Countergradient Heat Fluxes and The Impact of Soil Moisture on Katabatic Timing and Structure

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[1]**Derek D. Jensen**

[1]**Eric R. Pardyjak**

[2]**Daniel F. Nadeau**

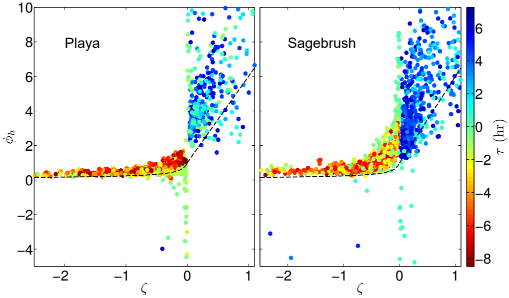
[1]*Department of Mechanical Engineering*
University of Utah
Salt Lake City, Utah 84112

[2]*Department of Civil and Water Engineering*
Université Laval
Quebec City, Canada

Countergradient Heat Flux Observations Near Sunset

Introduction

- MOST and analogy to Fourier's law (K–Theory) invalid
- Occurs when time of flux reversal differs from time of gradient reversal
- Flux reversal may precede gradient reversal and vice-versa
- Blay-Carreras et al. (2014) observed the flux reversal preceding the gradient reversal by 30–80 min
- Study Objective: *Understand and predict the type and duration of the countergradient behavior*



Countergradient Heat Flux Observations Near Sunset

Background and Definitions

- Paper accepted in *Boundary-Layer Meteorology* MATERHORN special issue, "Observations of near-surface heat-flux and temperature profiles through the early evening transition over contrasting surfaces"

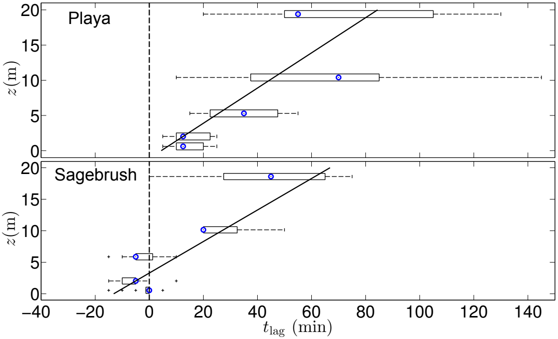
- A study of quiescent, clear sky transitions with fully functional instrumentation
  - 8 days at Playa, 13 at Sagebrush
  - Individual and ensemble averaged statistics analyzed

- Timing variable definitions [min]
  - Time relative to net-radiative sunset: $\tau \equiv t - t_{\mathrm{R_n}=0}$
  - Time of persistent heat flux reversal: τ_{flux}
  - Time of persistent gradient reversal: τ_{grad}
  - Countergradient duration: $t_{\mathrm{lag}} \equiv \tau_{\mathrm{flux}} - \tau_{\mathrm{grad}}$

Countergradient Heat Flux Observations Near Sunset

Countergradient Duration

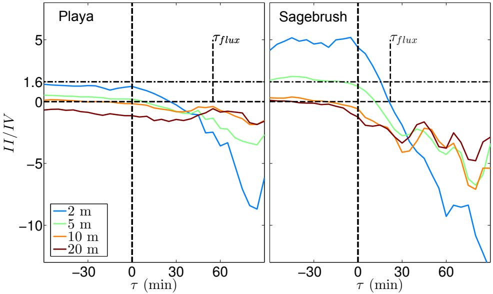
- $t_{\text{lag}} \equiv \tau_{\text{flux}} - \tau_{\text{grad}}$
- Hypothesis: $t_{\text{lag}}(z) \approx -\frac{\partial \tau_{\text{grad}}}{\partial z}(z - z_{\text{ref}}) - t_{\text{lag}}(z_{\text{ref}})$
- $t_{\text{lag}} < 0 \rightarrow$ flux reversal *precedes* gradient reversal (Blay-Carreras et al., 2014)
- $t_{\text{lag}} > 0 \rightarrow$ flux reversal *follows* gradient reversal



Countergradient Heat Flux Observations Near Sunset

Heat Flux Budget

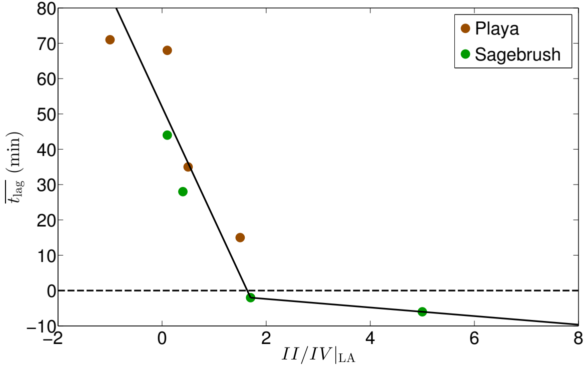
- Simplified Heat Flux Budget: $$\underbrace{\frac{\partial \overline{w'\theta'}}{\partial t}}_{\text{I}} = \underbrace{-\overline{w'^2}\frac{\partial \overline{\theta}}{\partial z}}_{\text{II}} \underbrace{-\frac{\partial(\overline{w'^2\theta'})}{\partial z}}_{\text{III}} \underbrace{+\frac{g}{\overline{\theta}}\overline{\theta'^2}}_{\text{IV}} \underbrace{-\frac{1}{\rho}\overline{\theta'\frac{\partial p'}{\partial z}}}_{\text{V}}$$
- Hypothesis: Terms II (gradient) and IV (buoyant) dictate countergradient behaviour
- The ratio of II/IV evaluated in the late afternoon indicate the countergradient type and duration: $\frac{II}{IV}|_{\mathrm{LA}} > 1.6 \rightarrow t_{\mathrm{lag}} < 0$ and $\frac{II}{IV}|_{\mathrm{LA}} < 1.6 \rightarrow t_{\mathrm{lag}} > 0$



Countergradient Heat Flux Observations Near Sunset

Late-Afternoon Gradient to Buoyant Production Ratio

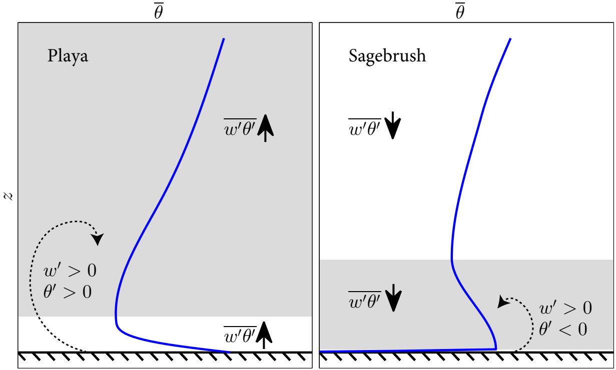
- $\overline{t_{\rm lag}} > 0$ – well-defined by a linear fit
- $\overline{t_{\rm lag}} < 0$ – Only 2 points
- Exact shape of the curve is unknown



Countergradient Heat Flux Observations Near Sunset

Idealized Schematic of Countergradient Behaviour

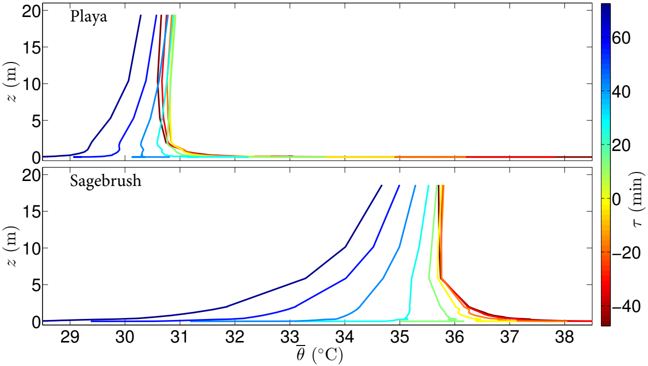
- Grey shading is a countergradient layer
- In both cases, the very near-surface flux is co-gradient
- Flux in countergradient layers is co-gradient with $\frac{\partial\overline{\theta}}{\partial z}|_{z=0}$



Countergradient Heat Flux Observations Near Sunset

Observed Countergradient Behaviour

- High density temperature with IR surface temperature
- Cyan curve shows Playa countergradient behaviour
- Green and cyan curves show Sagebrush countergradient behaviour



Effect of Soil Moisture on Katabatic Flow

Background

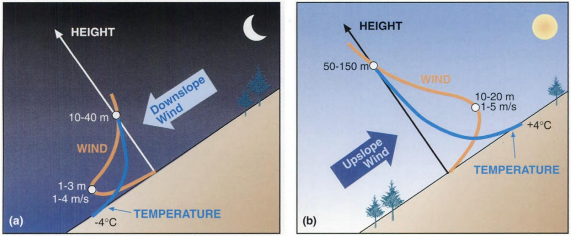


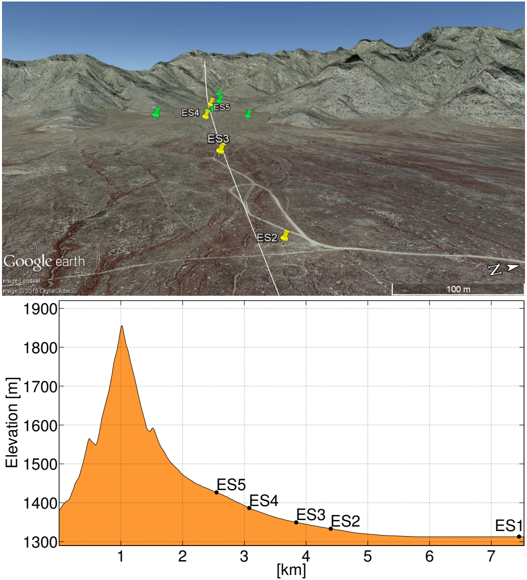
Figure: Taken from Whiteman (2000)

- Driven by horizontal temperature gradients between valley air mass and the slope
- Banta and Gannon (1995): From simulations, increased soil moisture retards katabatic flow
- Study Objective: *Observationally study the impact of increased soil moisture on katabatic development and structure; develop a simple model that incorporates soil moisture*

Effect of Soil Moisture on Katabatic Flow

Instrumentation

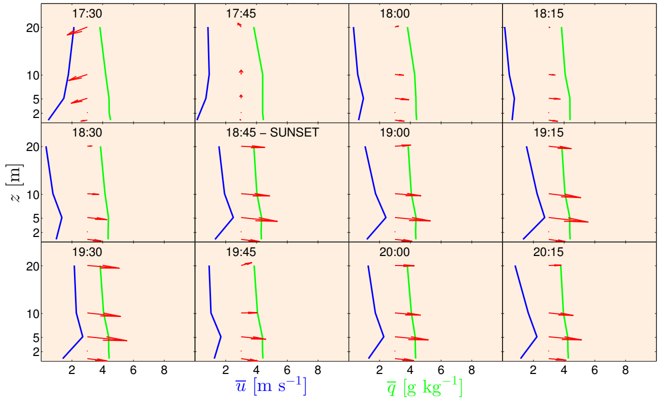
- Eastern Slope of Granite Peak
- Desert Steppe Vegetation
- Low soil moisture
- Anabatic/katabatic diurnal flow with frequent valley interaction
- Four 20 m + towers
- Sonic Anemometers at 5–8 levels
- Soil moisture and Solar Radiation observations at 6 locations throughout slope



Effect of Soil Moisture on Katabatic Flow

Low Soil Moisture Transition

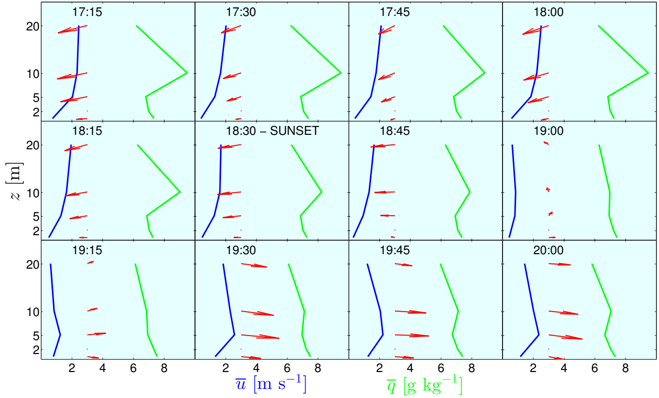
- 1 Oct. 2012 - Quiescent Synoptic Conditions
- Soil moisture at 5 cm: 0.052 $m^3\ m^{-3}$
- Air moisture at 10 m: 3.7 g $kg^{-}1$
- Katabatic flow develops at 18:00 MST, 45 min *before* sunset



Effect of Soil Moisture on Katabatic Flow

High Soil Moisture Transition

- 13 Oct. 2012 - “Quiescent” Synoptic Conditions
- Soil moisture at 5 cm: 0.113 m^3 m^{-3}
- Air moisture at 10 m: 7.1 g kg^{-}1
- Katabatic flow develops at 19:15 MST, 45 min *after* sunset



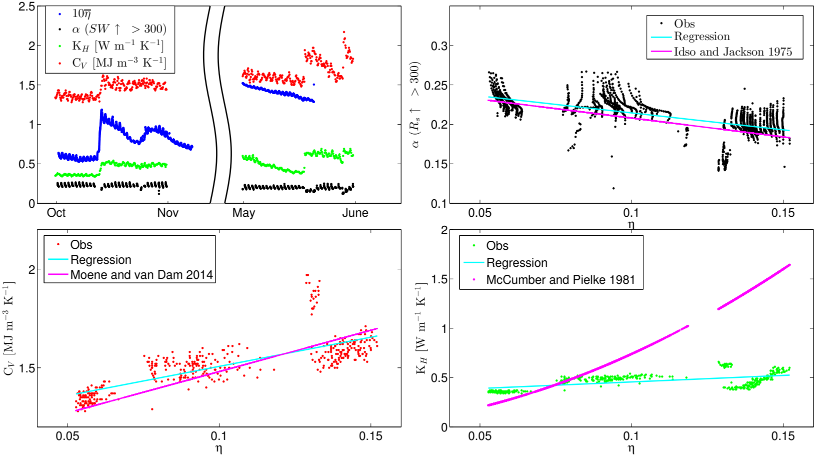
Effect of Soil Moisture on Katabatic Flow

Simple Model

- Model Objective: Use simple inputs to model SEB, katabatic timing and structure
- Surface Energy Budget
  - $SW \downarrow = S \cdot T_K \cdot \cos\hat{\theta}$ (Zhang and Anthes, 1982)
  - $LW \uparrow = \sigma T_0^4$
  - $LW \downarrow =$ constant
  - Ground Heat Flux: $H_G = C_v z_1 \frac{\partial \overline{T}}{\partial t} + K_H \frac{\partial T}{\partial z}|_{z=z1}$ (Bailey et al., 2015)
  - Sensible and Latent Heat Flux from Penman-Monteith (Allen, 1998)
- Soil Properties
  - Albedo: $\alpha = \eta_0(\alpha_{\mathrm{dry}} - \alpha_{\mathrm{sat}})/0.2 + \alpha_{\mathrm{dry}}$ (Idso and Jackson, 1975)
  - Thermal Conductivity: $K_H = exp[-\log(\psi_s(\frac{\eta_s}{\eta})^b) + 2.7]$ (Mccumber and Pielke, 1981)
  - Soil Heat Capacity: $C_v = (1-\eta_s) * C_p + \eta C_w$ (Moene and van Dam, 2014)
- Katabatic Timing and Structure (Manins and Sawford, 1979)
  - Height: $H = C_1(\sin\beta)^{2/3}s$
  - Velocity: $U = C_2(\sin\beta)^{2/9}(-\frac{g}{\theta_{va}}\overline{w'\theta_0'}s)^{1/3}$
  - Temperature Deficit: $\overline{d} = C_3(\sin\beta)^{-8/9}(-\frac{g}{\theta_{va}}\overline{w'\theta_0'})^{2/3}s^{-1/3}$
  - Start time: $\overline{u}\frac{\partial\overline{u}}{\partial x} \approx g\overline{d}\frac{\sin\beta}{\overline{\theta}}$ (Hunt et al., 2003)

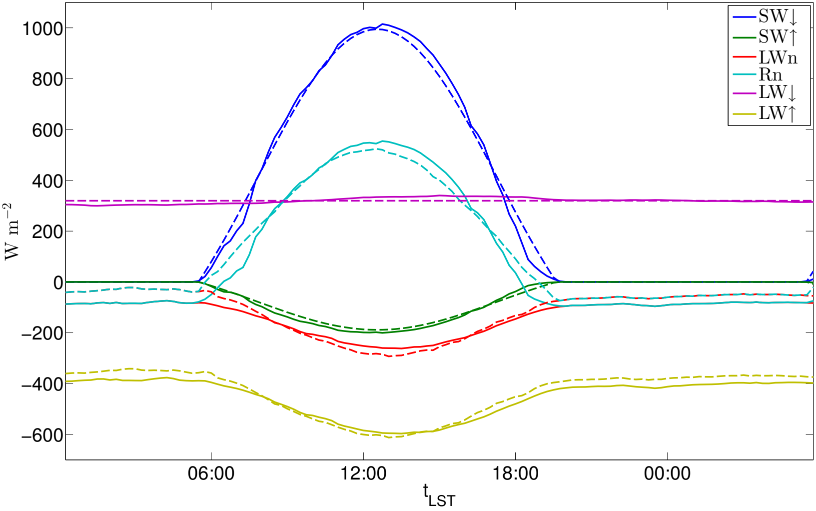
Effect of Soil Moisture on Katabatic Flow

Soil Properties



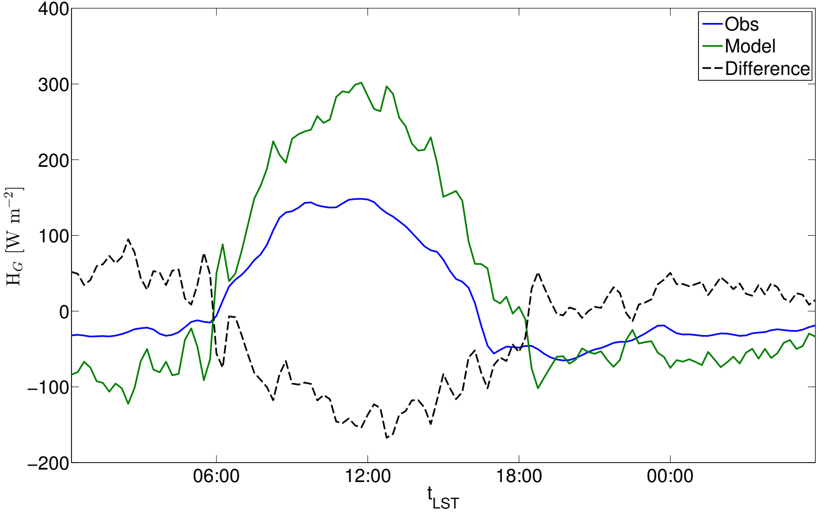
Effect of Soil Moisture on Katabatic Flow

Radiation Balance: Dashed Line is Modeled



Effect of Soil Moisture on Katabatic Flow

Ground Heat Flux



Conclusions

- Countergradient Heat Flux Observations Near Sunset
  - Countergradient type and duration can be forecast by the ratio of gradient to buoyant production of sensible heat flux
  - Heat flux at all levels is co-gradient with $\frac{\partial\overline{\theta}}{\partial z}|_{z=0}$, local countergradient fluxes due to "residual" layers
- Effect of Soil Moisture on Katabatic Flow
  - Observations show a delay in katabatic development during moist transitions
  - Models accurately estimate the albedo and heat capacity of the soil as a function of soil moisture, the thermal conductivity model performs poorly
  - The radiation balance is accurately model but H_G is overestimated
  - There's still a lot of work to do!

Thank You!

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