# Large Eddy Simulations of Planetary Boundary Layers

## *Turbulence-Resolving Modeling of Self-Organized Turbulence*

***Igor N. Esau***

**Nansen Environmental and Remote Sensing Centre**
**Bjerknes Centre for Climate Research**
**Bergen, Norway**

BCCR - Bjerknes Centre for Climate Research

Norwegian Centre of Excellence

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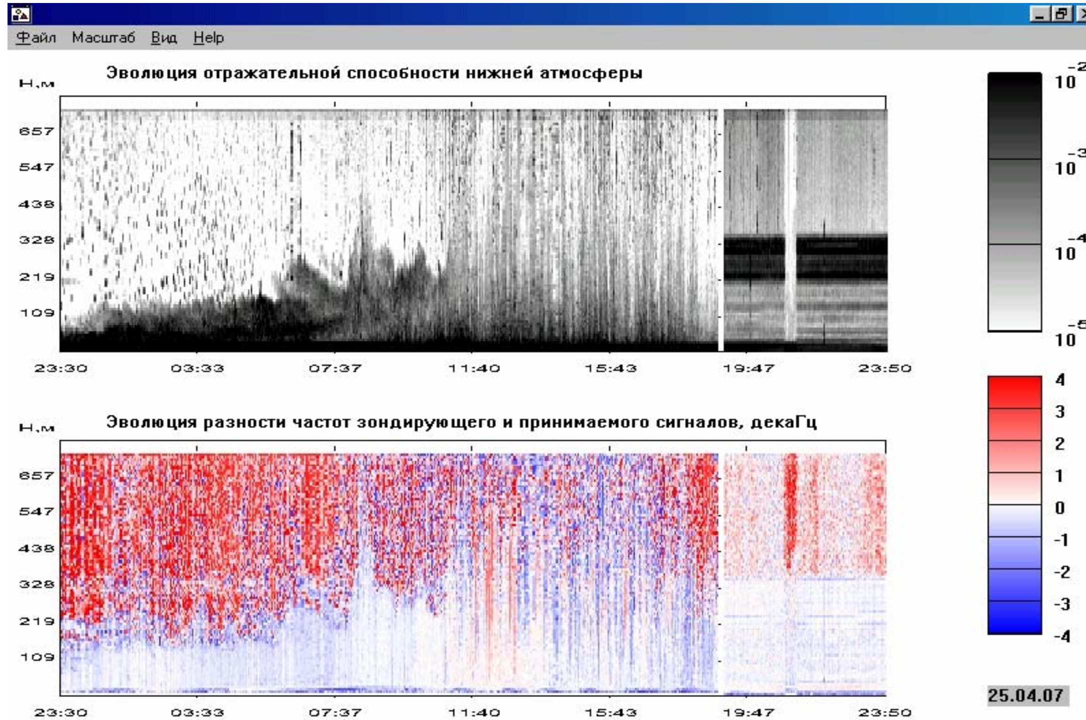
- Portraits of the most energetic eddies
- Role of turbulence self-organization
- Toward turbulence parameterization: LES versus Single-Column Models
- Conclusions

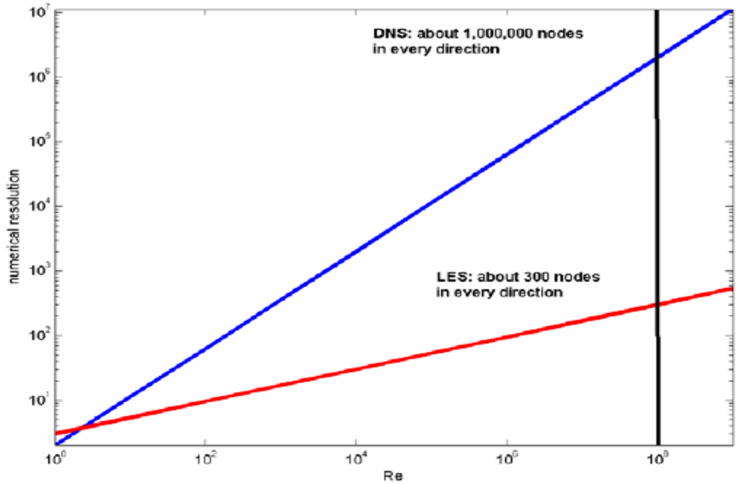
# Motivation

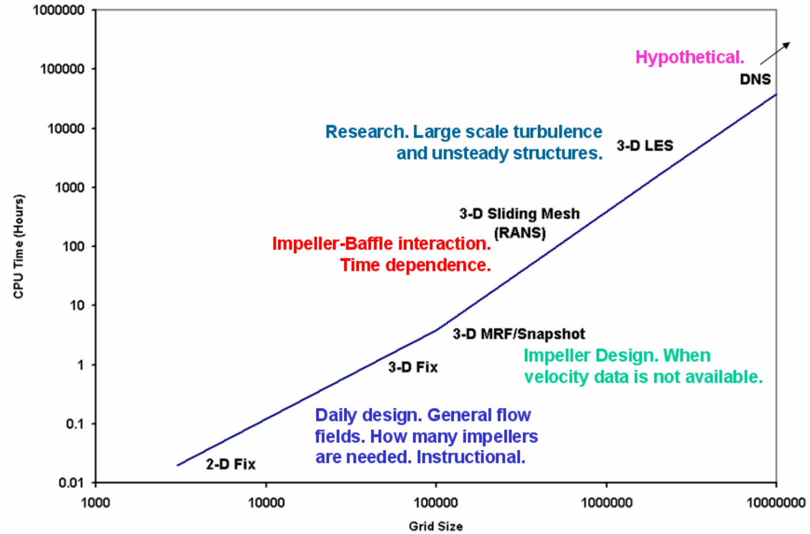



- The best observatories collect data only in the lower PBL (e.g. Obninsk 315 m meteorological mast, Russia, left panel) while PBL thickness often exceed 500 m (sodar data from Obninsk, IEM, April 2007, right panel).
- Accuracy is not very high due to transitional effects, site location
- Comprehensive meteorological measurements are very rare (exception e.g. May 1998 SHEBA)

# Motivation

- Simulations may help
- Observations difficult, expensive and cannot be repeated
- DNS resolve all scales but it is now feasible only up to Re ~ $10^3$
- DNS are still in the range of Re-dependent statistics
- Environmental Re ~ $10^9$
- Geoscientists are also interested in meteorological micro-physics
- Micro-physics simulations are costly

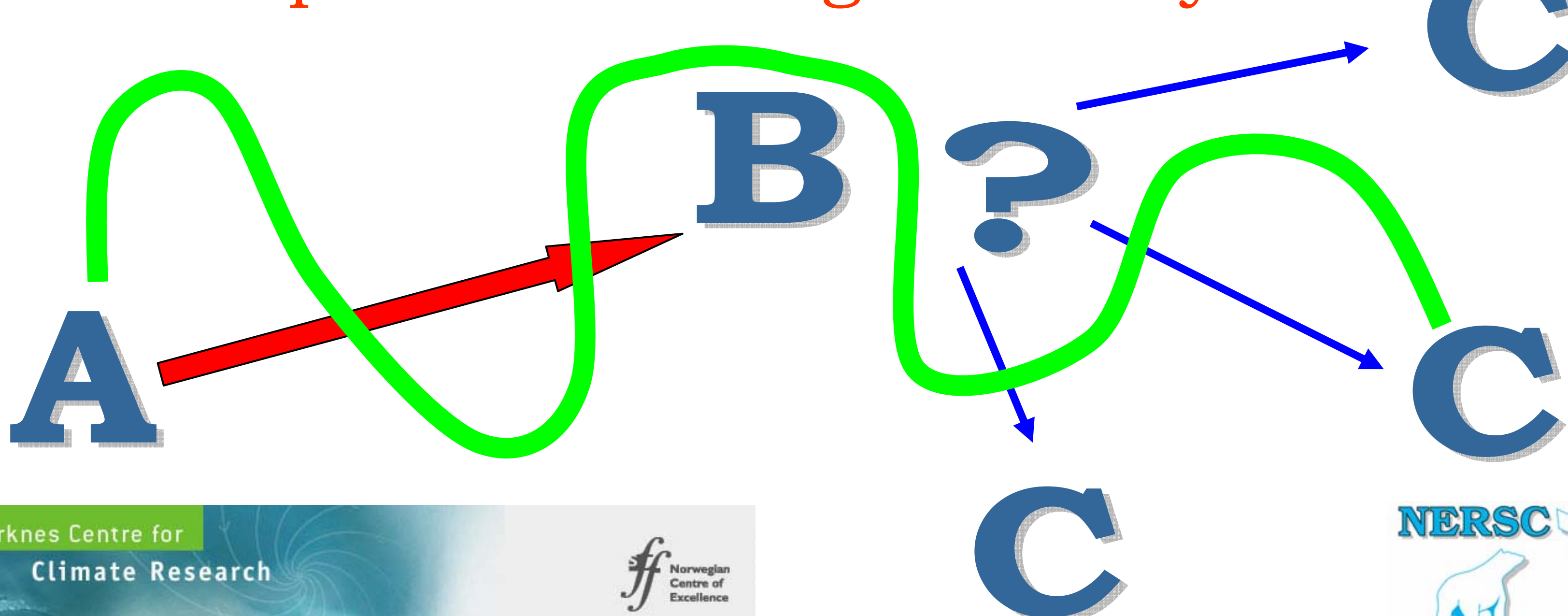



$$N_{3D} \sim \mathrm{Re}_t^{9/4}$$

# Motivation

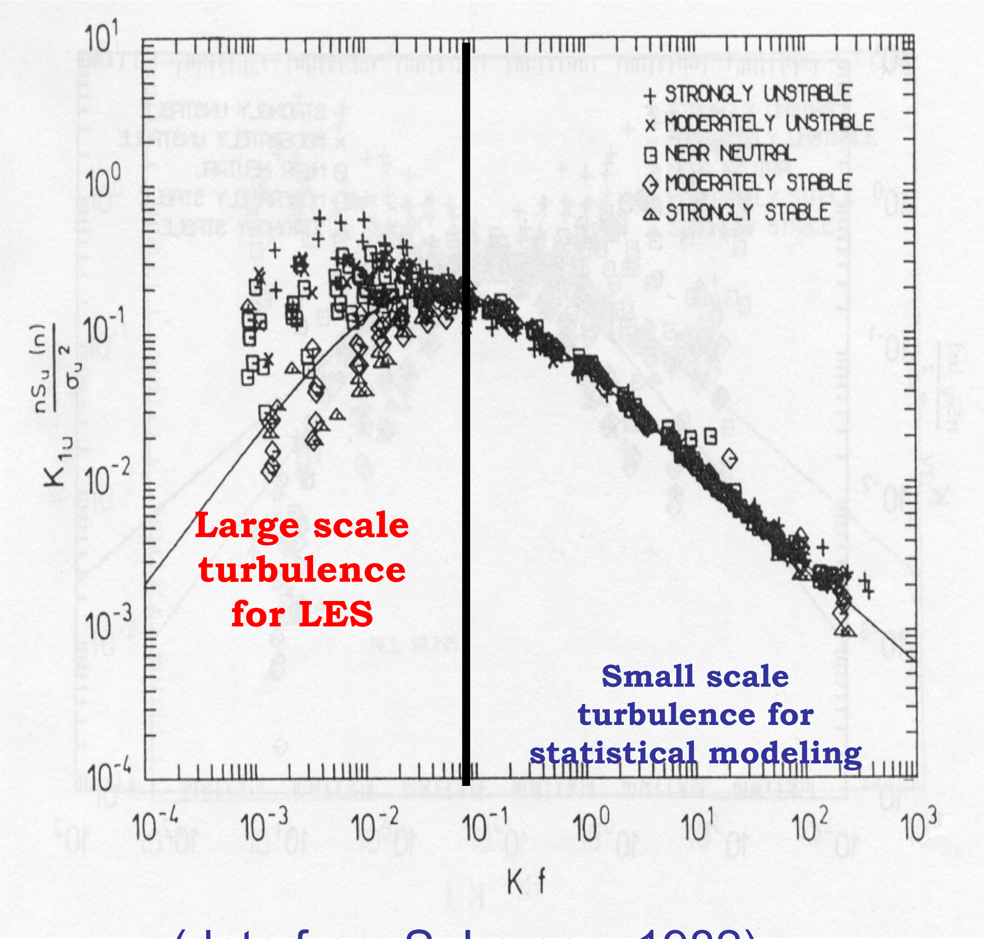
- Atmospheric and ocean physicists are looking for a techniques **much** more comprehensive than RANS but **much** less costly than DNS
- Fortunately the high Re turbulence exhibits properties, which allows us to construct such a technique in a semi-rigorous way



# Phenomenological Concept I

- Turbulence in inertial interval of scales is universal and could be modeled statistically
- Inaccuracy in modeling of Kolmogorov's turbulence could be large but it does not matter as its total energy is small

$\sim \mathbf{k}^{-5/3}$




(data from S. Larsen, 1982)

# Phenomenological Concept II

- In isotropic turbulence **95% of TKE** on resolved scales could be reached with only **100 nodes** in each direction

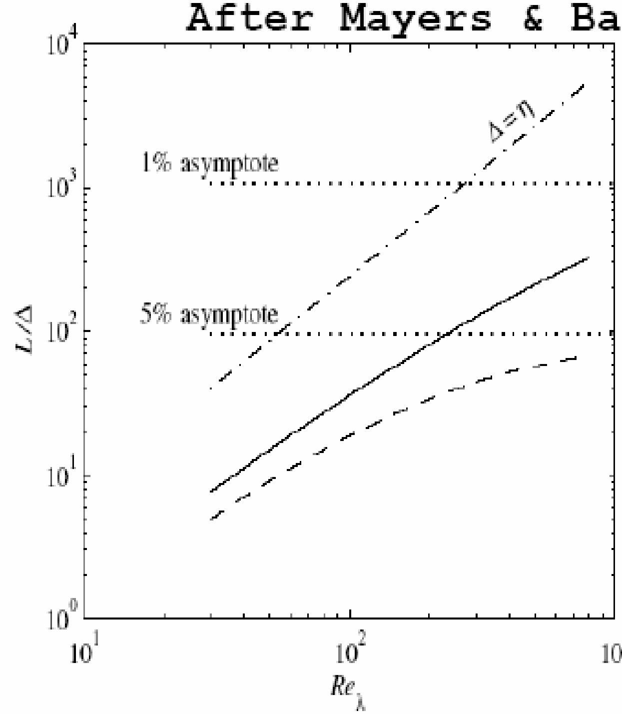



**Figure 6.** Required ratio of $L/\Delta$ as function of $Re_\lambda$ (with $a = 2$) for different levels of subfilter energy, i.e. $E_{sgs}/E = 1\%$ (—) and $E_{sgs}/E = 5\%$ (- -), respectively. (- ·) $\Delta = \eta$; (· · ·) respective asymptotes according to (30).

# Aim of Turbulence-Resolving Modeling at high Re

- At the high-frequency end of the spectrum:
- Energy decrease
- Correlations deteriorate
- Energy cascade is predominantly directed to small, dissipative scales
- In the inertial sub-range model statistic approaches an intermediate asymptote
- The aim is to recover this asymptote as accurate as possible in resolved-scales of the LES (S. Pope, 2004)

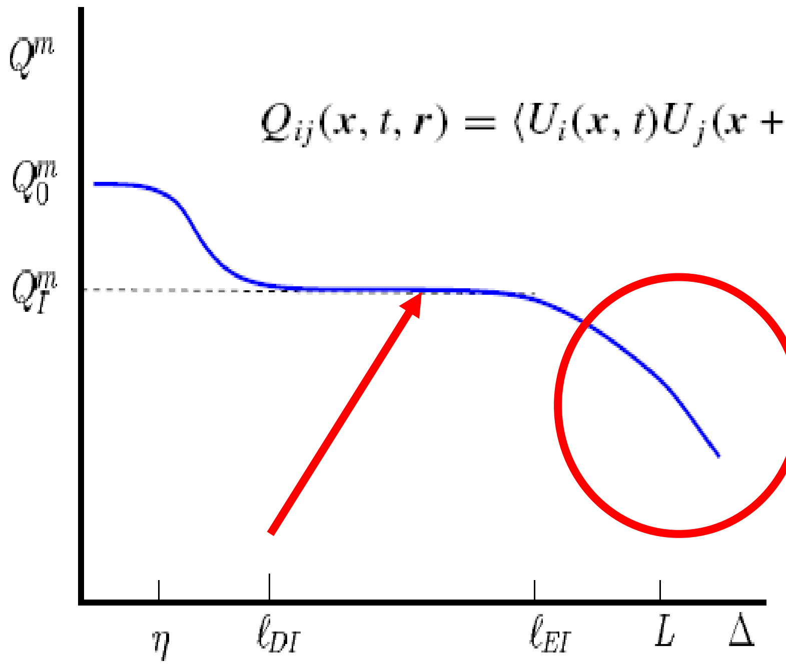



**Figure 2.** Variation of the model $Q^m$ for that statistic $Q$ as a function of the turbulence resolution length scale $\Delta$ (on a log scale): $Q_0^m$ is the DNS limit as $\Delta$ tends to zero; $Q_I^m$ is the intermediate asymptote in the inertial subrange.

# Mathematical Foundations I

- There are many approaches to derive LES equations ranging from ad hoc filtering (grid-filtered model of Deardorff, 1970) to statistical conditional modeling (perfect LES of Langford and Moser, 1999)
- The aim is to obtain a mathematical guidance on construction of low-dimensional models and their closures

$$\partial_t u + u \cdot \nabla u + \nabla p - \mathrm{Re}^{-1} \Delta u = f, \quad in \quad Q_T$$

$$\nabla \cdot u = 0, \quad in \quad Q_T$$

$$u\big|_{\Gamma} = 0 \; or \; \; periodic$$

$$u\big|_{t=0} = u_0, \quad Q_T = \Omega \not\subset \Gamma \times (0, T)$$

# Mathematical Foundations II

- The formidable mathematical problem in high Re LES is imparity of energy balance between TKE generation and dissipation
- Energy just accumulate at the cut of scale (aliasing)

$$\mathrm{Re} \to \infty$$

$$\partial_t E + u \cdot \nabla E = P, \quad in \quad Q_T$$
$$\int (u \cdot \nabla u) \cdot u = 0, \quad in \quad Q_T$$

- Hence there is no loss of energy and information in the infinite Re system

# Mathematical Foundations III

$$\partial_t E + u \cdot \nabla E = P, \quad in \quad Q_T$$
$$\int (u \cdot \nabla u) \cdot u = 0, \quad in \quad Q_T$$

- Exact filtering becomes possible with **Germano differential filter**

$$\overline{u} - l_{cut}^2 \Delta \overline{u} = u$$

- So that the complete solution can be restored on the basis of a filtered (large-scale) solution
- Thus no closure problem in filter-based derivations of LES (Germano, Adams, Carati, Winkelmans etc)

# Mathematical Foundations IV

- **To overcome the difficulty with aliasing, the original NSE must be perturbed (regularized)**
- Aliasing – piling up of the energy at the smallest resolved scale
- Leray's (1934) regularization idea can be expressed as large-scale velocity field transports small-scale velocity field
- Similar in some sense to the idea of *the Rapid Distortion Model* (or RTD by J.C.R. Hunt)
- Related to NSE-alpha model (Foias et al., Chen et al.)

$$\partial_t u + (\nabla \times u) \times \boxed{\bar{u}} + \nabla\left(p + \frac{1}{2}u^2\right) = \bar{f}, \nabla \cdot u = 0.$$

# Mathematical Foundations V

$$\partial_t u + (\nabla \times u) \times \overline{u} + \nabla\left(p + \frac{1}{2}u^2\right) = \bar{f}, \nabla \cdot u = 0.$$

- With Germano-Helmholtz differential filter
- Result in a closed, dissipative LES model

$$\text{Use} : \overline{u} = (I - l_{cut}^2 \Delta)^{-1} u$$

$$\partial_t \overline{u} + \overline{u} \cdot \nabla \overline{u} = \nabla \cdot (-pI + T), \nabla \cdot \overline{u} = 0,$$

$$T = 2 l_{cut}^2 (\partial_t S + \overline{u} \cdot \nabla S + S\Omega - \Omega S),$$

$$S = \frac{1}{2}(\nabla \overline{u} + (\nabla \overline{u})^T), \quad \Omega = \frac{1}{2}(\nabla \overline{u} - (\nabla \overline{u})^T).$$

# Leray Model Test

- Has a semi-rigorous model constructed?
- Not exactly!
- Leray LES filters out small scales at equation level
- Leray model do not demonstrate any superiority (Liu et al., 2006)
- Just opposite, Leray model is numerically ill-conditioned and therefore less stable than others

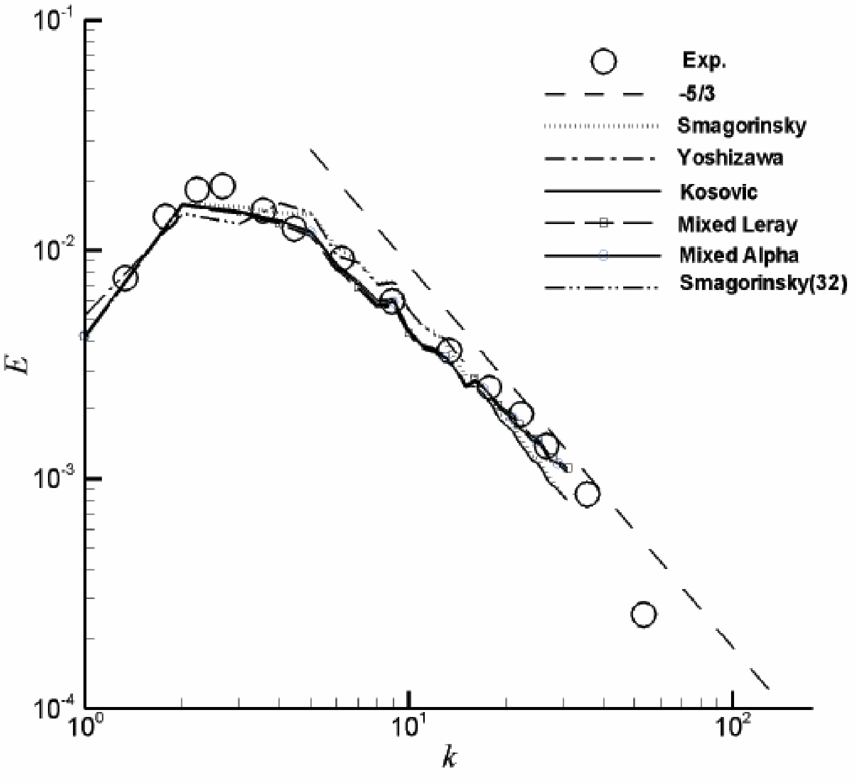



Fig. 3. Energy spectra for decaying isotropic turbulence.

# Mathematical Foundations VI

- Another regularization approach is taken in Ladyzhenskaya-Kaniel model (LKM)
- O. A. Ladyzenskaja (1969) introduced the second-order stress term into dissipation
- This term accounting for large velocity gradients in non-linear fluid
- This term is consistent with the Smagorinsky model (important for the following understanding)
- Finally, she proved the existence, uniqueness and convergence (to the NSE) theorem for such a regularized system

# Mathematical Foundations VII

$$\partial_t u + u \cdot \nabla u = \nabla \cdot (-pI + T^*), \nabla \cdot u = 0,$$

$$\text{Leonard equality :}$$

$$u \cdot \nabla u = \nabla\left(u \otimes u\right) = \nabla\left(\bar{u} \otimes \bar{u}\right) + \nabla\left(u \otimes u - \bar{u} \otimes \bar{u}\right)$$

$$T = 2l_{cut}^2(\partial_t S + \bar{u} \cdot \nabla S + S\Omega - \Omega S) \Leftrightarrow \boxed{T^* = 2l_{cut}^2 \left|S\right| S}$$

- Since the system has additional viscosity concentrated on small-scales, the following is satisfied

$$\bar{u} \to u, \quad if \ \delta_x >> l_{cut}$$

# Symmetry and Conservation Laws I

- Any particular conservation law is a mathematical identity to certain symmetry of a physical system
- Mathematically expressed through **Noether theorem**
- **Energy conservation – time shift symmetry**
- **Linear momentum conservation – space shift symmetry**
- **Angular momentum conservation – rotation shift symmetry**
- **Kolmogorov energy cascade – scaling transformations**

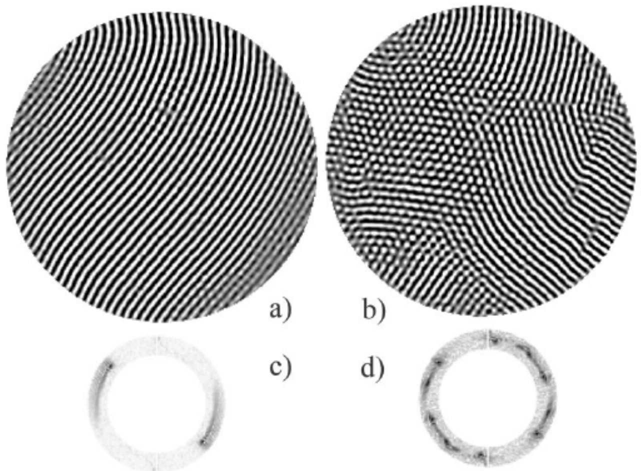



FIG. 10. (a,b) Images of the convective pattern (observed from above) in the cell with a ramp on the bottom plate, for $\varepsilon=0.012$ and $\varepsilon=0.046$, respectively. In both experiments, $\Omega=3.93$. (c,d) Structure functions associated with (a) and (b), respectively. Image processing has been required to obtain these pictures (see text).

Guarino, A. and Vidal, V., 2004:Hexagonal pattern instabilities in rotating Rayleigh-Bénard convection of a non-Boussinesq fluid: Experimental results, *Phys. Rev. E*, **69**

# Symmetry and Conservation Laws II

| Model Type | Translations | Rotations and reflections | Scaling transformations* | Material indifference** |
|---|---|---|---|---|
| Smagorinsky (Smagorinsky, 1963; Lilly, 1967) | Y | Y | N | Y |
| Dynamic Smagorinsky (Germano, 1986; Lilly, 1992; Vreman et al., 1994; Meneveau et al., 1999) | Y | Y | Y | Y*** |
| Structure function (Metais and Lesieur, 1992) | Y | Y | N | N |
| Gradient (Clark et al., 1979) | Y | Y | N | N |
| Scale-Similarity (Bardina et al., 1980) | Y | Y | Y | Y* |
| Lund-Novikov tensor diffusivity (1992) | Y | Y | N | N |
| Kosovic or non-linear Lund-Novikov model (Kosovic, 1997) | Y | Y | N | N |

* To held scaling invariance, **the length scale should not appear in the model explicitly**

** in the limit of 2D flow in simply connected domain

*** under special conditions on the filter core, **neither Gaussian nor box filters satisfy**

Razafindralandy D., and Hamdouni, A., 2006: Consequences of symmetries on the analysis and construction of turbulence models, *Symmetry, Integrability and Geometry: Methods and Applications*, 2, 052, 20 pp.

# Mathematical Foundations: Summary

- Regularization introduces physical filtering which eliminates small-scales form equations (no need to filter model fields)
- LKM is simpler and more stable than Leray's models
- Popular and reliable Smagorinsky sub-grid model is consistent with LKM
- Symmetry considerations however demand elimination of explicit length scale in sub-grid model
- It could be done through Germano Identity
- Mathematical analysis of NSE and symmetries gives a valuable guide for model closure development
- Of more than 100 sub-grid closures proposed over the last 30 years none satisfy all mathematical restrictions

# Turbulence Closure Problem I

- Start with Ladyzhenskaya-Kaniel model (LKM)
- Remember that the Smagorinsky sub-grid closure satisfies LKM conditions but do not follow from them
- Use Leonard equality to separate resolved and unresolved scales

$$\partial_t \bar{u} + \bar{u} \cdot \nabla \bar{u} = \nabla \cdot (-\bar{p}I + (\bar{u} \otimes \bar{u} - \overline{u \otimes u}) - T^*),$$

$$\nabla \cdot \bar{u} = 0,$$

$$T^* = 2 l_{cut}^2 \left| \bar{S} \right| \bar{S}$$

- To make the model consistent, express the regularization parameter (filter scale) through resolved quantities
- To do this apply Germano Identity

$$\overline{\bar{u}^h \otimes \bar{u}^h}^H - \overline{\bar{u}^h}^H \otimes \overline{\bar{u}^h}^H = \left( \overline{\overline{u \otimes u}^h}^H - \overline{\bar{u}^h}^H \otimes \overline{\bar{u}^h}^H \right) - \overline{T^*}^H$$

# Turbulence Closure Problem II

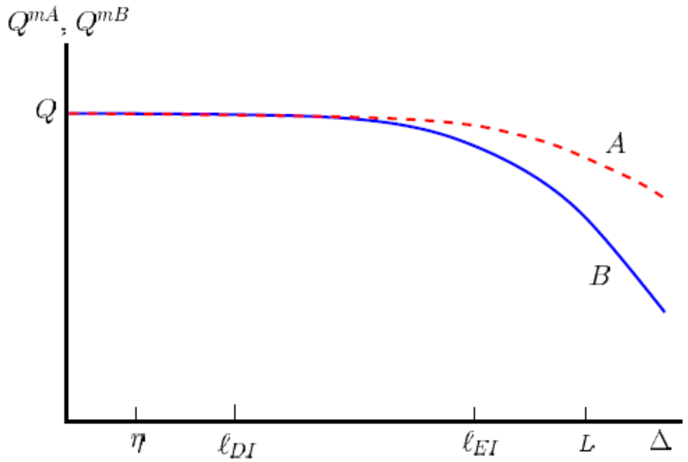



**Figure 6.** The predictions $Q^{mA}(\Delta)$ and $Q^{mB}(\Delta)$ of the statistic $Q$ obtained from LES models A and B as functions of the turbulence resolution length scale $\Delta$ for the case in which $Q$ and the processes affecting it are confined to the energy-containing range.

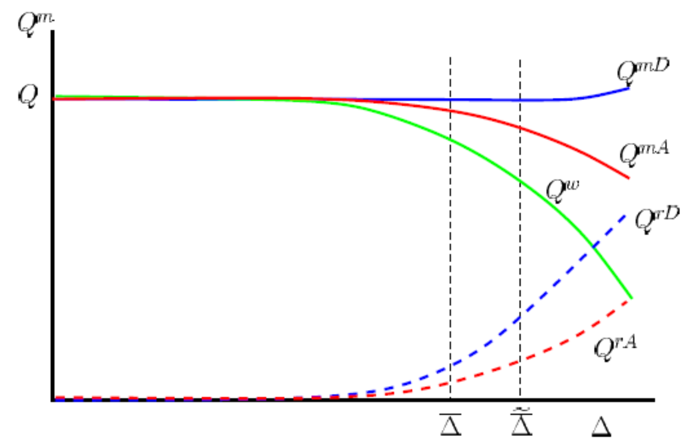



**Figure 8.** For the given model A, and the dynamic model D, a sketch of the resolved contribution $Q^w(\Delta)$ and of the modelled residual contributions $Q^{rA}(\Delta)$ and $Q^{rD}(\Delta)$ to the model predictions $Q^{mA}(\Delta)$ and $Q^{mD}(\Delta)$ of a large-scale statistic $Q$. The dynamic model selects the model coefficient $c_Q$ so that $Q^{mD}(\widetilde{\overline{\Delta}})$ equals $Q^{mD}(\overline{\Delta})$.

- Germano Identity does not give unique closure
- Closures based on GI called DYNAMIC closures
- Aim of the LES is to recover the intermediate asymptote in turbulent statistics (Figure 6)
- Dynamic procedure optimize this recovery as it provide the largest decrement of the error $||Q_{LES}(\Delta)-Q||_{L2}$ within the asymptotic range (Figure 8, Pope, 2004)

# Turbulence Closure Problem III

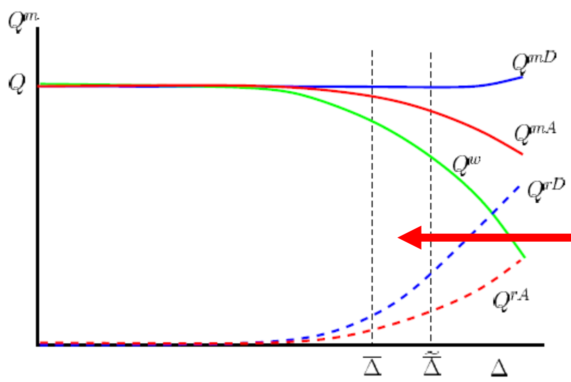
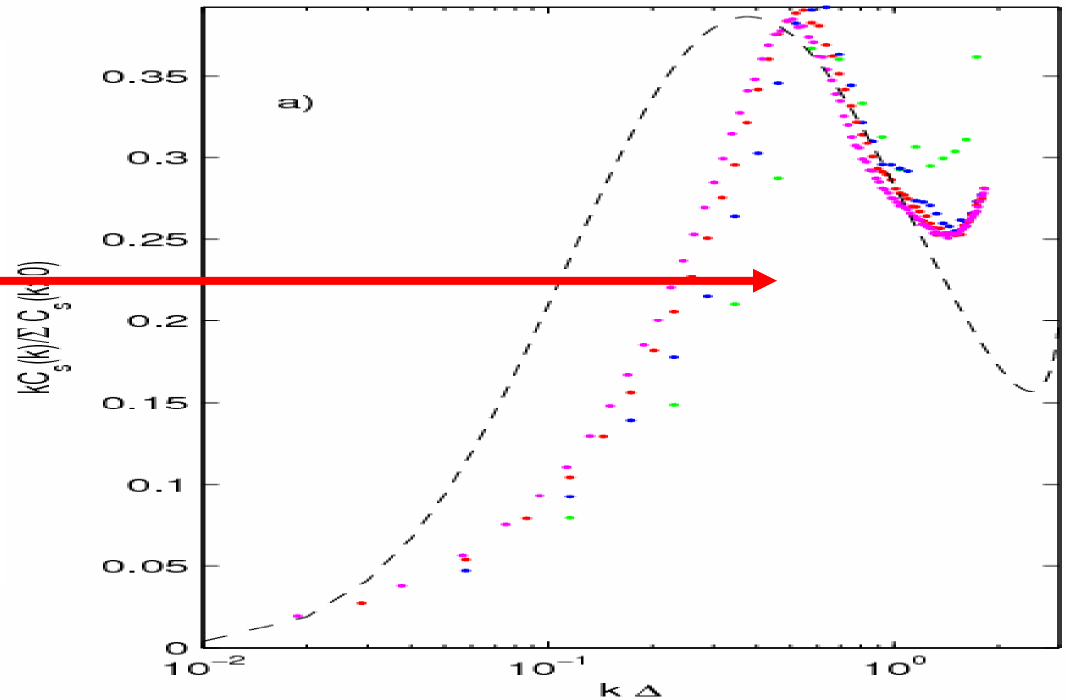



**Figure 8.** For the given model A, and the dynamic model D, a sketch of the resolved contribution $Q^w(\Delta)$ and of the modelled residual contributions $Q^{rA}(\Delta)$ and $Q^{rD}(\Delta)$ to the model predictions $Q^{mA}(\Delta)$ and $Q^{mD}(\Delta)$ of a large-scale statistic $Q$. The dynamic model selects the model coefficient $c_Q$ so that $Q^{mD}(\widetilde{\overline{\Delta}})$ equals $Q^{mD}(\overline{\Delta})$.




- The asymptotic behavior of statistics is a characteristic of high Re flow
- Dynamic procedure maintain high Re by shifting dissipation to high-frequency end of the resolved spectrum
- The best recovery of the asymptotic statistics is the reason behind the dynamic closures success

# Turbulence Closure Problem IV: Dynamic Mixed Model

- Dynamic Mixed Model (DMM) is the most straightforward implementation of a consistent LKM-LES
- Originally by Bardina et al. (1983) - scale-similarity arguments
- Improved by many authors, Vreman et al. (1997) form reads

$$T_{DMM} = (\overline{u}^h \otimes \overline{u}^h - \overline{u \otimes u}^h) - T^* = L - 2\left(C_s^2 \Delta^2\right)\left|\overline{S}^h\right|\overline{S}^h$$

$$\frac{l_{cut}^2}{\Delta^2} = C_s^2 = \frac{1}{2}\frac{(L_{ij} - H_{ij})M_{ij}}{\left\|M_{ij}\right\|_2^2},$$

**Takes the main burden of calculations in the optimization process**

$C_s$ - Smagorinsky constant, $\Delta$ - effective filter size of the mesh

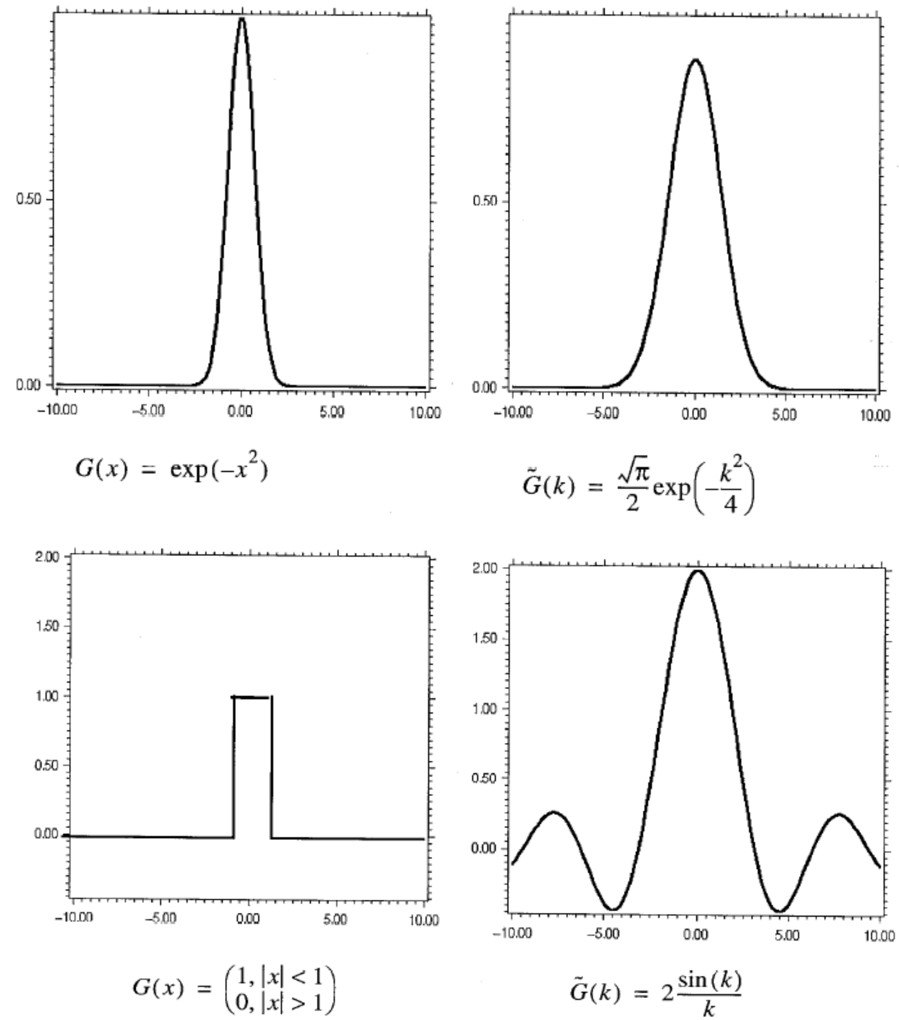
$$M = 2\overline{\left|\overline{S}^h\right|\overline{S}^h}^H - \alpha^2 2\left|\overline{\overline{S}^h}^H\right|\overline{\overline{S}^h}^H, \alpha = \frac{\overline{\overline{\Delta}^h}^H}{\overline{\Delta}^h},$$

$$H = \left(\overline{\overline{\overline{\overline{u}^h}^H \otimes \overline{\overline{u}^h}^H}^h}^H - \overline{\overline{\overline{\overline{u}^h}^H}^h}^H \otimes \overline{\overline{\overline{\overline{u}^h}^H}^h}^H\right) - \left(\overline{\overline{\overline{u}^h \otimes \overline{u}^h}^h}^H - \overline{\overline{\overline{u}^h}^h}^H \otimes \overline{\overline{\overline{u}^h}^h}^H\right),$$

$$L = \overline{\overline{u}^h \otimes \overline{u}^h}^H - \overline{\overline{u}^h}^H \otimes \overline{\overline{u}^h}^H$$

# Turbulence Closure Problem V

- For actual numerical simulations one have to construct a set of filters
- Most popular are Gaussian and Box filters
- Both filters are identical under second-order numerical schemes
- Both filters do not satisfy symmetry constrains
- It result in numerical instability of the dynamical procedure
- Ad hoc engineering modification either by limiters, e.g. $l_{cut}>0$, or by balance equations in Largangian formulation, e.g. TKE(x,t)>0.



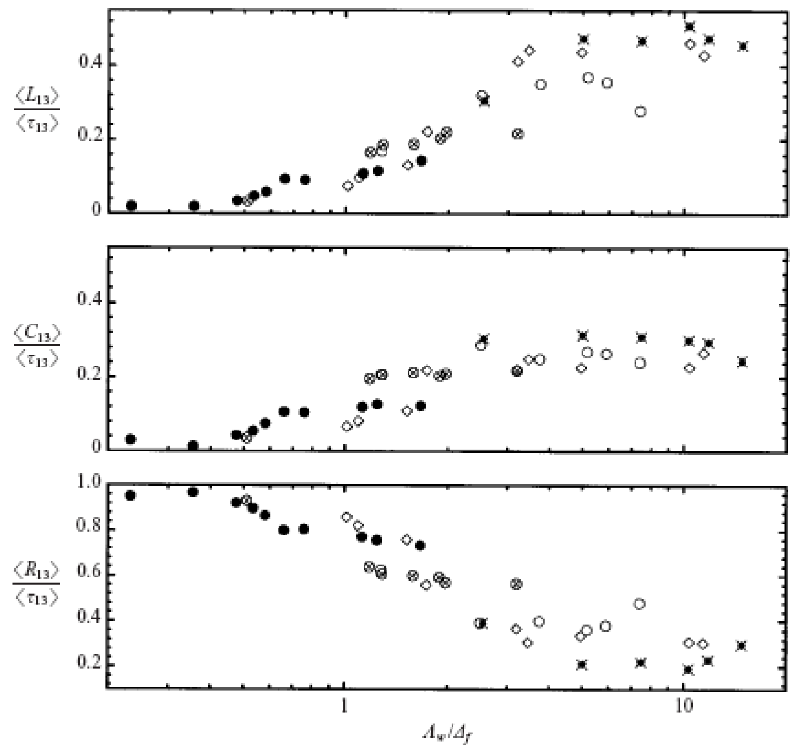

$$G(x) = \exp(-x^2)$$

$$\tilde{G}(k) = \frac{\sqrt{\pi}}{2}\exp\left(-\frac{k^2}{4}\right)$$

$$G(x) = \begin{pmatrix} 1, |x| < 1 \\ 0, |x| > 1 \end{pmatrix}$$

$$\tilde{G}(k) = 2\frac{\sin(k)}{k}$$

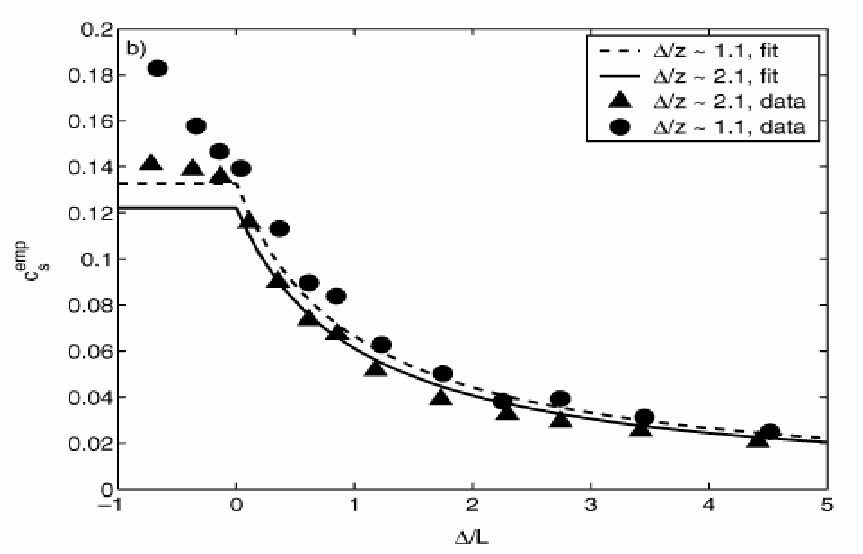
# Turbulence Closure VI

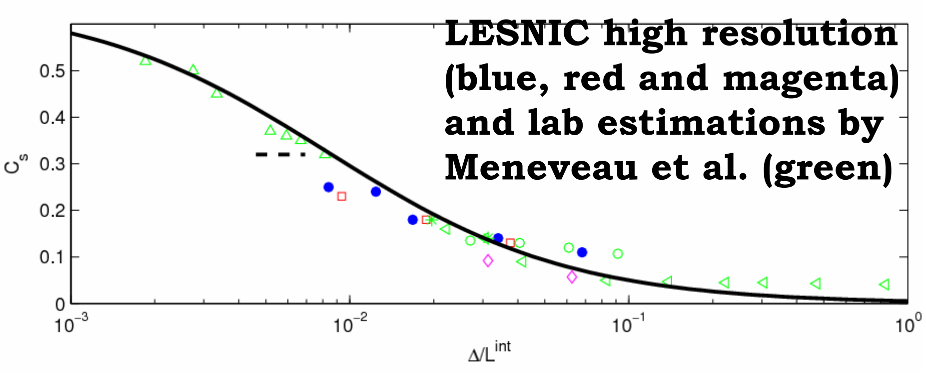


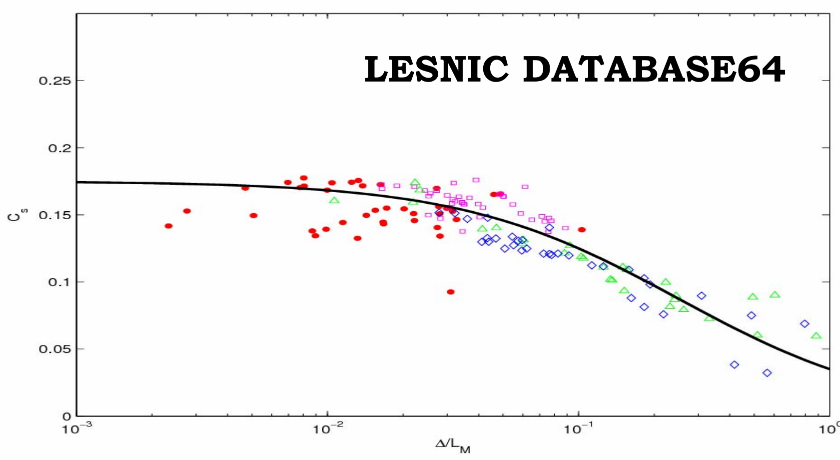

- As the most consistent model, DMM was extensively studied with observational data HATS, Campbell Tracks and other campaigns (Porte-Agel et al., 2001; Sullivan et al., 2003; Kleissl et al., 2004)
- It identify relative importance of different terms in the sub-grid closure (near surface)

# Turbulence Closure VII

- In unbounded shear flow determination of the sub-grid closure is difficult
- It is also computationally expensive, consuming >30% of time and >70% of memory
- Task is even more complicated in stratified and rotating PBL with variable background shear



# Turbulence Closure VIII
# Dynamic Model of Heat Diffusion

- Dynamic model for heat/scalar diffusion could be derive quite in the same way as for the momentum (Porte-Agel et al., 2004)
- Dynamic mixed model is however less stable for heat transport than for momentum, hence DMM is not applied in known LES

$$T_Q^* = \left(\frac{l_Q}{\Delta}\right)^2 \Delta^2 \left|\overline{S}^h\right| \nabla \overline{Q}^h \qquad \frac{l_Q}{\Delta} = \frac{C_s}{Sc^{1/2}},$$

$$Sc \equiv \Pr : Q = \theta$$

$$\left(\frac{l_Q}{\Delta}\right)^2 = \frac{K_i X_i}{\left\|X_i\right\|_2^2},$$

$$X = 2\left(\overline{\left|\overline{S}^h\right| \nabla \overline{Q}^h}^H - \alpha^2 \left|\overline{\overline{S}^h}^H\right| \overline{\nabla \overline{Q}^h}^H\right),$$

$$K = \overline{\overline{u}^h \overline{Q}^h}^H - \overline{\overline{u}^h}^H \, \overline{\overline{Q}^h}^H$$

**Dynamic coefficient as function of stability by Porte-Agel et al. (2001), Evaluation in Campbell Track field experiment, CA**

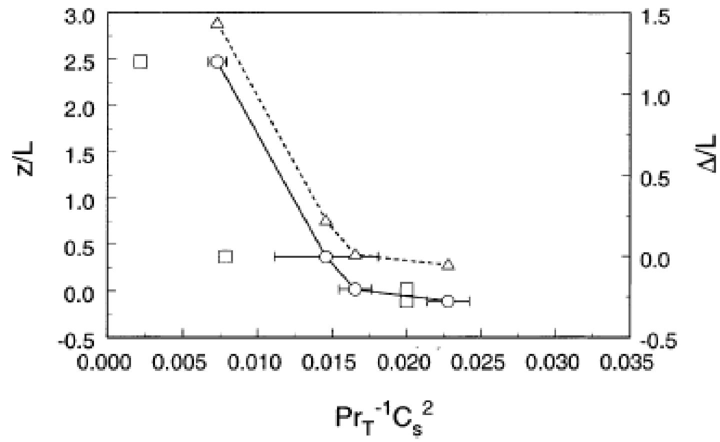
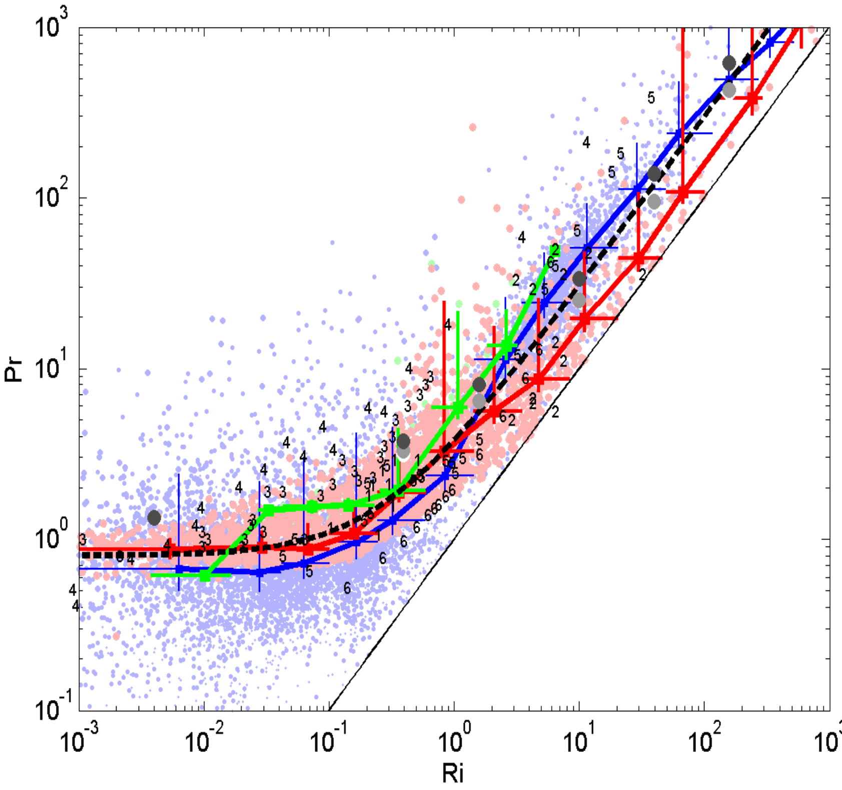



Fig. 10. Value of the eddy-diffusion model coefficient $Pr_T^{-1}C_S^2$ as a function of the stability parameter $z/L$ (left axis) and $\Delta/L$ (right axis), obtained for the four measurement periods with different atmospheric stabilities. Period A: $L = 1.36$ m ($z/L = 2.47$); period B: $L = 9.16$ m ($z/L = 0.37$); period C: $L = 196.4$ m ($z/L = 0.02$); and period D: $L = -31.71$ m ($z/L = -0.11$). The open circles (left axis) and triangles (right axis) are obtained by matching the mean measured and modeled SGS dissipations. Squares (left axis) are obtained using Deardorff's correction. Results are averages over three values obtained using 8-min subperiods. The error bars for the open circles show the approximated standard deviation associated with those three samples.

# Turbulence Closure IX

- If Cs is dynamical, than sub-grid Pr should be fairly constant with very little effect on resolved scales
- Intercomparisons demonstrate little sensitivity of simulations to sub-grid Pr
- Simulated with LESNIC
  $Pr = 0.8 + 5\,Ri$ at $Ri < 1$
  $Pr = 2\,Ri$ at $Ri > 10$
- Prescribed in LESNIC
  $Pr = 1 + 7\,Ri$
- Good deal of self-correlation is probably in this function but
- Mixing efficiency independence of closure results in automatic recovery of Monin-Obukhov similarity in boundary conditions



# Turbulence Closure: Summary

- Dynamic mixed model (DMM) satisfies mathematical requirements provided the correct filter choice
- DMM produces optimal recovery of the auto-model interval in the turbulence statistics provided that such interval exists (high Re flow)
- DMM shifts dissipation toward smallest resolved scales thus large eddies evolve (almost) without dissipation
- DMM seems to flexible enough to take care of stratification in PBL so that variability of sub-grid Pr is not important for simulations
- DMM is able to cure numerical errors at the smallest resolved scales as the dissipation increase does not distinguish physical or numerical energy cascade

# Boundary Conditions I

- Boundary conditions on large-scale fields in LES are non-trivial
- Observations of wind gusts and tornado (right, 1999 F5 Tornado in Oklahoma) reveals that vortices can slip over impenetrable rough surfaces
- Even more problematic to impose boundary conditions for heat and scalars

# Boundary Conditions II

- Numerical schemes require prescription of **fluxes as boundary conditions**
- Fluxes close to impenetrable walls are always **unresolved**
- In Prandtl's boundary layer, the vicinity of the wall is where turbulence is thought to be produced
- Unresolved production – Garbage simulations
- Nature is friendly for us however

# Boundary Conditions III

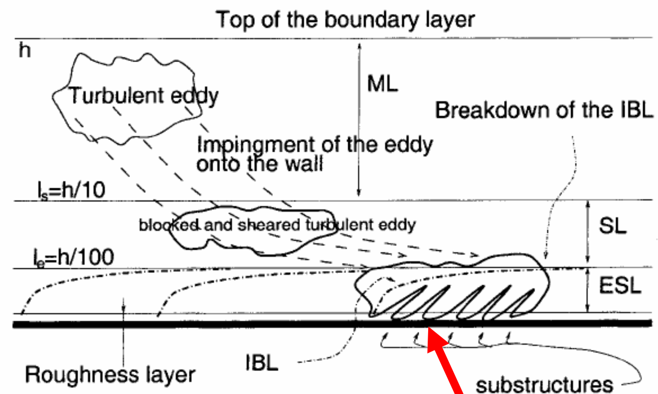
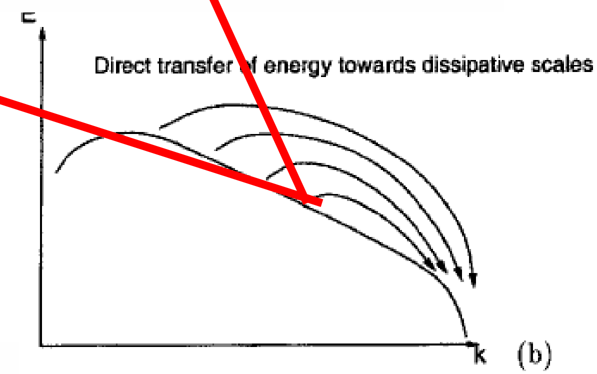
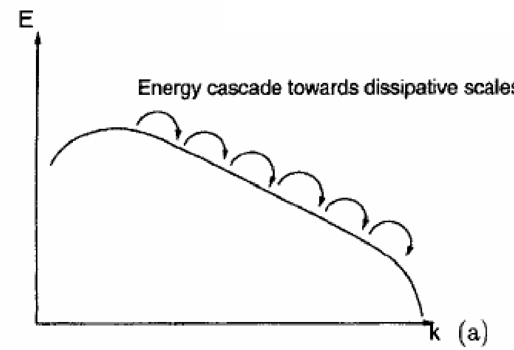



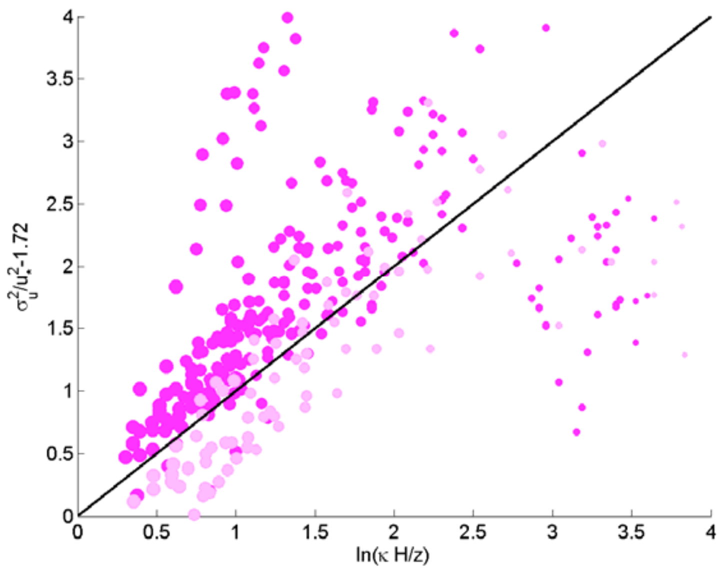

*Figure 1.* Sketch of a typical high Reynolds number boundary layer; $h \approx$ 1–2 km, $\ell_s \approx$ 100–200 m, $\ell_e \approx$ 10–20 m, the roughness length $z_0$ is less than 0.1 m over a field, less than 1 m over a typical city.




- Direct energy cascade generate turbulence (Hunt et al., 2001;02)
- Direct cascade helps to justify wall-law boundary conditions
- Detached (large-scale) eddies formerly considered “inactive” in Townsend and Bradshaw but indeed proven to be “active”

# Boundary Conditions IV



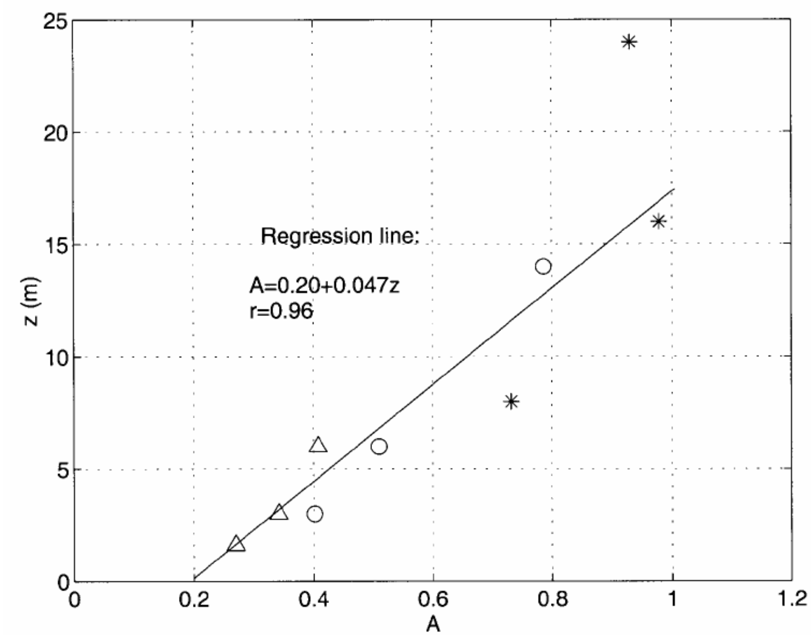




*Figure 6.* The scale parameter $A$ of the expression $\Lambda_{max} = Au_*/f_c$ plotted against height. Data from: 'Laban's mills' (Högström, 1992), △; Lövsta (Högström, 1990), ○; Östergarnasholm (cf. Smedman et al., 1999), *. Note that each symbol represents a mean over many measurements from each site and measuring height.

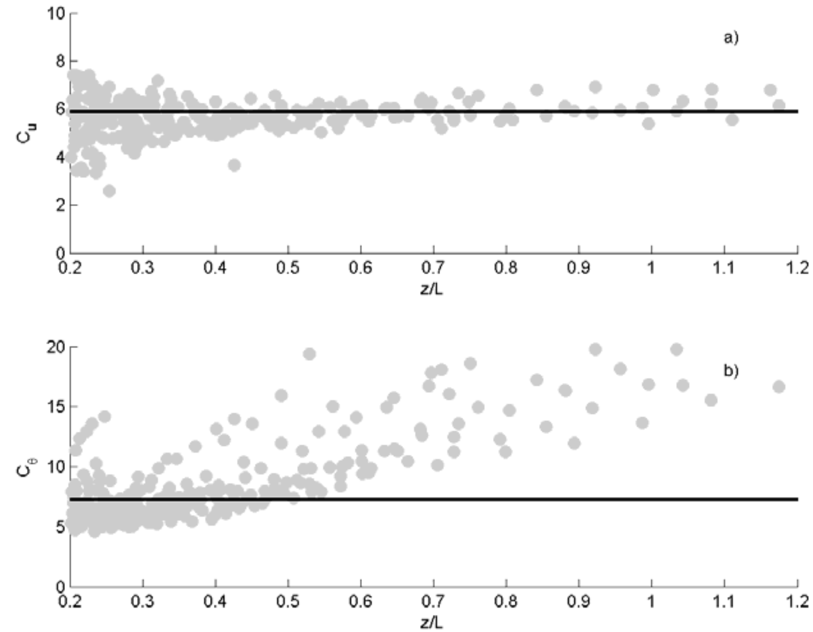
- Detached eddies originate in the shear motions immediately above the surface layer
- Eddies are of the PBL scale, descend and impinge onto the surface
- Supported by atmospheric observations (right, Hoegstroem et al., 2002)
- Supported by LES (left, Esau)
- Theory explain how PBL depth may influence (through large-eddies) surface fluxes

# Boundary Conditions V

- Theory predicts the log-law (in neutral PBL) for the velocity profile
- Neglecting velocity rotation, flux variability, and pressure gradients, the law reads

$$\tau_0^{1/2} = \frac{\kappa \left| u_{z\to 0} \right|}{\ln \frac{z}{z_0}} \frac{u}{|u|}$$

- Stratification corrects the log-law with Monin-Obukhov similarity function of the flow stability
- The MO function is simply a reflection of the turbulence mixing efficiency in stratified flow (Pr vs Ri)
- Thus, correct Pr vs Ri in LES should result in recovery of the non-dimensional velocity gradients and hence fluxes **automatically**
- DATABASE64 LES show it (right)




$$\tau_0^{1/2} = \frac{\kappa \left| u_{z\to 0} \right|}{\ln \frac{z}{z_0} + \psi(z/L)} \frac{u}{|u|},$$

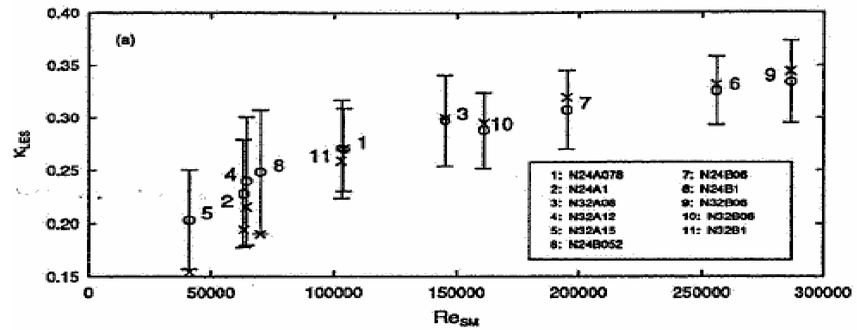
$$SBL: L > 0, \psi(z/L) = C_{u,\theta} \frac{z}{L}$$

# Boundary Conditions VI

$$\tau_0^{1/2} = \frac{\kappa \left| u_{z\to 0} \right|}{\ln \dfrac{z}{z_0}} \frac{u}{|u|} \qquad \kappa = 0.34 - 0.55, \quad M(\kappa) = 0.41$$

- Important issues are determination of $z_0$ and $\kappa$
- $\kappa$ cannot be determined independently of $z_0$ in data
- Semi-analytical analysis based on the structure function in sheared flow (Lvov et al., 2005) $\kappa = 0.42$
- Constant may depend on flow Re
- Lab exp. (Jinyin et al., 2002) and LES (Cai et al., 1996): Re increase, constant increase
- PBL (SHEBA) data (Andreas et al., 2006) suggests directly opposite

$$\kappa = -1.48 \cdot 10^{-2} \ln \mathrm{Re}_* + 0.427$$



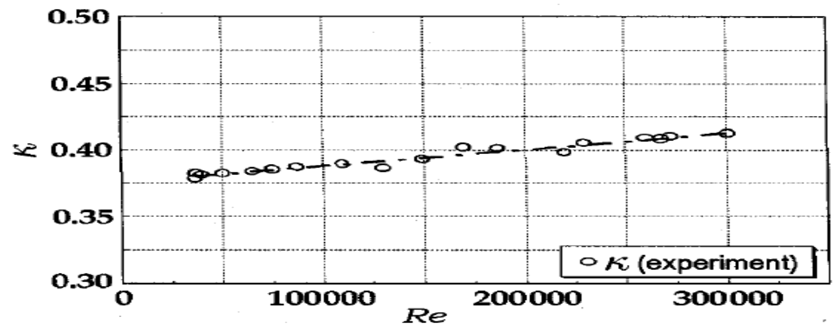
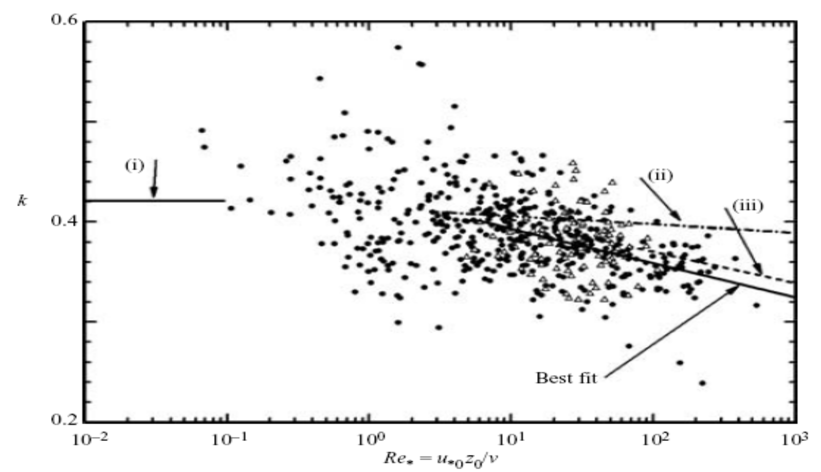



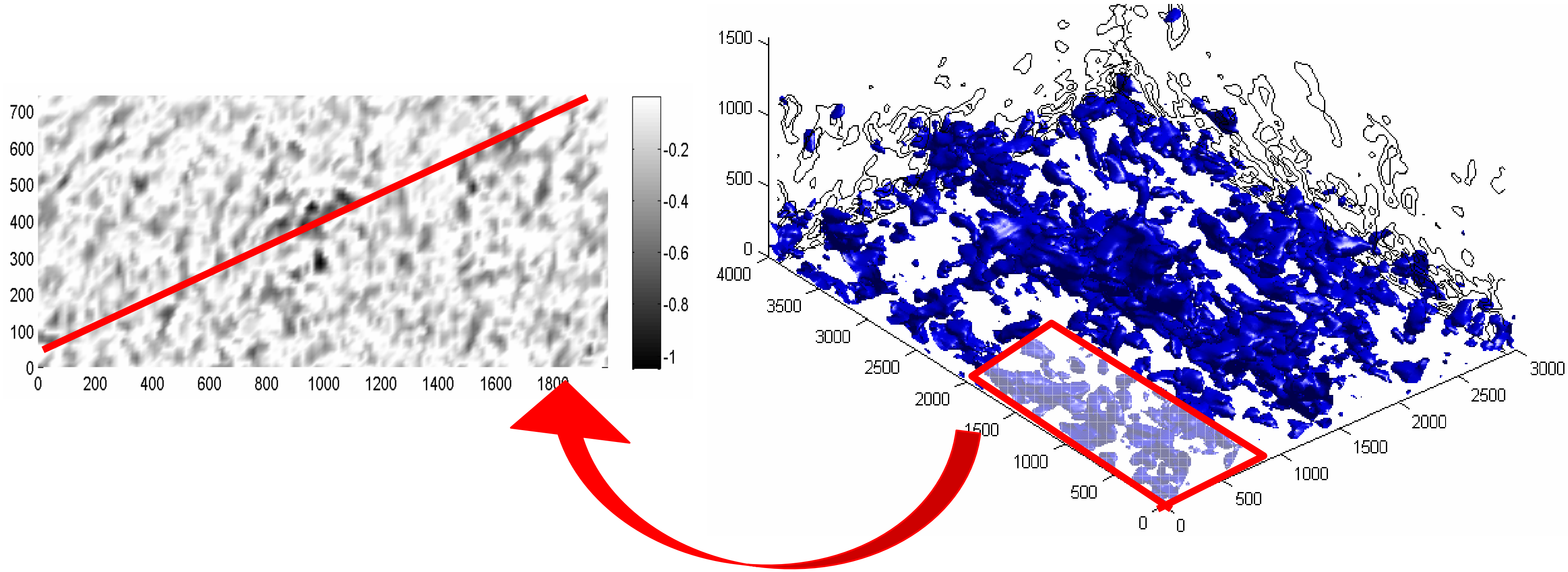

Fig.3 von Kármán's constant in the velocity profile



# Large-Eddy Simulations for Turbulence-Resolving Modeling

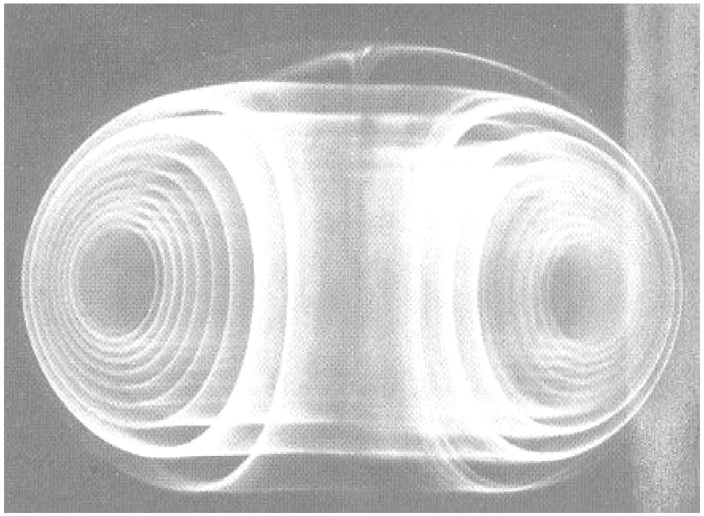
- Large-eddy Simulation (LES) resolve only large, presumably non-universal eddies in fluid flow
- The resolved scales in LES defined by Nyquist theorem (min 2 grid nodes per wave length)
- It has sense if such large eddies indeed dominate the turbulent mixing
- In this sense, LES is a science about turbulence self-organization

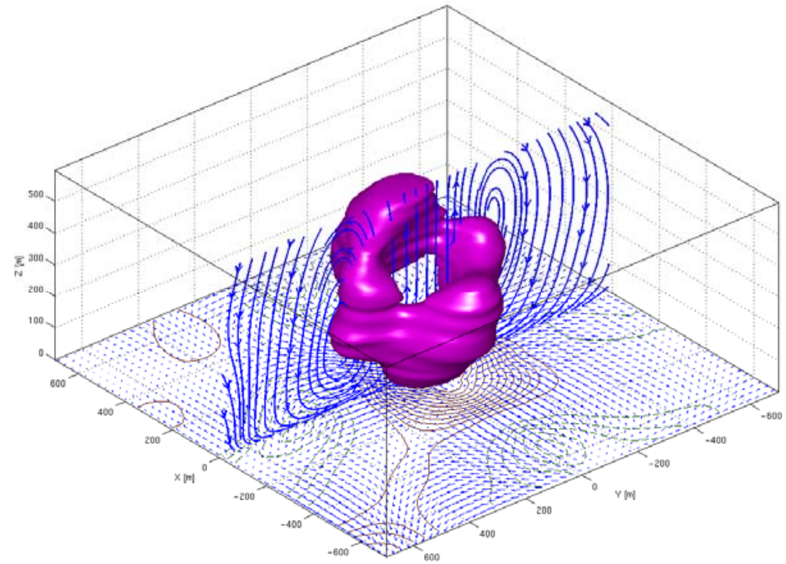
# Surface-Layer Turbulence Patterns in Neutral PBL LES




- Structure of resolved-scale turbulence stress (right)
- Its surface (the first resolved layer) imprint in a selected domain
- Self-organization of the instant turbulence stress and up to some degree imprints are visible

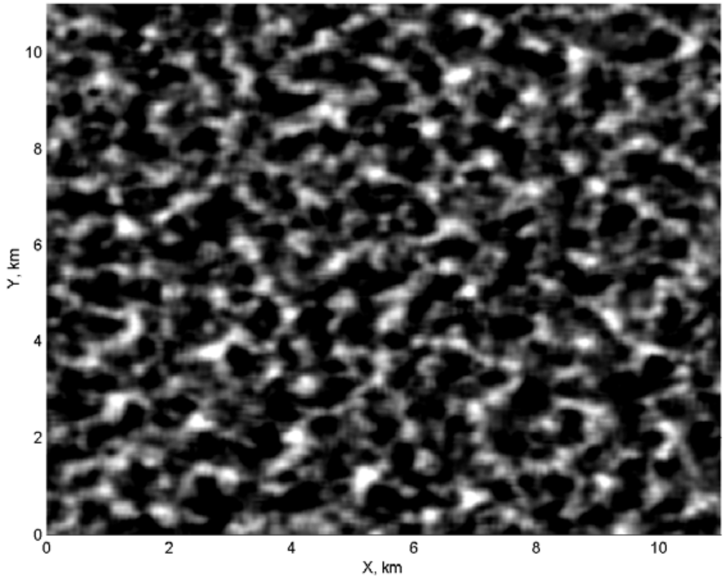
# Structure of Thermally-Driven Turbulence I





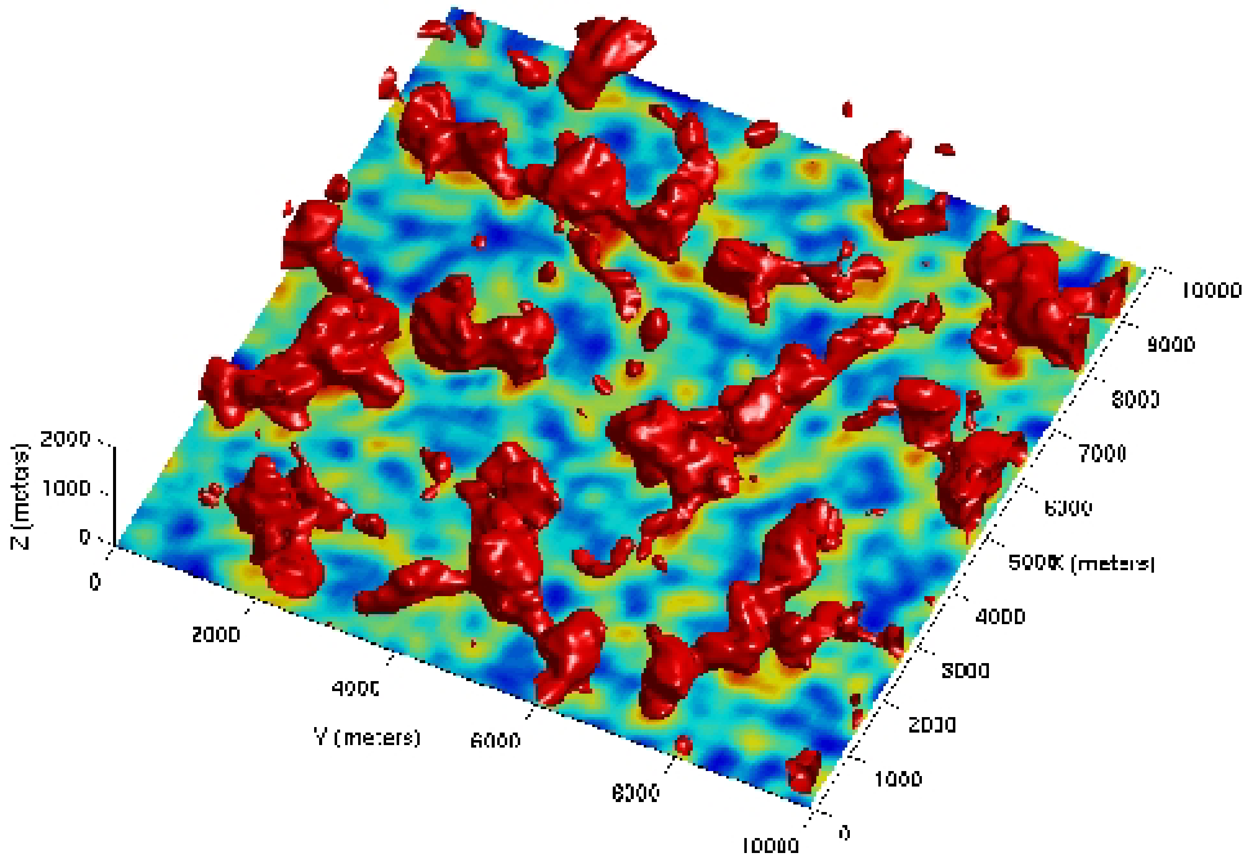

- Potential vorticity in fluid is a conservative quantity
- It drives free convection self-organization into vortex rings
- Lord Raylegh (1921) found the vortex ring as a fastest growing modal perturbation in shear-free convection
- Rings, multiplied and distorted, compact themselves into cellular convection patterns

# Structure of Thermally-Driven Turbulence II

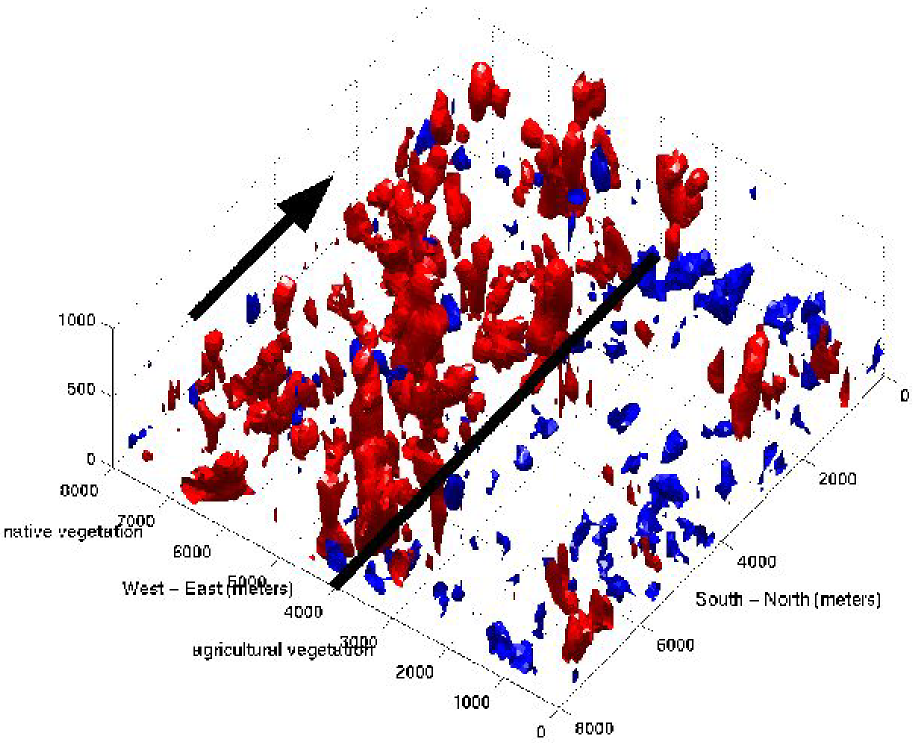



- Rings, multiplied and distorted by secondary flow instabilities, compact themselves into cellular convection patterns

# Structure of Thermally-Driven Turbulence III

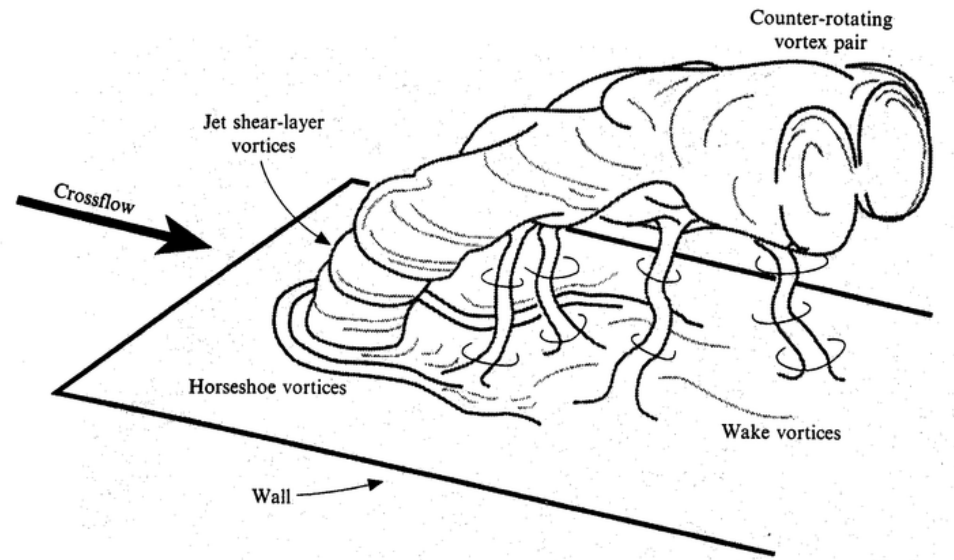


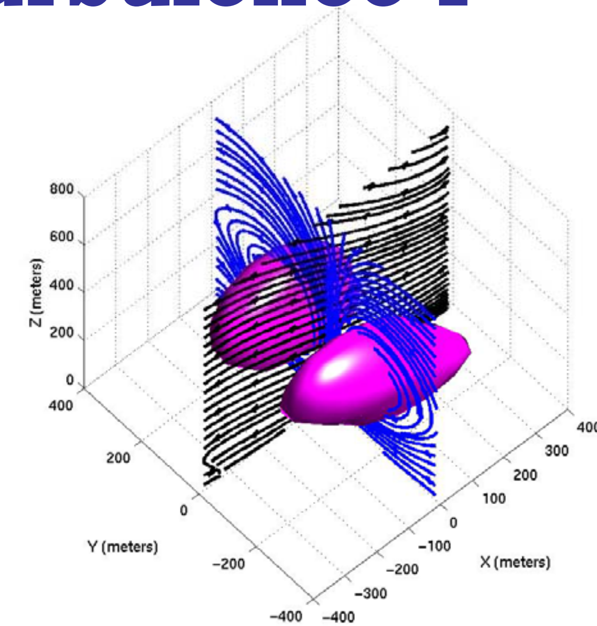
# Heterogeneous Convection




- Cloudiness build up over dryer and hotter terrain

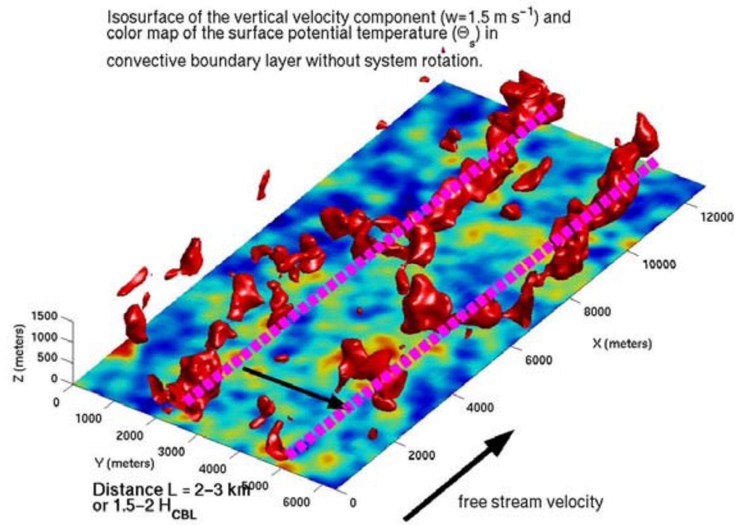
# Structure of Shear-Driven Turbulence I



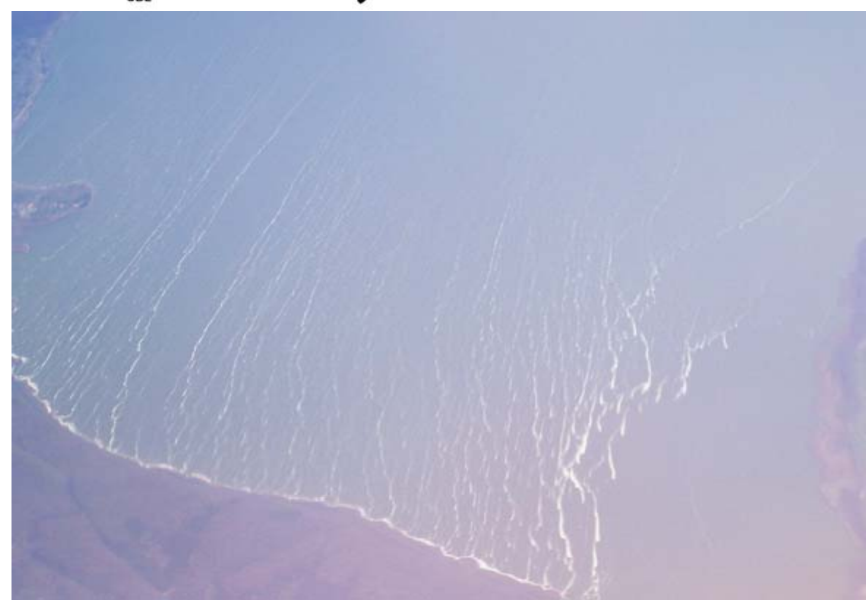

- In shear-driven PBL, the most energetic structure is a vortex pair aligned (?) with the mean flow direction
- Left panel – schematic picture of the flow structure adopted after lab. experiments [Fric & Roshko, 1989: Structure in the near field of the transverse jet Proc. 7th Symp. on Turbulent Shear Flows (no. 6-4. Stanford, August)]
- Right panel – the most energetic vortex pair structure computed with POD analysis from LES data (Esau, JoT, 2003)

# Structure of Shear-Driven Turbulence II

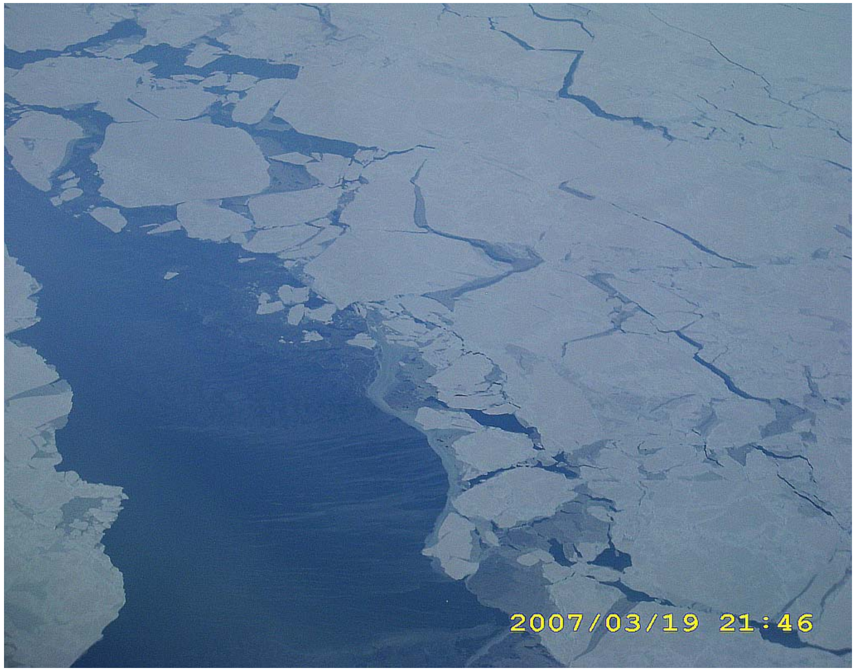


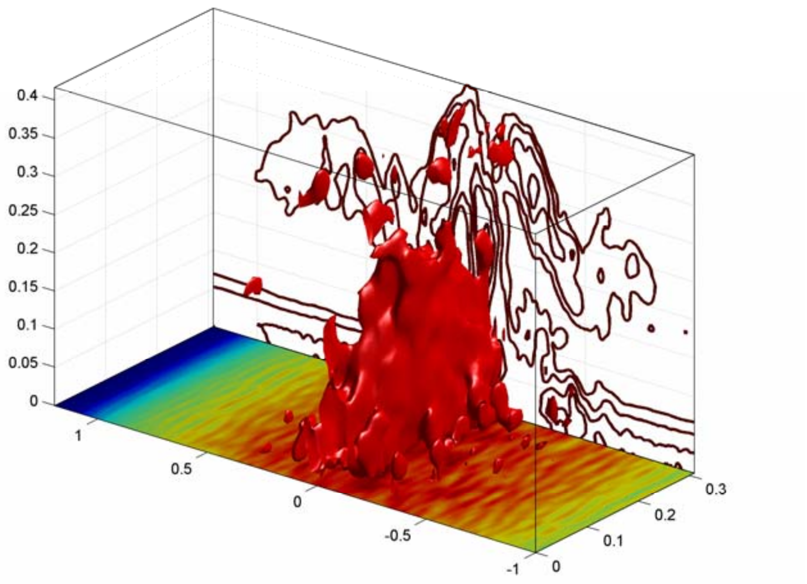

Observed very often as structures of the cloudiness organization, fog density in the atmosphere

Langmuir circulation in the ocean mixed layer



# Shear to Convective Transition I
# Leads




- Temperature difference generate convection
- Convection generate shear
- Shear enhances convections

# Conclusions

- Turbulence-resolving simulations are suitable and flexible tool to study
- Complex, self-organized turbulence on meteorological scales
- With realistic variability of boundary conditions and micro-physical phenomena