The Difference of the Slope Wind Between Day and Night

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Abstract

The response of the fluid stably stratified over the infinite slope was investigated by linear theory when finite length $2l$ in it was heated or cooled. If the angle of the slope was small, the nature of the flow near the slope changed depending on whether the half height of the slope $h_S^* = l \sin \phi$ (ϕ is angle of slope) was higher than that of thermal boundary layer $h_T^* = \alpha(\nu/N)^{1/3}l^{1/3}$ ($\alpha \sim 3.5$), which was developed over the heat island whose length was $2l$, or not.

On the real slope $h_S^* > h_T^*$ was often satisfied at night and the flow was close to the results from Prandtl theory, but $h_S^* < h_T^*$ in the daytime so that the flow behaved like a convection.

1. Introduction

One of the most striking characters of topography in Japan is an abundance of mountains, and local winds blown in Japan are more or less affected by these mountains. It was reported by some authors in both observations (Fujibe and Asai, 1979) and numerical experiments (Asai and Mitsumoto (1978), Oukouchi *et al.* (1978), Sahashi (1981) and Kikuchi *et al.* (1981)) that land and sea breezes which were the most general feature of local winds caused by the difference of thermal energy released into the atmosphere from the surface were affected by mountains and that they interacted with mountain and valley breezes.

Mannoji (1982) clarified by the numerical experiment that two kinds of breezes were contained in the breezes blown between plain and mountains. That is, slope winds and plain-plateau breezes. Tyson *et al.* (1972) also pointed out these two breezes by observations in South Africa. In these two breezes Prandtl had considered slope winds by parcel method. This theory explained downslope wind at night fairly well in a valley at mid-latitude and katabatic wind in antarctic but didn't agree

with the upslope wind in a valley in the daytime, as pointed out by several authors (for example Sutton, Mannoji *etc.*). From the observation McHattie (1968) concluded that small-scale convections which developed in the daytime brought the effect of upper wind into the valley. But in Mannoji's numerical calculations, even the case without the upper wind, also didn't agree with Prandtl's theory in the daytime. Mannoji concluded that this might be caused by the difference of stability of the atmosphere near the surface between day (neutral-slightly unstable) and night (stable).

Here we investigate the response of stratified fluid by linear theory over the infinite length slope in which finite length is heated or cooled and estimate the difference of the slope wind between day and night with the aid of numerical experiments.

2. Basic equations

We consider 2-dimensional rectangular coordinate system (ξ^*, ζ^*) which is inclined against usual (x^*, z^*) coordinate system at ϕ (Fig. 1).

Then we may represent basic equations as

Fig. 1 ξ - ζ coordinate system.

$$\begin{aligned} \frac{\partial u^*}{\partial t^*} + u^* \frac{\partial u^*}{\partial \xi^*} + w^* \frac{\partial u^*}{\partial \zeta^*} \\ = -c_P \Theta \frac{\partial \hat{\pi}}{\partial \xi^*} + \frac{g}{\Theta} \theta^* \sin \phi + \nu \frac{\partial^2 u^*}{\partial \zeta^{2*}}, \quad (1) \end{aligned}$$

$$\begin{aligned} \frac{\partial w^*}{\partial t^*} + u^* \frac{\partial w^*}{\partial \xi^*} + w^* \frac{\partial w^*}{\partial \zeta^*} \\ = -c_P \Theta \frac{\partial \hat{\pi}}{\partial \zeta^*} + \frac{g}{\Theta} \theta^* \cos \phi + \nu \frac{\partial^2 w^*}{\partial \zeta^{2*}}, \quad (2) \end{aligned}$$

$$\frac{\partial \theta^*}{\partial t^*} + u^* \frac{\partial \theta^*}{\partial \xi^*} + w^* \frac{\partial \theta^*}{\partial \zeta^*} = \kappa \frac{\partial^2 \theta^*}{\partial \zeta^{2*}}, \quad (3)$$

$$\frac{\partial u^*}{\partial \xi^*} + \frac{\partial w^*}{\partial \zeta^*} = 0, \quad (4)$$

under Boussinesq and anelastic approximations. Here (u^*, w^*) are (ξ^*, ζ^*) components of velocity, $\hat{\pi} = (p^*/P)^{R/C_P}$, where p^* is pressure, P is a reference pressure, R is gas constant and other symbols have usual meanings (The variables with * are dimensionalized forms.). We assume $\kappa = \nu$, for turbulent diffusivity of heat is nearly equal to that of momentum in most cases of usual atmosphere. For potential temperature

$$\begin{aligned} \theta^*(\xi^*, \zeta^*, t^*) &= \Theta_z + \bar{\theta}_z^*(z^*) + \theta_z^*(x^*, z^*, t^*) \\ &= \Theta + \bar{\theta}^*(\xi^*, \zeta^*) + \theta'^*(\xi^*, \zeta^*, t^*), \end{aligned}$$

where $\bar{\theta}^*(\xi^*, \zeta^*) = \gamma(\xi^* \sin \phi + \zeta^* \cos \phi)$.

As a basic state we consider static state which is stably stratified in vertical (z) direction such as $\partial \bar{\theta}_z^* / \partial z^* = \gamma$ (constant). Then square of buoyancy frequency is given by $N^2 = (g/\Theta)\gamma$.

Here we consider the motion near origin so that $\xi^* \cdot \gamma \sin \phi, \zeta^* \cdot \gamma \cos \phi \ll \Theta$.

We describe perturbation field with $(')$ and basic field with $(-)$ then equations for the basic field are reduced to

$$c_P \Theta \frac{\partial \bar{\pi}}{\partial \xi^*} = \frac{g}{\Theta} \bar{\theta}^* \sin \phi,$$

$$c_P \Theta \frac{\partial \bar{\pi}}{\partial \zeta^*} = \frac{g}{\Theta} \bar{\theta}^* \cos \phi,$$

and these mean hydrostatic equilibrium. For the perturbation field we neglect higher order terms than 1st order, the basic equations become

$$\frac{\partial u'^*}{\partial t^*} = -c_P \Theta \frac{\partial \pi'}{\partial \xi^*} + \frac{g}{\Theta} \theta'^* \sin \phi + \nu \frac{\partial^2 u'^*}{\partial \zeta^{2*}}, \quad (5)$$

$$\frac{\partial w'^*}{\partial t^*} = -c_P \Theta \frac{\partial \pi'}{\partial \zeta^*} + \frac{g}{\Theta} \theta'^* \cos \phi + \nu \frac{\partial^2 w'^*}{\partial \zeta^{2*}}, \quad (6)$$

$$\frac{\partial \theta'^*}{\partial t^*} + \frac{\Theta}{g} N^2 (u'^* \sin \phi + w'^* \cos \phi) = \nu \frac{\partial^2 \theta'^*}{\partial \zeta^{2*}}, \quad (7)$$

$$\frac{\partial u'^*}{\partial \xi^*} + \frac{\partial w'^*}{\partial \zeta^*} = 0. \quad (8)$$

Next, equations (5)–(8) are nondimensionalized as follows:

$$(\xi^*, \zeta^*) = (l\xi, l\zeta), \quad t^* = tN^{-1},$$

$$(u'^*, w'^*) = (lNu', lNw'), \quad c_P \Theta \hat{\pi}' = \frac{l^3 N^4}{g} \pi',$$

$$\theta'^* = \Theta \theta'.$$

Here l is a half of the slope length in which heating and/or cooling are given. Then nondimensionalized equations are

$$\frac{\partial u'}{\partial t} = -\delta \frac{\partial \pi'}{\partial \xi} + \delta^{-1} \theta' \sin \phi + R^{-1/2} \frac{\partial^2 u'}{\partial \zeta^2}, \quad (9)$$

$$\frac{\partial w'}{\partial t} = -\delta \frac{\partial \pi'}{\partial \zeta} + \delta^{-1} \theta' \cos \phi + R^{-1/2} \frac{\partial^2 w'}{\partial \zeta^2}, \quad (10)$$

$$\frac{\partial \theta'}{\partial t} + \delta (u' \sin \phi + w' \cos \phi) = R^{-1/2} \frac{\partial^2 \theta'}{\partial \zeta^2}, \quad (11)$$

$$\frac{\partial u'}{\partial \xi} + \frac{\partial w'}{\partial \zeta} = 0. \quad (12)$$

Here $\delta^{-1} = g/N^2 l$, $R^{-1/2} = \nu/Nl^2$.

First we investigate the phenomena led from (9)-(12) under several idealized conditions and then analyze the nature of the flow over the slope with finite heat and/or cool source.

3. Some features of stratified fluid obtained from reduced characteristic equation

From equation (12) we may introduce ϖ , where

$$u' = \frac{\partial \varpi}{\partial \zeta}, \quad w' = -\frac{\partial \varpi}{\partial \xi}.$$

Then equations (9)-(12) become

$$\begin{aligned} & \left(\frac{\partial}{\partial t} - R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \right) \left(\frac{\partial \theta'}{\partial \xi} \right) \\ &= \delta \left(\cos \phi \cdot \frac{\partial}{\partial \xi} - \sin \phi \cdot \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial \varpi}{\partial \xi} \right), \end{aligned} \quad (13)$$

$$\begin{aligned} & \left(\frac{\partial}{\partial t} - R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \right) \left(\frac{\partial^2}{\partial \xi^2} + \frac{\partial^2}{\partial \zeta^2} \right) \left(\frac{\partial \varpi}{\partial \xi} \right) \\ &= -\delta^{-1} \left(\cos \phi \cdot \frac{\partial}{\partial \xi} - \sin \phi \cdot \frac{\partial}{\partial \zeta} \right) \left(\frac{\partial \theta'}{\partial \xi} \right). \end{aligned} \quad (14)$$

From (13) and (14) we have

$$\begin{aligned} & \left[\left(\frac{\partial}{\partial t} - R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \right)^2 \left(\frac{\partial^2}{\partial \xi^2} + \frac{\partial^2}{\partial \zeta^2} \right) \right. \\ & \left. + \left(\cos \phi \cdot \frac{\partial}{\partial \xi} - \sin \phi \cdot \frac{\partial}{\partial \zeta} \right)^2 \right] \Phi = 0, \end{aligned} \quad (15)$$

where Φ is $\partial \theta' / \partial \xi$ or $\partial \varpi / \partial \xi$.

Here we assume that θ' and ϖ have next forms:

$$\theta'(\omega, k, n; \xi, \zeta, t) = e^{i\omega t} e^{ik\xi} e^{n\zeta} \hat{\theta}(\omega, k, n), \quad (16)$$

$$\varpi(\omega, k, n; \xi, \zeta, t) = e^{i\omega t} e^{ik\xi} e^{n\zeta} \hat{\varpi}(\omega, k, n). \quad (17)$$

These forms correspond to homogeneous wave-like solutions about time and ξ coordinates.

Substitute (16), (17) into (15) then we have

$$\begin{aligned} & (i\omega - R^{-1/2} n^2)(n^2 - k^2) + (ik \cos \phi - n \sin \phi)^2 \\ &= 0. \end{aligned} \quad (18)$$

Some ideal features of stratified fluid are derived by reducing equation (15) or (18).

3.1 Steady state with $\phi=0$

In this case (15) is reduced to

$$\left[\frac{\partial^4}{\partial \zeta^4} \left(\frac{\partial^2}{\partial \xi^2} + \frac{\partial^2}{\partial \zeta^2} \right) + R \frac{\partial^2}{\partial \xi^2} \right] \Phi = 0. \quad (19)$$

This corresponds to steady convection mode. When slab symmetric boundary condition given for θ' , the solution represents a heat island. If we expect to seek the solution which satisfies $\partial^2 / \partial \zeta^2 \gg \partial^2 / \partial \xi^2$ (i.e. the aspect ratio of the phenomenon is very small),

$$\left[\frac{\partial^6}{\partial \zeta^6} + R \frac{\partial^2}{\partial \xi^2} \right] \Phi = 0.$$

This corresponds to the convection of Stommel and Veronis (1957). If we introduce a vertical scale length h ($h \ll 1$) for the perturbation with horizontal scale length 2, then

$$h^6 = R^{-1}.$$

Next we seek the solution which satisfy $\partial^2 / \partial \zeta^2 \ll \partial^2 / \partial \xi^2$ (i.e. the aspect ratio of the phenomenon is very large), then

$$\left(\frac{\partial^4}{\partial \zeta^4} \cdot \frac{\partial^2}{\partial \xi^2} + R \frac{\partial^2}{\partial \xi^2} \right) \Phi = 0,$$

and

$$h \sim R^{-1/4}.$$

In dimensional form $h^* \sim (\nu/N)^{1/2}$, that is, h^* doesn't depend on horizontal scale of heat source.

3.2 Non steady state with $\phi=0$

In this case from (15) we obtain

$$\left[\left(\frac{\partial}{\partial t} - R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \right)^2 \left(\frac{\partial^2}{\partial \xi^2} + \frac{\partial^2}{\partial \zeta^2} \right) + \frac{\partial^2}{\partial \xi^2} \right] \Phi = 0.$$

In case of $\partial^2 / \partial \zeta^2 \gg \partial^2 / \partial \xi^2$, Kimura and Eguchi (1978) introduced this as land and sea breezes. If $\partial / \partial t \sim R^{-1/2} (\partial^2 / \partial \zeta^2)$, vertical structure of the phenomenon is affected by the periodic change of boundary condition of θ' . That is, there is a horizontal scale of the heat source over which the development of the boundary layer as l becomes larger is suppressed by the periodic change of the boundary condition for

$\theta',^{1)}$

3.3 Non steady state with $\phi \neq 0$

3.3.1 $R \gg 1$

Here we consider characteristic equation (18). In this case (18) is reduced to

$$-\omega^2(n^2 - k^2) + (ik \cos \phi - n \sin \phi)^2 = 0,$$

$$\text{i.e. } (\sin^2 \phi - \omega^2)n^2 - 2ikn \cos \phi \cdot \sin \phi + k^2(\omega^2 - \cos^2 \phi) = 0.$$

This is dispersion relation of internal gravity wave in ξ - ζ coordinate system. $R \gg 1$ means $\nu \ll Nl^2$. For example, in case of weak diffusion (small turbulent viscosity) the dominant phenomenon is internal gravity wave or in case of not so weak diffusion the dominant phenomenon except very near the surface is also internal gravity wave, if there are external forces to make perturbations.

3.3.2 $\partial^2/\partial \zeta^2 \gg \partial^2/\partial \xi^2$ with not small ϕ

Here returning to (15), the equation is reduced to

$$\left[\left(\frac{\partial}{\partial t} - R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \right)^2 + \sin^2 \phi \right] \Phi = 0. \quad (20)$$

This case was introduced in Asai and Mitsumoto (1978) as slope winds with periodic change of boundary condition. If $\partial/\partial t \ll \sin \phi$ (If periodic change with frequency ω is assumed, $\omega \ll \sin \phi$), and this is true in most cases of slope winds in the field as pointed out by Asai and Mitsumoto, (20) becomes,

$$\left[R^{-1/2} \frac{d^2}{d\zeta^2} \pm i \sin \phi \right] \Phi = 0. \quad (21)$$

This corresponds to the results obtained by Prandtl (1942). In case of $\phi = 0$ in (20),

$$\frac{\partial}{\partial t} \Phi = R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \Phi.$$

This case was introduced in Kimura and Eguchi (1978) as conduction wave.

3.3.3 $\partial^2/\partial \zeta^2 \ll \partial^2/\partial \xi^2$ with not small ϕ

In this case from (15)

$$\left[\left(\frac{\partial}{\partial t} - R^{-1/2} \frac{\partial^2}{\partial \zeta^2} \right)^2 + \cos^2 \phi \right] \Phi = 0.$$

The aspect ratio of disturbance is very large and this case may not exist in real field.

If we choose parameters given in Table 1 for (18) with the condition of $\omega = 0$, real part of three solutions for n out of six solutions in (18) are not positive. These three solutions are close to each other when $\phi = 0$, but as ϕ increases, two of them approach to Prandtl's case and another approaches the internal gravity wave (stationary) case (i.e. $\text{Re}(n) \rightarrow 0$ in Fig. 2).

Table 1 Parameters used in equation (18) for the calculation of Fig. 2.

l :	100 km
N^2 :	$1.96 \times 10^{-4} \text{s}^{-2}$
ν :	$10 \text{ m}^2 \text{s}^{-1}$
k :	2π
ω :	0

Fig. 2 Dependency of the real parts of three solutions (solid lines) of (18) on ϕ (with $\omega = 0$). Parameters are given in Table 1. Dotted line is obtained from Prandtl's theory.

1) Kimura and Eguchi (1978) pointed out that there was a scale over which the height of land and sea breezes could not 'feel' the scale of heat source (about 100 km).

4. Slope winds over the finite heat source

Here we consider the air flow caused by a heat source of finite length (The length is 2.) on the infinite slope. Then boundary conditions are,

$$u', w', \theta' < \infty \quad \text{as } \zeta \rightarrow \infty,$$

$$u', w' = 0 \quad \text{at } \zeta = 0,$$

$$\theta'(\xi, 0, t) = e^{i\omega t} \frac{2\theta_0}{\pi} \int_0^\infty \cos(k\xi) \frac{\sin k}{k} dk.$$

If we assume that $\tilde{\theta}(\omega, k, n; \xi, \zeta, t)$ is the solution of (15) for (ω, k, n) mode, then

$$\begin{aligned} \theta'(\xi, \zeta, t) = & \frac{1}{\pi} e^{i\omega t} \int_0^\infty \frac{\sin k}{k} \{ \hat{\theta}(k, n(k); \xi, \zeta) \\ & + \hat{\theta}(-k, n(-k); \xi, \zeta) \} dk, \end{aligned}$$

where $\tilde{\theta}(\omega, k, n(k); \xi, \zeta, t) = e^{i\omega t} \hat{\theta}(k, n(k); \xi, \zeta)$,

$$\hat{\theta}(k, n(k); \xi, 0) = \theta_0 e^{ik\xi},$$

and $\hat{\theta}(-k, n(-k); \xi, 0) = \theta_0 e^{-ik\xi}$.

Here after we consider stationary case ($\omega=0$) for the sake of simplicity.

If $\phi=0$, these boundary conditions mean a heat island. In case of $\phi \neq 0$ the phenomena contain not only heat island but also slope wind. We must separate these two phenomena to investigate the nature of slope wind. These two phenomena may be separated when we consider that the stream-function of heat island is an antisymmetric perturbation field about ζ axis. Under Boussinesq approximation, this antisymmetry of heat island may approximately hold in case of $\phi \neq 0$ for small ϕ . Then the perturbation field from which we subtract antisymmetric part may approximately represent the slope wind. That is, the motion on the ζ axis may be ascribed to the slope wind. Fig. 3 shows streamlines for $R^{1/4}=1000$. (a), (b) and (c) are $\phi=0^\circ$, $\phi=0.5^\circ$ and $\phi=4^\circ$, respectively (These figures still contain the two features discussed above.). In case of (a) streamlines are symmetric about ζ axis and two cells of convection are clear. In case of (b), this is an under-critical situation (see below), there are still two cells but left one is developed and elongated. The streamlines away from the surface become straight. In case of (c), this is a super critical situation,

Fig. 3 The streamlines over the infinite slope with finite heat source for $R^{1/4}=1000$. (a) $\phi=0^\circ$, (b) $\phi=0.5^\circ$, and (c) $\phi=4^\circ$. An arrow at upper right corner shows the direction of the gravity in the figure.

there is only one cell and the cell is elongated more than in case (b).

Now we pay attention two features of the results obtained by the solutions, the maximum velocity $u_{\max}^*$ and the height (h_u) where $u_{\max}^*$ is given on the ζ axis, and investigate ϕ -dependency of these two parameters. Fig. 4

shows the relation between $u_{\max}^*$ and slope angle ϕ . For the sake of convenience to compare with Prandtl's case, we show $u_{\max}$ in its dimensional form $u_{\max}^*$ and h_u nondimensionalized by $(\nu/N)^{1/2}$. In case of Prandtl (infinite slope length and heat source), $u_{\max}^*$ is independent of ϕ (about 2.2 m/s in the figure's case). $R^{1/4}$ means the half length of heating or cooling source nondimensionalized by

Fig. 4 The relation between maximum wind velocity $u_{\max}^*$ and slope angle ϕ . $u_{\max}^*$'s are in dimensional form with $\nu=10\text{ m}^2\text{s}^{-1}$ and $N=1.96\times 10^{-4}\text{ s}^{-2}$.

Fig. 5 The relation between h_u , the nondimensional height where $u_{\max}$ is given on the ζ axis, and ϕ ; To obtain dimensional height, multiply by $(\nu/N)^{1/2}$.

$(\nu/N)^{1/2}$. When ϕ is small $u_{\max}^*$'s are proportional to ϕ , but at $\phi=0.4^\circ$, $\phi=2^\circ$ and $\phi=9^\circ$ $u_{\max}^*$'s of $R^{1/4}=10^4$, $R^{1/4}=10^3$ and $R^{1/4}=10^2$ cease to increase and become very close to Prandtl's case. Fig. 5 shows the dependency of the heights, where $u_{\max}^*$'s are given, on ϕ . In case of Prandtl this height (h_u) is proportional to $(\sin\phi)^{-1/2}$ (c.f. equation (21)) so if ϕ is small $h_u \propto \phi^{-1/2}$. From Fig. 5 we see that these heights of $R^{1/4}=10^4$, 10^3 and 10^2 are almost constants independent of ϕ until ϕ takes critical angles ϕ_c defined as $\phi_c=0.4^\circ$, $\phi_c=2^\circ$ and $\phi_c=9^\circ$ respectively, and after that they also approach Prandtl's case.

Next we consider what the critical angles $\phi_c=0.4^\circ$, $\phi_c=2^\circ$ and $\phi_c=9^\circ$ mean. Table 2 shows the relation between h_T and $R^{1/4}\sin\phi$ on $R^{1/4}$ and ϕ_c , respectively. Here h_T is defined as the height, obtained by above linear theory and nondimensionalized by $(\nu/N)^{1/2}$, at which the temperature deviation on the ζ axis first become 0 over the heat island ($\phi=0$) which has the same half length ($R^{1/4}$) as the heat source on the slope. This parameter indicates the maximum height of the thermal boundary of the heat island (Fig. 6). Kimura (1975) showed $h_T^* = 3.6R^{-1/6}l$ in case of stationary heat island and this means $h_T^* = 3.6(\nu/N)^{1/3}l^{1/3}$ in our case. From the relation between $R^{1/4}$ and h_T in Table 2 we obtain $h_T \sim 3.5R^{1/12}$ (The unit of h_T is different from Kimura (1975).) and this become $h_T^* = 3.5(\nu/N)^{1/3}l^{1/3}$. So our calculation agree well with Kimura in heat island case. From the same table we can also see h_T is very close to $R^{1/4}\sin\phi_c$. This leads to the conclusion that the wind blows over the finite heat source on the slope behaves like slope wind (in Prandtl's sense; Here after we call this Prandtl-like slope wind.) when a half of the height of the heat source ($R^{1/4}\sin\phi$)

Table 2 The relation among $R^{1/4}$, $200R^{-1/6}$, $3.5R^{1/12}$, ϕ_c , h_T and $R^{1/4}\sin\phi_c$. We can find $\phi_c \sim 200R^{-1/6}$, $h_T \sim 3.5R^{1/12}$ and $h_T \sim R^{1/4}\sin\phi_c$.

$R^{1/4}$	$200R^{-1/6}$	$3.5R^{1/12}$	ϕ_c	h_T	$R^{1/4}\sin\phi_c$
10^2	9.3	16.2	9°	16.0	15.6
10^3	2.0	35.0	2°	34.5	34.9
10^4	0.4	75.4	0.4°	74.3	69.8

Fig. 6 (a) The depth of thermal boundary layer (h_T) and (b) a half of the height of the slope ($R^{1/4} \sin \phi$). When $h_T < R^{1/4} \sin \phi$ the phenomena are close to Prandtl's case.

is much higher than the height of the thermal boundary layer which the heat island of same half length ($R^{1/4}$) has.

5. Numerical experiments

In real case the situation is of course different from the linear theory. Since detailed observations of slope wind are not available, we will compare the results of linear theory with those of numerical experiments. Fig. 7 shows the results of 3-dimensional numerical calculation (Kondo, 1982, 1983) of local circulation in Harima area. These figures are cross sections from north to south through Himeji (the central city of this area). The configuration is relatively 2-dimensional around Himeji (Fig. 8) and mountain lies from east to west. The upper of the Fig. 7 is 1500 L.S.T. and the lower is 0400 L.S.T.. The diffusion coefficients of the numerical experiments are given

Fig. 7 Slope winds developed over Harima area resulting from numerical experiments. The upper is 1500 L. S. T. with $R^{1/4}=360$ and the lower is 0400 L. S. T. with $R^{1/4}=9500$.

Fig. 8 The location of Harima and Himeji. Fig. 7 is a part of cross section of A-B (Left hand is north side in Fig. 7.).

by Gambo (1978),

$$\left. \begin{aligned} K_M &= l^2 \left| \frac{\partial U}{\partial z} \right| f_1(R_f) \\ K_\theta &= l^2 \left| \frac{\partial U}{\partial z} \right| f_2(R_f) \end{aligned} \right\} \text{ for } R_f < R_{fc} = 0.29,$$

$$K_M = K_\theta = 0.1 \text{ m}^2/\text{s} \quad \text{for } R_f \geq R_{fc} = 0.29,$$

where K_M is the diffusion coefficient of momentum and K_θ is that of potential temperature. They depend on R_f (flux Richardson number); when $R_f > R_{fc}$ they become large but when $R_f \geq R_{fc}$ they are small constants.

From Fig. 7 we can see the difference of flow patterns between 1500 L.S.T. and 0400 L.S.T., for example, the thickness of the flows. So we investigate the difference using the results from above theory. We consider the average field between surface and 2000 m above.

In the daytime (1500 L.S.T.),

$$\nu \cong 50 \text{ m}^2\text{s}^{-1}$$

$$N \cong 7.4 \times 10^{-3} \text{ s}^{-1}$$

$$l = 30 \text{ km}$$

$$R^{1/4} = 360$$

at night (0400 L.S.T.),

$$\nu \cong 0.1 \text{ m}^2\text{s}^{-1}$$

$$N \cong 1.0 \times 10^{-2} \text{ s}^{-1}$$

$$l = 30 \text{ km}$$

$$R^{1/4} = 9500$$

and mean slope angle is 0.6° . From $h_T = 3.5R^{1/12}$ we obtain $h_T = 24.9$ (daytime) and $h_T = 74.1$ (night) so that for the daytime we have $R^{1/4} \sin \phi = 3.8 < h_T = 24.9$ and for night $R^{1/4} \sin \phi = 99.5 > h_T = 74.1$. Then in the daytime the flow is convective-slope wind but at night it is Prandtl-like slope wind. We may obtain same results from comparing ϕ with ϕ_c . From Table 2 we can get $\phi_c(^{\circ}) \sim 200R^{-1/6}$. This means $\phi_c = 4.0^\circ$ in the daytime and $\phi_c = 0.4^\circ$ at night in the case. So $\phi = 0.6^\circ < \phi_c$ in the daytime then convective-slope wind becomes dominant and $\phi = 0.6^\circ > \phi_c$ at night then Prandtl-like slope wind becomes dominant. These results are arranged in Table 3.

We can distinguish convective-slope wind from Prandtl-like slope wind by comparing $l \sin \phi$ with h_T^* ($h_T^* = 3.5(\nu/N)^{1/3}l^{1/3}$). Since only N and ν can change between day and night and other parameters are constants, we can estimate the cause of these difference of slope wind. The ratio of N^{-1} between day and

Table 3 The difference of parameters and characteristics of the flow between day and night.

		Night 0400 L. S. T.	Daytime 1500 L. S. T.
fundamental parameters	$\nu \text{ (m}^2\text{s}^{-1}\text{)}$	0.1	50
	$N \text{ (s}^{-1}\text{)}$	0.01	0.0074
	$R^{1/4}$	9500	360
	$(\nu/N)^{1/2} \text{ (m)}$	3.16	82.2
	$\phi \text{ (}^\circ\text{)}$	0.6	
	half of mountain height: $l \sin \phi \text{ (m)}$	315	
h_T		74	25
$R^{1/4} \sin \phi$		100	3.8
$\phi_c \text{ (}^\circ\text{)}$		0.4	4.0
$h_T^* \text{ (m)}$		230	2100
criteria for two patterns of flow		$R^{1/4} \sin \phi > h_T$ $l \sin \phi > h_T^*$ $\phi > \phi_c$	$R^{1/4} \sin \phi < h_T$ $l \sin \phi < h_T^*$ $\phi < \phi_c$
characteristics of flow		Prandtl-like slope flow	convective slow flow

night $(N_{\text{day}}/N_{\text{night}})^{-1}$ is 1.35 and this rather small but that of $\nu_{\text{day}}/\nu_{\text{night}}$ is 500. From this we may conclude that the difference of eddy diffusivity between day and night makes the difference of the flow patterns of slope winds.

6. Conclusions

The flow pattern over an infinite slope in which finite length was heated or cooled was investigated by linear theory. When the slope slightly inclined, the flow pattern changed from heat island (two cells) to slope wind (one elongated cell). In the slope winds the slope-angle dependency of two parameters, the maximum wind velocity u_{max}^* and the height h_u , where u_{max}^* occurred changed at the critical angle ϕ_c at which $l \sin \phi_c = h_f^*$. When a half of the slope height $l \sin \phi > h_f^*$, the height of thermal boundary layer over the heat island of length $2l$, these parameters agreed well with the results obtained by Prandtl's theory.

The difference of slope flow between day and night obtained by numerical model was estimated by this criterion. In the daytime eddy diffusivity became large and h_f^* was high so $l \sin \phi < h_f^*$ then the flow became convective-slope wind. At night eddy diffusivity became small and h_f^* became low so $l \sin \phi > h_f^*$ then the flow became Prandtl-like slope flow. This difference may be important when we consider the behavior of pollutants near the surface.

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斜面流の昼と夜の差について

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無限にのびる斜面のうちの有限長 $2l$ を熱するか、あるいは冷却した場合の成層流体の応答を線型論により調べた。斜面の角度が小さい場合には、斜面に近いところの流れの性質が斜面の高さの半分 $h_S^* = l \sin \phi$ (ϕ は斜面の角度) が同じ $2l$ の長さを持つヒートアイランド上に発達する熱的境界層の高さ $h_T^* = \alpha (\nu/N)^{1/3} l^{1/3}$ ($\alpha \sim 3.5$) よりも高いかどうかによって変化した。

実際の斜面においては $h_S^* > h_T^*$ は夜間にはしばしば満たされるので、流れはプラントルの理論の結果に近いが、昼間は $h_S^* < h_T^*$ であり、流れは対流に近くなる。