NOTES AND CORRESPONDENCE

Downslope Windstorms over a 3-dimensional Mountain

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Abstract

The effect of 3-dimensionality of a mountain profile on downslope windstorms is analytically investigated. The mountain is immersed in a stably stratified uniform environmental flow. The case of an almost-2-dimensional mountain is considered. The mountain profile has a maximum and is nearly uniform in the cross-stream direction. The downslope wind speed in the along-stream vertical section, in which the mountain profile has its maximum, is calculated. In comparison with the 2-dimensional case in which the profile is strictly uniform in the cross-stream direction, the following results are obtained. When an atmospheric height is prescribed, both the downslope wind speed and the mountain height, which is required for the downslope windstorm to occur, increase due to the 3-dimensional deviation of the profile. On the other hand, when a mountain height is prescribed, both the downslope wind speed and the required atmospheric height decrease due to the deviation.

1. Introduction

Smith (1985) is the first to propose a non-linear analytical model of downslope windstorms, which are experienced on the lee of a mountain immersed in a stably stratified environmental flow with a constant buoyancy frequency, N . The model is based on an assumption that there exists a critical atmospheric height H , at which the streamline splits into 2 branches over the mountain, one horizontal and the other descending. In the region between the 2 branches, which is usually called the dead region, the stratification is neutral and the flow is stagnant. This model predicts that if the mountain height is equal to a required value, then the downslope wind speed may become nearly NH , which is considerably greater than that of the environmental flow.

Smith (1985)'s model was further developed by many authors. For example, Gutman (1991) examined the effect of density decrease with height of the environmental flow. Gutman and Apterman (1992) investigated the case of an environmental flow with shear. Kanehisa (1995) considered an environmental flow with non-uniform stratification.

In the studies mentioned above, the mountain profile is assumed to be 2-dimensional, *i.e.*, uniform in the cross-stream direction so that the problem can

be analytically solved. Recently, the effect of the 3-dimensionality of the profile on downslope wind was numerically calculated by Peng *et al.* (1995). Their result shows that 2-dimensional models overestimate the amount of downslope wind speed. In this note, the effect of the 3-dimensionality is analytically examined for an almost-2-dimensional mountain profile.

The organization of this note is as follows. In Section 2, the formulation is presented. In Section 3, the equation of the stream function is derived. In Section 4, the equations of downslope windstorm is derived. In Section 5, the 2-dimensional case is reviewed. In Section 6, the deviation due to the 3-dimensionality is calculated. In Section 7, concluding remarks are given.

2. Basic equations

We begin with the 3-dimensional steady hydrostatic isentropic Boussinesq system of equations,

$$u\partial u/\partial x + v\partial u/\partial y + w\partial u/\partial z + \partial\phi/\partial x = 0, \quad (2.1a)$$

$$u\partial v/\partial x + v\partial v/\partial y + w\partial v/\partial z + \partial\phi/\partial y = 0, \quad (2.1b)$$

$$\partial\phi/\partial z = b, \quad (2.1c)$$

$$\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0, \quad (2.1d)$$

$$u\partial b/\partial x + v\partial b/\partial y + w\partial b/\partial z = 0, \quad (2.1e)$$

where x and y denote the horizontal coordinates. The vertical coordinate z is the pseudo-height of Hoskins and Bretherton (1972). u , v and w are the x , y and z components of velocity, respectively. ϕ is the geopotential. b is the sum of the buoyancy and gravitational acceleration, which is proportional to the potential temperature.

We consider downslope windstorms caused by a mountain in a uniform environmental flow with a constant buoyancy frequency. The environmental flow is assumed toward the positive x -direction. The mountain profile $m(x, y)$ is assumed to be almost 2-dimensional and symmetric with respect to y ,

$$\begin{aligned} m(x, y) &= 0 \text{ for } |x| > a, \\ m(x, 0) &> 0 \text{ for } |x| < a, \\ m(x, y) &= m(x) - \delta m(x, y), \\ 0 &< \delta m(x, y)/m(x) \ll 1, \\ \delta m(x, 0) &= 0 \text{ and } \delta m(x, -y) = \delta m(x, y). \end{aligned} \quad (2.2)$$

Because of the symmetry, there can exist such a solution that

$$\begin{aligned} u(z, x, y) &= u(z, x, -y), \\ w(z, x, y) &= w(z, x, -y), \\ v(z, x, y) &= -v(z, x, -y), \\ \phi(z, x, y) &= \phi(z, x, -y) \\ \text{and } b(z, x, y) &= b(z, x, -y). \end{aligned} \quad (2.3)$$

Hereafter, we consider the 2-dimensional system on the vertical plane at $y = 0$. On this plane, (2.1) are reduced to

$$u \partial u / \partial x + w \partial u / \partial z + \partial \phi / \partial x = 0, \quad (2.4a)$$

$$\partial \phi / \partial z = b, \quad (2.4b)$$

$$\partial u / \partial x + \partial w / \partial z + \partial v / \partial y = 0, \quad (2.4c)$$

$$u \partial b / \partial x + w \partial b / \partial z = 0. \quad (2.4d)$$

As in Smith (1985), it is assumed that at an altitude H the streamline splits into 2 branches, one being horizontal and the other descending. The flow is assumed to be stagnant and the buoyancy is uniform in the region between them (see Fig. 1).

From the mass conservation Eq. (2.4c), there exist such functions $A(z, x)$ and $\psi(z, x)$ that

$$\begin{aligned} w &= -A \partial \psi / \partial x, u = A \partial \psi / \partial z \\ \text{and} \\ \partial(\psi, A) / \partial(z, x) &= -\partial v / \partial y, \end{aligned} \quad (2.5)$$

where $A(z, x)$ is a positive function of (z, x) . The horizontal velocity u is assumed to be positive for $x \leq a$. In terms of ψ and A , (2.4d) is rewritten as $\partial(\psi, b) / \partial(z, x) = 0$, which implies that b is a function of ψ , i.e., b is conserved along the streamlines,

$$b(z, x) = b[\psi(z, x)]. \quad (2.6)$$

Differentiating (2.4a) with respect to z and using (2.4b,c) yields

$$(u \partial / \partial x + w \partial / \partial z)(\partial u / \partial z) - (\partial v / \partial y)(\partial u / \partial z) + \partial b / \partial x = 0. \quad (2.7)$$

Substituting (2.5) and (2.6) into (2.7), we obtain

$$\begin{aligned} \partial(\psi, \Omega) / \partial(z, x) &= 0, \\ \Omega &= A \partial u / \partial z - z db / d\psi \\ &= A(\partial / \partial z) A(\partial \psi / \partial z) - z db / d\psi. \end{aligned} \quad (2.8)$$

Multiplying (2.4a) with u and using (2.4b), (2.5) and (2.6), we obtain

$$\begin{aligned} \partial(\psi, B) / \partial(z, x) &= 0, \\ B &= u^2 / 2 + \phi - zb = A^2(\partial \psi / \partial z)^2 / 2 + \phi - zb. \end{aligned} \quad (2.9)$$

These equations imply that Ω and B are functions of ψ , i.e., conserved along the streamlines,

$$\Omega(z, x) = \Omega[\psi(z, x)], \quad (2.10a)$$

$$B(z, x) = B[\psi(z, x)]. \quad (2.10b)$$

3. Equation of ψ

As $x \rightarrow -\infty$, i.e., far upstream, the velocity components and buoyancy become

$$\lim_{x \rightarrow -\infty} u = u_{in} = U, \quad (3.1a)$$

$$\lim_{x \rightarrow -\infty} w = w_{in} = 0, \quad (3.1b)$$

$$\lim_{x \rightarrow -\infty} b = b_{in} = N^2 z + C(\text{const.}), \quad (3.1c)$$

where U and N are constant. From (2.5), (2.8) and (3.1a,b), A , ψ and Ω become as $x \rightarrow -\infty$,

$$\lim_{x \rightarrow -\infty} A = A_{in} = 1, \quad (3.2a)$$

$$\lim_{x \rightarrow -\infty} \psi = \psi_{in} = Uz, \quad (3.2b)$$

$$\lim_{x \rightarrow -\infty} \Omega[\psi] = \Omega[\psi_{in}] = -z db[\psi_{in}] / d\psi. \quad (3.2c)$$

From (3.1c) and (3.2b,c), the functional forms of $b[\psi]$ and $\Omega[\psi]$ are determined as

$$b[\psi] = (N^2 / U) \psi + b[0], \quad (3.3a)$$

$$\Omega[\psi] = -(N^2 / U^2) \psi. \quad (3.3b)$$

Substituting (3.3a,b) into (2.8), the equation of ψ is determined as

$$A(\partial / \partial z) A(\partial \psi / \partial z) + (N^2 / U^2) \psi = (N^2 / U) z. \quad (3.4)$$

Non-dimensionalizing variables as

$$(z, x, y) \rightarrow (U/N)(z, x, y),$$

$$(w, u, v) \rightarrow U(w, u, v),$$

$$A \rightarrow A, \psi \rightarrow (U^2 / N) \psi,$$

$$\phi \rightarrow U^2 \phi, b \rightarrow UNb,$$

$$\Omega \rightarrow N\Omega, B \rightarrow U^2 B,$$

Fig. 1. Schematic of downslope windstorms

the equations obtained above become

$$b[\psi] = \psi + b[0], \quad (3.5a)$$

$$\Omega[\psi] = -\psi, \quad (3.5b)$$

$$B[\psi] = u^2/2 + \phi - zb \\ = A^2(\partial\psi/\partial z)^2/2 + \phi - zb, \quad (3.5c)$$

$$A(\partial/\partial z)A(\partial\psi/\partial z) + \psi = z, \quad (3.5d)$$

$$\partial(\psi, A)/\partial(z, x) = -\partial v/\partial y. \quad (3.5e)$$

From (3.5e), A is related to the divergence of v as

$$A(z, x) = \text{Exp} \left[- \int_{-\infty}^x dx [(\partial v/\partial y)/u]_{\psi} \right], \quad (3.6)$$

where the integral is performed along the streamline with $\psi(z, x) = \text{constant}$. Introducing such a new vertical coordinate $Z(z, x)$ that

$$Z(z, x) = \int_{m(x)}^z dz/A(z, x) \\ = \int_{m(x)}^z dz \text{Exp} \left[\int_{-\infty}^x dx [(\partial v/\partial y)/u]_{\psi} \right], \quad (3.7)$$

the horizontal velocity u (2.5) and the equation of ψ (3.5d) become

$$u = \partial\psi/\partial Z, \quad (3.8a)$$

$$\partial^2\psi/\partial Z^2 + \psi = z(Z, x) = Z + m(x) - \xi(Z, x), \quad (3.8b)$$

where

$$\xi(Z, x) \\ = \int_{m(x)}^z dz \left\{ \text{Exp} \left[\int_{-\infty}^x dx [(\partial v/\partial y)/u]_{\psi} \right] - 1 \right\}. \quad (3.9)$$

The boundary conditions for ψ on the lower and upper boundaries are

$$\psi(0, x) = \psi_{in}(0) = 0$$

and

$$\psi(F, x) = \psi_{in}(H) = H, \quad (3.10)$$

where

$$F = F(x) = Z(m(x) + f(x), x), \quad (3.11)$$

and $f(x)$ is the fluid depth on the vertical plane at $y = 0$. If $\partial v/\partial y = 0$, then $F(x)$ is reduced to $f(x)$. There exists another condition on the upper boundary due to the conservation of B ,

$$\partial\psi(F, x)/\partial Z = \partial\psi_{in}(H)/\partial Z = 1. \quad (3.12)$$

4. Equations of downslope windstorms

The solution to (3.8b) under the boundary conditions (3.10) is given by

$$\psi(Z, x) = \{H - \Phi(F, x)\} \sin Z / \sin F \\ - \Phi(0, x) \sin(F - Z) / \sin F + \Phi(Z, x), \quad (4.1a)$$

where

$$\Phi(Z, x) = Z + m(x) - \int_0^Z dZ' \xi(Z', x) \sin(Z - Z') \\ = Z + m(x) - \Xi(Z, x). \quad (4.1b)$$

Substituting (4.1a) into (3.12) yields,

$$G(m, F, H, x) = m + (H - m - F) \cos F \\ + \Xi(F, x) \cos F \\ - \{\partial\Xi(F, x)/\partial Z\} \sin F = 0. \quad (4.2)$$

Differentiating (4.1a) with respect to Z , the wind speed at the lee foot ($Z, x) = (0, a)$ is given by

$$u(0, a) = 1 + \{H - F(a)\} / \sin F(a) \\ + \Xi(F(a), a) / \sin F(a), \quad (4.3)$$

where $F(a)$ is given by the solution of (4.2) at $x = a$,

$$\begin{aligned} G(0, F(a), H, a) &= \{H - F(a)\} \cos F(a) \\ &+ \Xi(F(a), a) \cos F(a) \\ &- \{\partial \Xi(F(a), a) / \partial Z\} \sin F(a) = 0, \end{aligned} \quad (4.4a)$$

where

$$\begin{aligned} \partial \Xi(F(a), a) / \partial Z \\ = \int_0^{F(a)} dZ \xi(Z, a) \cos(F(a) - Z). \end{aligned} \quad (4.4b)$$

We wish to calculate the downslope wind speed (4.3), which is a function(al) of the far-upstream atmospheric height H and mountain profile $m(x, y)$. Only if the H and $m(x, y)$ satisfy some required conditions, downslope windstorms occur.

5. Case of a 2-dimensional mountain

In the case of a 2-dimensional mountain, *i.e.*, $m(x, y) = m(x)$, the divergence of v is zero. In this case, from (3.9), $\xi(Z, x)$ is reduced to 0, and the above Eqs. (4.2), (4.3) and (4.4a) are reduced to

$$G(m, F, H) = m + (H - m - F) \cos F = 0, \quad (5.1a)$$

$$u(0, a) = 1 + \{H - F(a)\} / \sin F(a), \quad (5.1b)$$

$$G(0, F(a), H) = \{H - F(a)\} \cos F(a) = 0. \quad (5.1c)$$

For simplicity, we consider only the case of $0 < F < H < 2\pi$. Then, because of the positiveness of m and $H - m - F$, both the fluid depth F and atmospheric height H lie between $\pi/2$ and $3\pi/2$. From (5.1a), at the maximum point $x = x_m$ of $m(x)$,

$$\begin{aligned} \partial G(m_{\max}, F_m, H) / \partial x \\ = \{\partial F(x_m) / \partial x\} \partial G(m_{\max}, F_m, H) / \partial F \\ = 0, \end{aligned} \quad (5.2)$$

where $m_{\max} = m(x_m)$ and $F_m = F(x_m)$. One solution to (5.1c) is $F(a) = F(-a) = H$, for which $\partial F(x_m) / \partial x = 0$, and this gives $u(0, a) = 1$, which is equal to the inflow wind speed. On the other hand, if the atmospheric height H and mountain height $m_{\max}$ satisfy the following conditions,

$$\begin{aligned} G(m_{\max}, F_m, H) &= m_{\max} \\ &+ (H - m_{\max} - F_m) \cos F_m = 0, \\ \partial G(m_{\max}, F_m, H) / \partial F &= -\cos F_m \\ &- (H - m_{\max} - F_m) \sin F_m = 0, \end{aligned} \quad (5.3)$$

then the other solution to (5.1c), $F(a) = \pi/2 < F(-a) = H$, for which $\partial F(x_m) / \partial x \neq 0$, is possible, and then $u(0, a)$ becomes

$$u(0, a) = 1 + H - \pi/2 > 1,$$

or

$$\begin{aligned} u(0, a) &= NH - U(\pi/2 - 1) \gg U \\ &\text{in the dimensional form.} \end{aligned} \quad (5.4)$$

Eliminating H from (5.3), F_m is written in terms of $m_{\max}$ as

$$\begin{aligned} \sin F_m &= -m_{\max}/2 + \{m_{\max}^2/4 + 1\}^{1/2}, \\ &\text{i.e., } \pi/2 < F_m < \pi. \end{aligned} \quad (5.5)$$

6. Case of an almost-2-dimensional mountain

In this section, the deviation from the 2-dimensional downslope windstorms due to the 3-dimensionality is considered. In the case of the almost-2-dimensional mountain (2.2), the absolute value of the divergence of v is small,

$$|\partial v / \partial y| \ll 1. \quad (6.1)$$

In this case, from (3.9) and (4.1b), the absolute values of $\xi(Z, x)$ and $\Xi(Z, x)$ are also small,

$$\begin{aligned} |\xi(Z, x)| \\ = \left| \int_{m(x)}^Z dz \left\{ \text{Exp} \left[\int_{-\infty}^x dx [(\partial v / \partial y) / u]_{\psi} \right] - 1 \right\} \right| \\ \ll 1, \end{aligned} \quad (6.2a)$$

$$\begin{aligned} |\Xi(Z, x)| \\ = \left| \int_0^Z dZ' \xi(Z', x) \sin(Z - Z') \right| \\ \ll 1. \end{aligned} \quad (6.2b)$$

Since both the horizontal velocity u and the meridional divergence $\partial v / \partial y$ are positive on the upslope, the integral along $\psi = \text{constant}$ in (3.9) is positive there,

$$\begin{aligned} \int_{-\infty}^x dx [(\partial v / \partial y) / u]_{\psi} > 0 \\ \text{for } -a < x < x_m. \end{aligned} \quad (6.3)$$

On the downslope, $\partial v / \partial y$ may be weakly positive or negative and u is greatly enhanced. If $\partial v / \partial y$ is positive, then the integral along $\psi = \text{constant}$ in (3.9) is positive for $x_m < x < a$. Even if $\partial v / \partial y$ becomes negative in the vicinity of the lee, the integral can be assumed to be positive because of the great enhancement of u and (6.3),

$$\begin{aligned} \int_{-\infty}^x dx [(\partial v / \partial y) / u]_{\psi} > 0 \\ \text{for } x_m < x < a. \end{aligned} \quad (6.4)$$

From (6.4), we can assume that $\xi(Z, x)$ in (3.9) is positive and monotonically increasing over the mountain,

$$\xi(0, x) = 0, \quad \xi(Z, x) > 0$$

and

$$\frac{\partial \xi(Z, x)}{\partial Z} > 0 \quad \text{for } -a < x < a. \quad (6.5)$$

Let δH , $\delta m_{\max}$ and $\delta F(a)$ be the deviations due to $\delta m(x, y)$, respectively, from H , $m_{\max}$ and $F(a) = \pi/2$ in the 2-dimensional case. Then, from (4.2) and (4.4a) together with (5.3), to the first approximation, δH , $\delta m_{\max}$ and $\delta F(a)$ satisfy,

$$\begin{aligned} \delta m_{\max}(1 - \cos F_m) + \delta H \cos F_m \\ = \{\partial \Xi(F_m, x_m)/\partial Z\} \sin F_m - \Xi(F_m, x_m) \cos F_m \end{aligned} \quad (6.6a)$$

$$\delta F(a) = -\{\partial \Xi(\pi/2, a)/\partial Z\}/(H - \pi/2), \quad (6.6b)$$

where

$$\begin{aligned} \partial \Xi(F_m, x_m)/\partial Z &= \int_0^{F_m} dZ \xi(Z, x_m) \cos(F_m - Z) \\ &= \int_0^{F_m} dZ \xi(F_m - Z, x_m) \cos Z > 0, \end{aligned} \quad (6.7a)$$

$$\Xi(F_m, x_m) = \int_0^{F_m} dZ \xi(Z, x_m) \sin(F_m - Z) > 0, \quad (6.7b)$$

$$\partial \Xi(\pi/2, a)/\partial Z = \int_0^{\pi/2} dZ \xi(Z, a) \sin Z > 0. \quad (6.7c)$$

In deriving (6.7a,b,c), we used (5.5) and (6.5). From (4.3), the wind speed at the lee foot $(Z, x) = (0, a)$ is calculated to the first approximation as

$$\begin{aligned} u(0, a) &= 1 + (H - \pi/2) + \delta u(0, a), \\ \delta u(0, a) &= \delta H - \delta F(a) + \Xi(\pi/2, a), \end{aligned} \quad (6.8)$$

where

$$\Xi(\pi/2, a) = \int_0^{\pi/2} dX \xi(Z, a) \cos Z > 0. \quad (6.9)$$

If the atmospheric height H is prescribed, *i.e.*, $\delta H = 0$, then from (6.6a) and (6.8), the deviations from $m_{\max}$ and $u(0, a)$ become

$$\begin{aligned} \delta m_{\max} &= \{\partial \Xi(F_m, x_m)/\partial Z\} \sin F_m / (1 - \cos F_m) \\ &\quad - \Xi(F_m, x_m) \cos F_m / (1 - \cos F_m), \end{aligned} \quad (6.10a)$$

$$\delta u(0, a) = -\delta F(a) + \Xi(\pi/2, a). \quad (6.10b)$$

From (5.5), (6.6b) and (6.7a,b,c), we can see that

$$\delta m_{\max} > 0 \text{ and } \delta u(0, a) > 0. \quad (6.11)$$

On the other hand, if the mountain height $m_{\max}$ is prescribed, *i.e.*, $\delta m_{\max} = 0$, then from (6.6a) and (6.8), the deviations from H and $u(0, a)$ become

$$\begin{aligned} \delta H &= \{\partial \Xi(F_m, x_m)/\partial Z\} \sin F_m / \cos F_m \\ &\quad - \Xi(F_m, x_m), \end{aligned} \quad (6.12a)$$

$$\delta u(0, a) = \delta H - \delta F(a) + \Xi(\pi/2, a). \quad (6.12b)$$

From (5.5) and (6.7a,b), we can see that

$$\delta H = \int_0^{F_m} dZ \xi(Z, x_m) \sin Z / \cos F_m < 0. \quad (6.13)$$

Using (6.5), the deviation of the horizontal velocity is estimated as

$$\begin{aligned} \delta u(0, a) &= \int_0^{F_m} dZ \xi(Z, x_m) \sin Z / \cos F_m \\ &\quad + \{\partial \Xi(\pi/2, a)/\partial Z\} / (H - \pi/2) + \Xi(\pi/2, a) \\ &= -\{1/|\cos F_m|\} \int_0^{F_m} dZ \xi(Z, x_m) \sin Z \\ &\quad + \{2/(2H - \pi)\} \int_0^{\pi/2} dZ \xi(Z, a) \sin Z \\ &\quad + \int_0^{\pi/2} dZ \xi(Z, a) \cos Z \\ &< -\{2F_m/\pi|\cos F_m|\} \int_0^{\pi/2} dZ \xi(Z, x_m) \sin Z \\ &\quad + \{(2 + 2H - \pi)/(2H - \pi)\} \int_0^{\pi/2} dZ \xi(Z, a) \sin Z. \end{aligned} \quad (6.14)$$

Noticing that from (3.7) and (3.9), $\xi(Z, x)$ is written to the same approximation as

$$\xi(Z, x) \simeq \int_0^Z dZ \int_{-\infty}^x dx [(\partial v/\partial y)/u]_{\psi}, \quad (6.15)$$

and that

$$\begin{aligned} &\int_0^Z dZ \int_{-\infty}^{x_m} dx [(\partial v/\partial y)/u]_{\psi} \\ &\gg \left| \int_0^Z dZ \int_{x_m}^a dx [(\partial v/\partial y)/u]_{\psi} \right|, \end{aligned} \quad (6.16)$$

$\delta u(0, a)$ is further estimated as

$$\begin{aligned} \delta u(0, a) &< -[\{2F_m/\pi|\cos F_m|\} \\ &\quad - \{(2 + 2H - \pi)/(2H - \pi)\}] \int_0^{\pi/2} dZ \xi(Z, x_m) \sin Z + \{(2 + 2H - \pi)/(2H - \pi)\} \\ &\quad \int_0^{\pi/2} dZ \sin Z \int_0^Z dZ \int_{x_m}^a dx [(\partial v/\partial y)/u]_{\psi} \\ &\simeq -[\{2F_m/\pi|\cos F_m|\} \\ &\quad - \{(2 + 2H - \pi)/(2H - \pi)\}] \int_0^{\pi/2} dZ \xi(Z, x_m) \sin Z. \end{aligned} \quad (6.17)$$

Using (5.3) and (5.5), it is easily checked by a pocket computer that the right-hand side of (6.17) is negative for any H between $\pi/2$ and $3\pi/2$.

7. Conclusion

In this note, the effect of 3-dimensionality of a mountain profile on downslope windstorms was examined. The case of an almost-2-dimensional mountain profile was considered. The deviation from

Smith (1985)'s 2-dimensional result was calculated. In the case of a prescribed mountain height, both the downslope wind speed and critical atmospheric height are diminished by the 3-dimensionality. This is consistent with Peng (1995)'s numerical result, which shows that 2-dimensional models overestimate the amount of downslope wind speed. On the other hand, in the case of a prescribed atmospheric height, the downslope windstorm occurs for a higher mountain with a greater wind speed. Therefore, in this case, the 2-dimensional model underestimates the amount of downslope wind speed.

In the case of downslope windstorms over a saddle point instead of a mountain-top, the wind parallel to the mountain-range converges instead of diverges on the upslope of the mountain. As a result, the deviations due to 3-dimensionality of a saddle-point type have opposite signs from what are shown in this note.

The analytical investigation for strong 3-dimensionality is left for future study.

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3次元の山の風下のおろし風

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山の3次元性の、おろし風への影響を解析的に調べた。安定成層を持つ一様な一般流の中に在る、ほとんど2次元的な山の場合を調べた。山の形は一つの最高点(頂上)を持ち、流れに直交する方向にはほぼ一様とした。山の頂上を含む、流れに沿った鉛直断面でのおろし風の大きさを計算した。

山の形が流れに直交する方向に一様な2次元の場合と比較して、次の結果が得られた。大気の高さが指定されている場合には、おろし風の大きさと、おろし風が起こるために要求される山の高さの両方が、山の3次元性に依って大きくなる。他方、山の高さが指定されている場合には、おろし風の大きさと、おろし風が起こるために要求される大気の高さの両方が、山の3次元性によって小さくなる。