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# Stable boundary layer height on a gentle slope

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Stiperski et al. (2019) On the turbulence structure of deep katabatic flows on a gentle mesoscale slope. *QJRMS.* doi: 10.1002/qj.3734

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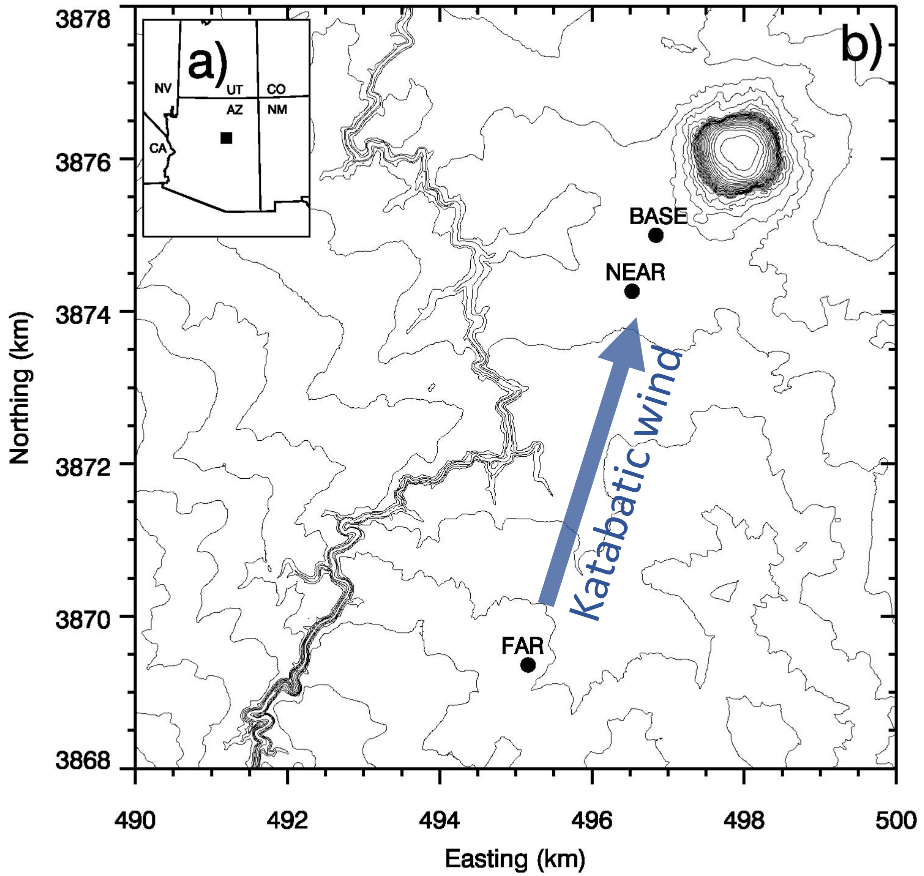
# How shallow a slope must be to differ from flat terrain?

- An SBL over sloping terrain leads to the development of katabatic flows
- Near-surface inversion strength plays a crucial role in katabatic flows, just as it does over flat terrain
- How does a sloping katabatic SBL then differ from a flat terrain SBL?
- We investigate the SBL in deep katabatic flows in the Second Meteor Crater Experiment (METCRAX II) measurement campaign (Lehner et al. 2016)

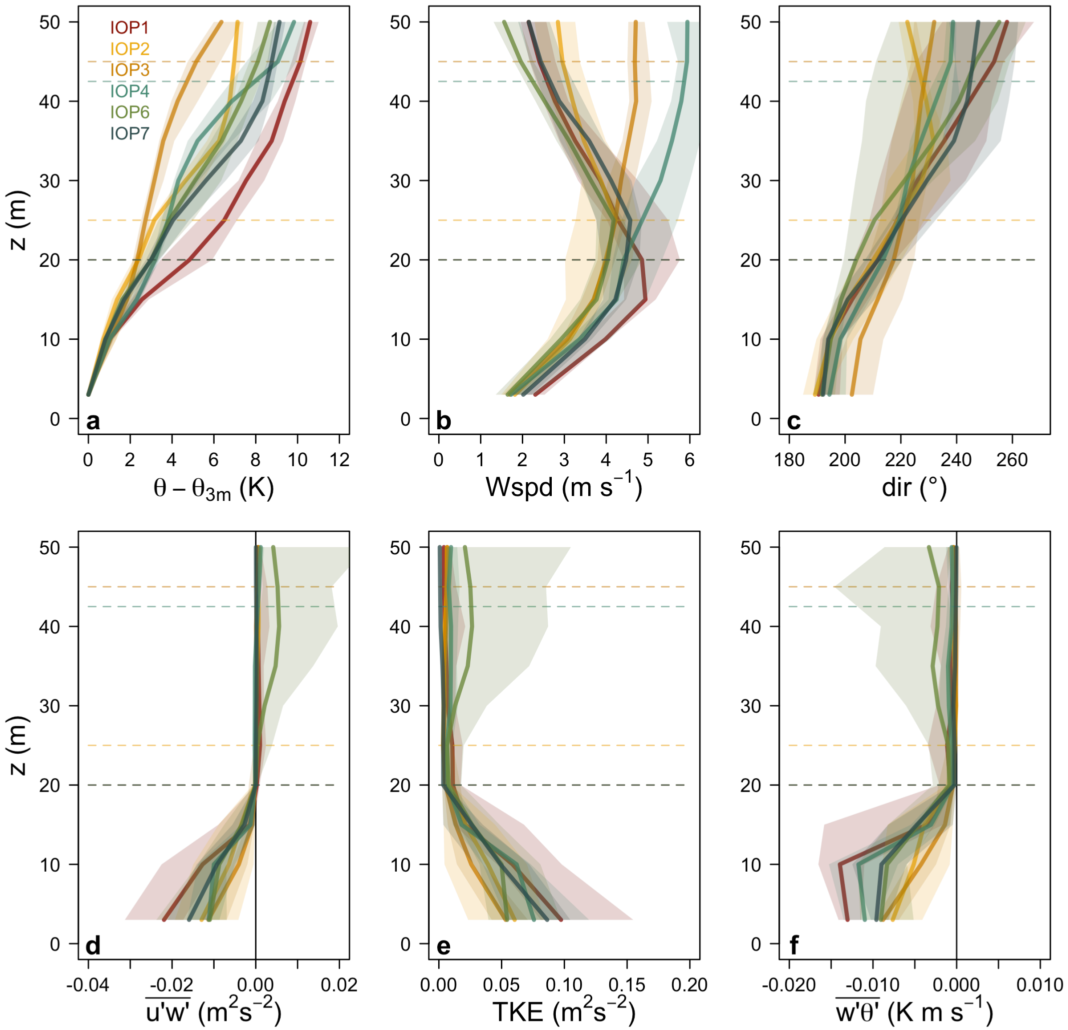
# Data set




## METCRAX II campaign: October 2013

- A low-angle (1°) mesoscale (30 km) slope
- Data from the 50-m-high NEAR tower with 10 levels of sonic anemometers
- Six IOPs with deep katabatic flows that develop outside the crater
- Data post-processing: planar fit, 1 min averages, coordinate system oriented into the wind direction at jet maximum

# Flow characteristics – deep and shallow flows




## What are the flow characteristics?

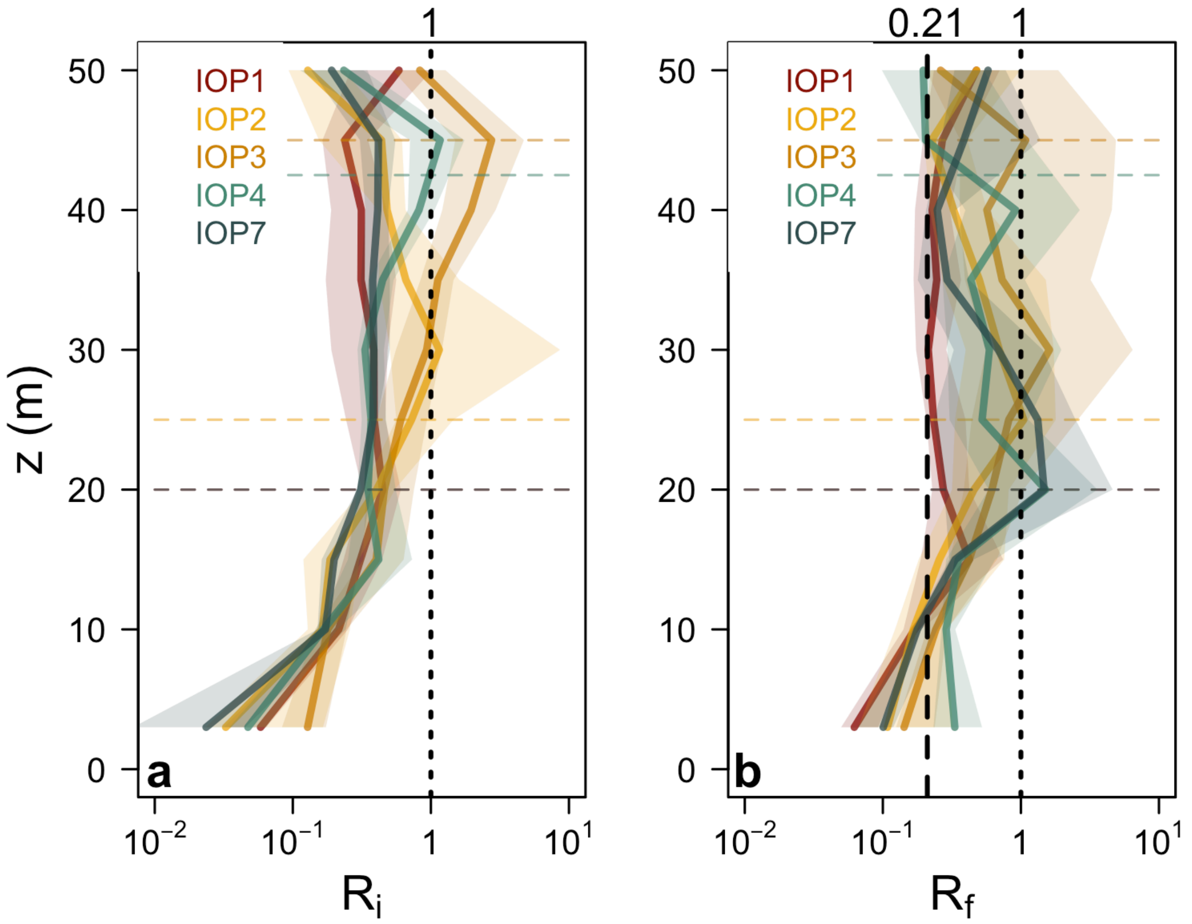
- Katabatic flows with a low-level jet maximum develop in stable stratification
- Strongest inversion is above the jet maximum
- Jet maximum height ($h_{jet}$) varies between IOPs:

→ deeper ($h_{jet}$ ~ 40 m)

→ shallower ($h_{jet}$ ~ 25m)

- Strong directional shear with height
- Well-developed turbulence below 20 m and strong damping above
- Height where turbulence ceases not related to $h_{jet}$

# Flow characteristics – deep and shallow flows




## Why does turbulence cease above 20 m?

- Profiles of flux ($R_f$) and gradient($R_i$) Richardson numbers increase beyond a critical value above 15 m
- This suggests the stratification is too strong to maintain turbulence
- Since turbulence is maintained to a greater height (20 m) than suggested by $R_f$ (>> 0.21), the turbulence structure is not governed only by the balance between buoyancy, shear and dissipation

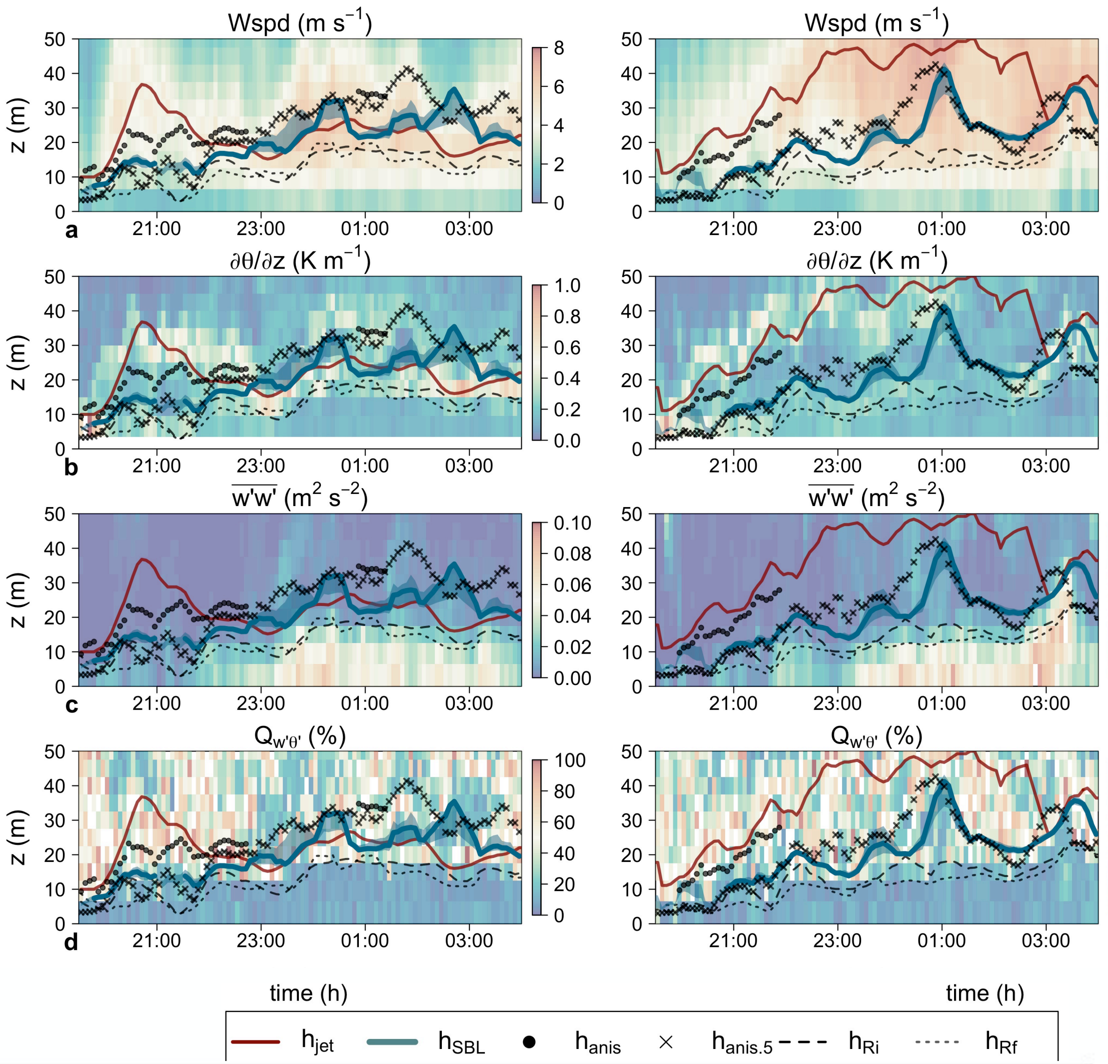
# Detecting SBL height – using fluxes

## How to detect the SBL top?

→ BL: “Atmospheric layer directly influenced by the surface and characterized by turbulence”

→ SBL height (**$h_{SBL}$**) = median height where turbulence (uw, wθ, TKE) becomes negligible

- $h_{SBL}$ is not correlated with jet maximum height (**$h_{jet}$**)
- $h_{SBL}$ is not correlated with the height of the strongest inversion ($\partial\theta/\partial z$)
- The height where $R_f > 0.21$ (**$h_{Rf}$**) is lower than $h_{SBL}$ but better identifies the layer of most stationary turbulence ($Q_{w'\theta'}$)

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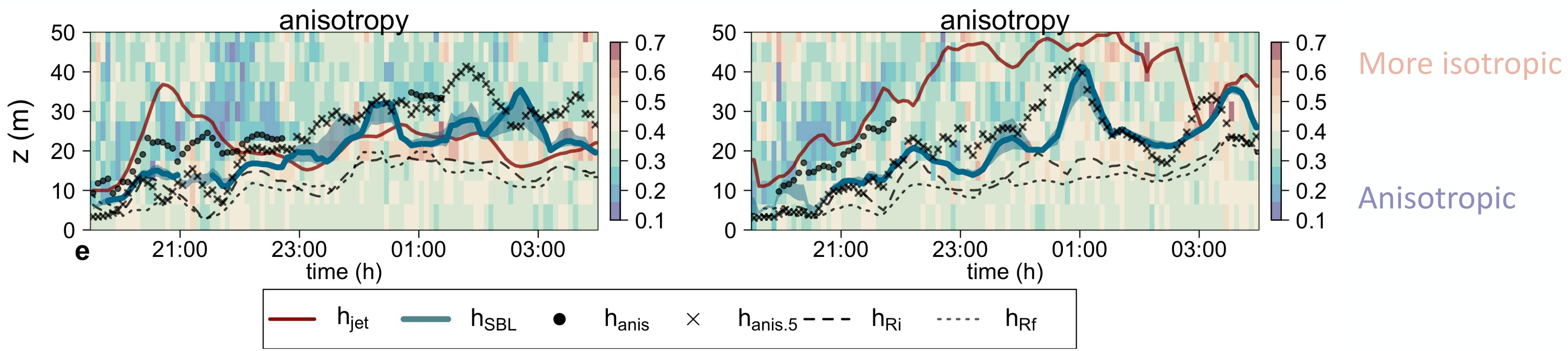
# Detecting SBL height – using anisotropy

## Can information on anisotropy help in identifying SBL top?

- Anisotropy provides information on directionality of TKE exchange
- Quantify degree of anisotropy by third invariant $y_B$ of the barycentric map (Stiperski et al, 2019)
- Well-developed turbulence in SBL is more isotropic ($y_B > \sqrt{3}/6$) than above SBL

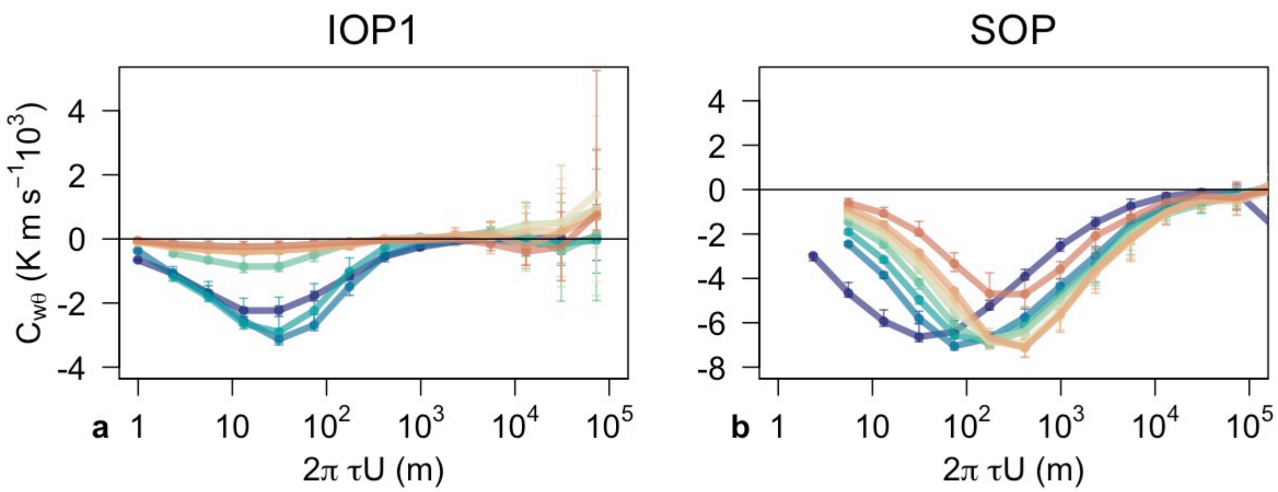
→ Use anisotropy ($y_B = \sqrt{3}/6$) to detect SBL top: $h_{anis}$ (1 min averages ●), $h_{anis.5}$ (5 min averages ×)



# Detecting SBL height – using size of most energetic eddy

## How does the size of the most energetic eddy change with height?

- We perform multi-resolution flux decomposition (MRD)
- Length scale of the most energetic eddy ($2\pi\tau U$) is semi-invariant with height in the katabatic flow
- This is different than in non-katabatic boundary layer cases (SOP) where the length scale varies significantly with height in line with surface-layer scaling

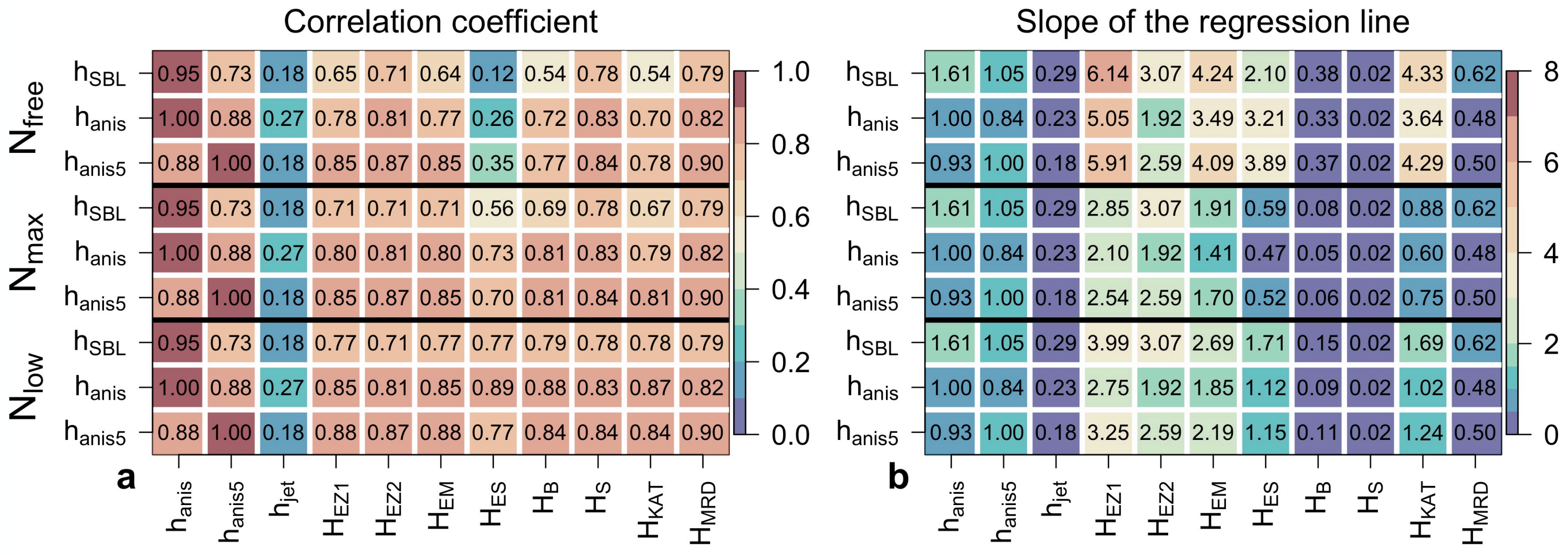


# Testing different flat terrain SBL height formulations

| Variable | Name | Definition | Reference |
|---|---|---|---|
| $H_{EZ1}$ | Flat-terrain equilibrium SBL height | $H_{EZ1} = \frac{0.4u_{*s}}{\lvert f\rvert}\left[1 + \frac{0.4^2 u_{*s}(1+0.25NL/u_{*s})}{0.75^2\lvert f\rvert L}\right]^{-1/2}$ | Zilitinkevich and Baklanov (2002) |
| $H_{EZ2}$ | Flat-terrain equilibrium SBL height | $H_{EZ2} = 0.5u_{*s}^2 \cdot \lvert fB_s\rvert^{-1/2}$ | Zilitinkevich *et al.* (2012) |
| $H_{ES}$ | Flat-terrain equilibrium SBL height | $H_{ES} = \begin{cases} 10u_{*s} \cdot N^{-1} & u_{*s}^2 N\lvert B_s\rvert^{-1} > 10 \\ 32(\lvert B_s\rvert \cdot N^{-3})^{1/2} & u_{*s}^2 N\lvert B_s\rvert^{-1} < 10 \end{cases}$ | Steeneveld *et al.* (2007) |
| $H_{EM}$ | Flat-terrain equilibrium SBL height | $H_{EM} = u_{*s} \cdot N^{-1}(\lvert f\rvert \cdot N^{-1})^{-1/2}$ | Mironov and Fedorovich (2010) |
| $H_B$ | Buoyancy length-scale | $H_B = (\sigma_w)_s \cdot N^{-1}$ | Monti *et al.* (2002) |
| $H_S$ | Shear length-scale | $H_S = (\sigma_w)_s \cdot \left\lvert \partial\overline{U}/\partial z \right\rvert_s^{-1}$ | Monti *et al.* (2002) |
| $H_{KAT}$ | Prandtl scale | $H_{KAT} = 1/4 \cdot u_{*s} \cdot (N\sin\alpha)^{-1}$ | |
| $H_{MRD}$ | MRD scale | $H_{MRD} = 2\pi U\tau_{max}$ | |

*Note*: $N$ is the buoyancy frequency, $u_*$ is friction velocity, $L$ is the Obukhov length, $\sigma_w$ is the standard deviation of vertical velocity, $f$ the Coriolis parameter, $k$ the von Kármán constant taken as 0.4, and $B_s$ is buoyancy defined as $B_s = (\overline{w'\theta'})_s g/\overline{\theta}_v$, where $(\overline{w'\theta'})_s$ is the kinematic sensible-heat flux. Subscript $s$ denotes values measured at the surface (i.e. 3 m).

# Testing different flat terrain SBL height formulations




- Compare the diagnostic heights to detected heights ($h_{SBL}$, $h_{anis}$, $h_{anis.5}$)
- Which buoyancy frequency to use?
  - $N_{free}$ – free tropospharic
  - $N_{max}$ – maximum inversion
  - $N_{low}$ – average in lowest 10 m

- Flat terrain equilibirum heights using $N_{free}$ show low correlation to detected height and significantly overestimate it
- Using local stability ($N_{low}$ or $N_{max}$) in flat terrain equilibrium height significantly improves the correlation with detected SBL heights
- Most appropriate formulations: $H_{ES}$ using $N_{low}$ , $H_{KAT}$ , $H_{MRD}$

# Testing different flat terrain SBL height formulations

## How to best detect the SBL height?

- $h_{anis}$ outperforms $h_{SBL}$

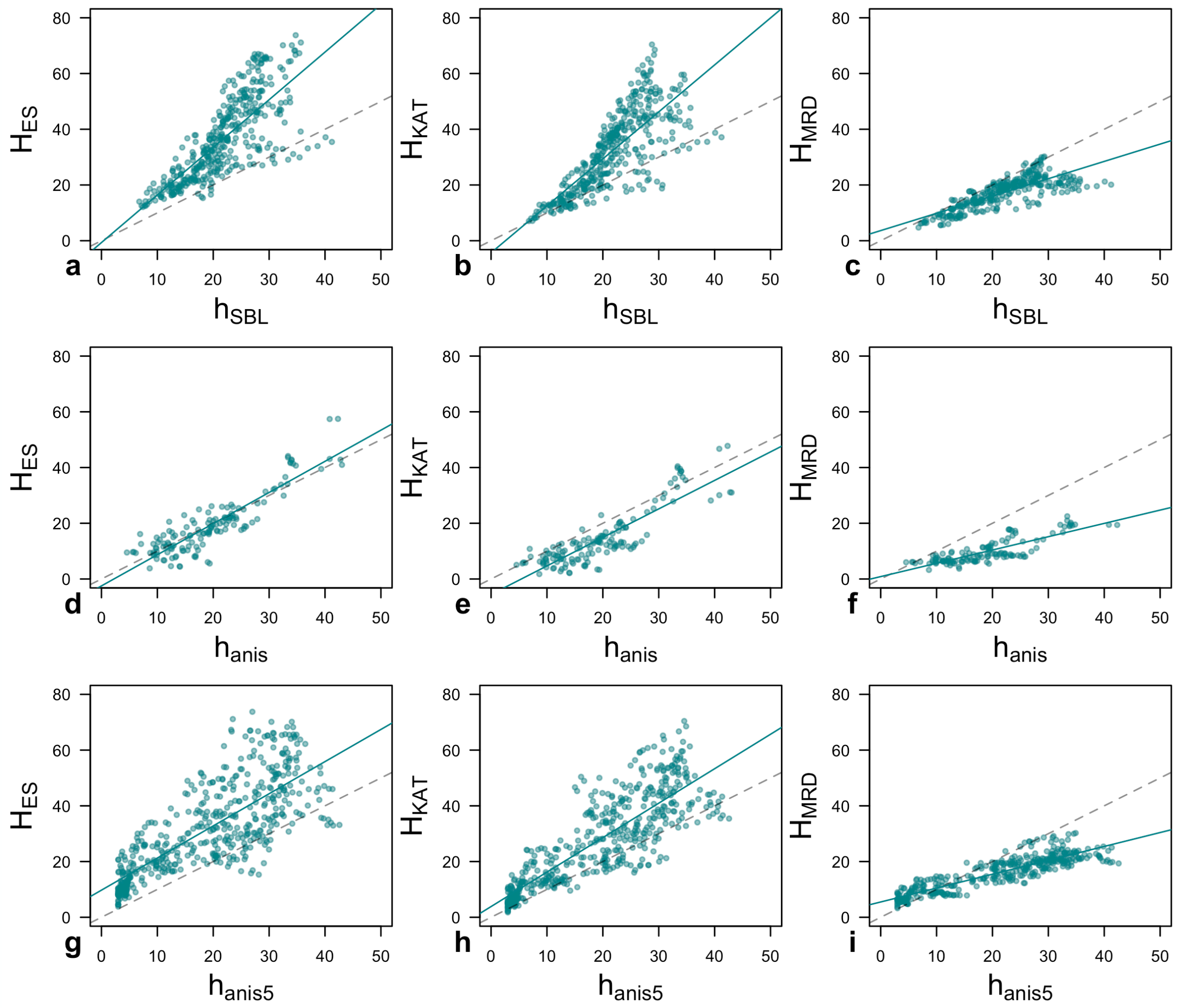
→ has larger correlations to diagnostic formulations

→ shows better distribution of residuals

→ regression slope is closer to 1

## Can we detect SBL from a single level?

- Good results for $H_{MRD}$ mean it is possible to detect SBL height in katabatic flows from a single measurement level if it is below the jet maximum



# Conclusions

- A shallow mesoscale slope (1°) leads to katabatic flow formation
- Katabatic flows determine the turbulence structure
- Determining SBL height ($h_{SBL}$) is ambigous
- $h_{SBL}$ is not correlated with the height of maximum inversion or the jet maximum height
- $h_{SBL}$ is shallower than flat terrain formulations suggest
- $h_{SBL}$ is controlled by local stability ($N_{low}$), not stability above the SBL ($N_{free}$)
- Anisotropy is a better diagnostic for identifying SBL height than fluxes
- In katabatic flows it is possible to diagnose SBL height from a single measurement level based on the size of the most energetic eddy