Experimental study of katabatic jets over steep slopes: buoyancy effect on turbulence and first insight on slope-normal velocity

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Context and stakes

Transport and storage of pollutants in valleys

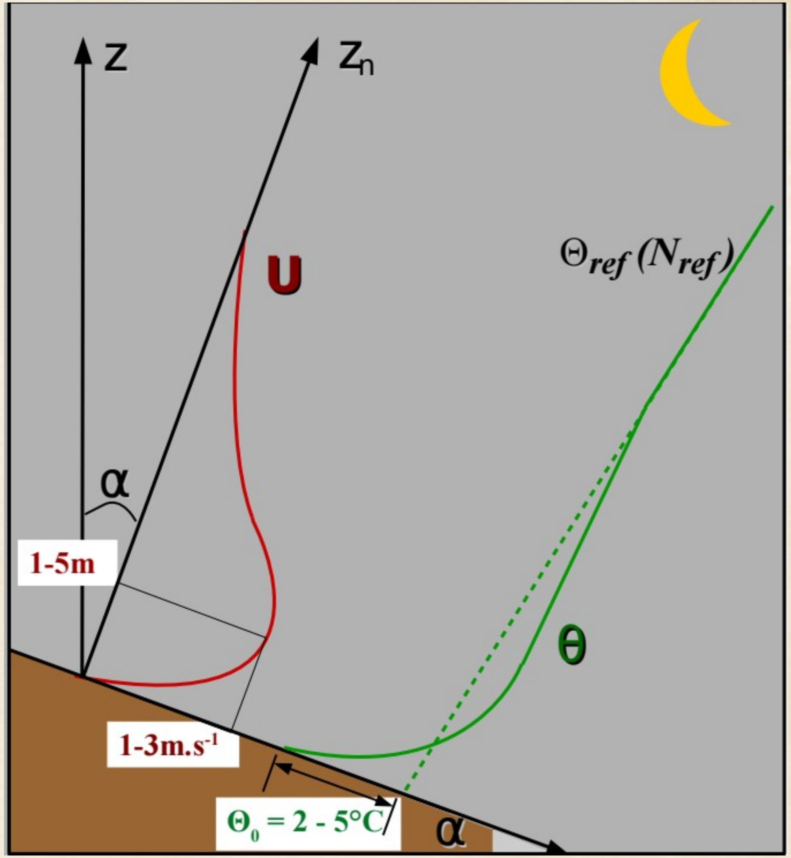
Whiteman D (2000)

Largeron Y, Staquet C (2016)

Parameterization of katabatic flows and turbulence in meteorological models

Blein S (2016)

Valley of Grenoble viewed from the measurement site – February 2019



Katabatic jet: gravity flow that develops in stably stratified conditions, due to a negative surface energy balance (often during nighttime)

Outlines

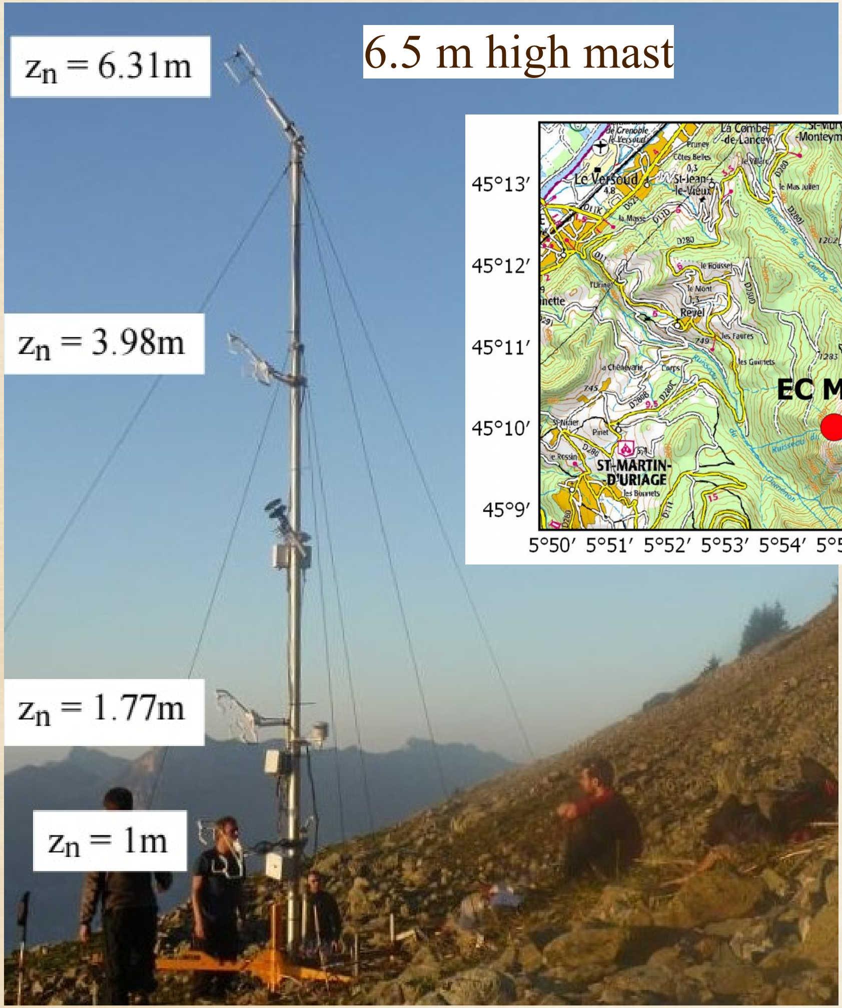
2012 November field experiment

* Presentation of the field campaign
* Buoyancy effect on turbulence kinetic energy (TKE)
* Buoyancy effect on turbulent shear stress $\overline{u'w'}$

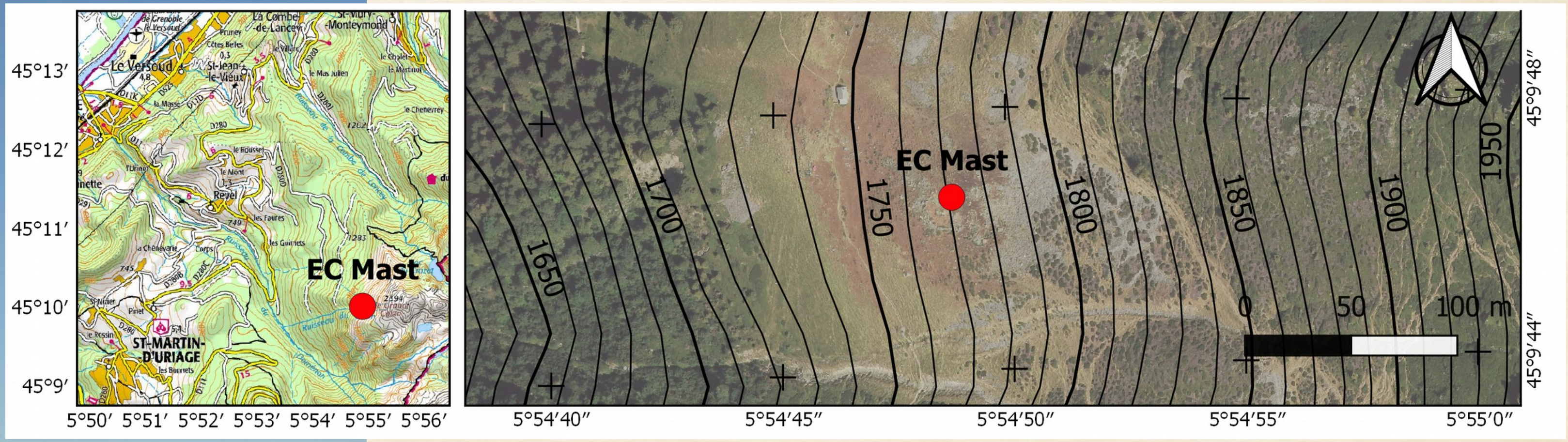
2019 February field experiment

* Presentation of the field campaign
* Improvements from the 2012 experiment
  - Tethered balloon above the mast and background stratification
  - Time-resolved measurements close to the ground (f=1250Hz)
  - Measurement of entrainment / detrainment in mean velocity profiles

2012 November field experiment



Belledonne mountain range (French Alps)



4 3D sonic anemometers (10-20 Hz)
1 2D sonic anemometer (0.5Hz)
1 thermo-hygrometer
1 infrared-thermometer

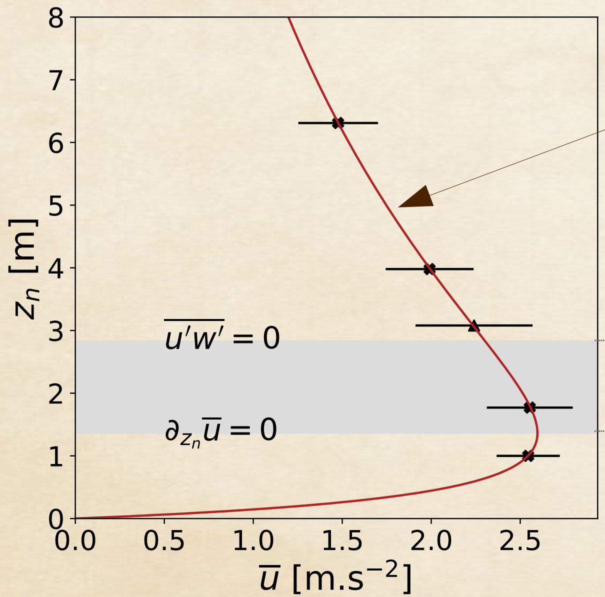
Slope angle $\alpha = 21°$ (streamline)

Anticyclonic conditions
Brünt-Väisälä frequency $N \sim 0.02$Hz

Reynolds decomposition with $\tau = 2$ min:

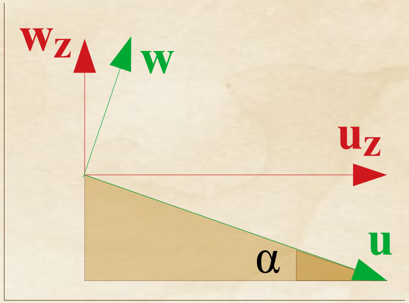
$$a(t) = \overline{a} + a'(t)$$

Pure katabatic event : 2012 November 19th (1915-1945 Local Time)



Prandtl model with varying eddy-diffusivity coefficients Km(z_n)[1,2]:

$$\bar{u}(z_n) = V_0(z_n).\sin\frac{z_n}{L_0(z_n)}.e^{\frac{-z_n}{L_0(z_n)}}$$



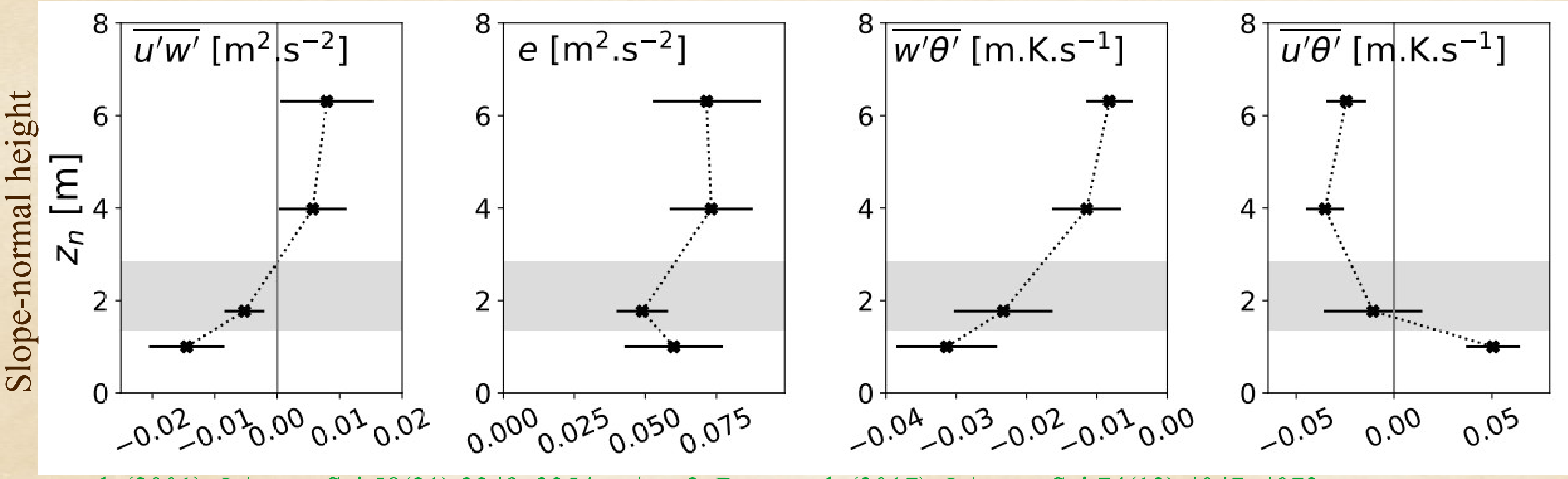
Outer layer : turbulent shear layer

$\overline{u'w'} > 0$

Region of the maximum of wind speed

Inner layer region : turbulent boundary layer

$\overline{u'w'} < 0$



1. Grisogono et al. (2001), J Atmos Sci 58(21):3349–3354 / 2. Brun et al. (2017), J Atmos Sci 74(12):4047–4073

Charrondiere et al. (2020), Boundary-Layer Meteorol (Under review)

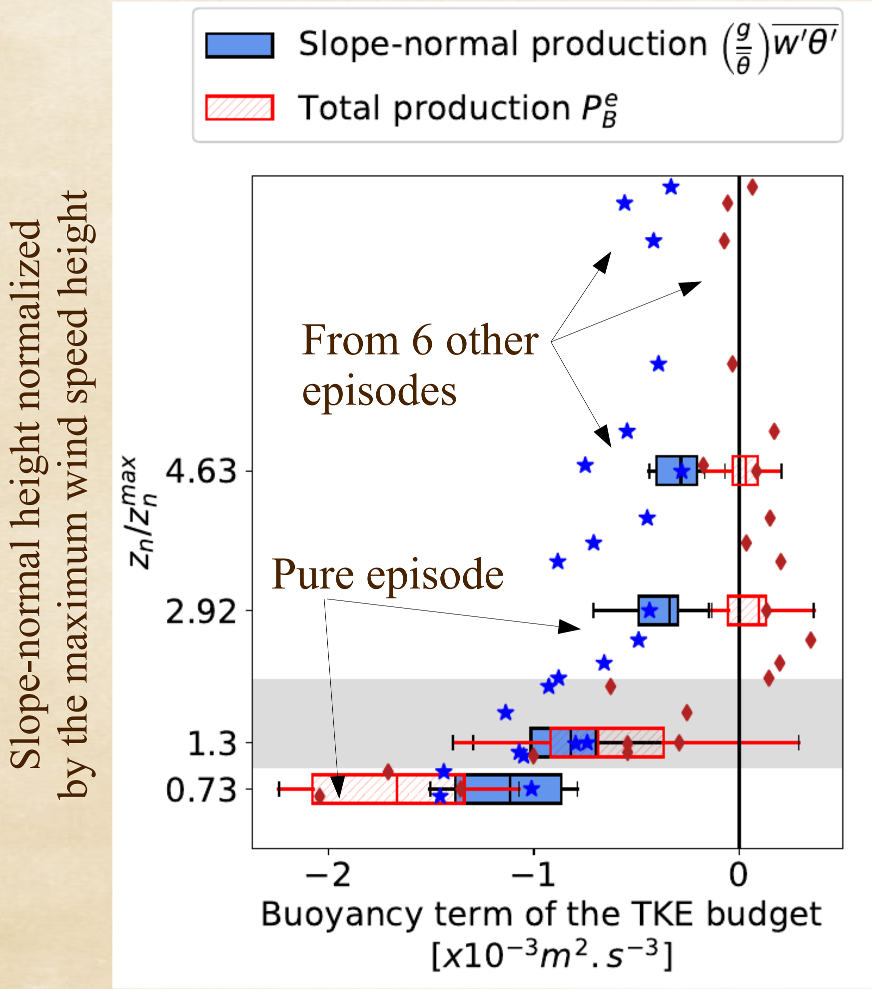
Buoyancy effect on turbulence kinetic energy

Turbulence kinetic energy (TKE)

$$e = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

Buoyancy term in the TKE budget

$$P_B^e = \frac{g}{\overline{\theta}} . \overline{w_z' \theta'} = \frac{g}{\overline{\theta}} . \left(\overline{w'\theta'} \cos\alpha - \overline{u'\theta'} \sin\alpha\right)$$



Production of TKE

Consumption of TKE

Consumption of TKE

Slope effect

Consumption of TKE

Production (limited consumption) of TKE

Weaker consumption

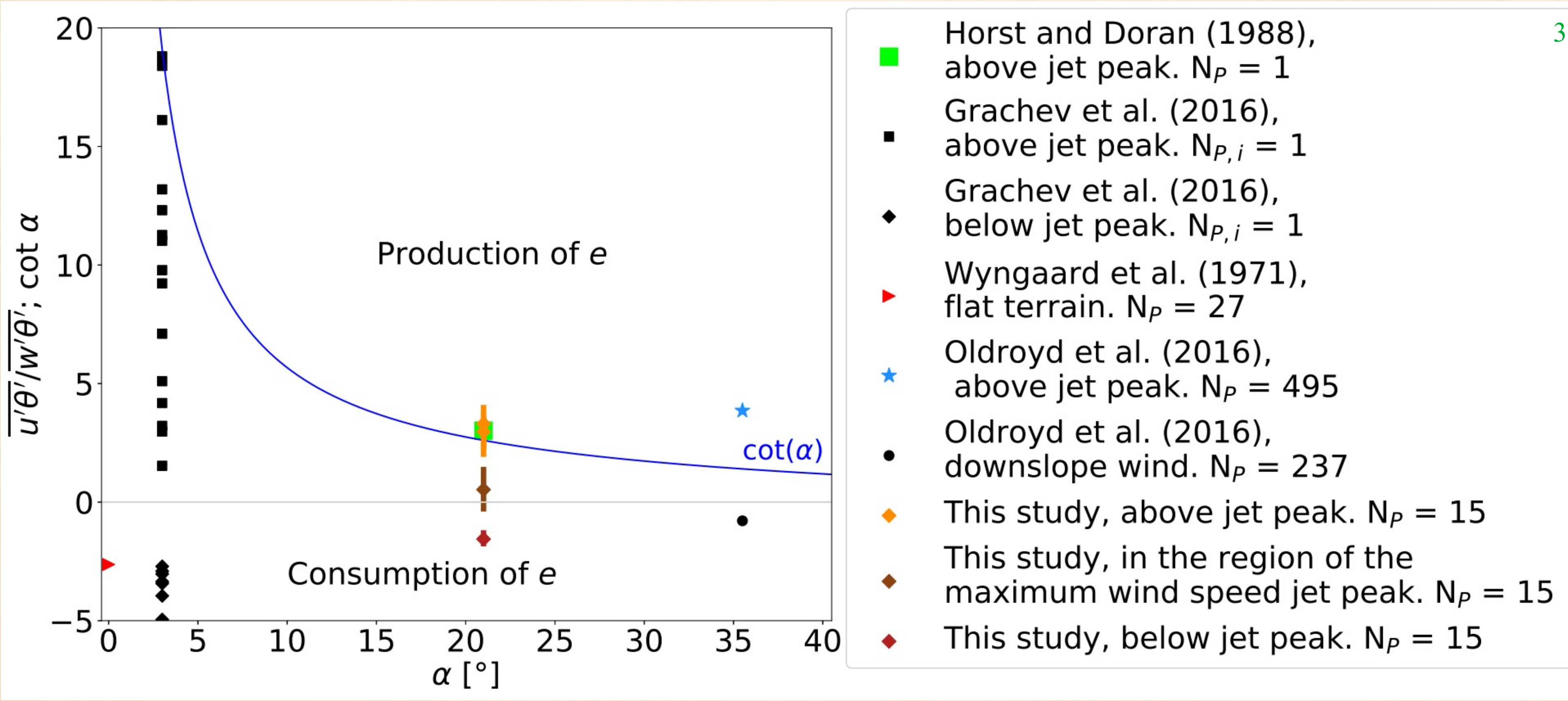
Enhanced consumption

Charrondiere et al. (2020), Boundary-Layer Meteorol (Under review)

Overview of the results from other field experiments

Limit between production and consumption of TKE by buoyancy

$$\frac{\overline{u'\theta'}}{\overline{w'\theta'}} = \cot(\alpha)$$



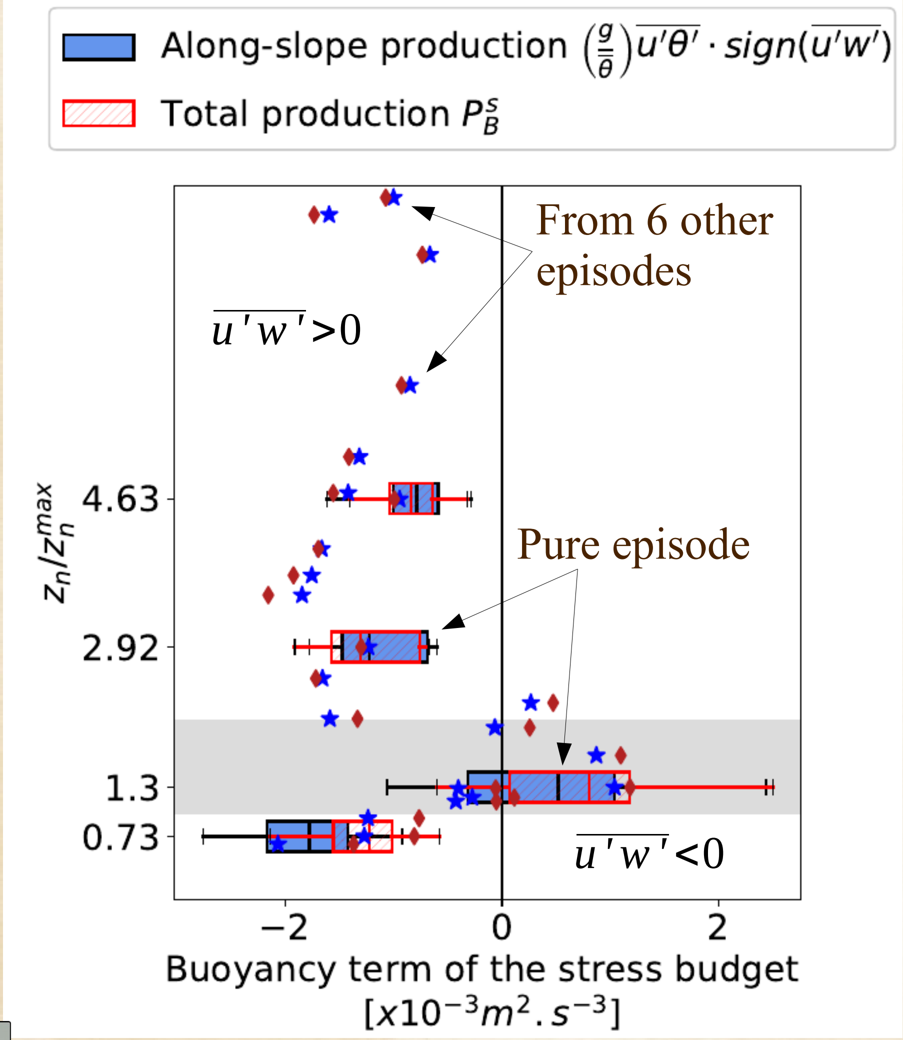
3. Oldroyd et al. (2016), Boundary-Layer Meteorol 161(3):405–416

Charrondiere et al. (2020), Boundary-Layer Meteorol (Under review)

Buoyancy effect on turbulent shear stress $|\overline{u'w'}|$

Buoyancy term in the turbulent shear stress budget

$$P_B^s.sign(\overline{u'w'}) = \frac{g}{\overline{\theta}}.\overline{u_z'\theta'} = \frac{g}{\overline{\theta}}.(\overline{u'\theta'}\cos\alpha + \overline{w'\theta'}\sin\alpha)$$



Slope-normal height normalized by the maximum wind speed height

Limited slope effect

Consumption of turbulent shear stress $|\overline{u'w'}|$

Production of turbulent shear stress $|\overline{u'w'}|$

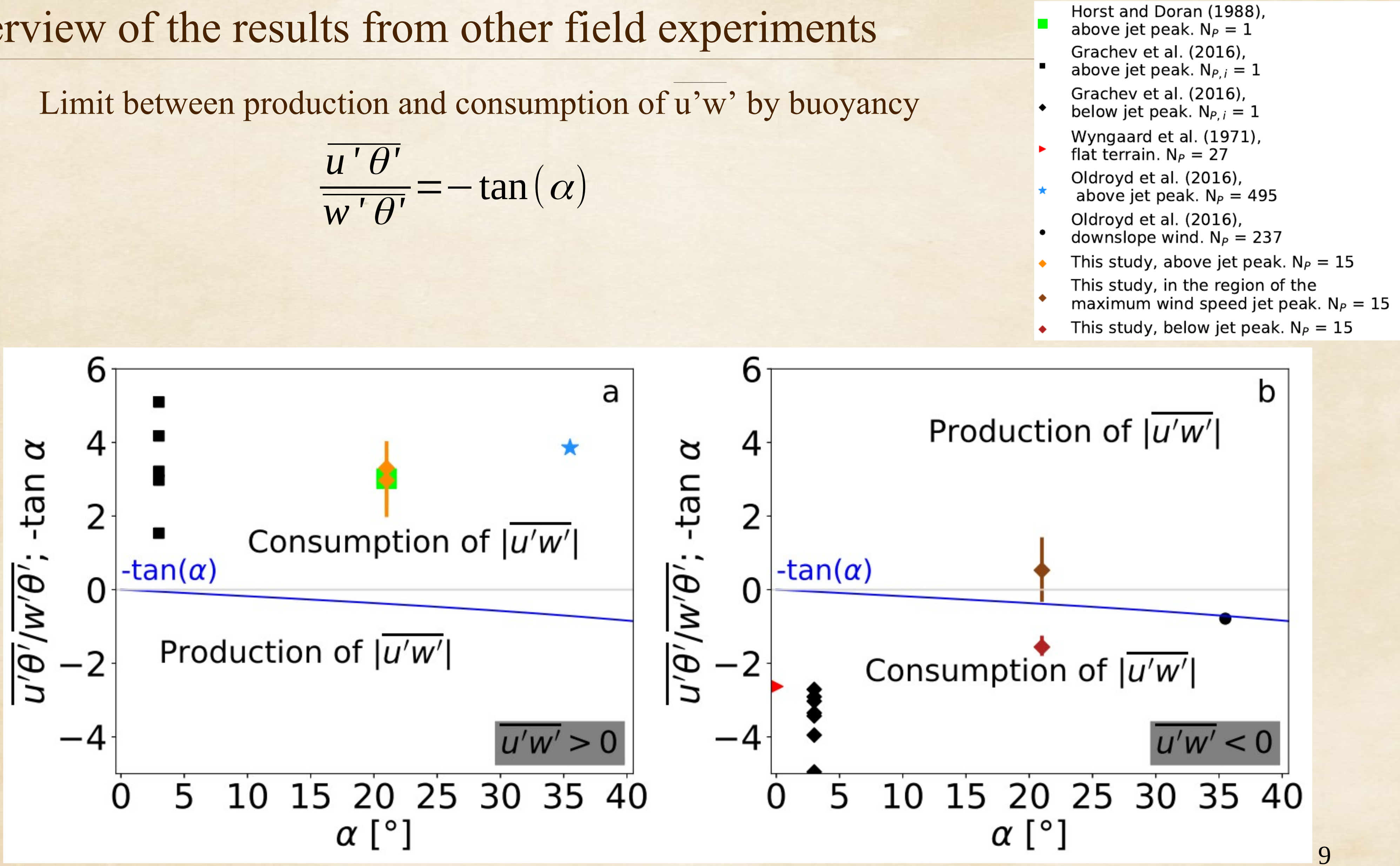
Consumption of turbulent shear stress $|\overline{u'w'}|$

Charrondiere et al. (2020), Boundary-Layer Meteorol (Under review)

Overview of the results from other field experiments

Limit between production and consumption of $\overline{u'w'}$ by buoyancy

$$\frac{\overline{u'\theta'}}{\overline{w'\theta'}} = -\tan(\alpha)$$



Charrondiere et al. (2020), Boundary-Layer Meteorol (Under review)

Weaknesses of the 2012 dataset → Design of a new field experiment

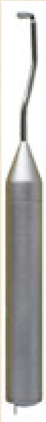
1. Ill-defined external conditions

2. Lack of information in the inner layer of the jet, close to the ground

3. Streamline divergence/convergence

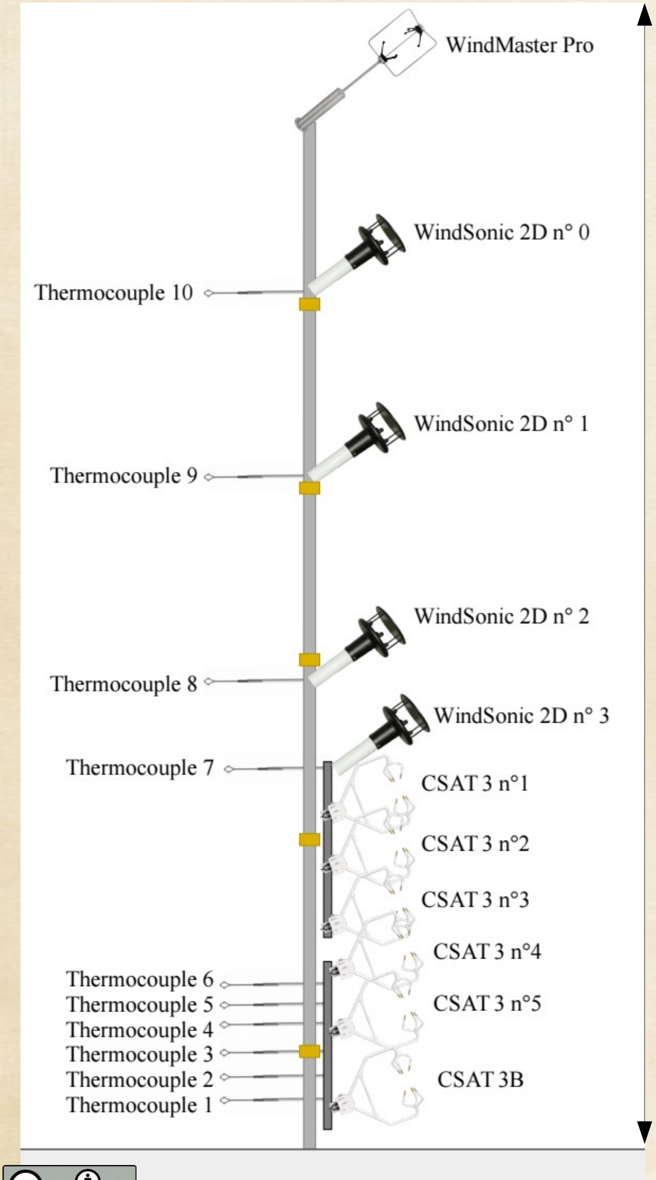
1. Thethered balloon up to 300m

2. Cobra pitot-type probe: 3D velocity components for measurements close to the ground



3. 6 sonic anemometers to measure entrainment/detrainment in the lower part of the jet

A new field campaign from winter 2019



2019 February 12-28th

- 11 wind speed levels
  * 7 3D sonic anemometers (20Hz)
  * 4 2D sonic anemometers (0.5Hz)

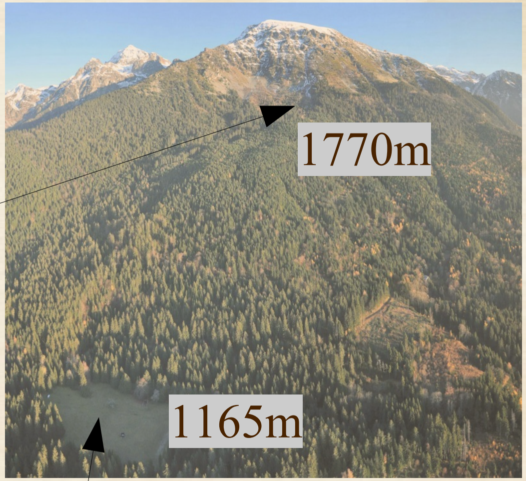
- 17 temperature levels (20Hz)
  * 10 thermocouples
  * 7 sonic anemometers

Meteorological mast:

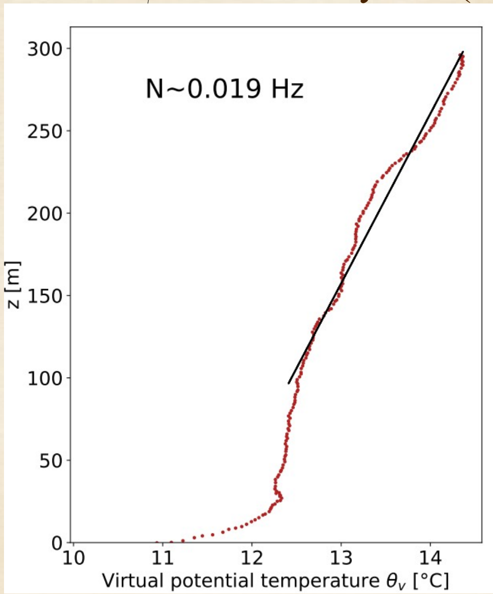
- Atmospheric pressure (CS100)
- Shortwave and longwave radiation fluxes (CNR1)
- Humidity and temperature (CS215)
- Distance sensor (SR50)

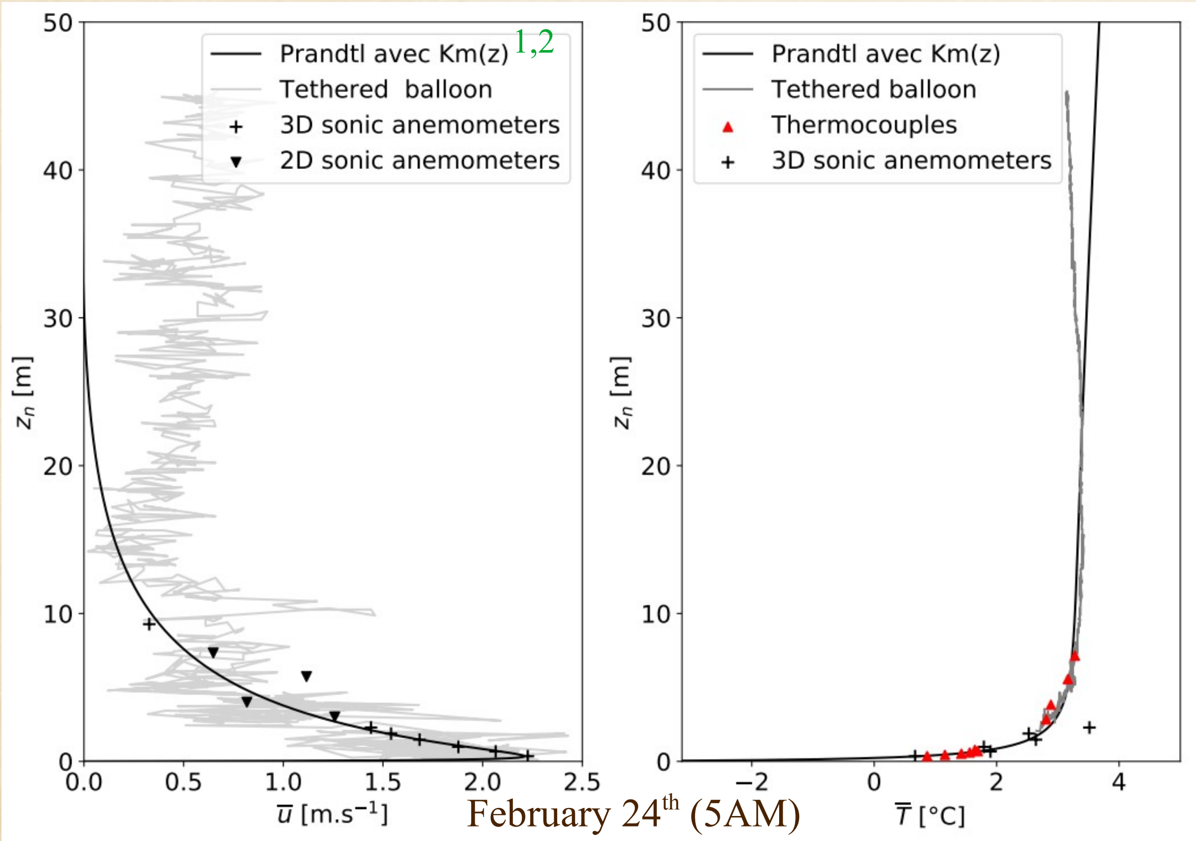
2019 dataset : improvements from the 2012 dataset

1. Tethered balloon:
   * Measurements above the mast: 10-50m
   * Background temperature stratification: up to 300m



February 15th (10AM)





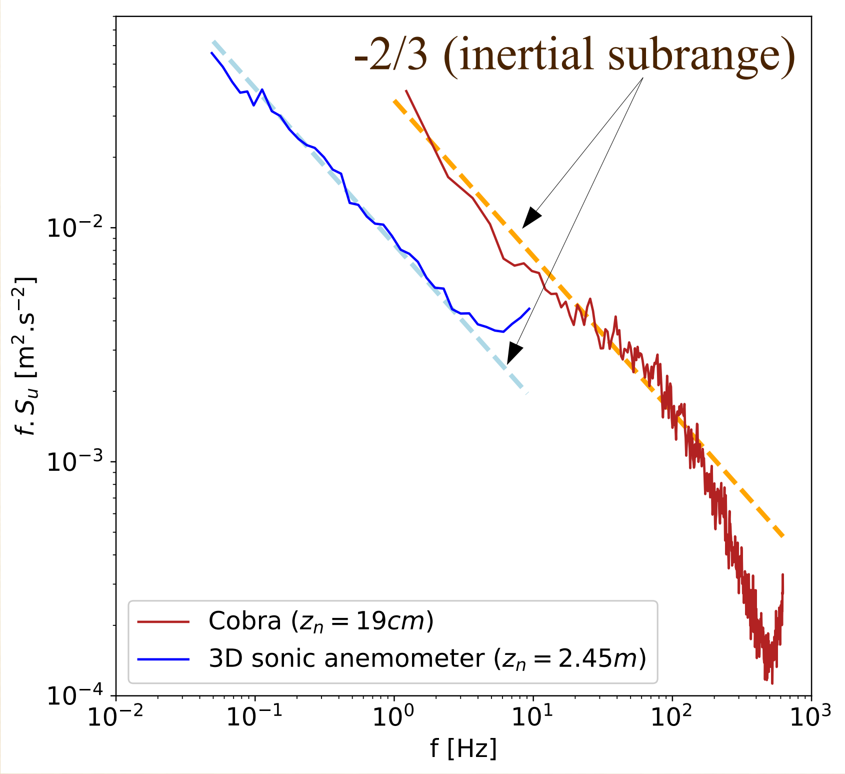
February 24th (5AM)

1. Grisogono et al. (2001), J Atmos Sci 58(21):3349–3354 / 2. Brun et al. (2017), J Atmos Sci 74(12):4047–4073

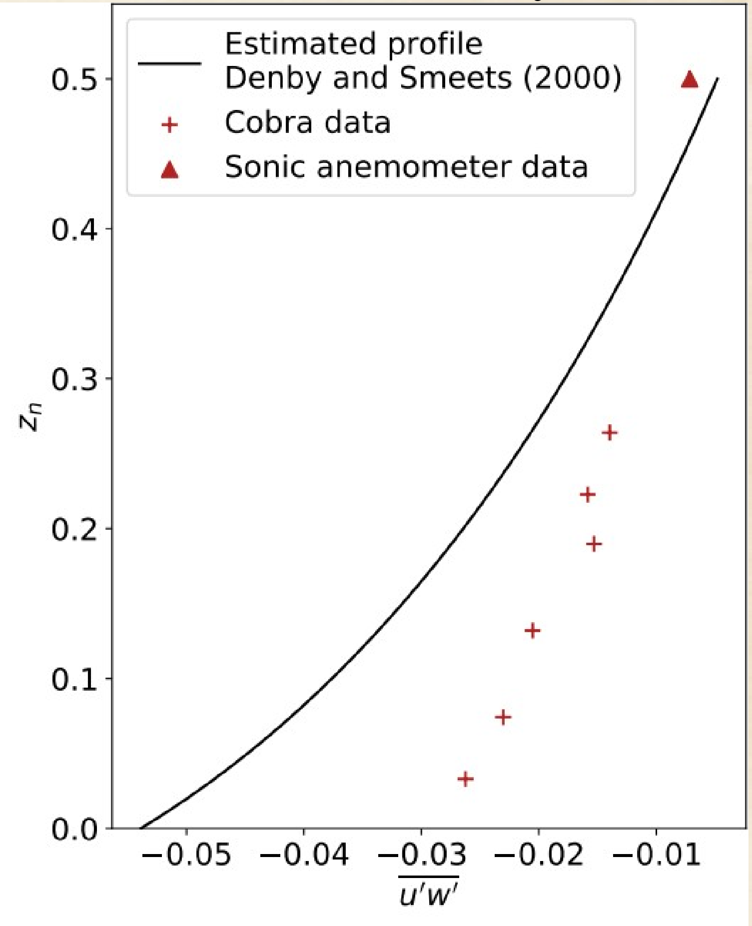
2019 dataset : improvements from the 2012 dataset

2. Cobra pitot-type probe : 3D velocity components
   * f = 1250 Hz
   * Level measurements : 4cm to 35cm

$$\overline{u'w'}(z_n)=\overline{u'w'}_0-\sin(\alpha)\frac{g}{\theta_0}\int_{z_0}^{z_n}\theta(z_n)\,dz_n$$ [4]



Streamwise velocity spectra with a well-developped inertial subrange

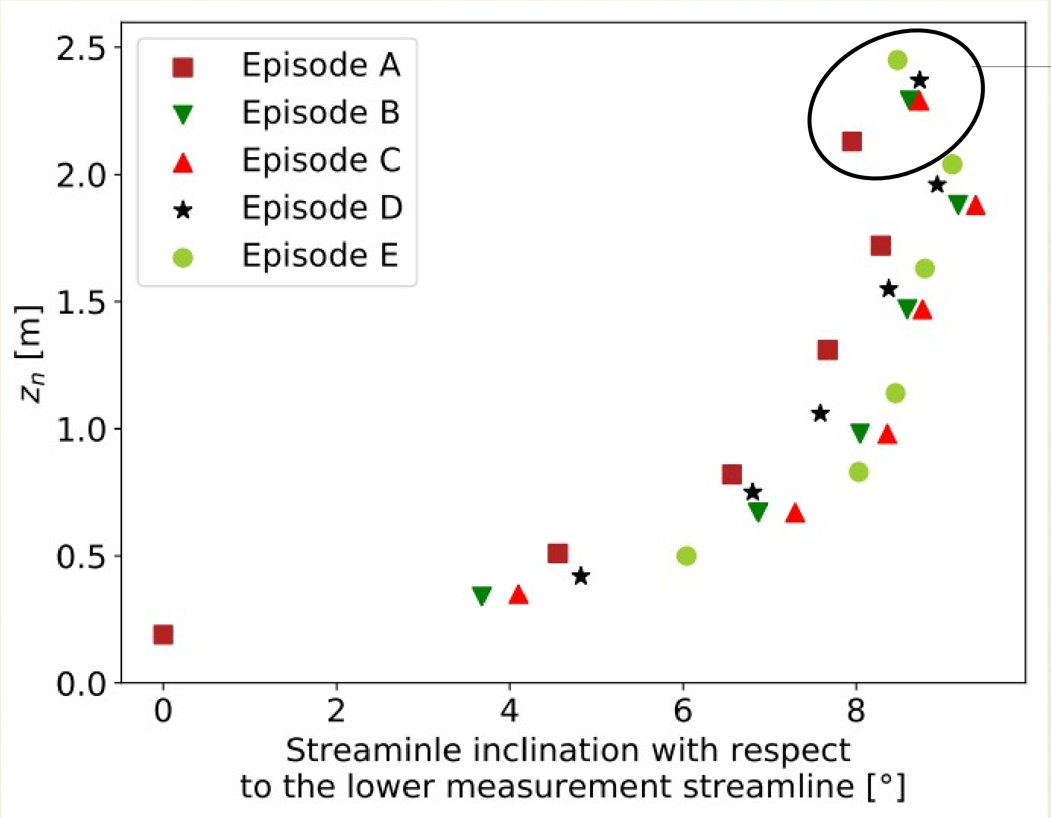


Turbulent shear stress variability along z_n close to the ground

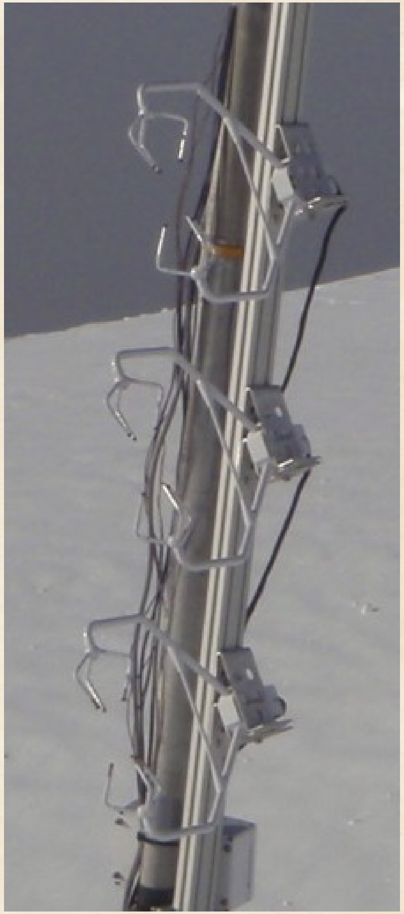
4. Denby and Smeets (2000), Journal of applied Meteorology 39(9):1601–1612

2019 dataset : improvements from the 2012 dataset

3. Slope-normal entrainment/detrainment
   * Streamline inclination up to 9° with respect to the lower measurement level
   * Slope-normal velocity W > 0 in the lower part of the outer shear layer



Variability of measurement height due to melting/packing of the snow



Take home messages

2012 field experiment: buoyancy effects over steep slopes

- TKE production in the outer layer of the jet
- TKE consumption enhanced in the inner layer
- Consumption of turbulent shear stress (except around the maximum wind speed height)

→ Design of flux Richardson for TKE and stress Richardson for $\overline{u'w'}$

Charrondiere et al. (2020), Boundary-Layer Meteorol (Under review)

Design of the 2019 field experiment to complete the 2012 dataset

2019 field experiment: to dig further with these data

- Variability of turbulent shear stress close to the ground
- Presence of slope-normal velocity in the jet: entrainment/detrainment
- Energy spectra distribution close to the ground
- Buoyancy effects to reinforce conclusion from 2012 November dataset
- Full budget of TKE and turbulent shear stress:
  * Buoyancy production/consumption
  * Mechanical shear production/consumption
  * Turbulent transport
  * Vertical advection
  * Dissipation

Cited references

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Oldroyd H, Pardyjak E, Higgins C, Parlange M (2016) *Buoyant turbulent kinetic energy production in steep-slope katabatic flow*. Boundary-Layer Meteorol 161(3):405–416

Whiteman CD (2000) *Mountain meteorology: fundamentals and applications*. Oxford University Press