MAUSAM, 52, 2 (April 2001), 325-332

551.551.8 : 551.559 (235.512)

Momentum flux, energy flux and pressure drag associated with mountain wave across western ghat

SOMENATH DUTTA

Meteorological Office, Pune – 411 005, India

(Received 2 August 1999, Modified 30 June 2000)

सार - इस शोध-पत्र में भारत के पश्चिमी घाट के पर्वतीय भाग के मुम्बई-पुणे क्षेत्र में तरंग संवेग अभिवाह, तरंग ऊर्जा अभिवाह तथा पर्वतीय तरंग से संबद्ध दाब कर्षण को प्राचलीकृत करने का प्रयास किया गया है।

क्रॉस पवन दिशा में असीमित विस्तार वाले मेसोस्केल पर्वत पर स्थायी बेसिक प्रवाह (*U*) और स्थायी ब्रंट वैसला आवृत्ति (*N*) वाले द्विआयामी, घर्षणहीन, रूद्धोष्म, द्रवस्थैतिक, बूसिने प्रवाह पर यहाँ विचार किया गया है।

उर्ध्वाधर प्रवर्तन (अथवा अपक्षयी) तरंग में तरंग संवेग अभिवाह के अद्योमुखी (अथवा उर्ध्वमुखी) तथा तंरग उर्जा अभिवाह के उर्ध्वमुखी (अथवा अधोमुखी) होने का पता चलता है। यहाँ यह भी बताया गया है कि पश्चिमी घाट के घंटाकार वाले भाग की चौडाई के आधे भाग में दोनों अभिवाह स्वतंत्र होते हैं। पश्चिमी घाट में पर्वतीय तरंग के विभिन्न मामलों में दाब कर्षण के परिकलन तथा तरंग संवेग अभिवाह और तरंग ऊर्जा अभिवाह के उर्ध्वाधर प्रोफाइल का पता लगाने के लिए, पहले के शोधकर्ताओं से प्राप्त जानकारी के अनुसार विश्लेषणात्मक पद्धति से प्राप्त किए गए फार्मूले का उपयोग किया गया है।

ABSTRACT. An attempt has been made to parameterize the wave momentum flux wave energy flux and pressure drag associated with mountain wave across the Mumbai-Pune section of western ghat mountain in India.

A two dimensional frictionless, adiabatic, hydrostatic, Boussinesq flow with constant basic flow (*U*) and constant Brunt Vaisala frequency (*N*) across a meso scale mountain with infinite extension in the Cross wind direction, has been considered here.

It has been shown that for a vertically propagating (or decaying) waves the wave momentum flux is downward (or upward) and the wave energy flux is upward (or downward). It has also been shown that both the fluxes are independent of the half width of the bell shaped part of the western ghat. The analytically derived formula have been used to compute the pressure drag and to find out the vertical profile of wave momentum flux and wave energy flux for different cases of mountain wave across western ghat, as reported by earlier workers.

Key words – Mountain drag, Mountain wave, Wave momentum flux, Wave energy flux.

1. Introduction

When air flows over a mountain ridge, a stationary wave disturbance is set up in the air current. These waves, when analysed with respect to their wave length or period, fall into three categories: short waves of period much smaller than the half pendulum day are gravity waves; and longer waves with larger periods are quasi - geostrophic, planetary waves of the Rossby type. Meso scale mountain can excite only gravity waves (Emeis,1990). These gravity waves propagate upwards, transferring energy and momentum possibly to great heights. Because of the mountain waves the pressure is systematically higher on the upwind slopes than on the down wind slopes and thus exerting a net force on the ground. This force is known as pressure drag or mountain drag. It is one of the sinks in the atmospheric momentum budget. This drag is a sub grid scale phenomenon in a numerical weather prediction model and it is required to be parameterized. To achieve this the dependence of the drag on grid scale parameters must be known. Usually this pressure drag is splitted into three main components, form drag, wave drag and hydrostatic drag. Form drag again can be splitted into viscous form drag due to the viscosity of the air and turbulent form drag due to the additional production of turbulence mainly in the lee of the obstacle (Emeis, 1990). Wave drag includes the effects of gravity waves, inertial waves and Rossby waves. For meso scale mountain, inertial waves and Rossby waves do not occur. In response to the net pressure drop between the wind ward and leeward side of the mountain, the lee waves transport momentum from a stably stratified air stream to the earth's surface. Sawyer (1959) first pointed out the relative importance of this momentum loss, due to wave drag by meso-scale stationery lee waves in comparison with surface frictional drag over rough terrain. He examined a case of two-dimensional flow over a bell - shaped obstacle and determined that typical surface stress is of the order 1 - 10 dyne/cm^2. It was further confirmed by Blumen (1965). Bretherton (1969) provided additional confirmation by computing the stress due to two-dimensional flow over the Welsh mountains using observed atmospheric conditions. A conclusive verification of the importance of the wave drag, at least over the Front Range of the Colorado Rockies, was obtained from data collected by instrumental air craft and reported by Lilly (1972). Smith (1978) had determined the pressure drag on the Blue Ridge Mountain in the central Appalachians. During the first two weeks of January 1974 several periods with significant drag were observed by him with pressure differences typically 50N/m^2 across the ridge. It can be shown that the wave drag is equal to the vertical flux of horizontal momentum by the wave. Eliassen and Palm (1961) had shown that vertical flux of horizontal momentum does not change with height, except possibly at levels where basic flow (U) becomes zero. They had also shown that in a layer where U is everywhere positive the vertical fluxes of wave energy and that of momentum are of opposite sign. Smith and Yuh-Lang (1982) have confirmed the above theoretical findings of Eliassen & Palm. He has also shown that in the presence of thermal forcing, the mountain drag is reversed and the momentum flux is strongly convergent at the heating level.

In India mountain wave problem was studied by Das (1964), Sarker (1965, 66, 67), De (1971), Sarker *et al.* (1978), Sinha Ray (1988), Tyagi & Madan (1989), Kumar *et al.* (1995) *etc*. Over different mountains in India. But most of the above studies were concerned with properties of mountain wave. In India this is the first study addressing the problems of fluxes of momentum & energy generated by mountain waves over India.

In this paper attempt has been made to compute the value of pressure drag and to get the vertical profiles of wave momentum flux & wave energy flux associated with mountain wave across the Mumbai-Pune section of western ghat.

2. Data

For the present study we have selected those dates on which mountain wave was reported by Sarker (1965) and the Radiosonde data for those dates of Mumbai have been used.

3. Methodology

Let us consider an adiabatic hydrostatic frictionless, steady Boussinesq flow across a two-dimensional north south oriented ridge. It is assumed that the actual flow consists of a basic flow and a perturbation super imposed on the basic flow. It is also assumed that the basic flow is normal to the ridge and is constant with height. This constant value is taken as the mean of the basic flow at all levels upto the height where westerly component exists. Similarly it is also assumed that the Brunt-Vaisala frequency is constant with height. Here horizontal length scale is small enough so that effect of earth rotation may also be neglected. Under the above assumptions the linearized governing equations may be written as:

$$U\frac{\partial u'}{\partial x} = -\frac{1}{\rho'}\frac{\partial p'}{\partial x} \tag{1}$$

$$U\frac{\partial w'}{\partial x} = -\frac{1}{\rho_0}\frac{\partial p'}{\partial z} - g\frac{\rho'}{\rho_0} \tag{2}$$

$$\frac{\partial u'}{\partial x} + \frac{\partial w'}{\partial z} = 0 \tag{3}$$

$$U\frac{\partial \theta'}{\partial x} + w'\frac{d\theta_0}{dz} = 0 \tag{4}$$

Where U is basic state wind speed and ρ_0 is basic state density, a function of z only.

θ_0 is basic state potential temperature.

u', w' are zonal & vertical component of perturbation wind velocity.

ρ', p' and θ' are perturbation density, pressure & potential temperature respectively. Here we have taken the origin at 250 mtrs below the mean sea level.

Now if $\hat{f}(k,z)$ be the Fourier transform of any function $f(x,z)$ then we know that they are related by :

$$\hat{f}(k,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(x,z)\exp(-ikx)\mathrm{d}x \tag{5}$$

$$f(x,z) = \int_{-\infty}^{\infty} \hat{f}(k,z)\exp(ikx)\mathrm{d}k \tag{6}$$

Now performing Fourier transform on (1), (2), (3), & (4) we obtain the following equations:

$$ikU\rho_0\hat{u} = -ik\,\hat{p} \tag{7}$$

$$ikU\rho_0\hat{w} = -\frac{\partial\hat{p}}{\partial z} - g\hat{\rho} \tag{8}$$

$$ik\hat{u} + \frac{\partial\hat{w}}{\partial z} = 0 \tag{9}$$

$$ikU\hat{\theta} + \hat{w}\frac{d\theta_0}{dz} = 0 \tag{10}$$

Again using Poisson's equation for the basic flow & for the total flow we obtain:

$$\frac{\rho'}{\rho_0} = \frac{p'}{\gamma P_0} - \frac{\theta'}{\theta_0} \tag{11}$$

[where $P_0 = P_0(z)$, is the basic state pressure]

Since the fluctuation in density is more due to fluctuation in temperature than due to fluctuation in pressure, hence we have

$$\frac{\rho'}{\rho_0} = -\frac{\theta'}{\theta_0} \tag{12}$$

Performing Fourier transform on (12), we have

$$\frac{\hat{\rho}}{\rho_0} = -\frac{\hat{\theta}}{\theta_0} \tag{13}$$

Then it is readily seen that w satisfies the vertical structure equation

$$\frac{\partial^2\hat{w}}{\partial z} + \frac{1}{\rho_0}\frac{d\rho_0}{dz}\frac{\partial\hat{w}}{\partial z} + (l^2 - k^2)\hat{w} = 0 \tag{14}$$

Now by the substitution,

$$\hat{w} = \sqrt{\frac{\rho_0(0)}{\rho_0(z)}}\hat{w}_1 \tag{15}$$

equation (14) reduces to

$$\frac{\partial^2\hat{w}_1}{\partial z^2} + \left\{l^2 - k^2 + \frac{1}{4\rho_0^2}\left(\frac{d\rho}{dz}\right)^2 - \frac{1}{2\rho_0}\frac{d^2\rho_0}{dz^2}\right\}\hat{w}_1 = 0 \tag{16}$$

Now the last two terms in side bracket of equation (16) are very small compared to other terms, so they may be neglected. So equation (16) reduces to

$$\frac{\partial^2\hat{w}_1}{\partial z^2} + \{l^2 - k^2\}\hat{w}_1 = 0 \tag{17}$$

where, $l = \frac{N}{U}$, is the Scorer's parameter & N is the Brunt-Vaisala frequency.

Here in present case we take N to be independent of height and we shall take the vertically averaged value N throughout the atmosphere.

Now for a vertically propagating hydrostatic wave, we have, $k \ll l$. Hence the solution of (17) can be taken as

$$\hat{w}_1(k,z) = \mathrm{A}\exp(ilz) + \mathrm{B}\exp(-ilz) \tag{18}$$

Where, A, B are constants.

Again at the ground the flow is assumed to follow the terrain, thus

$$w(x, z=0) = U\frac{\partial\varsigma}{\partial x} \tag{19}$$

Where $\varsigma(x)$ represents the terrain height. Now the E-W profile of western ghat in the X-Z plane along Mumbai-Pune section is given by as Sarkar (1965).

$$\varsigma(x) = \frac{a^2 b}{a^2 + x^2} + a'\tan^{-1}\frac{x}{a} \tag{20}$$

Where $a = 18.0$ km, $b = 0.52$ km,

$a' = \frac{2\times.35}{\pi}$ km, where $\pi = \frac{22}{7}$

Now,

$$\hat{w}_1(k,0) = \hat{w}(k,0) = Uik\left(ab - i\frac{a'}{k}\right)\exp(-ak) \tag{21}$$

Thus from (18) & (21) we obtain

$$\mathrm{A+B} = Uik\left(ab - i\frac{a'}{k}\right)\exp(-ak) \tag{22}$$

Again to allow the energy to propagate upward, we must have B = 0

Therefore,

$$\mathrm{A} = Uik\left(ab - i\frac{a'}{k}\right)\exp(-ak) \tag{23}$$

Thus,

$$\hat{w}_1(k,z) = \mathrm{A}\exp(ilz) = Uik\left(ab - i\frac{a'}{k}\right)\exp(-ak + ilz) \qquad (24)$$

Now the pressure drag per unit length along the ridge is given by:

$$\mathrm{F} = \int p'dx = \int_{-\infty}^{\infty} p'\frac{\partial\varsigma}{\partial x}\mathrm{d}x \qquad (25)$$

[Gill(1982)]

Again from Bernoulli's theorem we know that for a flow at any level the sum of kinetic energy & pressure energy is constant. Hence at any level we have

$$\frac{u^2}{2} + \frac{p}{\rho_0} = \text{constant}, \qquad (26)$$

(since ρ_0 is homogeneous horizontally)

Bernoulli's theorem for the mean flow is

$$\frac{U^2}{2} + \frac{P_0}{\rho_0} = \text{constant}, \qquad (27)$$

Again $u = U + u'$, $p = P_0 + p'$

Hence (26) reduced to

$$\frac{(U+u')^2}{2} + \frac{P_0 + p'}{\rho_0} = \text{Constant} \qquad (28)$$

Subtracting (27) from (28) and after applying perturbation hypothesis we obtain

$$Uu' + \frac{p'}{\rho_0} = 0, \ i.e., p' = -\rho_0 Uu' \qquad (29)$$

Again,

$$w'(x, z=0) = U\frac{\partial\varsigma}{\partial x} \qquad (30)$$

Thus applying (29) & (30) in (25) we obtain,

$$\mathrm{F} = -\int_{-\infty}^{\infty}\rho_0 u'w'(x, z=0)\mathrm{d}x \qquad (31)$$

Again the momentum flux generated by mountain wave at any level in the atmosphere is given by the momentum flux integral $\int_{-\infty}^{\infty}\rho_0 u'w'\mathrm{d}x$

Thus from (31) it is clear that pressure drag is equal to the negative of the wave momentum flux *i.e.* the wave drag generated by mountain wave in the layer of the atmosphere bounded by the bottom & top of the mountain.

From the above equation (31) it is seen that here horizontal momentum budget at any level contains only two terms; a momentum sink at the lower boundary and a momentum source at that level. The momentum source is a downward flux of momentum due to wave motion forced by the presence of the mountain in the stratified flow. This wave momentum flux is convergent in the layer below the level under consideration and the momentum is transferred to the surface via pressure force. The momentum had been extracted from the flow far aloft.

$$\text{Now momentum flux} = \int_{-\infty}^{\infty}\rho_0 u'w'\mathrm{d}x \qquad (32)$$

$$\text{Now, } \int_{-\infty}^{\infty} u'w'\mathrm{d}x = 2\pi\int_{-\infty}^{\infty}\hat{u}\hat{w}*\mathrm{d}k$$

Where, $\hat{w}*$ is the complex conjugate $\hat{w}$. Since, here we consider only non-negative wave number, hence

$$\int_{-\infty}^{\infty}u'w'\mathrm{d}x = 2\pi\int_0^{\infty}\hat{u}\hat{w}*\mathrm{d}k = 2\pi\int_0^{\infty}\frac{-1}{ik}\hat{w}*\frac{\partial\hat{w}}{\partial z}\mathrm{d}k \ \text{[from(9)]}$$

$$= 2\pi i\int_0^{\infty}\frac{\hat{w}*}{k}\frac{\partial\hat{w}}{\partial z}\mathrm{d}k \qquad (33)$$

$$\text{Now, } \hat{w}_1(k,z) = Uk\left(\frac{a'}{k} + iab\right)\exp(-ak + ilz)$$

$$\hat{w}(k,z) = \sqrt{\frac{\rho_0(0)}{\rho_0(z)}}Uk\left(\frac{a'}{k} + iab\right)\exp(-ak + ilz)$$

Hence,

$$\frac{\partial\hat{w}}{\partial z} = \sqrt{\frac{\rho_0(0)}{\rho_0(z)}}Uk\left(\frac{a'}{k} + iab\right)\left(il - \frac{1}{2\rho_0(z)}\right)\exp(-ak + ilz)$$

$$\text{and, } \hat{w}* = \sqrt{\frac{\rho_0(0)}{\rho_0(z)}}Uk\left(\frac{a'}{k} - iab\right)\exp(-ak - ilz)$$

Hence,

$$\hat{w}*\frac{\partial\hat{w}}{\partial z} = \frac{\rho_0(0)}{\rho_0(z)}U^2k^2\left(\frac{a'^2}{k^2} + a^2b^2\right)\left(il - \frac{1}{2\rho_0(z)}\right)\exp(-2ak) \qquad (34)$$

Now, using (34) in (33) we get,

$$\int_{-\infty}^{\infty} u'w'\mathrm{d}x = 2\pi\frac{\rho_0(0)}{\rho_0(z)}\left(-l-\frac{i}{2\rho_0(z)}\right)U^2\int_0^{\infty}\left(\frac{a'^2}{k}+a^2b^2k\right)\exp(-2ak)\,\mathrm{d}k$$

Since the left hand side of the above is purely a real quantity, hence

$$\int_{-\infty}^{\infty} u'w'\,\mathrm{d}x = -2\pi NU\frac{\rho_0(0)}{\rho_0(z)}\left(\begin{array}{l}\int_0^{\infty}\frac{a'^2}{k}\exp(-2ak)\,\mathrm{d}k\\ +\int_0^{\infty}a^2b^2k\exp(-2ak)\,\mathrm{d}k\end{array}\right) \quad (35)$$

$$\text{Now, } \int_0^{\infty} k\exp(-2ak)\mathrm{d}k = \frac{1}{4a^2} \quad (36)$$

To evaluate $\int_0^{\infty}\frac{\exp(-2ak)}{k}\mathrm{d}k$, let us first consider

$$\int_0^{\infty}\exp(-ak)\exp(ikx)\mathrm{d}k = \frac{\mathrm{d}\left[\tan^{-1}\frac{x}{a}+\frac{i}{2}\ln\left(\frac{a^2+x^2}{a^2}\right)\right]}{\mathrm{d}x}$$

So, Fourier transform of $\frac{\mathrm{d}\left[\tan^{-1}\frac{x}{a}+\frac{i}{2}\ln\left(\frac{a^2+x^2}{a^2}\right)\right]}{\mathrm{d}x}$

$= exp(-ak)$

Thus, Fourier transform of

$$\tan^{-1}\frac{x}{a}+\frac{i}{2}\ln\left(\frac{a^2+x^2}{a^2}\right) = \frac{\exp(-ak)}{ik}$$

Hence,

$$\int_0^{\infty}\frac{\exp(-ak)\exp(ikx)}{k} = i\left[\tan^{-1}\frac{x}{a}+\frac{i}{2}\ln\left(\frac{a^2+x^2}{a^2}\right)\right]$$

for all x. (37)

putting $x = 0$ in (35),

$$\text{we obtain } \int_0^{\infty}\frac{\exp(-ak)}{k}\mathrm{d}k = 0 \quad (38)$$

$$\text{So, } \int_0^{\infty}\frac{\exp(-2ak)}{k}\mathrm{d}k = 0 \quad (39)$$

Using (36) & (39) in (35) we obtain

$$\int_{-\infty}^{\infty} u'w'\mathrm{d}x = -\frac{\pi NUb^2}{2} \quad (40)$$

So, the momentum flux at any level in the vertical is given by

$$\int_{-\infty}^{\infty} \rho_0(z)\,u'w'\mathrm{d}x = -\frac{\pi\rho_0(0)NUb^2}{2} \quad (41)$$

Thus (41) shows that for a vertically propagating (or decaying) mountain wave across western ghat along Mumbai-Pune section, the flux of wave momentum at any level is vertically downward (or upward) and it is independent of the half width of the bell shaped portion. It is also clear from (39) that the plateau portion $\left(a'\tan^{-1}\frac{x}{a}\right)$ of the mountain does not contribute towards the generation of wave momentum flux.

Again the pressure drag or mountain drag across western ghat $= -\int_{-\infty}^{\infty}\rho_0(0)u'w'(x, z=0)$

$$= \frac{\pi\rho_0(s)NUb^2}{2} \quad (42)$$

where $\rho_0(s)$ is the average of the densities at 1000hPa, 950hPa & 900hPa.

Equation (41) shows that vertical wave momentum flux associated with mountain wave across Pune-Mumbai section of western ghat is independent of height, which is in conformity with earlier findings of Eliassen & Palm (1961) and Smith & Lin (1982). Vertical profile of wave momentum flux for a typical case has been shown in Fig. 1.

Now the vertical flux of wave energy is given by

$$E = \int_{-\infty}^{\infty} p'w'\mathrm{d}x \quad (43)$$

[Eliassen & Palm (1961)]

$$= 2\pi\int \hat{p}\hat{w}^*\mathrm{d}k \quad (44)$$

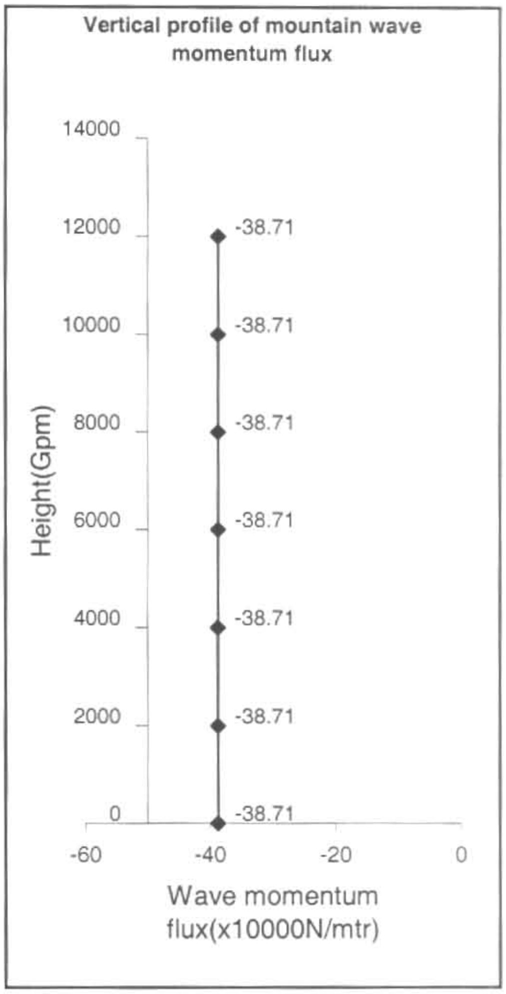

Fig. 1. Vertical profile of mountain wave momentum flux

Again from (7) we have $\hat{p} = -U\rho_0(z)\,\hat{u}$.

Hence vertical flux of wave energy

$$= -2\pi U\rho_0(z)\int_0^{\infty} \hat{u}\hat{w}^* \mathrm{d}k = -U\int_{-\infty}^{\infty} \rho_0(z)\,u'w' = \pi\rho_0(0)\,NU^2b^2 \tag{45}$$

Thus from (45) it is clear that the flux of wave energy is vertically upward (or downward) for a vertically propagating (or decaying) mountain wave. Thus the vertical flux of wave energy and wave momentum are oppositely directed. This is in conformity with the findings of Eliassen & Palm(1961). The same equation also shows that wave energy flux is independent of height, which is in conformity with earlier findings of Eliassen & Palm (1961).

The vertical profile of wave energy flux for a typical case has been shown in Fig. 2.

4. Results and discussion

Results of this study consist of computation of mountain drag, vertical flux of wave momentum, and vertical flux of wave energy.

Expression for mountain drag at surface, given by equation (31), shows that the mountain drag at surface is equal to the downward flux of wave momentum in the layer between the top and bottom of the mountain.

Wave momentum flux at any level is given by (41). Vertical profile of wave momentum flux is shown for a typical case under study in Fig. 1. This shows that wave momentum flux at any level is downward. This result can be used to interpret turbulence generated by gravity waves. Since the wave momentum flux is downward at any level, hence the momentum is being extracted from that level and passed to the ground *via* pressure force. Consequently at a certain time the basic wind speed may be equal to the horizontal phase speed of the wave, so that the intrinsic frequency of the wave becomes zero at that level.

Another one important result is that, the plateau part of the Pune - Mumbai section of western ghat does not contribute towards the generation of momentum flux. This can be explained physically also. It is clear that wave drag is due to the net pressure difference between the wind ward and leeward side of the mountain. All the air masses coming to the windward side of the mountain can not come to the leeward side flowing over the mountain. Thus a high pressure forms on windward side and low pressure on leeward side. But the plateau portion behaves like a plane land and there is no such formation of alternate high pressure and low pressure area. Hence perturbation pressure distribution will be uniform over the plateau, as a result of which plateau cannot contribute to the wave momentum flux.

Wave energy flux at any level is given by the expression (45). Vertical profile of wave energy flux is shown for a typical case under study in Fig. 2. From this figure it is seen that wave energy flux is directed vertically upward at any level. It should be so also, because, the source of disturbance *i.e.*, the wave energy is the mountain, which is at surface.

While discussing vertical flux of wave momentum it has been pointed out that, due to continuous extraction of momentum from mean flow by the vertically propagating internal gravity wave, excited by a mountain, at some level intrinsic frequency of the wave becomes zero. In such situation the wave breaks down and all the wave energy is transferred to the mean flow, which makes the mean flow turbulent.

Computation of mountain drag for different cases is given below in tabular form.

S. No	*Date*	*Time* (UTC)	*Mean basic flow* (m/s)	*Mean Brunt Vaisala frequency* (/s)	*Mountain drag or Pressure drag* (N/m)
1.	4 Jan '59	1200	12.3	0.60	3381501
2.	21 May '59	1200	13.7	0.61	3849731
3.	6 Dec '60	1200	12.3	0.61	3466613
4.	14 Dec '60	0000	6.7	0.61	1892394
5.	26 Dec '60	0000	9.6	0.61	2686633
6.	6 Mar '65	0000	12.8	0.61	3689302

5. Conclusions

From the above study following conclusions can be made:

(*i*) The mountain drag or pressure drag across Mumbai - Pune section of western ghat is independent of the half width of bell shaped portion of the mountain.

(*ii*) Wave momentum flux is vertically downward (or upward) for a vertically propagating (or decaying) mountain wave and is independent of the half width of the bell shaped portion of western ghat mountain.

(*iii*) Wave energy flux is vertically upward (or downward) for a vertically propagating (or decaying) mountain wave and is independent of the half width of the bell shaped portion of western ghat mountain.

(*iv*) The plateau part of the Mumbai-Pune section of western ghat mountain does not contribute towards the generation of mountain drag, wave momentum flux & wave energy flux.

(*v*) In the cases under study the values of mountain drag, in general lies between 20,00000N/m and 40,00000 N/ m.

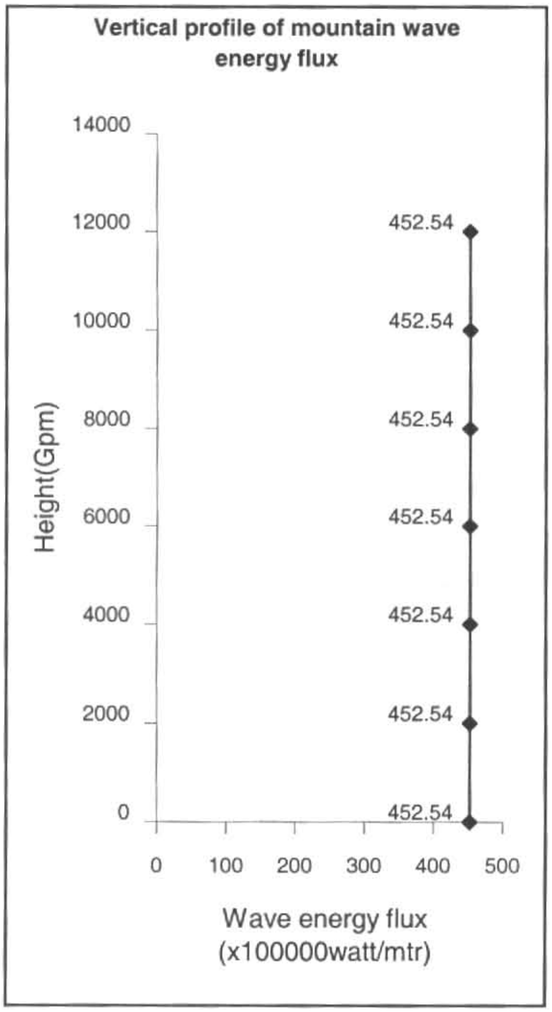

Fig. 2. Vertical profile of mountain wave energy flux

Acknowledgements

The author is thankful to DDGM (WF) for his kind support and facilities provided to carry out this research work.

Author is grateful to Dr.U.S.De, ADGM(R), for his valuable guidance in carrying out this study. The author is also indebted to Dr. K. C. Sinha Ray, Director, ADGM(R) Office for his useful suggestions and discussions on this topic.

Thanks are also due to Sri A.V. Pawer and Sri Amit Kesarkar for the preparation of the paper.

References

Blumen, W., 1965, "A random model of momentum flux by mountain waves", *Geofys. publ.*, **26**, 1-33.

Bretherton, F.P., 1969, "Momentum transport by gravity waves", *Quarterly journal of Royal meteorological society*, **95**, 213-243.

Das, P.K., 1964, "Lee waves over large circular mountain", *Indian journal of meteorology and geophysics*, **15**, 4, 547-554.

De, U.S., 1971, "Mountain waves over north east India and neighbouring region", *Indian journal of meteorology and geophysics*, **22**, 3, 361-364.

Eliassen, A. and Palm, E., 1961, "On the transfer of energy in stationary mountain waves", *Geophys.publ.*, **22**(3), 1-23.

Emeis, S.,1990, "Surface pressure distribution and pressure drag on mountains", *Meteorology and Atmospheric physics*, **43**, 173-185.

Gill, A.E., 1982, "Atmosphere and ocean dynamics", Academic press.

Kumar, P., Singh, M.P., Padmanabhan, N. and Natarajan, N., 1995, "Effect of latent heat release on mountain waves in a sheared mean flow", *Mausam*, **46**, 2, 111-126.

Lilly, D.K., 1972, "Wave momentum flux - A GARP problem", *Bulletin of American Meteorological society*, **53**, 17-23.

Sawyer, J.S., 1959, "The introduction of the effects of topography into methods of numerical forecasting", *Quarterly journal of Royal meteorological society*, **85**, 31-43.

Sarker, R.P., 1965, "A theoretical study of mountain waves on western ghat", *Indian journal of meteorology and geophysics*, **16**, 4, 563-584.

Sarker, R.P., 1966, "A dynamical model for orographic rainfall", *Monthly weather review*, **94**, 9, 555-572.

Sarker, R.P., 1967, "Some modification in a dynamical model of orographic rainfall", *Monthly weather review*, **95**, 673-684.

Sarker, R.P., Sinha Ray, K.C. and De,U.S., 1978, "Dynamics of orographic rainfall", *Indian journal of meteorology and geophysics.*, **29**, 1&2, 335-348.

Sinha Ray, K.C., 1988, "Satellite observations of mountain waves over north east India and neighbouring regions and their theoretical verification", *Mausam*, **39**, 3, 257-262.

Smith, R.B., 1978, "A measurement of mountain drag", *Journal of the atmospheric science*, **35**, 9, 1644-1654.

Smith, R.B. and Lin, Yuh-Lang, 1982, "The addition of latent heat to stratified air stream with application to the dynamics of orographic rain", *Quart. Journal of Royal meteorological society*, **108**, 353-378.

Tyagi, A. and Madan, O.P., 1989, "Mountain waves over Himalayas", *Mausam*, **40**, 2, 181-184.