12A.4 NUMERICAL STUDIES OF THERMALLY INDUCED SLOPE WINDS

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1. INTRODUCTION

Slope winds along with valley winds and mountain-plain winds are responsible for dispersion and transport of air pollutants over mountainous areas since these thermal circulations may dominate the atmospheric boundary layer (ABL), especially during fair-weather conditions. To study the surface energy balance, estimate the mass balance and effects of climate change, we also need a good understanding of the atmospheric boundary layer over glaciers or ice caps. As we know, downslope winds (katabatic winds) are a common feature over all sloping terrain at high latitudes due to low solar radiation. Motivated by these effects related to slope winds, many field experiments, theoretical and numerical research have been performed. Such experiments include “Vertical Transport and MiXing” (VTMX) field experiment (Monti, et al., 2002), Pacific 2001 Air Quality Field Study (Reuten et al., 2002), measurement campaign taken over the sloping ice surface of the Vatnajökull in Iceland (Oerlemans et al., 1999; Van Der Avoird and Duynkerke, 1999), and so on.

Slope flows are quite different from flows over flat terrain. Flows change rapidly over a small vertical extent and all the vertical gradients of wind, temperature and turbulence quantities are significant, especially for katabatic winds due to the stable stratification. To validate our slope flow model, two observations are compared with model results using the turbulence closure of $q^2 \ell$ Model I based on its good performance (Sun et al. 2006). We also included a discussion of the impacts of slope steepness on katabatic winds.

2. THE MODEL

The model used in this study, the simple description of turbulent closure and numerical schemes are given in Sun et al. (2006). Six commonly used turbulence closure schemes for the ABL are evaluated in the context of modeling slope flows. Model results show that $q^2 \ell$ Model I performs quite well in most conditions. Boundary and initial conditions are also given in Sun et al. (2006).

Table I. Model parameters and case conditions

Model parameter	Vatnajokull	Pasterze	Sensitivity case
Surface cooling rate (Khr^{-1})			2
Surface temperature deficit (K)	10.0	12.0	6
Stratification ($K\ km^{-1}$)	4.5	3.0	6
Slope (°)	4.5	4.0	20, 10, 5, 3, 2, 1, 0.6
Geostrophic wind (Ug,Vg) (ms^{-1})	0,0	0,0	0.0
z_t, z_0 (m)	0.00004, 0.002	0.00004, 0.002	0.1
Entrainment velocity (cms^{-1})	+1.0	3.5	-

3. MODEL RESULTS

3.1 *Comparison with Observations*

The observations of the katabatic flows taken over the sloping ice surface of Vatnajökull, Iceland were used to test the ability of the model to simulate the slope flows (Sun et al. 2006). The modelled results, not only mean values but also turbulent quantities, agree well with the observational data (See figure 1). The model is applied to simulate the katabatic flows made in Pasterze Glacier, Austria (Van den Broeke, 1997 a, b; Smeets et al., 1998). Model parameters are given in Table I. However, the wind speed is not reproduced well even though a downward velocity is also introduced into the model simulations to represent effects of horizontal divergence as was done by Denby 1999 (Shown in figure 2). This is probably because slope flows depend sensitively on and are complicated by the ambient conditions. The katabitic winds in Vatnajökull are well developed while winds in Pasterze include several other effects, such as valley winds and large-scale forcing that are not represented by the 1D model.

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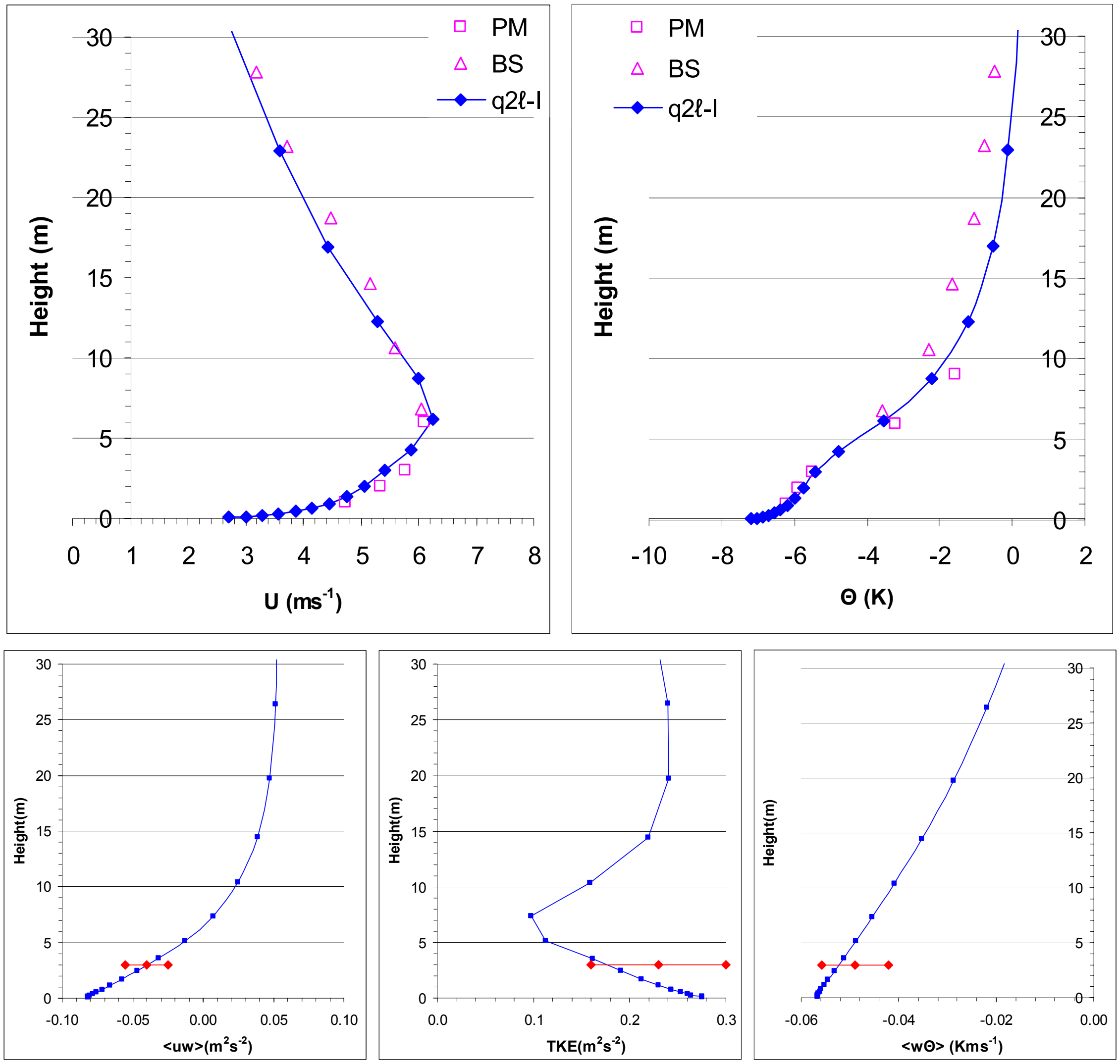

Figure 1. Comparison of modeled q2ℓ Model I and observed mean profiles and turbulent quantities from Vatnajökull. Solid lines indicate the model simulation. Squares indicate profile mast measurements; triangles represent balloon sounding measurements and diamonds with error bars, indicating the standard deviation over the observational period.

3.2 *Effects of Slope Steepness*

The impacts of slope steepness on thermally induced upslope flow development with no ambient winds were investigated using analytical and numerical model approaches by Ye, et al. (1987). The results showed that in the Prandtl's analytic solution, the intensity of upslope flows doesn't change with the slope change and the height (h_{max}) at which the maximum mean velocity (u_{max}) is obtained decreases with the increasing steepness, but in their work, the modified Prandtl analytic model and numerical model show the maximum wind speed increases significantly with the increasing steepness. In our simulations (shown in figure 3), the steady state slope wind depth and the height of h_{max} decrease as the slope increases; the maximum wind speed increases with the increasing steepness in the range of the slope angle smaller than around 2º while it decreases with the increasing slope angle when the angle is larger than 2º. The change in the velocity is not significant for these pure shallow katabatic flows. Therefore, the maximum velocity could be thought to be not very sensitive to the change in the slope steepness (Rao and Snodgrass 1981). We need to point out that these discussions are based on the steady-state or

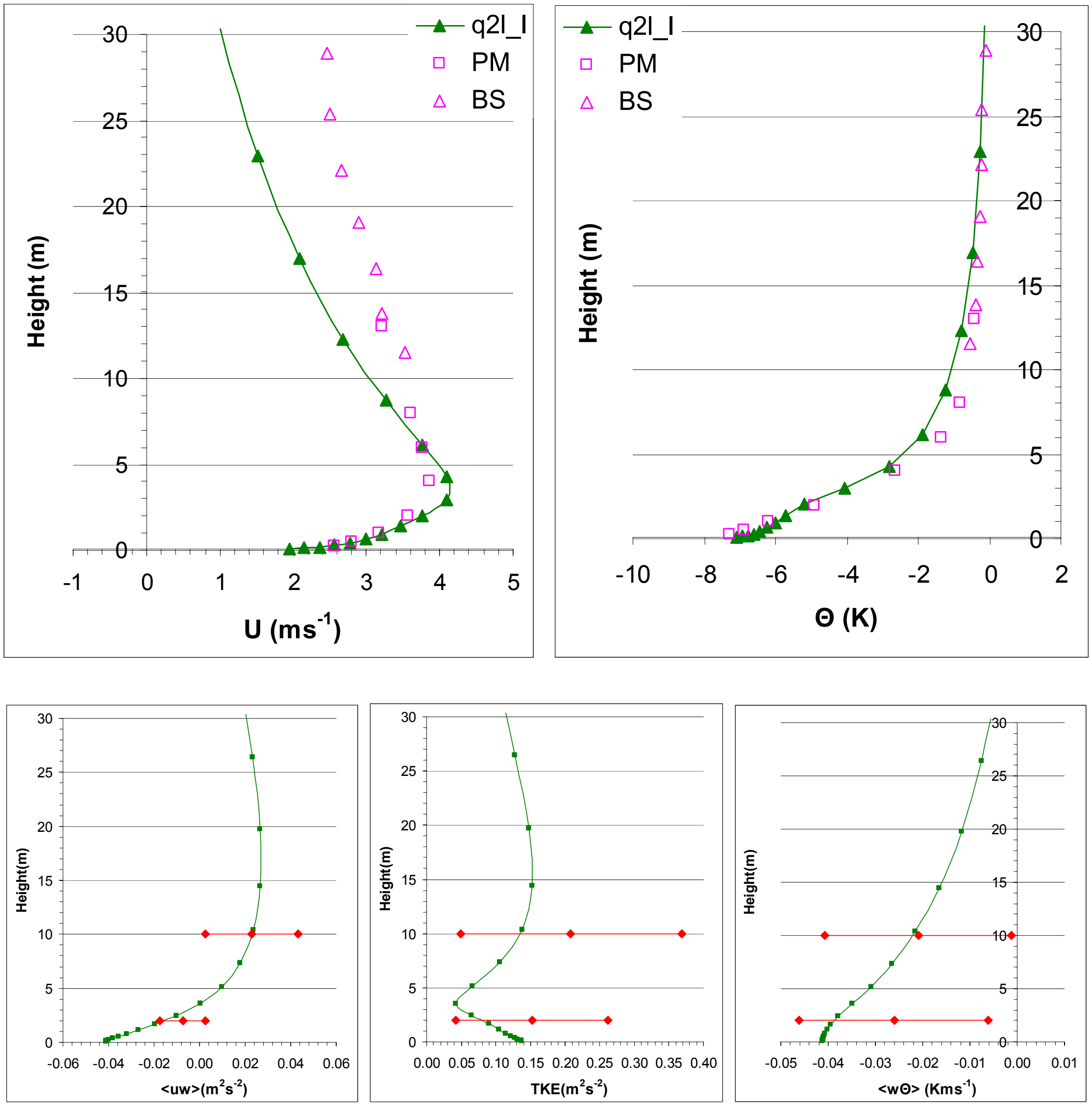

Figure 2. As in figure 1but for Pasterze in Austria.

quasi steady-state of the developed slope flows. However, the model has been run for several hours and can approach the steady state for the group of the larger slope angles (referred as group A), but cannot for the another group of the smaller angles (named group B). This also occurred in the simulations of case I and case II made by Denby 1999. To some extent, the mean profiles of group B depend on the modelling time (Figure 3). All the slope angles (20°, 10°, 5°) used in the simulations of Rao and Snodgrass (1981) fall in one group A. All the slope angles (2.3°, 1.15°, 0.57°, and 0.23°) used in the numerical simulations of Ye, et al. (1987) are in group B. Does that mean there is a slope angle that is a favorable angle for the development of the maximum value in the slope wind? When the angle is smaller than that value, the steeper the slope, the larger is the maximum velocity. The maximum velocity decreases with the increasing slope angle when the angle is larger than that value. Is the above difference due to the different setup of the models? In the 1D model, to study the effect of slope angle, the model is run in the condition where only the angle varies. In the 2D modeling with the limited slope extent (Ye, et al., 1987), the cases with the different slope angle have different surface temperature deficit and in the case the larger angle is accompanied by the

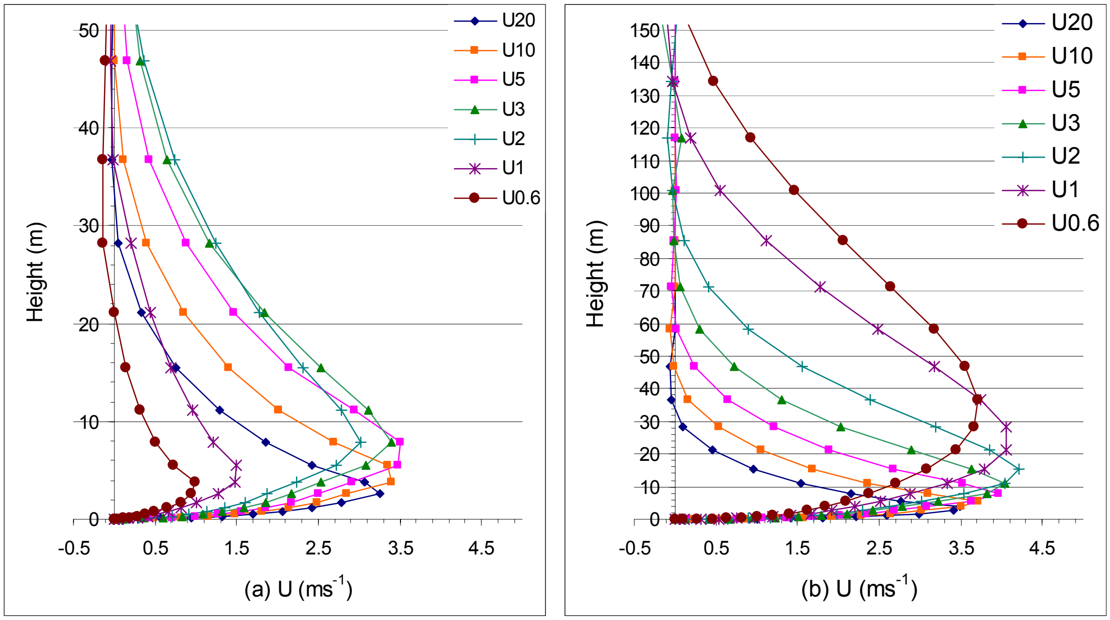

Figure 3. Predicted profiles of wind at different slope angle (a) after 3hr cooling and (b) steady-state

larger surface temperature deficit. Most studies show the surface temperature deficit significantly intensifies the slope wind. Therefore, the relationship between intensity and slope angle needs further studies.

4. SUMMARY AND DISCUSSION

A 1D ABL model for studying slope flows is applied to simulate the observations of katabatic flows after being used for an evaluation of several turbulence closure schemes. Modeled results show the model can reproduce well-developed local katabatic flows in the middle of the slope, not only for the mean variables but also turbulent fluxes. The large scale forcing or multi-dimensional effects accompanied by katabatic winds are not represented in the simulations. They need studies using a high resolution multi-dimensional numerical model. The Advanced Regional Prediction System (ARPS) is now being used for this.

The relationship between maximum wind speed and slope angle is discussed. The difference from the previous investigations is interesting but needs further studies.

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