A simple model for the convective boundary layer over wavy terrain with variable heat flux

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Abstract

A simple analytical model is derived for the convective boundary layer over a wavy surface with variabel surface heat flux and for zero mean wind. The amplitude of the surface wave is δ, its wavelength is λ. The surface heat flux varies by q around a mean flux Q. The surface roughness height is z_0, and the domain height is H. The flow domain is approximated by four control volumina. For steady state, the related budgets of heat and momentum predict the horizontal and vertical velocities, u and $w = 2uH/\lambda$. The solutions show a mean convective circulation induced by the undulated surface which is strongest at wavelength $\lambda \cong 4H$. For small amplitudes $\delta \ll H$ and $q \ll Q$ and for $\lambda = 4H$, we find $u/w_* \cong 0.7[1 + \delta/(2H) + q/(2Q)]$, where w_* is the convective velocity scale. At larger wavelengths, a variable heat flux has the same effect as a surface height variation if $\delta/(2H) = q/Q$. Results from large-eddy simulations and observations from motorgliders support the model up to a factor of two, but show also that small-scale thermals may be important which are not resolved by the present model.

1. Introduction

The effects of surface inhomogeneities on the structure of the atmospheric boundary layer, the related surface fluxes of heat and momentum, their parameterization and remote sensing are subject of intensive research within the World Climate Research Programme (Becker, Bolle and Rowntree, 1988). It is well-known to glider pilots (Reinhardt, 1985) that wavy and thermally inhomogenous terrain induces a regular convective flow structure with updrafts above hills or relatively warmer surfaces. By means of large-eddy simulation (LES), the flow field in a convective boundary layer at weak mean winds has been determined for homogeneous surfaces (Schmidt and Schumann, 1989), for variable heat fluxes at the surface (Graf and Schumann, 1991), and above sinusoidally variing surfaces (Krettenauer and Schumann, 1991). We found that the convection is dominated by a coherent structure at wavelength $\lambda = 4H$, and this motion structure reacts most strongly to surface inhomogeneities at such wavelengths. Other related numerical studies and some experimental results are summarized in the references cited. In this paper, a simple model is deduced which explains these findings quasi analytically.

2. The Model

We consider the turbulent convection in a boundary layer of mean depth H driven by a mean surface temperature flux Q at zero mean wind. The surface is assumed to have a regular sinusoidal wavy form with wavelength λ and amplitude δ. The surface heat flux varies also periodically with the same wavelength and amplitude q around the positive mean value Q. The surface is assumed to be rough with roughness height z_0 (we take equal values for momentum and heat transfer, for simplicity). The top of the boundary layer is assumed to be represented by a very stable inversion such that it can be approximated by a rigid free-slip adiabatic boundary. The fluid is exposed to gravity g. We assume the Boussinesq approximation for a fluid with uniform density ρ, and constant volumetric expansion coefficient $\beta = -(\partial\rho/\partial T)/\rho$; $\beta = 1/\overline{T}$ in air. Because of constant surface heating, the volume averaged temperature $\overline{T}$ increases at constant rate

$$d\overline{T}/dt = Q/H. \tag{1}$$

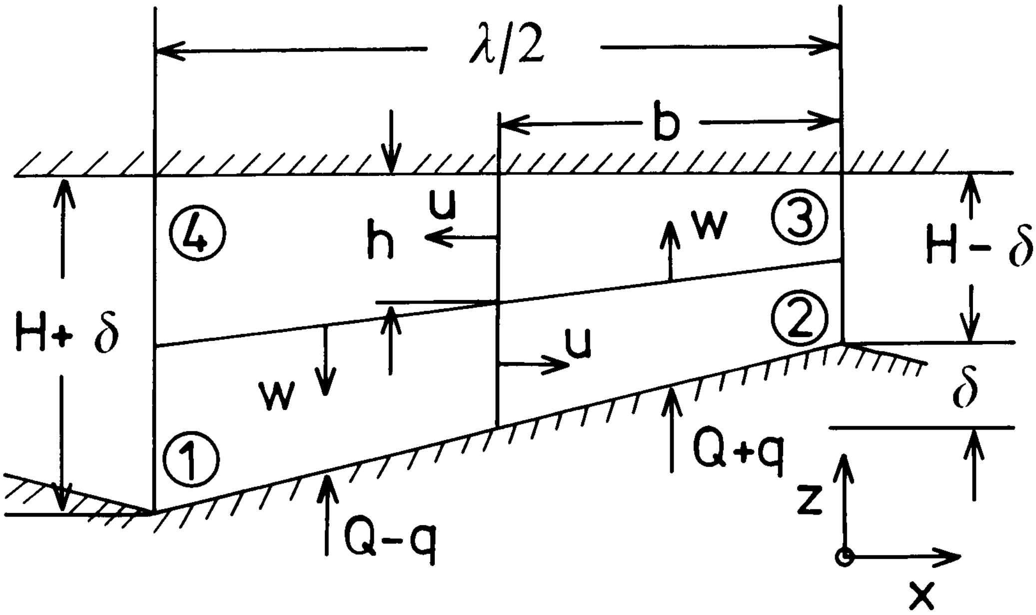

Figure 1. Sketch of a half-wave (wavelength $\lambda = 4b$) of a vertical cross-section of the periodic flow domain of mean height $H = 2h$ with surface height amplitude δ and variable surface temperature flux $Q \pm q$, showing the four control volumina 1 to 4, and characteristic horizontal and vertical velocities u and w. The domain extends infinitely in the homogeneous direction y normal to the depicted cross-section.

In order to obtain an estimate of the resultant convective motions we approximate the flow domain, as sketched in Fig. 1, by four subdomains, 1 to 4, each of width $b = \lambda/4$. On average the depth of the subdomains is $h = H/2$. Between the subdomains, we assume a flow with surface averaged velocities u from domain 1 to domain 2, and, for continuity, at the same rate from domain 3 to 4. In the vertical directions the corresponding flow velocities from 2 to 3 and from 4 to 1 have the mean value w. Flow across other boundaries of the subdomains are zero because of symmetry, periodicity and because of top and bottom boundary conditions. Because of continuity,

$$u\,h = w\,b. \tag{2}$$

This equation applies for arbitrary values of $\delta < H$ because the velocities are the Cartesian components and because the domain height is $2\,h$ at the mid-interface for symmetry. The volume sizes of the four subdomains, per unit length in y-direction, are

$$V_1 = V_4 = b(h + \delta/4), \quad V_2 = V_3 = b(h - \delta/4). \tag{3}$$

Let T_i, i = 1, 2, 3, 4, denote the mean local temperature deviations from the (arbitrary) mean temperature $\overline{T}$. We approximate advective fluxes by "upstream" values, e.g. the flux from volume 1 to volume 2 equals $h\,u\,T_1$. Without loss of generality, this requires $u \geq 0$. Moreover, we apply Eq. (2). Then, the heat balance for each of the subdomains results in

$$V_1 \frac{dT_1}{dt} = -\,(uh + w'b)(T_1 - T_4) - u'h(T_1 - T_2) + (Q - q)b - V_1 \frac{d\overline{T}}{dt}, \qquad (4)$$

$$V_2 \frac{dT_2}{dt} = +\,(uh + u'h)(T_1 - T_2) - w'b(T_2 - T_3) + (Q + q)b - V_2 \frac{d\overline{T}}{dt}, \qquad (5)$$

$$V_3 \frac{dT_3}{dt} = -\,(uh + w'b)(T_3 - T_2) - u'h(T_3 - T_4) - V_3 \frac{d\overline{T}}{dt}, \qquad (6)$$

$$V_4 \frac{dT_4}{dt} = +\,(uh + u'h)(T_3 - T_4) - w'b(T_4 - T_1) - V_4 \frac{d\overline{T}}{dt}. \qquad (7)$$

Here, u' and w' are effective turbulence velocities such that, e.g., $w'b(T_1 - T_4)$ describes the turbulent flux between volumes, e.g. from 1 into 4. They are related to horizontal and vertical diffusivities, $K_h = u'b$ and $K_v = w'h$, respectively.

The horizontal momentum balance is set up for a control volume of size $V_u = b\,h$ enclosing either the lower or the upper lateral interfaces between volumes 1 and 2 and between 3 and 4. The shear stress at the bottom surface is denoted by $-u_*^2$ as a function of the friction velocity u_*. To first order in geometrical terms, the balances are

$$V_u \frac{du}{dt} = p_1(h + \delta/4) - p_2(h - \delta/4) - 2w'ub - u_*^2 b + (p_1 + p_2 + p_3 + p_4)\delta/8 - p_s\delta, \qquad (8)$$

for the lower of the two volumes V_u, and

$$V_u \frac{du}{dt} = p_3(h - \delta/4) - p_4(h + \delta/4) - 2w'ub + (p_1 + p_2 + p_3 + p_4)\delta/8. \qquad (9)$$

for the upper volume. Here p_i is the mean pressure (per unit mass) in the i-th control volume; p_s is the pressure at the bottom surface of the lower domain V_u. By hydrostatic approximation, to first order in geometrical terms,

$$p_s = (p_1 + p_2)/2 - \beta g(T_1 + T_2)h/4. \qquad (10)$$

Similarly, the vertical momentum balance is formulated for the two control volumina enclosing the interface between subdomains 2 and 3 and 4 and 1. The left of these has the size V_1, the right one has the size V_2:

$$V_1 \frac{dw}{dt} = (p_4 - p_1)b - \beta g(T_1 + T_4)V_1/2 - 2u'h\,w, \qquad (11)$$

$$V_2 \frac{dw}{dt} = (p_2 - p_3)b + \beta g(T_2 + T_3)V_2/2 - 2u'h\,w. \qquad (12)$$

Here, the last term describes lateral mixing of vertical momentum, which is a non-hydrostatic effect.

To close the set of equations, we have to specify the turbulent diffusivities K_h, K_v, and the surface friction velocity u_*. The latter is related to the horizontal flow velocity u according to the Monin-Obukhov relationships, following Dyer (1974):

$$u = \frac{u_*}{\kappa}\left[\ln(z/z_0) - \psi_m(z/L) + \psi(z_0/L)\right], \quad L = -u_*^3/(\kappa\beta g Q), \tag{13}$$

$$\psi_m(\zeta) = 2\ln\left(\frac{1+\varphi_m^{-1}}{2}\right) + \ln\left(\frac{1+\varphi_m^{-2}}{2}\right) - 2\,arc\,tan\,(\varphi_m^{-1}) + \frac{\pi}{2}, \tag{14}$$

$$\varphi_m(\zeta) = (1 - 16\zeta)^{-1/4}, \quad \kappa = 0.41. \tag{15}$$

These equations apply to the unstable case, i.e. for $Q \geq 0$, where the Obukhov-length L is negative. They are evaluated for $z = h/2$.

The turbulent diffusivities are roughly approximated by

$$K_h = 3\alpha v' h, \quad K_v = \alpha v' b, \quad v' = (w_*^2 + 4u_*^2)^{1/2}, \quad w_* = (\beta g H Q)^{1/3}. \tag{16}$$

Here, $\alpha \cong 0.1$ and $K_h/K_v \cong 3$ are empirical parameters, w_* is Deardorff's convective velocity scale and v' one possible form of a scaling velocity for sheared convection, proposed by Penc and Albrecht (1987).

3. Solutions

For steady state, i.e. $dw/dt = 0$, Eqs. (11), (12) with Eq. (2), determine the pressure differences

$$p_4 - p_1 = \beta g(T_1 + T_4)(h + \delta/4)/2 + 2u'uh^2/b^2, \tag{17}$$

$$p_3 - p_2 = \beta g(T_2 + T_3)(h - \delta/4)/2 - 2u'uh^2/b^2. \tag{18}$$

The sum of Eqs. (8) and (9) gives

$$2V_u\frac{du}{dt} = (p_1 + p_3 - p_2 - p_4)h + (p_1 + p_2 - 2p_s)\delta/2 - 4w'u\,b - u_*^2 b. \tag{19}$$

Using Eqs. (10), (17), and (18) results in

$$\begin{aligned} 2V_u\frac{du}{dt} &= -(4u'h^3/b^2 + 4w'b)u - u_*^2 b \\ &+ \beta g\left[(T_2 + T_3 - T_1 - T_4)h^2/2 - (T_3 - T_2 + T_4 - T_1)h\delta/8\right]. \end{aligned} \tag{20}$$

For steady state, i.e. $dT_i/(dt) = 0$, Eqs. (4) - (7) together with (1) result in

$$T_1 - T_4 = -\mu(T_1 - T_2) + W_1; \quad W_1 = \frac{b\{(1 - \delta/(4h))Q/2 - q\}}{uh + w'b}, \tag{21}$$

$$T_2 - T_1 = -\nu(T_2 - T_3) + W_2; \quad W_2 = \frac{b\{(1 + \delta/(4h))Q/2 + q\}}{uh + u'h}, \tag{22}$$

$$T_2 - T_3 = \mu(T_3 - T_4) + W_3; \quad W_3 = \frac{b(1 - \delta/(4h))Q/2}{uh + w'b}, \tag{23}$$

$$T_3 - T_4 = \nu(T_4 - T_1) + W_4; \quad W_4 = \frac{b(1 + \delta/(4h))Q/2}{uh + u'h}, \tag{24}$$

where

$$\mu = \frac{u'h}{uh + w'b}, \quad \nu = \frac{w'b}{uh + u'h}. \tag{25}$$

This set of linear equations can be solved to obtain the temperature differences

$$T_4 - T_1 = D^{-1}(-W_1 - \mu W_2 + \mu\nu W_3 + \mu^2\nu W_4), \tag{26}$$

$$T_1 - T_2 = D^{-1}(-W_2 + \nu W_3 + \mu\nu W_4 - \mu\nu^2 W_1), \tag{27}$$

$$T_2 - T_3 = D^{-1}(W_3 + \mu W_4 - \mu\nu W_1 - \mu^2\nu W_2), \tag{28}$$

$$T_3 - T_4 = D^{-1}(W_4 - \nu W_1 - \mu\nu W_2 + \mu\nu^2 W_3). \tag{29}$$

The solutions exist as long as the determinant

$$D = 1 - \mu^2\nu^2 = (1 - \mu\nu)(1 + \mu\nu), \tag{30}$$

stays positive, which is the case for $u > 0$.

Inserting the temperature results into Eq. (20) gives,

$$\begin{aligned} 2V_u du/dt &= -4\left(u'h^3/b^2 + w'b\right)u - u_*^2 b \\ &+ \frac{\beta g h^2}{2D}\Big\{W_2 + W_4 - \nu(W_3 + W_1) - \mu\nu(W_4 + W_2) + \mu\nu^2(W_1 + W_3) \\ &+ \frac{\delta}{4h}\left[W_3 + W_1 + \mu(W_2 + W_4) - \mu\nu(W_1 + W_3) - \mu^2\nu(W_2 + W_4)\right]\Big\}. \end{aligned} \tag{31}$$

If we insert the various abbreviations, we get finally,

$$\begin{aligned} \frac{H}{w_*^2}\frac{du}{dt} &= -4\left(\frac{u'}{w_*}h^3/b^3 + \frac{w'}{w_*}\right)\frac{u}{w_*} - u_*^2/w_*^2 \\ &+ \frac{w_*}{u + u'}\frac{1}{4(1 + \mu\nu)}\left\{1 + \frac{\delta}{4h} + \frac{q}{Q} - \frac{w'b}{uh + w'b}\left(1 - \frac{\delta}{4h} - \frac{q}{Q}\right)\right. \\ &\left. + \frac{\delta}{4h}\frac{uh + u'h}{uh + w'b}\left[1 - \frac{\delta}{4h} - \frac{q}{Q} + \frac{u'}{u + u'}\left(1 + \frac{\delta}{4h} + \frac{q}{Q}\right)\right]\right\}. \end{aligned} \tag{32}$$

For steady state ($du/dt = 0$), the solution u/w_* of this equation for given values of $\lambda/H = 2b/h$, $\delta/H = \delta/(2h)$, q/Q, and for given z_0/H can be determined iteratively by solving

$$\frac{u}{w_*} = -x' + \sqrt{x'^2 + r}\,, \quad \text{where } x' = \frac{u'}{2w_*}, \tag{33}$$

with

$$r = \left[4\left(\frac{u'}{w_*}h^3/b^3 + \frac{w'}{w_*}\right) + C_d\frac{u_*}{w_*}\right]^{-1} \frac{1}{4(1+\mu v)}$$

$$\left\{1 + \frac{\delta}{4h} + \frac{q}{Q} - \frac{w'b}{uh + w'b}\left(1 - \frac{\delta}{4h} - \frac{q}{Q}\right)\right. \tag{34}$$

$$\left. + \frac{\delta}{4h}\frac{uh + u'h}{uh + w'b}\left[1 - \frac{\delta}{4h} - \frac{q}{Q} + \frac{u'}{u + u'}\left(1 + \frac{\delta}{4h} + \frac{q}{Q}\right)\right]\right\}.$$

Here $C_d = u_*/u$ is the drag coefficient given by the solution, using Eq. (13).

4. Discussion

4.1 Limiting analytical results

The model equations show that a surface undulation of height δ/H has the same effect as a variable heat flux of magnitude q/Q if $q/Q = \delta/(2H)$ as long as the surface undulation is small. Note that δ denotes the wave amplitude while q the mean of the wavy deviation, so that the factor 2 is irrelevent. For large values of δ/H the orographic undulation causes a stronger convection than the equivalent surface heat variation. If both types of inhomogeneity are present, the two effects tend to reduce each other for large undulation.

For the limiting case of $\lambda/H \to \infty$, we find

$$\frac{u}{w_*} = \left\{-\frac{u'}{w_*} + \sqrt{\left(\frac{u'}{w_*}\right)^2 + \frac{1}{2}\frac{q/Q + \delta/(2H)}{4w'/w_* + C_d u_*/w_*}}\right\}. \tag{35}$$

Hence, we obtain a finite coherent circulation which magnitude depends strongly on the turbulent velocity scales w' and u_*. In this limit the equivalence of $\delta/(2H)$ and q/Q is given even for large values of δ/H. Since $u'/w_* \to 0$ for large λ/H, we obtain

$$\frac{u}{w_*} = \sqrt{\frac{1}{2}\frac{q/Q + \delta/(2H)}{4w'/w_* + C_d u_*/w_*}}\,. \tag{36}$$

Obviously, the large-scale convection is the larger the smaller the turbulent velocity scales are. Since $C_d \ll 1$, surface friction will in general be less important than the convective turbulence in limiting the coherent motions.

In the other extreme, for very short wavelengths, $\lambda/H \ll 1$, we have to assume that δ decreases in proportion to λ, because otherwise we would have an infinitely rough terrain. In this limit we obtain,

$$\frac{u}{w_*} = \frac{1}{9216}\frac{1}{\alpha^2}\frac{\lambda^5}{H^5}\left(\frac{\delta}{2H} + \frac{q}{Q} + 12\frac{\delta}{\lambda}\frac{H}{\lambda}\right). \tag{37}$$

However, this limit is valid only as long as $u \ll u'$. Since, as we will see below, u' is small, we also have the range where $0 < \lambda/H < 1$, $w' \ll u$, $u' \ll u$, $u_* \ll u$, $\delta/H \ll 1$, for which we find

$$\frac{u}{w_*} = \frac{1}{16}\frac{\lambda^2}{H^2}\sqrt{\frac{1}{3\alpha}\left(1+\frac{q}{Q}+\frac{\delta}{H}\right)}\,. \tag{38}$$

i.e. a weaker increase with λ/H. In any case we find a strong dependence on α. The results for the limiting cases of large and small wavelengths together show the existence of a critical wavelength λ_{crit} with maximum coherent motion.

The limiting results for a homogeneous surface, i.e. $\delta = q = 0$, are easily derived from the above equations. We see that $u/w_* \rightarrow 0$ both for very small and very large wavelengths. This is a noteworthy result because it deviates from the linear theory of convection (Krettenauer, 1991) which predicts onset of convection over a uniformly heated surface at infinite wavelengths.

4.2 Estimate for the circulation at critical wavelength

As discussed below, the critical wavelength is of order $4H$. Moreover, the model solutions suggest that $u' \ll u$ and $w' \ll u$ for this wavelength. For these conditions, Eq. (33) reduces to an explicit expression for the coherent flow amplitude,

$$\frac{u}{w_*} = \sqrt{\frac{1+\delta/H+q/Q-(\delta/(2H)+q/Q)\delta/(2H)}{19\alpha+4C_d u_*/w_*}}\,. \tag{39}$$

It shows that the surface friction plays the smaller role in comparison to the convective turbulence in limiting the coherent motions. Moreover, we note again the nonlinear interaction of undulation and variable heat flux which tends to reduce the convection for large values of δ/H.

Since $C_d \ll 1$, we find, for $\alpha = 0.1$, and for small inhomogeneities, the simple result

$$\frac{u}{w_*} \cong 0.7[1+\frac{\delta}{2H}+\frac{q}{2Q}]. \tag{40}$$

Obviously, this motion amplitude is much larger than the asymptotic value for $\lambda/H \rightarrow \infty$, compare Eq. (36).

4.3 Numerical results for the general cases

Figures 2 and 3 show the numerical solutions of Eq. (33) for cases with zero heat flux variations (full curves) and for cases with plane surfaces (dashed curves) and for various values of the inhomogeneity parameters, δ/H and q/Q, as a function of wavelength λ/H. The figures contains two sets of solutions, one for $\alpha = 0.1$, and one for 0.05, where $\alpha = u'/v' = w'/v'$ is the open empirical parameter of this model. As expected from Eq. (39), u increases strongly with decreasing α. Moreover, smaller values of α shift the wavelength of maximum reaction to rather large values. From LES, we expect a coherent motion amplitude of order unity and a wavelength of order $4H$. Therefore, the value $\alpha = 0.1$ appears to be more realistic than $\alpha = 0.05$. Tests with other models for v', including $v' = w_*$, and $v' = w_* + 0.1u(1+h/b)$, showed smaller effects. Hence, we recommend to use $\alpha = 0.1$ and v' as given in Eq. (16).

For $\alpha = 0.1$, Fig. 2 shows that the coherent flow part achieves a maximum at about $\lambda_{crit} \cong 4H$ with respect to the horizontal component. The vertical one is maximum near $\lambda_{crit} \cong 2H$. The critical wavelength increases slightly for increasing inhomogeneity parameters. The effect from surface undulation is little larger than from variation of the heat flux but approximately the same for $\delta/H = q/Q$. The numerical results show the strong increase proportional to $(\lambda/H)^5$ for $\lambda/H < 0.1$, see Eq. (37), but proportional to $(\lambda/H)^2$ for larger values with $\lambda/H < 1$, as predicted by Eq. (38). The results also show the tendency towards a finite asymptotic value at large wavelengths. The asymptotic value is zero for $\delta = q = 0$, compare Eq. (36). We see that both inhomogeneity parameters increase the coherent circulation, but the circulation is quite large already for a homogeneous surface. Further parameter studies have shown a very weak sensitivity to the surface roughness height; its effect is less than 3 % for $z_0/H < 10^{-4}$.

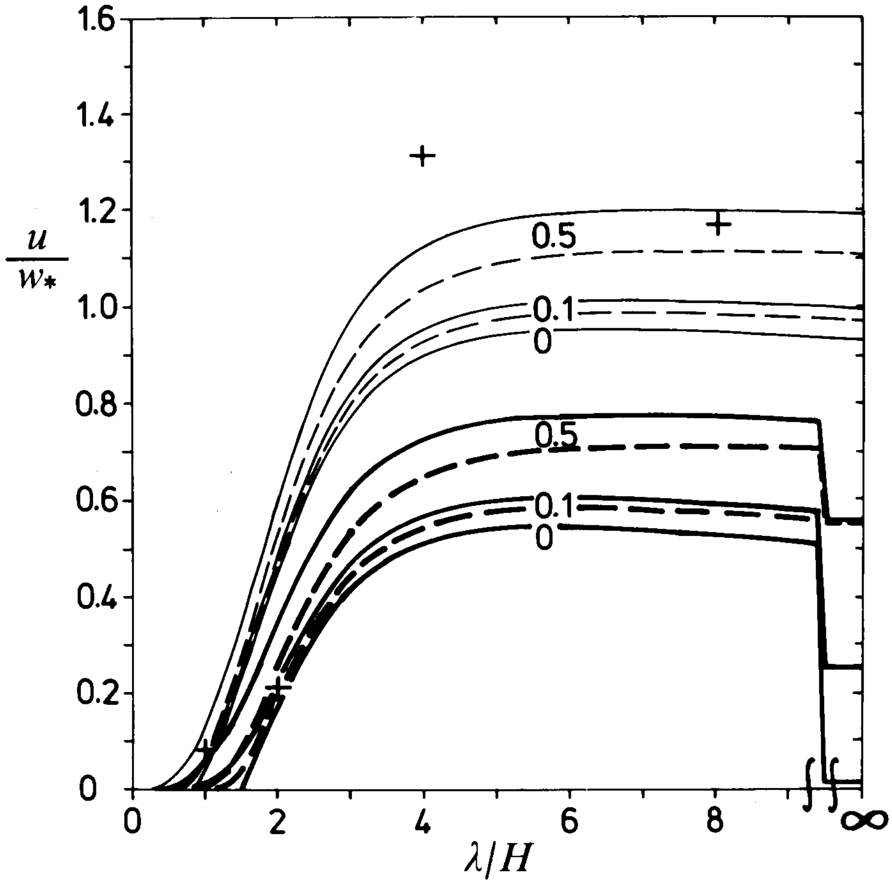

Figure 2. Horizontal convection velocity u/w_* versus wavelength λ/H for various values of surface heating $2q/Q = 0$, 0.1, and 0.5 (note factor 2), with $\delta/H = 0$ (dashed curves), and for various values of terrain amplitude $\delta/H = 0$, 0.1, and 0.5, with $q/Q = 0$ (full curves). Thick curves for $\alpha = 0.1$, thin curves for $\alpha = 0.05$, see Eq. (16). Asymptotic solutions for $\lambda/H = 1000 \cong \infty$ ($\alpha = 0.1$) are indicated at the right vertical axis. The symbols denote the LES results from Krettenauer and Schumann (1991) for $\delta/H = 0.1$ and $q/Q = 0$. In all cases, $z_0/H = 10^{-4}$.

4.4 Comparisons with numerical and observational results

As shown by LES results and observations, see Schmidt and Schumann (1989), Graf and Schumann (1991) and Krettenauer and Schumann (1991), the characteristic distance between updrafts and the wavelength of w-spectra is of order 2 to $4H$ for homogeneous surfaces. Also, the maximum root-mean-square value of the horizontal velocity fluctuations and the maximum value of u in conditional plume averages is of order $0.7w_*$. Moreover, Krettenauer and Schumann (1989) found a maximum response to wavy terrain for $\lambda \cong 4H$. These findings are in rough agreement with the prediction of the model, for $\alpha = 0.1$, as shown in Fig. 2 and 3. However, the figures show that the simple model underestimates the maximum response in motion amplitude for wavy terrain of amplitude $\delta/H = 0.1$, in comparison to the LES results. It should be noted that the LES results refer to the maximum values of u/w_*, where u denotes the local maximum of the mean horizontal circulation velocity, whereas the present theory predicts an average velocity u within a volume of size $(H/2)\cdot(\lambda/4)$. Moreover, the simple model excludes variations on smaller scales which may react more strongly. Hence we cannot expect complete agreement. However, both the LES and the present model agree in predicting approximately the same trends in velocity magnitude. In view of the differences between the LES and the model, the agreement appears to be satisfactory. The present model predicts the mean circulation magnitude up to about a factor of two.

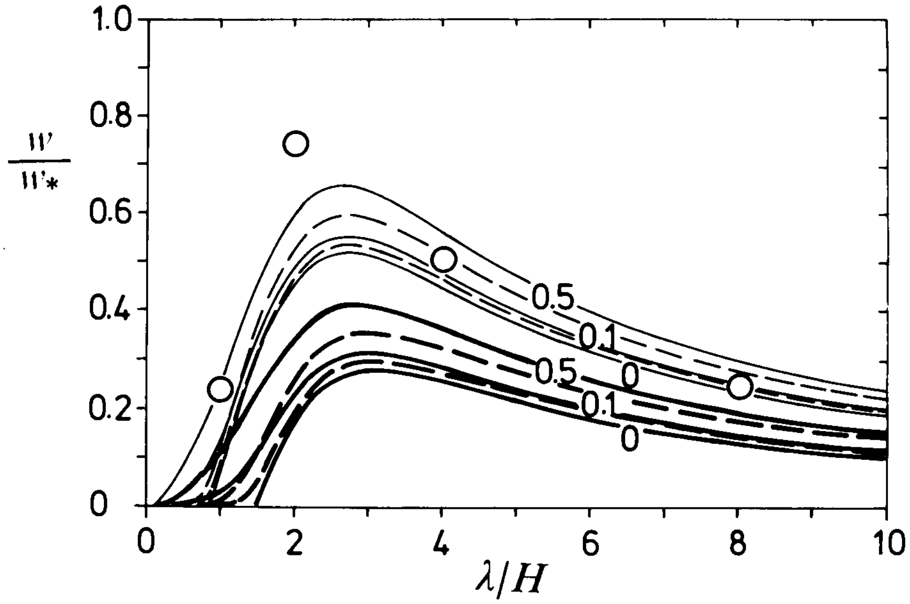

Figure 3. Same as Fig. 2 for the vertical convection velocity w/w_* versus wavelength λ/H.

As discussed in Krettenauer and Schumann (1991), no laboratory experiment exists on the effects of surface inhomogeneities as studied here. Field observations deal with non-ideal conditions with respect to terrain and always are affected by the more complex terrain of real surfaces and by the ever present mean wind. In addition, long times are required to reach a steady circulation. The time scales of the present model can be read from Eqs. (4) to (7) and (20). The largest time scales are those to reach thermal equilibrium (of order $b/u' + h/w'$) whereas those for velocity are smaller (of order $(2u'h^3/b^3 + 4w' + C_d u_*)/(2h)$) because of continuity and imposed symmetry. From LES we know that steady state is reached after a time of about $6H/w_*$ for $\lambda/H \cong 4$, which amounts to more than one hour for typical scale values in the atmosphere. The time scale increases with λ/H. The mean circulation cannot fully develop if the flow passes over the surface wave within a time interval shorter than the time in which the circulation develops. Hence, the mean wind U must be small in comparison to w_* to establish strong circulations and to make the present theory applicable. Otherwise, the reactions to surface variations will be smaller than predicted by the present model. However, the effects of inhomogeneities should be notable at smaller spatial scales with shorter time scales (e.g. by triggering local thermals or bubbles), which are not resolved by the simple model. Such local motions have been observed by Reinhardt (1985). He reported about bursts at the edges of forest areas surrounded by cultured acres.

The present model shows that scales smaller than the depth of the boundary layer should be of small relevance for climate modelling. In a future study, one might extend the present model to include the effects of prescribed variations in surface temperature or the effect from momentum and heat exchange at the top of the domain for an entraining mixed layer below a finite inversion.

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