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Climatology of mountain waves over Indian region based on the study of NOAA satellite imageries

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सार - इस शोध पत्र में 1982 से 1985 तक की चार वर्षों की अवधि के NOAA (ए. वी. एच. आर. आर.) मेघ चित्रों का अध्ययन किया गया है। एक ही पखवाड़े के विभिन्न मेघ चित्रों में क्रमिक रूप से 1 से 7 के पैमाने में अतिव्यापी तरंग क्षेत्रों को अधिक महत्व दिया गया है। भिन्न-भिन्न प्रभावों के लिए अलग-अलग मोनोक्रोमैटिक हैचिंग योजना अपनाई गई है। क्षेत्र की तरंग और उसकी लम्बाई के स्तर पर पवन की दिशा अंकित की गई है। इस प्रकार से जलवायविकी के 24 पखवाड़ों के अभिलेख तैयार किए गए है। क्षेत्र में तरंगें प्रायः निम्नलिखित दो अवधियों में देखी जाती हैं।

(*i*) 16 नवंबर से 15 अप्रैल - इसमें मानसून पूर्व ऋतु के आरम्भ होने तक की शीत ऋतु आती है।

(*ii*) 1 जून से 15 अक्तूबर - इसमें मानसून ऋतु के बाद के तीसरे सप्ताह तक की दक्षिणी पश्चिमी मानसून ऋतु आती है।

संक्रमण अवधि के दौरान प्रतिपवन तरंगें कम पाई जाती हैं। ये तरंगें मई के अंत तक अप्रैल के दूसरे पखवाड़े में तथा नवंबर के मध्य तक अक्तूबर के दूसरे पखवाड़े में पाई जाती है। सूक्ष्म प्रेक्षण से यह पता चलता है कि उपरोक्त (*i*) तथा (*ii*) दोनों अवधियों के दौरान प्रतिपवन तरंगें नियमित रूप से पूर्व की ओर बढ़ती रहती है और आरम्भ से अंत तक लगातार भारतीय प्रायद्वीप में विभिन्न वायु भार बनते रहते हैं। भारत में (90° पूर्व के पश्चिम में) तरंगों का विवरण चित्रों में प्रस्तुत किया गया है।

ABSTRACT. NOAA (AVHRR) imageries have been studied for four years from 1982 to 1985. Overlapping wave zones in different imageries of the same fortnight have been given successively higher weightage in the scale of 1 to 7. Different monochromatic hatching scheme for different weight has been adopted. Direction of wind at the level of wave and its wavelength has also been marked over the region. Thus, the climatology has been documented into 24 fortnights. The following two periods emerge, while waves are generally seen over the region.

(*i*) 16 November to 15 April – This includes Winter Season upto the beginning of pre-monsoon.

(*ii*) 01 June to 15 October – This includes Southwest monsoon upto the third week of postmonsoon.

The occurrence of lee waves during the transition period is less. They are the second fortnight of April till the end of May and the second fortnight of October till the middle of November. A scrupulous observation shows that during both the periods (*i*) and (*ii*) mentioned above there is systematic eastward shift of the leewave zones with gradual induction of different airmasses over Indian subcontinent from beginning till end. A pictorial representation of the waves over India (West of 90° E Long.) is presented here.

Key words – Climatology, Mountain wave, NOAA satellite.

1. Introduction

Launching of the first Weather Satellite TIROS-1 in 1960 opened a new and challenging field for the meteorologists world over. Conover (1964) first attempted to classify the types of clouds based on their distinctive futures. By using the cloud imageries obtained by weather satellites he observed that clouds associated with lee-

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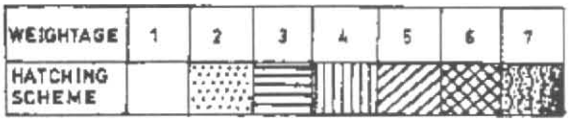


Fig. 1. Hatching scheme based on weightage

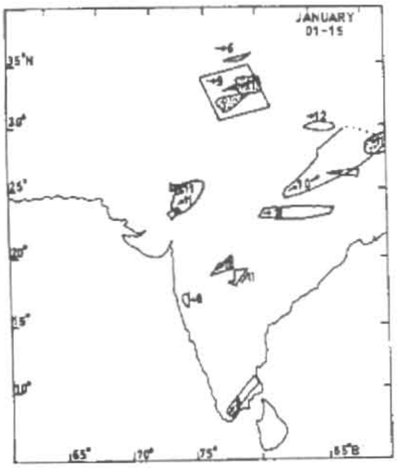


Fig.2. In the southern peninsula during the months of December and January, on rare occasions, lee-waves are observed, when the Equatorial airmass crosses the southern end of the Western Ghats

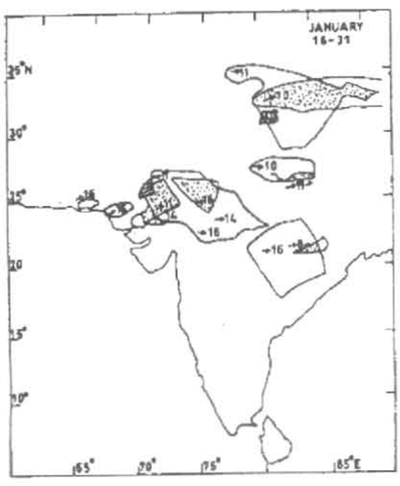


Fig.3. By the end of January, scattered zones of lee-wave clouds may be observed over the entire north India as Pc (in the wake of active western disturbance) establishes over the region

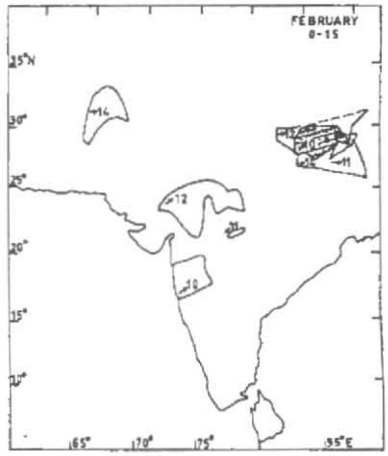


Fig.4. Gradually, by the end of February, the core region of occur-rence of lee-waves shift further eastward and lies around 86° E long.

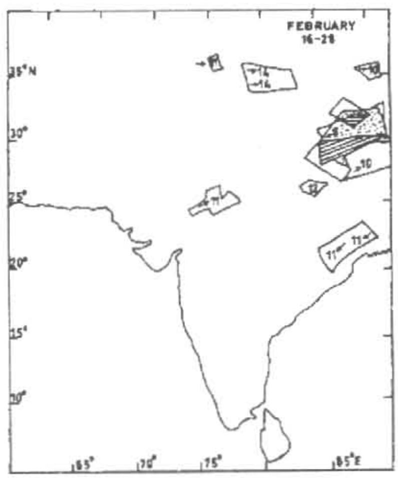


Fig.5. Month of March is synoptically marked with weak-ening of Siberian anticyclone and depleted induction of Pc airmass from Asia and Europe. Approach of this airmass over Tibet, Assam and Burma (By subsidence), however, continues over the Central/East Tibet

waves, commonly depicted simple and regular wave motion. Complex contour of the underlying terrain and wave interference from two or more peaks, however, introduced gaps and buckles in the individual bands. With the induction of Advanced Very High Resolution Radiometer (AVHRR) sensors on - board U.S. Polar orbiting satellite in TIROS-N (NOAA) series, the study of lee-waves with satellite imageries was greatly facilitated.

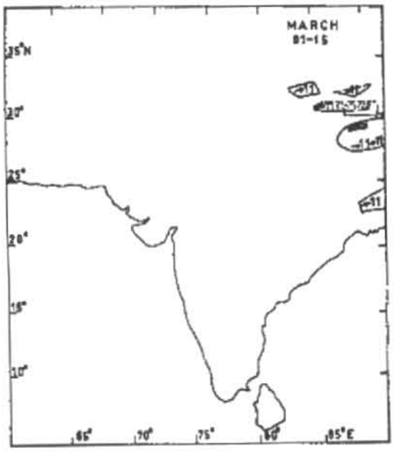


Fig.6. First fortnight of March is characterised by the beginning of the transition period. Pc airmass is replaced by Tc airmass over the western Himalayas and lies only over the eastern Himalayas and its neighbourhood with its source region from China and occasionally from adjoining seas. Hence although isolated patches of lee-wave can still be observed in the fortnight of the month over the Central and South-Central Tibet, its core region has shifted completely east of 90°E long

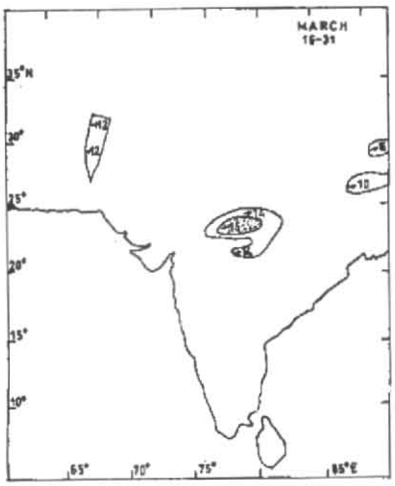


Fig.7. As the Tc airmass establishes over the country, the frequency of the occurrence of lee-wave clouds decreased significantly over the Himalayas as well as over the plains

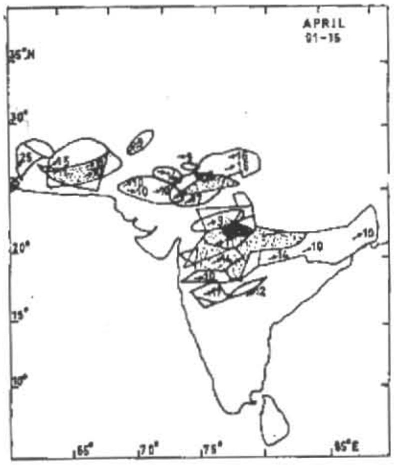


Fig.8. In the month of April, major portion of the country is under the sway of Tropical Continental (Tc) airmass, which originates in the Middle-East. Although this air, during its travel over Iran and Pakistan gets progressively heated and becomes unstable, but as it moves southwards over Arabian sea, the lower layer acquires moisture and becomes Tm Tc airmass. This modified airmass is not unstable in the lower layers, since it is less warm below (Tm) than warm Tc air above. Under favourable synoptic situation, if air flow exists across the mountain barriers (*e.g.* Aravali, Vindhya or Sathipura ranges), well marked lee-wave clouds may be observed over the planes of Central India. Since conditional instability is present in the atmosphere, vertical lifting due to the wave motion may also give rise to large cumulus buildups on favourable areas

NOAA satellites, with a resolution of 1.1 km provided an extremely useful platform for the study of lee-waves, since these waves are commonly observed in the wavelength band of 6–38 km. There are five-channel scanning radiometer, sensitive in the visible, near infrared and infrared regions. These channels are chosen in the windows of water vapour absorption spectrum.

Channel 2 and 4 are widely used Channel 2 (0.725 – 1.10) lies just beyond the visible (0.4 – 0.7) region. But, it is commonly considered as visible image made in sunlight. It can observe fairly well through the haze to the ground and through thin cirrus to lower cloud or ground. Hence, ground features, clouds, shadow and dense dust clouds are manifested by thischannel in a similar way as seen by human eyes. Channel 4 (10.5 – 11.5) lies close to the wavelength of maximum intensity of the black body emission spectrum at 300° K. Therefore, the intensity of the image depends on the temperature of the object as per the Stefen's law.

$$\text{Intensity} \propto (\text{temperature K})^4$$

This channel is particularly useful to observe lee-waves in the medium level against snow cloud background, since cold objects, *e.g.*, cirrus clouds, ice and snow surface are shown as white and warmer objects are progressively darker. Therefore, for observations of

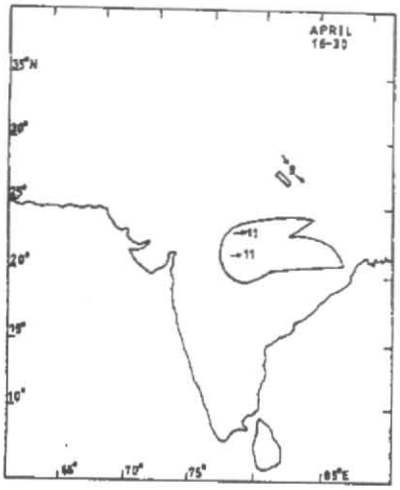


Fig. 9

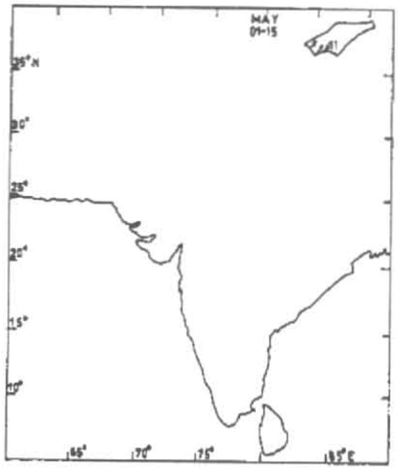


Fig. 10

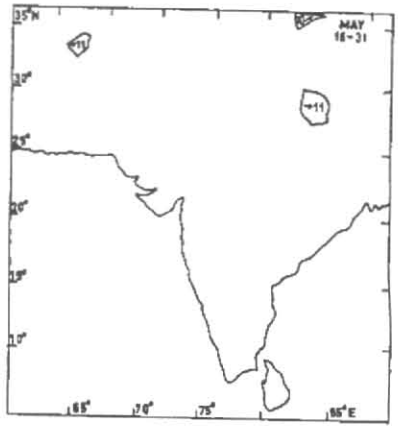
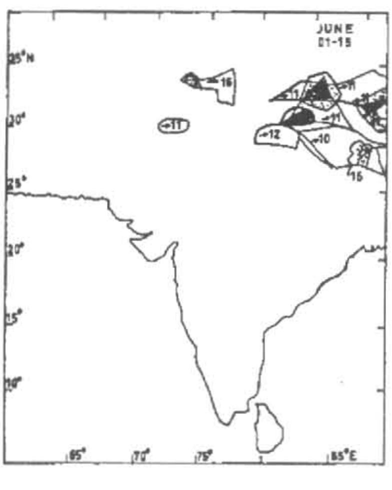


Fig. 11

Figs.9,10 & 11. The second fortnight of April is characterised by intense heating of the land mass resulting in hot unstable Tc airmass over the entire subcontinent. This situation continues till the end of May. Over the Himalayan region, in the wake of active western disturbance, very rarely, stable Pc or nPc airmass may penetrate result in a few patches of only isolated lee-wave clouds during this period. In general, therefore, no lee-wave cloud zones are observed anywhere, over the subcontinent during this period



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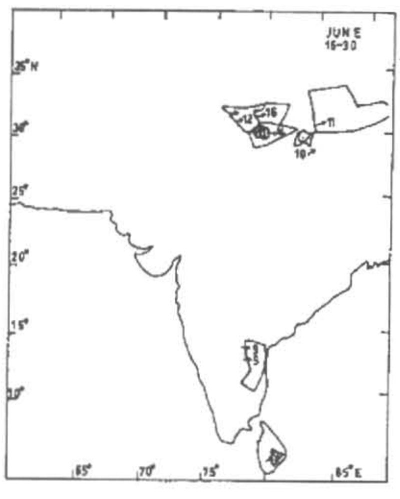


Fig. 13

Figs.12 &13. Em airmass of the plain of India becomes unfit to support the waves mainly due to the frequent instability induced due to latent heat of precipitation and cyclogenesis on the axis of monsoon trough. During monsoon season, however, Tc airmass which originates from Central Asia, the Middle East, Arabian and the North-West Africa serves as a favourable stable air for lee-waves to exist over the Himalayas. Hence, during the southwest monsoon season lee-wave may be frequently seen as the trapped moisture over the hills condenses to form systematic wave clouds

Himalayan region, where snow cover is quite a common feature during winter, this channel is particularly useful.

Over Indian region very limited and isolated documented studies are available on the satellite observed lee-waves. De (1970) had first of all mentioned such waves over NW India. He studied 16 typical cases of occurrence of waves over Assam and Burma region between January to March during 1966 – 68 with the help of ESSA-3 imageries. Sinha Ray (1988) also presented the observatioal evidence of mountain waves over the western Himalayas between July 1982 to October 1985 east

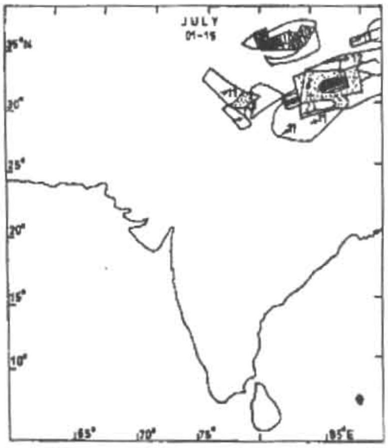
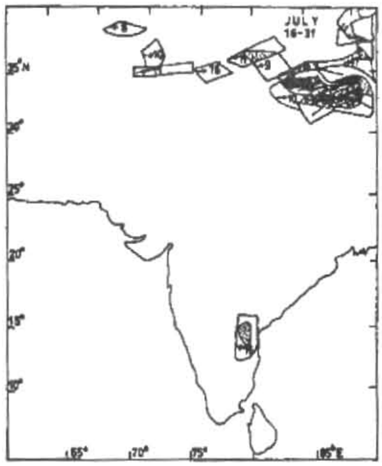


Fig. 14



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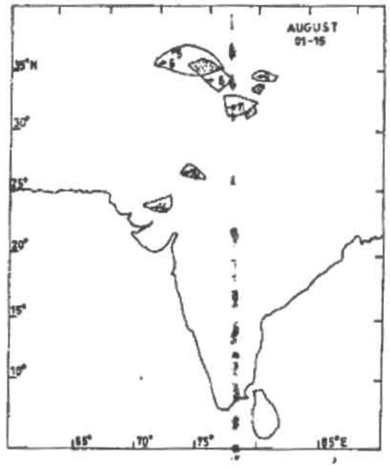

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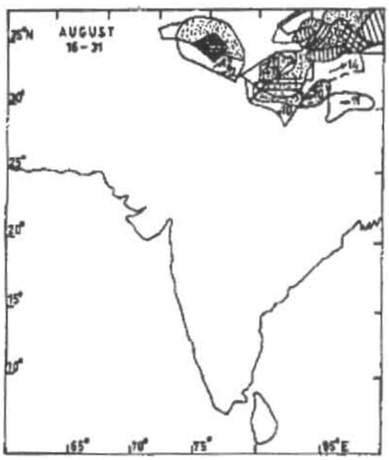

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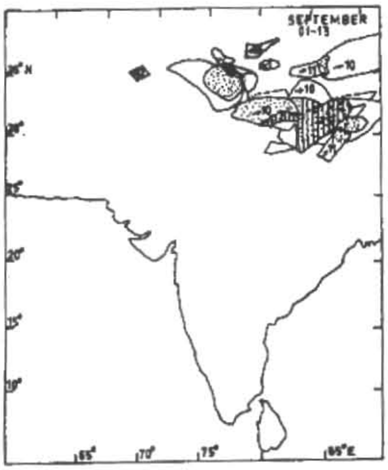

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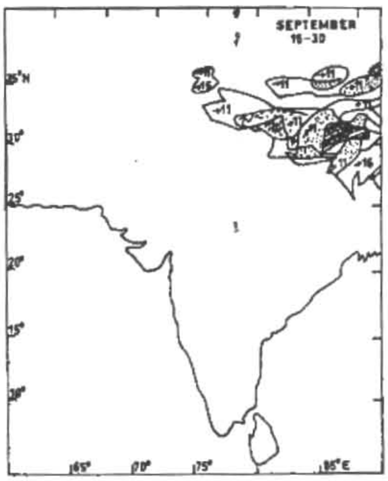

Fig. 19

Figs. 14,15,16,17,18 & 19. With the progress of season Tc air spreads eastward and southward over the Himalayas. Core region of lee-waves during July lies around 85° long. This zone progressively shifts eastward till winter months, though rate of shift is slower in summer. The occurrence of these waves is also fairly well marked till last week of September, covering vast areas extending from north J & K region to Central Tibet

of 90^0 E long. with the help of NOAA imageries. Findings in the present paper are to the west of 90^0E long. Both finding together are complementary to one another for the Indian region as a whole. Rao *et al.* (1989) in their study over NE India also reported waves with the help of LANDSAT satellite imageries. They studies 112 winter-pictures from 1980 to 1982. Due to limited repetitive of this satellite, one in 18 days – over one place, they could find only 7 occasions of mountain waves. Based on their restricted observations, they, however, concluded that mountain waves can occur all over the eastern region in Assam, Meghalaya, Burma, Bangladesh and Bhutan at different times. One advantage of chosing LANDSAT satellite was its good resolution (80 m). The study detected waves of 1 to 2 km over NE India. In the present climatic study it was noticed by the authors that Assam region in general shows occurrence of waves throughout the year. And climatically no season or region may be delineated as higher or lower wave-prone within NE India – east of 90°E long. In the present study, therefore, only Indian region west of 90°E long has been considered for preparing an atlas guide of climatic zones where lee waves

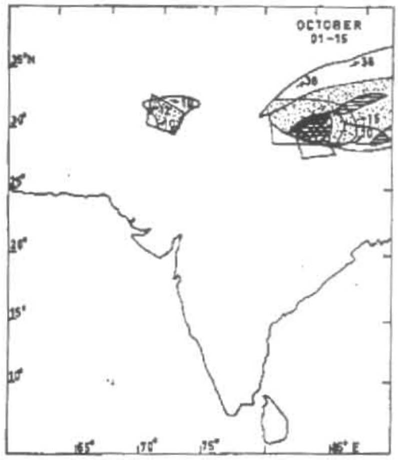

Fig. 20. In the first fortnight of October, the eastward shift of the core region is quite distinct. Thus, location of core region, now can be placed around 88°E long. which further shifts east of 90° E long. by the end of October

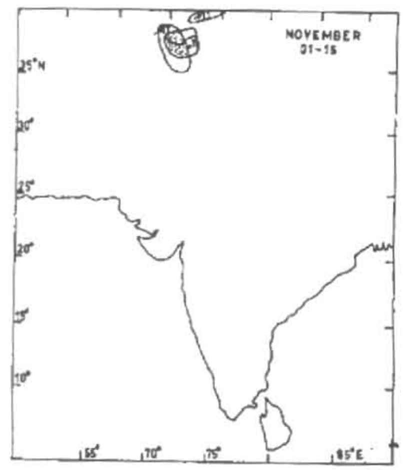

Fig.22. Intense Siberian anticyclone acts as one of the most extensive source of stable Polar Continental (Pc) airmass over western and eastern Himalayas. Thus, with the onset of winter in the first fortnight of November, lee-waves begin appearing over North-west Afghanistan and adjoining Russian region

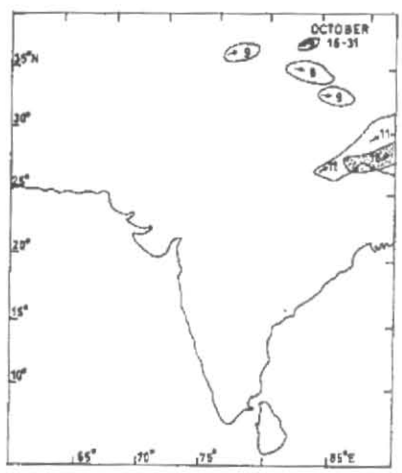

Fig. 21. By this time the summer pattern is gradually changing over to be replaced by winter pattern. Em airmass from the country has receded southward. With the weakening of the monsoon low over north-west India, Pakistan and adjoining Iran regions, the supply of Tc airmass also becomes less organised and hence the transition period begins. Remnants of Tc airmass overlying the Himalayan region gradually loses its large lapse rate, *vis-à-vis* stability. Thus, between 16 October and 15 November no lee-wave zones are observed anywhere over the country. Isolated patches of lee-wave (Fig.22) over North-East Afghanistan and adjoining Russian region is indicative of the approaching stable Pc airmass, *i.e.* sign of onset of winter season over the country

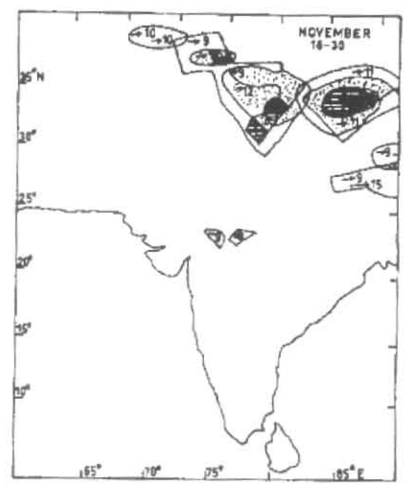

Fig. 23. By the end of November, as the Pc airmass spreads further over western and central Himalayas and Tibetan plateau, region of occurrence of waves gradually shifts East/South-eastward and lee-wave zones extend from J & K region to Central Tibet in a quite irregular and scattered manner

normally form in different fortnights. Great accuracy has been exercised in delineating the zones of lee-waves.

Identification of the occurrence of lee-waves is accomplished by a careful scrutiny of all the NOAA

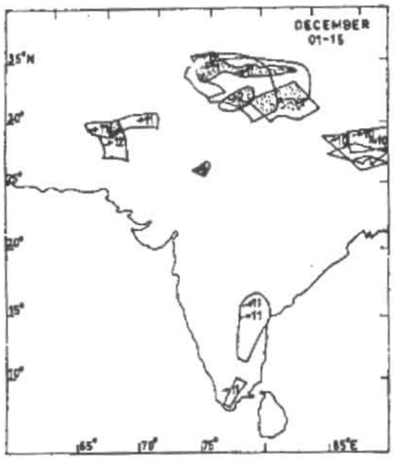

Fig. 24. As Pc airmass is established over the Himalayas in the first fortnight of December, the core region may be placed around 80° long. mainly confined to J & K and South-west Tibetan region

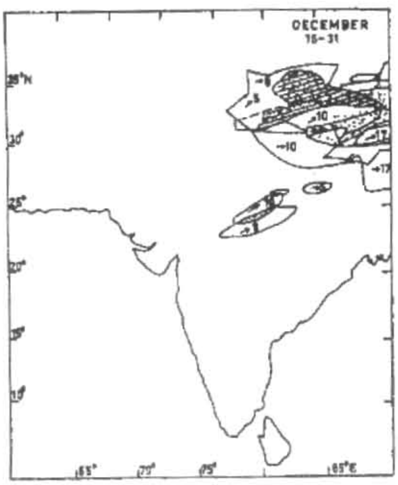

Fig. 25. The advancing airmass over N-W region retains its stability for some distance till it mixes with the already prevailing airmass over north India and modified into less stable transition Polar Continental airmass (nPc). The ridge of high pressure in NW-India acts as a secondary source of Pc air for north Indian plains. On occasions, after the passage of an active western disturbance, intense cold polar air penetrates into north India and lee-waves are observed even over west Uttar Pradesh and Madhya Pradesh regions, possibly due to the Vindhya and Aravali ranges

pictures. A complete familiarity on the interpretation of imageries is essential for such study. Though all such

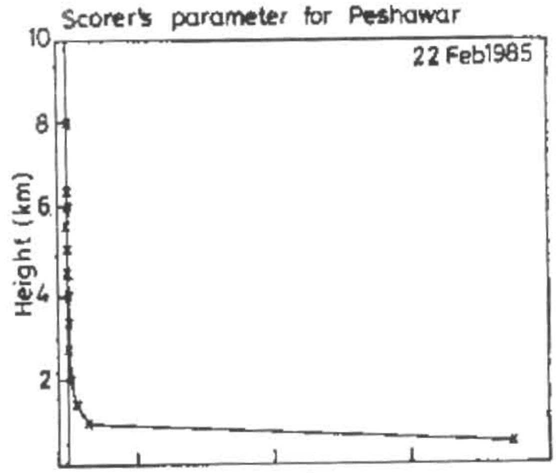

Fig. 26

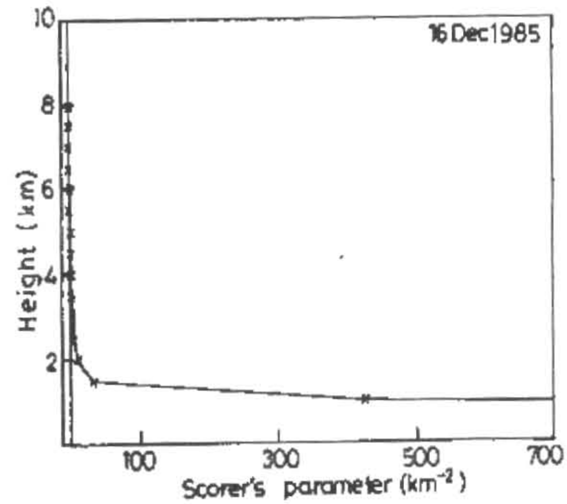

Fig. 27

occasions of lee-wave clouds have been identified, it is always kept in mind that non-occurrence of lee-wave clouds does not rule out the presence of wave-activity. The wave length and the location of such waves are measured with utmost care by proper gridding care by proper gridding of the imageries.

The present study is based on four years study from 1982 to 1985. 1986 pictures were not included since during this period many of the archived pictures were not having any gridding over it, at I.M.D. Lodi Road, New Delhi. This had severely restricted the continuity of the study in the fifth year *i.e.* 1986. It is, however, emphasised that 10 years study would certainly give a better delineation of occurrence and non-occurrence zones. But a beginning has been made in the present paper towards

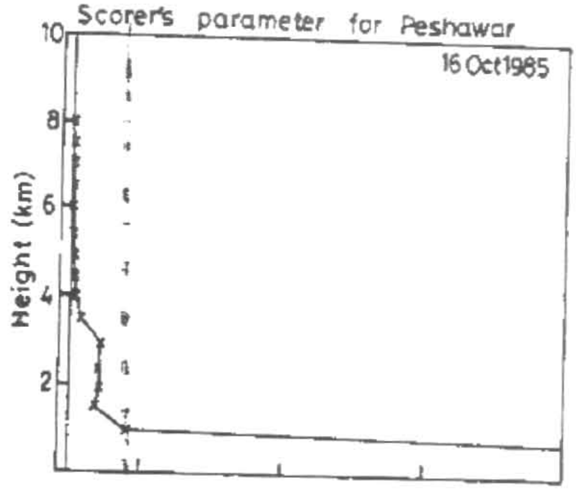

Fig. 28

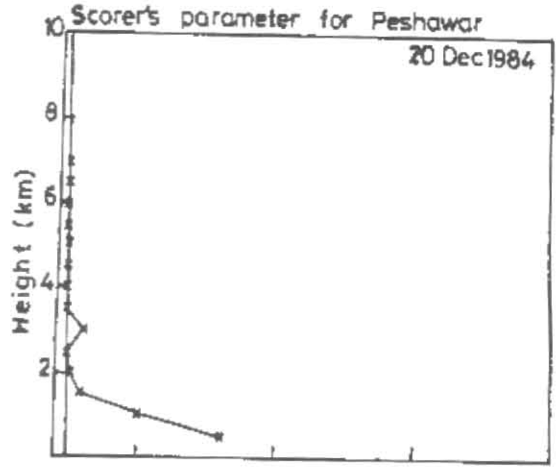

Fig. 30

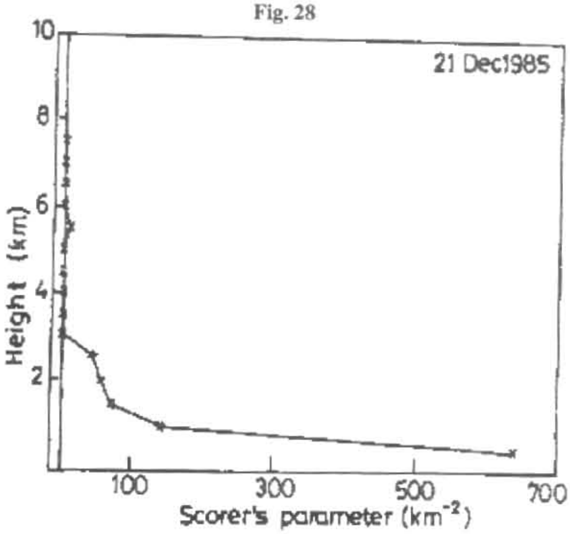

Fig. 29

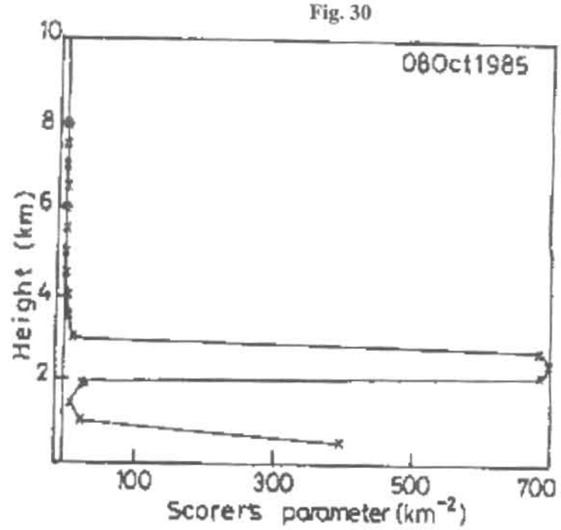

Fig. 31

making such an atlas available to users. At present there is no atlas available anywhere.

2. Area and period of study

In the present study, the Indian subcontinent lying between 60°E and 90°E long. and between 10°N and 35°N lat. has been considered. East of 90°E which includes N-E Himalayas and Assam region are not covered in this study. Since the occurrence of lee-waves over Assam (India), and Yunan region (China) are quite frequent, a similar study over these regions will also be quite revealing.

All the satellite pictures of the four year period between 1982 and 1985, were carefully examined and climatological details covering these four years have been documented in 24 fortnightly periods. For example, the first climatological period begins from 01 Jan and ends on 15 Jan. Each subsequent period covers 15-16 days. One consolidated map for each fortnight is presented.

2.1. *Methodology*

Since the objective of the present paper is to present on atlas to the users for ready reference, very great accuracy is needed in delineating the zones of the occurrence of lee - waves. If we resort to tabular representation, the fine details, of spatial occurrence cannot be presented. Hence it has been decided to provide only a pictorial representation in temporal span of one fortnight each. All the cases of occurrences of lee-waves during each fortnight as mentioned above were depicted on one transparency. Overlapping zones were given progressively higher weightage. Thus, areas which overlapped twice were given weightage 2 ; area which overlapped thrice were given weightage 3 and so on. Due to the curvature of earth's surface and the angle of inclination of the satellite, all pictures did not have the same alignment of the latitude and longitude. Hence, utmost care was taken in reprojecting each picture into a frame with identical vertical and horizontal longitudinal and latitudinal areas respectively. Suitable hatching scheme was adopted to ensure clarity in the understanding of the maps as shown in Fig 1.

All the 24 maps thus prepared are presented in Figs. 2- 25 in a sequential order. Each map represents the sum total of the lee-waves that can be observed in NOAA imageries during the corresponding fortnight of all four years (1982-85) under consideration.

3. Seasonal occurrence of airmasses and corresponding variations of lee-wave zone

3.1. Examination of lee-wave zones for various fortnights indicates their systematic eastward shift with gradual induction of different airmasses over the region. Periodic occurrence of lee-waves during any single year covers the following two periods :

(*i*) *Season – A* : Period including Winter season (16 November to 15 April).

(*ii*) Season – *B* : Period including South-west monsoon season (01 Jun to 15 October).

It has been observed that the lee-waves in winter season occur mainly due to stable Polar Continental (pc) or Transitional Polar Continental (nPc) airmasses and during Southwest monsoon season mainly due to Tropical Continental (Tc) airmasses over high altitudes in the Himalayas. These two periods (season's A and B) are interposed by two transition months, *i.e.* 16 April to 31 May (which includes pre-monsoon period) and 16 October to 15 November (which includes post-monsoon period). The frequency of occurrence of lee-waves over the entire country during the transition periods was almost nil.

3.2. Scrupulous study of Scorers parameter (commonly known as l^2) was carried out over Indian region, when mountain waves formed. l^2 is computed through following expression.

$$l^2 = \left(\frac{g\beta}{U^2} + \frac{U''}{U} + \frac{sU'}{U} - \frac{s^2}{4} + \frac{1}{2} s' \right)$$

where (′) refers to differentation with respect to z and

$$\beta = \frac{1}{\theta}\frac{d\theta}{dz}, \quad s = \frac{1}{\rho}\frac{d\rho}{dz}$$

θ = Potential temperature,

U = Wind velocity at right angle to the ridge,

g = Acceleration due to gravity,

ρ = Air density.

l^2 values were plotted against the height z (henceforth referred to as l^2 - profile). Broadly three l^2 - profile categories were identified which supported the formation waves. They are as under :

Category – I : Scorers parameter (l^2 - profile) exhibit very high l^2 - values below 1 km level and above this level rapidly decreases *w.r.t.* height *e.g.* Figs. 26 & 27.

Category – II : Scorer Parameter (l^2 - profile) exhibit very high l^2 - values below 1 km level. Between 1.0 & 3.0 km level it shows moderate values decreasing slowly or almost constant *w.r.t.* height *e.g.* Figs. 28 & 29.

Category – III : Scorers parameter (l^2 – profile) exhibit very high l^2 - values below 1 km which rapidly decreases aloft but three exists secondary maxima between 1.0 to 3.0 km *e.g.* Figs. 30 & 31.

4. Distribution of wavelength of the observed lee-wave clouds over the Indian region

The wavelength of lee-waves observed with the help of NOAA satellite pictures is shown on various fortnightly maps over different regions of the country. It is found that, in general, the lee-waves occur in the wavelength spectrum of 8 to 18 km over the Indian sub-continent.

Waves over Eastern Himalayas are having comparatively higher wavelength of the order of 15 to 18 km upto 90°E long. Further, east of this longitude, over Assam, Burma and Yunan regions (China), (not shown in the fortnightly maps), lee-waves of much longer wavelength (15-22 km) are observed. Over the Central India, wavelength of 9-14 km were observed in various months. Waves over peninsular India and Sri Lanka werea, however, comparatively shorter of 8-11 km. Waves over Pakistan / Baluchistan and Afghanistan regions are mostly slightly longer than those over Central Indian plains. They are, in general, of the order of 12-15 km length, although longer waves of the order of 25 km have also been observed over southwest Pakistan and adjoining Iran regions. Waves over Russian latitudes are appreciably smaller in length, 6-9 km or even less. Longest waves of the order of 38 km in length have also been observed over North Tibet and Kunlun-Shan regions (China).

In the present study, an analysis for the seasonal distribution of wavelengths has also been made. However, no convincing results *w.r.t.* relation between swave length and season could be established from the NOAA satellite imageries during the years 1982-85.

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