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# Lee waves as evidenced by satellite cloud pictures

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ABSTRACT. The paper presents the observational evidence of mountain waves in the Indian region with particular reference to the Assam and Burma hills with the help of satellite pictures. In all, sixteen cases have been studied and the observed wavelengths vary between 17-34 km. In all the cases the conditions for formation of mountain waves were found favourable as evidenced by the wind profile and thermal stability of the atmosphere.

## 1. Introduction

It is now a well known fact that when winds blow across a mountain range, waves are formed in the lee of the mountain provided the conditions of thermal stability and wind flow are favourable. The effects of mountain on air flow are generally manifested as orographic cloudiness, mountain waves and orographic precipitation etc.

Considerable theoretical work has been done on the formation of mountain waves during the last twenty years and several theories have been propounded. Observational studies have also been made in different parts of the world with the help of gliders, light air-planes and radar tracked no-lift balloons. Quite recently satellite pictures have been made use of by Döös (1962), Fritz (1965), Cohen *et al.* (1966 and 1967) to identify mountain waves in the different mountain ranges. With the help of these pictures wave-lengths of the lee waves have been measured and then compared with the existing theories.

In India theoretical studies of mountain waves have been made by Das (1964) and Sarker (1965). Sarker made an investigation of mountain waves of the Western Ghats based on a two-dimensional model, while Das examined the effect of the Himalayas with the help of a three-dimensional one. A single visual observation of mountain waves on an isolated peak of the Western Ghats has been reported by Sinha (1966). But detailed observational evidence of mountain waves is still lacking in this part of the world.

The aim of the present paper is to furnish observational evidence of mountain waves with particular reference to the Assam and Burma hills with the help of satellite pictures.

## 2. Description of topography

The topography of the area is shown in Fig. 1. The area mainly represents the Assam-Burma hills. Assam hills run approximately in a north-south direction with a westward extension along Khasi-Jaintia and Garo hills upto approximately 91°E. The surrounding topography is the Brahmaputra valley which almost reaches sea level. The orography to the north is the narrow Patkai hills forming a wall between India and Burma. To the south, it broadens gradually as the Naga and the Manipur hills, and further south narrows down into the Lushai hills. The height of these ranges vary between 1-2 km.

Beyond 96°E to the east of Patkai hills are the Northern Burma hills which separate Burma from Tibet and Assam. These hills extending southward as the Kumon range are flanked on the east and the west by the low lying valleys of Irrawaddy and Chindwin respectively. As a narrow chain it extends southwards upto 24·5°N and runs almost parallel to the Assam hills, separated by the Chindwin valley. To east of these ranges beyond the Irrawaddy valley is situated the Yunnan Plateau across the Burma-China border. The height of the orography in this region varies between 2-3 km.

## 3. Data and technique

The satellite cloud pictures from ESSA-3 for the period 1966-68 have been used. From the available catalogue of APT pictures identifiable cases of mountain waves were selected and from these photographs, only such were selected on which the mountain waves were clearly identifiable. The wave length was taken to be the measured distance devided by the number of waves in the interval

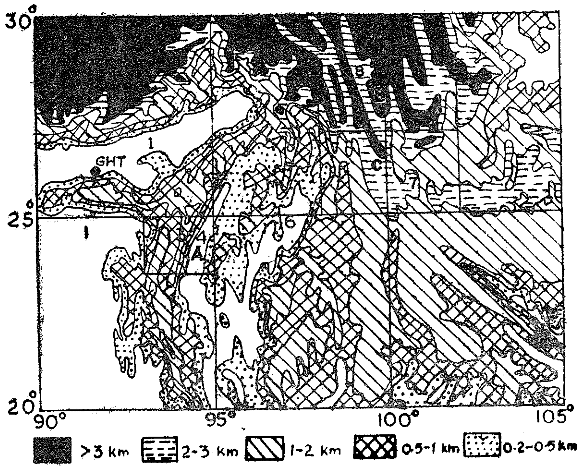


Fig. 1

1. Brahmaputra Valley
2. Khasi and Jaintia Hills
3. Manipur and Naga Hills
4. Chindwin Valley
5. Kumon range and north Burma Hills
6. Irravaddy Valley
7. Yunnan Plateau
8. Great Snowy mountains

TABLE 1

| Date | Time (GMT) | | | Location | | Region | Mean wave-length (km) |
|---|---|---|---|---|---|---|---|
| | *h* | *m* | *s* | Lat. (°N) | Long. (°E) | | |
| 23-11-66 | 08 | 00 | 22 | 26·5-27·5 | 98·5-100 | B | 23 |
| 1-12-66 | 07 | 02 | 00 | 25-26 | 99-100 | C | 20 |
| 8-1-67 | 06 | 29 | 15 | 27·5-29 | 99-101 | B | 22 |
| 9-1-67 | 07 | 19 | 40 | 25-27 | 99·5-102 | C | 22 |
| 10-1-67 | 06 | 15 | 29 | 27·5 | 100-102 | B | 29 |
| 28-1-67 | 08 | 02 | 14 | 24-25 | 94-95 | A | 28 |
| 28-1-67 | 06 | 07 | 23 | 25-26 | 98·5-100 | C | 20 |
| 29-1-67 | 06 | 58 | 24 | 24·5-27 | 99-101·5 | C | 22 |
| 30-1-67 | 07 | 48 | 05 | 25 | 98·8-100 | C | 20 |
| 3-2-67 | 06 | 11 | 30 | 24-26 | 98-101 | C | 31 |
| 10-2-67 | 07 | 29 | 29 | 25 | 94-95 | A | 17 |
| 14-2-67 | 07 | 02 | 01 | 25-26 | 98-100 | C | 22 |
| 5-3-67 | 07 | 43 | 43 | 23·5-24 | 93·5-95 | A | 21 |
| 1-1-68 | 05 | 25 | 11 | 27·5-28·5 | 98-100·5 | B | 34 |
| | | | | 25-26 | 98-100·5 | C | 29 |
| 2-2-68 | 05 | 35 | 37 | 27·5 | 99-100 | B | 29 |
| 9-2-68 | 05 | 44 | 38 | 27·5 | 99·5 | B | 23 |

Several measurements were made along different lines parallel to the direction of the waves in the wave cloud.

The elaborate technique of gridding the photographs by Fujita (1963) method was not followed as has been adopted by Fritz (1965) in his work. The pictures, gridded by the National Environmental Satellite Centre (NESC), Washington's operational programme, were used in this study.

The cases of mountain waves presented in the text are the best among a large number of cases in which wave clouds were clearly discernable and the measurements stated above could be made without difficulty. Accuracy of the gridding given by NESC was also verified against the true position of some of the prominent geographical landmarks. Accounting for the error in estimating number of waves etc the wavelength thus computed can be in error at the most by 10 per cent. With this value of error it is possible to compare the observed values of wavelengths with those computed theoretically.

Döös (1962) has used a similar method to estimate the wavelength, *i.e.*, by measuring the distance over several cloud bands in region covering a degree or two longitudinally. The average value for wavelength in his case was 11·3 km. The uncertainty of this value is approximately 1 km.

#### 4. Discussion and Results

In all 16 cases of mountain waves in the Assam–Burma mountain region have been reported in the paper. The date, time, latitude and longitude of the place of occurrence and the observed wavelength are shown in Table 1. In all these cases the mountain ranges are extending approximately in a north-south direction and for a westerly air flow the waves are formed on the eastern lee side.

Broadly the regions of occurrence have been classified into three groups and are shown in Fig. 1.

1. Assam Hills 93-95°E and 23·5-25°N (Region A).
2. Upper Burma-China Mountains 98-102°E, 27·1-29°N (Region B)
3. Lower Burma-China Mountains 98-102°E, 25-27°N (Region C).

*Region A* — The mountain waves are formed on the leee side of the Assam-Manipur hills. One such case is shown in Fig. 2 (a). It is seen from Table 1 that wavelength vary from 17 to 28 km.

*Region B* — The mountain waves are formed on the lee side of upper Burma-China ranges and one such case is shown in Fig. 2(b). Wavelength vary from 22-34 km (Table 1).

*Region C* — The mountain waves are formed on the lee side of lower Burma-China ranges and one such case is shown in Fig. 2(c). Wavelength vary from 20-31 km (Table 1).

It has been established by theory and observations that in order that mountain wave should form on the lee side, the following conditions should be satisfied.

1. Wind should blow roughly perpendicular to the mountain ridge and the wind speed should increase with height, and
2. The atmospere should be statically stable.

A two dimensional frame of co-ordinates in x–z plane with x-axis running west to east and z-axis

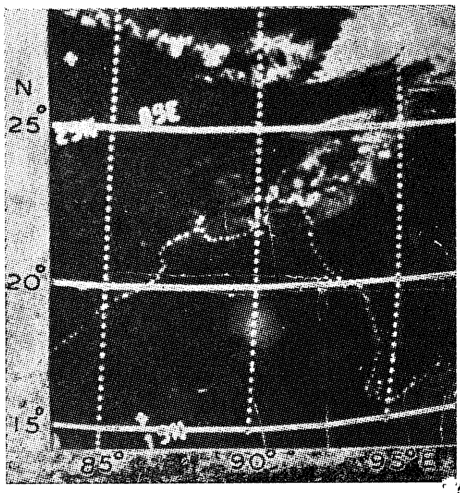


Fig. 2(a)
ESSA 3, Orbit 1480, 28 Jan 1967, 0802Z

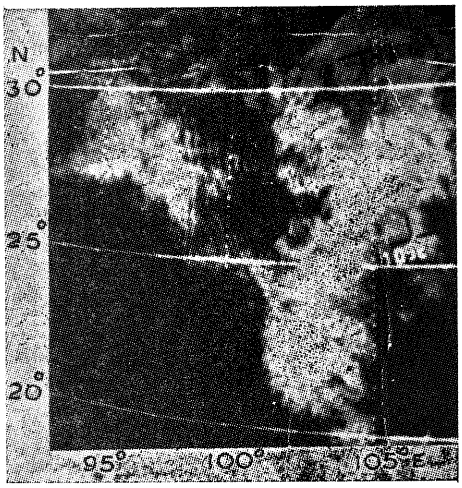


Fig. 2(b)
ESSA 3, Orbit 5724, 1 Jan 1968, 0525 Z

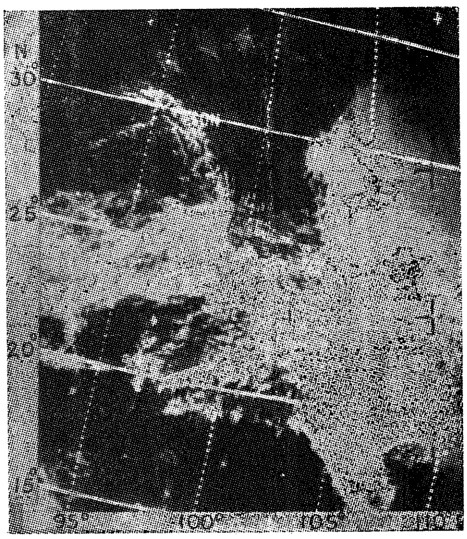


Fig. 2(c)
ESSA 3, Orbit 1241, 9 Jan 1967, 0719 Z

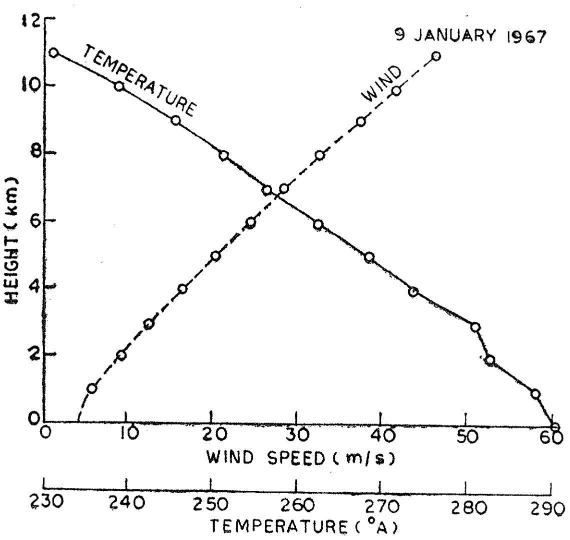


Fig. 3(a)

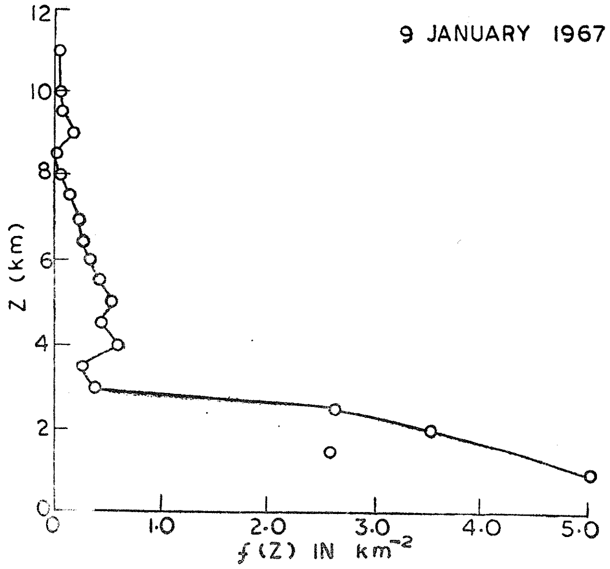


Fig. 3(b)

vertically is considered. The air stream blows perpendicularly across a ridge which is having a north-south extension. The equation for the perturbation vertical velocity $w$ $(x, z)$ can be written 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, $w = w_1 \exp\left(\frac{g - R\nu}{2RT} z\right)$

and

$$f(z) = g\frac{(\nu^* - \nu)}{U^2 T} - \frac{1}{U}\frac{d^2U}{dz^2} + \left(\frac{\nu^* - \nu}{T} - g/XRT\right)\frac{1}{U}\frac{dU}{dz} - \frac{2}{XRT}\left(\frac{dU}{dz}\right)^2 - \left(\frac{g - R\nu}{2RT}\right)^2$$

where, $U$ $(z)$ is the undisturbed wind speed assumed to be a function of height only (Sarker 1965).

$g$ is the acceleration due to gravity

$\nu^*$ is the dry adiabatic lapse rate

$\nu$ is the actual lapse rate

$T$ is the undisturbed temperature

$R$ is the universal gas constant ($29 \times 10^{-5}$ km/sec/deg)

and

$X = cp/cv$ $(1 \cdot 4)$

The function $f(z)$ is function of wind speed, wind shear, and stability. This corresponds to the $i^2$ parameter of Scorer (1949).

An examination of the wind and temperature profiles of Gauhati (Lat. 26°06′N, Long. 91°35′E) which is the only available radiosonde station on windward side of the region considered, was made. The $f(z)$ values were computed for several levels from ground upwards by evaluating the complete expression at intervals of 0·25 km. These values were plotted against the corresponding values of $z$ to give a vertical profile of $f(z)$. The profiles were examined with a view to finding out favourable conditions for the growth of mountain waves in this region. Three different cases are discussed below—

*Case I (9 January 1967)*—The wind and temperature distribution are given in Fig. 3 (a) and the corresponding $f(z)$ profile in Fig. 3(b). The wind and the temperature distribution represent average values from the radiosonde ascents corresponding to 0 and 12 GMT. The wind speed increases from 4 mps at the surface to 47 mps at 11 km and it is more or less westerly. The wind shear is fairly uniform though it is less in the lower layers. The temperature values fall from 290·5°K at surface to 231°K at 11 km. The lapse rate of the individual layers are variable (mostly between 5-8°/km) but on the whole the atmosphere is quite stable and hence favourable for the formation of mountain waves.

The $f(z)$ values decrease from 5·04 km$^{-2}$ at 1 km rapidly at lower levels, to 2·6 km$^{-2}$ at 2·0 km and then more gradually to ·062 km$^{-2}$ at 11 km. The vertical distribution of $f(z)$ appears favourable for

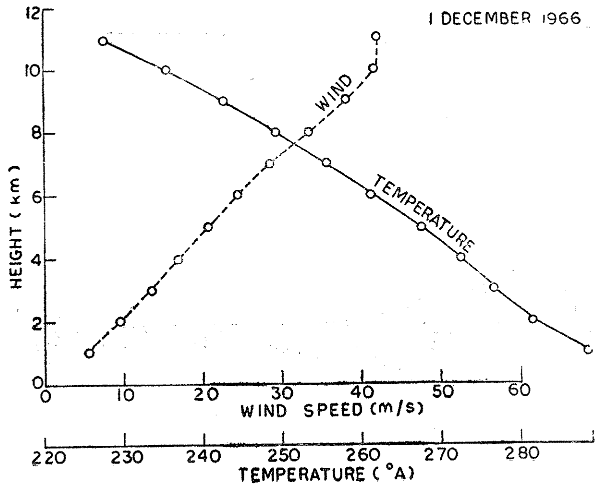


Fig. 4(a)

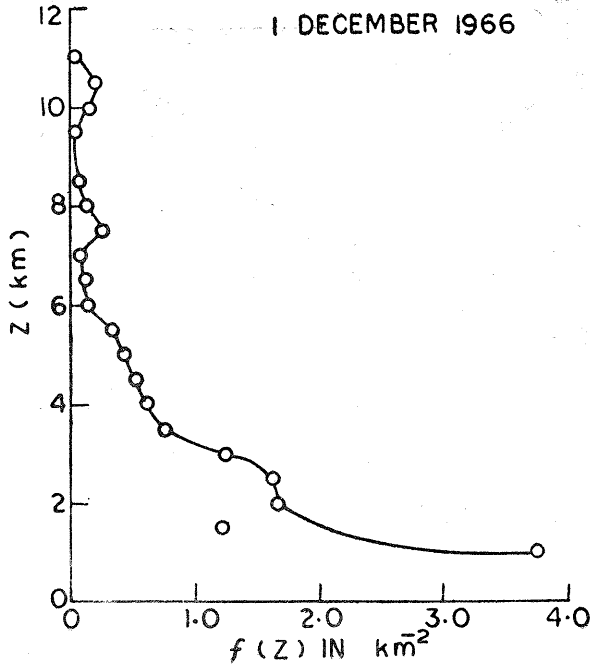


Fig. 4(b)

the growth of mountain waves (Scorer 1949, Döös 1961, Sarker 1965).

*Case II* (*1 December 1966*)— 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 profiles represent the average values from the two radiosonde ascents corresponding to 0 to 12 GMT. The wind speed increases from 3·6 mps at the surface to 41·7 mps at 11 km with wind shear increasing with height. The temperature decreases from 288·5 °K at 1 km to 227·5 at 11 km. The atmosphere is stable, the lapse rate varying between 4·7°/km. The $f(z)$ values decrease from 3·79 km$^{-2}$ at 1 km to 1·66 km$^{-2}$ at 2 km and then more gradually to ·039 km$^{-2}$ at 11 km. The distribution of $f(z)$ with height appears favourable for the formation of mountain waves.

*Case III* (*5 March 1967*) — The wind and temperature profiles have been shown in Fig. 5(a). The corresponding $f(z)$ profile has been shown in Fig. 5 (b). The wind speed increases from 4·6 mps at the surface with fairly uniform shear (4·2 mps/km at the lower levels to 5·0 mps/kms at 8 km). The surface temperature is 295°K and decreases with height to 250·5 at 8 km. The lapse rate is 4-6°/km at lower levels and it varies from 4 to 5°/km between 6 to 7 km.

The $f(z)$ values decrease rapidly from 6·98 km$^{-2}$ at the surface to 2·05 km$^{-2}$ at 1 km and then afterwards more gradually to ·048 km$^{-2}$ at 8 km. Thus the decrease of $f(z)$ values with height appears favourable for the growth of mountain waves in all the cases.

Presence of jet streams with its high wind speed and vertical shear is an important factor in the occurrence of powerful waves particularly in the lee of large mountains such as the Rockies. Of course, the presence of a jet stream is not essential for the generation of waves by small individual ridges. However, if several such ridges act as a single large ridge the presence of a jet stream aloft either directly above the station or at short distance away may be conducive for the formation of waves. For all the cases of mountain waves reported in the paper the analysed upper air charts for India and neighbouring regions were examined. The jet core was never directly situated over the area where the waves were observed, *i.e.*, 95-105°E and 25-28°N. In most of the cases the core of the strong winds ascribed to jet stream at nearly 200 mb was situated over NW India in the neighbourhood of Delhi. However, the wind speeds, over northeast India were also sufficiently high being of the order of 100-110 kt at 200 mb with sufficiently large vertical shears. On the other hand, the wind speeds over Delhi were of the order of 150 kt. Over

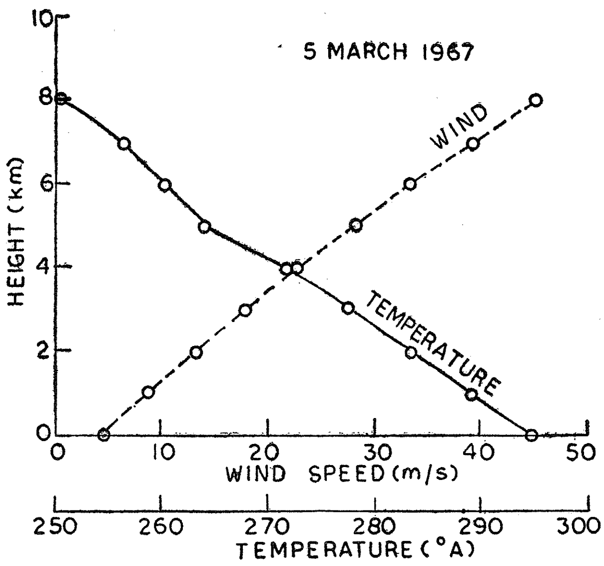


Fig. 5(a)

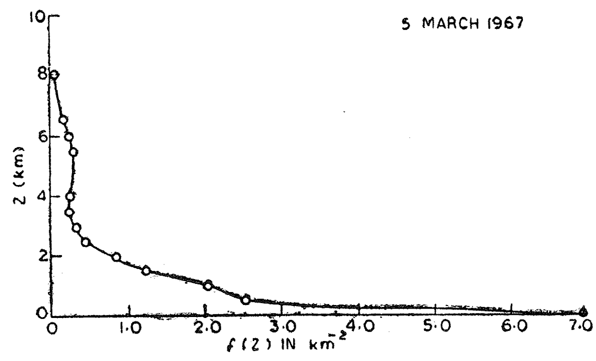


Fig. 5(b)

eastern Tibet and Burma the winds were weaker at the jet level as compared to Northern India. But there is uncertainty in locating the jet stream on individual days specially over the data sparse Northeast India and Burma region. Therefore, from the examination of synoptic charts the association of otherwise or jet streams with mountain waves cannot be definitely concluded, *i.e.*, being essentially situated over the region where mountain waves are reported.

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