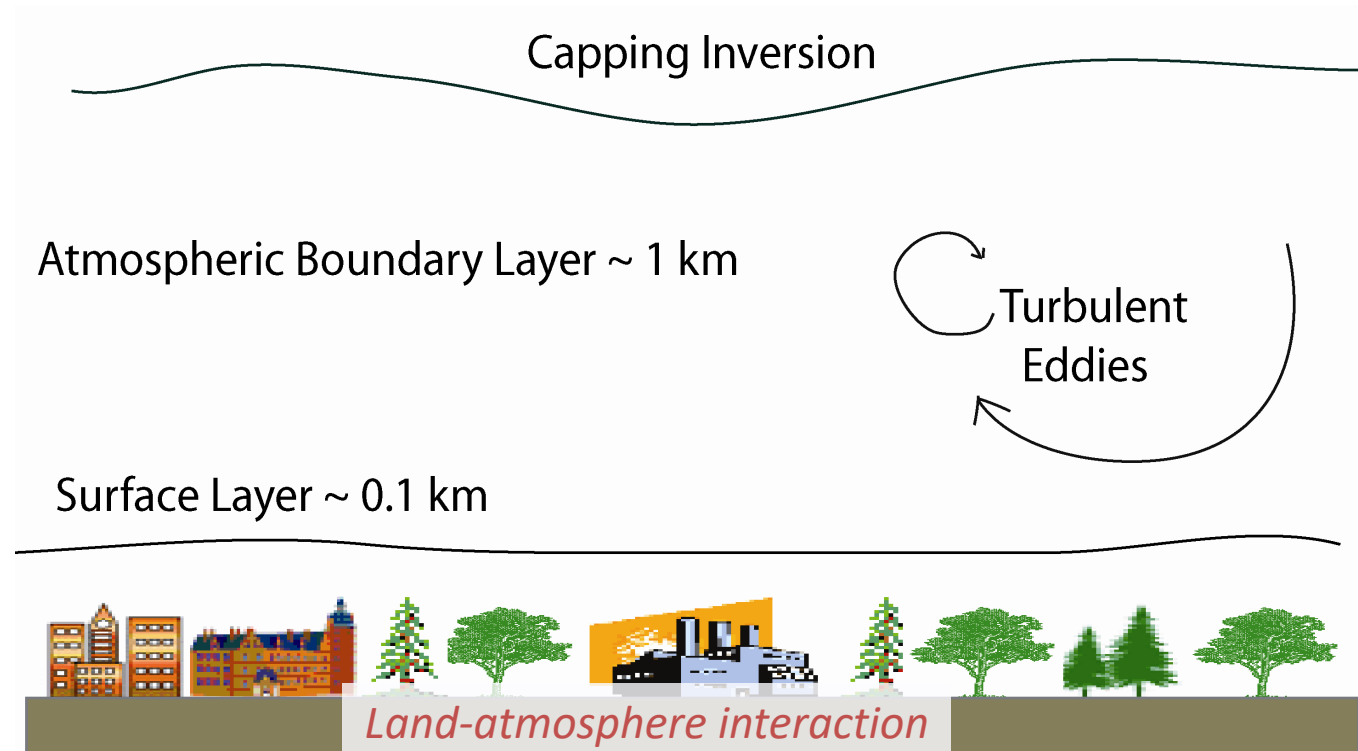


Scale Interactions and Anisotropy of Turbulence in Stable Boundary Layers

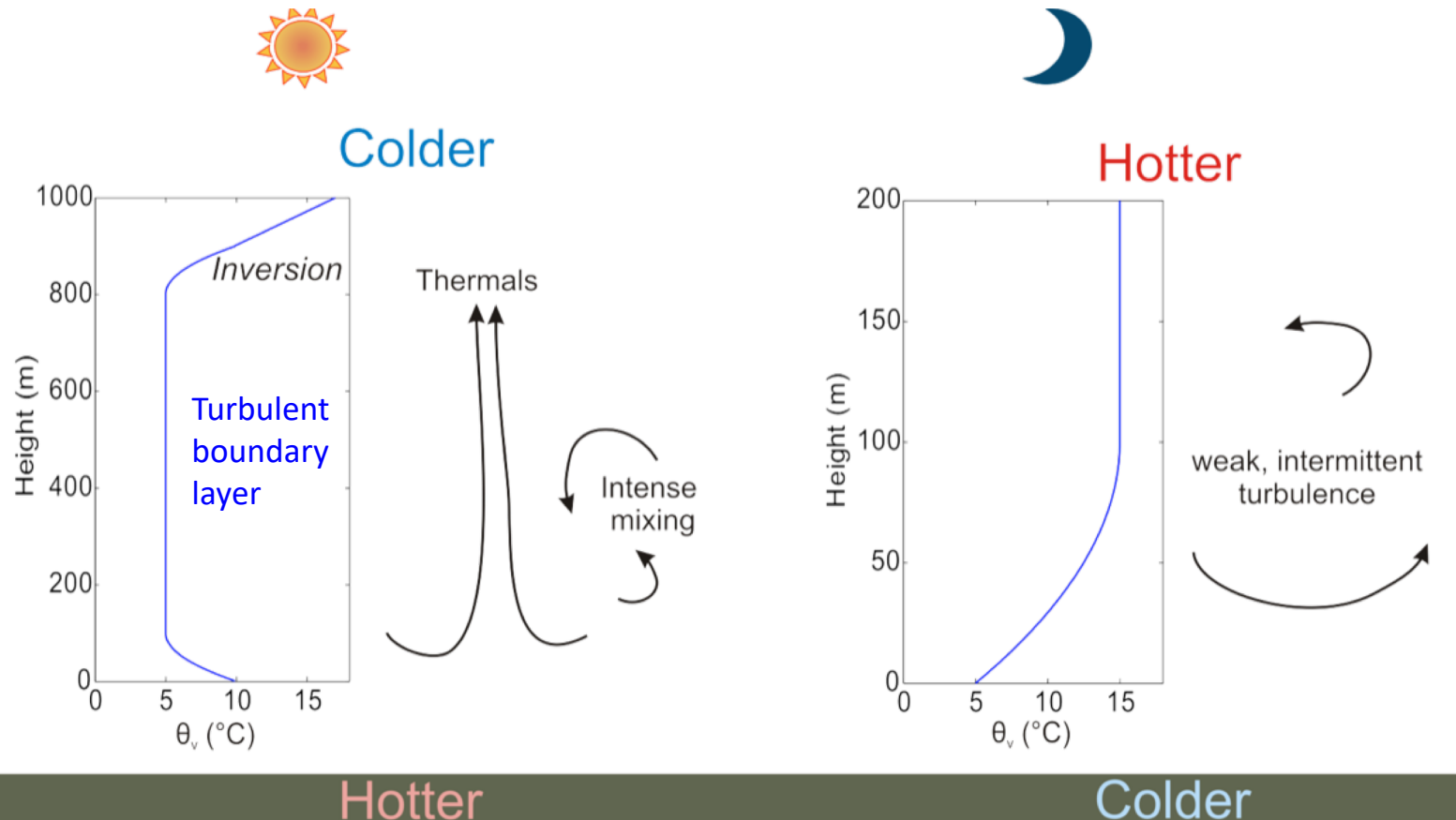
Turbulence in the atmospheric boundary layer



Problem

Turbulence parameterization schemes typically fail in stably stratified contexts (nighttime, Polar Boundary Layer).

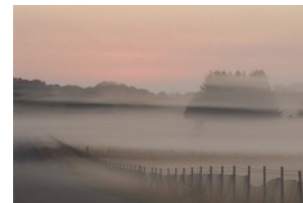
Unstable and stable boundary layers



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)

Surface layer modeling

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

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

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

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

Used by all numerical weather prediction models (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).

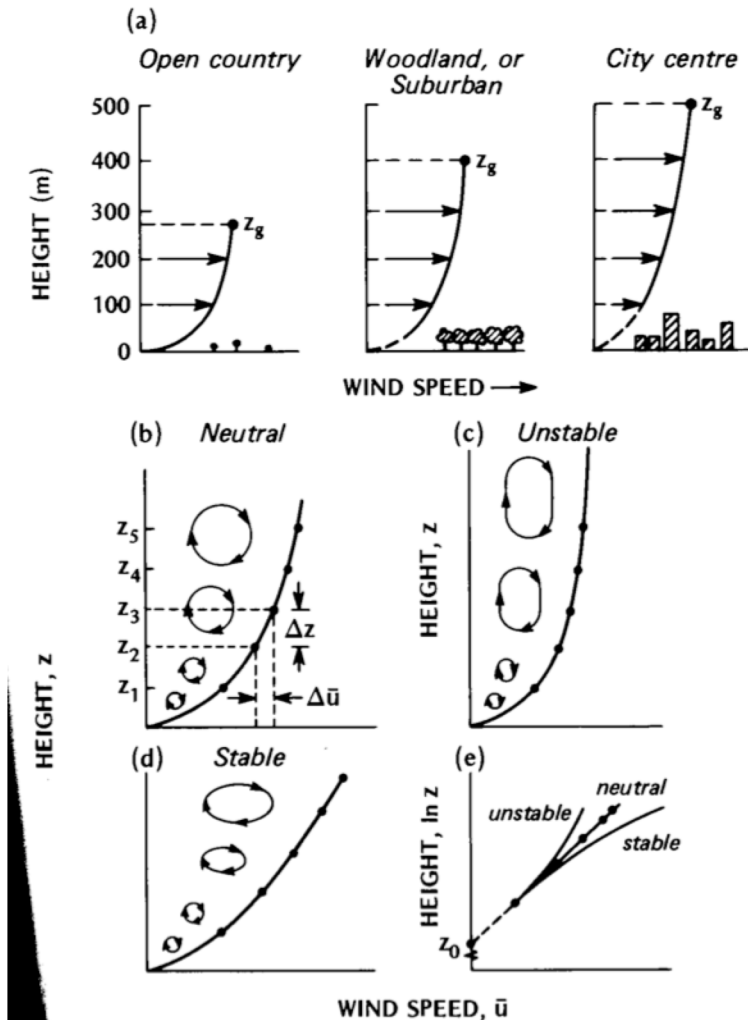
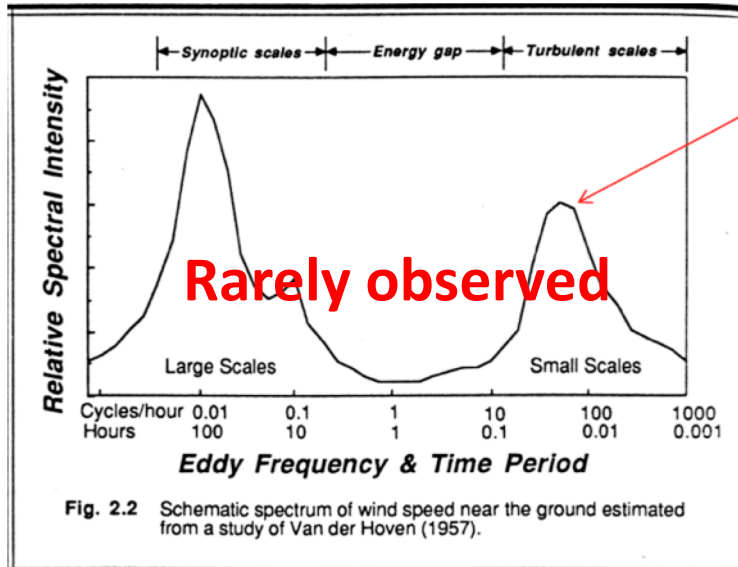


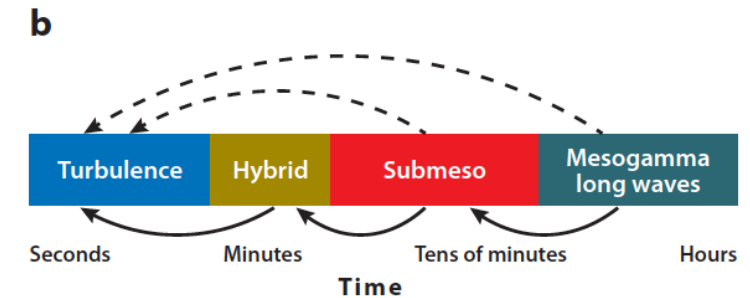
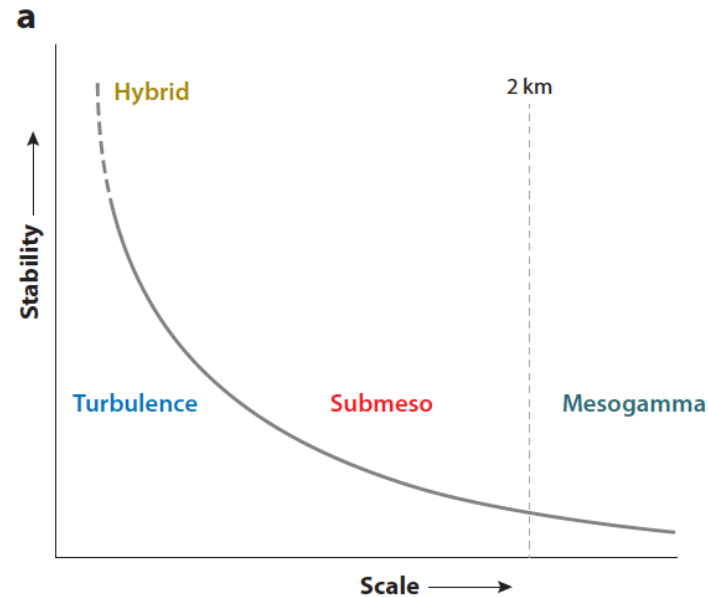
Figure 2.10 The wind speed profile near the ground including: (a) the effect of terrain roughness (after Davenport, 1965), and (b) to (e) the effect of stability on the profile shape and eddy structure (after Thom, 1975). In (e) the profiles of (b) to (d) are re-plotted with a natural logarithm height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

Scale separation in models

Can we isolate turbulent scales and larger scales in models?



Spectral peak: length scale of dominant turbulent eddies



Real world:

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

Distinct regimes of stable boundary layer flows

Weakly stable boundary layers:
continuous turbulence, windy conditions



- Similarity theory applicable.

Strongly stable boundary layers:
weak turbulence, calm nights



[submeso.org]

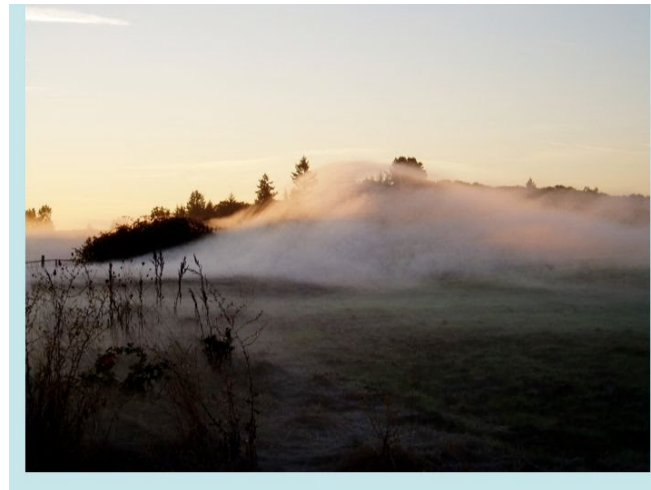
- Intermittent, non-stationary turbulence.
- Instabilities, submeso motions. Turbulence not in equilibrium with the forcing.
- Similarity theory not applicable.

External forcing of nighttime turbulence: submesoscale motions

At night, besides turbulence...



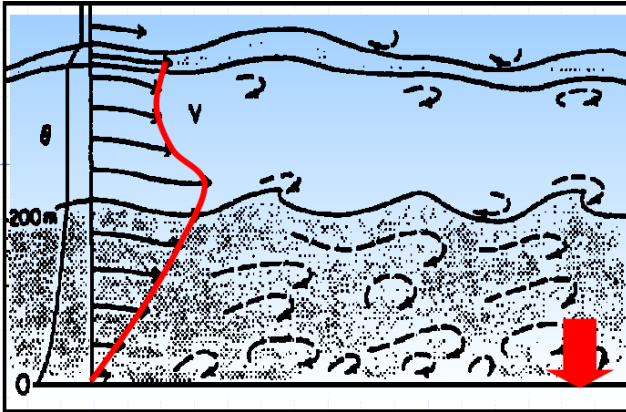
Van Gogh, Starry night



From submeso.org

Data-driven investigations of turbulent flows

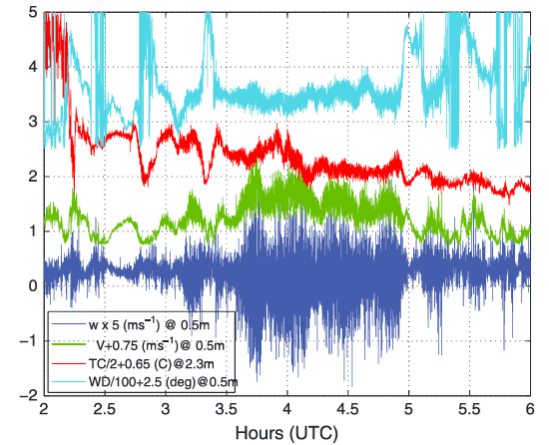
A nonstationary, multiscale, metastable system:
the stably stratified boundary layer



Turbulence by friction (Mechanical forcing of turbulence),
stabilization by surface cooling, large gradients in
temperature and wind.

Friction by unresolved, small-scale motions

Intermittent turbulence.



[Sun et al., JAS, 2012]

Questions addressed:

- **When** is turbulence **triggered** by localized flow accelerations ? Separate **flow regimes**.
- What are the **anisotropy characteristics** of the stress tensor in different stable flow regimes?
- What are the **dynamical properties** of different topologies of turbulence?

Methods applied:

- **FEM-BV-VARX** to cluster different regimes of scale interactions.
- **Anisotropy analysis** of the Reynolds stress tensor.
- **Dimension and persistence** of the dynamics of the anisotropy tensor

Detecting regimes – FEM-BV-VARX method

FEM-BV-VARX methodology (Horenko): Model a timeseries x_t using several **locally stationary** VARX models:
(Vector Auto Regressive with eXhogeneous factors)

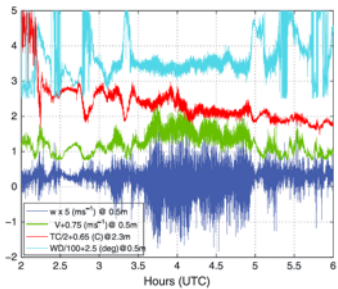
Regime detection

Scale interactions

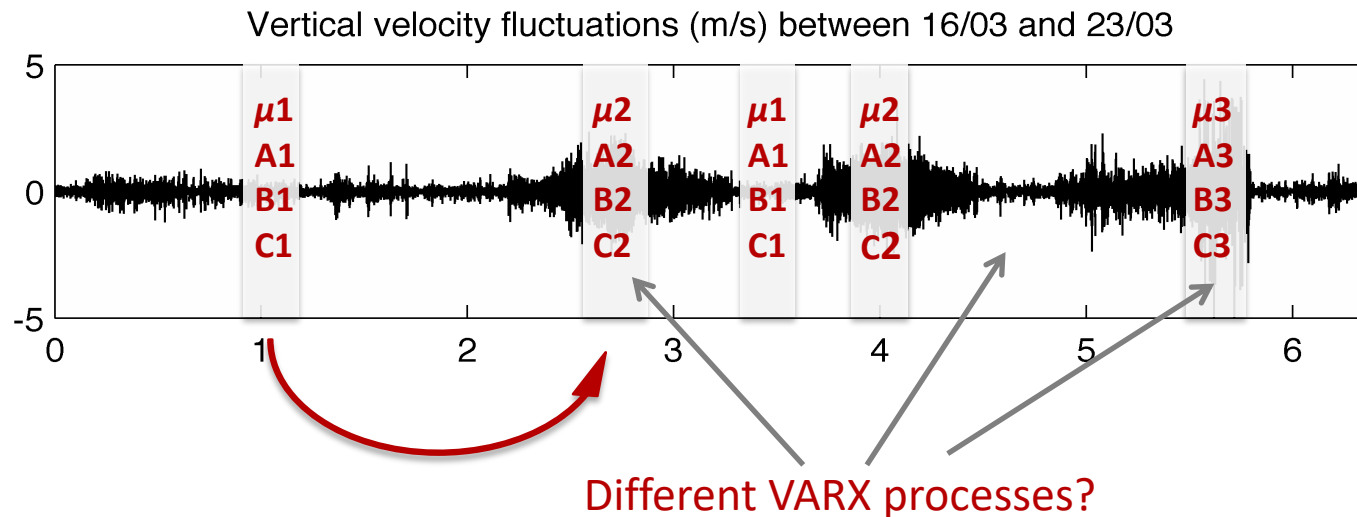
Turbulent mixing:
vertical velocity variance (1 min)

$$\sigma_w^t = \mu(t) + B_0(t)u_t^* + \dots + B_p(t)u_{t-p\tau}^* + C(t)\varepsilon_t$$

Memory depth



[Sun et al., JAS, 2012]



External forcing:
submeso wind velocity

$$u^* = \bar{u} - \langle u \rangle$$

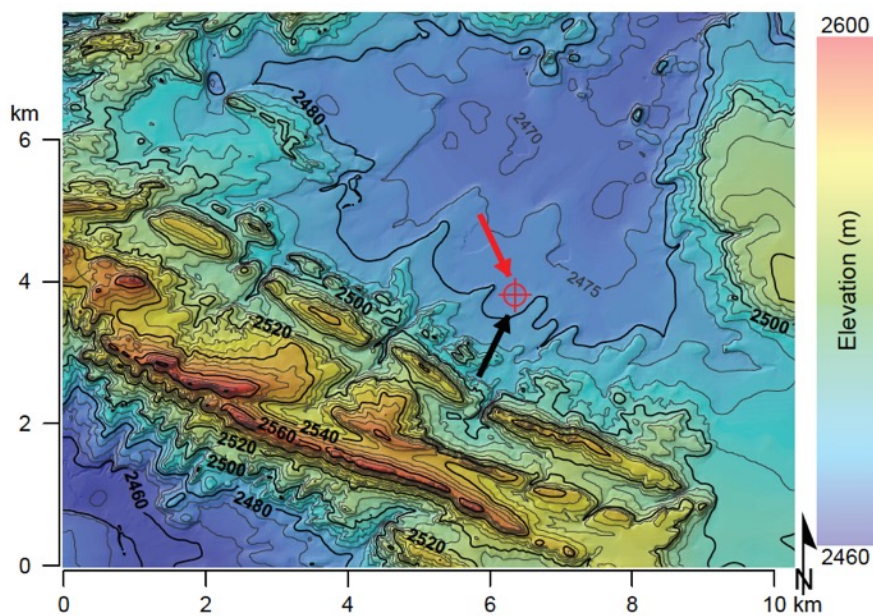
1 min 30 min

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-BV-VARX method**

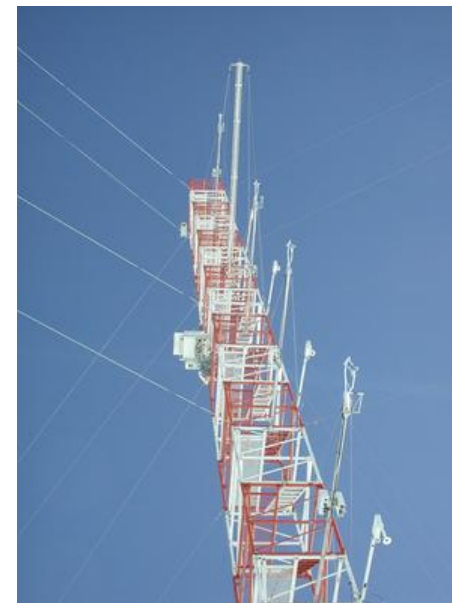
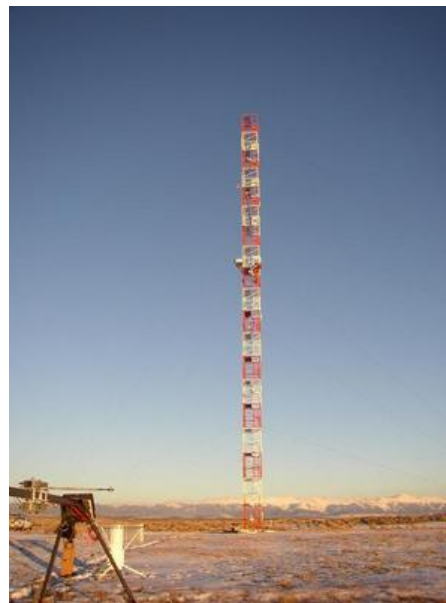
FLOSSII Dataset

Flow Over Snow Surfaces (FLOSSII), Colorado (NCAR)



Arrows: dominant wind directions (black followed by red).

[Mahrt and Vickers, BLM, 2005]

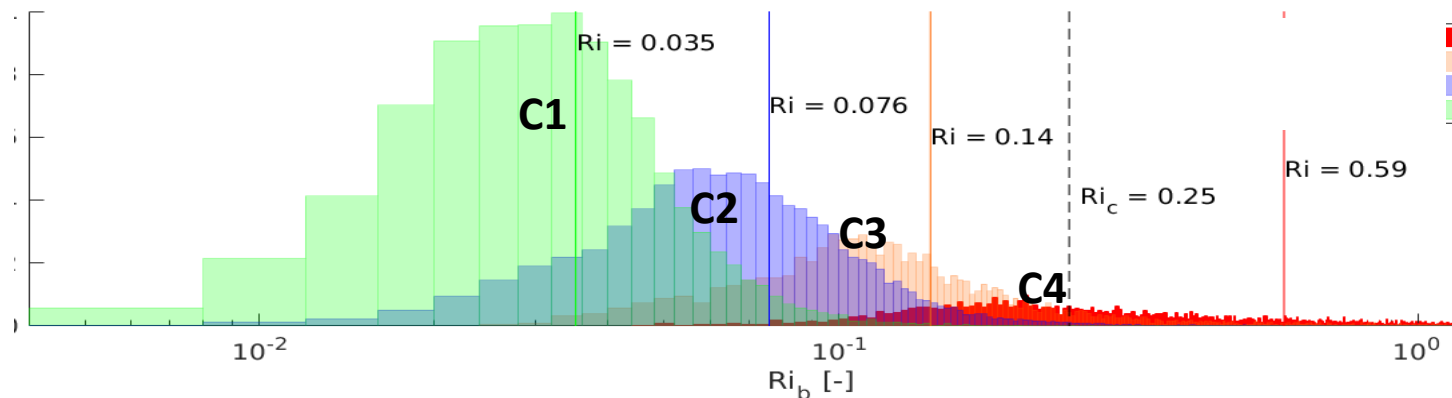
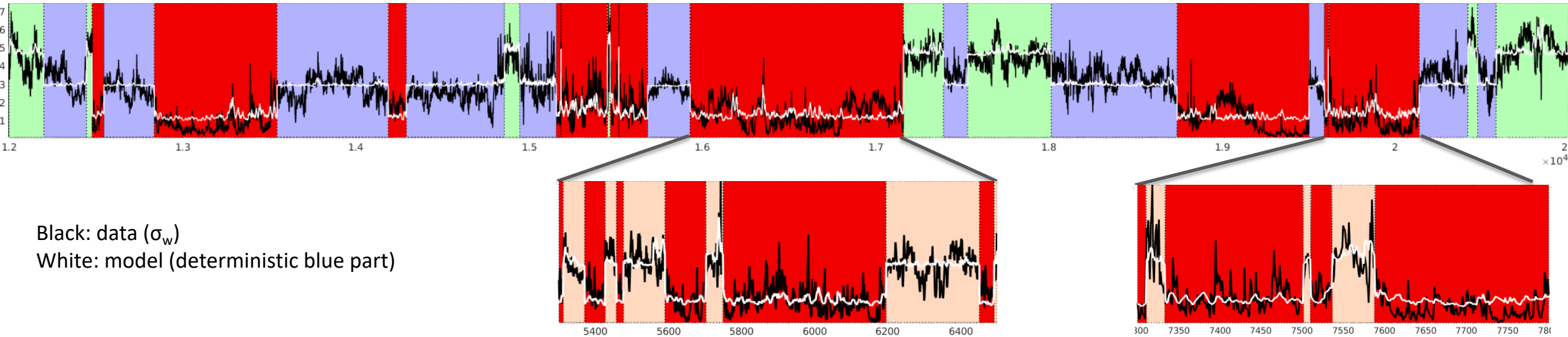


7 measurement heights.

Clustering results – Submeso wind influence

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

$$\sigma_w^t = \mu(t) + B_0(t)u_t^* + \dots + B_p(t)u_{t-p\tau}^* + C(t)\varepsilon_t$$



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

[Vercauteren and Klein, JAS, 2015]

Dynamics of turbulence and Richardson number

Categorizing atmospheric stability: **Richardson number**

Ri number, bulk form:

$$Ri = \frac{\frac{g}{\bar{\theta}} \frac{\Delta \bar{\theta}}{\Delta z}}{\left(\frac{\Delta \bar{u}}{\Delta z} \right)^2 + \left(\frac{\Delta \bar{v}}{\Delta z} \right)^2}$$

Buoyant forces damping
(or generating) turbulence

Shear generating
turbulence

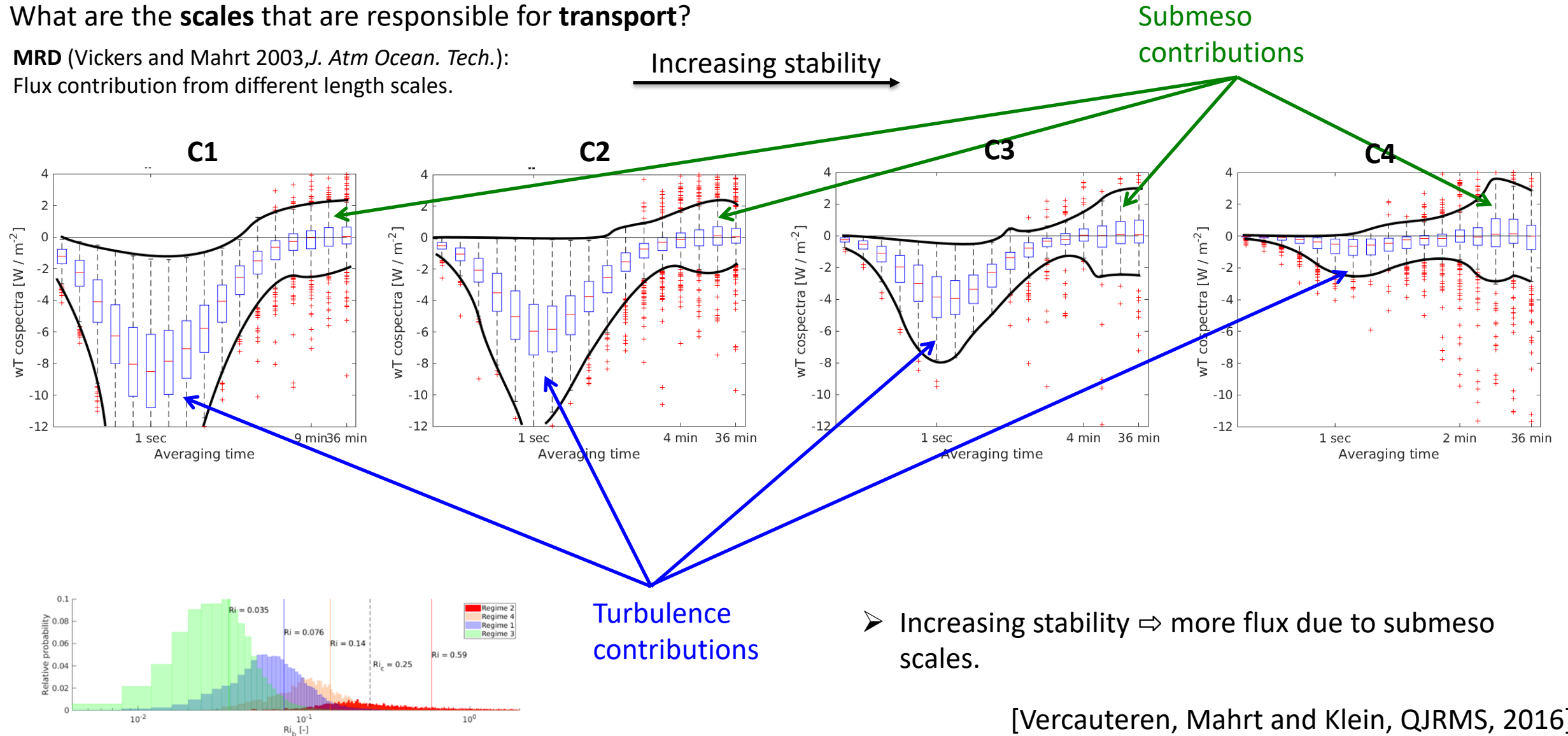
On a clear night the surface is cooled and the boundary layer becomes stable, *Ri* is positive.

Vertical movements of air parcels are **suppressed** (*Ri* large).

Multiresolution flux decomposition

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

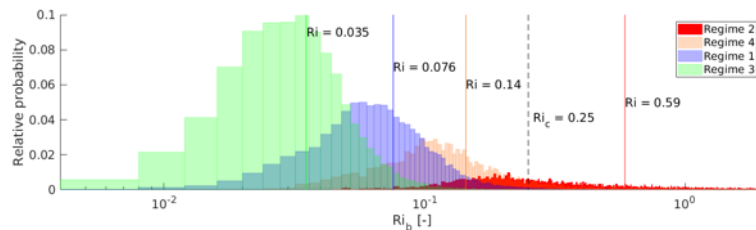
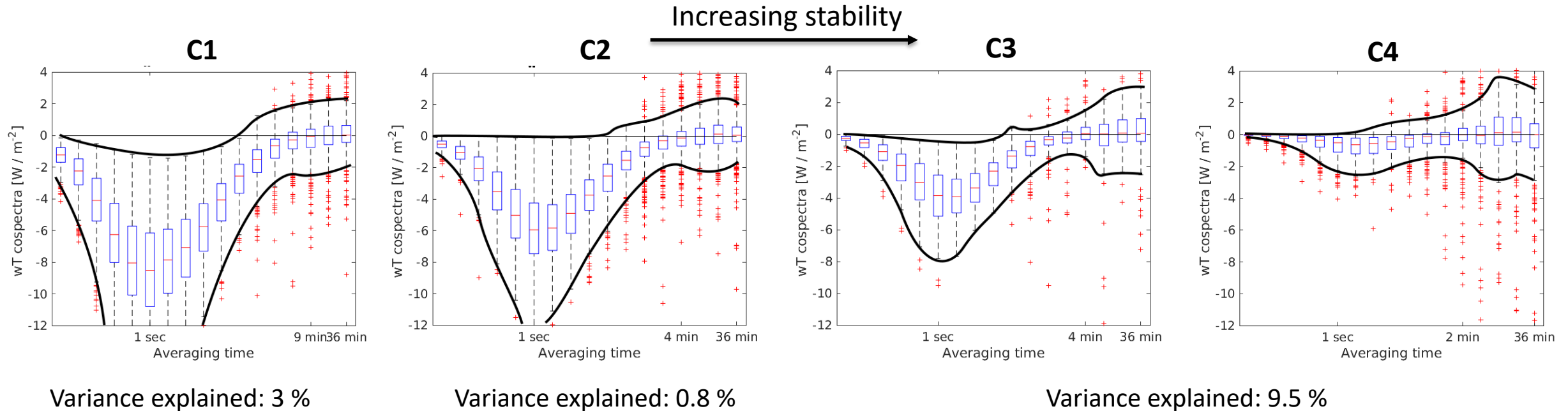
MRD (Vickers and Mahrt 2003, *J. Atm Ocean. Tech.*):
Flux contribution from different length scales.



Multiresolution flux decomposition

How much do **submeso scales** and **vertical velocity variance** relate? Amount of **variance explained** by the statistical model.

$$\sigma_w^t = \mu(t) + B_0(t)u_t^* + \dots + B_p(t)u_{t-pt}^* + C(t)\varepsilon_t$$



- Increasing stability \Rightarrow more flux due to submeso scales.
- Increasing stability \Rightarrow more variance of the signal (σ_w) explained by submeso scale wind variability (u^*).

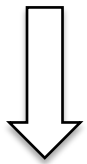
Anisotropy of turbulence

Reynolds stress tensor (1 minute averages):

$$\overline{u'_i u'_j} = \begin{pmatrix} \overline{u'_1 u'_1} & \overline{u'_1 u'_2} & \overline{u'_1 u'_3} \\ \overline{u'_2 u'_1} & \overline{u'_2 u'_2} & \overline{u'_2 u'_3} \\ \overline{u'_3 u'_1} & \overline{u'_3 u'_2} & \overline{u'_3 u'_3} \end{pmatrix}$$

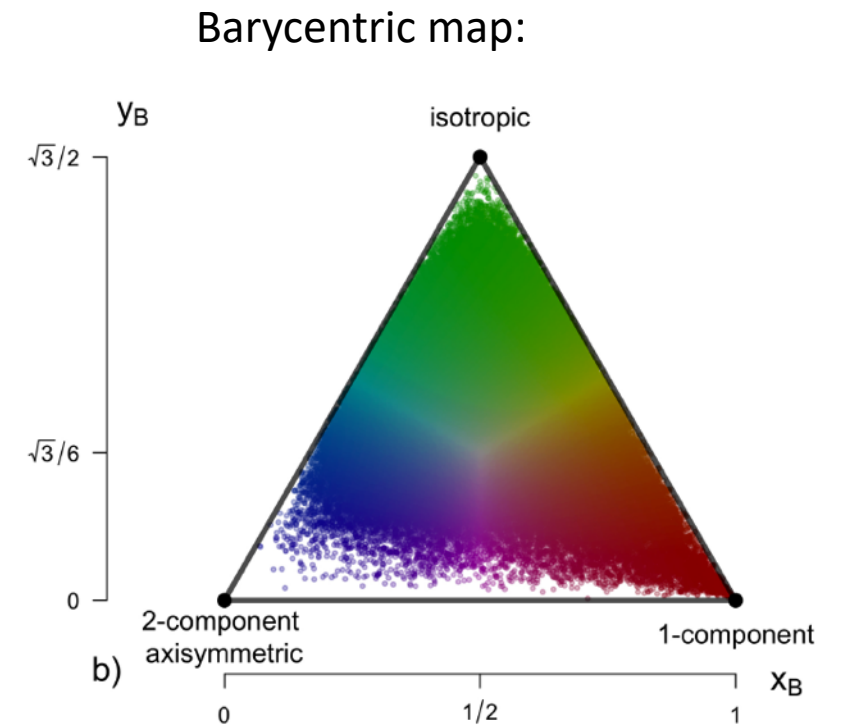
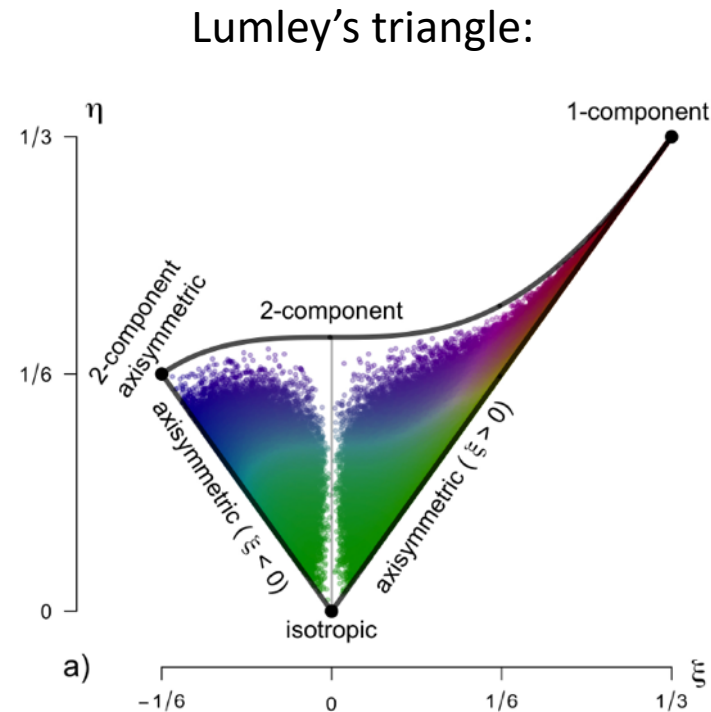
Anisotropy tensor:

$$b_{ij} = \frac{\overline{u_i u_j}}{\overline{u_l u_l}} - \frac{1}{3} \delta_{ij}$$

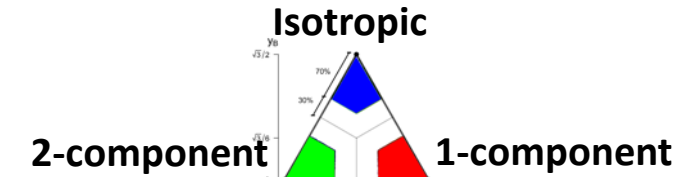
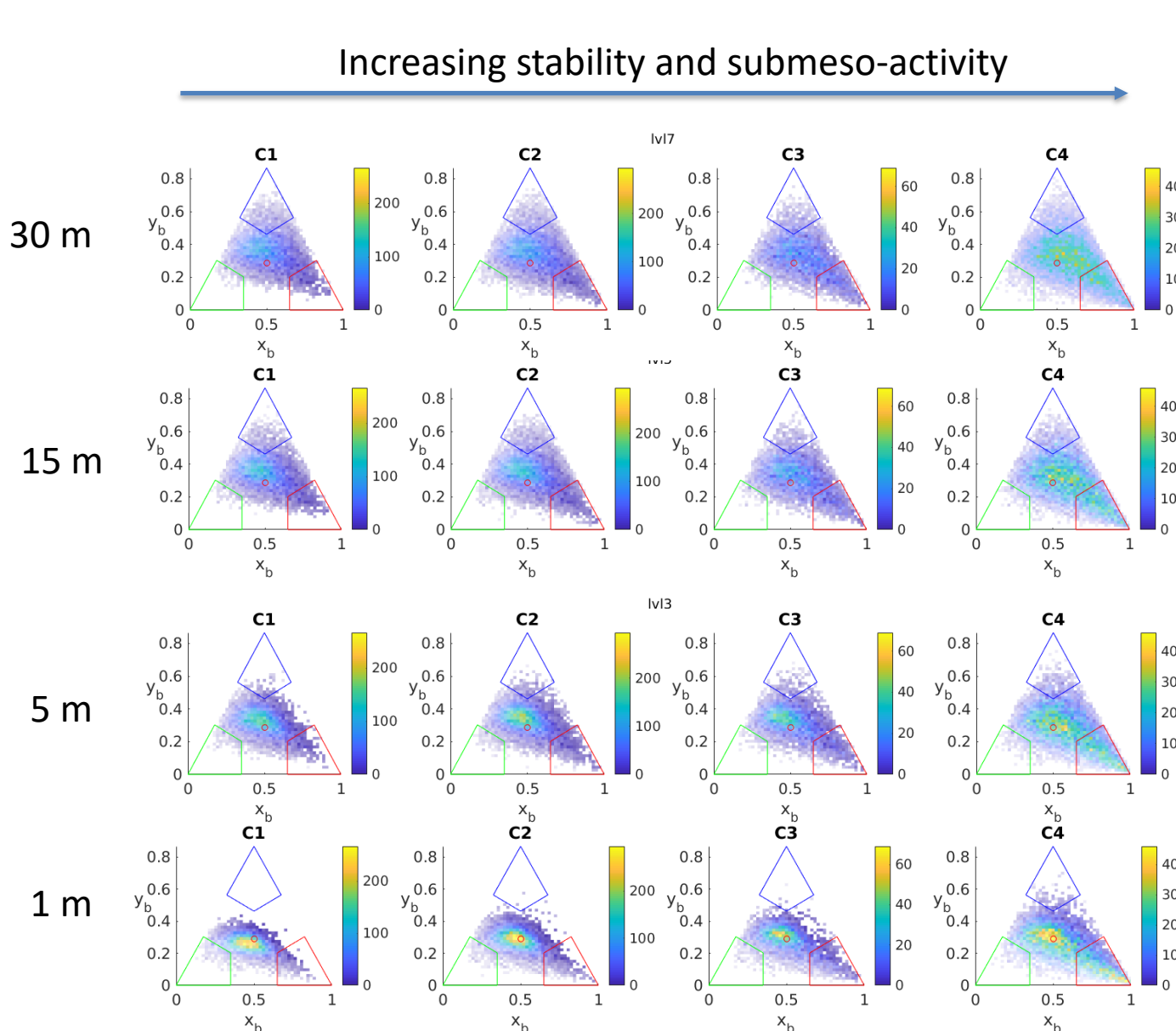


Anisotropy invariant maps:

Lumley's triangle



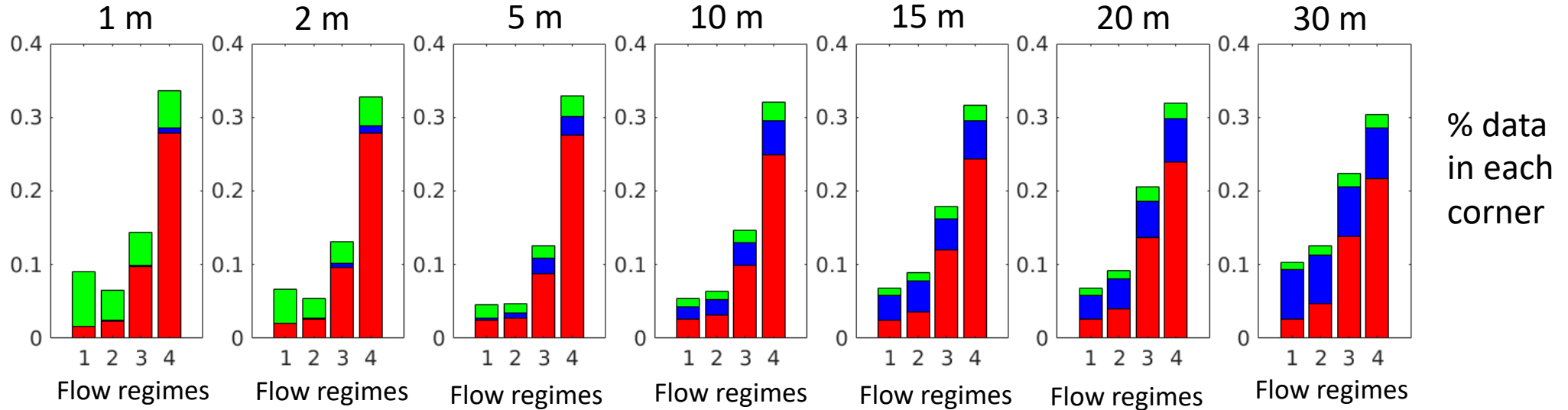
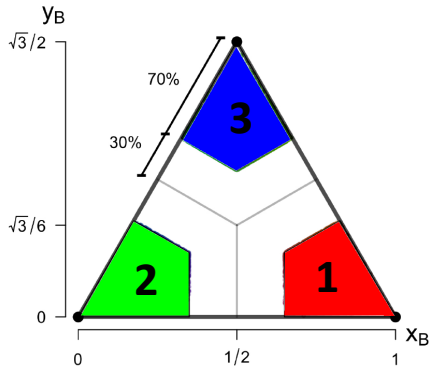
Barycentric maps – height and flow regime dependence



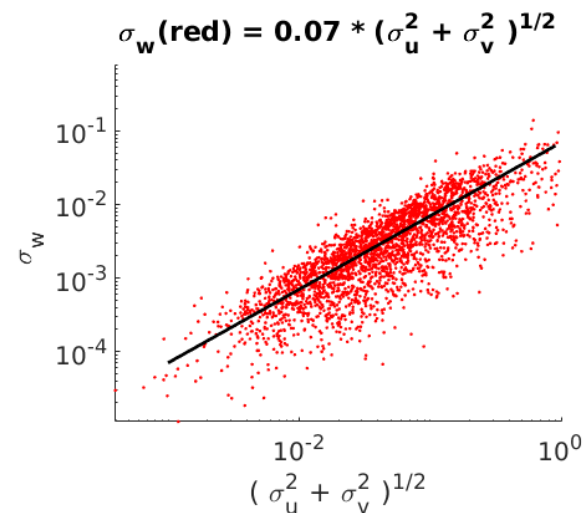
- Isotropic stresses only further from the ground.
- Close to the surface: closer to axisymmetric stresses.
- Submeso-influenced flow regime (C4): preference for 1 component axisymmetric stresses.

Color: Number of cases.

Limiting anisotropy states

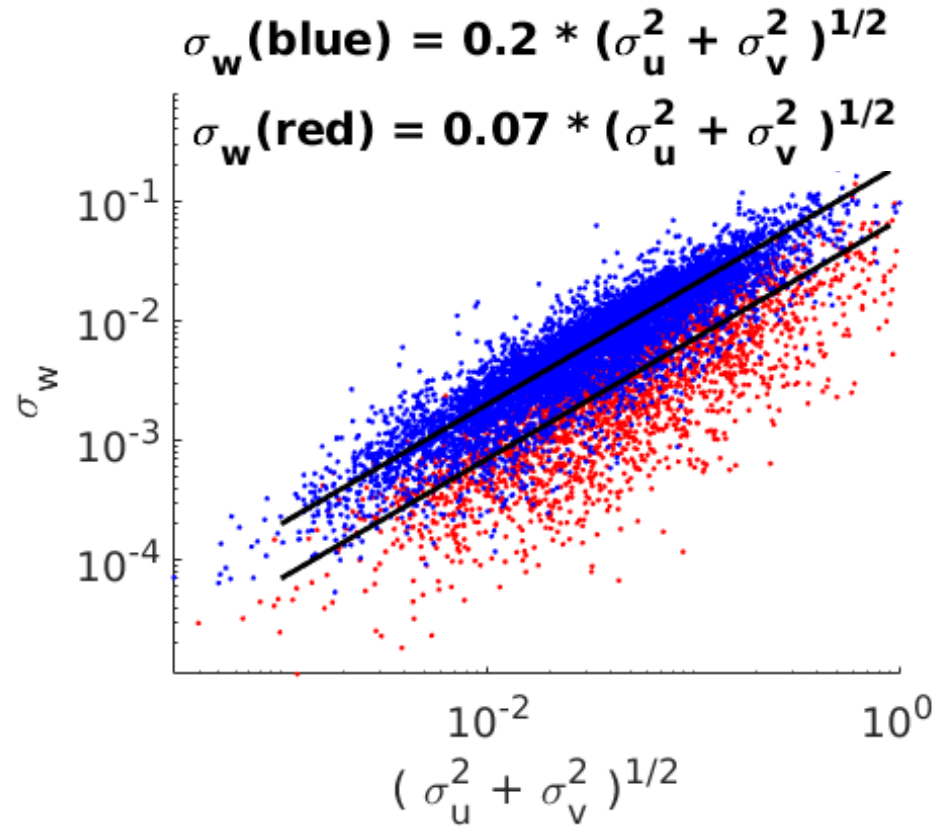
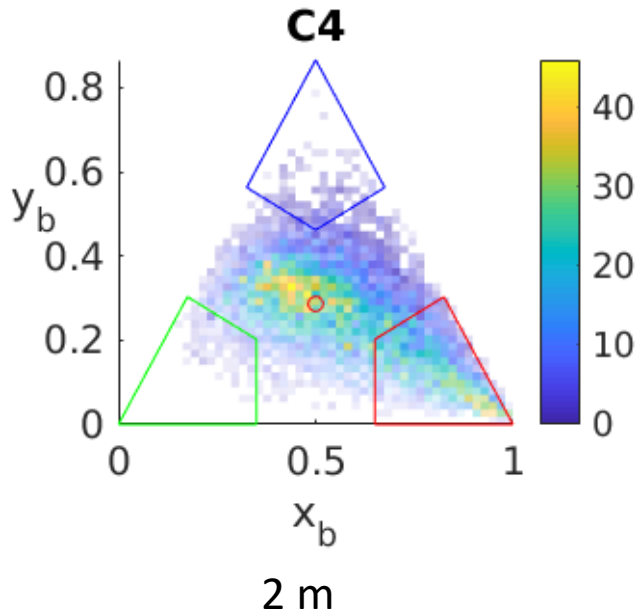


One-component stresses in physical space?
Flow regime C4 at 2 m height:



- Most submeso-influenced regime (C4): largest proportion of 1-component axisymmetric states.
- One-component (C4): “pancake” vortices

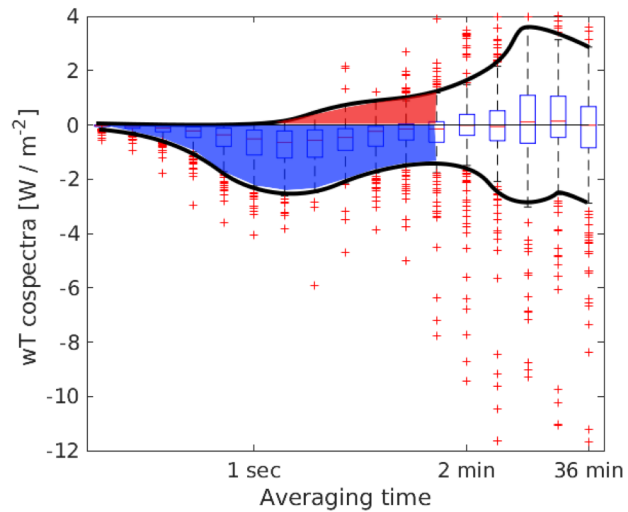
One component axisymmetric state



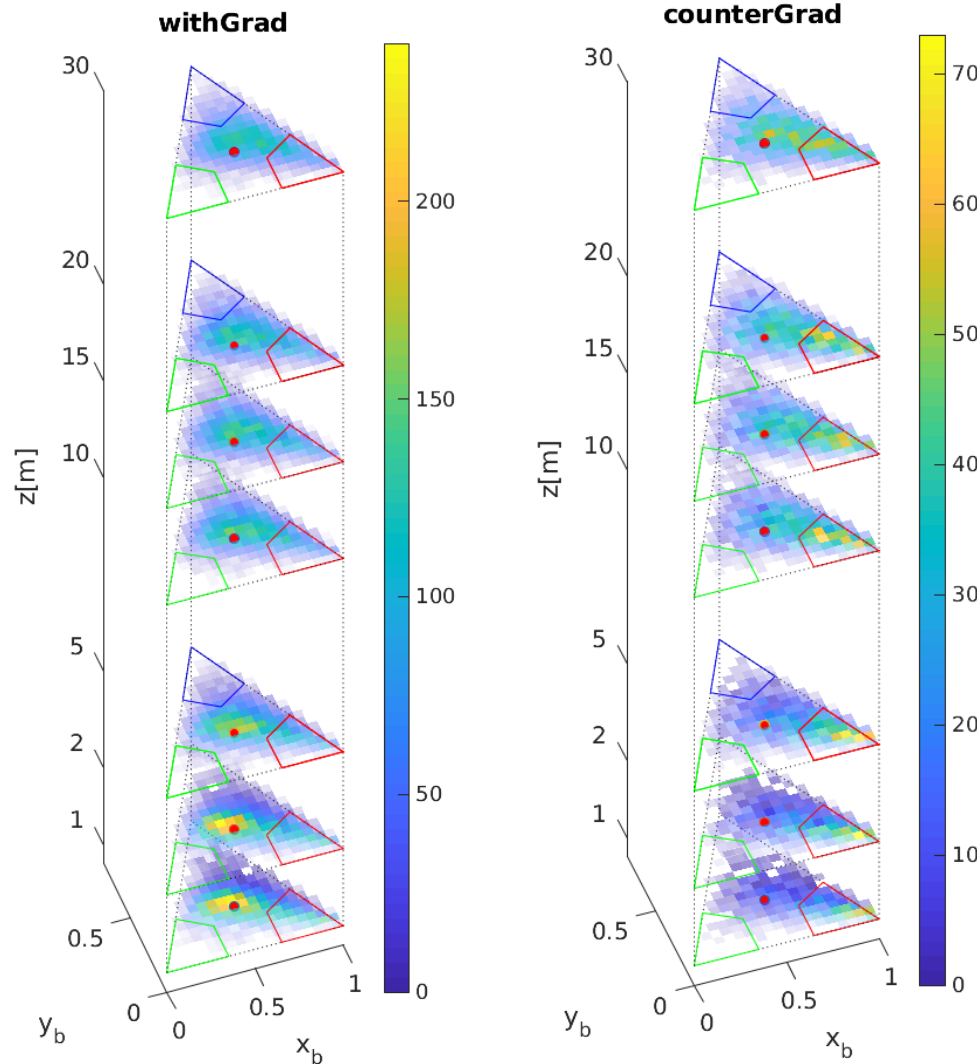
Only non-limiting states

Only limiting (1-component) states

Counter gradient (positive heat flux) cases



Separation of positive and negative heat flux cases (@2 m)



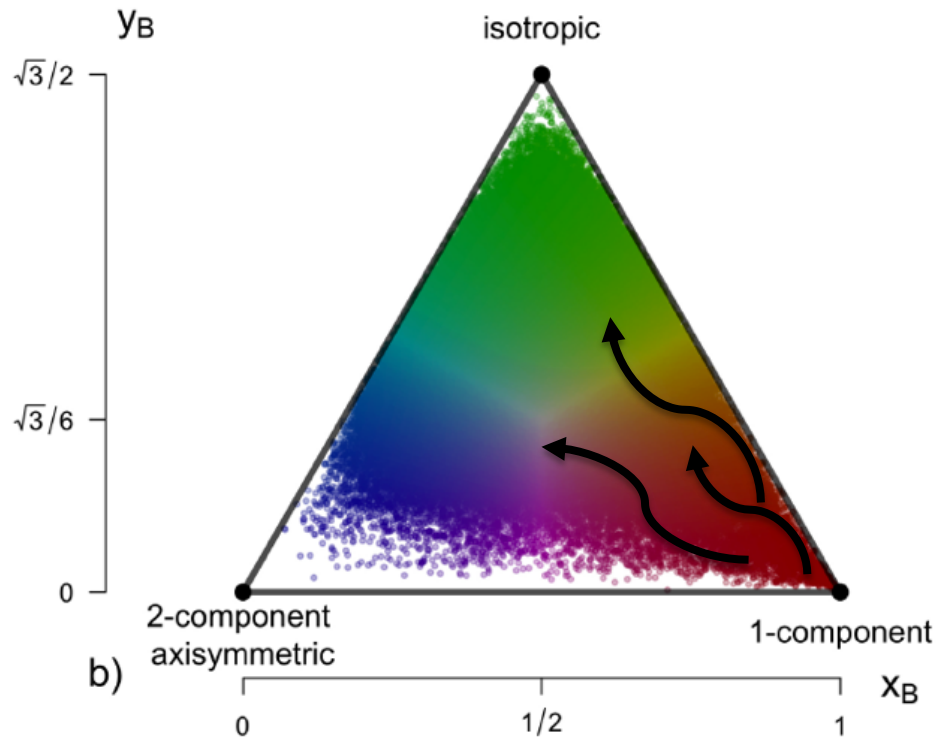
➤ Positive heat flux cases (counter gradient) have predominantly 1-component axisymmetric cases.

Very stable boundary layer turbulence

- Very stable boundary layer:
 - Turbulence influenced by sub-mesoscales just larger than the turbulent scales (**non-equilibrated**)
 - Highly **anisotropic stresses** (one-component), even at small scales (1 minute averaged Reynolds stresses)
 - **Dynamical evolution** of the anisotropic turbulence? Is there a **preferred trajectory** in the anisotropy phase space? How **persistent** are different states of anisotropy?

Dynamical systems viewpoint on the anisotropy

Phase space: barycentric map



- Are there constraints in the time evolution of the states of anisotropy?
- Is there a **preferred direction** in the evolution towards or away from a certain state of anisotropy?
- Consider the barycentric map as a projection of the attractor of our turbulent flow.
- Estimate the **local dimension** of the attractor.
- Estimate the **persistence** of each point of the attractor

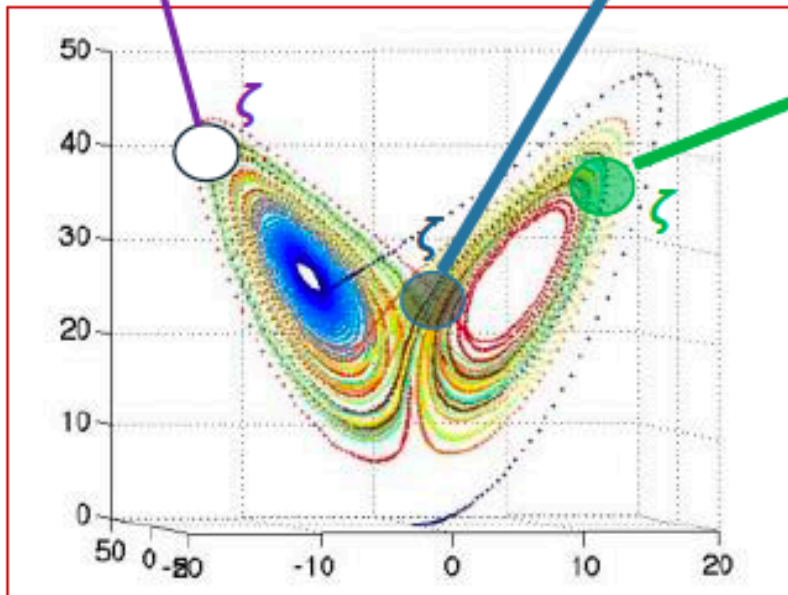
Local dimension of attractors



Line: $d(\zeta)=1$

Patch: $d(\zeta)=2$

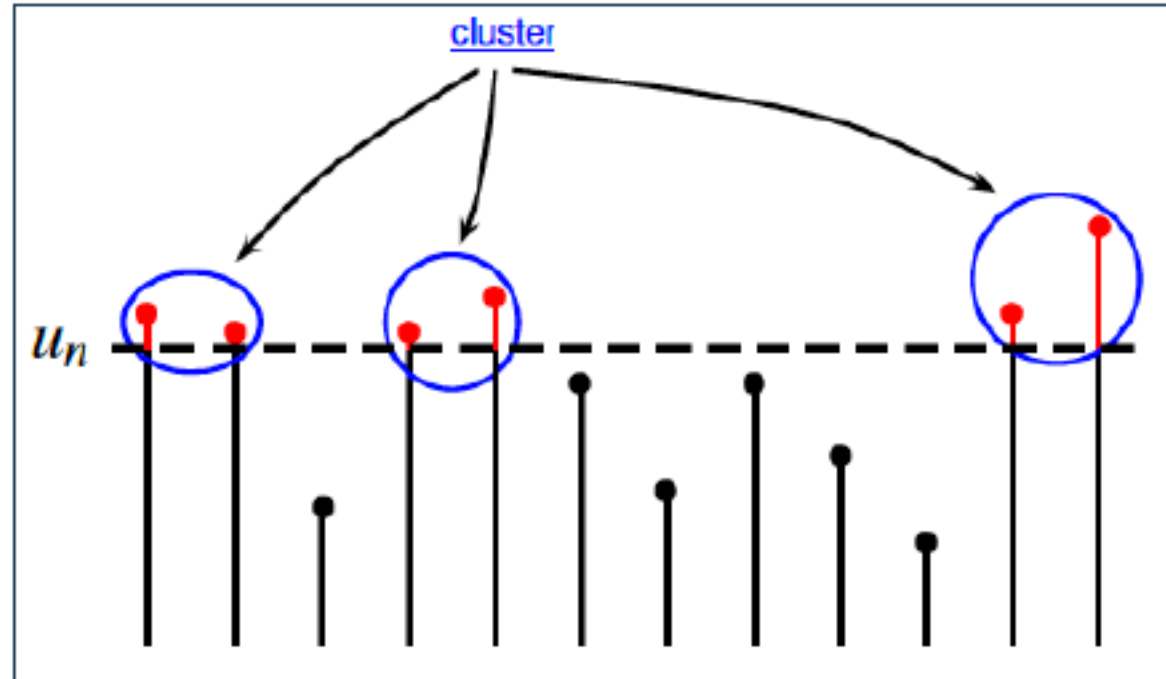
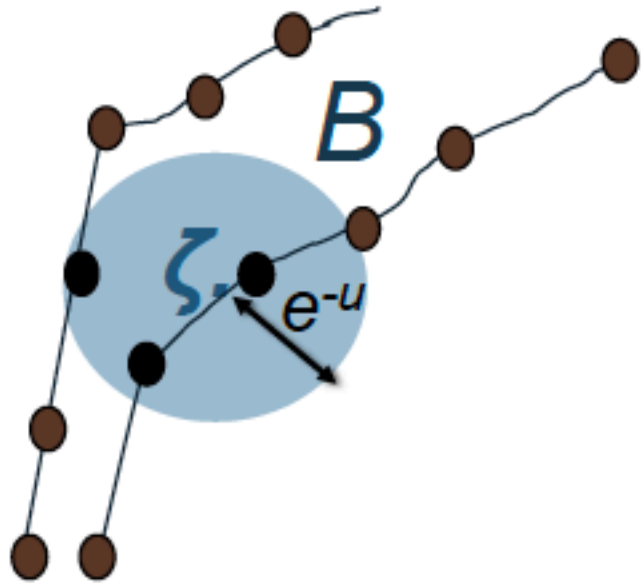
Fractal: $1 < d(\zeta) < 2$



The local dimension depends on the point
of the attractor considered

Computing it from timeseries: Davide's talk

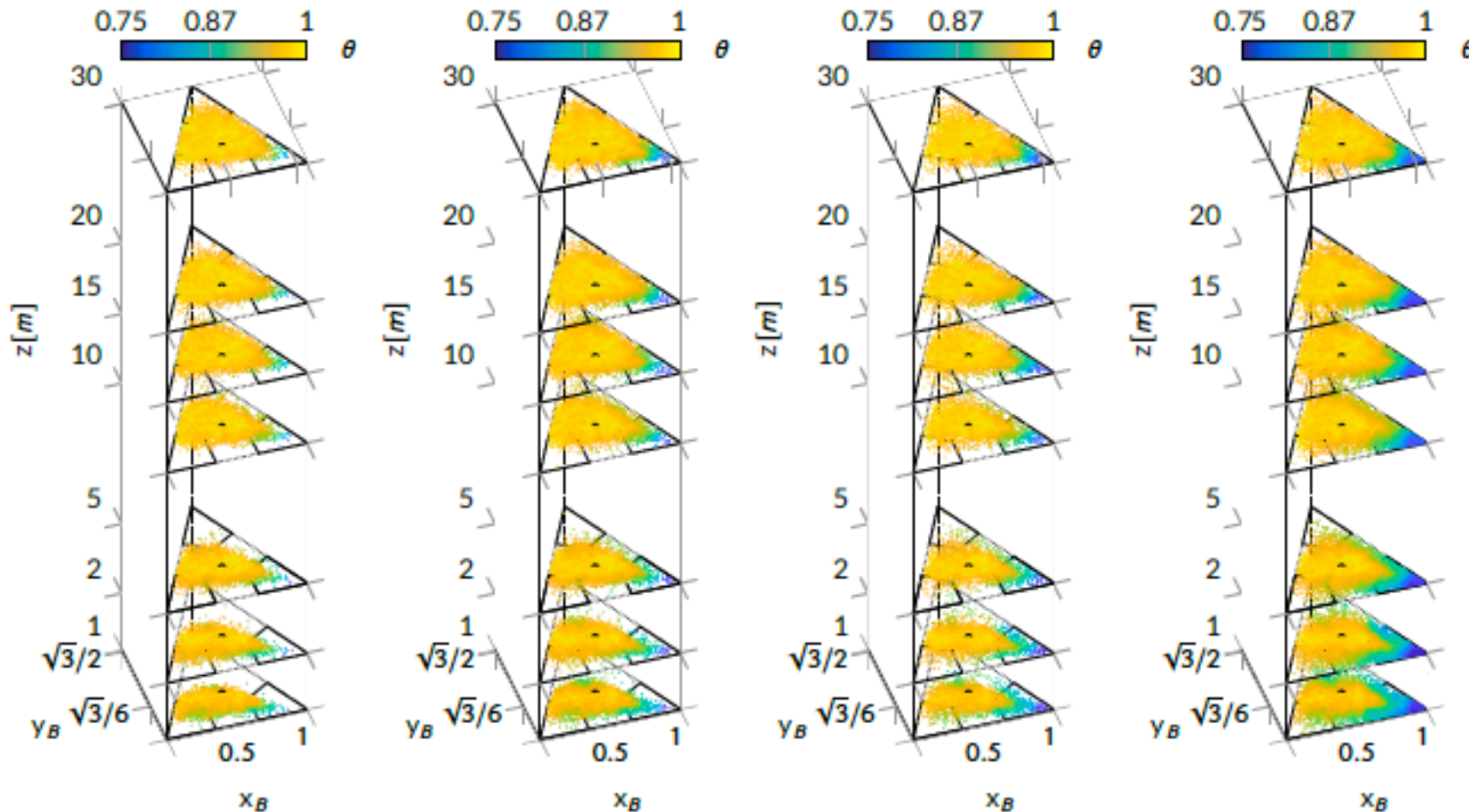
Persistence of dynamical states



If a threshold u is applied to a series of observations x_1, x_2, \dots, x_S , the exceedances are those for which $x_i > u$. The extremal index θ can then be thought of as the average inverse time spent above u .

Persistence of states of anisotropy

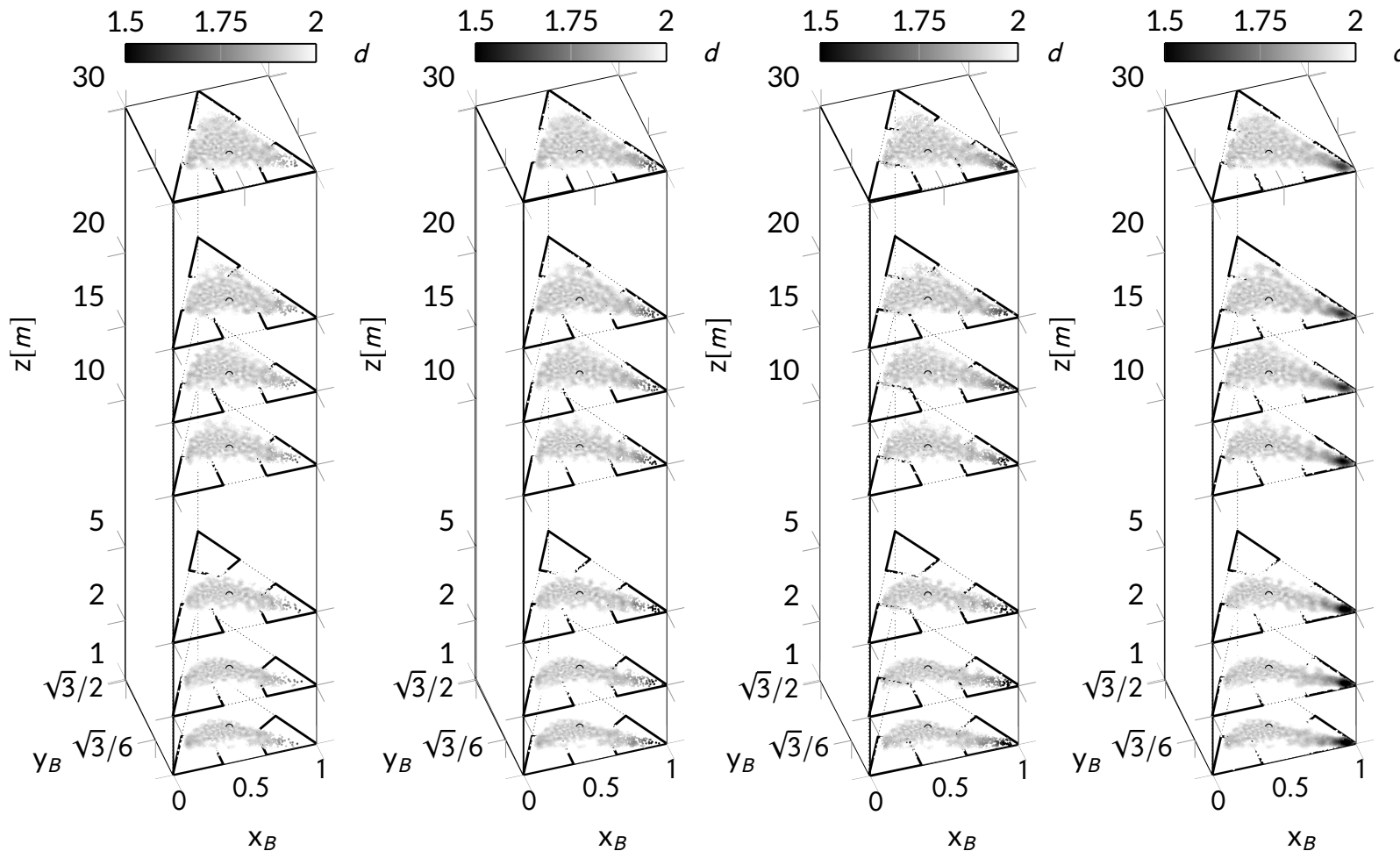
Increasing stability and submeso-activity



- $\Theta=1$: leaves immediately. Smaller, more persistent
- One-component stresses are more persistent in time

Local dimension of the attractor

Increasing stability and submeso-activity



➤ Dimension is smallest near the one-component states of anisotropy

Summary

- The influence of submeso motions on the turbulence differs in different regimes.
- Isotropic stresses are only found in the higher levels.
- Preference for one-component axisymmetric stresses in the most submeso influenced regime.
- Persistence of one-component cases, and preferred direction of evolution

Implication for turbulence parameterisations

- Similarity scaling fails in highly anisotropic conditions – need to revise it in very stable conditions.
- Modelling turbulence diffusivity in very stable conditions requires modelling the anisotropy.
- The anisotropy matters when the variability of sub-mesoscales is comparable or larger than the variability of turbulent scales.
- Preferred route towards or away from one-component anisotropy: study it to adapt return-to-isotropy schemes.

Thank you!

FLOSSII data from Larry Mahrt, field campaign by NCAR

FEM-VARX method by the team of Illia Horenko