In situ measurements of katabatic downslope wind

profiling of the turbulent boundary layer near the surface below the jet maximum

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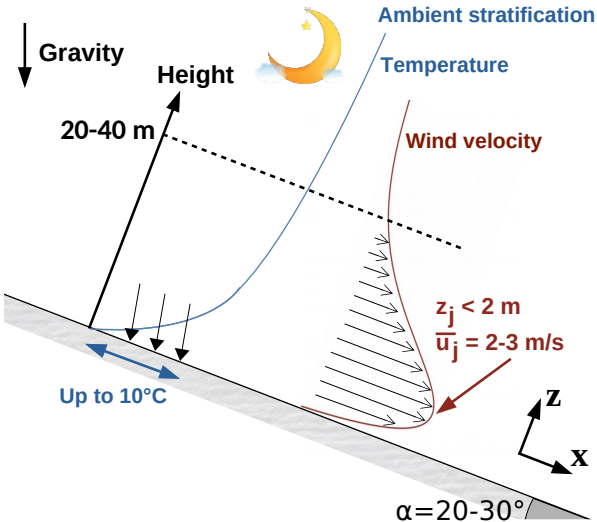
Katabatic wind process



Negative radiative budget

$$R_n^{night} = LW_{received} - LW_{emitted} < 0$$

$\Downarrow$

Surface temperature cooling

$\Rightarrow$ Temperature gradient

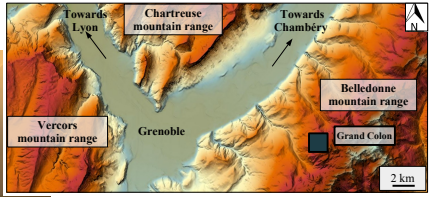
$\Rightarrow$ Air cooling / densification

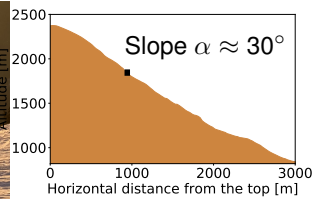
$\Downarrow$

Downslope flow

$\Rightarrow$ Turbulent mixing

Measurement setup





Snow cover:

Weak surface roughness

$z_0 \approx 0.2 - 0.3$ mm

background stratification:

$$N = \sqrt{\frac{g}{\theta_0}\frac{\partial \theta_v}{\partial z}} \approx 0.02 \text{ Hz}$$

Measurement setup

2D sonic anemometer (Waissala)

LW radiation sensor (KT15)

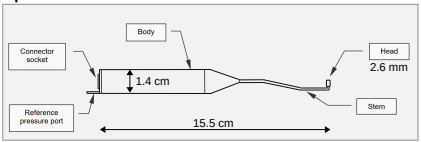
3D sonic anemometer (CSAT3B)

4 Thermocouples (FW3)

3D Pitot sensor

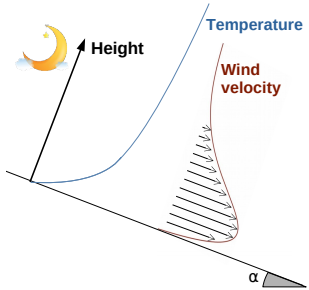
'Cobra' 3D pitot tube *TFI*
pressure transducers: $f = 1250$ Hz

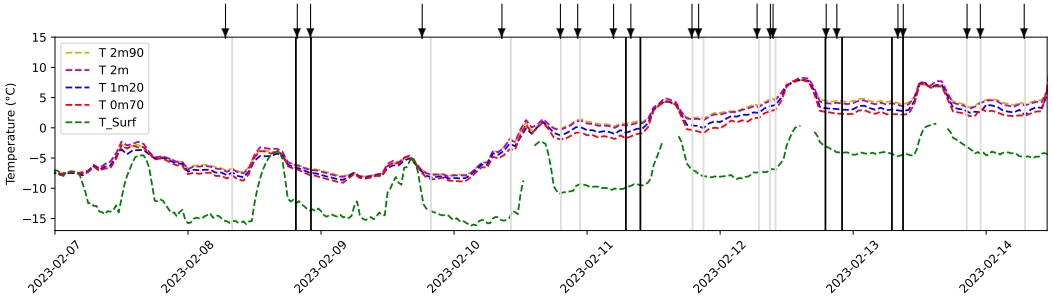
Micrometric displacement system) (Rosier)



21 katabatic profiles

- Wind in the downslope direction
- Positive temperature gradient
- Velocity profiles $\sim$ wall jet



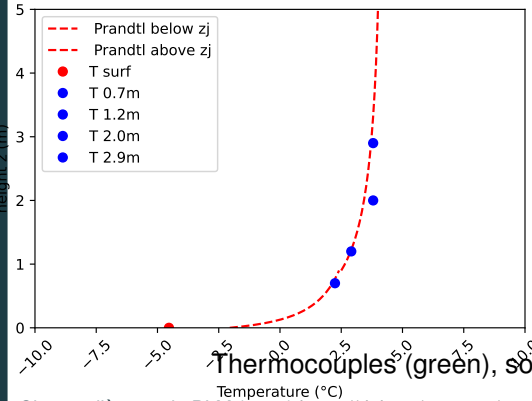


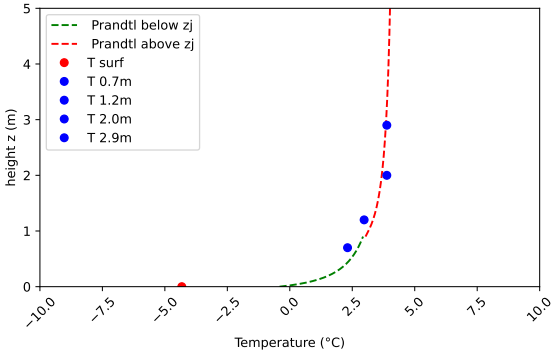
Potential temperature profiles $\overline{\theta}$

February 13, 2023
(7h13-7h46)

February 13, 2023
(9h21-9h52)

February 28, 2019
(19h-21h40)



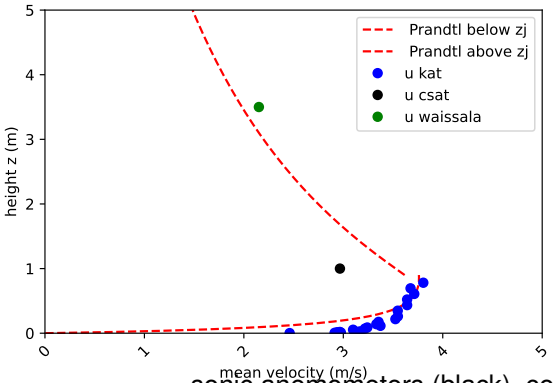


Thermocouples (green), sonic anemometers (black), Prandtl model (red)

Charrondière et al., BLM (2022) https://doi.org/10.1007/s10546-021-00644-y
Charrondière et al., JFM (2022) https://doi.org/10.1017/jfm.2022.281

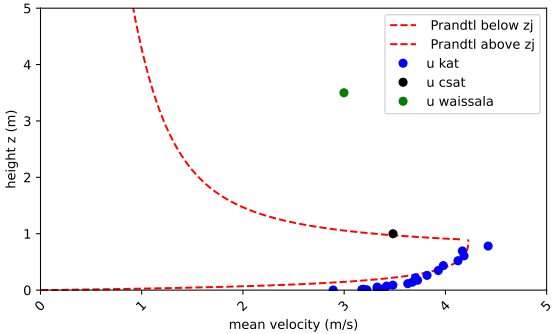
Along the slope velocity $\overline{u}$

February 13, 2023
(7h13-7h46)



February 13, 2023
(9h21-9h52)

February 28, 2019
(5h30-6h36)



sonic anemometers (black), cobra pitot (green), Prandtl model (red)

Charrondière et al., BLM (2022) https://doi.org/10.1007/s10546-021-00644-y
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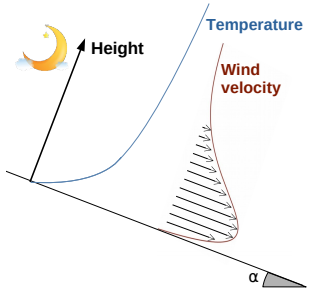
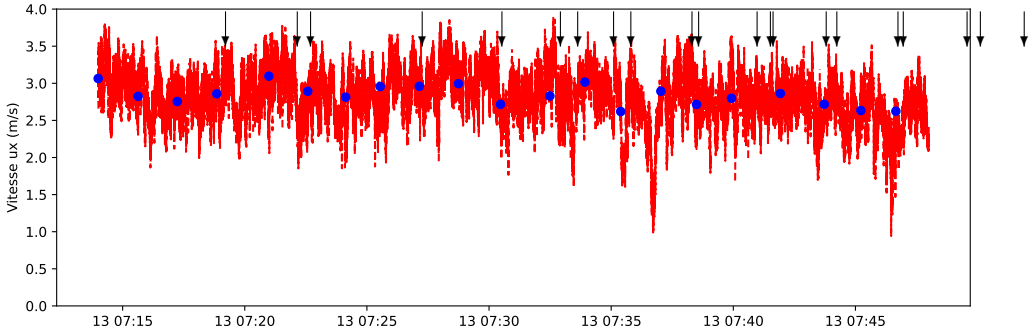
katabatic profile

- 21 samples from $z = 2mm$ to $z = 0.9m$
- 1 minute sampling time each
- 30 minutes measurements
- CSAT: $+ -$ 10% variability





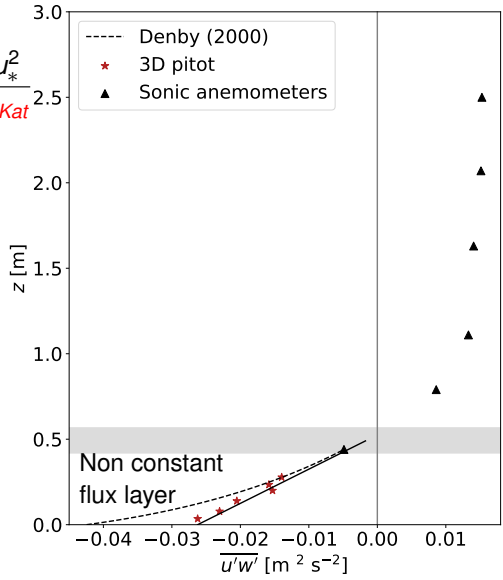
Momentum budget along the slope

$$\underbrace{\frac{\partial \overline{u}}{\partial t}}_{\text{Inertia}} + \underbrace{\overline{w}\frac{\partial \overline{u}}{\partial z}}_{\text{Advection}} + \underbrace{\frac{\partial \overline{u'w'}}{\partial z}}_{\substack{\text{Divergence of the turbulent} \\ \text{momentum flux}}} \approx \underbrace{-g\frac{\overline{\theta_s} - \theta_a}{\theta_a}\sin\alpha}_{\text{Katabatic forcing}} = \frac{u_*^2}{L_{Kat}}$$

Denby (2000)

Non constant flux profile

$$-\overline{u'w'} = u_*^2\left(1 - \frac{z}{L_{Kat}}\right) = \left(\kappa z \frac{\partial \overline{u}}{\partial z}\right)^2$$



Charrondière et al., BLM (2022)
Charrondière et al., JFM (2022)

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Denby (2000)

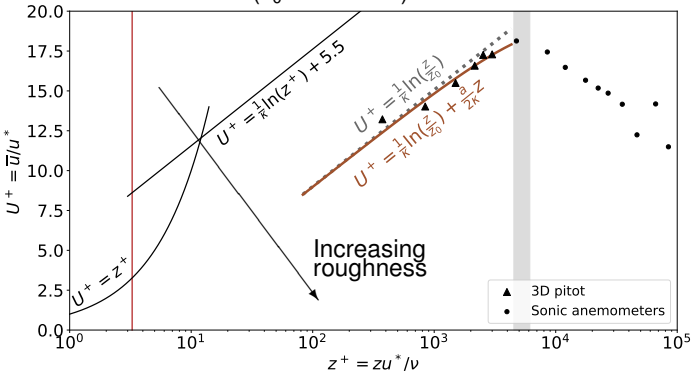
February 28, 2019 (5h00-6h36)

($z_0 \approx 0.3$ mm)

Turbulent velocity profile

$$\overline{u}^+ = \frac{1}{\kappa}\ln\frac{z}{z_0} - \frac{1}{2\kappa}\frac{z}{L_{Kat}} + \beta\frac{z}{L_{MO}}$$

avec $L_{Kat} \approx 0.5m$ et $L_{MO} \approx 200m$



Charrondière et al., BLM (2022)
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Momentum budget along the slope

$$\underbrace{\frac{\partial \overline{u}}{\partial t}}_{\text{Inertia}} + \underbrace{\overline{w}\frac{\partial \overline{u}}{\partial z}}_{\text{Advection}} + \underbrace{\frac{\partial \overline{u'w'}}{\partial z}}_{\substack{\text{Divergence of the turbulent} \\ \text{momentum flux}}} \approx \underbrace{-g\frac{\overline{\theta_S} - \theta_a}{\theta_a}\sin\alpha}_{\text{Katabatic forcing}} = \frac{u_*^2}{L_{Kat}}$$

Denby (2000)

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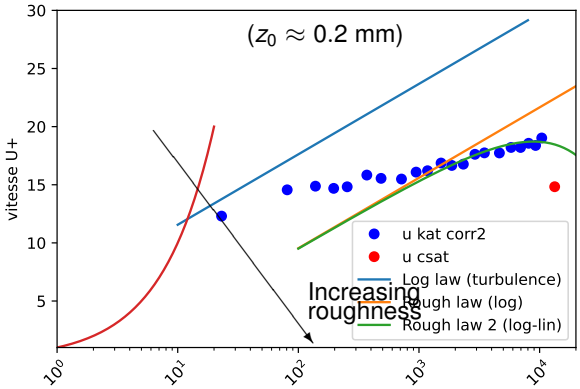
Charrondière et al., BLM (2022)
Charrondière et al., JFM (2022)

February 13, 2023 (7h13-7h46)



Momentum budget along the slope

Denby (2000)

Turbulent velocity profile

$$\overline{u}^{+} = \frac{1}{\kappa} \ln \frac{z}{z_0} - \frac{1}{2\kappa} \frac{z}{L_{Kat}} + \beta \frac{z}{L_{MO}}$$

avec $L_{Kat} \approx 0.5m$ et $L_{MO} \approx 200m$

Charrondière et al., BLM (2022)
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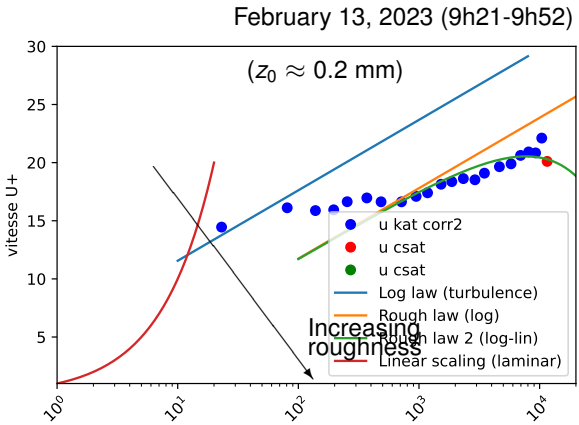
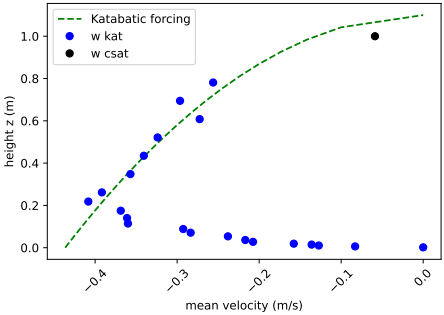
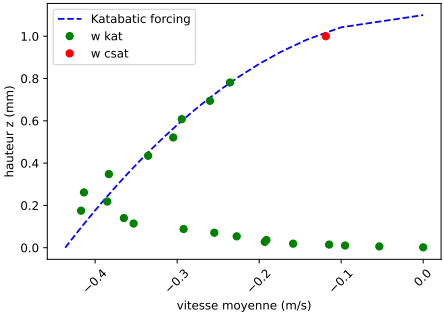


Normal to the slope velocity $\overline{w}$

February 13, 2023 (7h13-7h46)



February 13, 2023 (9h21-9h52)



$$\underbrace{\frac{\partial \overline{w}}{\partial t}}_{\text{Inertia}} + \underbrace{1/2\frac{\partial \overline{w}^2}{\partial z}}_{\text{Advection}} + \underbrace{\frac{\partial \overline{w'^2}}{\partial z}}_{\substack{\text{Divergence of} \\ \text{the turbulent} \\ \text{velocity variance}}} \approx \underbrace{g\frac{\overline{\theta} - \theta_a}{\theta_a}\cos\alpha}_{\text{Katabatic forcing}}$$

Charrondière et al., BLM (2022)
Charrondière et al., JFM (2022)

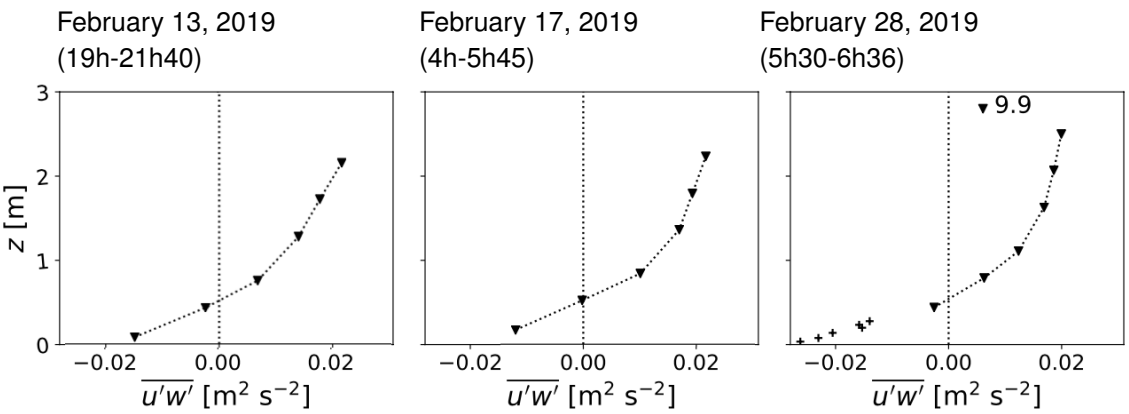
Conclusion & overlook

Katabatic jet along a steep slope

$\Rightarrow$ **Turbulent boundary layer in the inner layer**
– **non constant turbulent fluxes (gravity effect)**
– **log-lin law for the along the slope velocity**
– **normal to the slope velocity contribution** $10\%Uj$

$\Rightarrow$ **Data available on a zenodo repository**
– **https://doi.org/10.5281/zenodo.6546702**

Momentum turbulent flux



sonic anemometers (triangles), cobra pitot (plus)

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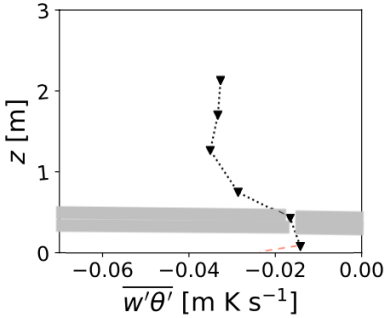
Charrondière et al., JFM (2022) https://doi.org/10.1017/jfm.2022.281

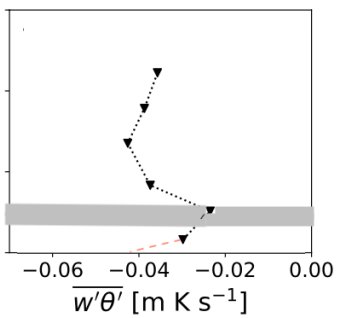
Potential temperature budget & turbulent sensible heat flux $\overline{w'\theta'}$

$$\underbrace{\frac{\partial \overline{\theta}}{\partial t}}_{\text{Inertia}} + \underbrace{\frac{\partial \overline{w'\theta'}}{\partial z}}_{\text{Flux divergence}} \approx - \underbrace{\overline{w}\frac{\partial \overline{\theta}}{\partial z}}_{\text{Advection}} - \underbrace{\overline{u}\frac{\partial \theta_a}{\partial z}\sin\alpha}_{\text{Ambient stratification effect}} > 0$$

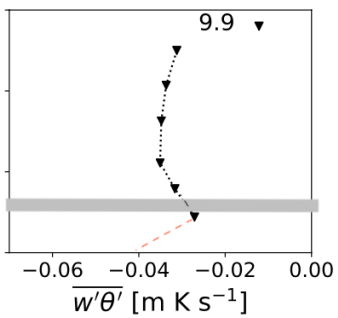
February 13, 2019
(19h-21h40)



February 17, 2019
(4h-5h45)



February 28, 2019
(5h30-6h36)



Momentum budget along the slope

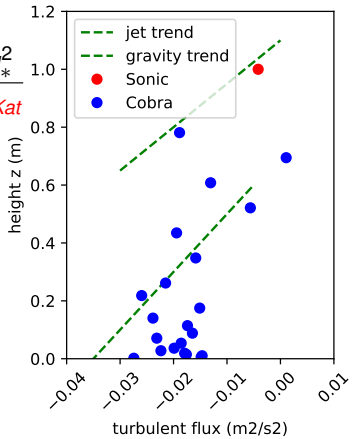
February 13, 2023 (7h13-7h48)

$$\underbrace{\frac{\partial \overline{u}}{\partial t}}_{\text{Inertia}} + \underbrace{\overline{w}\frac{\partial \overline{u}}{\partial z}}_{\text{Advection}} + \underbrace{\frac{\partial \overline{u'w'}}{\partial z}}_{\text{Divergence of the turbulent momentum flux}} \approx \underbrace{-g\frac{\overline{\theta_s} - \theta_a}{\theta_a}\sin\alpha}_{\text{Katabatic forcing}} = \frac{u_*^2}{L_{Kat}}$$

Denby (2000)

Non constant flux profile

$$-\overline{u'w'} = u_*^2\left(1 - \frac{z}{L_{Kat}}\right) = \left(\kappa z \frac{\partial \overline{u}}{\partial z}\right)^2$$



Non constant flux layer

Momentum budget along the slope

$$\underbrace{\frac{\partial \overline{u}}{\partial t}}_{\text{Inertia}} + \underbrace{\overline{w}\frac{\partial \overline{u}}{\partial z}}_{\text{Advection}} + \underbrace{\frac{\partial \overline{u'w'}}{\partial z}}_{\substack{\text{Divergence of} \\ \text{the turbulent} \\ \text{momentum flux}}} \approx \underbrace{-g\frac{\overline{\theta_S} - \theta_a}{\theta_a}\sin\alpha}_{\text{Katabatic forcing}} = \frac{u_*^2}{L_{Kat}}$$

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Non constant flux profile

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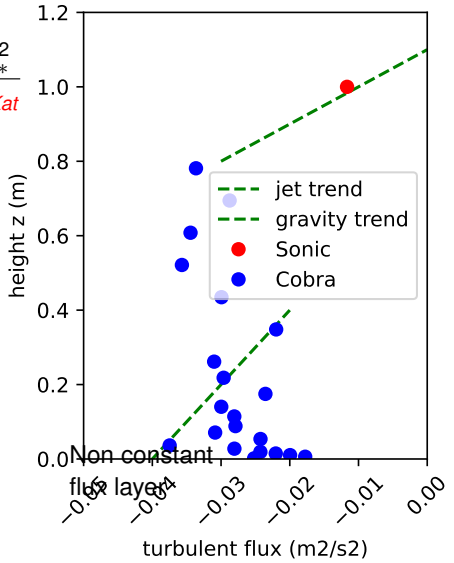
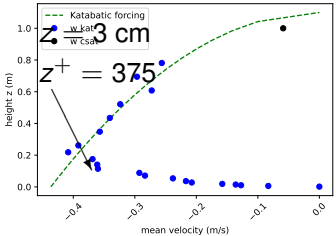
February 13, 2023 (9h20-9h52)



Slope-normal velocity - viscous sublayer



$$\underbrace{\frac{\partial \overline{w}}{\partial t}}_{\text{Inertia}} + \underbrace{\overline{w}\frac{\partial \overline{w}}{\partial z}}_{\text{Advection}} + \underbrace{\frac{\partial \overline{w'^2}}{\partial z}}_{\text{Divergence of the turbulent velocity variance}} - \underbrace{\nu \frac{\partial^2 \overline{w}}{\partial z^2}}_{\text{Diffusion}} \approx \underbrace{g \frac{\overline{\theta} - \theta_a}{\theta_a} \cos\alpha}_{\text{Katabatic forcing}}$$

Integration from z to Z_{max}:

$$\frac{\partial \overline{w}}{\partial z} = \frac{g}{\nu} \frac{\overline{\theta_S} - \theta_a}{\theta_a} \cos\alpha \, (Z_{max} - z) < 0$$

$$\overline{w} = \frac{1}{\nu \tan\alpha} \frac{u_*^2}{L_{Kat}} \, (Z_{max} - z/2) \, z$$