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Cooperative control of katabatic flows within canopies with terrain slope, canopy structure, and thermal velocity

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Nearly 70% of earth's land surface is covered with hills and mountains. These rugged land surfaces create complexity in the understanding of air-land exchanges, such as the introduction of pollutants into the atmosphere, and the transfer of water and carbon dioxide between soil, vegetation, and the atmosphere. Katabatic flows are a persistent feature over the rugged land surfaces. Particularly, the katabatic flows within canopy (drainage flows) persistently exist even in cases where synoptic forcing is strong (Feigenwinter et al, 2010). These drainage flows result in many problems in measuring and modeling air-land interactions, such as serious advection errors in nocturnal eddy flux measurements (Foken, 2008). Therefore, studying the driving mechanisms of drainage flows within the canopy has many practical implications.

Physically, katabatic flows are associated with slope cooling, ambient stratification, slope angle, vegetation structure, and other factors (Yi et al., 2005; Yi, 2009; Fedorovich and Shapiro, 2009). What are the major controls of katabatic flows? And how do they work together for maximum katabatic flows? These are still open questions even though katabatic flows have been studied for a long time since Prandtl (1942) first developed one-dimensional model for katabatic flows. Particularly, two opposite findings of slope effects on katabatic flows exist: katabatic winds are stronger on: (1) steep slopes ...(Horst and Doran 1986; Nappo and Rao 1987); and (2) gentle slopes ...(Mcnider 1982; England and Mcnider 1993; Zhong and Whiteman 2008; Axelsen and van Dop 2009).

We developed a theoretical model for katabatic flows and derived that optimal conditions for katabatic flows within the canopy are synergistically controlled by terrain angle, canopy structure, and thermal velocity through a simple equation, $L_c V_T^{-2} \sin^3 \alpha = b$, where α is terrain slope, L_c=1/$(c_D a)$is canopy length scale, c_D is drag coefficient, a is leaf area density, $V_T = R_c/\gamma$is thermal velocity, $R_c = \partial\theta_0/\partial t$is ambient cooling rate, $\gamma = \partial\theta_0/\partial z$is ambient lapse rate, θ_0 is ambient potential temperature, $b = (2g)^{-1}[\theta_0/(\theta_0 - \theta_c)]$ is constant, g is the gravitational acceleration, and θ_c is potential temperature as the cooling rate is zero. The optimal conditions for katabatic flows can be geometrically expressed by a two-dimensional surface in a three-dimensional parameter space that is spanned by a canopy length scale (L_c), a sine function of slope angle ($\sin\alpha$), and thermal velocity (V_T).

The above controversial issues that maximum katabatic flows can occur on both deep and gentle slope are solved. Katabatic flows are not determined by slope angle alone, but controlled synergistically with slope cooling, ambient stratification, and vegetation structure. Katabatic flows can increase or decrease with increasing slope angle, depending on the conditions of thermal velocity and canopy length scale.

A new concept, thermal velocity (V_T=R_c/γ), is introduced, which represents heat transfer speed from surface cooling to the air aloft in a stable boundary layer. Thus, the relationship among surface cooling, heat transfer speed, lag time of heat transfer, and atmospheric stability can be well understood. The concept of thermal velocity is fundamentally useful to understanding many aspects of measuring and modeling the nocturnal boundary layer.

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