LES of turbulent wind flows in the Atmospheric Boundary Layer

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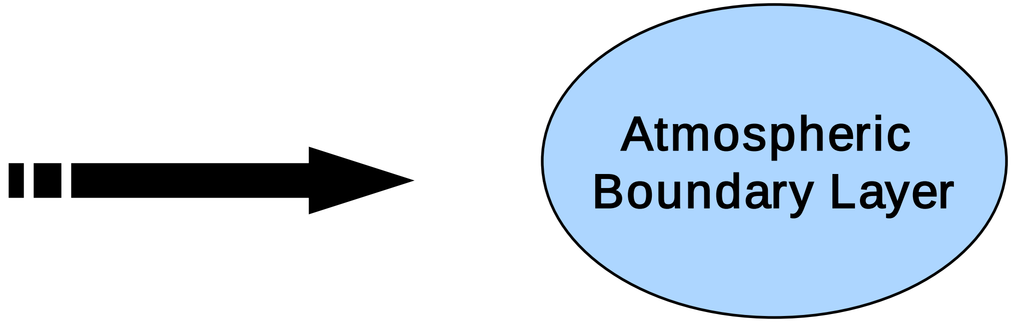
Wind Resource Assessment: The Process



Wind Resource Assessment: The Process

Atmospheric Boundary Layer

- Turbulence
- Vertical structure / Wind shear
- Diurnal variability
- Spatial variability (heterogeneity)
- Land-atmosphere interactions
- Flow – structure interactions/ Wake

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Wind Resource Assessment

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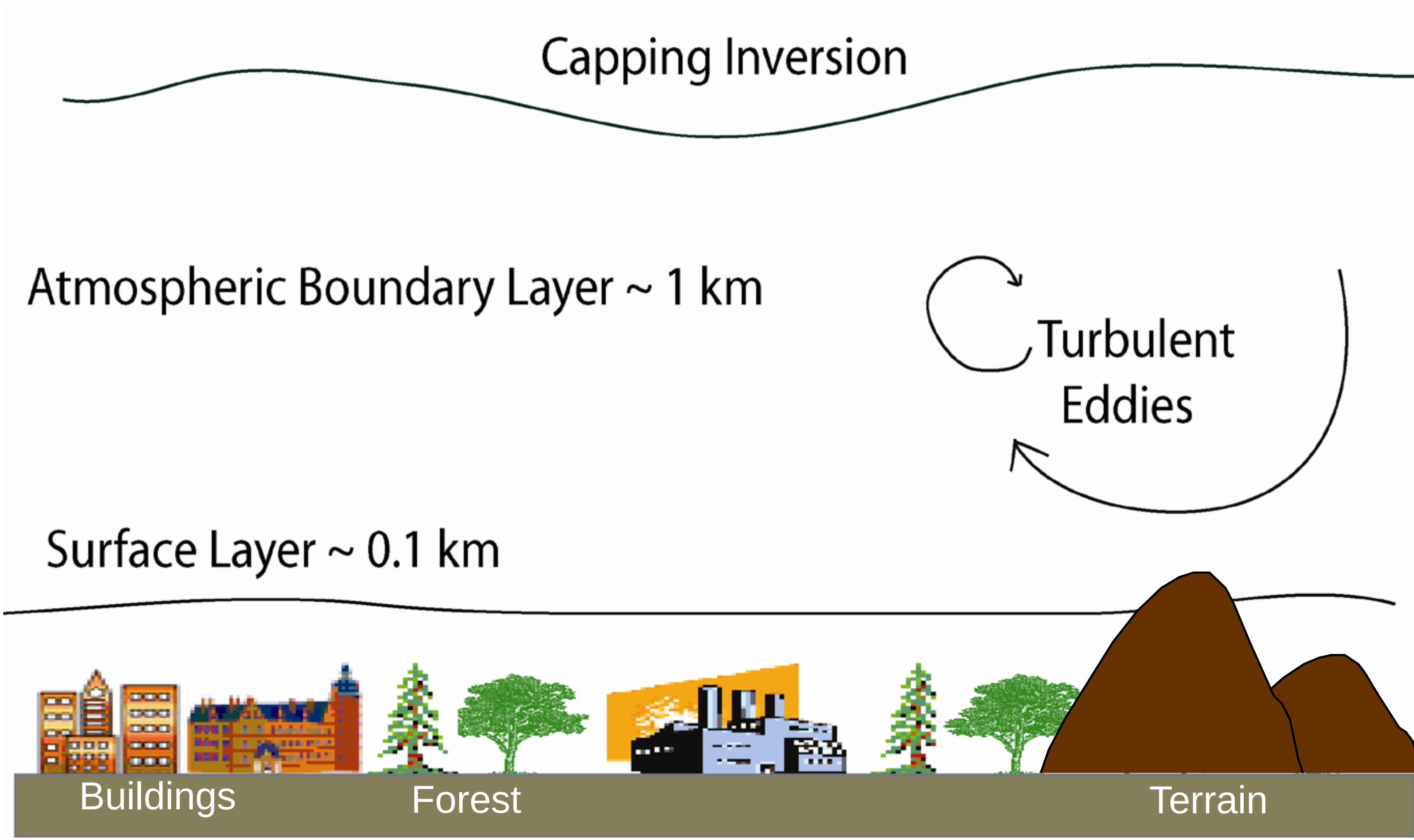
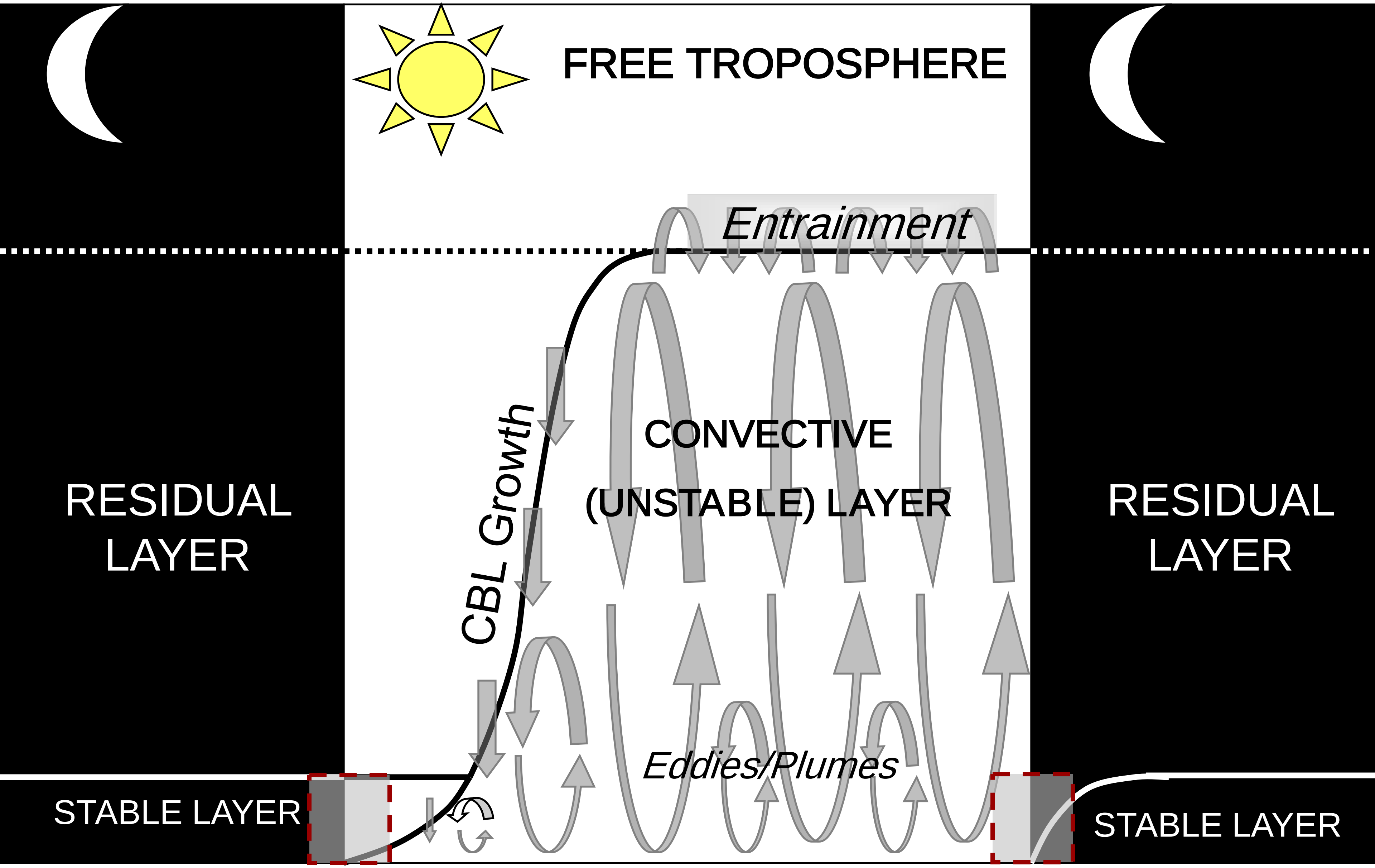
Wind Resource Assessment

Atmospheric Boundary Layer: Spatial Complexity



Atmospheric Boundary Layer: Temporal Complexity



Understanding the ABL: Methods

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Observational/
Experimental

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Observational/ Experimental

+

- “Truth”
- Code / model validation

-

- Height limitations
- Lack of spatial info
- Sensitivities
- Expensive
- Not comprehensive

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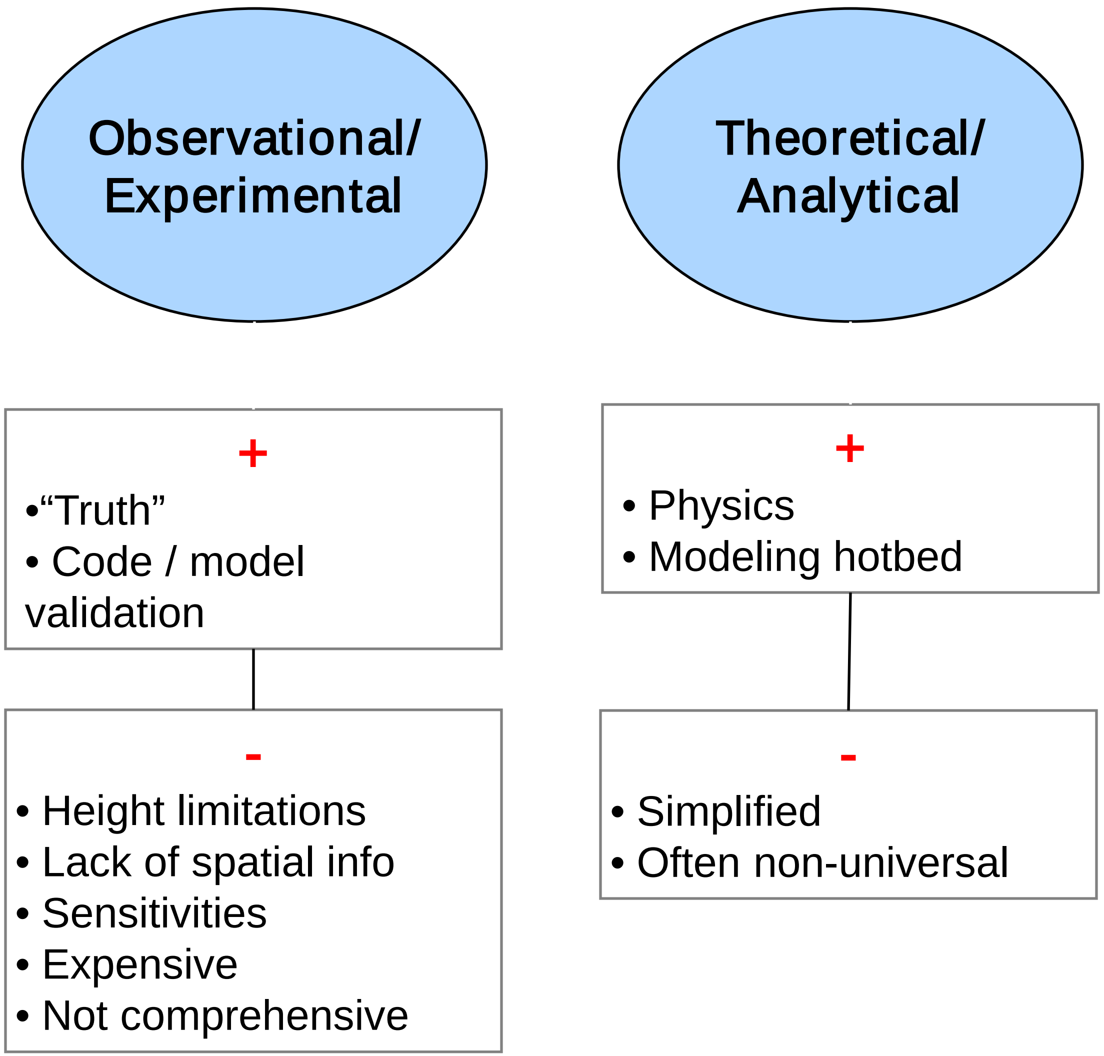

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- Simplified
- Often non-universal

Numerical/ Computational

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Numerical/ Computational

\+
- Complex flows
- Repeatability
- Test models

\-
- Infrastructure
- Accuracy / Validation
- Over-tweaking
- GIGO

CFD: Microscale ABL flow (DNS, LES, RANS)

DNS: Direct Numerical Simulation

LES: Large Eddy Simulation

RANS: Reynolds Averaged Navier-Stokes Model

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Level of Detail: DNS>LES>>RANS
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Direct Numerical Simulation (DNS) → Resolve all scales

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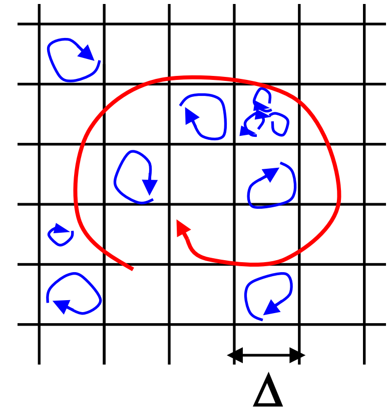
Large Eddy Simulation (LES)

- Predict instantaneous flow characteristics **(+)**
- A large portion of the turbulence spectrum is completely resolved **(+)**
- Represent complex flow regimes such as separation, wakes, stability transitions & stable boundary layers **(+)**
- Subgrid scale models can be universally applied **(+)**
- High computational cost: Parallel **(-)**
- Quality of results = $f(\text{user})$ => GIGO **(-)**

Large Eddy Simulation (LES)

Incompressible Navier-Stokes, Re ~ 10^8



Filtering

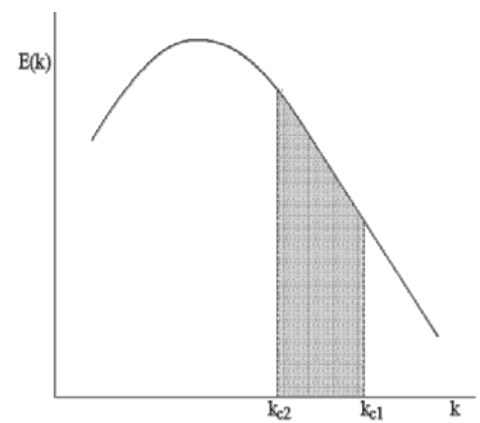
$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + g\left(\frac{\tilde{\theta} - \tilde{\theta}_0}{\tilde{\theta}_0}\right)\delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - V_g)\delta_{i1} - f(\tilde{u}_1 - U_g)\delta_{i2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j}$$

$$\tau_{ij} = \widetilde{u_i u_j} - \widetilde{u_i}\widetilde{u_j} \qquad \pi_{ij} = \widetilde{u_i \theta} - \widetilde{u_i}\widetilde{\theta}$$

Subgrid scale modeling

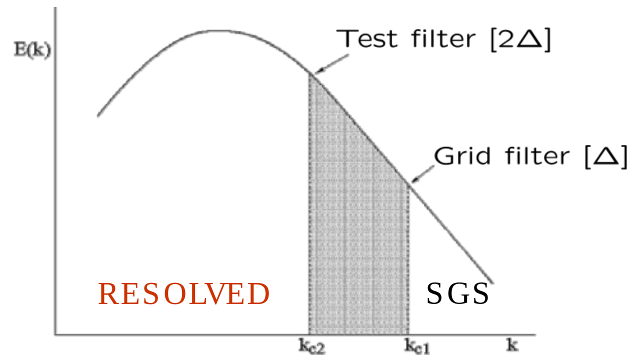


LES: SGS Modeling

$$\tau_{ij} = -2\nu_t \widetilde{S}_{ij};\ \pi_j = -\frac{\nu_t}{Pr_{sgs}}\frac{\partial\widetilde{\theta}}{\partial x_j};\ \nu_t = (C_{s,\Delta}\Delta)^2|\widetilde{S}_{ij}|;\ \widetilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial\widetilde{u}_i}{\partial x_j} + \frac{\partial\widetilde{u}_j}{\partial x_i}\right)$$

Eddy Viscosity (ν_t) type models:

Static Smagorinsky	Dynamic Model
Constant value $C_{s,\Delta}$ imposed everywhere	• $C_{s,\Delta}$ determined dynamically from the resolved scales • $C_{s,\Delta}$ is spatially averaged

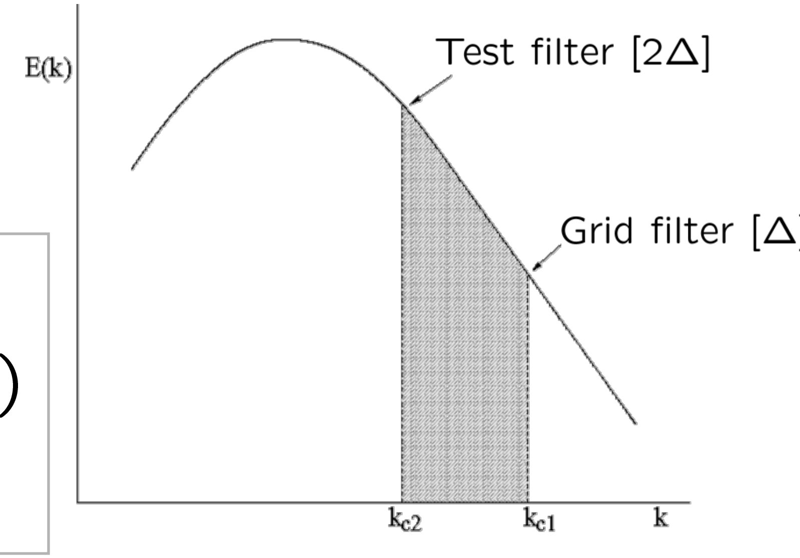


Dynamic SGS model formulation

$$\tau_{ij}^{\Delta} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$$

$$\tau_{ij}^{\Delta,\mathrm{m}} = -2(C_{s,\Delta}\Delta)^2 |\tilde{S}_{ij}| \tilde{S}_{ij}$$

$$\begin{aligned} L_{ij} &= T_{ij} - \hat{\tau}_{ij} \\ &= \widehat{\widetilde{u_i u_j}} - \hat{\tilde{u}}_i \hat{\tilde{u}}_j - \left(\widehat{\widetilde{u_i u_j}} - \widehat{\tilde{u}_i \tilde{u}_j}\right) \\ &= \widehat{\tilde{u}_i \tilde{u}_j} - \hat{\tilde{u}}_i \hat{\tilde{u}}_j \end{aligned}$$



$$L_{ij}^m = T_{ij}^m - \widehat{\tau_{ij}^m}$$

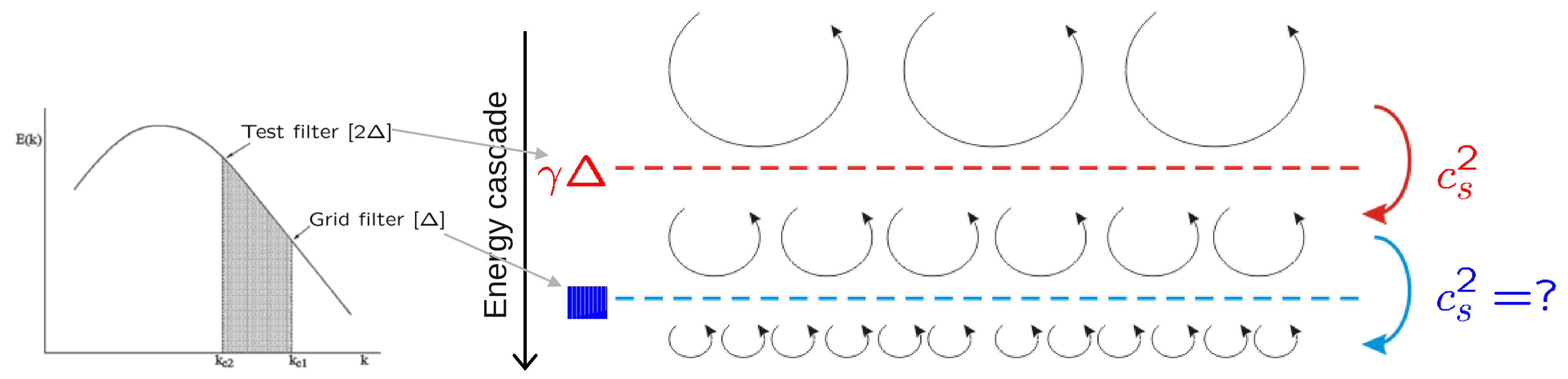
Assume scale invariance → $C_{s,2\Delta} = C_{s,\Delta}$

$$L_{ij}^m = C_{s,\Delta}^2 M_{ij};\ M_{ij} = 2(\Delta)^2 \widehat{|\tilde{S}|\tilde{S}_{ij}} - 2(2\Delta)^2 |\hat{\tilde{S}}| \hat{\tilde{S}}_{ij}$$

$$e_{ij} = L_{ij} - L_{ij}^m = L_{ij} - C_{s,\Delta}^2 M_{ij}$$

Minimize e_{ij} → $$C_{s,\Delta}^2 = \frac{\langle L_{ij}^m M_{ij} \rangle}{\langle Mij M_{ij} \rangle}$$

SGS modeling: The Dynamic model



Scale invariance

$$c_s^2 = c_s^2$$

→

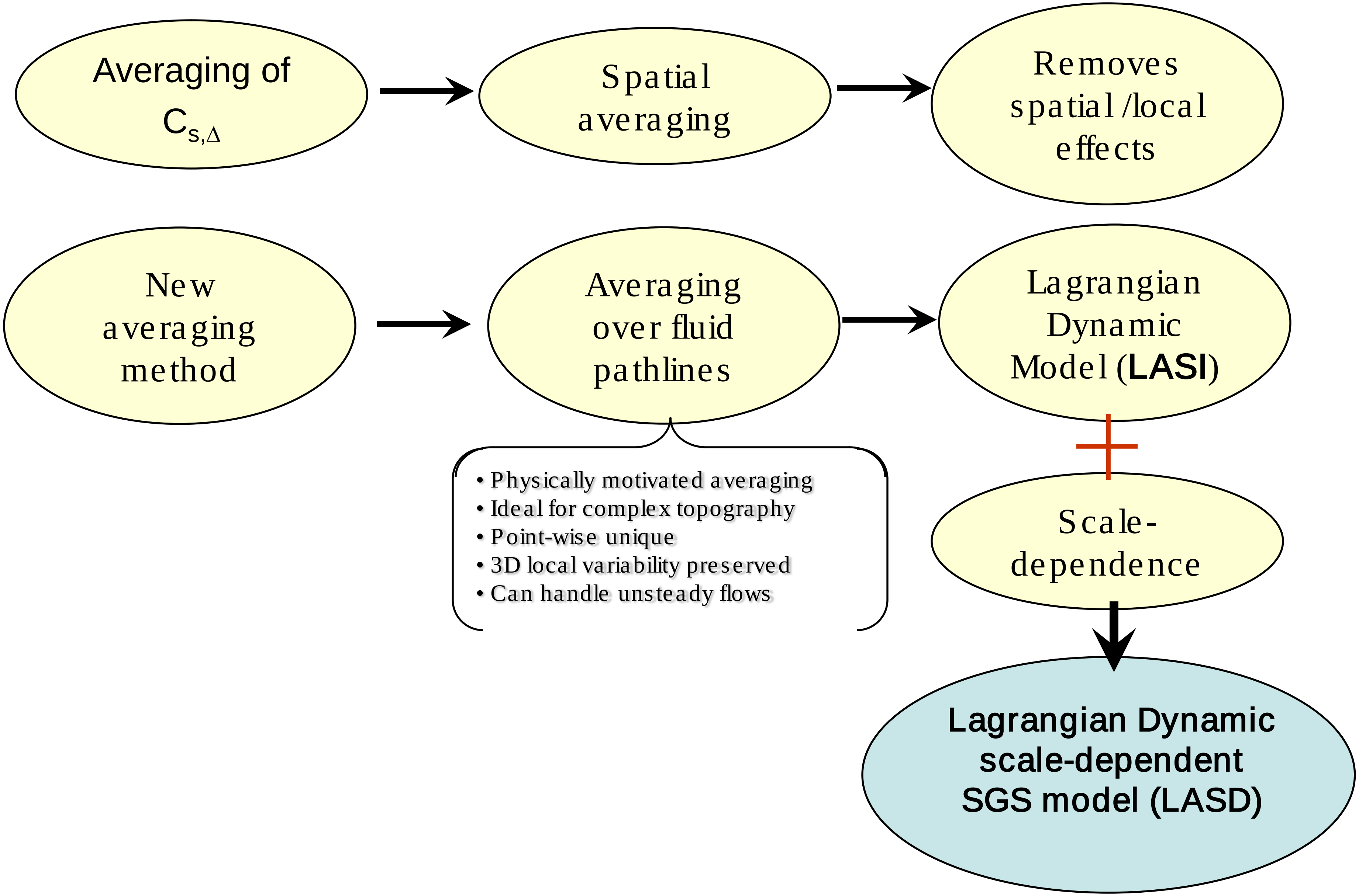
- Does not hold in near-surface region
- Results in incorrect energy dissipation

→

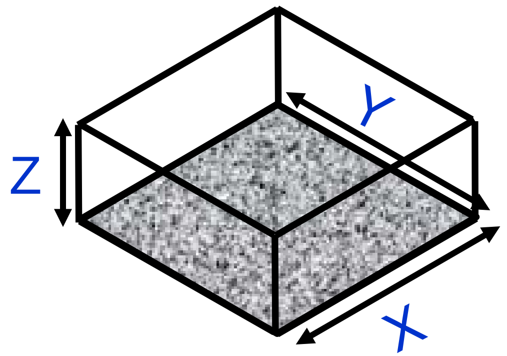
Scale Dependence

$$c_s^2 = \beta c_s^2$$

SGS modeling: Lagrangian averaging



LES code

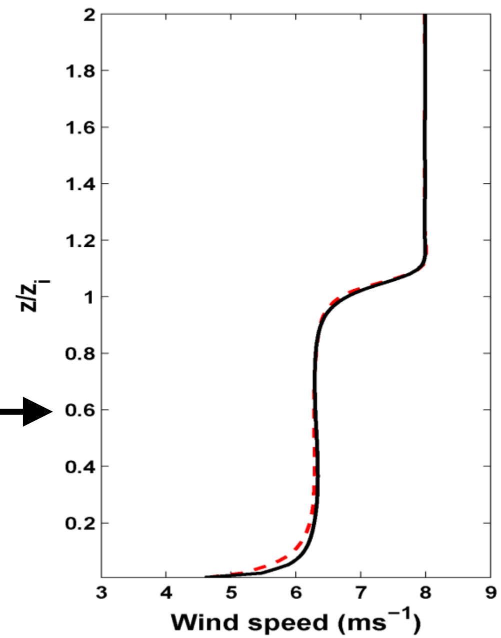


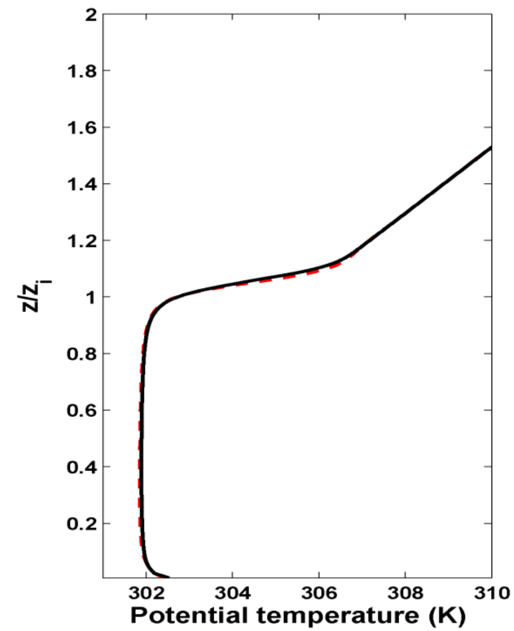
- Modular Fortran 90/95
- Parallel with FFTW solver
  - Independently verified to be the most efficient parallel code on the NCAR supercomputing clusters
- Lagrangian scale-invariant (LASI) and scale-dependent (LASD) SGS models
- Stability effects => Potential Temperature, Humidity
  - Surface boundary conditions : **Flux** or **Temperature**
- Derivatives: Pseudo-spectral (x,y), finite difference (z)
- Pressure forcing: Geostrophic wind (U_g,V_g)
- Terrain: Level set method, Immersed boundary method

LES of Unstable ABL

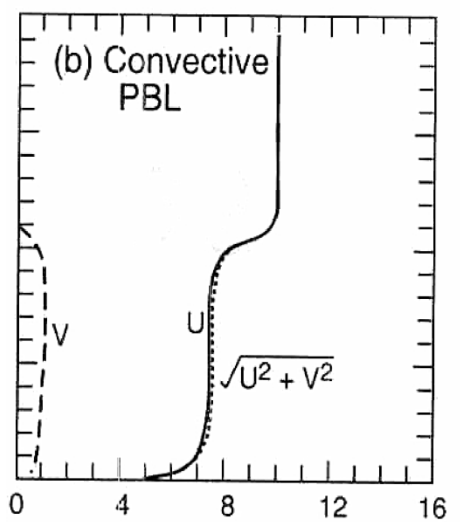
Good agreement:

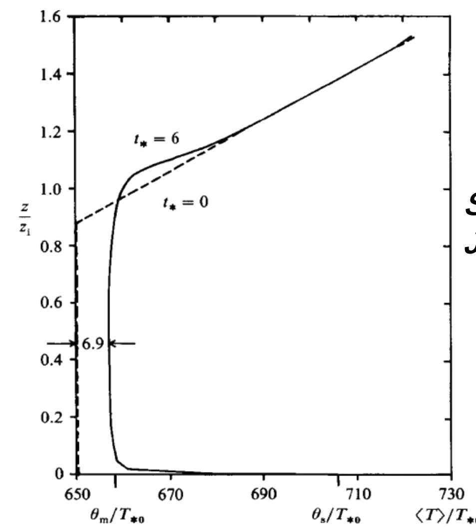
“Large structures”





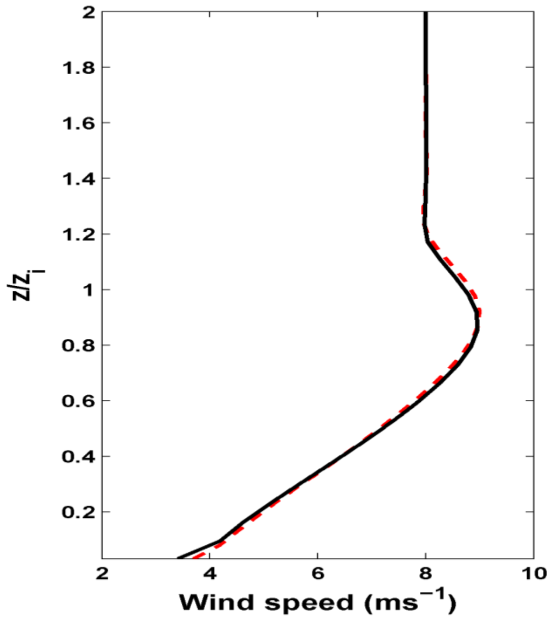
Moeng and Sullivan, JAS, 1994

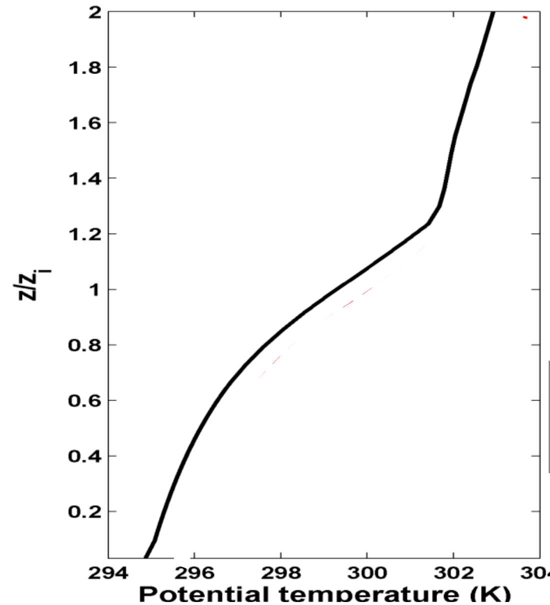




Schmidt and Schumann, JFM, 1989

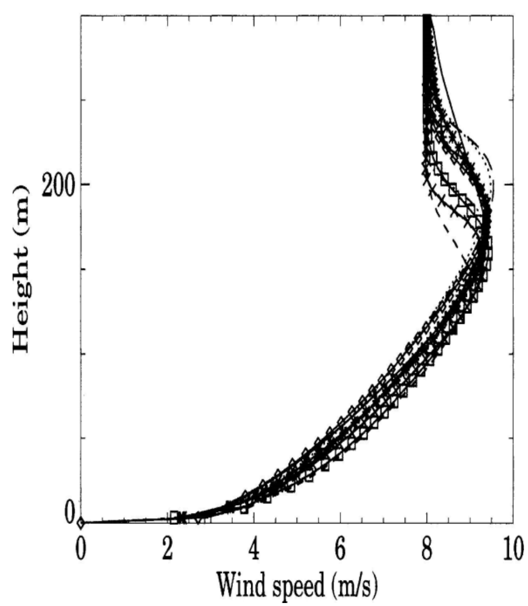
LES of Nocturnal Stable ABL

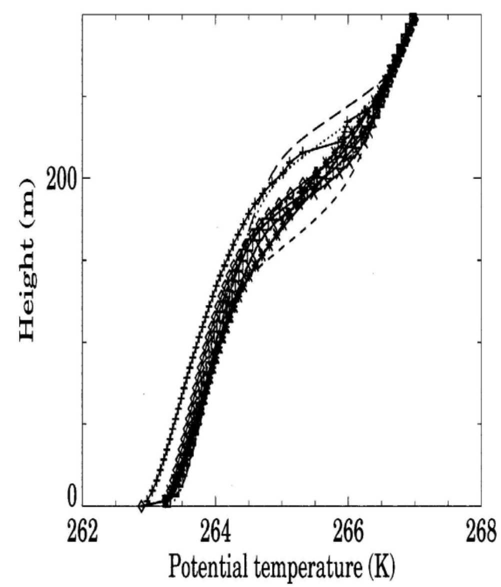




SGS models become important

Beare et al., BLM, 2006





Beare et al., BLM, 2006

LES of Quasi-steady ABLs: A review

Unstable ABL (Schmidt & Schumann, 1989; Nieuwstadt et al., 1991)

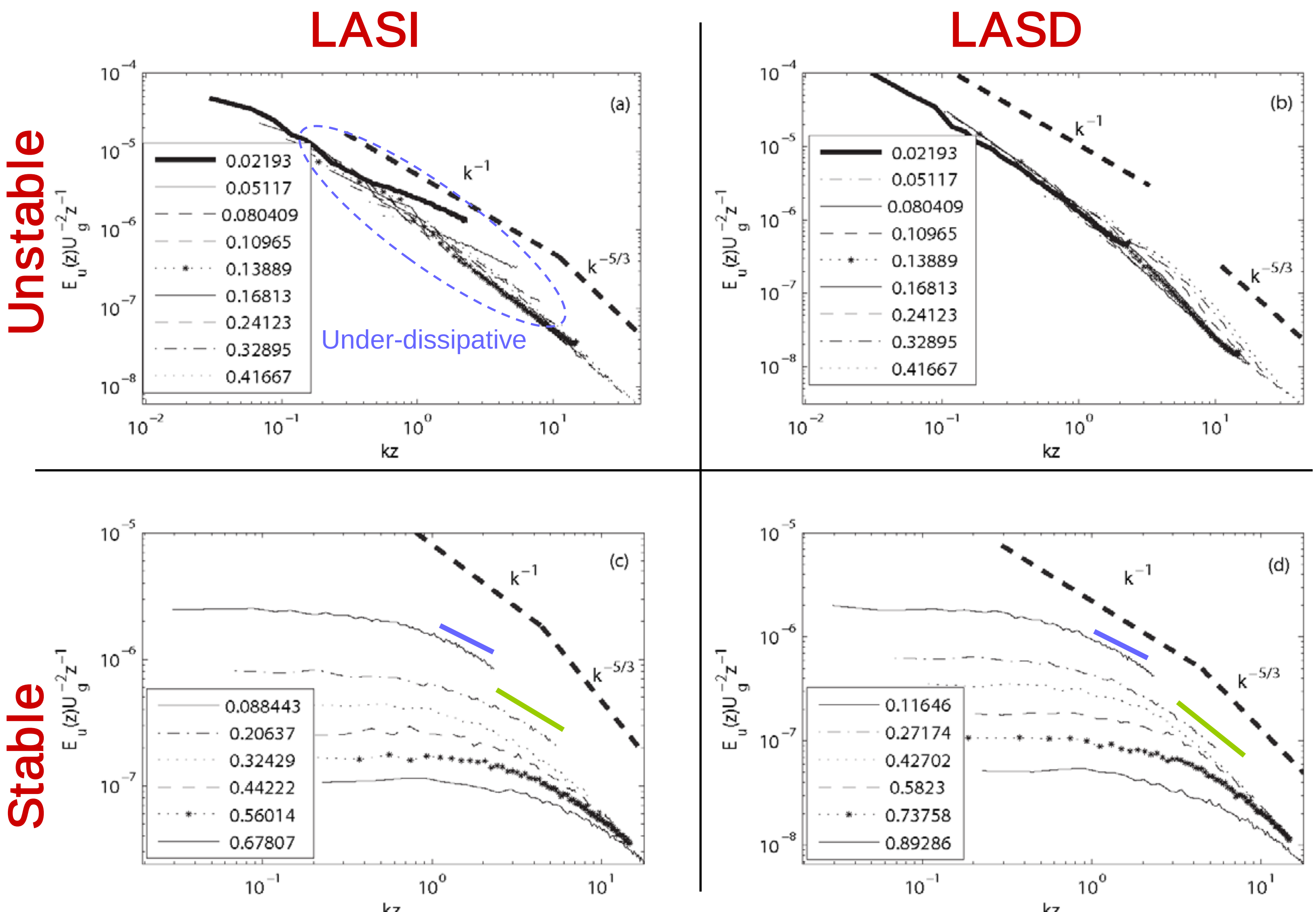
- Suited for LES: Large-scale structures e.g. plumes, thermals
- Energy spectra: Over-dissipative SGS models

Stable ABL (Kosovic & Curry, 2000; Beare et al., 2006)

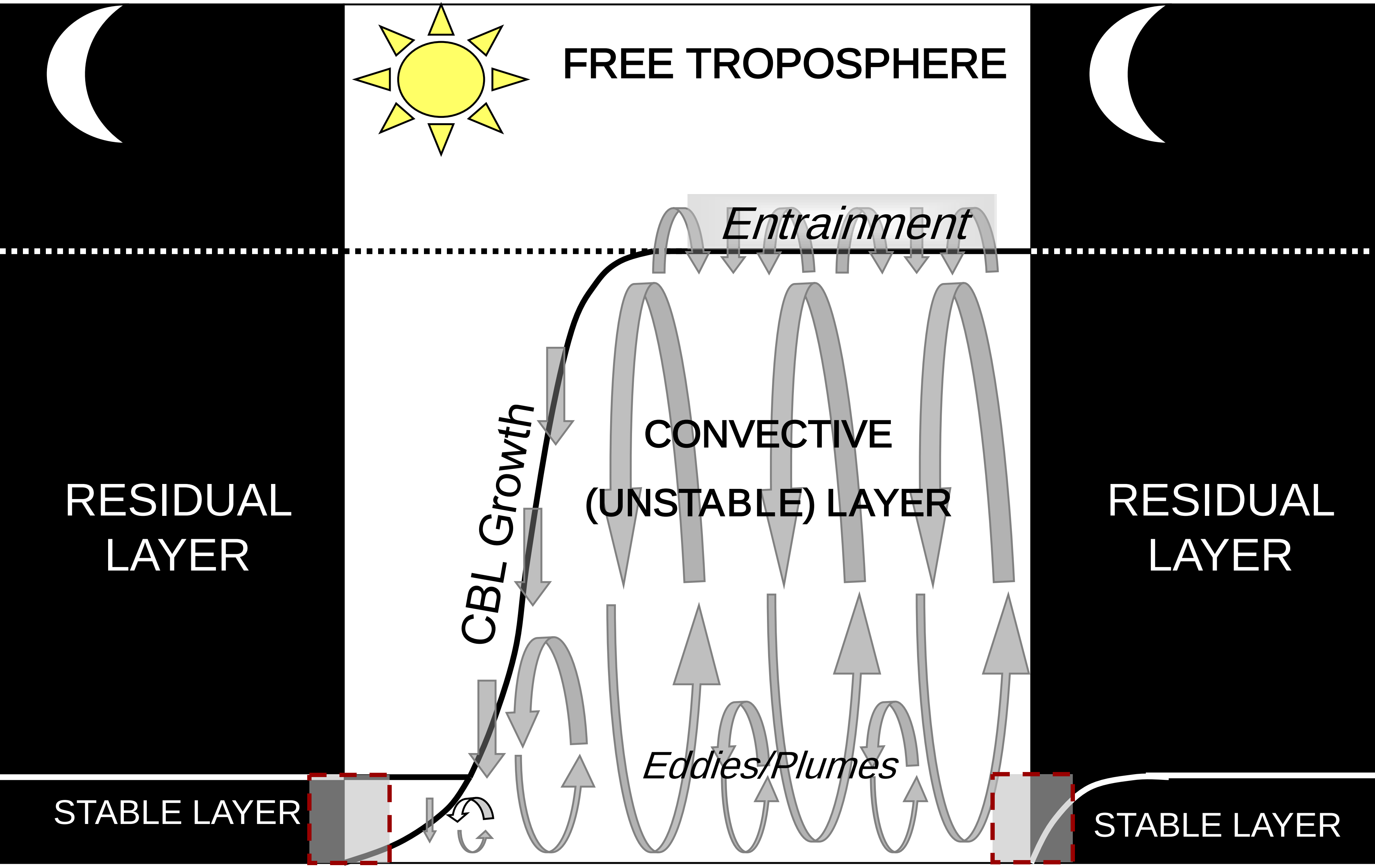
- Small-scale structures: Burden on SGS model
- Poor SGS models: Numerical instabilities
- Poor representation of energy spectra
- High resolution required with non-dynamic SGS models

SGS model performance: Energy spectra

Unstable (0.2 Km/s) and **Stable (-0.02 Km/s)** simulations:
Lagrangian Dynamic Scale-invariant and Scale-dependent models

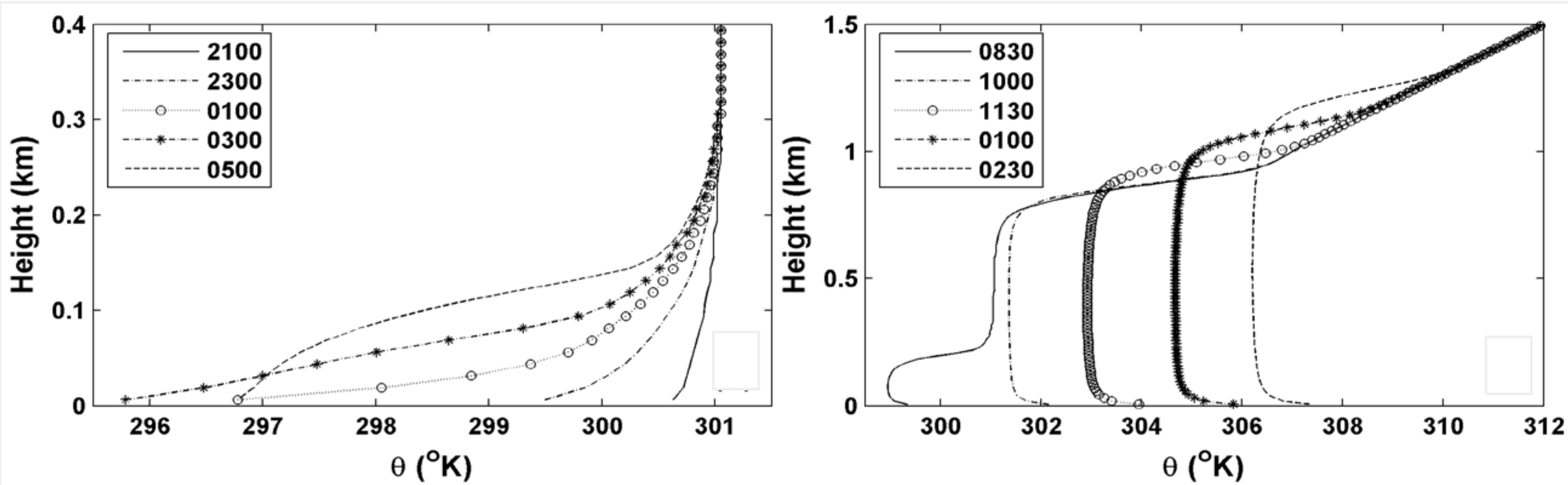


LES of Diurnal ABL

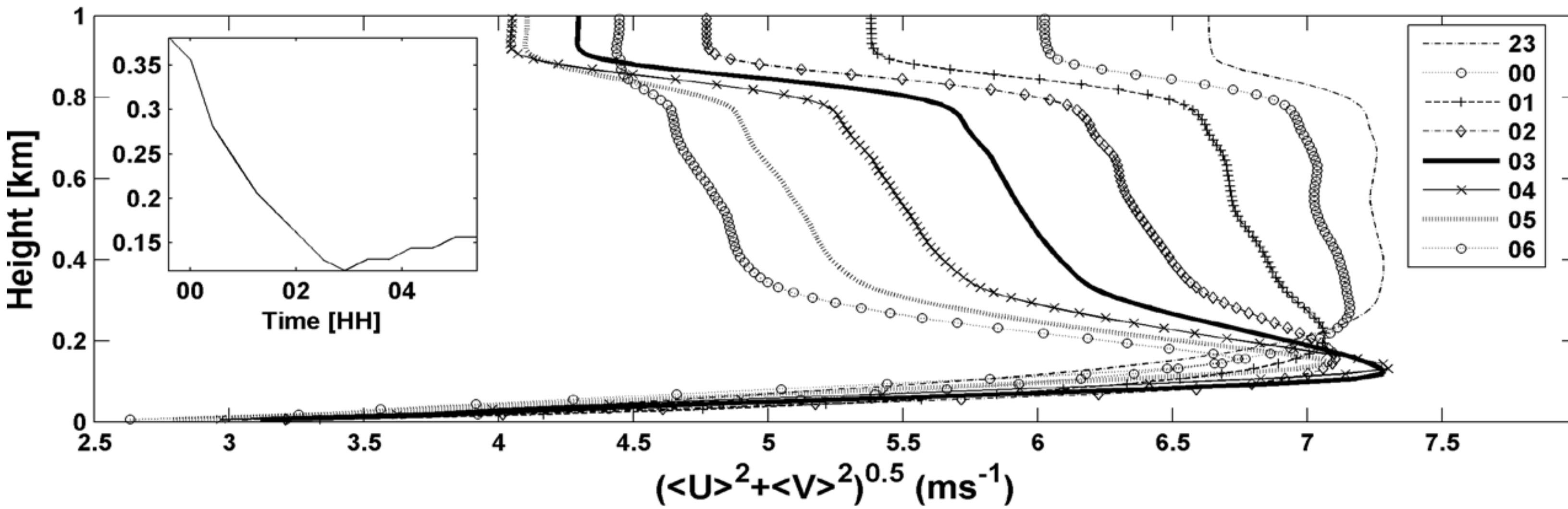


Results: Diurnal ABL characteristics

Evolution of the stable and unstable ABL

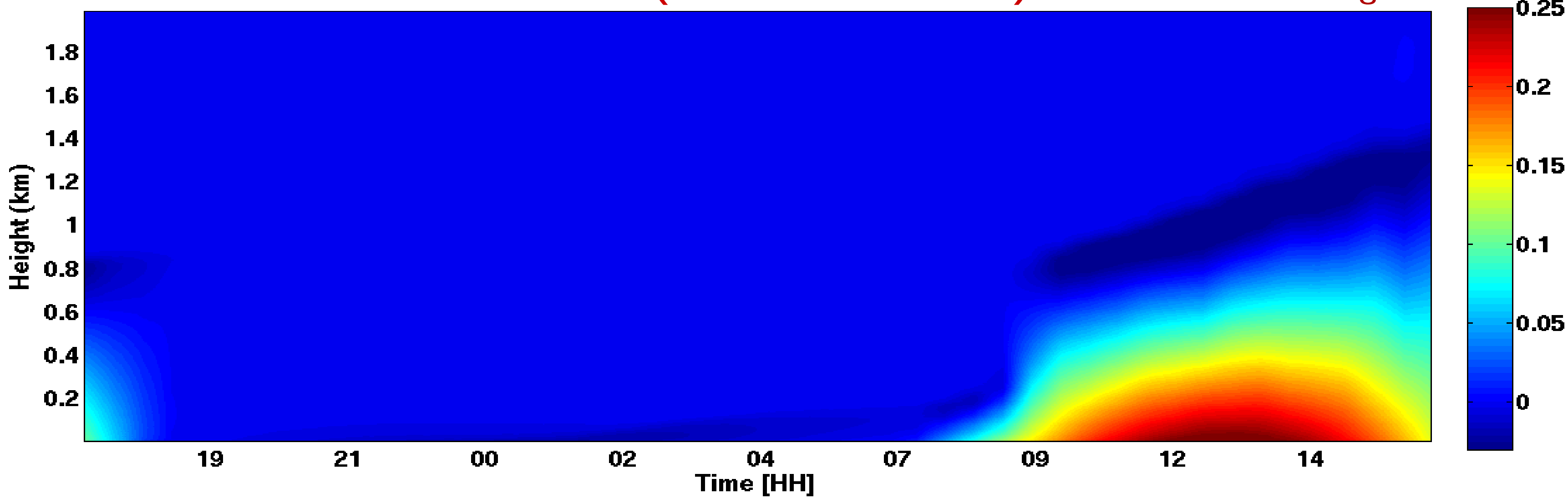


Evolution of the nocturnal low-level jet

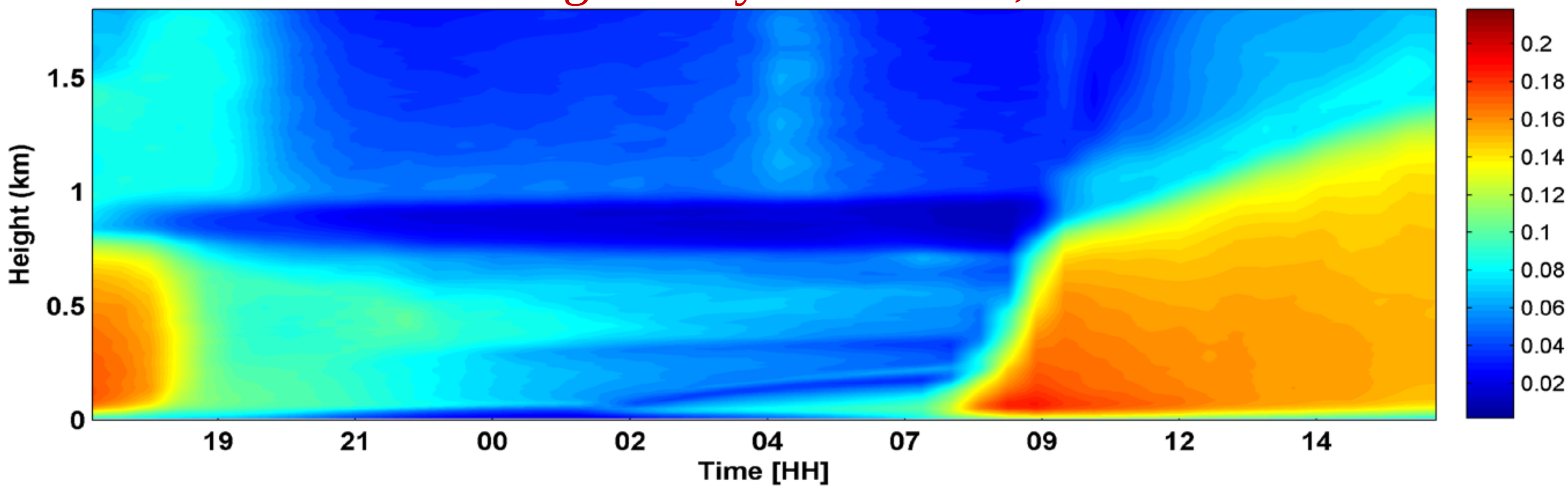


Results: Diurnal ABL characteristics

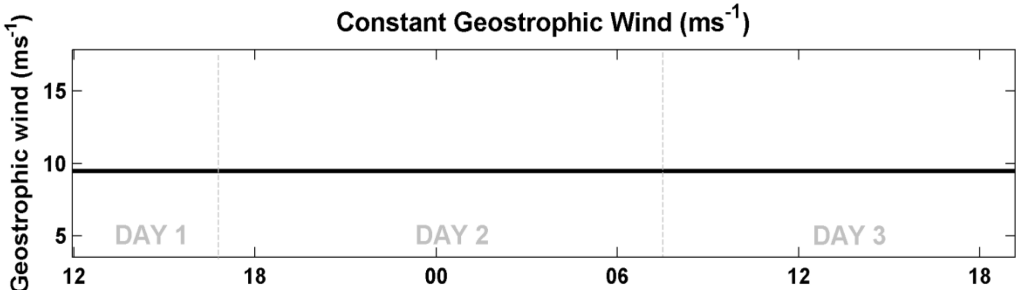
Sensible Heat Flux (resolved+SGS): $\overline{w'\theta'} + \pi_3$

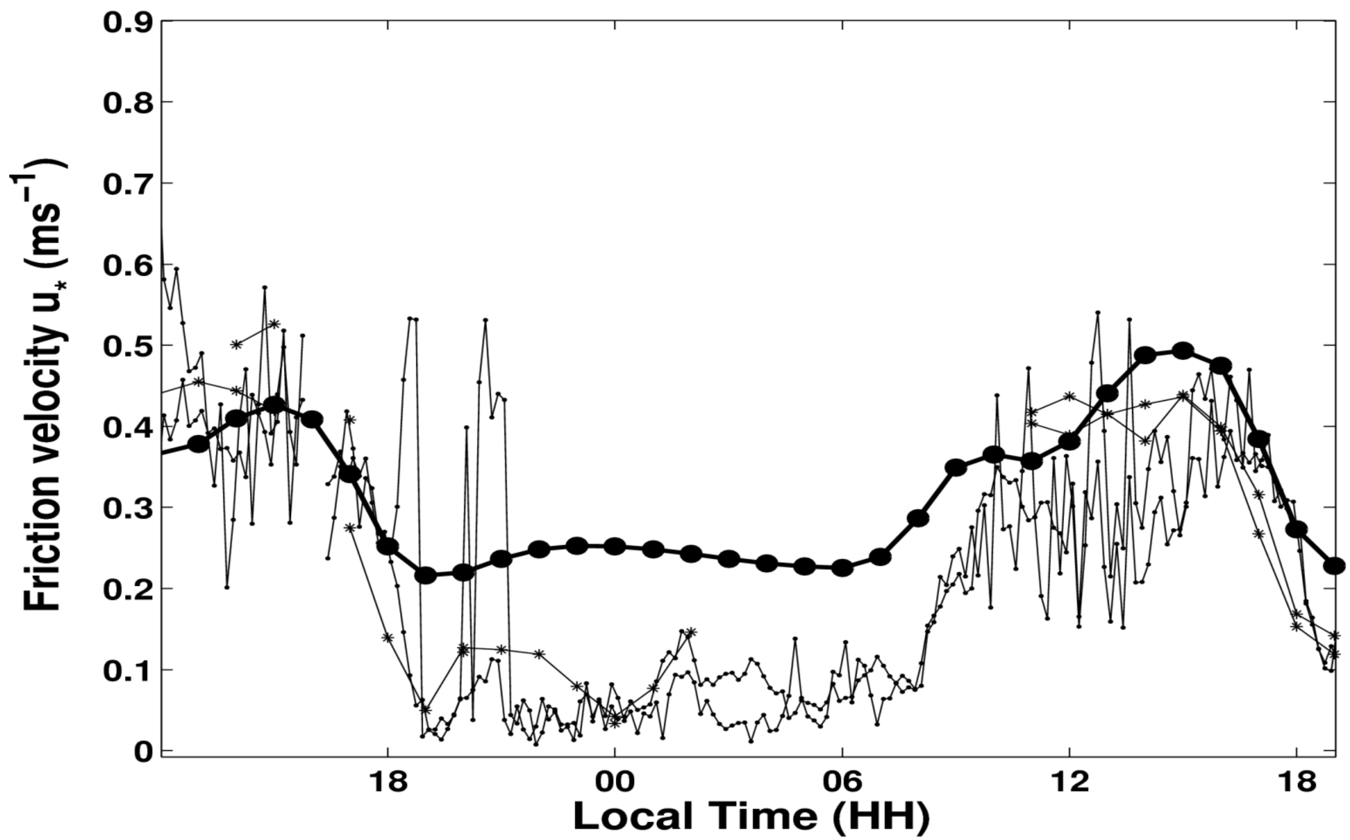


Smagorinsky coefficient, Cs



LES: Impact of Pressure forcing/BC





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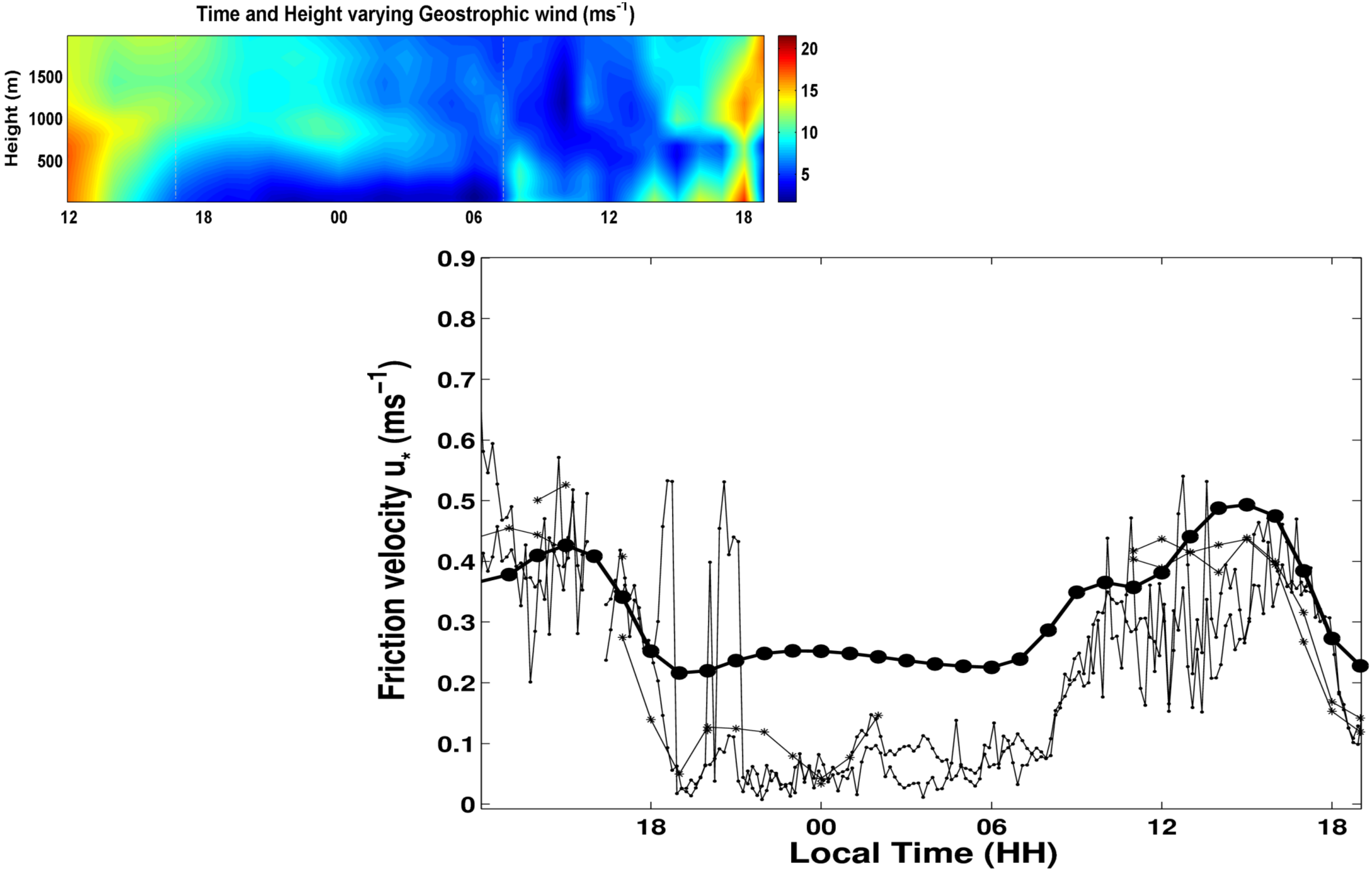

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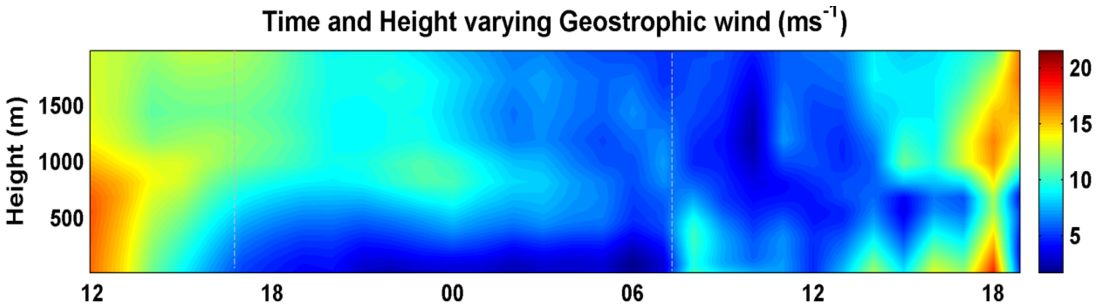
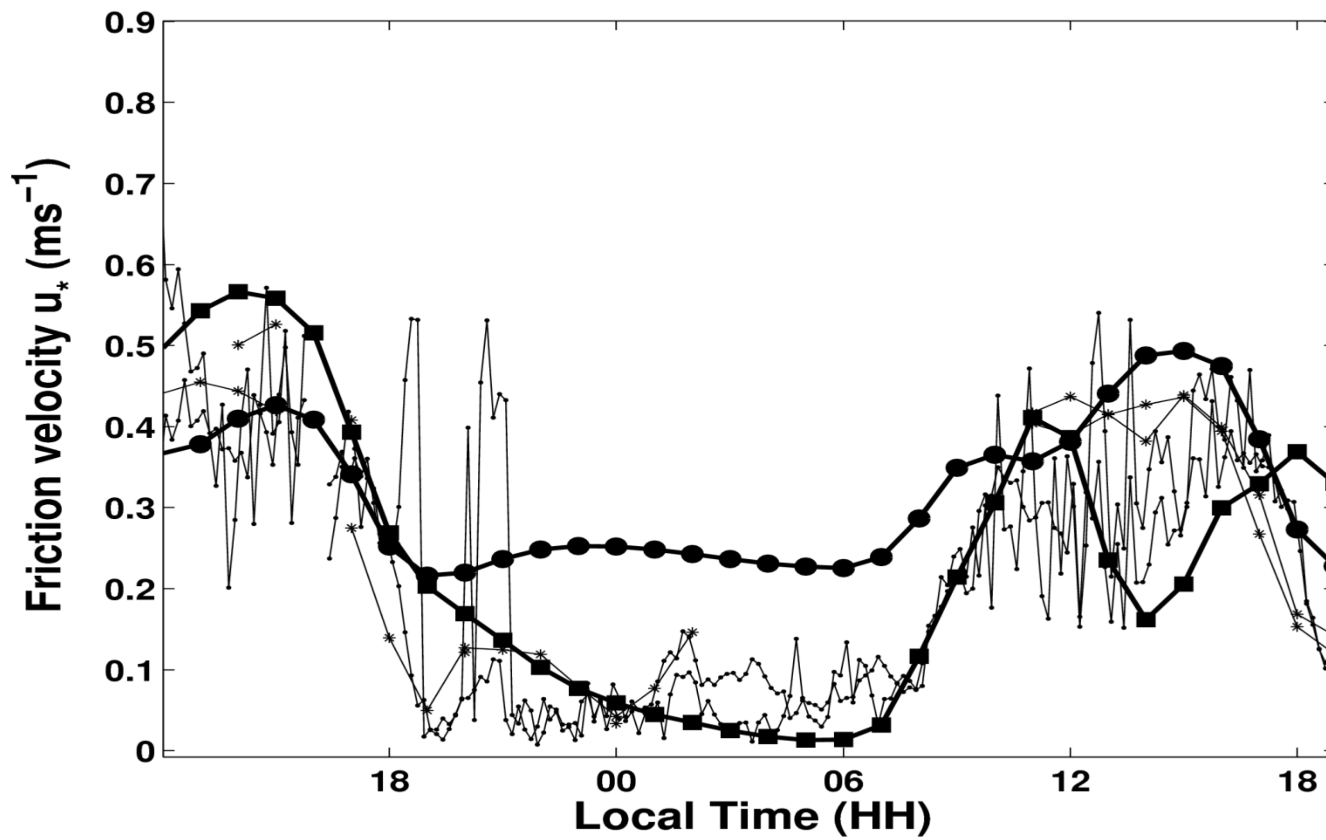
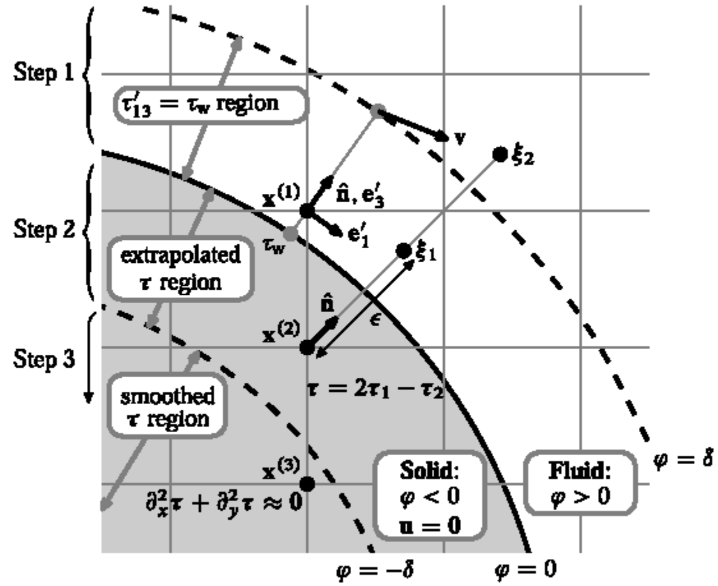


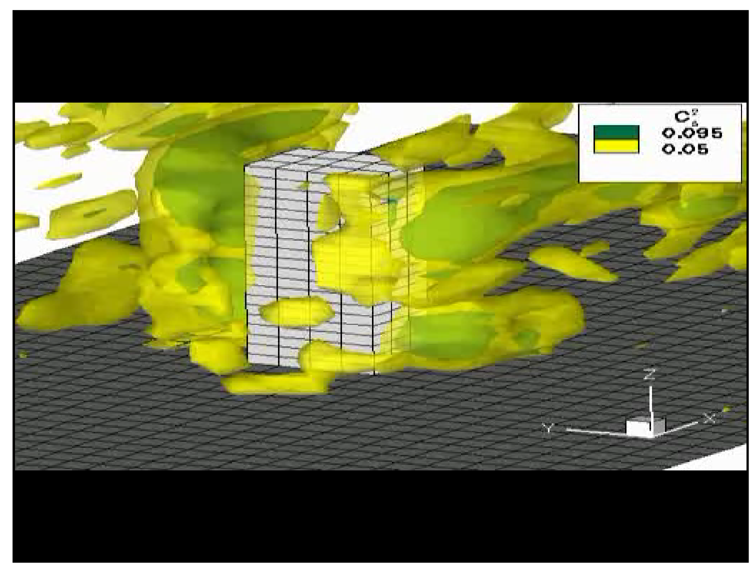


LES: Representation of structures and topography

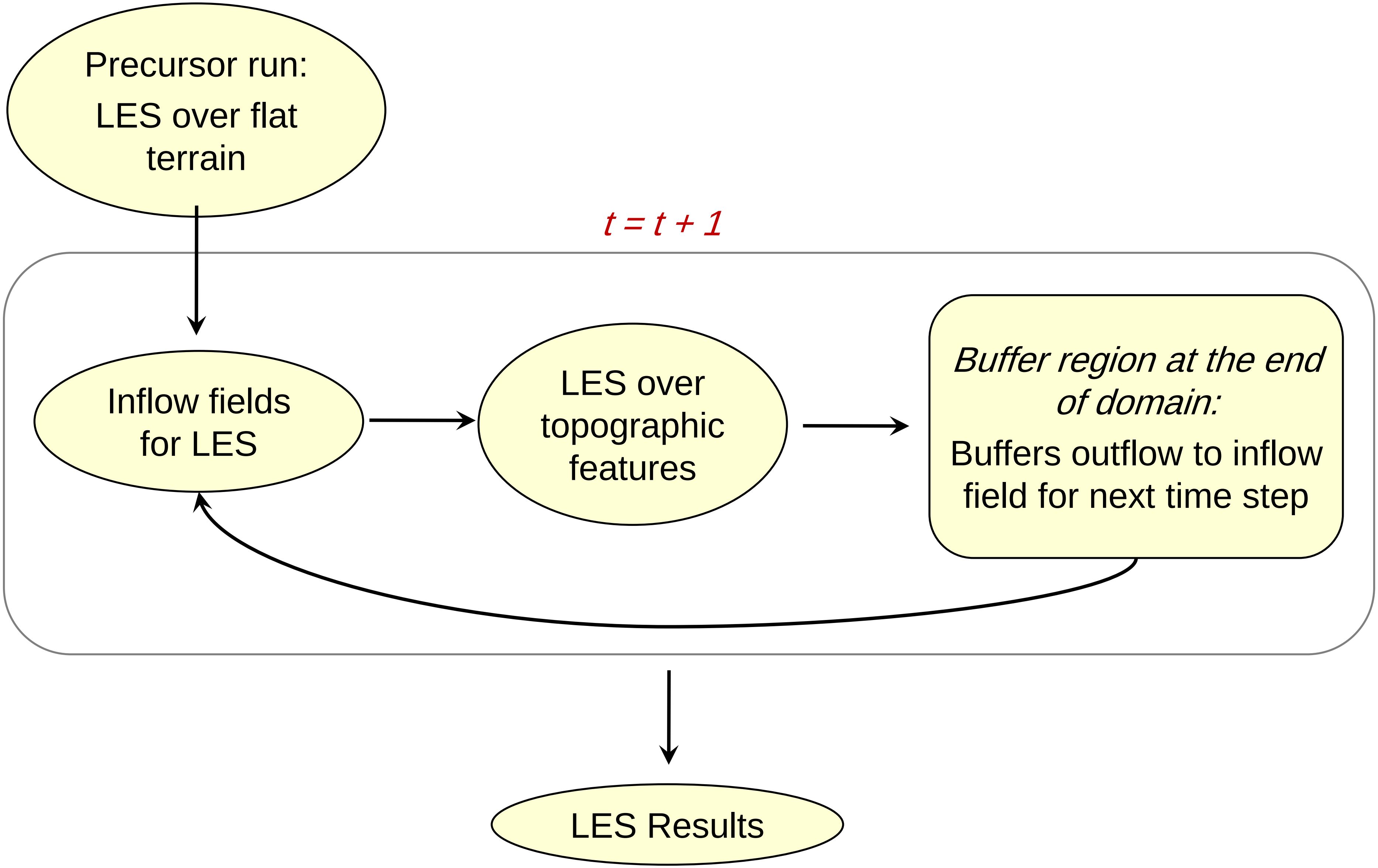
Methodology:

1. Describe surface using the level set method & Fluid-structure interaction represented through immersed boundary method
2. Define a band just outside the surface
3. Pick a point define the surface normal
4. Define a tangential velocity and apply a log law to obtain the sheer stress
5. Extrapolate the stress field into the body
6. Smooth the stress profile inside the body using iterative over-relaxation of the Laplace equation in stress, τ

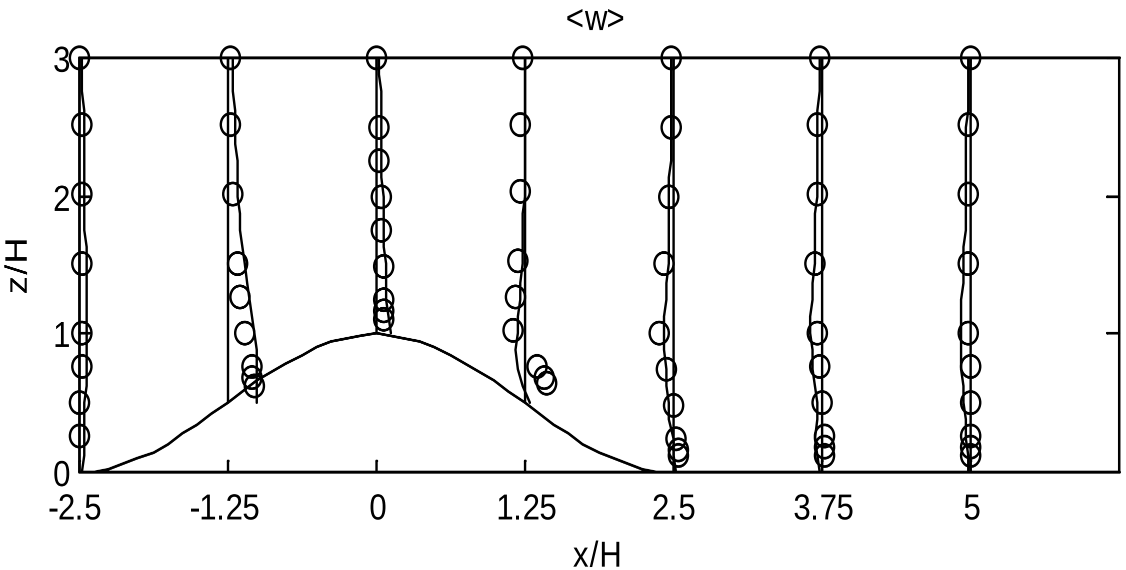


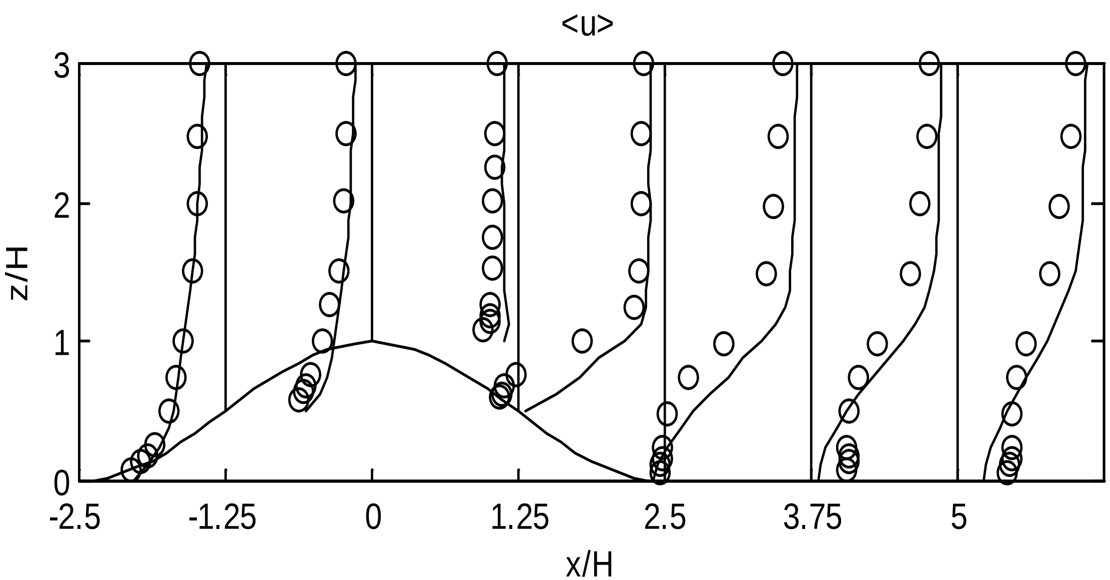


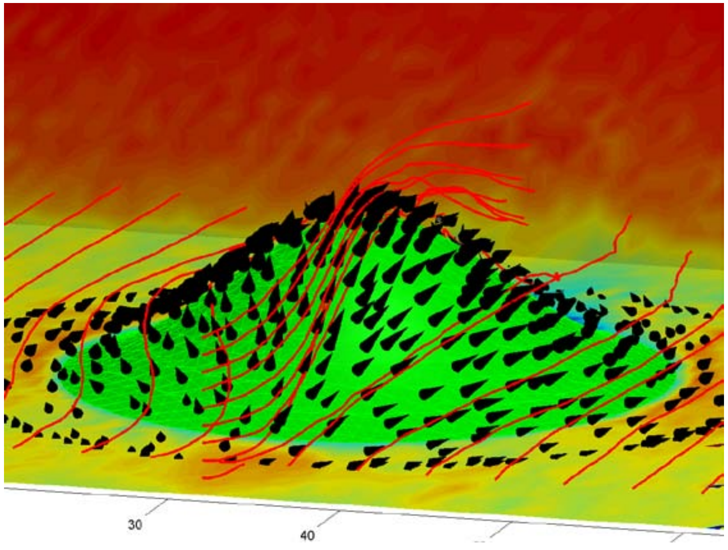
LES: Simulation setup for flow over terrain



LES study: Flow over a Gaussian Hill

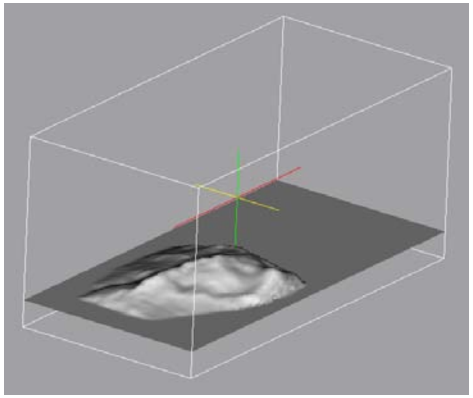




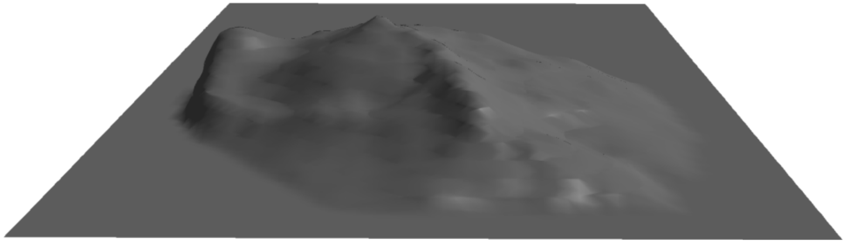


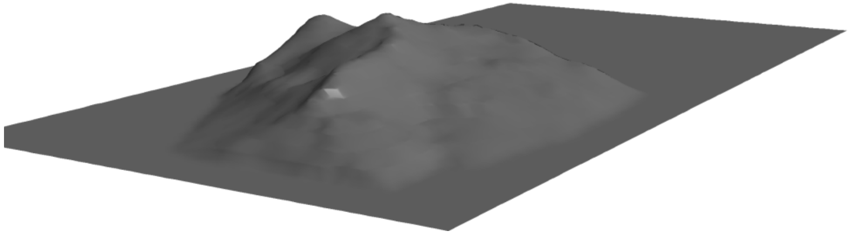
Data from Iwamura et al, 1991

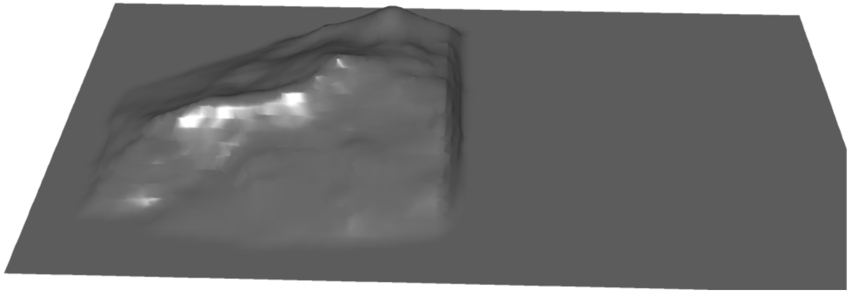
LES study: Flow over a steep real-world Hill

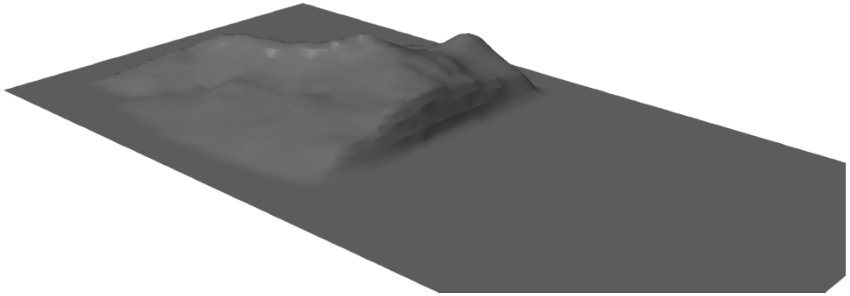


- Gaudergrat ridge, Switzerland
- Dimensions: 1.5kmx1kmx250m
- Slopes of about 45 degrees
- Results to be compared with extensive observations, RANS and mesoscale models

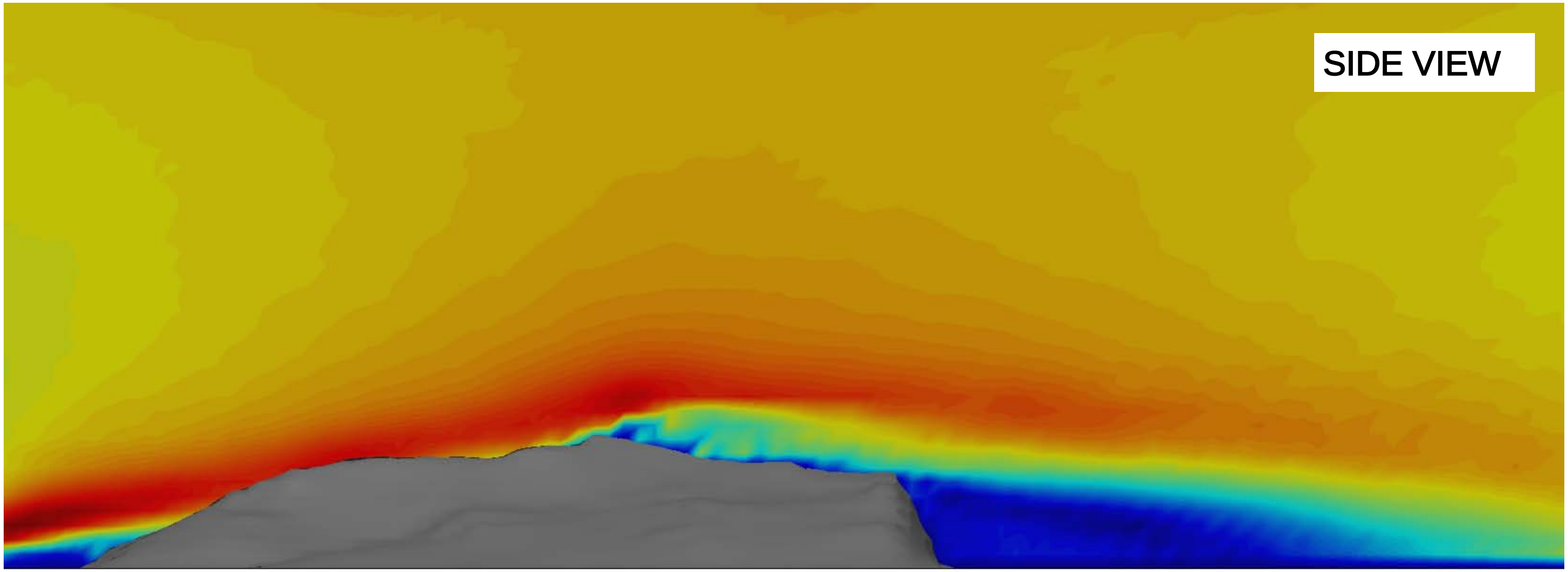


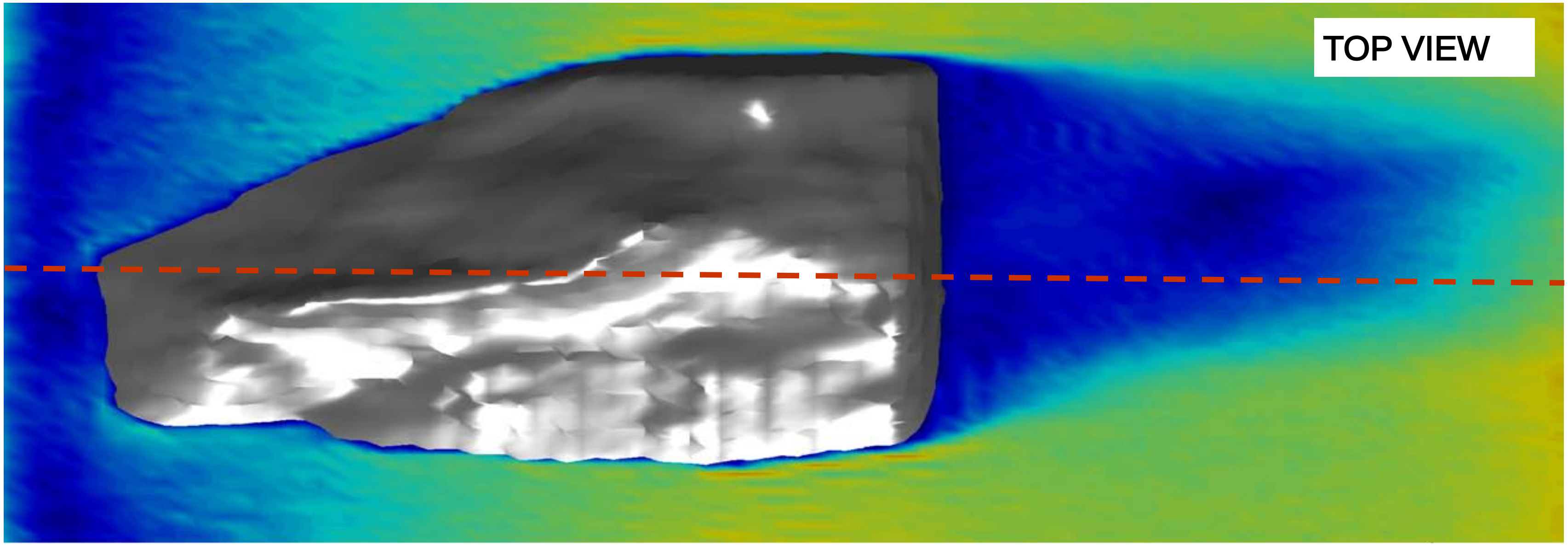






LES study: Flow over a steep Alpine Hill





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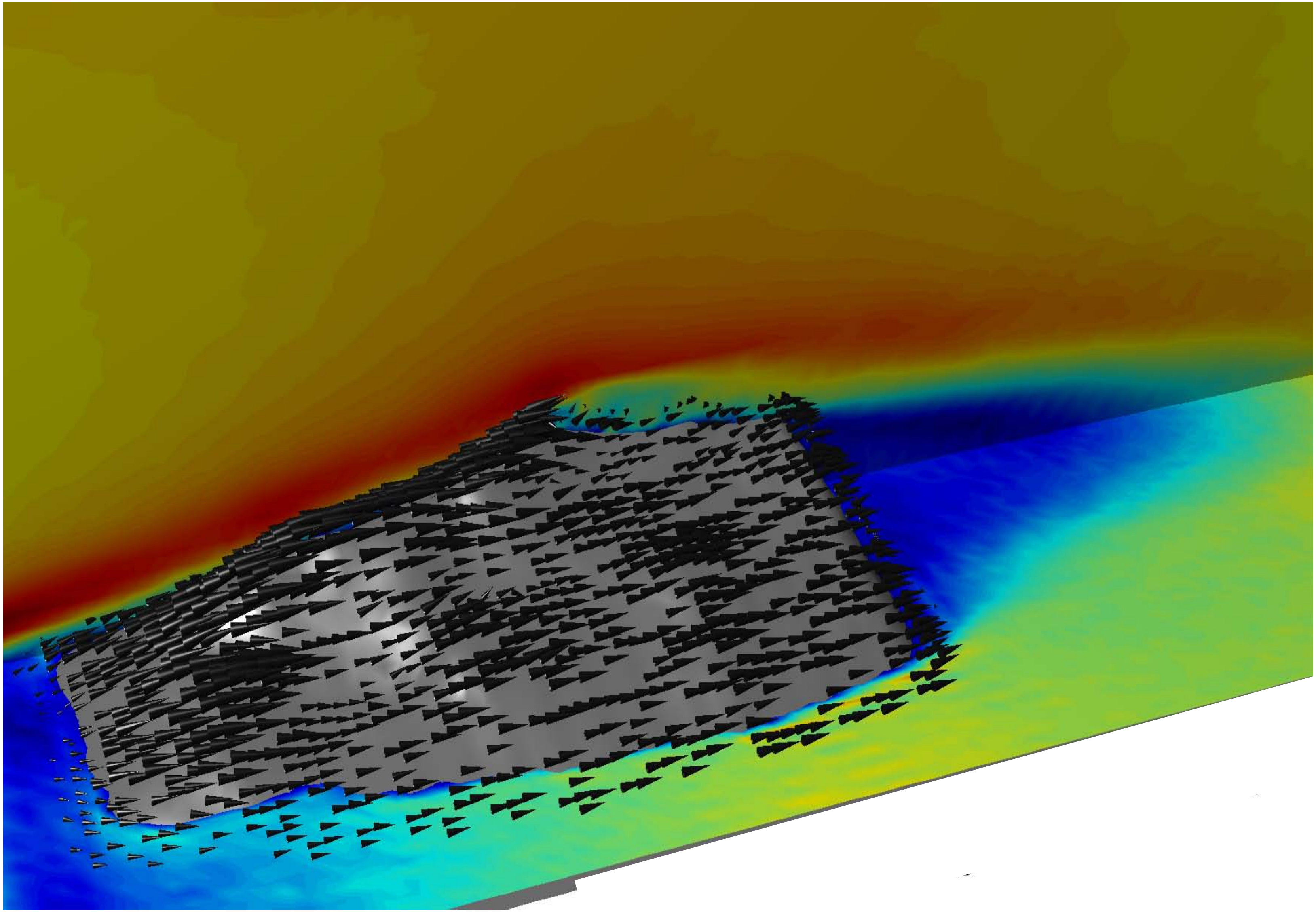

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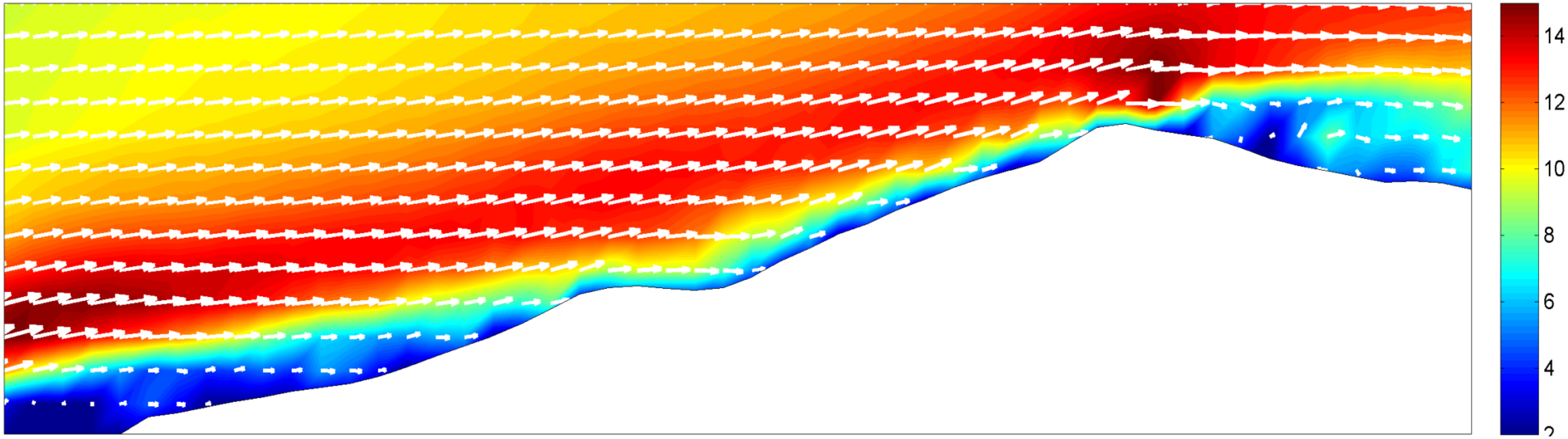
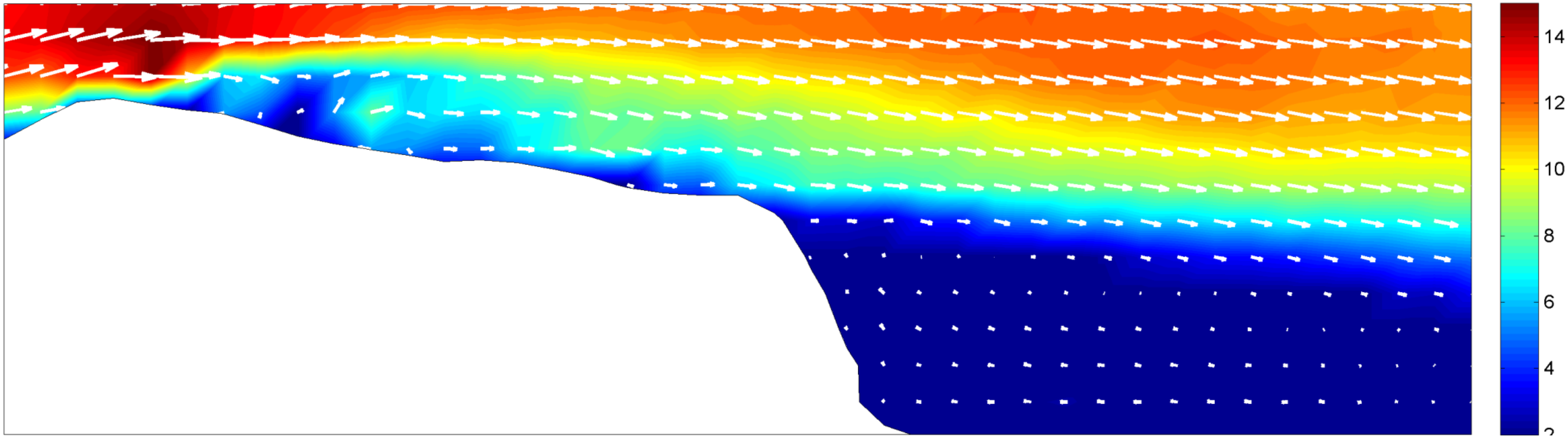
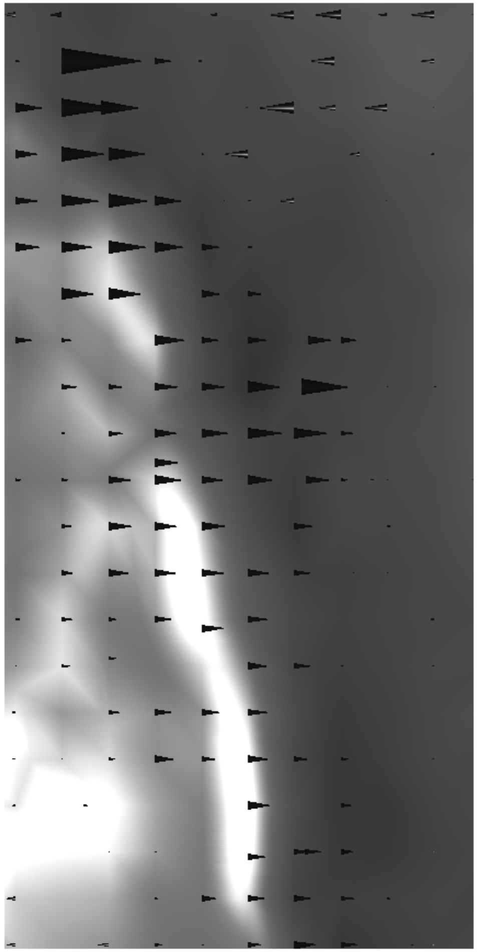




LES study: Flow over a steep Alpine Hill

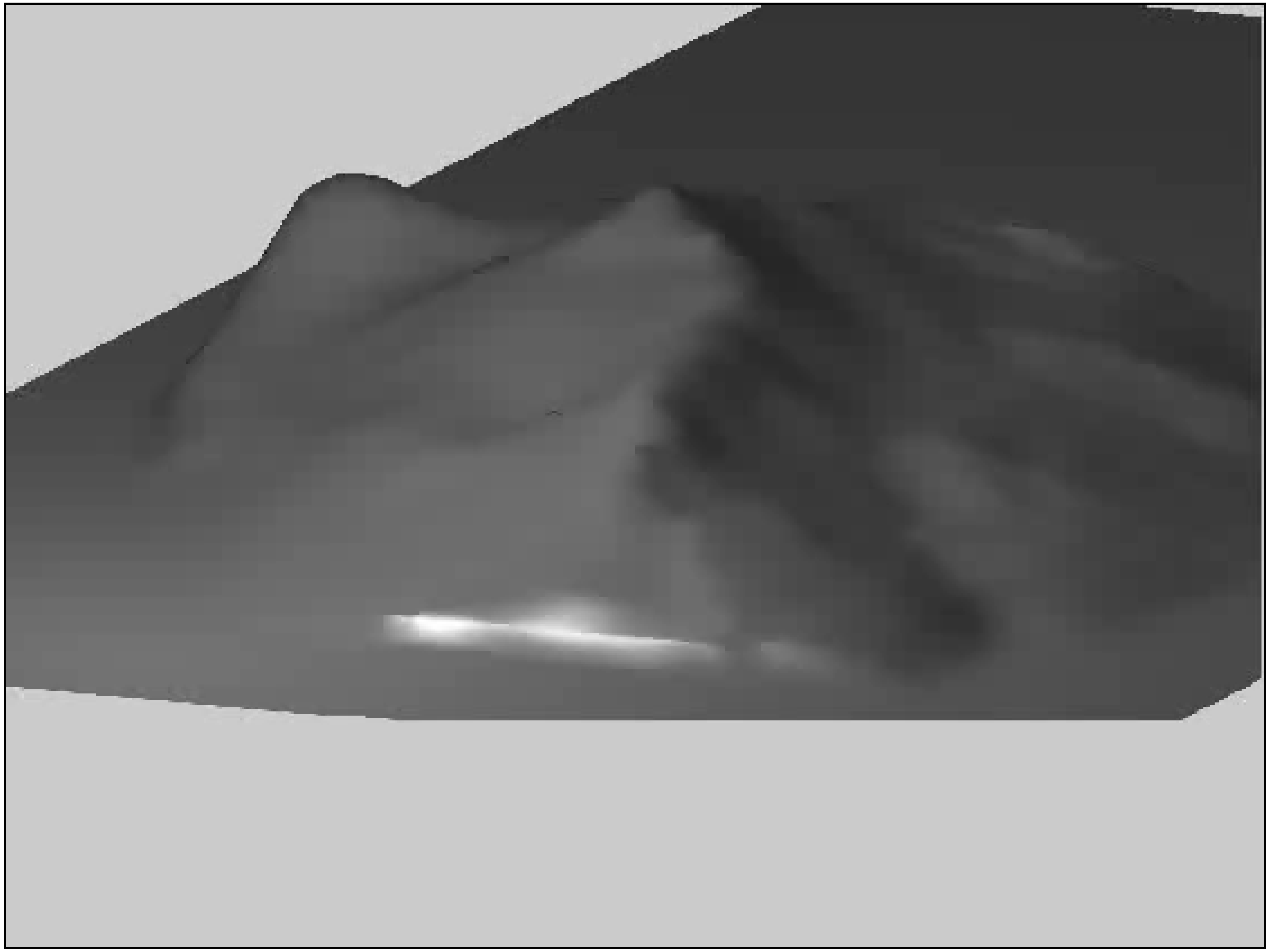
Cross ridge flow

- Cross ridge flows have been observed even when the mean wind direction is along the ridge*
- Also seen in mesoscale simulation of Gaudergradt ridge (Courtesy: Rebecca Motte)
- In LES results, we observe cross-ridge flows with ~20% strength of the predominant flow along the ridge.



** Lewis et al. (2008), QJRMS*

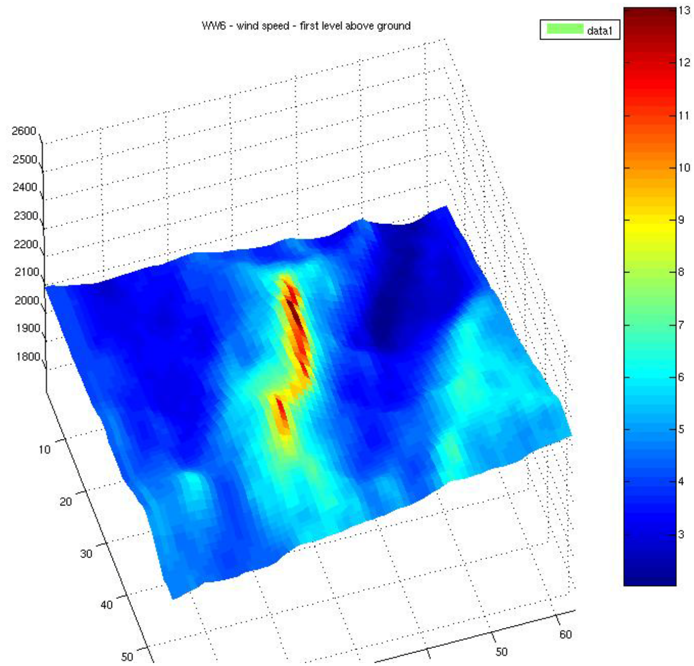
LES study: Flow over a steep real-world Hill

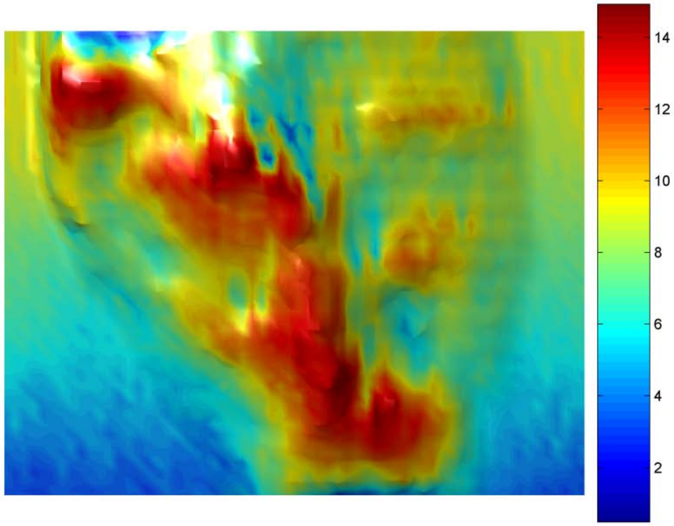


Additional Slides

LES study: Flow over a steep Alpine Hill

Comparison with ARPS simulation (courtesy of Rebecca Mott): LES shows more spatial variability





Computational Methods

Why the need?

- Standard wind assessment tools (WAsP / WindPro etc) not suited for complex flow situations:
  - Use models meant for simple terrain
  - Deficient in flow physics e.g. turbulence & atmospheric stability
- Wind assessment in complex terrain requires:
  - Correct boundary conditions and forcing (pressure, flux)
  - Detailed understanding of atmospheric stability
  - Appropriate modeling/representation of turbulence
  - Accurate representation of fluid-structure/topography interactions

Options:

- Mesoscale models => Not suited for micro-siting
- Local/Microscale => Computational Fluid Dynamics
  - Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Reynolds Averaged Navier Stokes (RANS) modeling

Computational Fluid Dynamics (CFD)