A Source-Like Model for Two-Dimensional Airflow Over Mountain Ranges: Comparison with Field Experiments

DANIEL T. VALENTINE
David W. Taylor Naval Ship Research and Development Center
Bethesda, Maryland 20084

TIMOTHY W. KAO
The Catholic University of America
Washington, D.C. 20064

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ABSTRACT

A source-like model for two-dimensional airflow over mountain ranges is used to generate a steady-state solution from prescribed mean atmospheric values as initial conditions. A pronounced mid-tropospheric jet with upstream blocking and two lee-wave modes are found. Downward momentum flux as well as phase differences between the (u', v') velocity components in the lee-wave system are given. The results are in good agreement with field observations of the Colorado lee-wave experiments.

1. Introduction

When wind flows across a mountain range waves are generated on the lee side due to the density stratification in the troposphere. Sometimes cloud formations and, in particular, lee wave (altocumulus lenticularis) clouds at various heights in the lee wave system reveal the existence of these waves (e. g., Flohn (1969)). On February 17, 1970, a day when a steady cross-mountain wind occurred, data were obtained from instrumented aircraft flights in a mountain wave west of Denver, Colorado. Lilly (1971) and Lilly and Kennedy (1973) presented the data analysis and results of this observational program which was conducted to investigate the mountain lee wave and associated turbulence and wind phenomena in Colorado. The temperature, pressure, and motion field components were measured. In the Lilly and Kennedy (1973) study emphasis was put on the determination of the downward flux of westerly momentum generated by the wave. Their results are compared in this paper with a theoretical analysis of a similar lee wave system.

Wong and Kao (1970) investigated the effects of stratified flow over an extended obstacle to study the effect of irregular topography on vertical wind shear. For a medium of finite depth, they computed the streamlines (represented by lines of constant density) indicating the lee waves behind a source like disturbance, and the upstream velocity profile. Their work points to the importance of topographical influence on wind shear in the vertical within the troposhere, and the establishment of steady wind and density profiles characterized by variable local Richardson numbers independent of thermal wind effects, provided the topography is source-like. To investigate the flow over a mountain range the source model is perhaps the appropriate model to use as compared with a closed body model. This is because, first, the earth's topography downstream of the mountain is irregular and not flat as a closed body model would suggest. Second, the high levels of sporadic turbulence observed by Lilly and Kennedy on the downstream side of the Rocky Mountains indicate the possibility of a separated wake region, the effects of which would persist for great distances downstream. Such separated flow has also been reported in laboratory experiments by Davis (1969). Finally, the blocking effects observed in the approach flow are known to be caused by source-like disturbances. In this paper, with the same assumptions made by Wong and Kao (1970), formulas for the horizontal and vertical velocity perturbations downstream of a source-like disturbance in a finite, density stratified medium are developed. From these equations the average momentum flux is computed. A calculation is presented for a densimetric Froude number equal to 0.145 corresponding to the average mean flow observations reported by Lilly and Kennedy. The upstream velocity profile, the lee waves, and the downstream momentum flux profile for the steady-state limit are presented graphically. The results which show two lee wave modes and two upstream modes are compared with the observations of Lilly and Kennedy (1973).

2. Mathematical Formulation

The governing equations for an inviscid, incompressible fluid, under the Boussinesq and Oseen approximations, are:

$$\rho_0\left(\frac{\partial u}{\partial t}+U\frac{\partial u}{\partial x}\right)=-\frac{\partial p}{\partial x} \tag{1}$$

$$\rho_0\left(\frac{\partial v}{\partial t}+U\frac{\partial v}{\partial x}\right)=-\frac{\partial p}{\partial y}-\rho g \tag{2}$$

$$\frac{\partial \rho}{\partial t}+U\frac{\partial \rho}{\partial x}=-v\frac{d\bar{\rho}}{dy} \tag{3}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=q(x, y, t) \tag{4}$$

where ρ_0 is a constant mean density over the whole layer, $\bar{\rho}$ the unperturbed equilibrium density distribution, U the uniform flow, p the pressure perturbation, (u, v) the velocity perturbation, g the acceleration due to gravity which acts in the $-y$ direction, and q the source disturbance in the flow. From equations (1) through (4) we obtain the following equations for ρ alone, u alone, and v alone:

$$\left[\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)+N^2\frac{\partial^2}{\partial x^2}\right]\rho = \frac{\rho_0 N^2}{g}\frac{\partial}{\partial y}\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)q \tag{5}$$

$$\left[\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)+N^2\frac{\partial^2}{\partial x^2}\right]u = \frac{\partial}{\partial x}\left[\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2+N^2\right]q \tag{6}$$

$$\left[\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)+N^2\frac{\partial^2}{\partial x^2}\right]v = \frac{\partial}{\partial y}\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2 q \tag{7}$$

where $N^2=(-g/\rho_0)(d\bar{\rho}/dy)$ is the square of the Brunt-Väisälä frequency and is assumed constant in this investigation.

For the troposphere wind system which behaves like a medium with finite depth, it is assumed that a flow between paralled planes, $y=0$ and $y=d$, over a barrier generated by a source distribution is an appropriate model. The proper boundary condition on $y=0$ and $y=d$ is, of course, $v=0$, which, in terms of ρ, is

$$\frac{\partial \rho}{\partial t}+U\frac{\partial \rho}{\partial x}=0 \text{ on } y=0 \text{ and } y=d \tag{8}$$

Equations (3), (5), and (8) form the proper initial-boundary value problem where the source is switched on at time $t=0$, i.e., the source disturbance is $q(x, y)H(t)$.

Wong and Kao (1970) solved the equations for the density perturbation by taking the Fourier-Laplace transform in x and t and the finite Fourier sine transform in y. Taking the inverse of the transformed equation and using the Tauberian theorem, they obtained the solution for large time. The corresponding integrals were evaluated by the method of residues about the appropriate singularities. To do the integral in the inversion theorem for the x-dependence, the following argument was applied to simplify the integrand, and thereby make the problem tractable. In the steady state limit it can be argued from group velocity considerations introduced by Lighthill (1967) that contributions to the fore and after unattenuated waves come from poles at the value of zero of the exponential coefficient of the x-dependent Fourier transform. Using this idea, Wong and Kao simplified the denominator of the inversion theorem integral for the x-dependence. The details of the development of the density perturbations are presented presented in Wong and Kao (1970), and, therefore, will not be repeated here. With $q(x, y)=Q\delta(x)\delta(y)$, which means the Fourier transformed value $q=Q/\mathrm{d}$, the dimensionless total density field obtained by Wong and Kao is given by the equations:

$$r=(1-\bar{\beta}\eta)+\varepsilon\left\{\sum_{n=1}^{m}\frac{\sin n\pi\eta}{1-n\pi F}+\sum_{n=\pi+1}^{\infty}\frac{n\pi F\sin n\pi\eta}{n^2\pi^2F^2-1}\exp[(n^2\pi^2F^{-2})^{1/2}\xi]\right\},\ \text{for } \xi<0 \tag{9}$$

$$r=(1-\bar{\beta}\eta)$$
$$+\varepsilon\Big\{\sum_{n=1}^{m}\Big[\frac{\sin n\pi\eta}{1+n\pi F}+\frac{n\pi F\sin n\pi\eta}{1-n^2\pi^2F^2}$$
$$2\cos((F^{-2}-n^2\pi^2)^{1/2}\xi)\Big]$$
$$+\sum_{n=m+1}^{\infty}\frac{n\pi F\sin n\pi\eta}{n^2\pi^2F^2-1}$$
$$[2-\exp((-n^2\pi^2F^{-2})^{1/2}\xi)]\Big\},$$
$$\text{for } \xi>0 \qquad (10)$$

where $\xi=x/d$, $\eta=y/d$, and $\bar{\beta}=-(1/\rho_0)(d\bar{\rho}/d\eta)$, so that $\bar{\rho}=\rho_0(1-\bar{\beta}\eta)$; and $F=U/Nd$ the densimetric Froude number, $r=(\bar{\rho}+\rho)/\rho_0$, $\varepsilon=NQ/(gd)$, which are dimensionless, and Q is the source strength. Equations (9) and give the entire density field in the steady-state limit.

Since one of the objectives of this investigation is to compute the momentum flux downstream of the source, in addition to the density perturbation, the vertical and horizontal velocity perturbations are required. From equation (3) for steady-state

$$v'=(1/\bar{\beta})\frac{\partial\rho'}{\partial\xi} \qquad (11)$$

where $v'=v/U$, $\xi=x/d$ and $\rho'=\rho/\rho_0$. Taking the derivative of equation (10) with respect to ξ and substituting into (11) we obtain for $\xi>0$

$$v'=-\varepsilon'\Big\{\sum_{n=1}^{m}\frac{n\pi F\sin n\pi\eta}{(1-n^2\pi^2F^2)^{1/2}}$$
$$\sin[(F^{-2}-n^2\pi^2)^{1/2}\xi]$$
$$+\sum_{n=m+1}^{\infty}\frac{n\pi F\sin n\pi\eta}{(n^2\pi^2F^2-1)^{1/2}}$$
$$\exp[-(n^2\pi^2-F^{-2})^{1/2}\xi]\Big\} \qquad (12)$$

where $\varepsilon'=Q/Ud$.

For the velocity field at a distance from the source (i. e., in fluid excluding the source) continuity requires

$$\frac{\partial u'}{\partial\xi}+\frac{\partial v'}{\partial\eta}=0 \qquad (13)$$

Using equation (11) and integrating (13) with respect to ξ, we obtain

$$u'=G(\eta)-(1/\bar{\beta})\frac{\partial\rho'}{\partial\eta} \qquad (14)$$

The constant of integration, $G(\eta)$, is determined by matching the unattenuated part of ρ' for $\xi>0$ from equation (10) with the unattenuated part of the downstream horizontal velocity, u', determined by Wong and Kao, viz.,

$$\varepsilon\Big\{\sum_{n=0}^{m}\frac{\cos n\pi\eta}{n\pi F+1}-2\sum_{n=m+1}^{\infty}\frac{\cos n\pi\eta}{n\pi F-1}\Big\} \qquad (15)$$

The reader is referred to Wong and Kao (1970) for details in obtaining (15). Knowing $G(\eta)$ and the entire density perturbation (equation (10)) the total u' can be determined from (14). The results are as follows:

$$G(\eta)=\varepsilon'\Big\{1+\sum_{n=1}^{m}\cos n\pi\eta+2\sum_{n=m+1}^{\infty}\cos n\pi\eta\Big\}$$

For $\xi>0$,

$$u'=\varepsilon'\Big\{1+\sum_{n=1}^{m}\frac{\cos n\pi\eta}{n\pi F+1}\Big[1+2\Big(\frac{n^2\pi^2F^2}{n\pi F-1}\Big)$$
$$\cos((F^{-2}-n^2\pi^2)^{1/2}\xi)\Big]$$
$$-\sum_{n=m+1}^{\infty}\frac{\cos n\pi\eta}{n^2\pi^2F^2-1}[2+n^2\pi^2F^2$$
$$\exp(-(n^2\pi^2-F^{-2})^{1/2}\xi)]\Big\} \qquad (16)$$

We let, for convenience,

$$\left.\begin{aligned}
A_n&=\varepsilon'\cos n\pi\eta/(n\pi F+1)\\
B_n&=2n^2\pi^2F^2\varepsilon'\cos n\pi\eta/(n^2\pi^2F^2-1)\\
C_n&=2\varepsilon'\cos n\pi\eta/(n^2\pi^2F^2-1)\\
\alpha_n&=(F^{-2}-n^2\pi^2)^{1/2}\\
D_n&=\varepsilon' n\pi F\sin n\pi\eta/[(1-n^2\pi^2F^2)^{1/2}\\
\gamma_n&=(n^2\pi^2-F^{-2})^{1/2}\\
E_n&=\varepsilon' n^2\pi^2F^2\cos n\pi\eta/(n^2\pi^2F^2-1)\\
F_n&=\varepsilon' n\pi F\sin n\pi\eta/(n^2\pi^2F^2-1)^{1/2}
\end{aligned}\right\} \qquad (17)$$

Substituting (17) into (12) and (16) we obtain

$$v'=-\sum_{n=1}^{m}D_n\sin\alpha_n\xi+\sum_{n=m+1}^{\infty}F_ne^{-\gamma_n\xi},$$
$$\text{for } \xi>0 \qquad (18)$$

$$u'=\varepsilon'+\sum_{n=1}^{m}A_n-\sum_{n=m+1}^{\infty}C_n$$
$$+\sum_{n=1}^{m}B_n\cos\alpha_n\xi-\sum_{n=m+1}^{\infty}E_ne^{-\gamma_n\xi},$$
$$\text{for } \xi>0 \qquad (19)$$

All sums in equations (18) and (19) aɹe finite or convergent for $\xi>0$.

To investigate the momentum flux, the integral of $u'\ v'$ was first considered. For $\xi\gg0$ case, multiplying (18) and (19) neglecting the last terms (which are transcendentally small) in those equations, and integrating over a characteristic wave length in the ξ-direction (viz., we choose, arbitrarily, $\xi=0$ to $-\lambda$ where $\lambda=2\pi/\alpha_2$) we obtain

$$\int_0^\lambda u'v'd\xi=[\varepsilon'+\sum_{n=1}^m A_n-\sum_{n=m+1}^\infty C_n]$$
$$\cdot\sum_{n=1}^m \frac{D_n}{\alpha_n}\left[\cos\left(\frac{2\pi\alpha_n}{\alpha_2}\right)-1\right]$$
$$-\sum_{j=1}^m\left\{\frac{B_j}{2}\sum_{n=1}^m(1-\delta_{jn})D_n\right.$$
$$\left[(\alpha_j+\alpha_n)^{-1}\left(\cos(\frac{\alpha_j+\alpha_n}{\alpha_2}2\pi)-1\right)\right.$$
$$\left.\left.-(\alpha_j-\alpha_n)^{-1}\left(\cos(\frac{\alpha_j-\alpha_n}{\alpha_2}2\pi)-1\right]\right\}$$
$$-\sum_{j=1}^m\left\{\frac{B_j}{2}\sum_{n=1}^m\delta_{nj}\frac{D_n}{\alpha_n}\sin^2\left(\frac{\alpha_n}{\alpha_2}2\pi\right)\right\} \tag{20}$$

where δ_{nj} is the kronecker delta. Equation (20) is proportional to the momentum flux if we can neglect the density perturbations. This will be checked subsequently.

Using equations (10), (12), and (16) the momentum flux for a constant was numerically computed by Simpson's rule, viz.,

$$\int_0^\xi \rho u'v'd\xi=\frac{\Delta\xi}{3}[\rho_1u_1'v_1'+4\rho_2u_2'v_2'+2\rho_3u_3'v_3'$$
$$+4\rho_4u_4'v_4'+\cdots+2\rho_{2\ell-1}u_{2\ell-1}'v_{2\ell-1}'$$
$$+4\rho_{2\ell}u_{2\ell}'v_{2\ell}'+\rho_{2\ell+1}u_{2\ell+1}'v_{2\ell+1}']$$

where ℓ is an integer corresponding to $(2\ell+1)$ equally spaced values of $\rho(\xi,\eta)$, $u'(\xi,\eta)$, $v'(\xi,\eta)$ and ξ.

The $\xi>0$ equations for both the $u'v'$ correlation and numerical computation of the momentum flux were developed. The exponential terms, which represent the near field parts ($\xi\to 0$ for $\xi>0$), were found to small to be significant in the example considered. Therefore, it appears reasonable to neglect these terms; consequently, equations (10), (12), and (16) with the last terms in each dropped and equation (20) for the far field can be considered good approximations for good approximations for the near field.

3. Results and Discussions

The upstream velocity profile, the lee wave system, and the variation in momentum flux are plotted in Fig. 1, 2, and 3, respectively. The case considered can be summarized as follows:

$$F=0.145 \qquad m=2$$
$$\varepsilon'=0.05 \tag{21}$$
$$\varepsilon=0.00145 \qquad \bar{\beta}=0.2$$

corresponding to a depth of 18 km, and initial unperturbed velocity of 25 m/sec, and an average Väisälä frequency of 9.5. The values in (21) were selected based on the mean flow observations presented in Lilly and Kennedy (1973). Comparison of the steady-state solutions as given in the Figures will now be made with the observations of Lilly and Kennedy.

The plot of isotachs in m/sec in theis paper indicated a strong upstream influence due to the mountain range, especially the decrease in velocity above 12 km, which is similar to the decrease in vvelocity above $\eta=0.5$ in Fig. 1. The cross section of potential temperature presented by Lilly and Kennedy (1973) indicated that the wavelength for the lee waves in Colorado was approximately two atmospheric heights

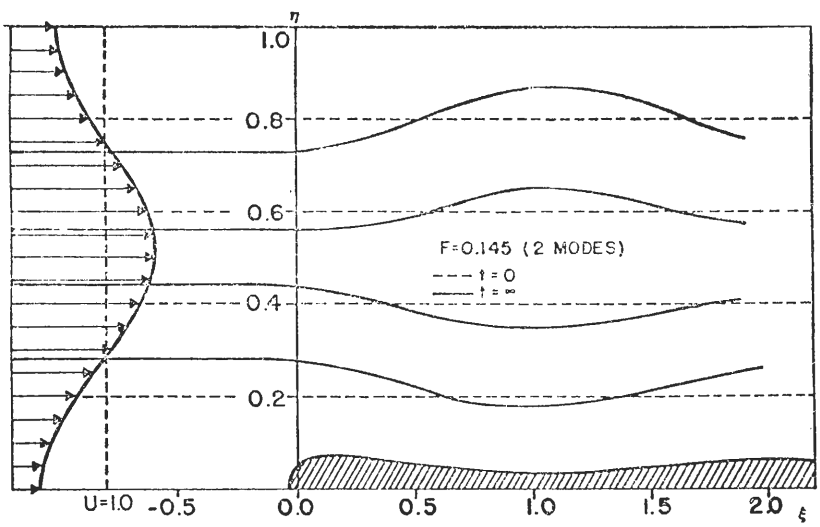

Fig. 1. Steady-flow pattern showing the velocity profile far upstream and lee waves.

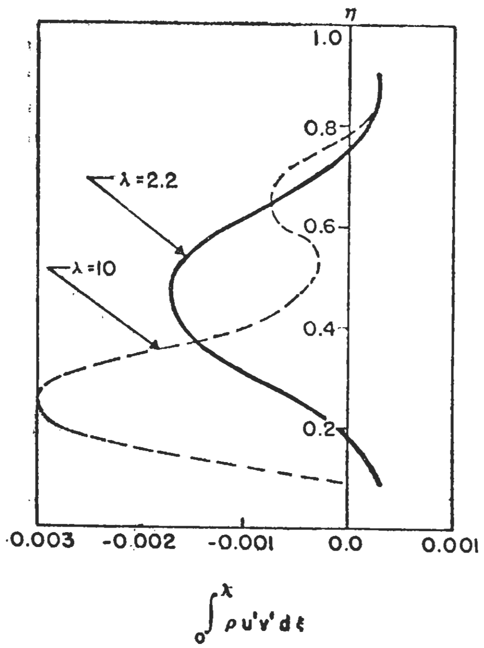

Fig. 2. Horizontally averaged momentum flux of a lee wave corresponding to a densimetric Froude numbdr of 0.145.

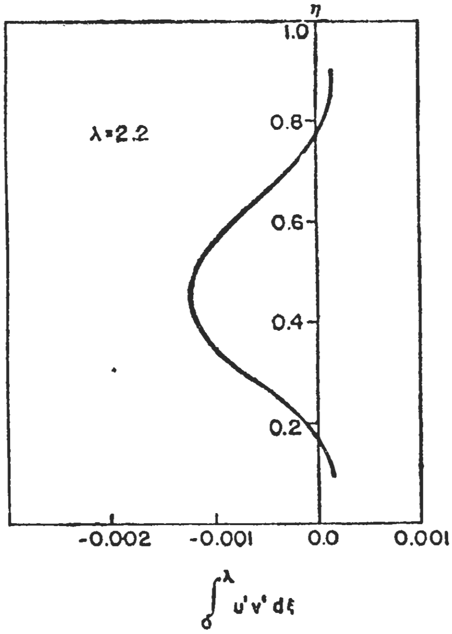

Fig. 3. Velocity perturbations correlation integral integrated over the longest of the two wavelength modes corresponding to a lee wave with a densimetric Froude number equal to 0.145.

in their experiment according to the upstream velocity profile is of the order of 20 km). Fig. 1 shows that the example presented in this note contains similar length lee waves.

In Lilly and Kennedy the u' versus v' correlation spectrum giving the phase relation between u' and v' at large scales gave a phase difference of 100° to 105° based on the flight data. They pointed out that this result is contrary to simple wave theory, which predicts an approximately 180° phase reversal. However, the theoretical approach used in the investigation reported herein conforms with the measured results of Lilly and Kennedy. Table 1 gives the variation in the phase difference between the vertical and horizontal perturbation velocities with height (values were approximated from the calculations of u' and v' at equal interveals for the Simpson's integration). The tabulated data indicate an approximate 90° phase difference, which is consistent with the Colorado measurements. It appears that the simple wave theory fails to give the unattenuated fore and aft modes which account for the correct phase relationship given herein.

Table 1. The phase of the u' versus v' variations

η	wavelengths		Approximate Phase Differences
	$\lambda u'$	$\lambda v'$	
0.1	2.21 ζ	2.21 ζ	90
0.2	2.21 ζ	2.21 ζ	90
0.3	2.21 ζ	2.21 ζ	−108
0.4	2.21 ζ	2.21 ζ	−100
0.5	2.21 ζ	1.02 ζ	+ 60
0.6	2.21 ζ	2.21 ζ	+ 60
0.7	2.21 ζ	2.21 ζ	+ 60
0.8	2.21 ζ	2.21 ζ	− 90
0.9	2.21 ζ	2.21 ζ	−108

The numerical values of the momentum flux depend on the interval of integration. The dashed line in Fig. 2 corresponds to an interval which is approximately the interval ($\xi=0$ to $\xi=10$) used Lilly and Kennedy. The solid line corresponds to the longest wavelength of the two modes, viz., $\xi=0$ to $\xi=2\pi/\alpha_2$. In Table 2, estimates of the magnitudes of the momentum

Table 2. Horizontally averaged momentum flux distribution of a lee wave corresponding to a densimetric Froude number of 0.145 over $\zeta=2.2$

η	$\rho u'v'$	$\rho^* u'_* v'_*$ (dyues/cm²)
0.05	0.001	0.8
0.1	0.00013	0.98
0.15	0.000074	0.6
0.2	−0.000051	−0.4
0.25	−0.000223	−1.7
0.3	−0.000420	−3.2
0.35	−0.000596	−4.5
0.4	−0.000723	−5.4
0.45	−0.000779	−5.8
0.5	−0.000757	−5.7
0.55	−0.000662	−5.0
0.6	−0.000515	−3.9
0.65	−0.000340	−2.6
0.7	−0.000167	−2.3
0.75	0.000020	0.2
0.8	0.000081	0.6
0.85	0.000127	0.95
0.9	0.000120	0.9

flux calculations based on the latter interval of integration are presented. To determine these estimates, the following was assumed for the reference density of the atmosphere.

$\rho_0 = 1.2\ \mathrm{kg/m^3}$

The average momentum flux is

$$\overline{\rho u'v'} = \frac{d}{10d}\int_0^{10d} \rho u'v' d\xi, \text{ nondimensional}$$

and

$$\overline{\rho^* u'_* v'_*} = C\overline{\rho u'v'}, \text{ dimensional}$$

where C is a proper conversion factor depending on the atmospheric conditions. C is, in this example, given by

$$C = \rho_0 \quad U^2 = 7500\ \mathrm{dynes/cm^2}$$

where $U = 25$ m/sec is the appropriate characteristic velocity. The results are of the same order of magnitude as what was determined from observations by Lilly and Kennedy. For the interval of integration corresponding to the longest wavelength of the two downstream lee wave modes, the average momentum flux is determined to be downward between the vertical interval $0.3<\eta<0.7$ with an average value of approximately 4 dynes/cm², with a maximum of about 5.8 dynes/cm² at $\eta=0.55$. Between approximately the same vertical interval, Lilly and Kennedy (1973) observed values of downward momentum flux between 3 and 8 dynes/cm². However, their interval of integration was arbitrarily selected as 200 km or about 10 atmospheric heights. Therefore, the apparent conclusion is that the theory predicts the downward momentum flux observed by Lilly and Kennedy (1973), which they have related to the removal of energy associated with the dissipation of the gravity waves.

Can we neglect the density perturbations in computing the momentum flux? Fig. 3 presents the values of the $u'v'$ correlation integral for the interval of integration over the longest characteristic wavelength, viz., $2\pi/\alpha_2$ (one of the wavelengths corresponding to the two downstream modes). The average momentum flux is determined by multiplying the average value determined by the integration by the appropriate conversion factor as follows:

$$\overline{\rho^* u'_* v'_*} = C(1-\bar{\beta}\eta)\left(\frac{1}{(2\pi/\alpha_2)}\right)\int_0^{2\pi/\alpha_2} u'v' d\xi$$

where $C = 7500$ dynes/cm², as before. Looking, e. g., at $\eta=0.50$, the integration gave $\overline{u'v'}=.0012$, which gives an average downward momentum flux of about 8 dynes/cm². Therefore, it is apparent that the density perturbation does not influence the order of magnitude of the momentum flux significantly.

The main point of this paper is that a source like model in a medium of finite depth describes the salient features of the mountain wave problem. The restrictions of an inviscid, incompressible fluid did not hamper the calculations of the major features of the mountain wave and its associated momentum flux. The velocity and density profiles upstream of the disturbance exhibit the correct jet-like behavior and nonuniform local Richardson numbers, illustrating the importance of the unattenuated fore and aft modes. Blocking effects were observed in the Rocky Mountain wave system, a feature predicted by the theoretical analysis presented herein. Also, the theory verifies the resulting downward momentum flux in the mid region of the lee wave system of the appropriate magnitude. An important point is that the choice of the horizontal averaging interval affects significantly the values and distribution of the momentum flux. Since the flux to be determined is the result of a wave phenomenon, the averaging interval should be over a characteristic wavelength; in this investigation the wavelength selected was the length of the longest of the two downstream modes. The present model also shows that a tropospheric jet may be a concomittant event with the occurence of lee-waves. The upstream shear wind profile may not be prescribable a priori but is a part of the total wave system due to the disturbance. The agreement of the results predicted by the model with the field observation in the larger features as well as in some subtle details such as the phase relationship between u' and v' in the lee-wave system tend to suggest the usefulness of such a model.

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大氣流經山脈模型與觀察實驗之比較

范倫泰 高鋙

美國海軍造船研究所 美國天主教大學

摘要

本文以穩恆狀態源流模型 (source-like model) 研究大氣經過山脈之結構，模型分析結論爲山脈影響增强中對流層噴射氣流 (mid-tropospheric jet) 及阻擋低空氣流 (blocking)，本研究計算山後波 (lee-wave) 之向下動量通量 (momentum flux) 及波相差異 (phase difference)，計算結果與 Colorado 山後波觀察實驗比較極爲符合。