in Fig. 5(a). The corresponding $f(z)$ profile has been shown in Fig. 5(b). The wind and temperature profiles represent the values from 26 August 1982 (12 GMT) radiosonde ascent of Patiala. The wind speed increases from 1.9 mps at 0.25 km to 13.2 mps at 11 km. The wind shear is less in the lower level and is more in the upper level above 4 km. The temperature decreases from 305° K at the surface to 216° K at 14 km. The lapse rate is 4°-9°/km.

The $f(z)$ values decrease rapidly from 69.7 km^{-2} at 0.25 km to 6.8 km^{-2} at 6.0 km level and then decrease more gradually to 0.0 at 12 km. Thus, decrease of $f(z)$ values with height appears favourable for the growth of mountain waves.

Case IV — 21 *December* 1983

The wind and temperature profiles have been shown in Fig. 6(a). The corresponding $f(z)$ profile has been shown in Fig. 6(b). The wind and temperature profiles represent the values from 21 December 1983 (00 GMT) radiosonde ascent of Patiala. The wind speed increases from 1.0 mps at 0.25 km to 57.2 mps at 10.5 km. The wind shear is less in the lower level and it is more in the upper level above 3.5 km. The temperature decreases from 291° K at the surface to 225°K at 10.5 km. The lapse rate is 4°-9°/km.

The $f(z)$ values decrease rapidly from 96.0 km^{-2} at 0.25 km level to 9.0 km^{-2} at 3.0 km level and then decrease more gradually to 0.01 km^{-2} at 8.75 km. Thus, the decrease of $f(z)$ values with height appears favourable for the growth of mountain waves in all these cases.

3. Theoretical estimation of wavelength

Using a two dimensional mountain wave model, Sawyer (1960) gave an expression for computing vertical velocity numerically. He solved an equation of the type :

$$\frac{\partial^2 \psi}{\partial z^2} + (l^2 - k^2)\,\psi = 0$$

where, ψ is the stream function and l^2 is Scorer's parameter.

If $w_1(x, z)$ is resolved into its harmonic components by Fourier transform we get,

$$w_1(x, z) = \int_0^\infty w(z, k)\, e^{ikx}\, dk \qquad (2)$$

substitution of (2) in (1) leads to

$$\frac{\partial^2 w(z, k)}{\partial z^2} + \{f(z) - k^2\}\, w(z, k) = 0 \qquad (3)$$

and

$$w(x, z) = \exp\left(\frac{g - R\gamma}{2R\bar{T}}\, z\right) Re \int_0^\infty w(z, k)\, e^{ikx}\, dk$$

Eqn. (3) is the lee wave equation.

The approximate solution of Eqn. (1) in the region of constant $f(z)=0$ is of the form :

$w(z, k) = A \exp(-kz)$

and the upper boundary conditions is

$$\frac{\partial}{\partial z} w(z, k) = -kw(z, k) \qquad (4)$$

To solve Eqn. (3) numerically a function $\psi(z, k)$ satisfying Eqn. (3) and the boundary condition (4) at upper boundary has been considered.

TABLE 2

Mountain waves in Western Himalayas

Date	Time (GMT)	Observed wave-length (km)	Computed wave-length (km)
25 Sep 83	0228	14.4	15.6
1 Sep 85	0841	16.0	17.1
21 Dec 83	0848	10.2	9.6
30 Aug 82	0816	14.0	13.0
27 Aug 82	0851	22.3	20.3
13 Oct 85	0756	13.5	16.7
10 Jul 84	0919	10.9	7.9
25 Jul 82	0843	10.1	7.4

The expression for vertical velocity then becomes

$$w(z, k) = \left(\frac{\bar{\rho}_0}{\bar{\rho}_z}\right)^{\frac{1}{2}} \bar{U}(\zeta_s)\, a\, b \int_0^{\infty} \frac{\psi(z,k)}{\psi(0,k)} \exp(-a\,k)\, dk$$

where,

$\zeta_s = \dfrac{a^2 b}{a^2 + x^2}$, the mountain profile.

$\bar{\rho}_0$ = density of air at the surface.

$\bar{\rho}_z$ = density of air at a height z km above the surface.

a = half width of a mountain.

b = height of the mountain ridge.

$\bar{U}(\zeta_s)$ = wind component along the profile at the surface.

The above integral becomes indeterminate when $\psi(0, k)=0$. These sigularities of the integrand correspond to the occurrence of lee waves.

Following Sawyer (1960) and Sarker (1967) the function $\psi(z, k)$ was computed numerically using a finite difference form of Eqn. (3) after replacing $w(z, k)$ by $\psi(z, k)$ with appropriate boundary condition. The roots of $\psi(0, k)$ were, then, determined by Newton-Raphson method. The roots give the wave number for the lee wave. The computed values by the above method alongwith the observational results are shown Table 2.

4. Conclusions

(*i*) The air stream in the winter and SW monsoon season have the required static stability and vertical wind shear to give rise to mountain wave in northwest India.

(*ii*) The observed and computed wavelengths of mountain waves were found to vary between 10 and 30 km approximately.

(*iii*) Computed wavelengths agree well with the observed values.

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