Current experimental challenges in atmospheric boundary-layer research and their impact on parameterisations

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Outline

1. Relating ABL experimental work and model parameterizations.

2. Surface Energy Budget and terrain heterogeneity

3. Subgrid variability: land uses and topography

4. Similarity theory

5. Concluding remarks

ECMWF Annual Seminar, Sept 2022, Reading (England, UK)

1. Relating ABL experimental work and model parameterizations.

Related to the surface energy budget and its closure in heterogeneous terrain:
* Convenient surface boundary condition in models: closure of the surface energy budget.
* Experimentally closure is not happening: best hope 10%, usual 20%, complex 40%.
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* If non-resolved, they should be considered in the SEB, especially if a residual method is used.

Related to surface variability:
* Different land uses, topography (slopes, gentle topography, complex terrain) and presence of canopies.
* It induces changes in data at small (subgrid) scales: a challenge for initialisation and validation.

Related to the similarity theory:
* It is customarily applied at the first flux model level.
* It was derived (60’s-70’s) using profiles of some tens of meters on seemingly homogeneous areas.
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* Well-behaved stability functions are used for momentum and temperature, less clear for matter.

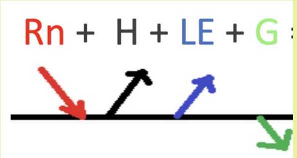
Surface Energy Budget:
observations vs models

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = -\frac{1}{\rho C_p}\frac{\partial Rn}{\partial z} - \frac{\partial \overline{w'T'}}{\partial z} - \frac{\partial G^*}{\partial z} + S^* + B^* + LE^* + Ot^*$$

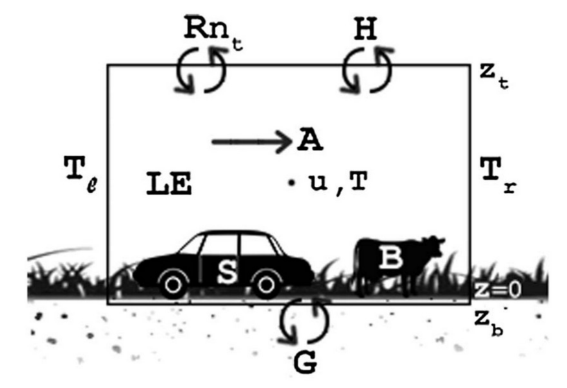
$$Rn + H + LE + G = -TT - A + S + B + Ot = Imb$$

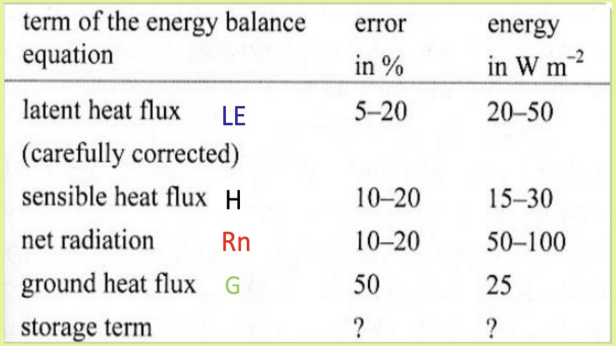
Model:
layer of infinitessimal depth
S=B=0,
Small timestep TT~0
No instrumental uncertainty Ot~0
No subgrid variability A=0

Rn+H+LE+G=0



Observations:





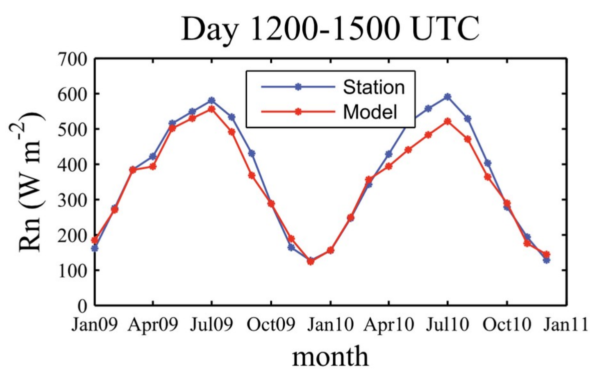
term of the energy balance equation		error in %	energy in W m^{-2}
latent heat flux (carefully corrected)	LE	5–20	20–50
sensible heat flux	H	10–20	15–30
net radiation	Rn	10–20	50–100
ground heat flux	G	50	25
storage term		?	?

LIAISE semi-arid site

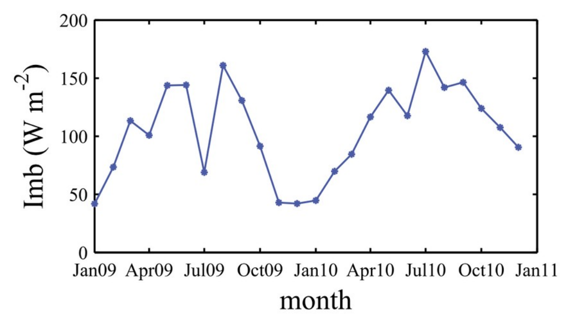
Observed SEB imbalance and model surface wrong representation:

2 years of data (2009 & 2010) in a drip-irrigated vineyard in the Eastern Ebro valley. Monthly averages of the 12-15 UTC values of surface fluxes are compared to the corresponding ECMWF values.

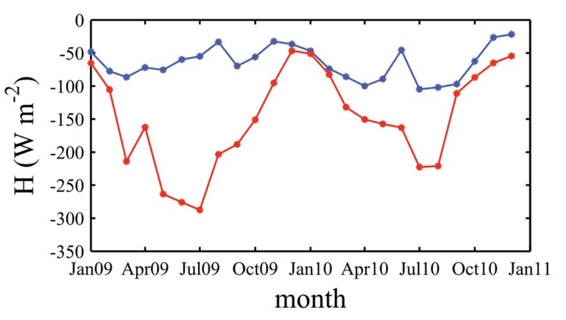
Net Radiation



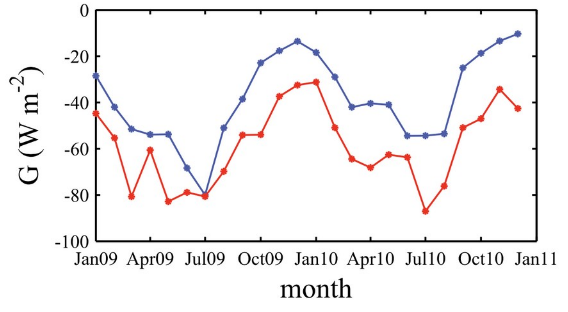
Imbalance



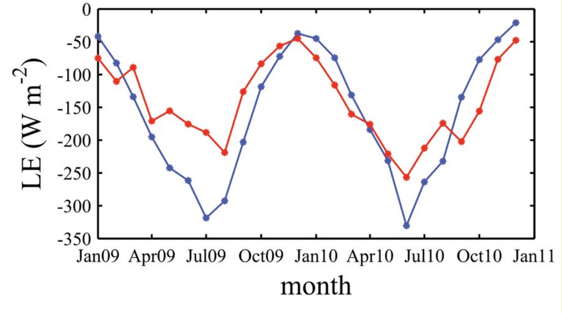
Sensible heat flux



Ground heat flux



Latent heat flux



Cuxart, Conangla & Jiménez, JGR, 2015

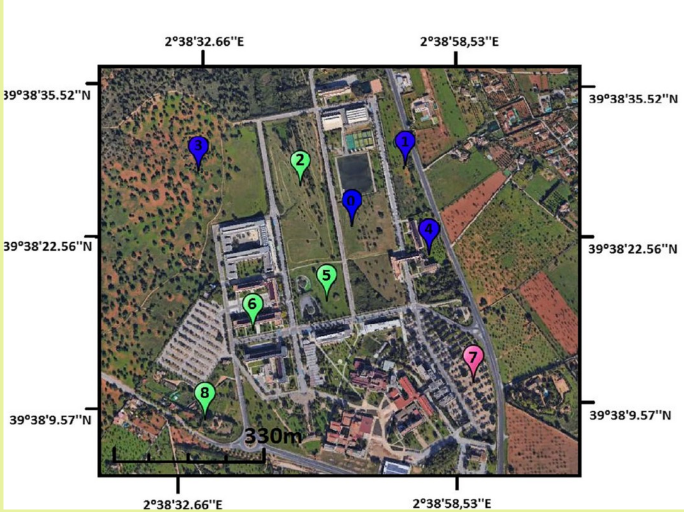
Hectometer-scale advection

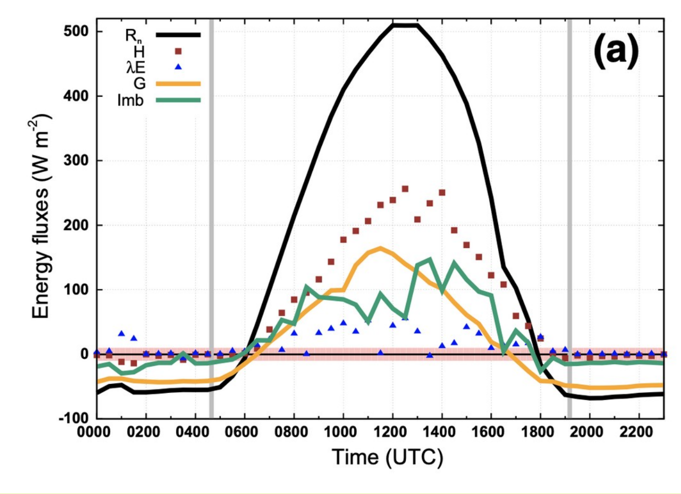
The UIB Campus is flat,
1 km-wide,with buildings
in between vegetated spaces.

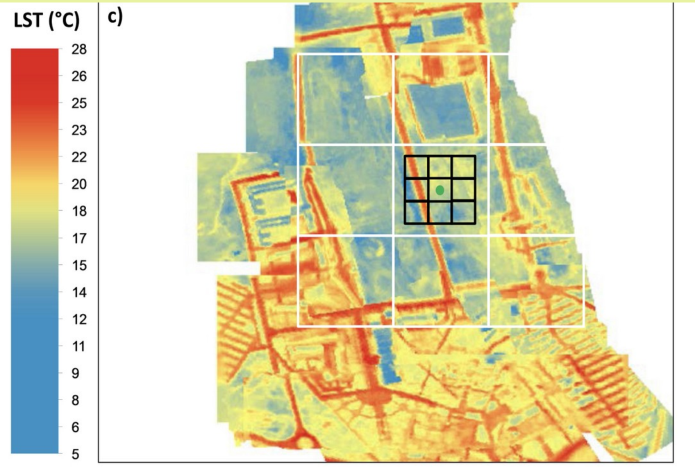
In 2016 a SEB station plus 9 gradient stations were deployed and a thermal camera was flown providing estimates of LST at the 10cm-scale.

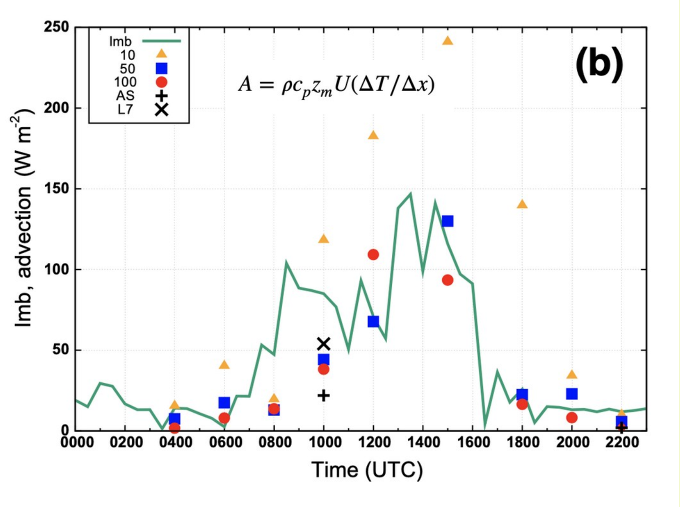
It was seen that the daytime imbalance correlated well with hectometer-scale estimates of thermal advection.

Garcia-Santos et al, IEEE, 2018
Simó et al, JGR, 2019
Mauder et al, BLM. 2020









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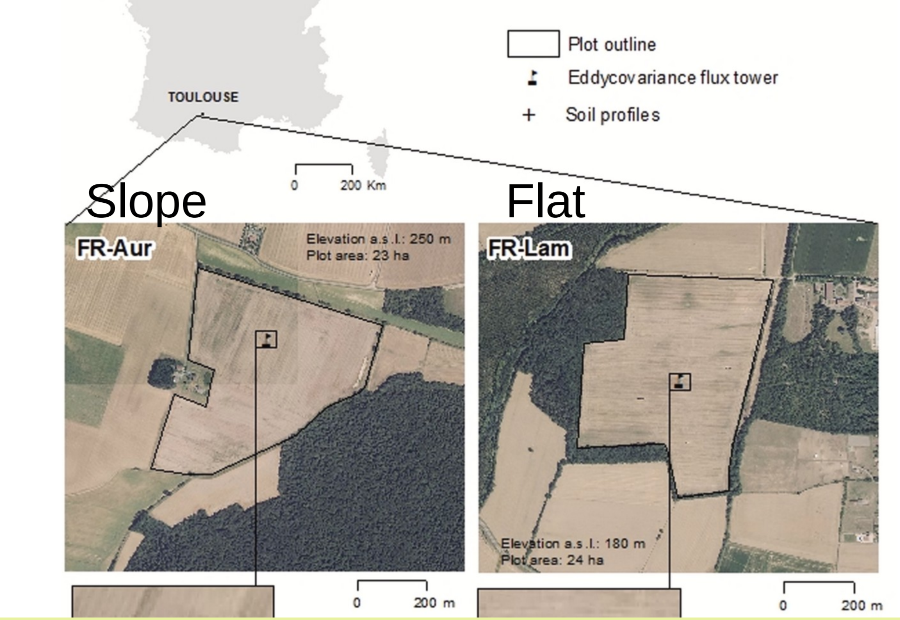
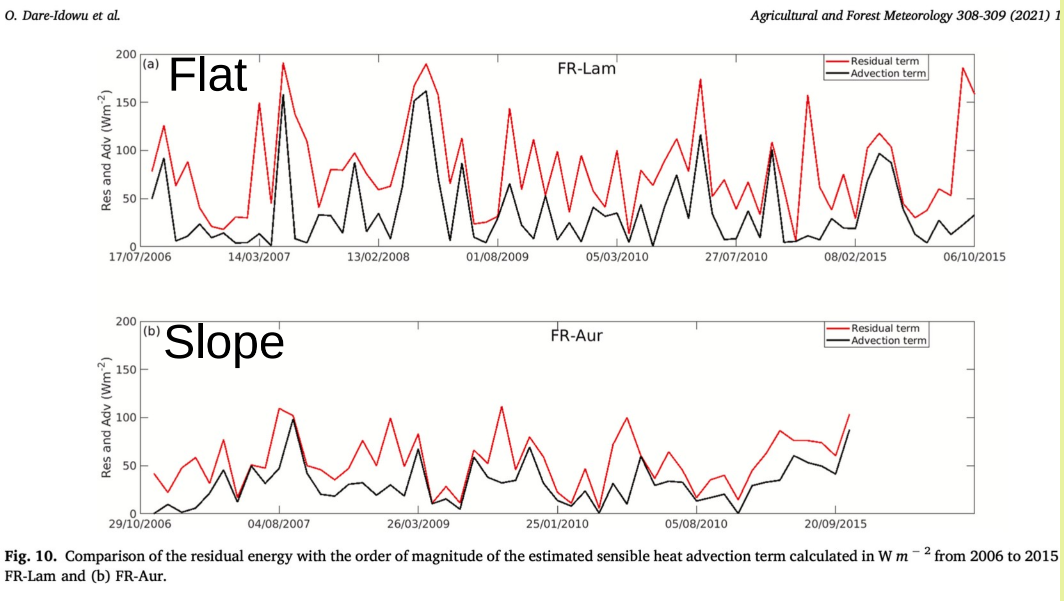


Imb~10-20%

Imb~30-40%

$$A = \rho c_p z_m U(\Delta T/\Delta x)$$


O. Dare-Idowu et al.

Agricultural and Forest Meteorology 308-309 (2021) 1

Fig. 10. Comparison of the residual energy with the order of magnitude of the estimated sensible heat advection term calculated in W m^{-2} from 2006 to 2015 FR-Lam and (b) FR-Aur.

Series of A estimated with 138 landsat images between 2005 and 2015 compared to the corresponding values of SEB imbalance.

Dare-Idowu et al, Agric. For. Meteorol., 2021

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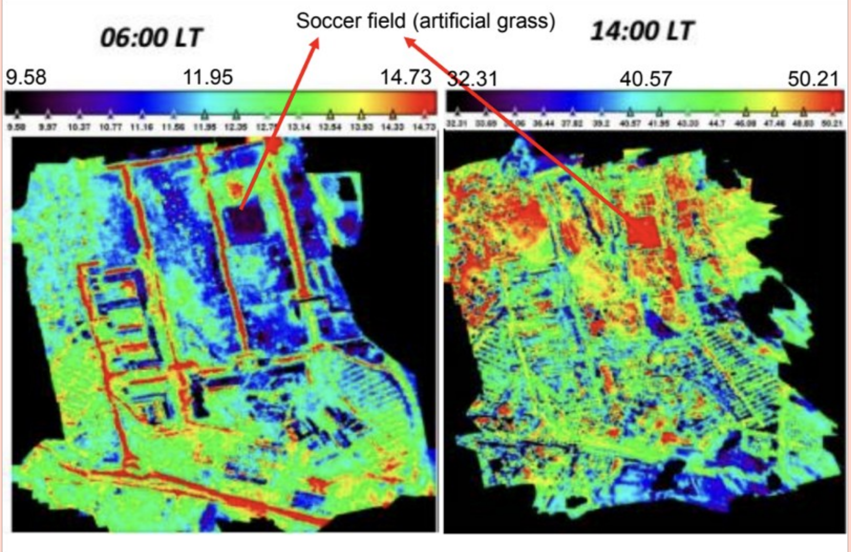
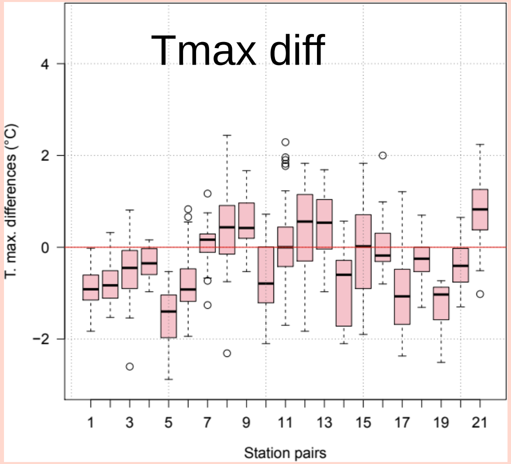
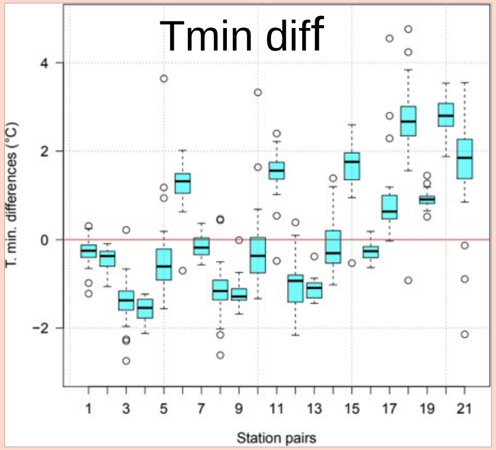
Variability in flat terrain

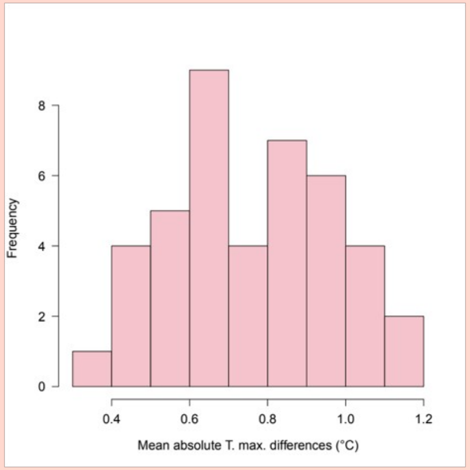
Stations differ in
**Microtopography (Δh~2m)*
**soil type and cover*
**distance to obstacles*

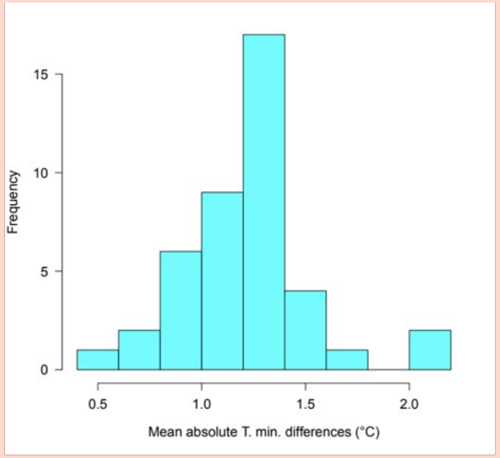


For station pairs









Simo et al, JGR, 2018; Guijarro et al, IJOC, 2023 (in prep)

Variability in hilly terrain

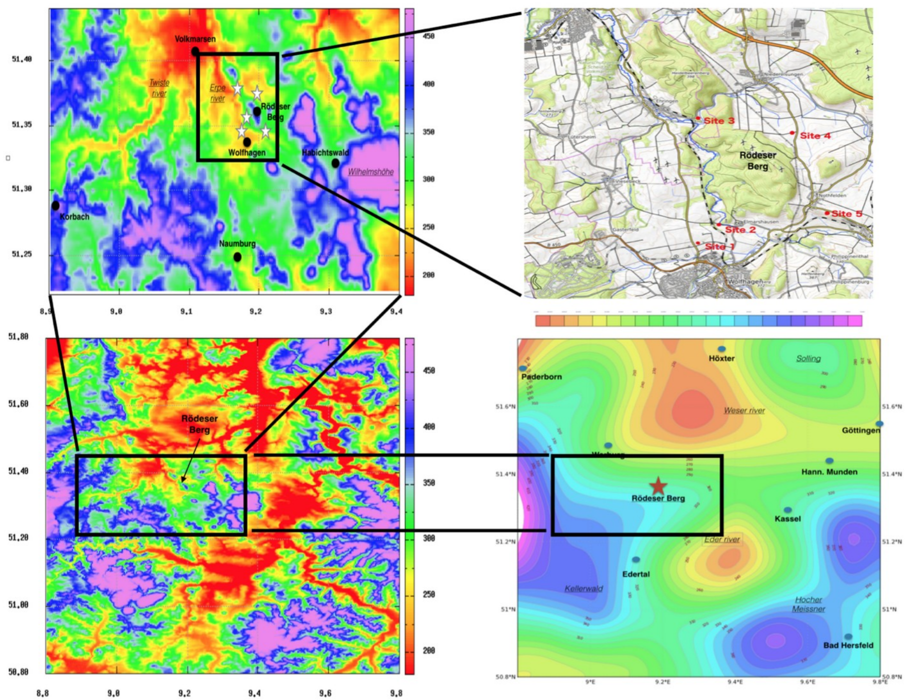
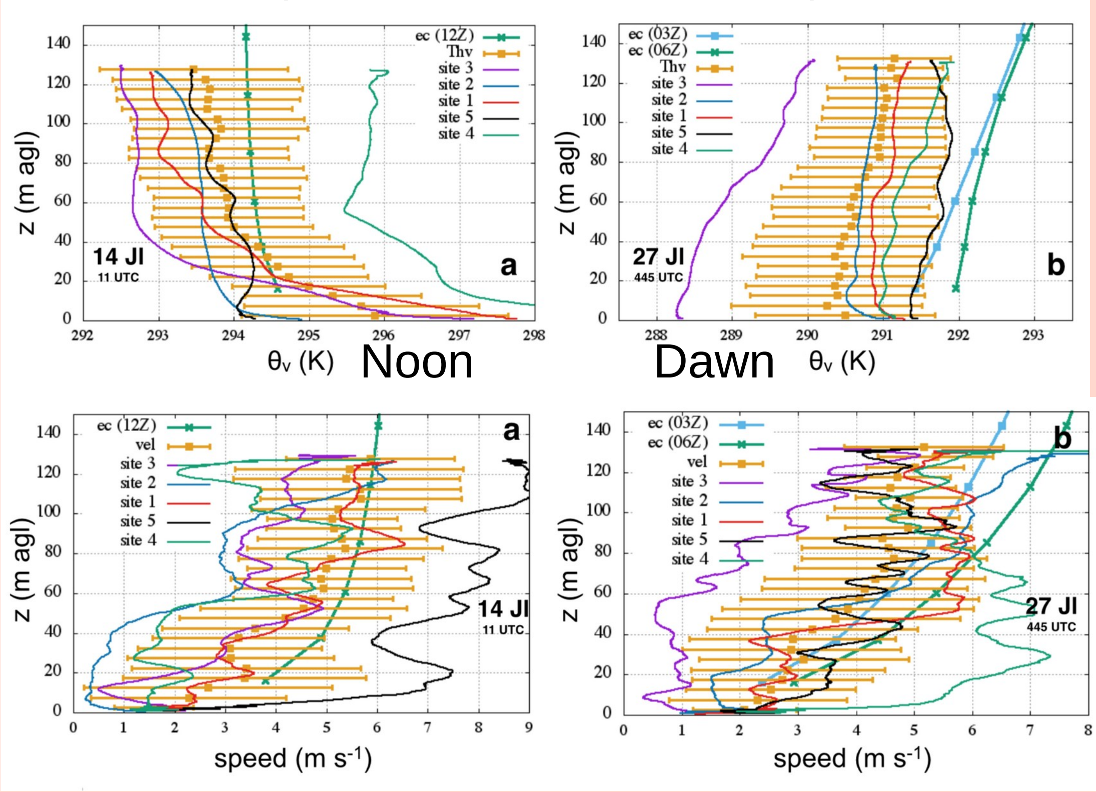
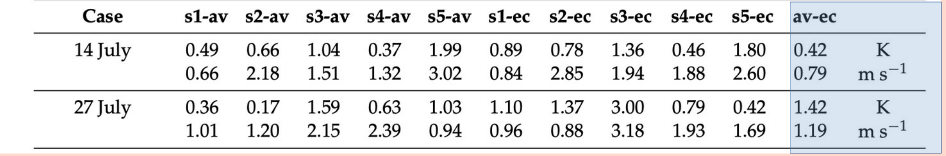


Figure 1. (**Top left**): topography of the area surrounding Rödeser Berg at a resolution of 90 m (approx. 35 km E–W × 25 km N–S); (**top right**): detailed topography and terrain uses at Rödeser Berg (6 km × 6 km), green represents woods; (**bottom left**): topography at a resolution of 90 m in a larger area (approx. 60 km E–W × 80 km N–S); (**bottom right**): the same but at a resolution of 9 km as seen by the European Centre for Medium-Range Weather Forecasts (ECMWF) model.

Vertical profiles made with a multicopter UAS





Case	s1-av	s2-av	s3-av	s4-av	s5-av	s1-ec	s2-ec	s3-ec	s4-ec	s5-ec	av-ec	
14 July	0.49	0.66	1.04	0.37	1.99	0.89	0.78	1.36	0.46	1.80	0.42	K
	0.66	2.18	1.51	1.32	3.02	0.84	2.85	1.94	1.88	2.60	0.79	$m\,s^{-1}$
27 July	0.36	0.17	1.59	0.63	1.03	1.10	1.37	3.00	0.79	0.42	1.42	K
	1.01	1.20	2.15	2.39	0.94	0.96	0.88	3.18	1.93	1.69	1.19	$m\,s^{-1}$

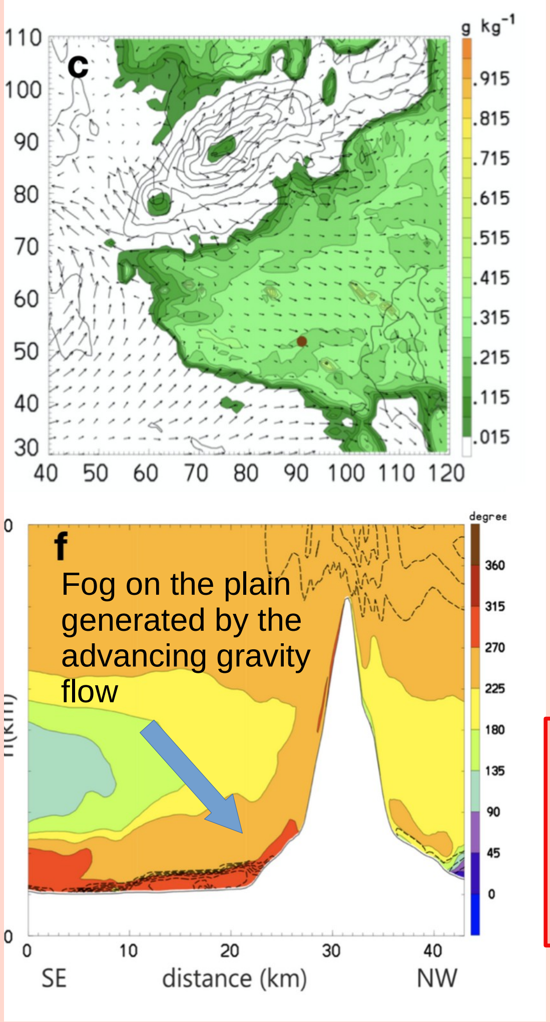
Noon

Dawn

Stations differ in
i) topography (Δh~100m), ii) fields vs forests
iii) position in respect to hill

Cuxart, Wrenger, Matjacic & Mahrt, Atmosphere, 2019

Slope flows



Fog on the plain generated by the advancing gravity flow

Medvenica mountain over the Sava plain by Zagreb.

900m drop in 10 km.

Interaction with valley flows and thermal inversion

slope flow

speed increases

more turbulence

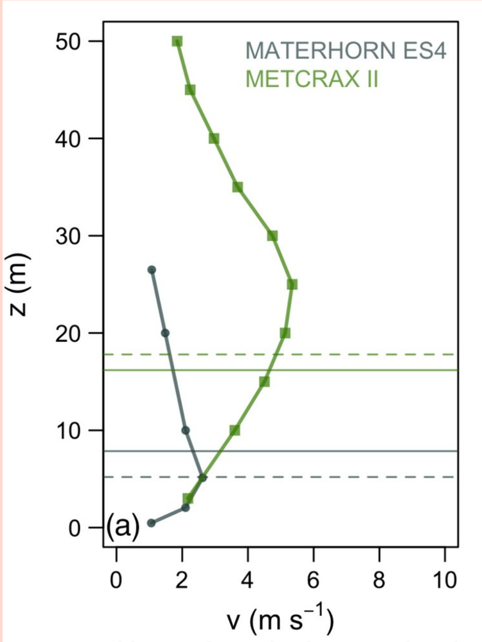
Cuxart, Telisman-P & Matjacic, Atmosphere, 2021

Simple relation between angle, speed and heat flux (assuming depth of the slope flow is the depth of turbulence)

$$\frac{d\theta}{dt} = \frac{\partial\theta}{\partial t} + v\frac{\partial\theta}{\partial x'} + w\frac{\partial\theta}{\partial z'} = -\frac{1}{\rho_0 C_p}\frac{\partial Q^*}{\partial z'} - \frac{\partial H}{\partial z'}$$

$$D_{\max} = \frac{-H}{v\sin(\alpha)\frac{d\theta}{dz}}$$

Compression warming~surface cooling → not appropiate for steep slopes



Horizontal lines indicate the diagnostic length scale D_{max} (solid) and SBL height h_{Ri_g} (dashed)

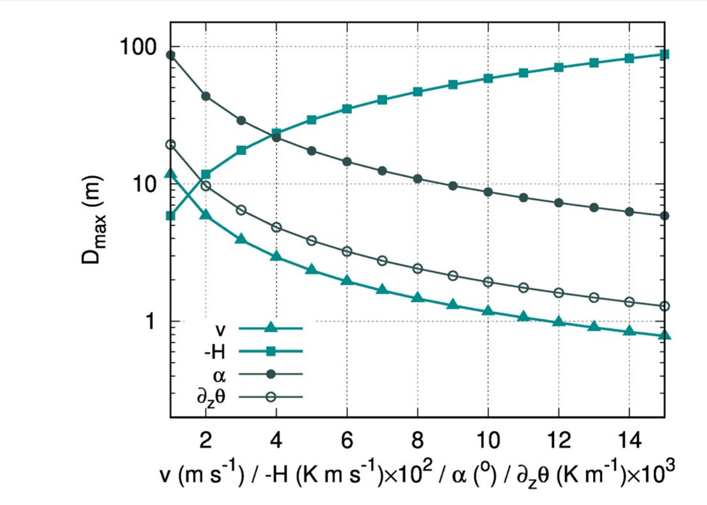
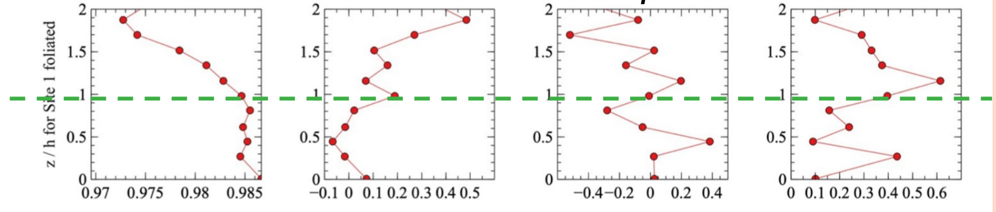


FIGURE 1 Variation of the depth of the downslope flow ($D_{\max}$) allowing only one variable to change. The values for the variables when fixed are $v = 2\ \mathrm{m{\cdot}s^{-1}}$, $H = -0.01\ \mathrm{K{\cdot}m{\cdot}s^{-1}}$, $\partial_z\theta = 0.0033\ \mathrm{K{\cdot}m^{-1}}$ and $\alpha = 15^{\circ}$

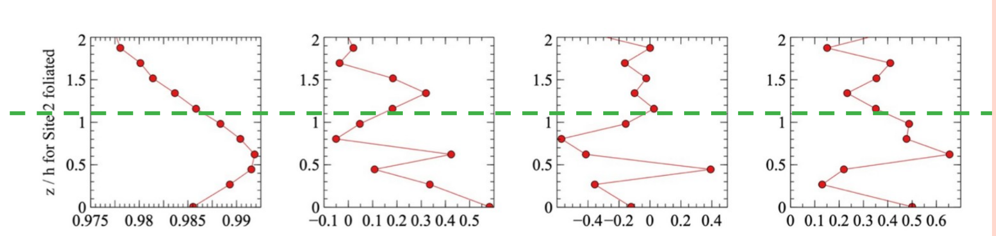
Cuxart, Martínez-Villagrasa & Stiperski, ARL 2020

Forest canopy

Forest on a slope



Pot. T Speed Momentum flux Heat flux



Clearing downhill

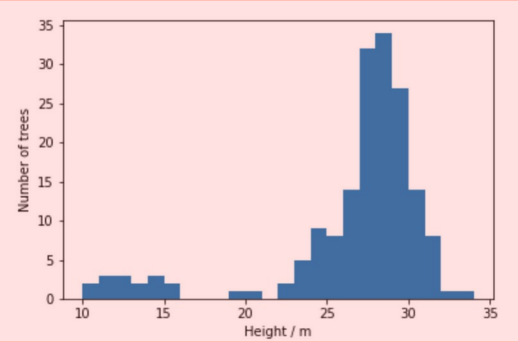
Evening transition: average of 3 ascending flights for 3 different days

600m

Slope flow in the lowest 10 m
Elevated porous floor at 30 m
Inverted stability in the canopy

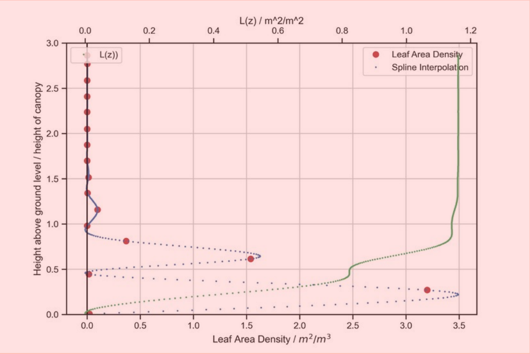
Where would the vertical levels of a model be?
Prescription of L(z) would be needed.

Model of forest by inspection



L(z) profile from UAS data

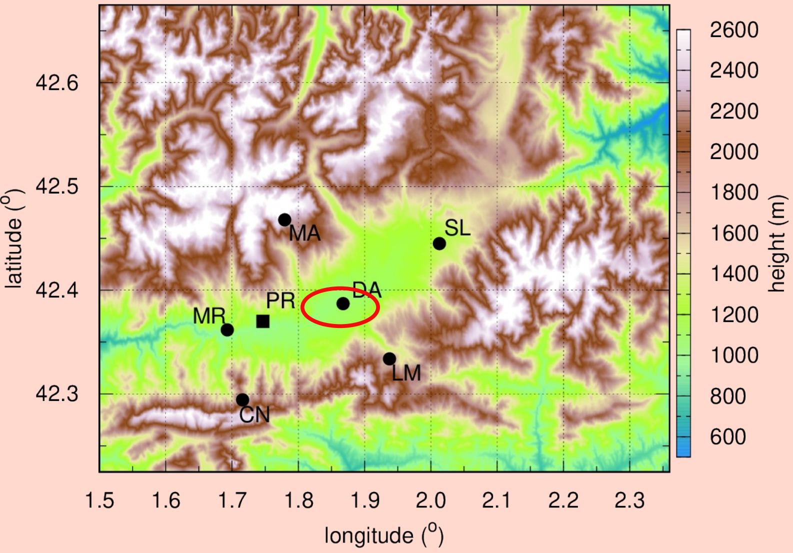
$$\frac{-d\overline{u'w'}(z)}{dz} + a(z)\overline{u'w'}(z) = 0$$

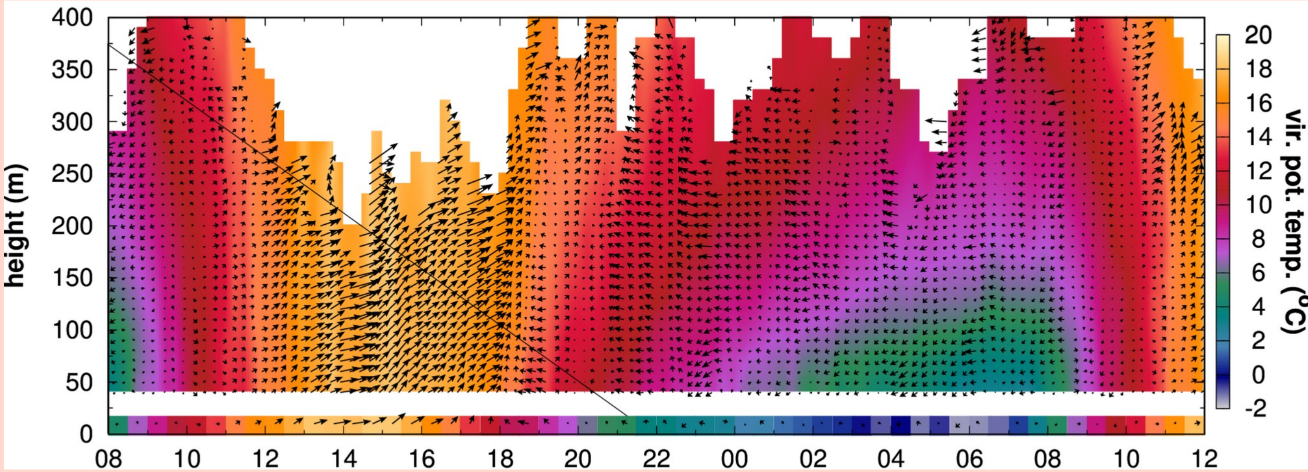


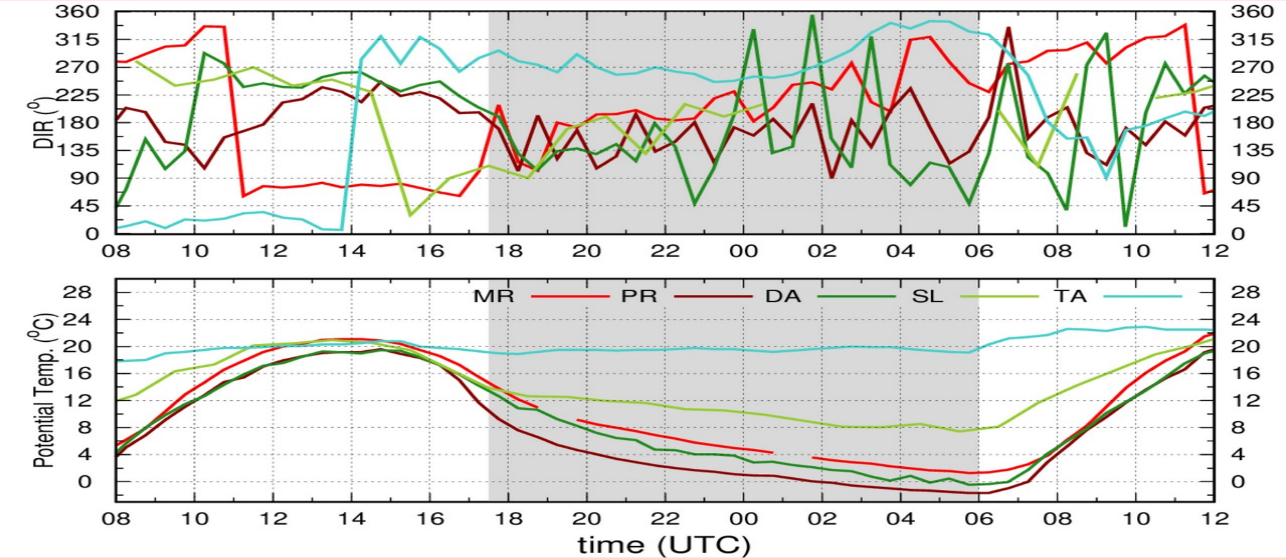
Wrenger & Cuxart, 2023 (in prep)

Rough topography

Cerdanya valley (Pyrenees)







General features (valley flows, thermal inversion) well seen by profiler above the surface layer, not in it.

Stations at the valley bottom may differ up to 8 K in Tmin depending on their position respect to the surrounding topography.

Conangla et al, IJOC, 2018; Martínez-Villagrasa et al, 2023 (in prep)

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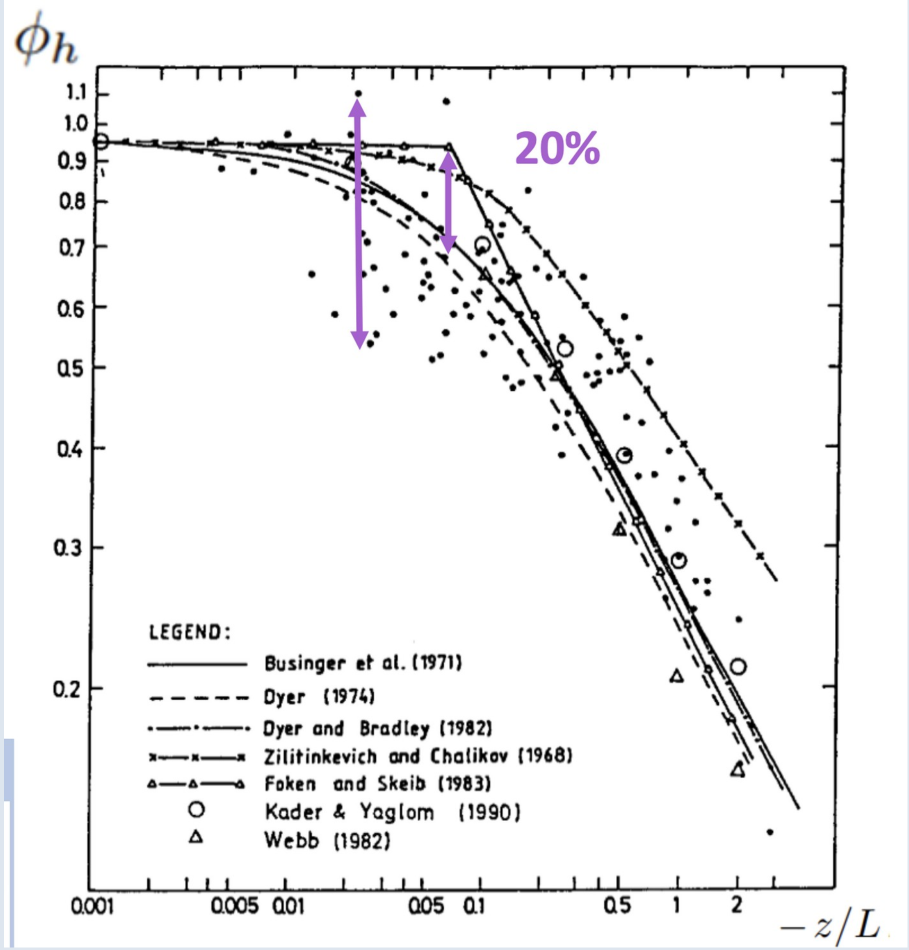
MOST: uncertainties of the method



$$\sqrt{\frac{\tau}{\rho}} = u_* = \frac{\kappa z}{\phi_m}\frac{\partial \bar{u}}{\partial z},$$

$$\frac{H}{\rho c_p} = (\overline{w'\theta_v'})_0 = -\frac{\kappa u_* z}{\phi_h}\frac{\partial \bar{\theta}_v}{\partial z},$$

$$\frac{LE}{\rho L_v} = (\overline{w'q'})_0 = -\frac{\kappa u_* z}{\phi_q}\frac{\partial \bar{q}}{\partial z},$$

Φx=f(u, H) through z/L*
(iterative process)

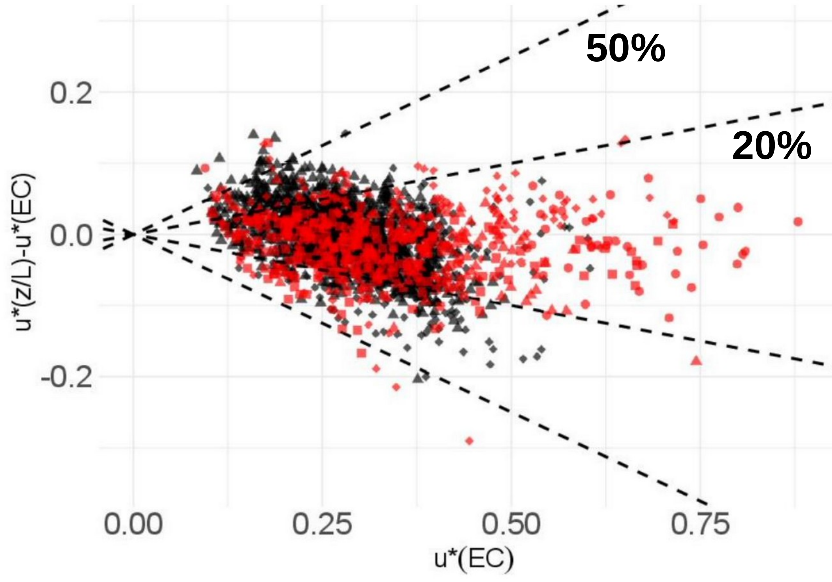
Φx=f(Ri), non iterative, tunable

Lower Boundary Condition:
**roughness length*
Or
**2 levels close to the surface*

**Z0 imposed based on the characteristics of the surface elements*
**Z0T, Z0q difficult to define (tunable)*

T,q (and perhaps wind) at ~0.4 m
How to do this is in numerical models?

MOST: momentum flux very close to the surface in complex terrain

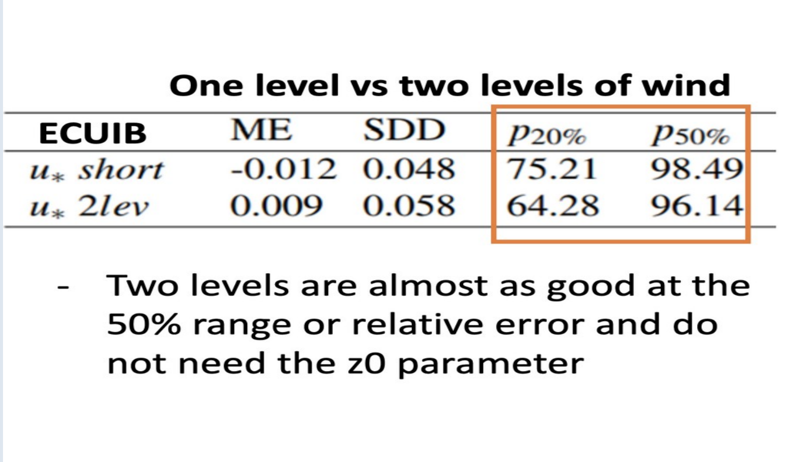


u estimated with wind at 2m and a given value of z0.*

$$u_* = \frac{\kappa z}{\phi_m} \frac{\partial \bar{u}}{\partial z}$$

Most values have errors within the inherent uncertainty of the method.

Tested for three flat locations surrounded by significant topography.



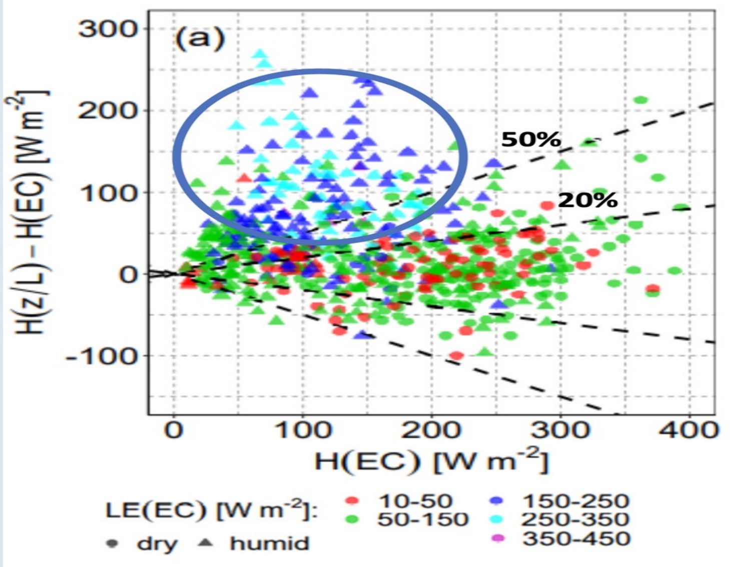
One level vs two levels of wind

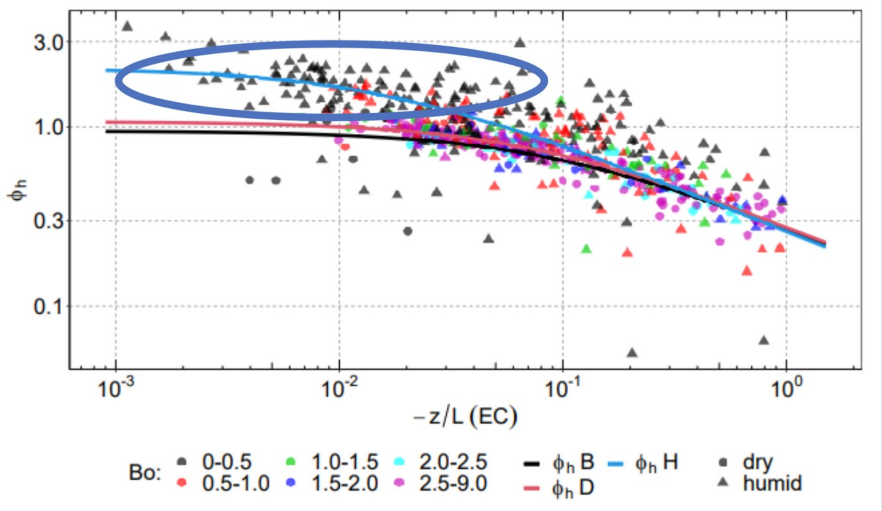
ECUIB	ME	SDD	$p_{20\%}$	$p_{50\%}$
u_* *short*	-0.012	0.048	75.21	98.49
u_* *2lev*	0.009	0.058	64.28	96.14

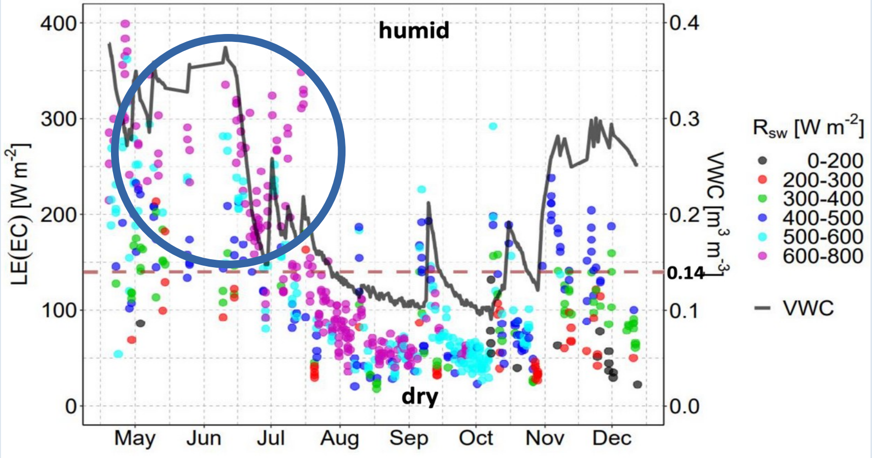
- Two levels are almost as good at the 50% range or relative error and do not need the z0 parameter

MOST: Sensible heat flux using two levels of T

Data in a pre-Pyrenean valley (ALEX campaign)







H is estimated with temperature values at 2 m and 0.4 m.

As for u, most values have errors within the inherent uncertainty of the method (20%).*

The exception is found when high values of ET and high solar radiation take place. This configuration requires a modified stability function.

This result has been found also in the ECUIB at Mallorca.

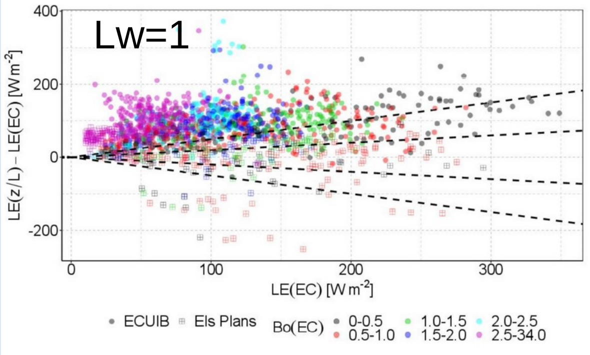
Martí, Martínez-Villagrasa and Cuxart, BLM 2022

MOST: Latent heat flux using two levels of q

$$\phi_h \overset{?}{=} \phi_q \Rightarrow K_h = K_q$$

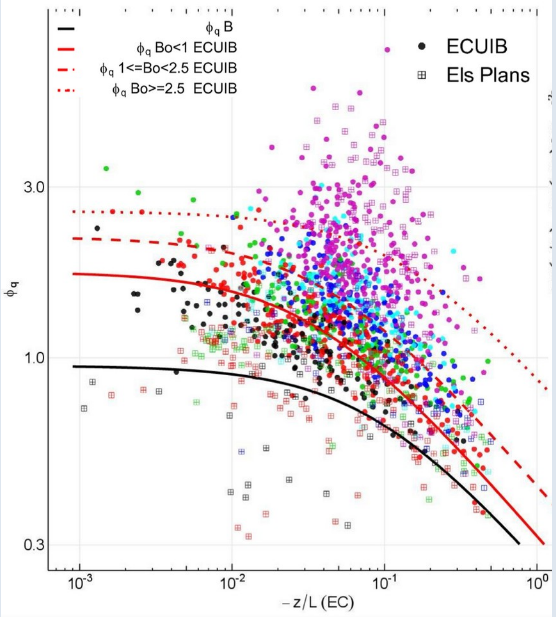
Bowen ratio $Bo = \frac{H}{LE}$

$$Lw = \frac{K_h}{K_q} = \frac{\phi_q}{\phi_h}$$

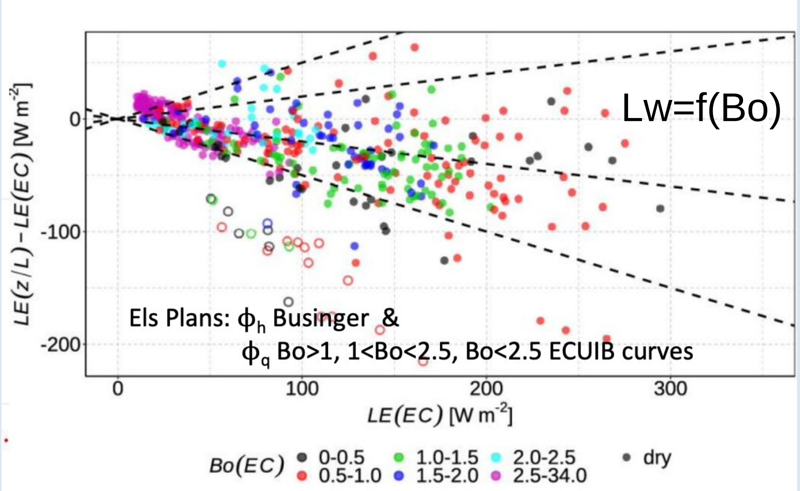


The hypotesis K_h=K_q is not fulfilled in our data bases in a general manner.

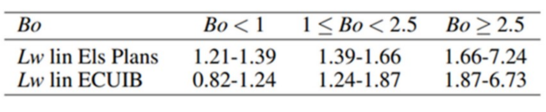
Test Φ_q depending on Bo



Testing Φ_q (Bo) over an independent database



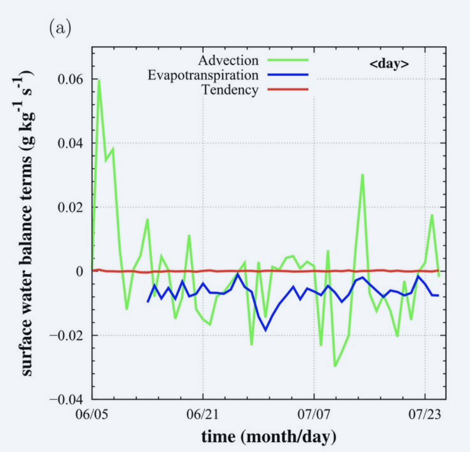
Els Plans: ϕ_h Businger &
ϕ_q Bo>1, 1<Bo<2.5, Bo<2.5 ECUIB curves



Bo	$Bo < 1$	$1 \leq Bo < 2.5$	$Bo \geq 2.5$
Lw lin Els Plans	1.21-1.39	1.39-1.66	1.66-7.24
Lw lin ECUIB	0.82-1.24	1.24-1.87	1.87-6.73

Arid conditions: adv(q)~E

$$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - w\frac{\partial q}{\partial z} + E + \text{Other}$$



Simó et al, JGR, 2019;
Martí et al, 2023 (in prep)

Concluding remarks

On the SEB:

- direct comparison of experimental and models values must be made with care
- subgrid surface variability induces motions involving significant energy exchanges

On surface variability:

- at the hectometer scale, different land uses may induce T changes of the order of 1 K
- on hilly terrain, at the km scale, differences can be large for wind and T
- slope flows provide more organized structures and lesser effect of the small-scale features
- tall canopies need the prescription of L(z), perhaps a physiographic field.
- the position relative to nearby important topographical features results in very large differences.

On similarity theory (daytime, using two observed levels of T and q):

- expressions for u* and H work well with data taken at 2m.
- in the case of large LE and insolation, H seems to need a different stability function.
- $K_h \neq K_q$, the mixing efficiency of water diminishes as the surface becomes drier.
- over dry soils, local advection may be playing an important role.