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Reply

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The profound comments by Vergeiner on my recent paper give me the opportunity to clarify and elaborate on some of the issues he raises. The intention behind my study was to produce data, improve understanding and deduce parametrizations of up-slope flow properties under idealized conditions. How far it is possible to apply the results to real slopes cannot be assessed because no complete set of measurements for such flows exists. I expect, however, that the bulk properties, including the mean turbulence statistics, are not too unrealistic for real slope flows for which the basic assumptions of the model are satisfied, at least approximately. I had clearly stated that mountain slope flows would hardly become stationary at small slope angles. I also acknowledged the possibly strong impact of nonuniformities on real slope flows. Vergeiner's concept on how slope flows contribute to the heat budget of valleys is very important but is outside the scope of my paper.

It is certainly highly desirable to develop some elementary working concept to predict slope flows effectively, and I had tested various proposals in my paper. Vergeiner argues that Scorer's bubble model, adapted by him to slope flows, "could not be far wrong", if the bulk properties involved are properly defined. I had tested Vergeiner's proposal using standard definitions which applied to integral budgets, but I was not aware of his restriction to rather steep slopes. In his comment he now proposes alternative definitions of the bulk properties, and specifies a lower limit of slope angle for validity of this model. This proposal is worth further investigation beyond the estimate he deduced from the subset of data presented in the figures in my paper. For this purpose, I evaluated my LES results to obtain

$$\overline{U} = \frac{1}{d_u}\int_0^{d_u} u\,\mathrm{d}n, \qquad \overline{T} = \frac{1}{d_T}\int_0^{d_T} T\,\mathrm{d}n, \qquad C = \frac{\overline{U}^2}{\overline{T} d_T \beta g \sin\alpha}.$$

Following Vergeiner, the bulk averaged velocity $\overline{U}$ and temperature $\overline{T}$ are defined by averaging across the slope up to the first internal zero of the respective profiles of mean velocity and temperature deviation, with $u(d_u) = 0$ and $T(d_T) = 0$. The other symbols are as defined in my previous paper. The results are given in Table 1 for all cases that I had studied. Figure 1 depicts the dependence of the results on the slope angle α for $z_0/H = 0.003$. The scatter around a smooth interpolating curve indicates the level of uncertainties in the LES statistics as discussed by Schumann (1990). If the whole range of slope angles is considered, we see that $\overline{U}$ and $\overline{T}$ vary considerably.

TABLE 1. BULK MEAN VALUES AND COEFFICIENT C

var. unit	$\overline{U}$ v_*	$\overline{T}$ θ_*	C 1	var. unit	$\overline{U}$ v_*	$\overline{T}$ θ_*	C 1
B02	3.24	3.15	13.6	R02	3.20	2.82	15.3
B04	2.41	1.98	10.4	R10	1.52	1.26	5.11
B07	1.74	1.52	5.4	R30	1.11	1.47	2.19
B10	1.53	1.22	5.27	R45	1.27	1.56	2.72
B20	1.17	1.01	3.18	R90	1.40	1.91	3.44
B30	1.08	1.20	2.14	C10	1.51	1.38	3.63
B45	1.21	1.35	2.84	E10	1.67	1.31	6.67
B90	1.36	2.01	3.04	F10	1.81	1.41	8.35
D90	1.44	2.67	2.79	D10	1.59	1.29	5.59

Cases Bxx etc. and units are as defined by Schumann (1990). The number xx denotes the angle, e.g. $\alpha = 2°$ for B02. $z_0/H = 0.003$ for cases Bxx and Dxx; $z_0/H = 0.0015$ for cases Rxx; $z_0/H = 3 \times 10^{-2}$, 3×10^{-4}, 3×10^{-5}, for C10, E10, F10, respectively. Dxx corresponds to Bxx except for doubled grid resolution in the LES. The values of d_T required to evaluate C are given in Table 2 of Schumann (1990).

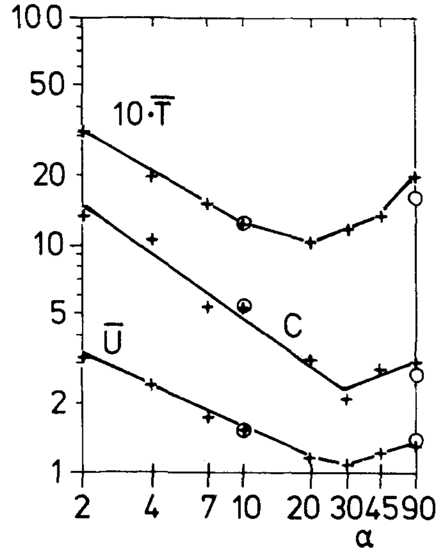

Figure 1. Bulk mean velocity $\overline{U}/v_*$ and temperature deviation $\overline{T}/\theta_*$ together with the coefficient C versus $\sin\alpha$ in double-logarithmic scales for $z_0/H = 0.003$. +: results from cases B02 to B90; O: D10, D90.

Note that C is strongly dependent on α and decreases slightly for increasing z_0. However, I agree with Vergeiner that C differs less from unity in the present terms than for other bulk definitions.

In principle, we have to expect that C depends on α and z_0 for the following reasons. Scorer's relationship was designed for steadily rising thermals with turbulence generated only by buoyancy within a neutral environment far from any boundary. In contrast, the slope flow is limited in depth and depends on the environmental stability. More importantly, shear at the surface and at the inversion contributes to turbulence generation in addition to buoyancy. The amount of buoyant forcing depends on the slope angle because thermals may rise over longer distances (measured in terms of boundary-layer thickness) on steep slopes than they do over less inclined slopes. The importance of shear, relative to buoyant turbulence production, grows with increasing angle, in particular for $\alpha > 20°$. Hence, one has to expect considerable variation of C with α. The impact of surface roughness, z_0, or of any other more realistic descriptor of real surface properties, depends on how much of the turbulence is created by shear at the surface relative to other sources. For $\alpha = 10°$, the LES results (which are based on a constant heat flux) show a weak dependence on z_0, $C \approx (2.5 \pm 0.3)(z_0/H)^{-0.12}$. For steeper slopes, I found that turbulence generation by shear at the surface increases, which suggests a stronger impact of z_0. Only for a fixed z_0 and for steep slopes, does Fig. 1 show C to be approximately constant. In rough agreement with Vergeiner's analysis, $C \approx 2.8 \pm 0.6$ for $\alpha > 20°$, and $z_0/H \approx 0.003$. However, since the bubble model does not apply to the idealized slope flow over the whole range of parameters, it can hardly be expected to work better for more complex situations.