Daytime, anabatic winds over a steep Alpine slope: Turbulence structure and modeling implications

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MAC-MAQ 2019

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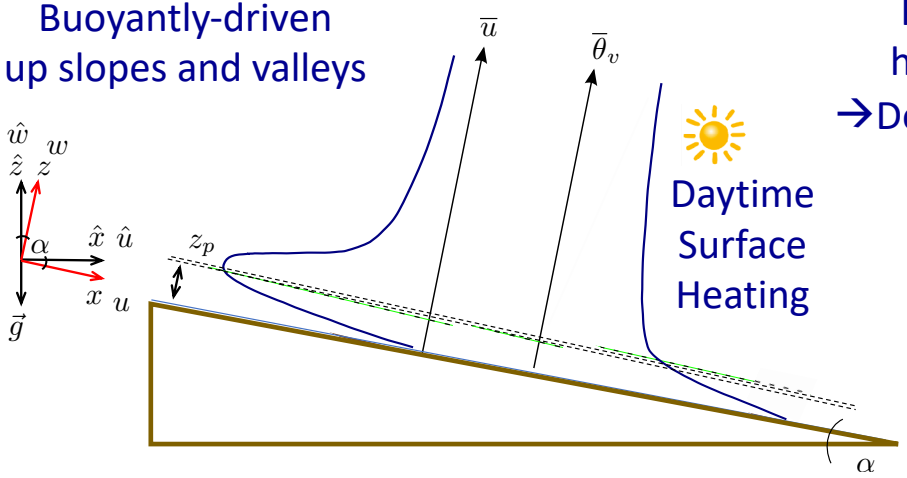
Introduction & Motivations

Anabatic flow

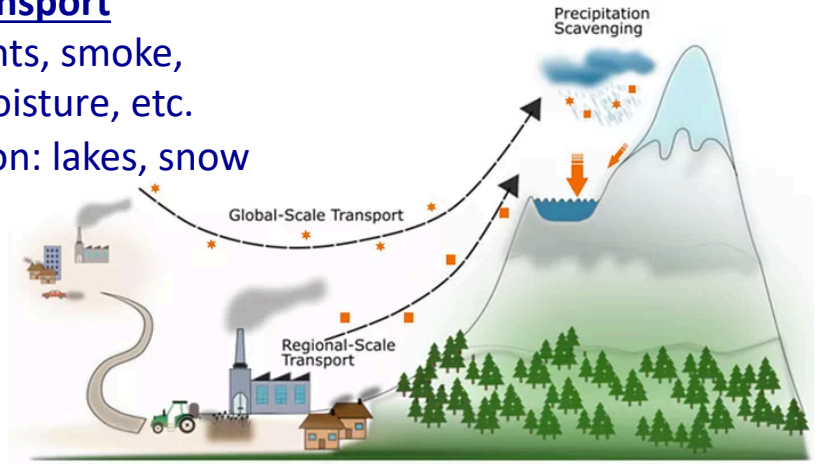
Buoyantly-driven
up slopes and valleys



Daytime
Surface
Heating

Transport

Pollutants, smoke,
heat, moisture, etc.
→Deposition: lakes, snow



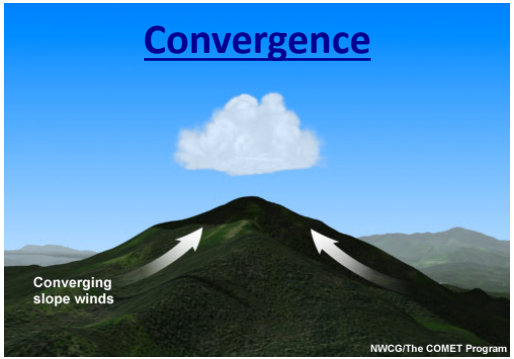
https://www.p3mountains.org/single-post/2018/07/18/More-firsts

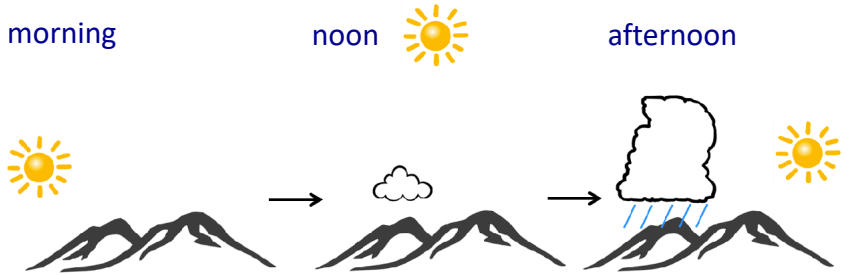
Hydrology & Meteorology

Evapotranspiration &
water balances

Convection:
clouds & precipitation

Convergence





adapted from Keller (2016)

Introduction & Motivations

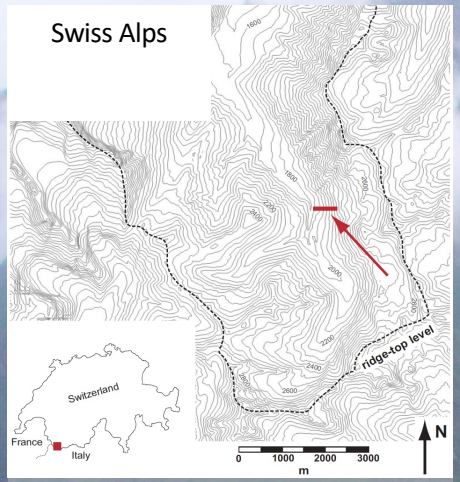
Overarching Question
- Why do numerical models perform poorly for mountainous terrain?

Objectives:
- Show turbulence observations of daytime, anabatic flows
- Implications/Challenges to:
  - Common numerical modeling techniques
  - Flux-gradient parameterizations (wall models and closures)

Modeling Challenges:
{a priori}
- Steep terrain & grid anisotropy (e.g., Lundquist et al., 2009)
- Heterogeneous land cover
- Heterogeneous topography: local slope & aspect

Field Experiment Setup

Summer 2011
Slope angle = 35.5°



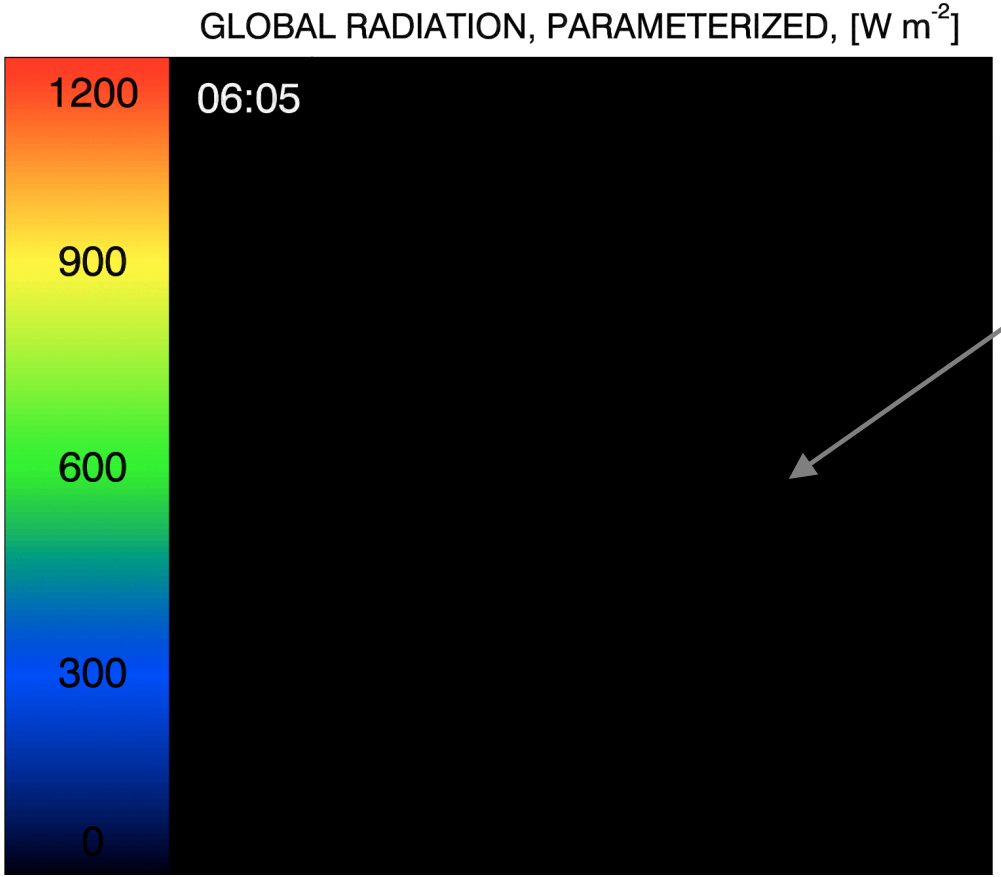
--Nadeau et al. (2011)

10-minute block averaging Multi-Resolution Decomposition (Vickers and Mahrt 2003;2006)

10 m Flux Tower

- 5 Sonic anemometers slope-parallel
- 20 Hz sampling

Slope Site: Insolation



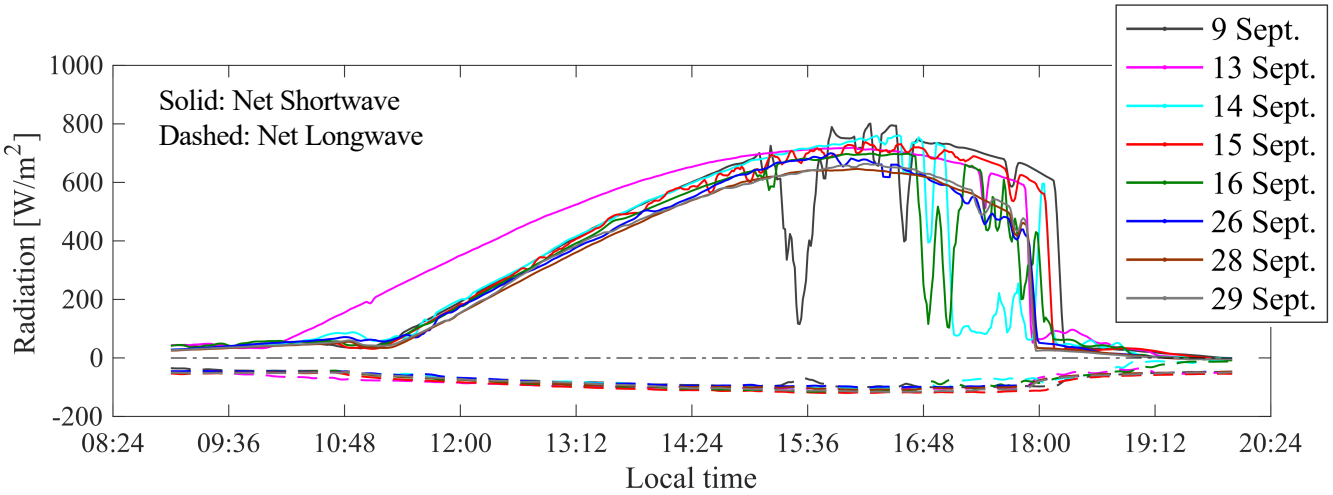
Courtesy of Sebastien Hoch, Univ. of Utah

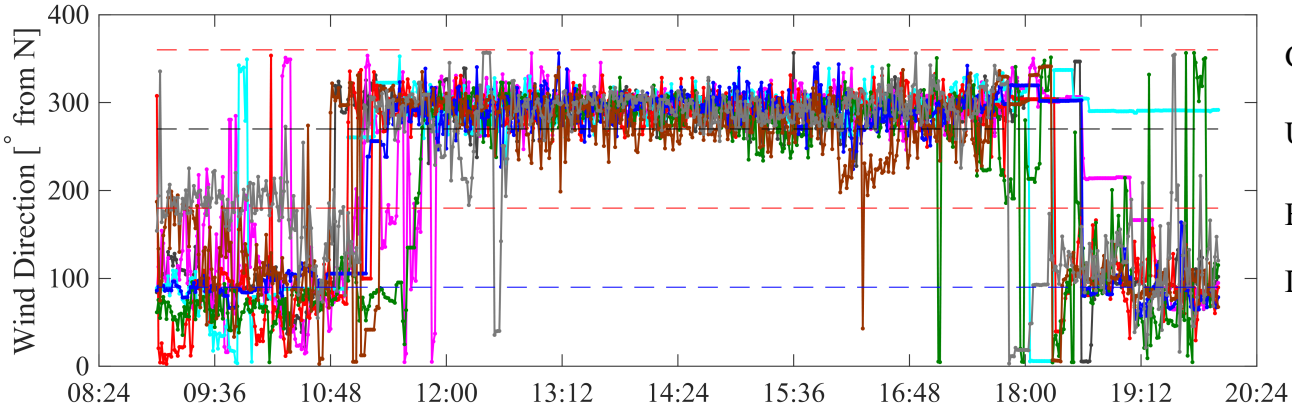
Key Times (local hour):

- ~11:00 → Direct insolation. One of the last locations in the valley.
- ~14:00 → Opposite slope starts to get shaded.
- ~18:00 → Shadow front triggers evening transition.

Nadeau et al. (2012; 2018)

Slope Site: Convective Characteristics





8 'clear-sky' days with weak synoptic forcing

Convective Regime:

12:00 to 18:00

Cross-slope (~ up valley)

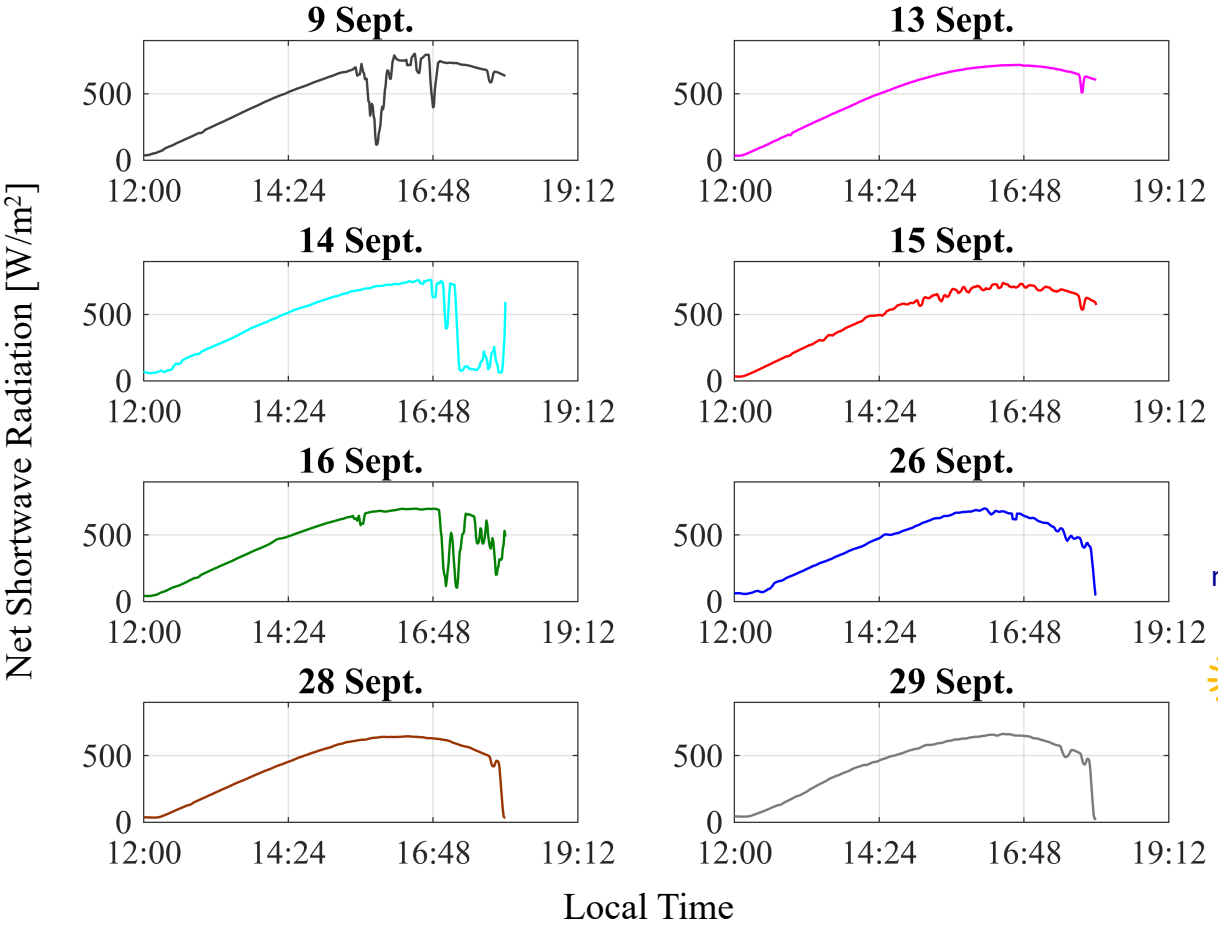
Up-slope

Foehn?

Down-slope

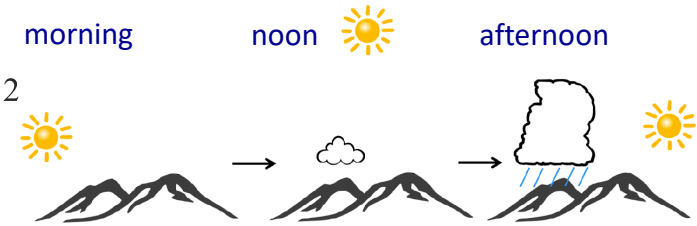
Same site: Transitions: Nadeau et al. (2012; 2018); Katabatic: Oldroyd et al. (2014;2016b)

Slope Site: Convective Characteristics



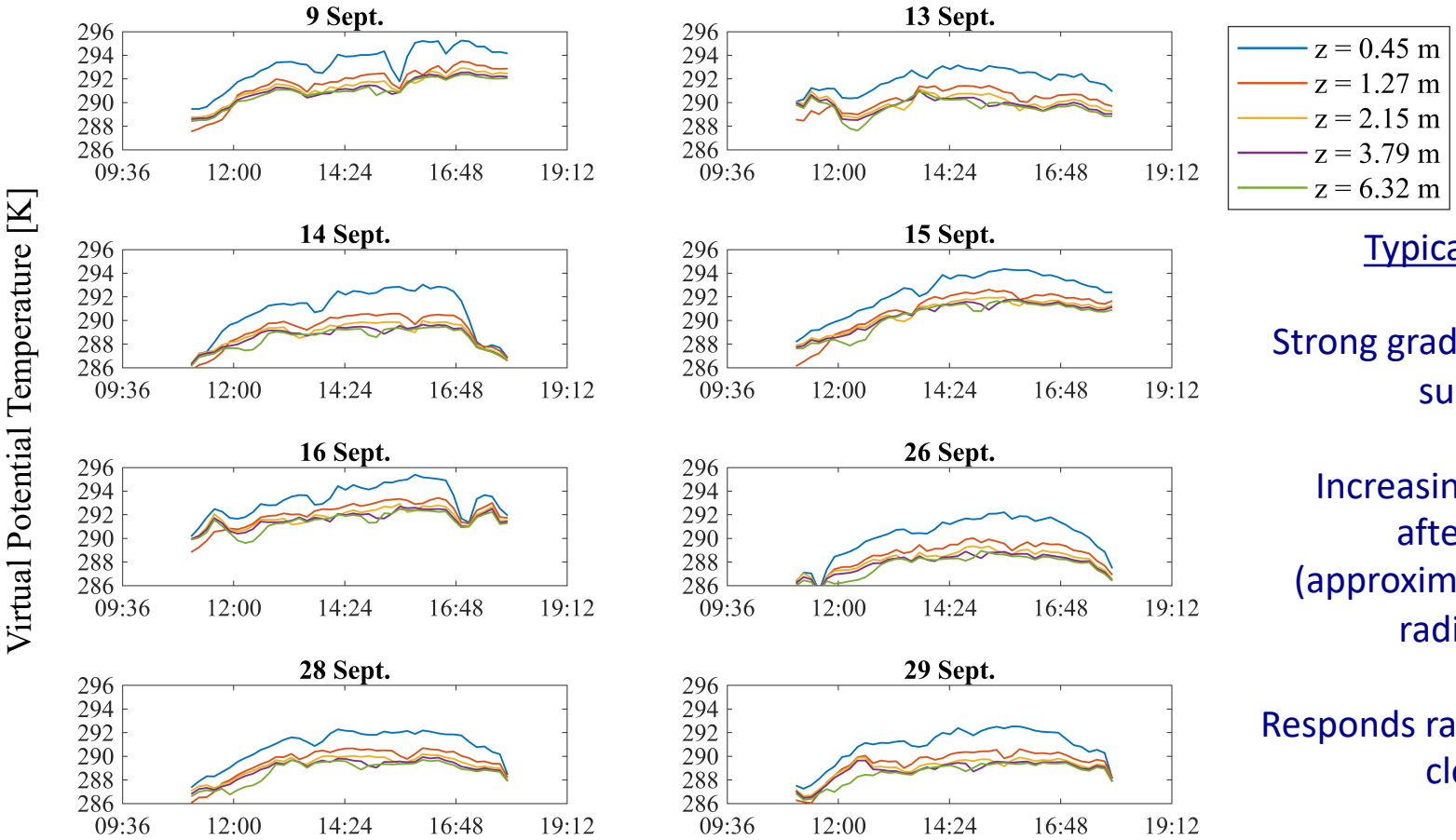
Convective Regime:
12:00 to 18:00

Tendency for afternoon cloud development



adapted from Keller (2016)

Convective Characteristics



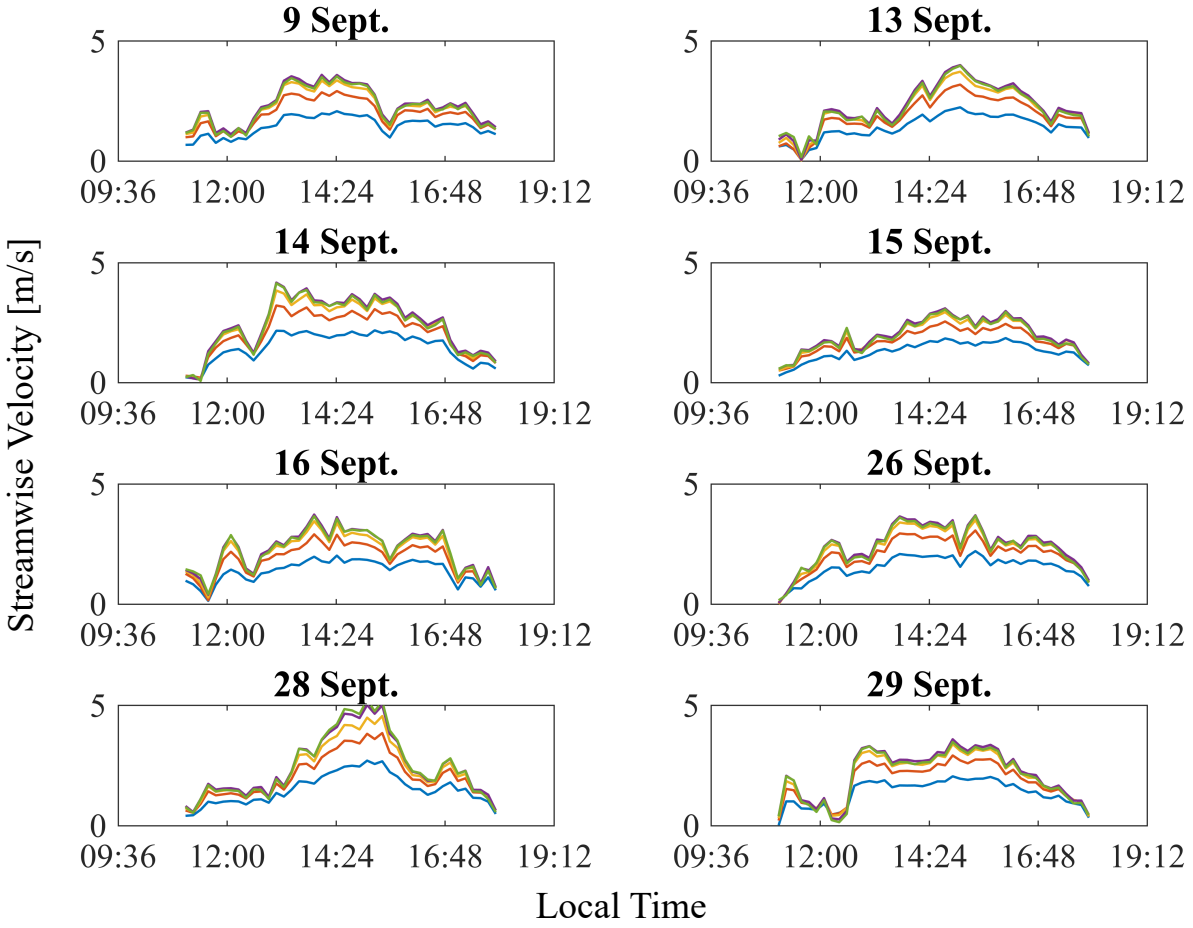
Typical Trends

Strong gradients near the surface

Increasing until late afternoon (approximately follows radiation)

Responds rapidly to patchy clouds

Convective Characteristics



Typical Trends

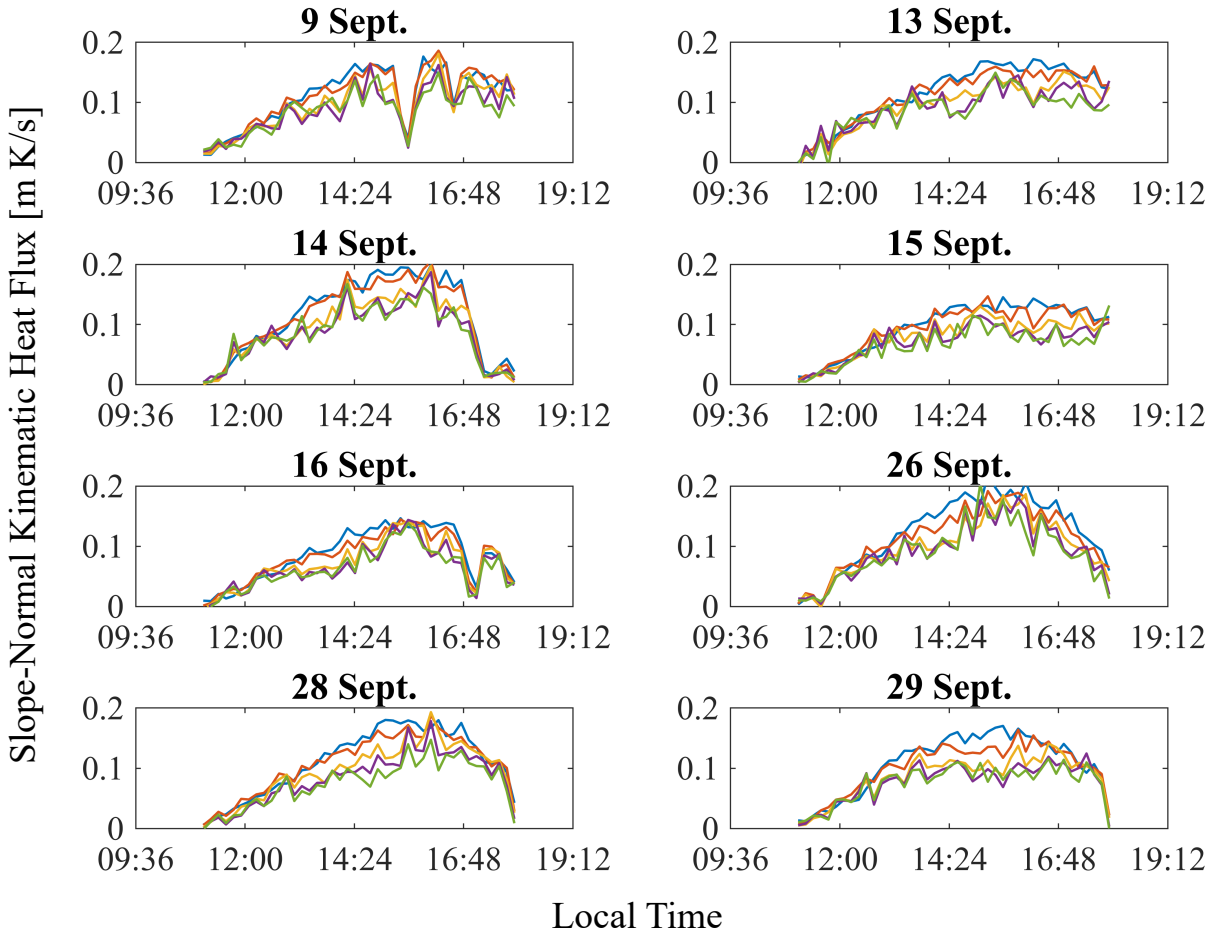
Building speeds & wind shear Until about 15:00

Then slow decay & weakening wind shear

drop-off at the evening transition

~ Correlates with temperature

Convective Characteristics



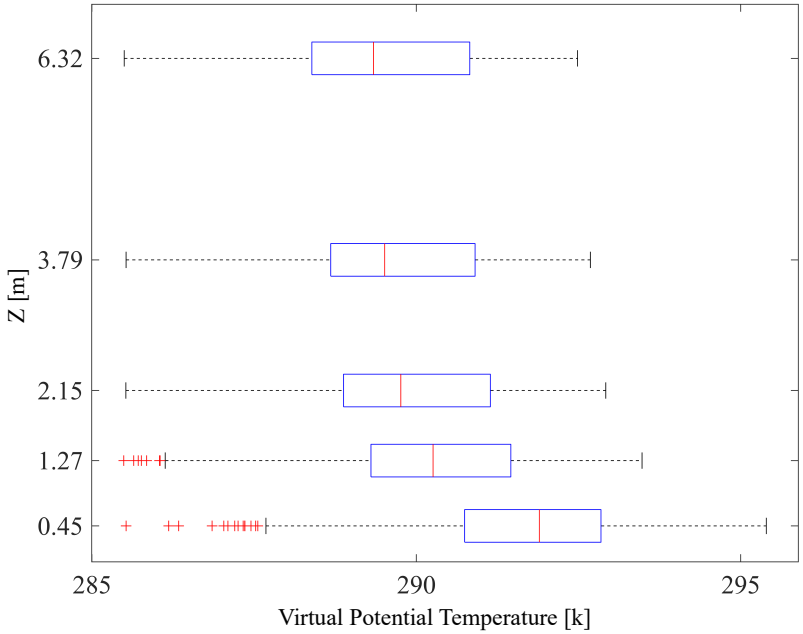
Typical Trends

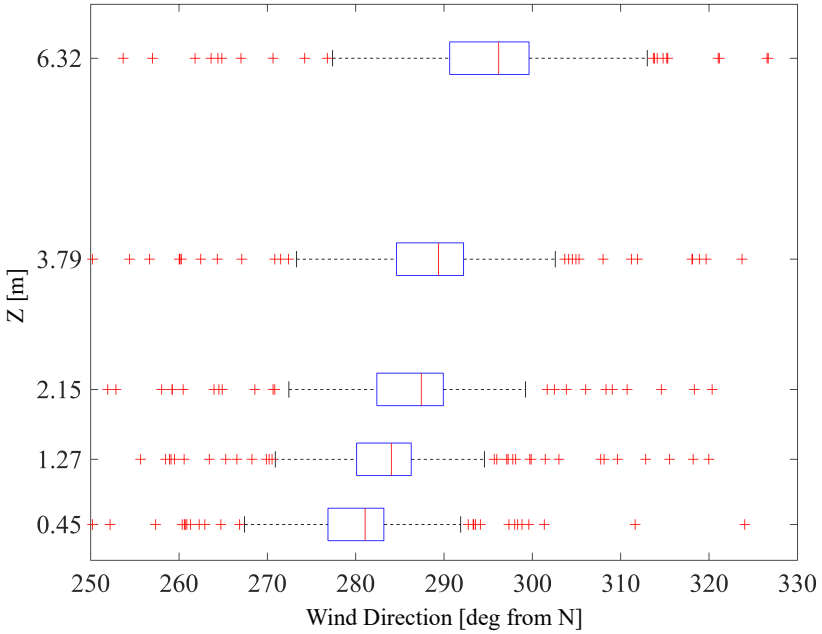
Increasing flux and divergence
Until about 15:00

Then weakening until
drop-off at the
evening transition

~ Correlates with temperature

Flow Structure



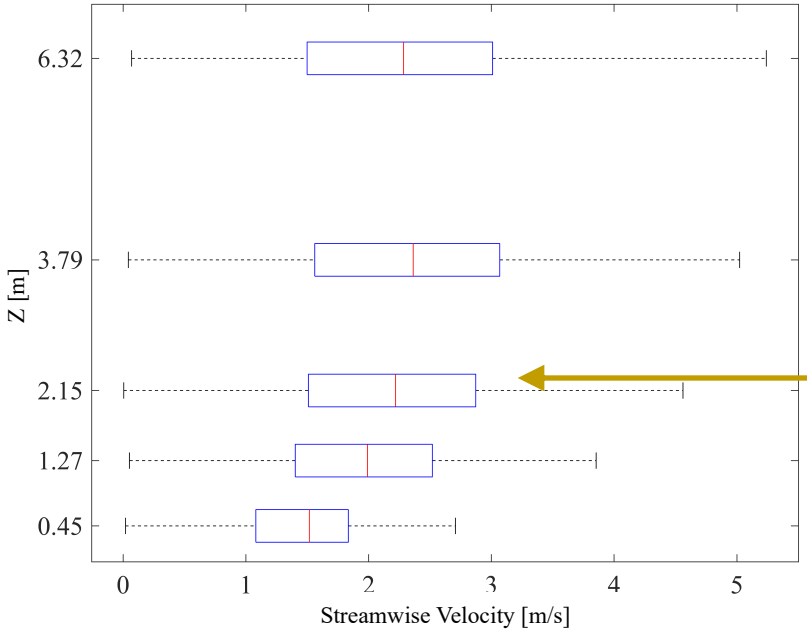


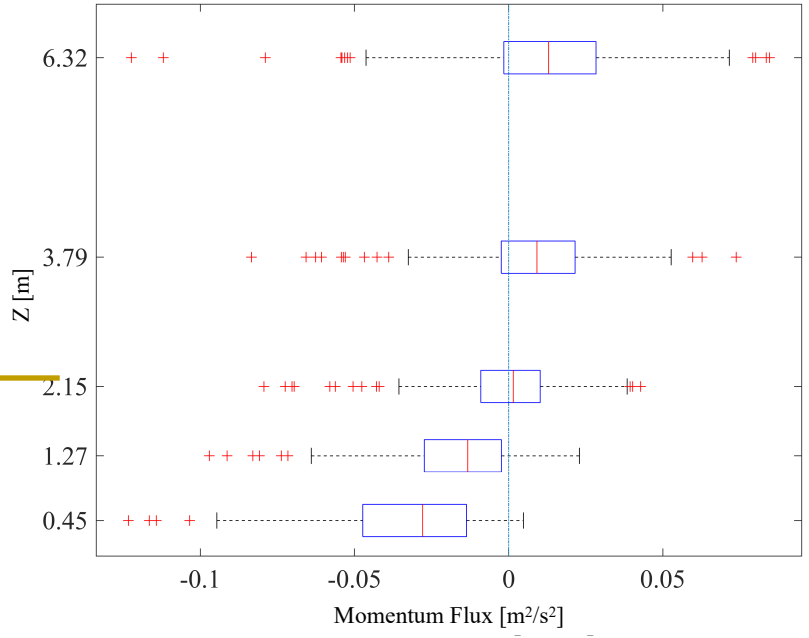
Shallow slope-flow layer

Valley flow influence increases with distance from the surface

Directional shear

Flow Structure





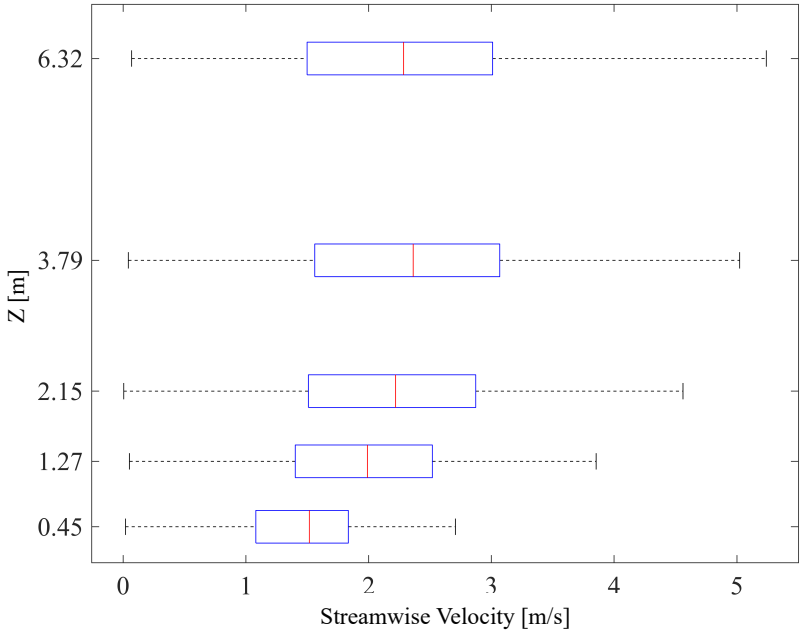
Do we have a Jet Profile?

Anabatic Jet:
Peak Approx. 2-3 m

Momentum flux divergence & sign change

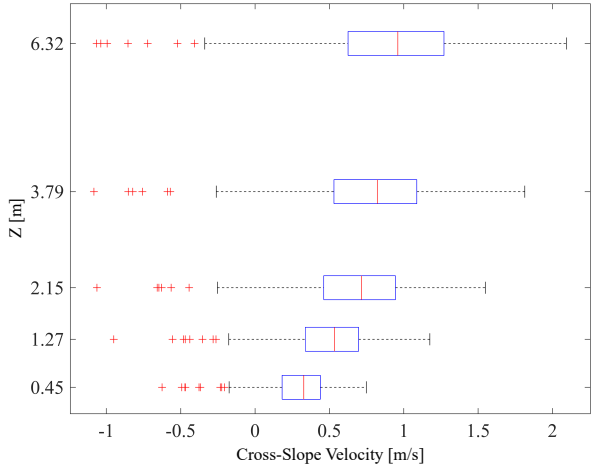
No constant-flux surface layer →
Monin-Obukhov Similarity Breaks Down!

Flow Structure

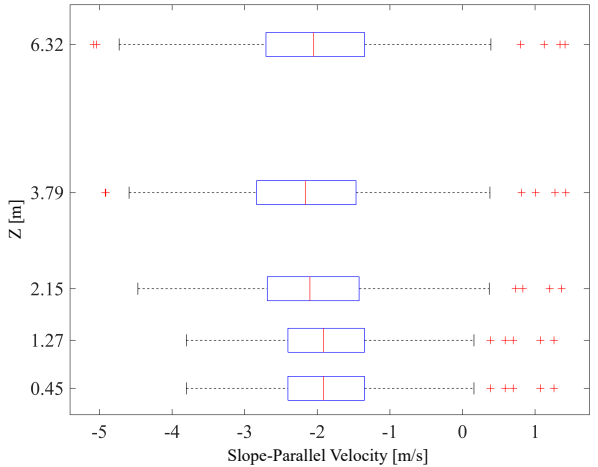


Superposition of two flows

Probably not that simple:
Modeling Challenge: What is local vs non-local?



'Valley' flow



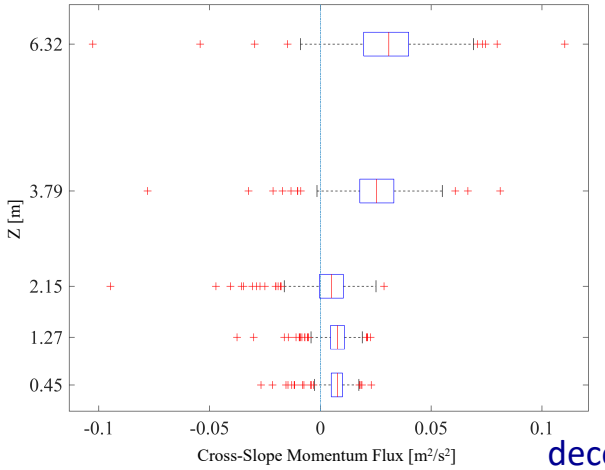
Slope flow

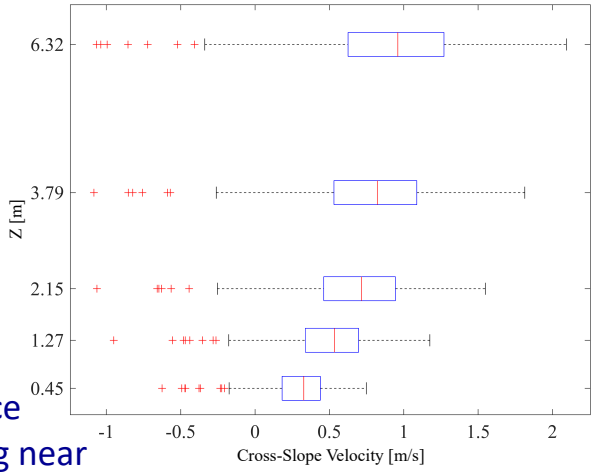
(negative = up the slope)

Flow Structure

Cross-Slope momentum flux:

Two ‘constant’-flux layers: above & below jet peak





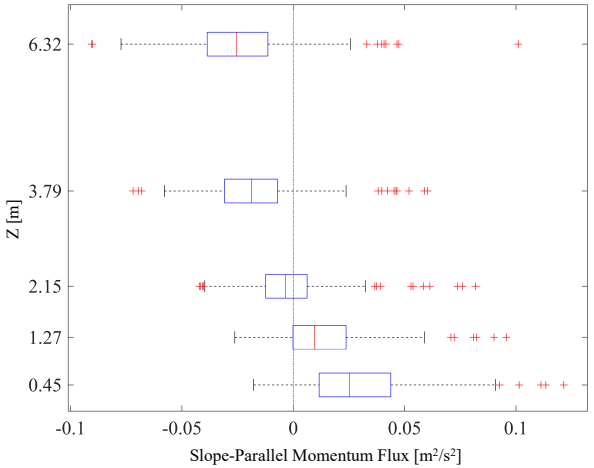
'Valley’ flow

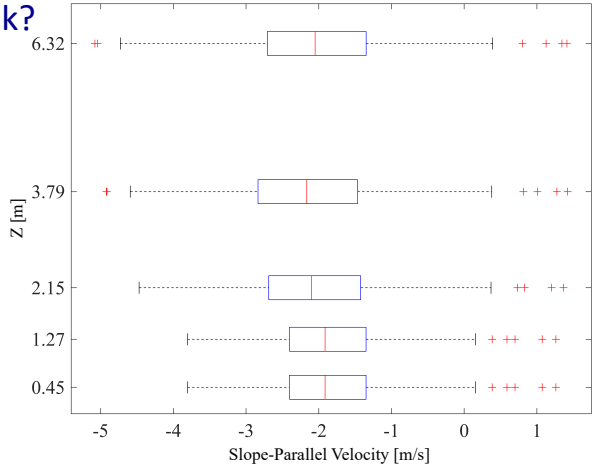
Surface decoupling near jet peak?

Slope Parallel momentum flux:

Significant flux divergence

Sign change





Slope flow

Flow Structure: Buoyancy Fluxes

TKE budget
In slope coordinate system

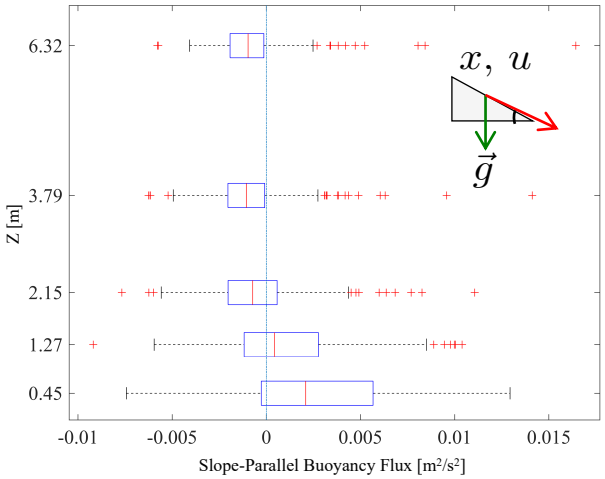
$$\frac{\partial \overline{e}}{\partial t} + \overline{w}\frac{\partial \overline{e}}{\partial z} = \boxed{-\frac{g}{\overline{\theta}}\overline{(u'\theta')}\sin\alpha + \frac{g}{\overline{\theta}}\overline{(w'\theta')}\cos\alpha} - \overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{w'w'}\frac{\partial \overline{w}}{\partial z} - \frac{\partial \overline{(w'\overline{e})}}{\partial z} - \frac{1}{\overline{\rho}}\frac{\partial \overline{(w'P')}}{\partial z} - \varepsilon$$

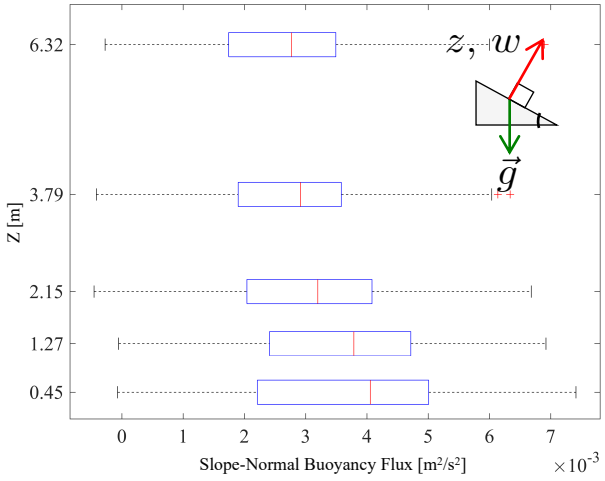
Along-Slope Buoyancy Flux

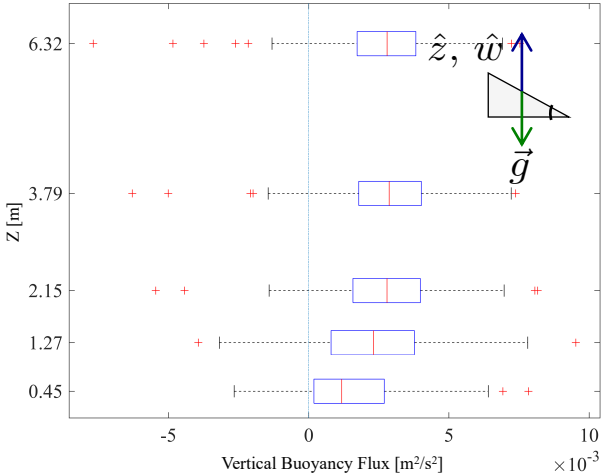
Slope-Normal Buoyancy Flux

Net (vertical) buoyancy flux = vector sum

Oldroyd et al., *BLM* 2016 a & b







Significant flux divergence

Changes sign near jet peak

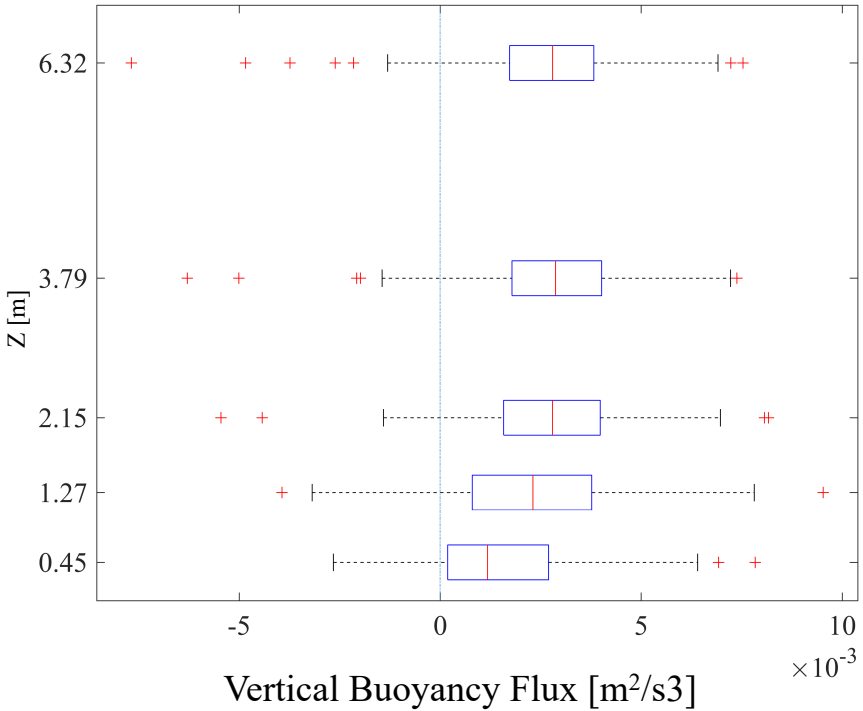
Significant flux divergence

Positive (convective)

Significant flux divergence

Mostly positive→ produces TKE

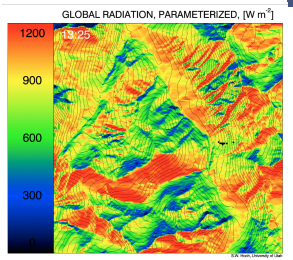
Flow Structure: Buoyancy Fluxes



Modeling Challenges

- No constant-flux surface layer → Monin-Obukhov Similarity Theory Breaks Down!
- What drives the along-slope buoyancy flux?
  - How can we parameterize it?
- How best to define stability parameters over slopes?

Summary



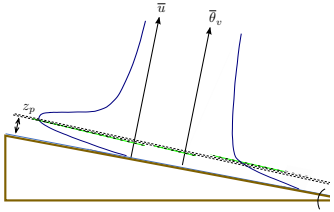
Modeling Challenges {a priori}

- Steep terrain & grid anisotropy (e.g., Lundquist et al., 2009)
- Heterogeneous land cover
- Heterogeneous topography: local slope & aspect

Flow Observations

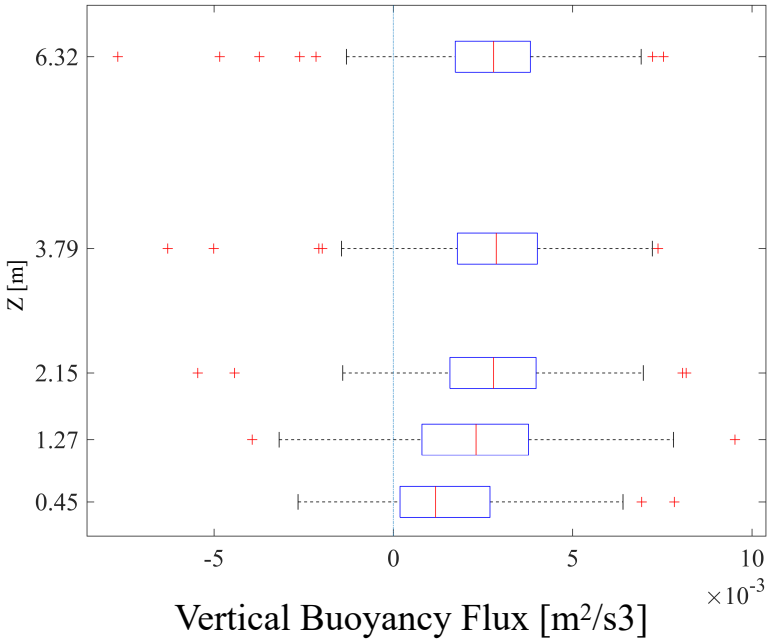
Anabatic jet velocity profile

- Peak height ≈2-3 m
- Upslope-Upvalley wind direction



Modeling Challenges

- Shallow slope-flow layer
- Multiscale-forcing (local & valley-scale)
- Turbulence flux divergence: No constant-flux surface layer → Monin-Obukhov Similarity Theory Breaks Down! Need new parameterizations.
- Along-slope buoyancy flux reduces TKE production near the surface. How can we parameterize it?
- How best to define stability parameters over slopes?



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Thanks