Freie Universität Berlin

Data-driven investigations of flow structures in the stable atmospheric boundary layer

Nikki Vercauteren
Collaborators: Rupert Klein, Larry Mahrt, Amandine Kaiser, Danijel Belušić.

DFG

Scale separation in models

Can we isolate turbulent scales and larger scales in models?

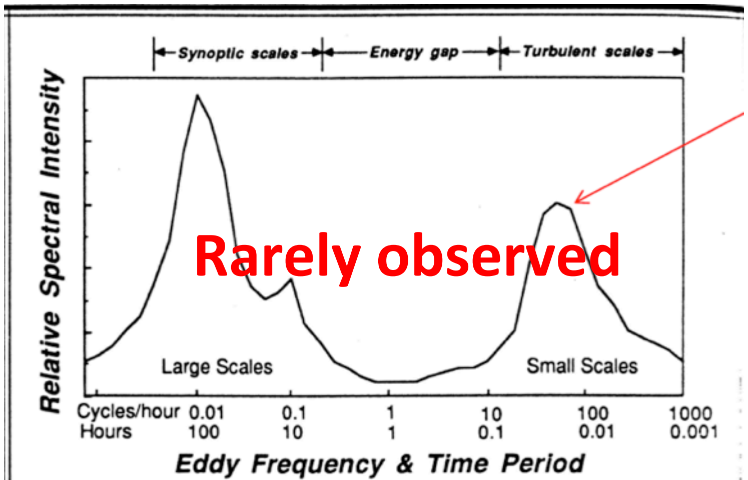
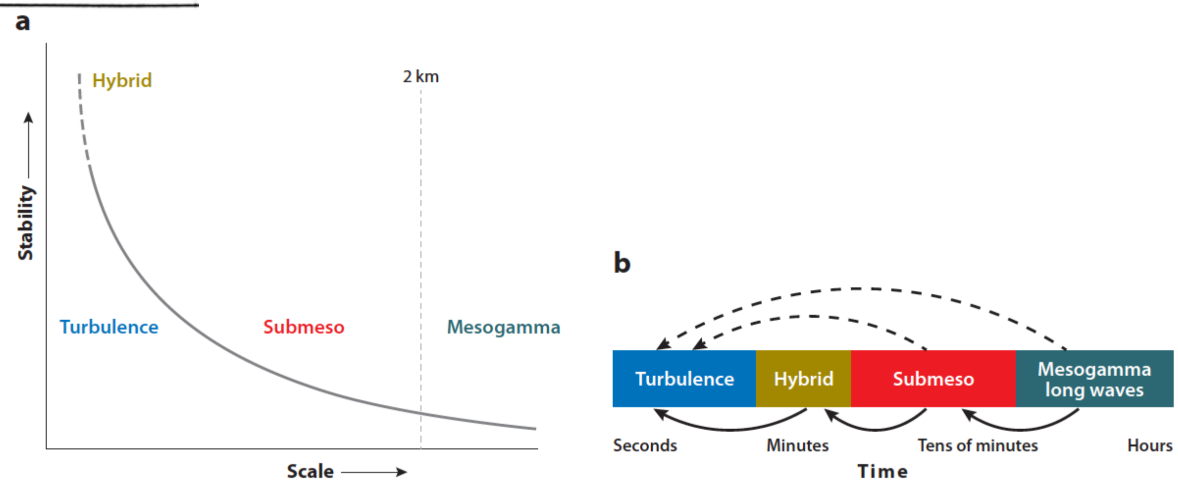


Fig. 2.2 Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).

Spectral peak: length scale of dominant turbulent eddies

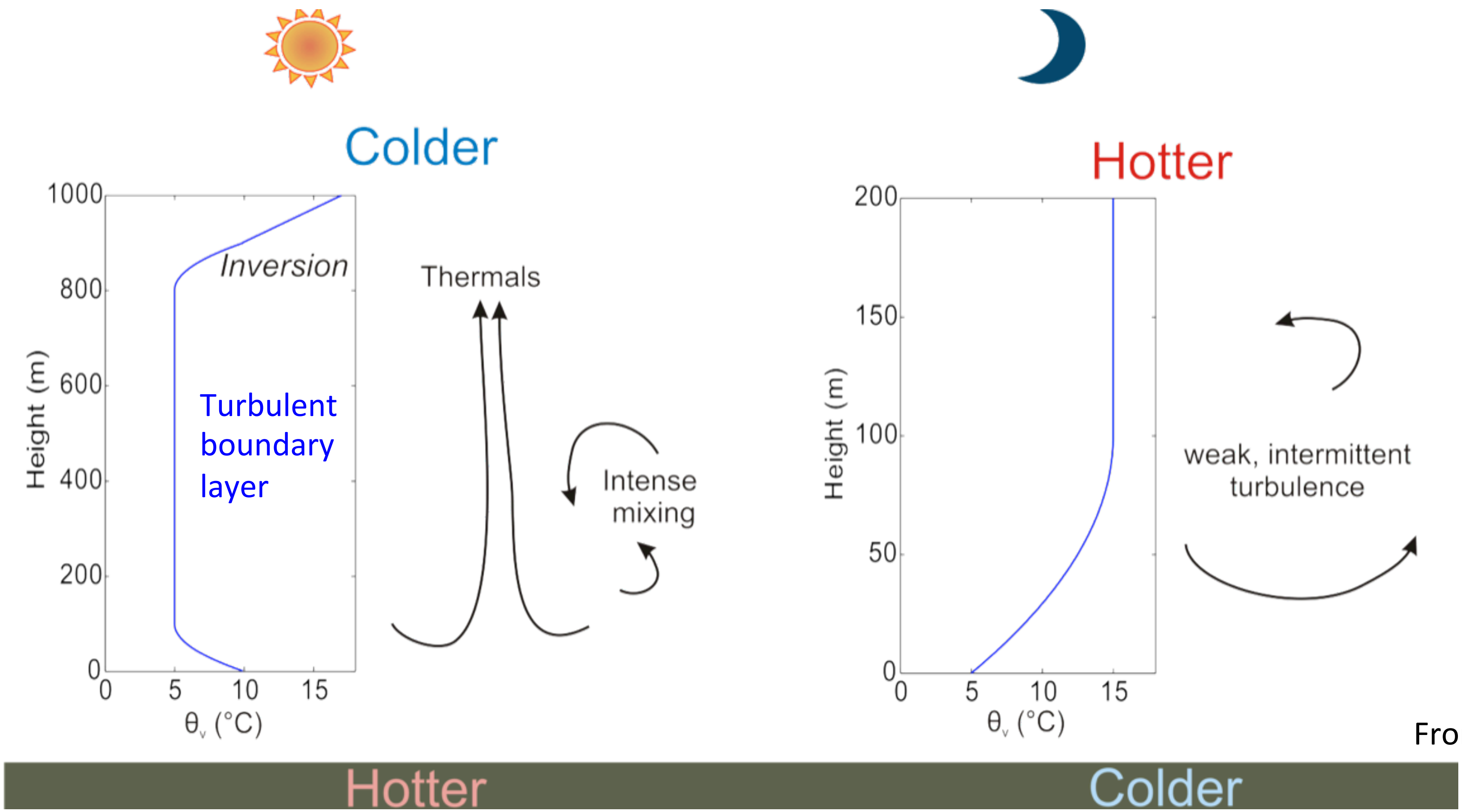
Real world:

- Heterogeneity simultaneously on multiple scales
- Non-stationarity simultaneously on multiple scales



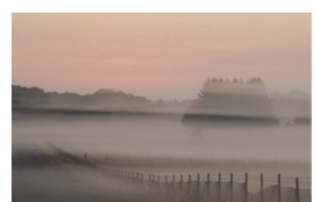
From Mahrt, Ann. Rev. Fluid Mech (2014)

Unstable and stable boundary layers



From Bou-Zeid

Unstable: turbulence produced
Displaced warmer air rise on its own (thermals, thunderstorm updrafts)



Stable: turbulence suppressed
Displaced cooler air sinks back (pollutant trapping, fog)

Distinct regimes of nighttime flow

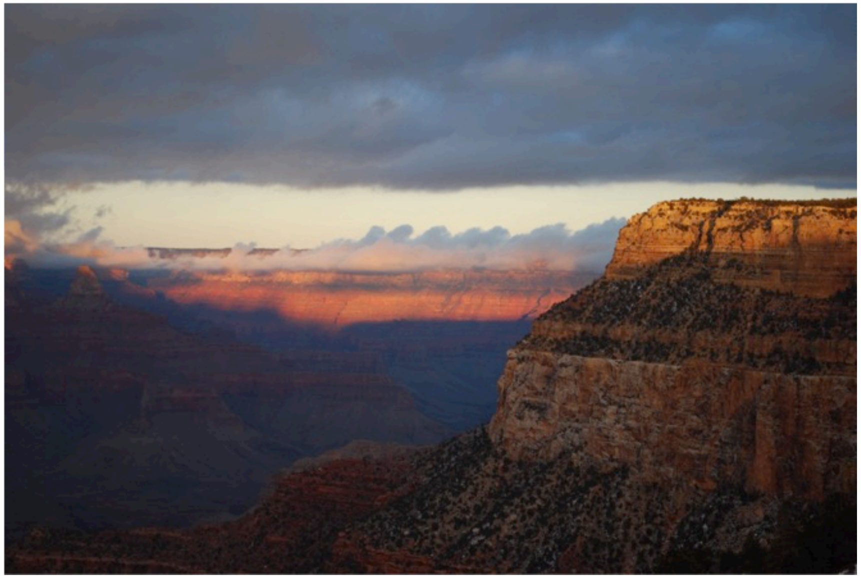
- **Weakly stable boundary layers**: continuous turbulence, windy conditions

- **Strongly stable boundary layers**: weak turbulence, calm nights

Strongly stable boundary layers - submesomotions

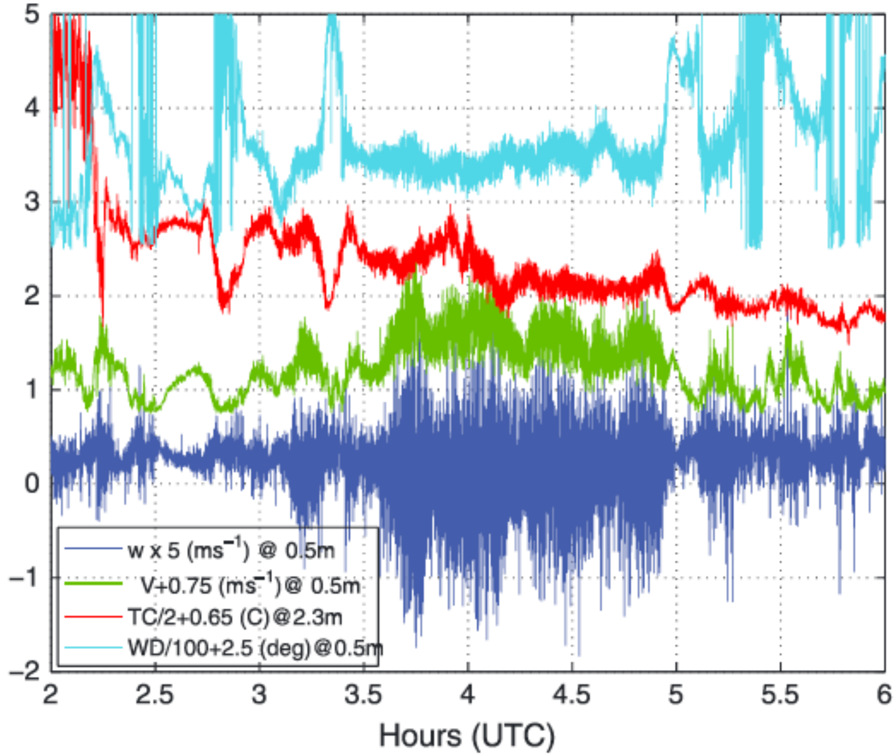
At night, besides turbulence…

Van Gogh, Starry night



From submeso.org

Interactions of scales of motion - example

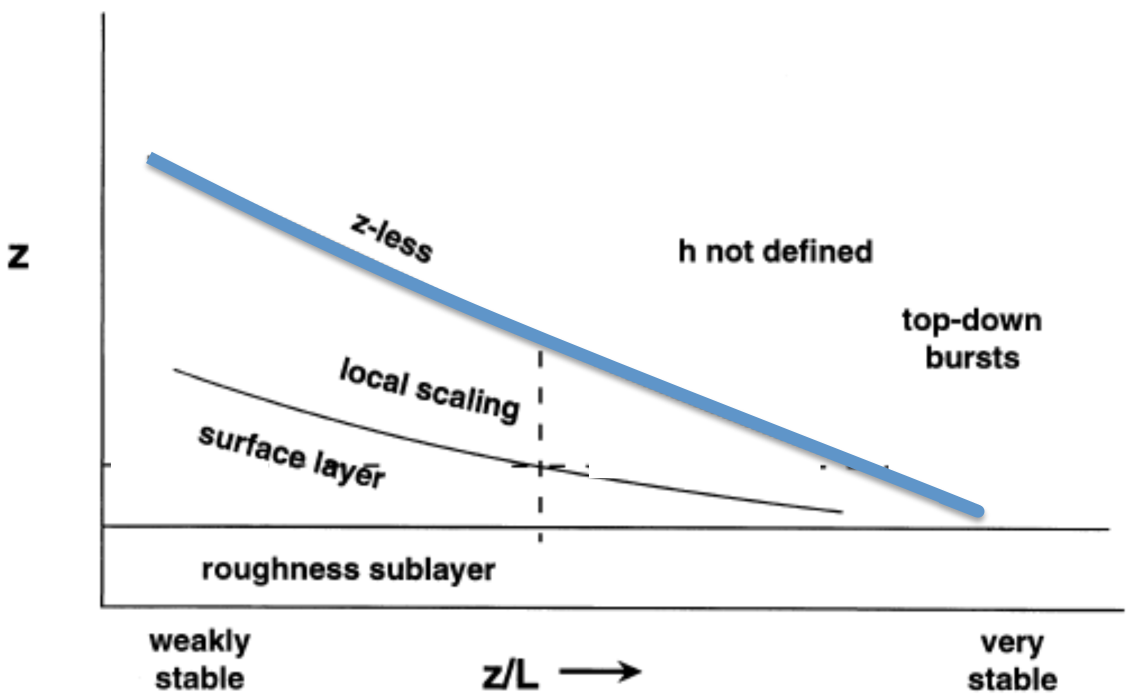


From Sun et al., 2012, JAS

- Do all submeso motions have an influence on turbulence?
- Can we characterize submeso motions?

What makes stable boundary layers complicated?

Parameterization in the very stable case?



From Mahrt 1999, *BLM*

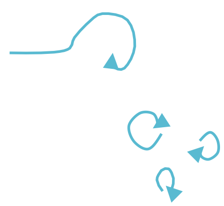
Existing issues and questions
(Mahrt 2014, *Annu Rev Fluid Mech*):

- Patching existing similarity theories does not seem useful.
- **When** is turbulence generated primarily by submeso motions?
- Is intermittency of turbulence a results of **external forcing** by submeso motions?
- Can the **scale of shear instabilities** be estimated by observations?
- Can submeso motions be **stochastically** parameterized?

Approach to Stable Boundary Layer analysis

<u>Existing issues and questions</u>
(Mahrt 2014, *Annu Rev Fluid Mech*):

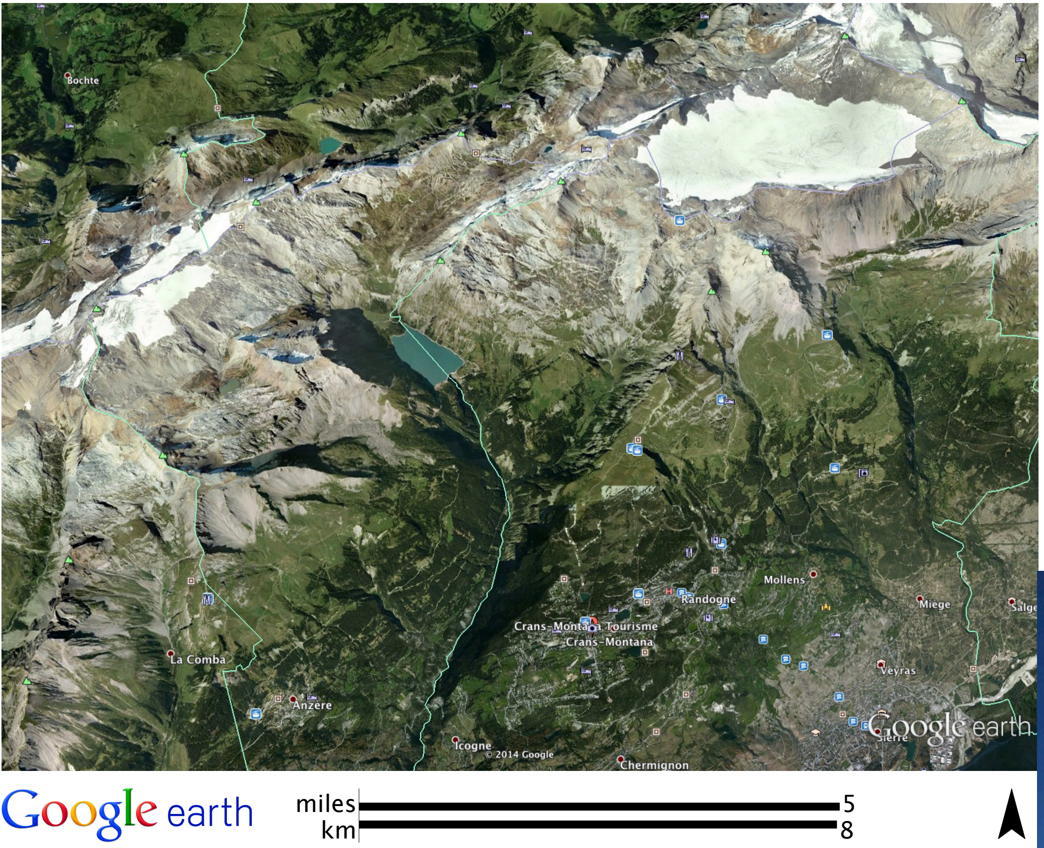
- Patching existing similarity theories does not seem useful.
- **When** is turbulence generated primarily by submeso motions?
- Is intermittency of turbulence a results of **external forcing** by submeso motions?
- Can the **scale of shear instabilities** be estimated by observations?
- Can submeso motions be stochastically parameterized?

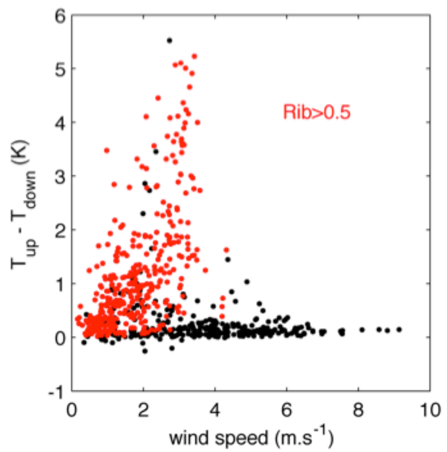


Two complementary approaches:

- **Regime detection:** detect periods in which submeso motions trigger the turbulence
- **Scale interactions:** in depth analysis of scales responsible for transport and for shear generation of turbulence in different regimes – analysis of submeso motions in different regimes

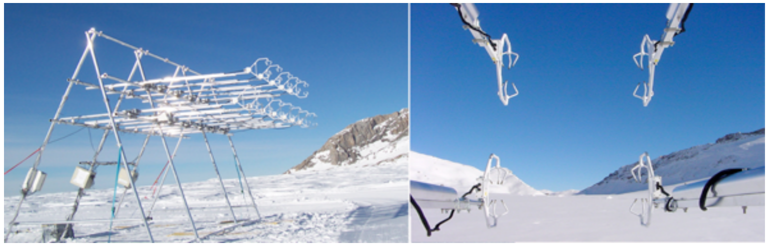
SnoHATS dataset

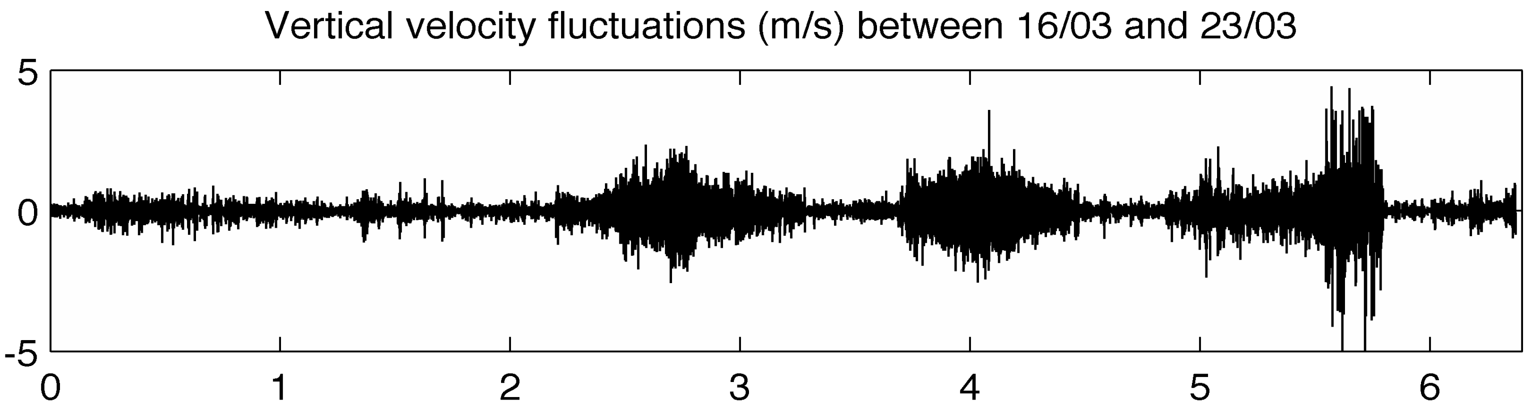




Intermittency in the measurements

Regime detection





➡ Can we use advanced statistical methods to cluster and represent **different regimes** of scale interactions in SBL turbulence?

Detecting regimes – FEM-VARX method

Model the timeseries x_t using several locally stationary VARX models:
(Vector Auto Regressive with eXhogeneous factors)

Regime detection

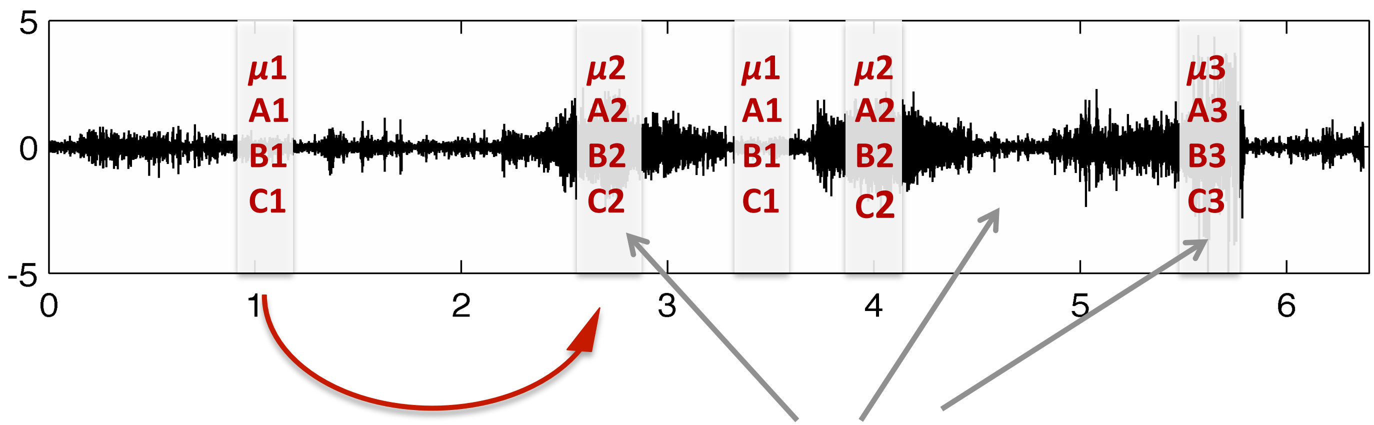
Scale interactions

$$x_t = \mu(t) + A(t)\phi_1(x_{t-\tau},\ldots,x_{t-m\tau}) + B(t)\phi_2(u_t,\ldots,u_{t-p\tau}) + C(t)\varepsilon_t,$$

Memory depth

External forcing: **submeso motions**

Vertical velocity fluctuations (m/s) between 16/03 and 23/03



Different VARX processes?

The **jumps** between the locally stationary VARX models (different *μ, A, B, C*) are represented through a statistical process.

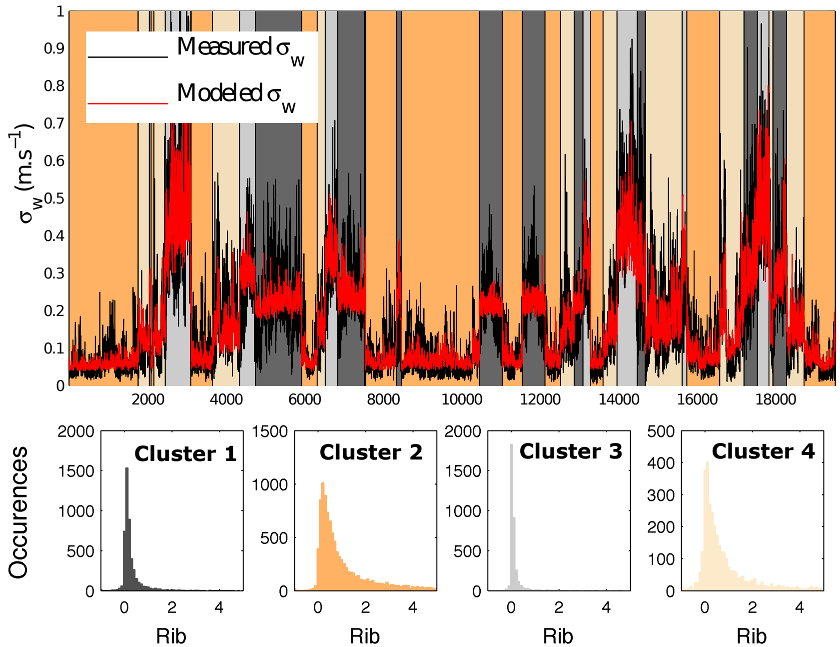
Horenko, I. (2010), On the Identification of Nonstationary Factor Models and Their Application to Atmospheric Data Analysis, *J. Atmos. Sci.*, *67*(5), 1559–1574, doi:10.1175/2010JAS3271.1. **FEM-VARX method**

Clustering results – Submeso wind influence

When do non turbulent motions (u^*) influence turbulent mixing?

Regime detection

Scale interactions



Vertical velocity fluctuations σ_w

$$\sigma_{wt} = \mu(t) + B(t)\phi_2(u^*_t, \ldots, u^*_{t-p\tau}) + C(t)\varepsilon_t$$

External forcing: submeso wind velocity u^*_t

Under the influence of submesomotions, strongly stable and weakly stable periods are separated.

What else can we learn? Are there **physical patterns** in each cluster?

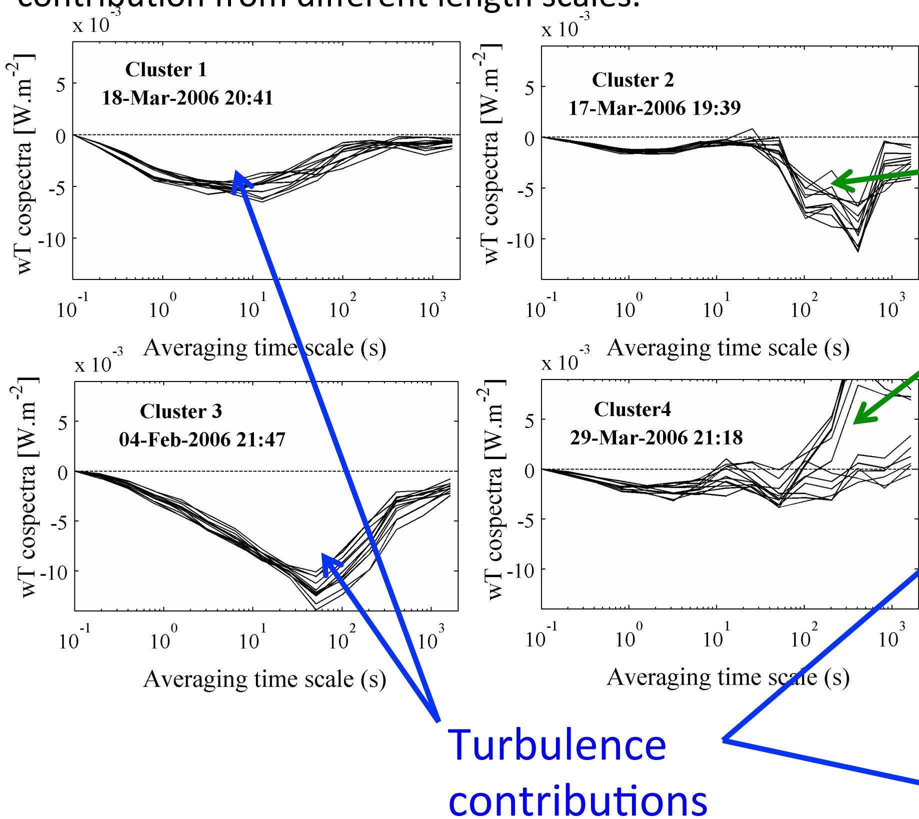
Do the regimes make physical sense?

Vercauteren N., Klein R. ***A clustering method to characterize intermittent bursts of turbulence and interaction with submeso motions in the stable boundary layer***. *J. Atmos. Sci*, 2015

Multiresolution flux decomposition

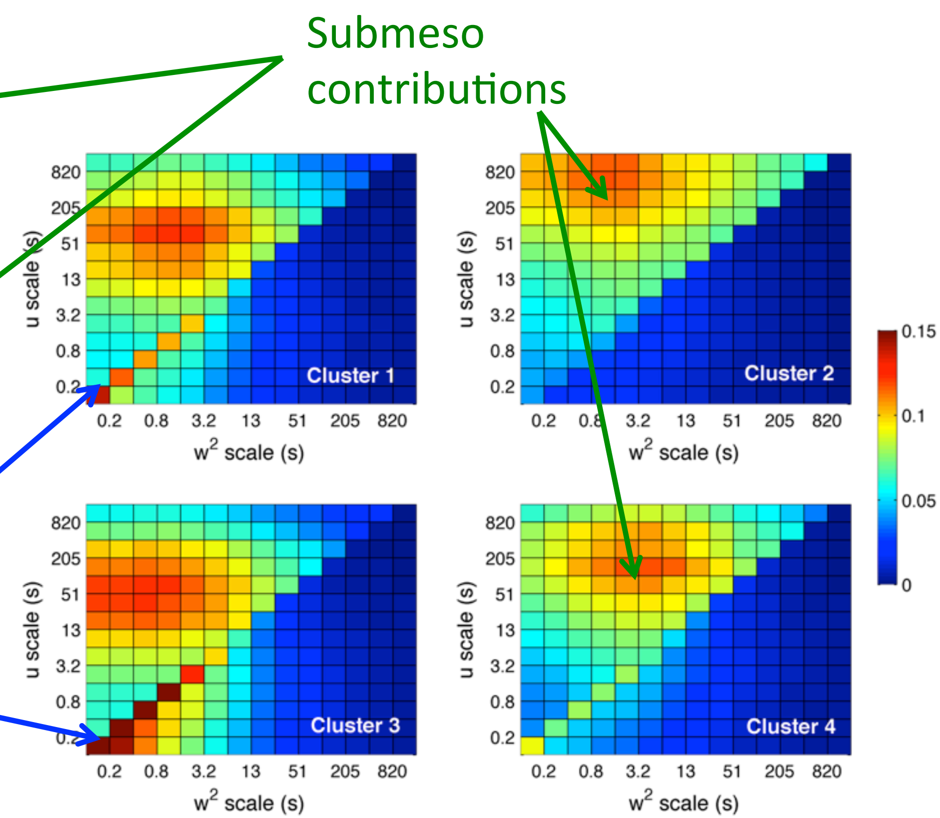
What are the **scales** responsible for **transport**?

MRD (Vickers and Mahrt 2003,*J. Atm Ocean. Tech.*): Flux contribution from different length scales.



What are the scales of maximum influence of u on w^2? **Shear generation** of turbulence.

Extended MRD (Nilsson et al. 2014, QJRMS): scales of maximum influence.



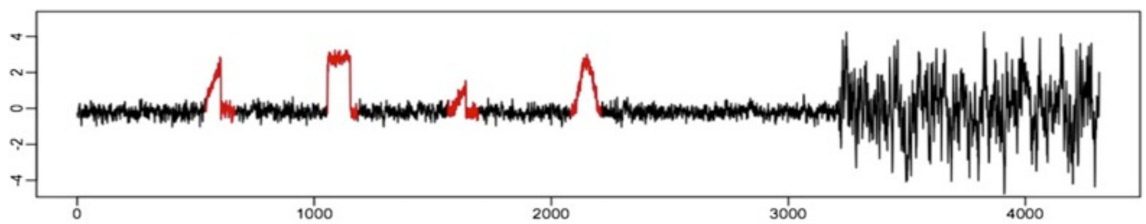
Scale interactions

Vercauteren N., Mahrt L., Klein R. ***Investigation of interactions between scales of motion in the stable boundary layer*** . QJRMS, 2016

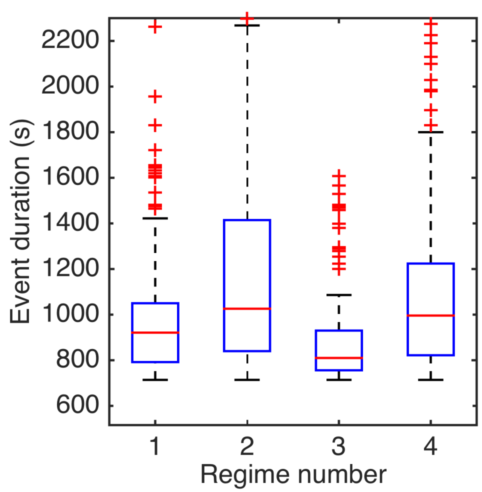
Flow structures in different regimes

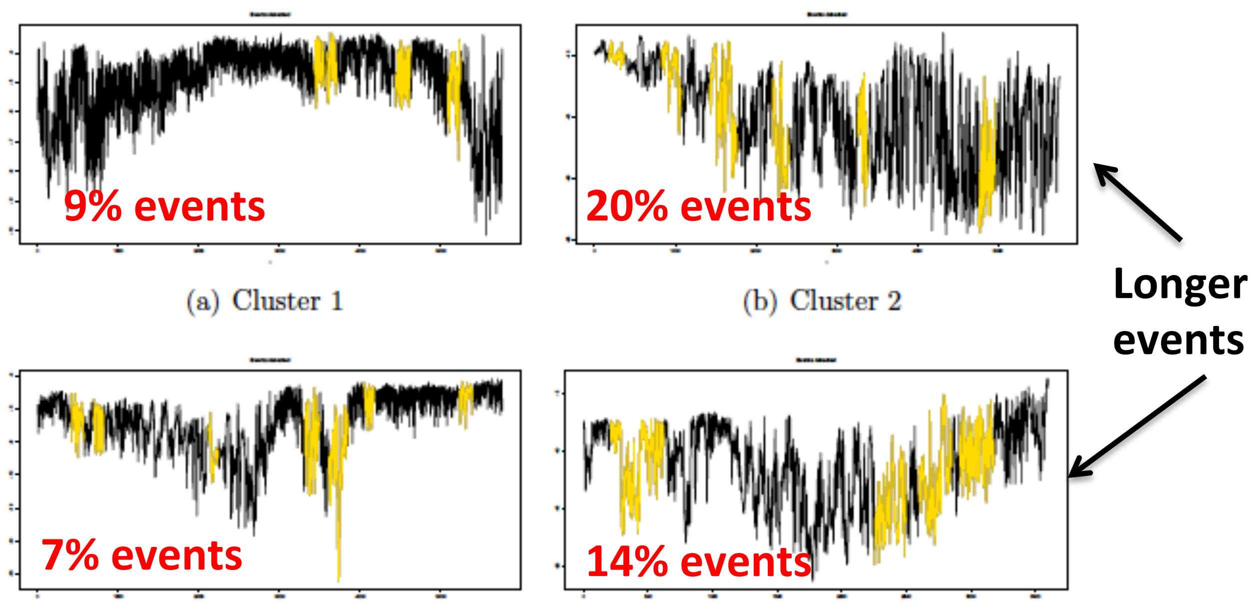
- **Method** to identify submesomotions: Turbulent Events Detection **TED**

  Work by Kang and Belušić (2014, JAS): classifying events (submeso motions) in turbulent timeseries.



- **Application to the SnoHATS dataset (temperature) –** Bachelor Thesis of Amandine Kaiser



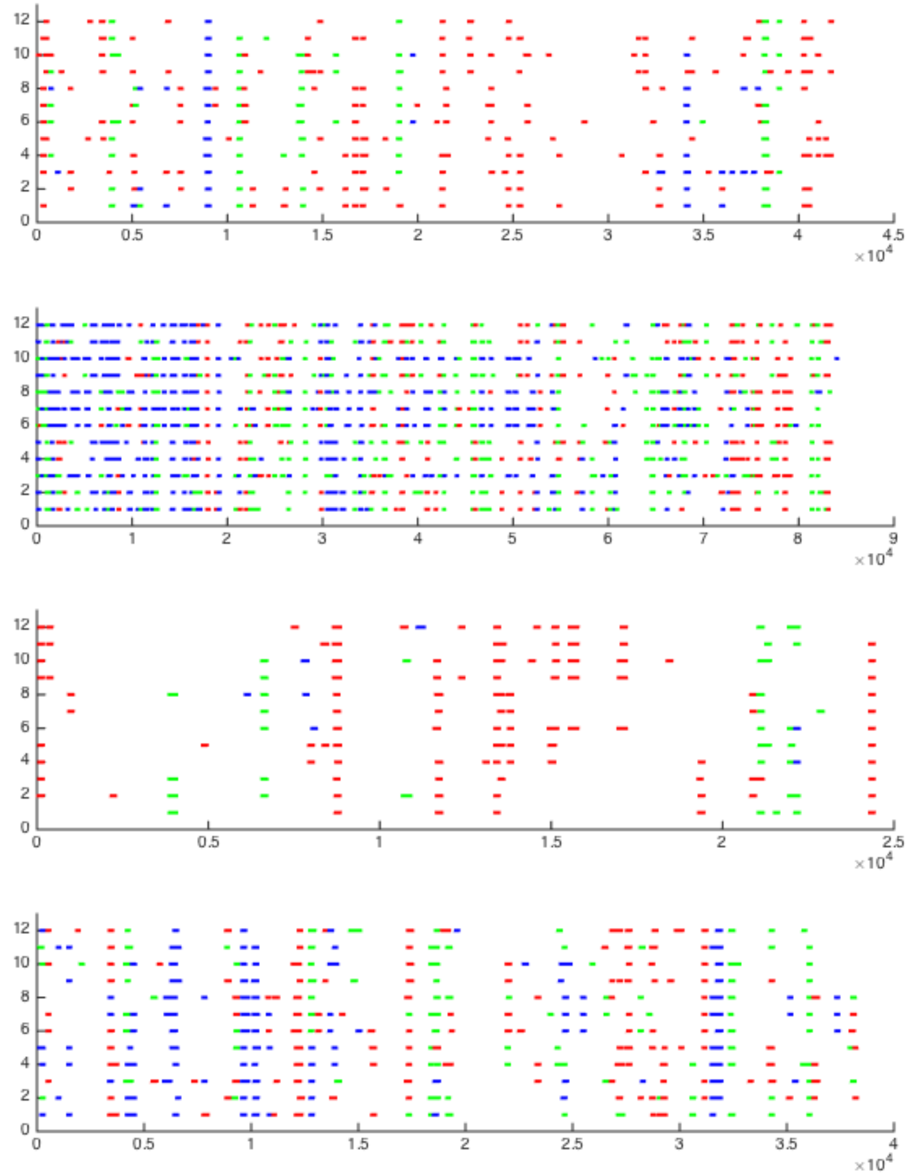


(a) Cluster 1 (b) Cluster 2

(c) Cluster 3 (d) Cluster 4

Clustering flow structures in different regimes

Events from 12 neighboring sonic anemometers



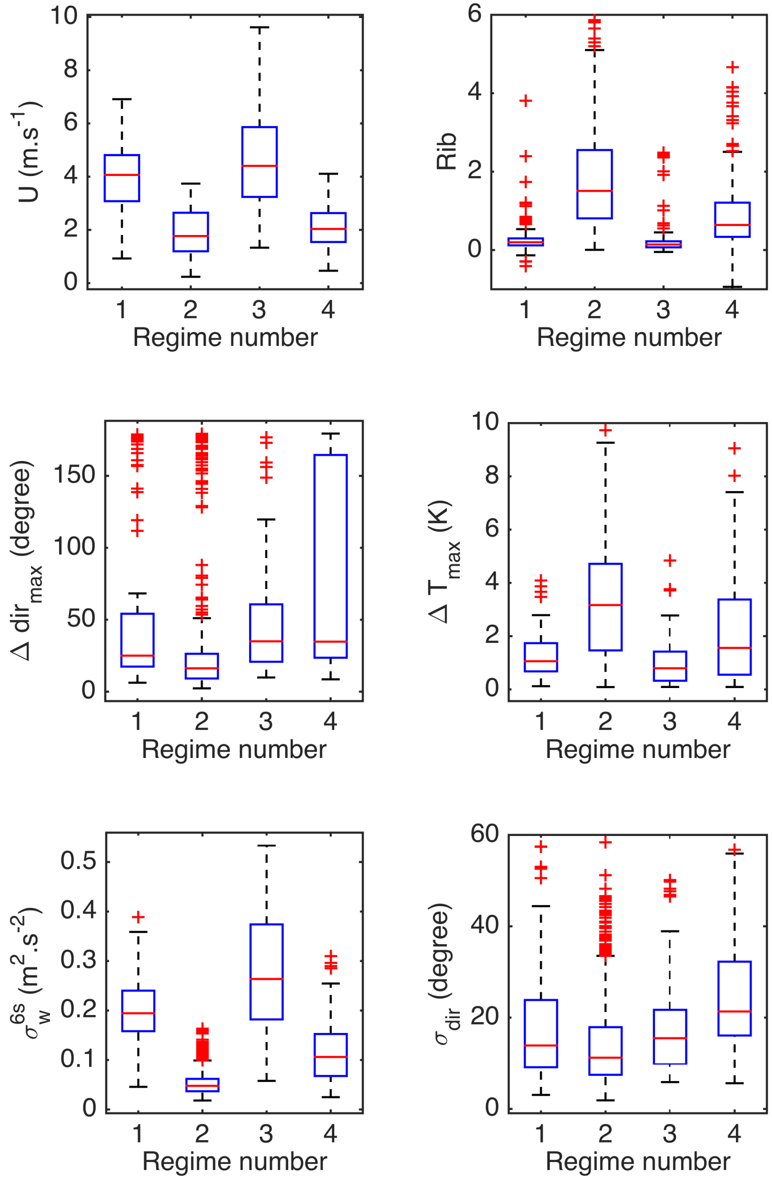
Regime 1:
181 red, 66 green, 38 blue

Regime 2:
277 red, 339 green, 391 blue

Regime 3:
104 red, 35 green, 7 blue

Regime 4:
138 red, 102 green, 115 blue

Characteristics of flow structures



Summary

- **Weak stability** (Regime 1 and 3): short and fewer events, higher wind speeds.

- **Strong stability:** preferential type of flow structures

- Regime 2: scale separation, longest and most frequent events, microfronts.
  Hypothesis: Advected air masses and shear triggering turbulence locally on very small scales.

- Regime 4: scale overlap, long and frequent events, wind direction variability.
  Hypothesis: Wave-like phenomena that break into turbulence through a cascade of scales.

- **Outlook:** build a regime dependent stochastic model to represent forcing of turbulence by submeso motions

Stochastic closure in NWP models

- Idea: add a **stochastic forcing term** in the turbulent kinetic energy closure.
- The stochastic forcing term would account for extra turbulence generated by local shear acceleration due to unknown causes.
- Make the forcing term **regime dependent**.

Example in a single column model Ri-based steady-state TKE equation (He, McFarlane and Monahan, J. of Climate, 2013):

$$\ell \frac{k^{1/2}}{c_0^{1/2}} F_m (1 - Ri / \mathrm{Pr}) S^2 - \Lambda (1 - 1/\mathrm{Pr}) \frac{k^{3/2}}{\ell} + \mathsf{F} - \frac{k^{3/2}}{c_0^{3/2} \ell} + \frac{\alpha}{\ell} k^{1/2} (k_* - k) = 0$$

Thank you!

Unterstützt von / Supported by Alexander von Humboldt Stiftung / Foundation

DFG

Freie Universität Berlin

SnoHATS and LATEX field campaigns by the team of Marc Parlange

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

eflum environmental fluid mechanics

FEM-VARX method by the team of Illia Horenko

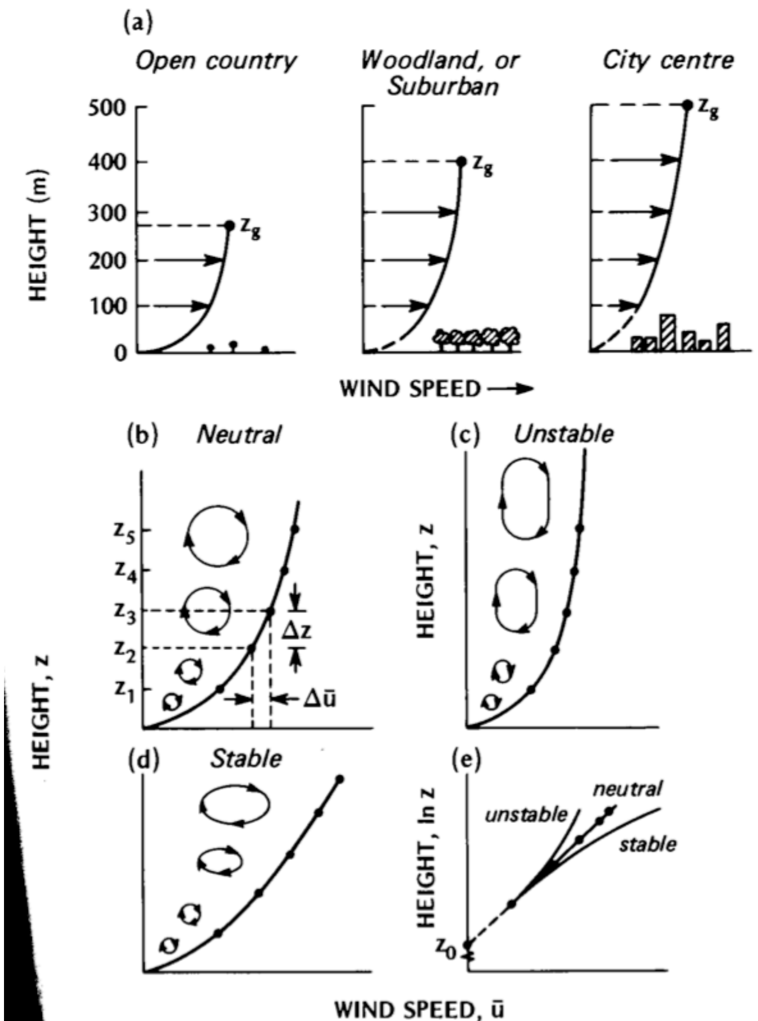
Università della Svizzera italiana — Faculty of Informatics

TED method by the team of Danijel Belušić

MONASH University

Contact: Nikki.vercauteren@fu-berlin.de

Surface layer modeling



gure 2.10 The wind speed profile near the ground including: (a) the effect terrain roughness (after Davenport, 1965), and (b) to (e) the effect of bility on the profile shape and eddy structure (after Thom, 1975). In (e) profiles of (b) to (d) are re-plotted with a natural logarithm height scale.

From Oke, 1987

Monin-Obukhov similarity theory (MOST): similarity relations to take into account the effect of the surface forcing (**frictional** and **buoyant**). Dependence on stability

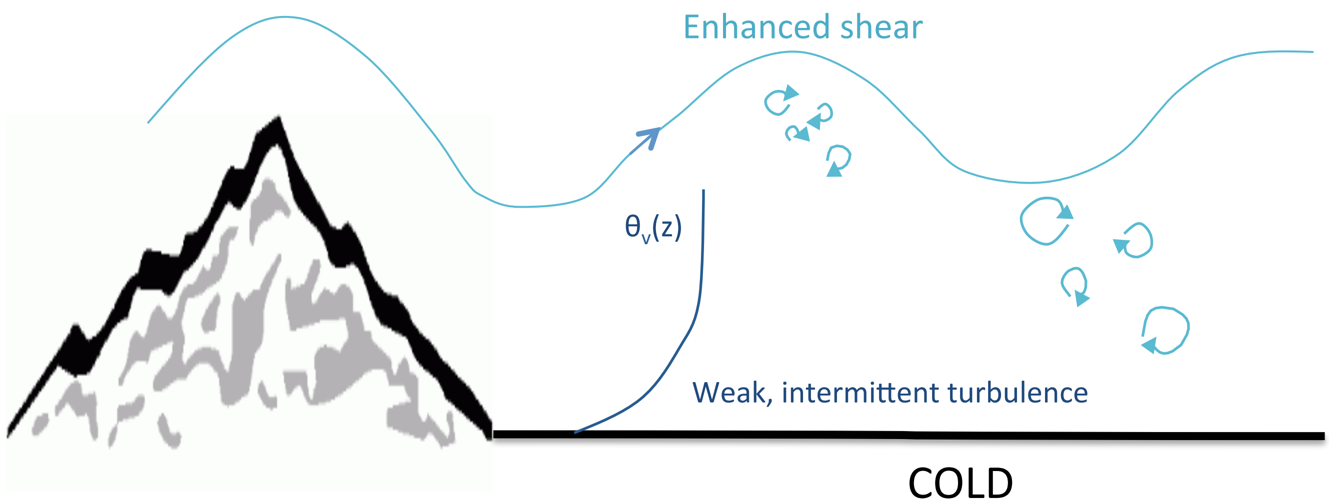
Used by all NWP. Used to define values for wind speed and scalar concentrations at the first grid point above the surface, or in the full boundary layer (resolution dependent).

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z-d_0}{z_{0m}}\right) - \psi_{sm}(\zeta)\right]$$

$$q_s - q = \frac{E}{a_v k u_* \rho}\left[\ln\left(\frac{z-d_0}{z_{0v}}\right) - \psi_{sv}(\zeta)\right]$$

$$\theta_s - \theta = \frac{H}{a_h k u_* \rho c_p}\left[\ln\left(\frac{z-d_0}{z_{0h}}\right) - \psi_{sh}(\zeta)\right]$$

Interactions of scales of motion



Scale interactions:

Turbulence triggered by shear instabilities, (Kelvin-Helmholtz, submesoscale motions)

Turbulence is discontinuous, detached from the surface (top-down bursts)

Break down of surface based turbulence parameterizations ➔ New ideas needed

Non-turbulent (submeso) motions

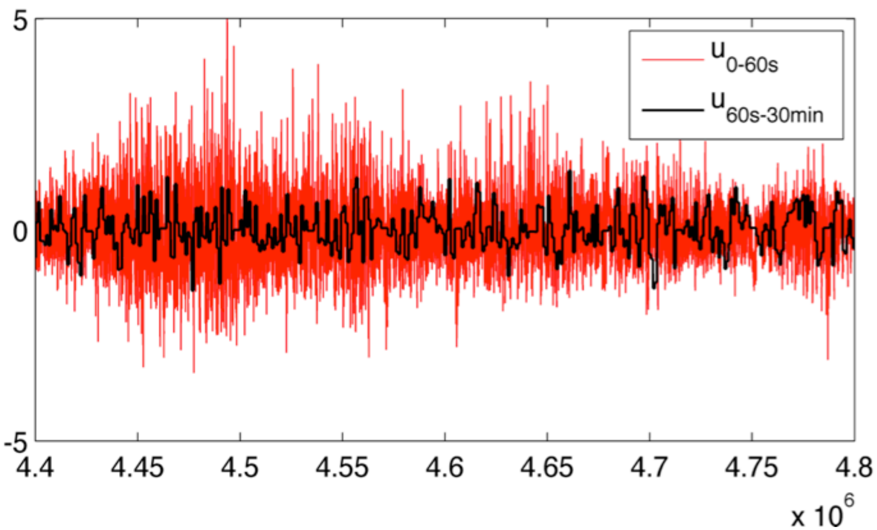
Scale interactions

Separation of the scales of motion: $u' = u - \bar{u}, \quad u^* = \bar{u} - [u]$

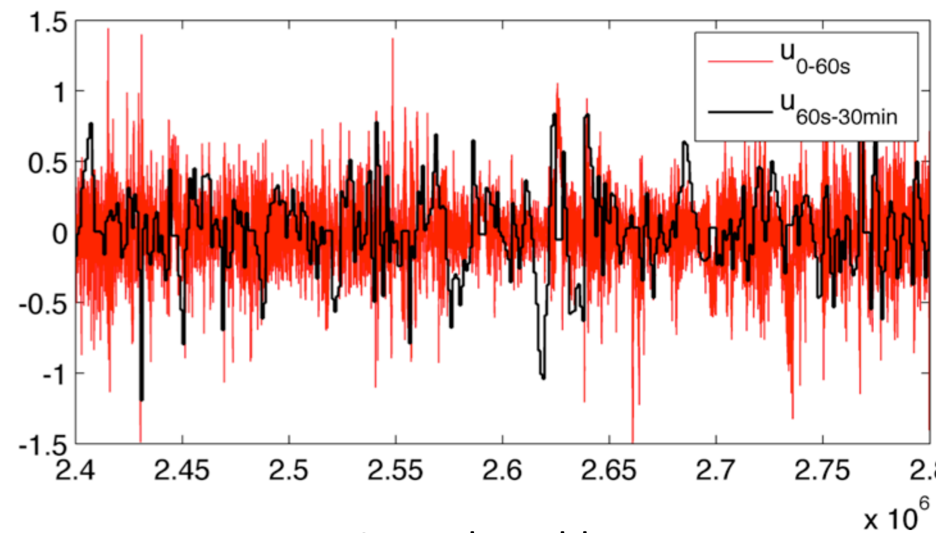
1 minute average

30 minute average

➔ the wind is filtered between fast scales and slower scales



Weakly stable case



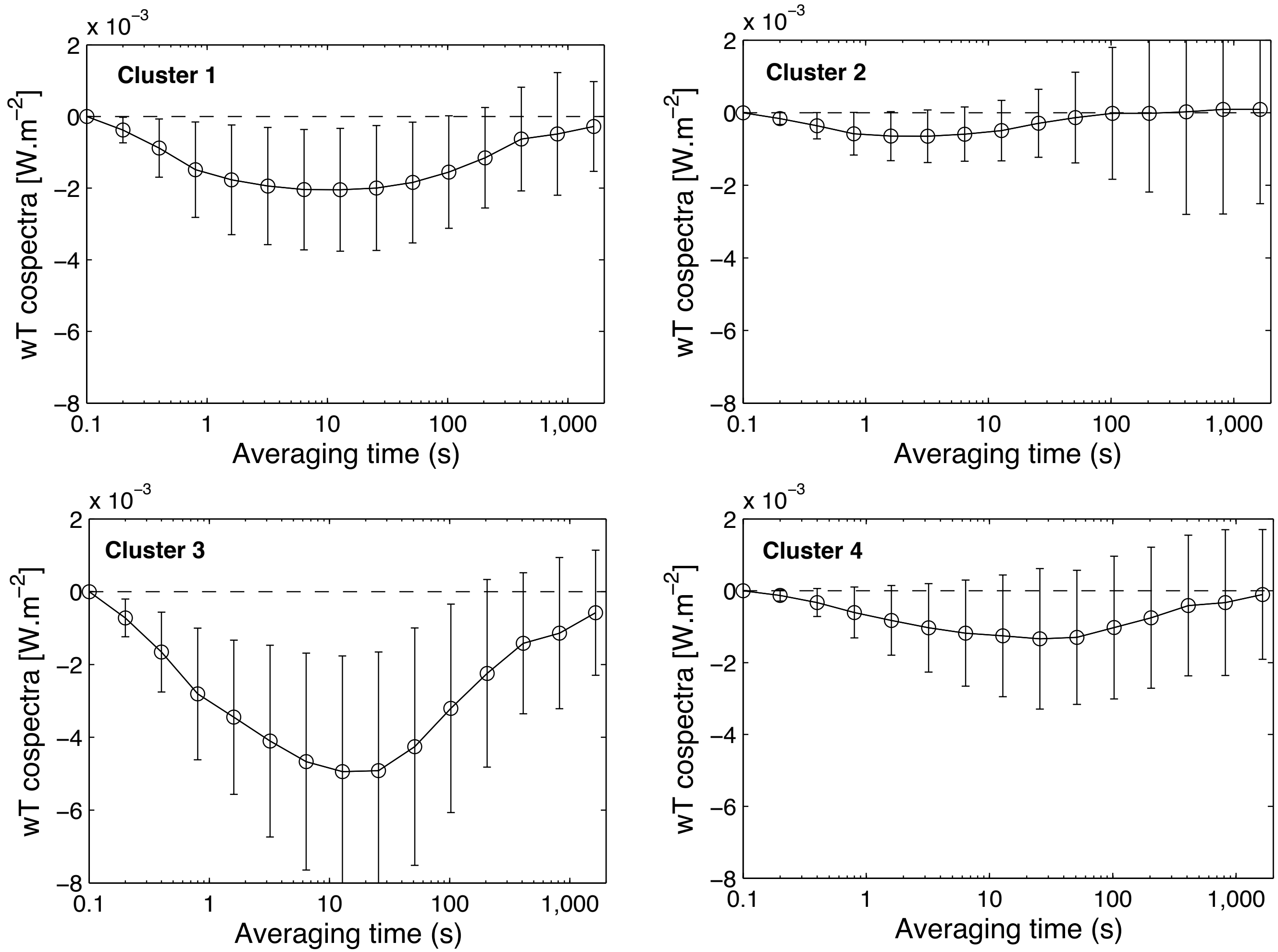
Strongly stable case

Clear presence of non turbulent motion in the very stable case.

How do non turbulent motions (u*) influence turbulent mixing?

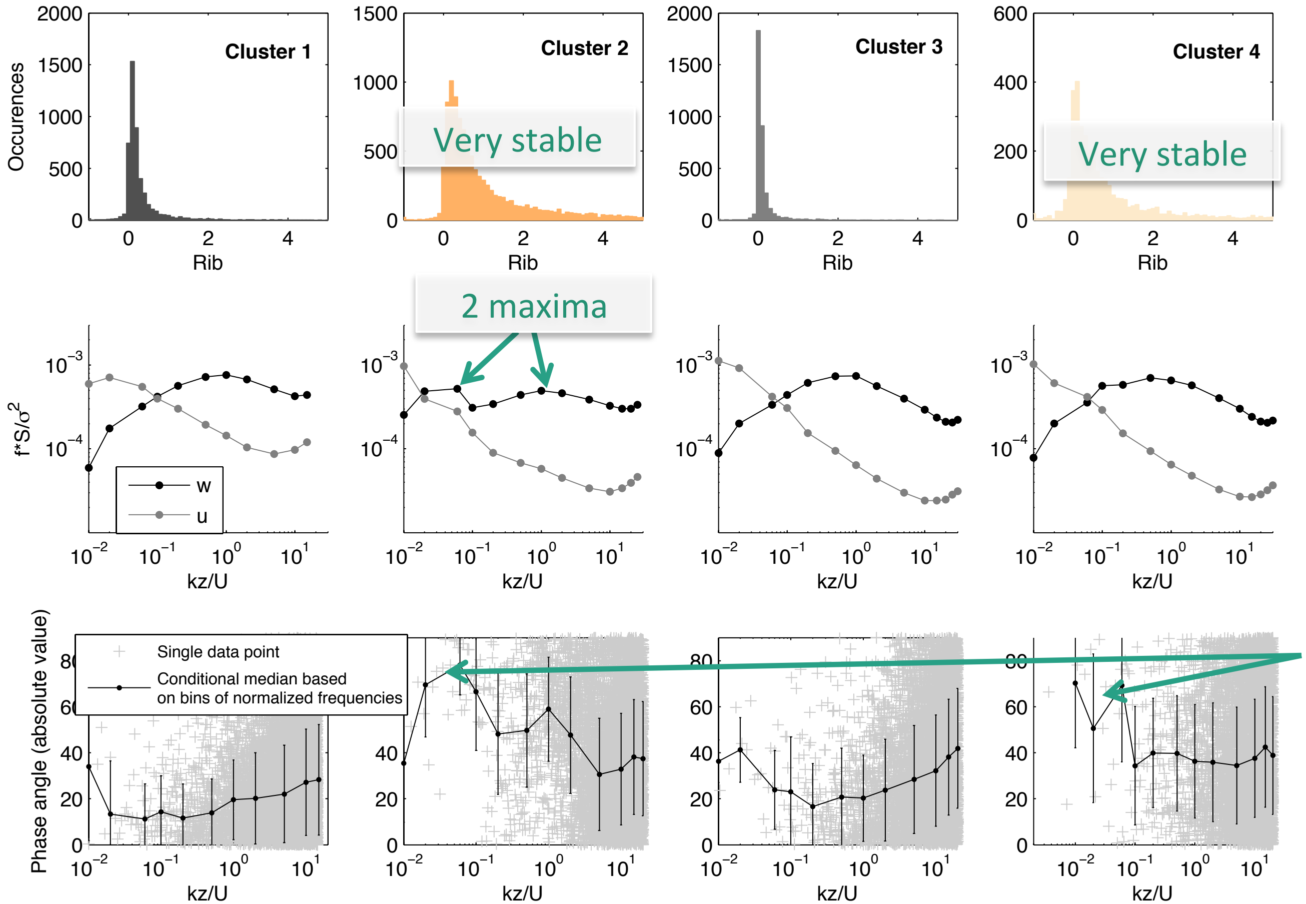
Multiresolution flux decomposition

Average and standard deviation of MRD cospectra for each cluster



Clusters and spectra

Regime detection



Phase spectra of temperature and vertical velocity.
±90° indicates **waves**.

Vercauteren N., Klein R. ***A clustering method to characterize intermittent bursts of turbulence and interaction with submeso motions in the stable boundary layer***. *J. Atmos. Sci*, 2015