Turbulence Numerical Model as a Research Tool

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Objectives

- Discuss numerical modeling of turbulence in terms of philosophical concepts
- Consider cultural aspects of modeling and its impact on result interpretation
- Illustrate shift of paradigms in turbulence research facilitated by modeling
- **My ultimate objective is to highlight emergence of meaning out a set of numbers**

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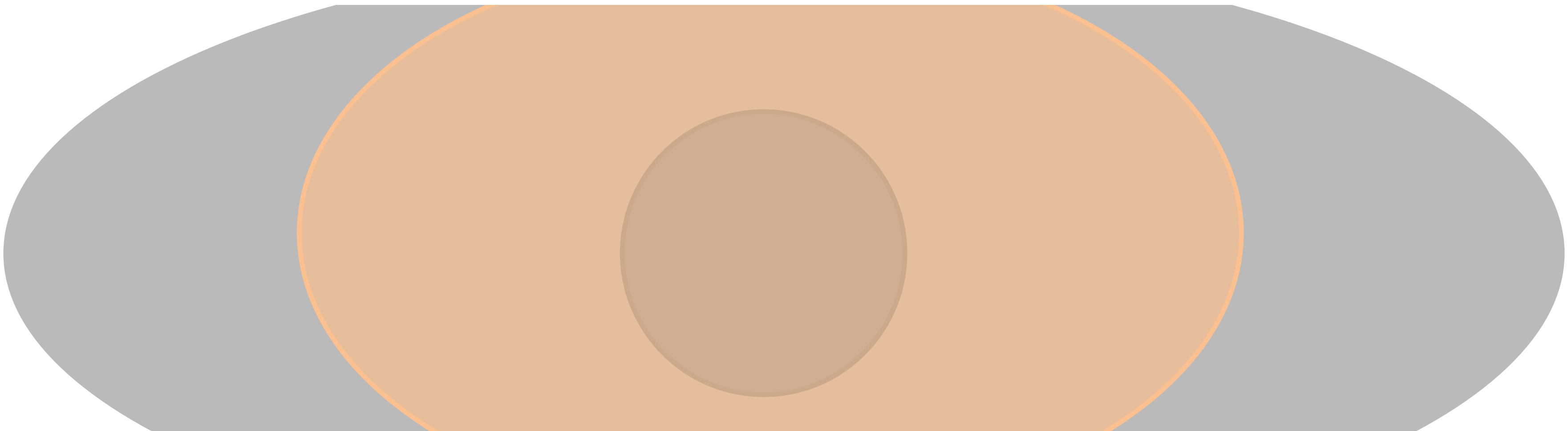
Part I:
Philosophical Frameworks

Philosophical Concepts of Scientific Endeavor



Open systems in post-modern, post-positivist formulation
Formulations unclear and incomplete
Models are non-deterministic
Not only data in IBC are uncertain but also the systems themselves
Evidences are ambiguous or absent; values fluid and in change
Science develops in democratic way through consensus discussion
Continues shift of popular subjects and fashions

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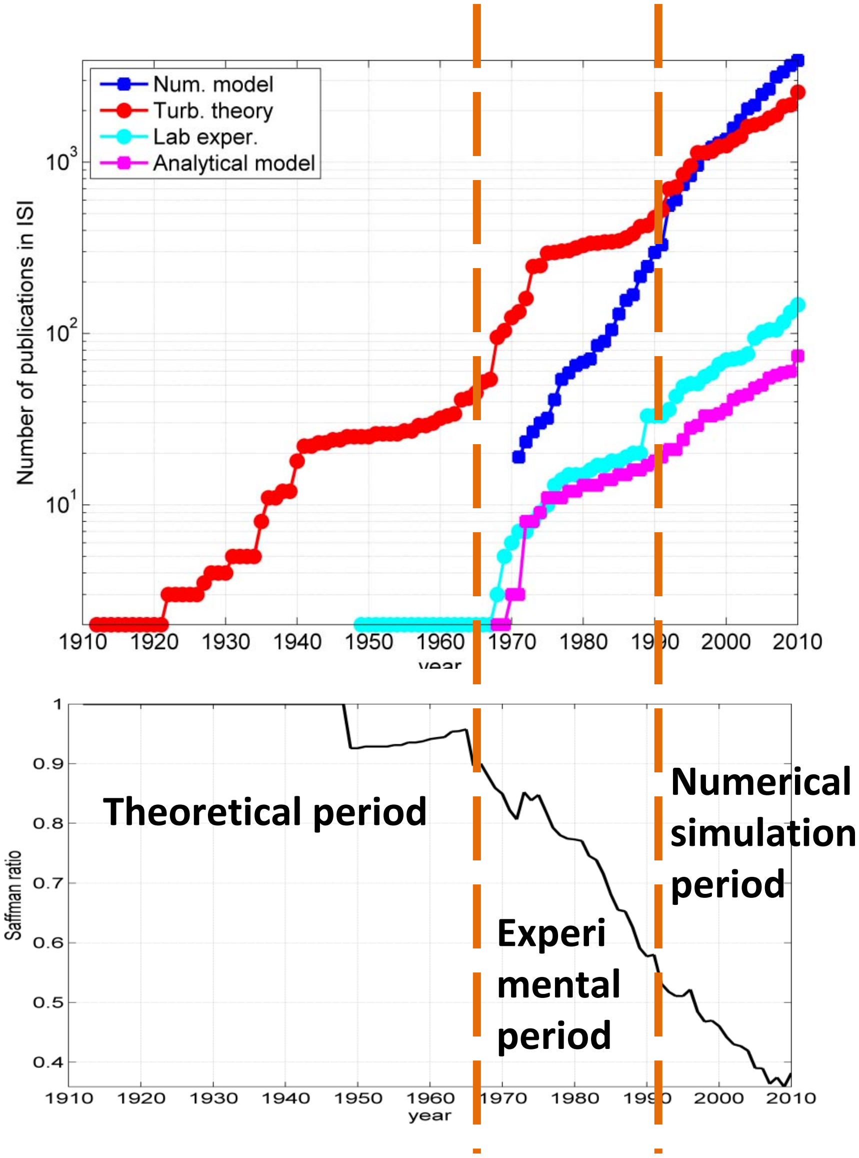
Disciplinary Positivism in Crisis

- Positivism in normal science (T. Kuhn)
  - A set of epistemological perspectives and philosophies of science which hold that the scientific method is the best approach to uncovering the processes by which both physical and human events occur
- Positivist seeks for quantitative data (numbers) to falsify existing hypotheses
- Positivist's final goal is to predict
- Positivism does not explain (I. Lacatos)
  - Where those hypotheses come from
  - How do they emerge and mature
- Disciplinary crisis occur without a fresh inflow of new conceptual qualitative ideas
- Illustration: A linear (S trend -0.012/yr) drop of the Saffman ratio (Tsinober, 2009) in the turbulence research since mid-60s



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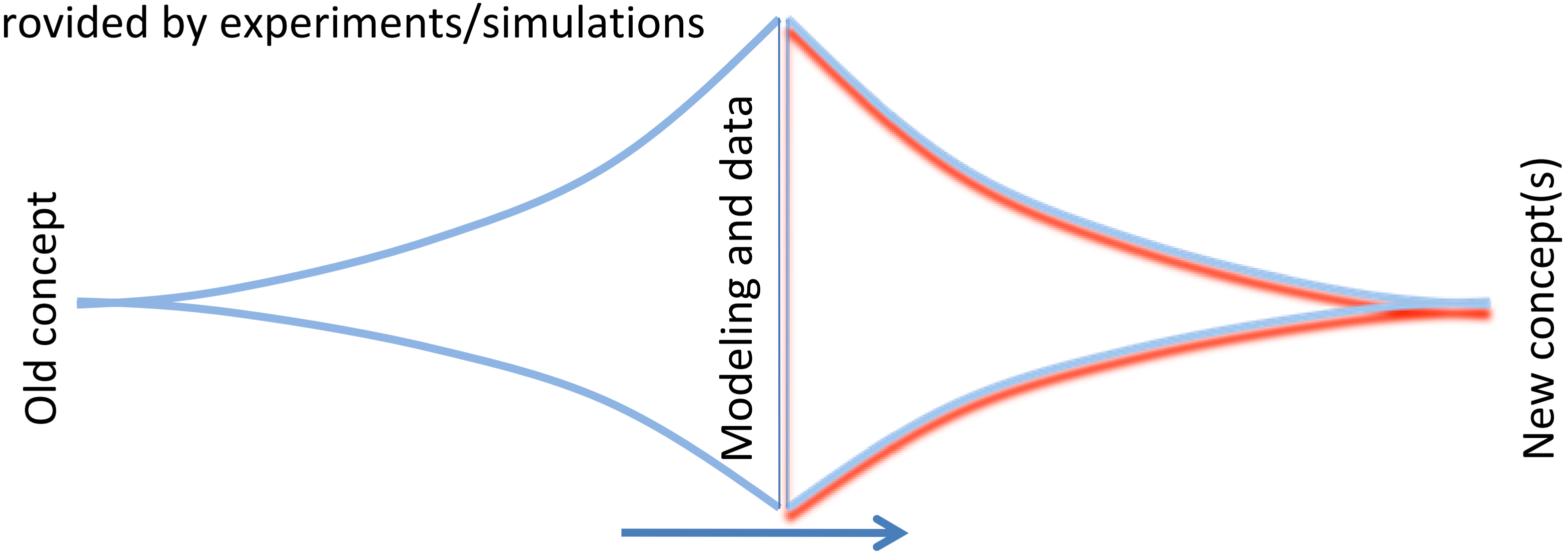
On the Way Out of Crisis

Disciplinary crisis is obvious …

To resolve the crisis, one must design a way to generate new concepts out of data provided by experiments/simulations



This design is addressed by qualitative or interpretive approach inherently linked to the post-modern, post-positivist paradigm (Quantz, 1992)

By coincidence (?), the first understanding of the positivist crisis and attempts to find a way out have been published in 1960s, e.g. Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory*. Chicago, IL: Aldine Publishing Company

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Qualitative versus Quantitative Approach

POSITIVIST APPROACH	INTERPRETIVIST APPROACH
Assumptions	*Assumptions*
• Social facts have an objective reality	• Reality is socially constructed
• Variables can be identified and relationships measured	• Variables are complex, interwoven, and difficult to measure
Research Purposes	*Research Purposes*
• Generalizability	• Contextualization
• Causal explanations	• Understanding
• Prediction	• Interpretation
Research Approach	*Research Approach*
• Begins with hypotheses and theory	• May result in hypotheses and theory
• Uses formal instruments	• Researcher as instrument
• Experimental	• Naturalistic
• Deductive	• Inductive
• Component analysis	• Searches for patterns
• Seeks the norm	• Seeks pluralism, complexity
• Reduces data to numerical indices	• Makes minor use of numerical indices
• Uses abstract language in write-up	• Descriptive write-up
Researcher Role	*Researcher Role*
• Detachment	• Personal involvement
• Objective portrayal	• Empathic understanding

EXHIBIT 1.1 Predispositions of Positivist and Interpretivist Approaches to Research

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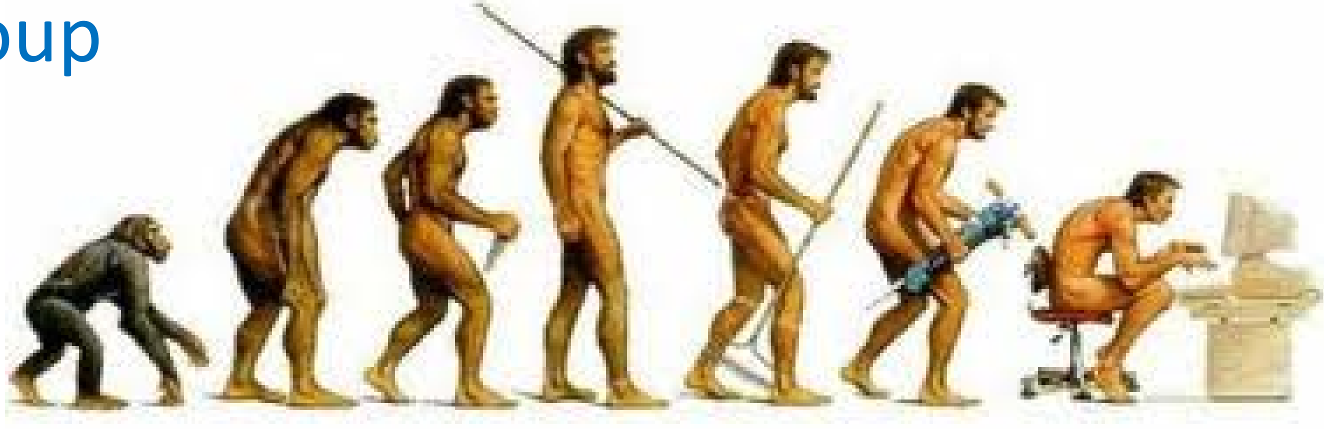
Glesne, C., 2011: Becoming Qualitative Researchers: An Introduction, Fourth Edition, Allyn & Bacon, 336 pp.

Culture

- (definition from Wiki) – An integrated pattern of human knowledge, belief, and behavior that depends upon the capacity for symbolic thought and social learning; The set of shared attitudes, values, goals, and practices that characterizes an institution, organization or group



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Narrow the Perspective: Numerical Modeling (Simulations)

- Culture of Calculation
- Numbers are the meaning
- Models justified by affirmation of theory
- Observations are objective and external
- Science ends with model development
- Model goal is to predict
- Model accuracy can be always improved

- Culture of Simulations
- Numbers are meaningless
- Models justified by new relationships
- Observations are another kind of models
- Science begins with model development
- Model goal is to understand
- Model accuracy may not improve

Search for meaning of numbers and consensus of meanings

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Turkle, S., 2009: Simulation and its discontents, MIT Press

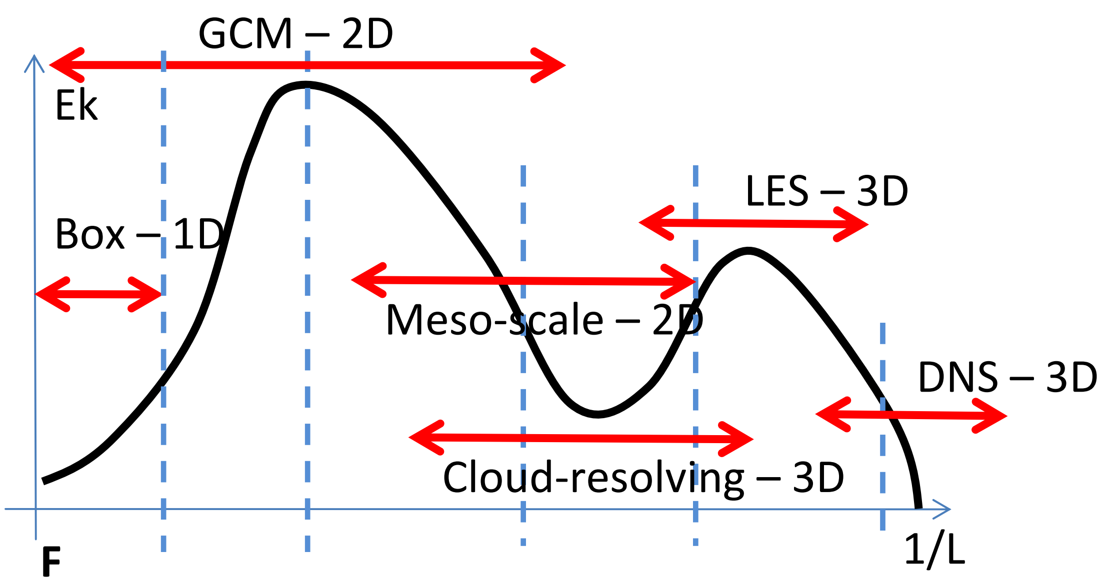
Turbulence Modeling

The major difficulty of turbulence modeling is linked to the fact that the turbulence involves a wide range of length and time scales as well as their non-linear interactions

Models reduce the range of scales limiting either the largest scale (DNS) or the smallest one (LES) or totally eliminating them (RANS)

A picture of a friend is useless if it covers a football field and exhibits every pore.

(Achen, 1991, p. 13)



All models resolve only limited range of scales

How can we judge them as superior to each other?

Historical Assessment

Expectations

One should not expect too much from these "*calibrated surrogates for turbulence*." They should work satisfactorily in situations not too far removed geometrically, or in parameter values, from the *benchmark situations used to <u>calibrate</u> them*.

John Lumley, "Atmospheric modeling," Mech. Eng. Trans., Inst. of Eng. Australia, 1983:

I am convinced that much of this huge effort will be of passing interest only… The only encouraging prospect is *<u>that current progress in understanding turbulence</u>* will . . . guide these efforts to a more reliable discipline.

Hans Liepmann, "The rise and fall of ideas in turbulence," Am. Scientist, 1973

Practice

"DNS is a tool [in the turbulence research endeavor], in which it complements the time-trusted methodology of experimental research"

"*Significant insight has been gained from DNS of certain idealized flows that cannot be easily attained in laboratory*" [IE: i.e. cannot be calibrated]

Moin and Mahesh (Ann. Rev. Fluid Mech., 1998, 30, 539-78)

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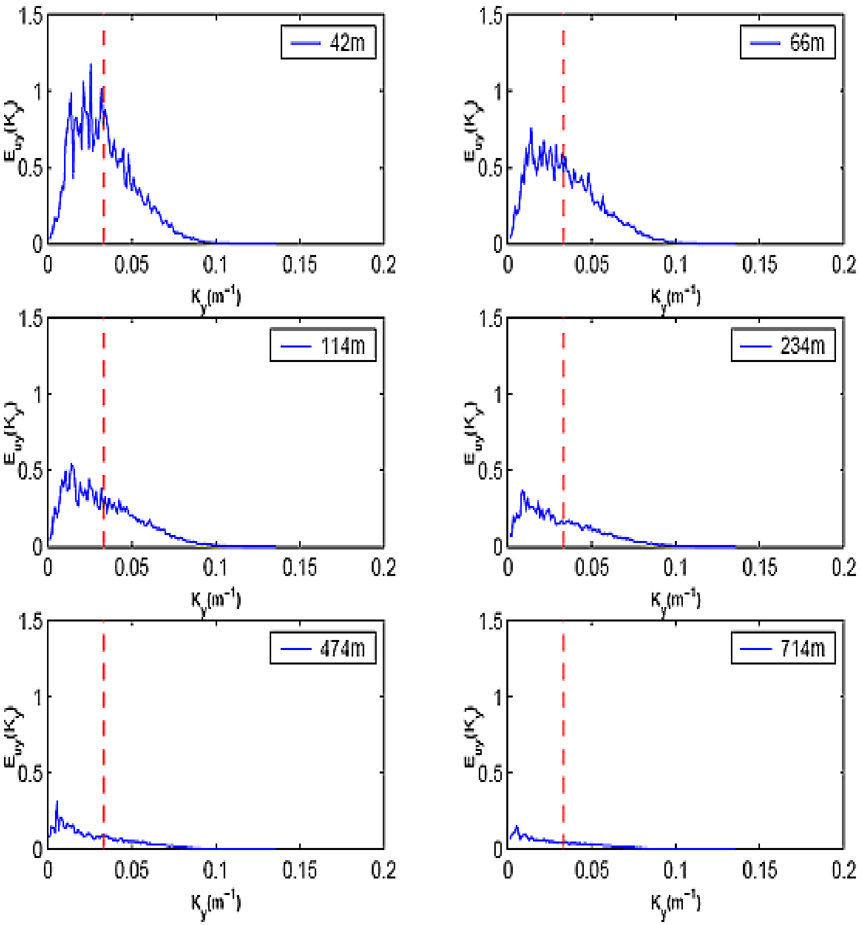
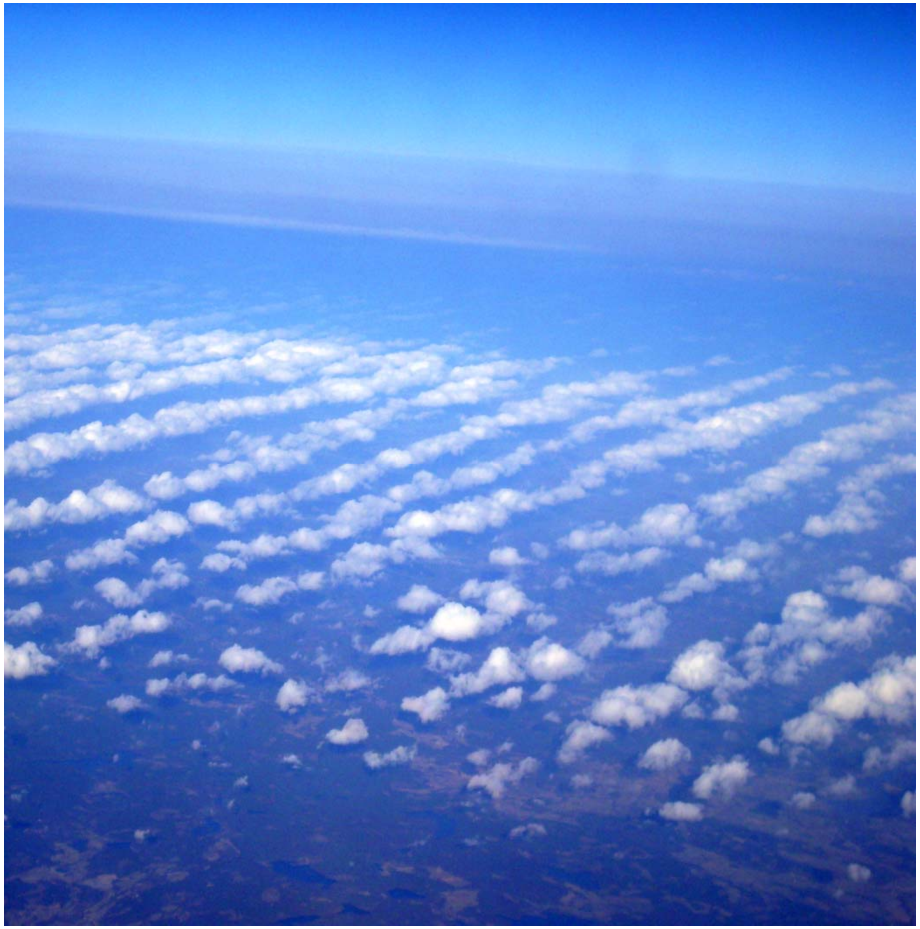
Part II:
Illustration

Planetary Boundary Layer Structure





No clear signature when standard methods are used

Only elusive pattern on level of cognitive perception

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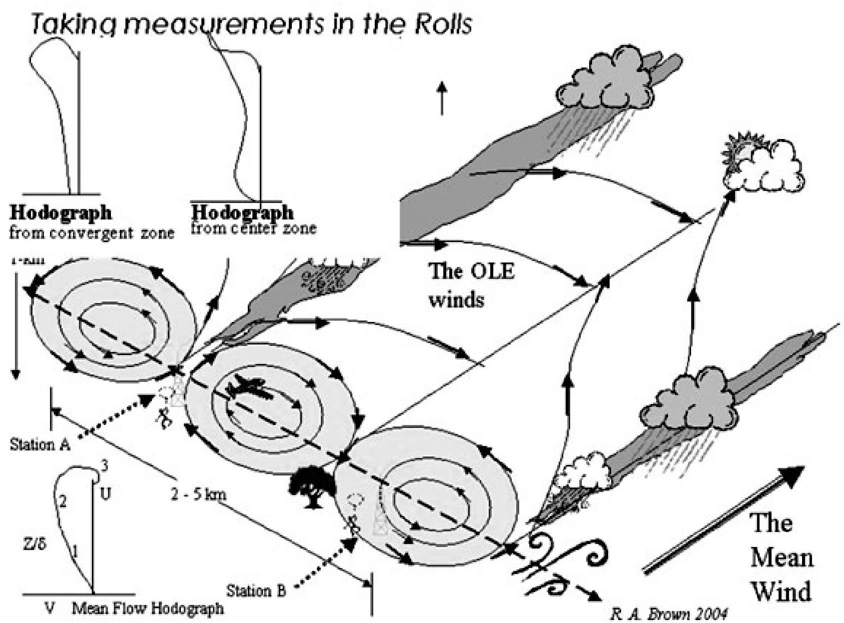
Uncertainty of Observations – Freedom of Conceptualization

- Theory A (D. Lilly, R. Brown ...; meteorology) – EBL is organized due to Ekman instability ... Ω_V
- Theory B (P. Bradshaw, S. Leibovich ...; oceanography) – EBL is organized due to ... Ω_H
- Theories C (many authors) – EBL is organized due to other dynamical processes, e.g. oblique instability of the Tollmien-Schlichting waves, *not related to the Coriolis force*

A

B



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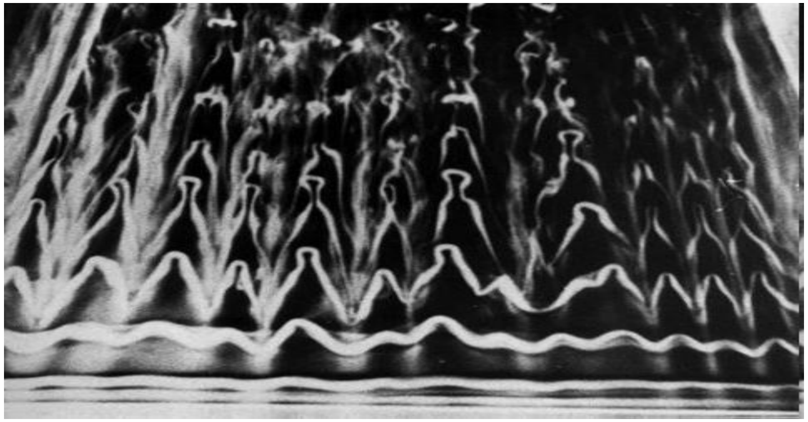

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Perry, A.E., Lim, T.T. & Teh, E.W. (1981) A visual study of turbulent spots, J. Fluid Mech., 104 , 387

Calculations versus Simulations

- Calculations
  - Develop a model and a set of runs corresponding a chosen theory (e.g. Mason and Sykes, 1980; Zikanov, 2004)
  - Calibrate the model and affirm the theory
  - If the theory cannot be supported, correct the model
- Theoretical simplifications are logically derived and therefore correct (L. Landau approach)
  - Requires irrational intuition

- Simulations
  - Develop a model and a set of runs reproducing all alternatives
  - Obs: Superiority does not follow from the model resolution
  - Falsify the model against a set of evidences
  - Obs: Not against those which affirm the theory
  - Modify the runs to single of relevant simplifications
- Theoretical simplifications are logically derived and therefore could be irrelevant to the subject of study

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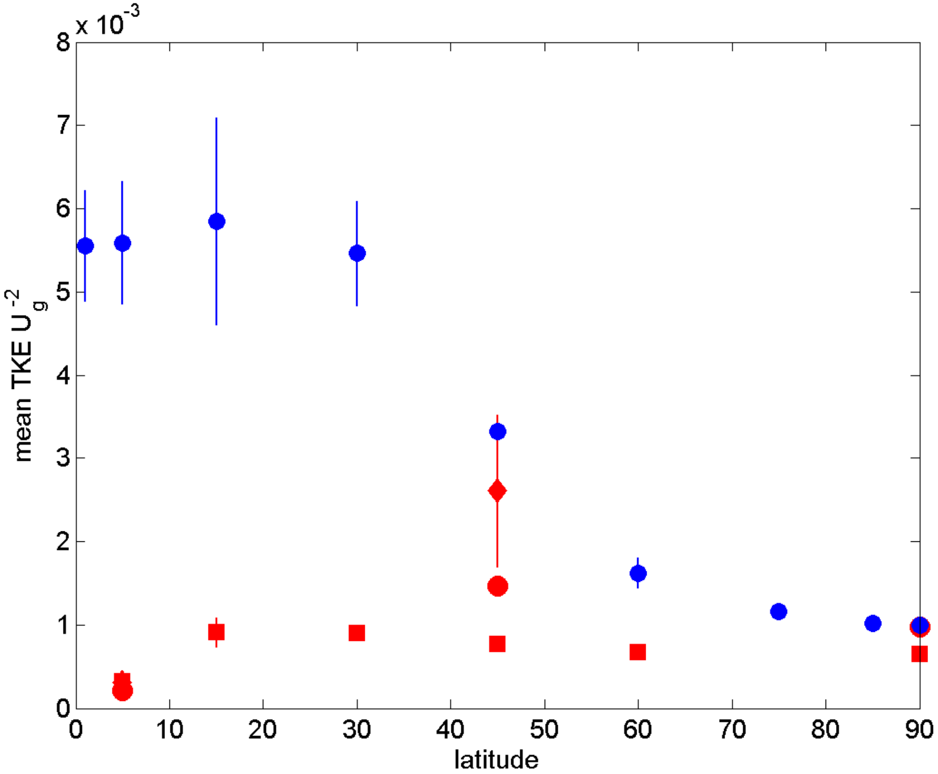
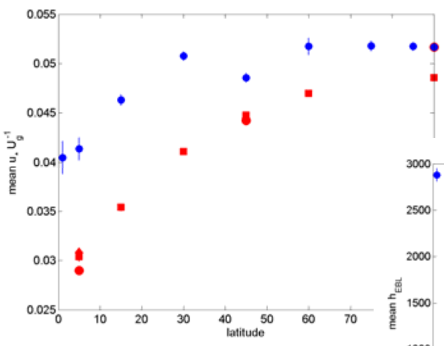
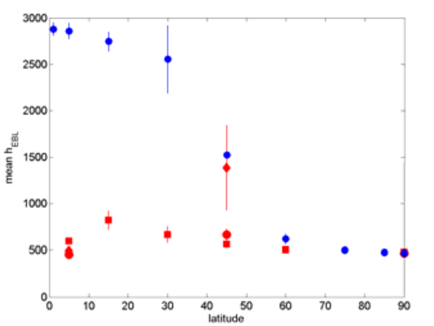
Bulk flow characteristics:
Effects of latitude



Mean normalized turbulent kinetic energy (TKE) in the LES domain.
Blue – E-W flow (180 deg.);
Red – W-E flow (0 deg.);
Symbols – different Ly and Ug
Similar dependences are found for EBL thickness and friction velocity





No dependence on wind direction at high latitudes!
6-10 times larger TKE of easterlies at low latitudes!!!

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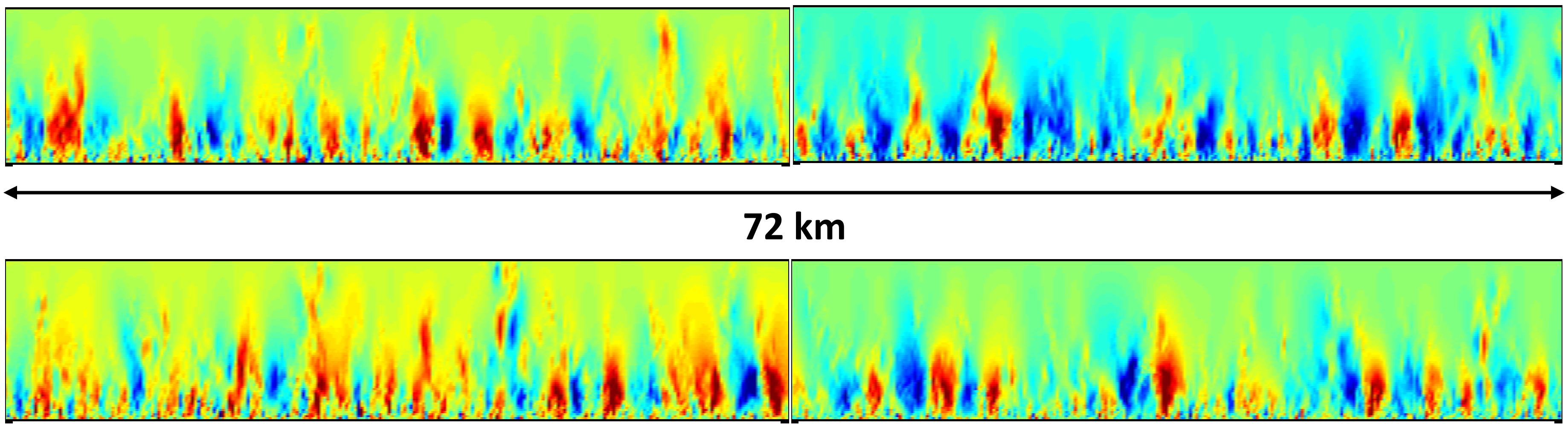
Flow structure: *The pole (90 deg. Latitude)*

E-W wind (180 deg.)



W-E wind (0 deg.)

Red – upward velocity; blue – downward velocity

At the pole, the EBL turbulence is organized in the rolls but there is <u>no structural dependences on the mean flow direction</u>.

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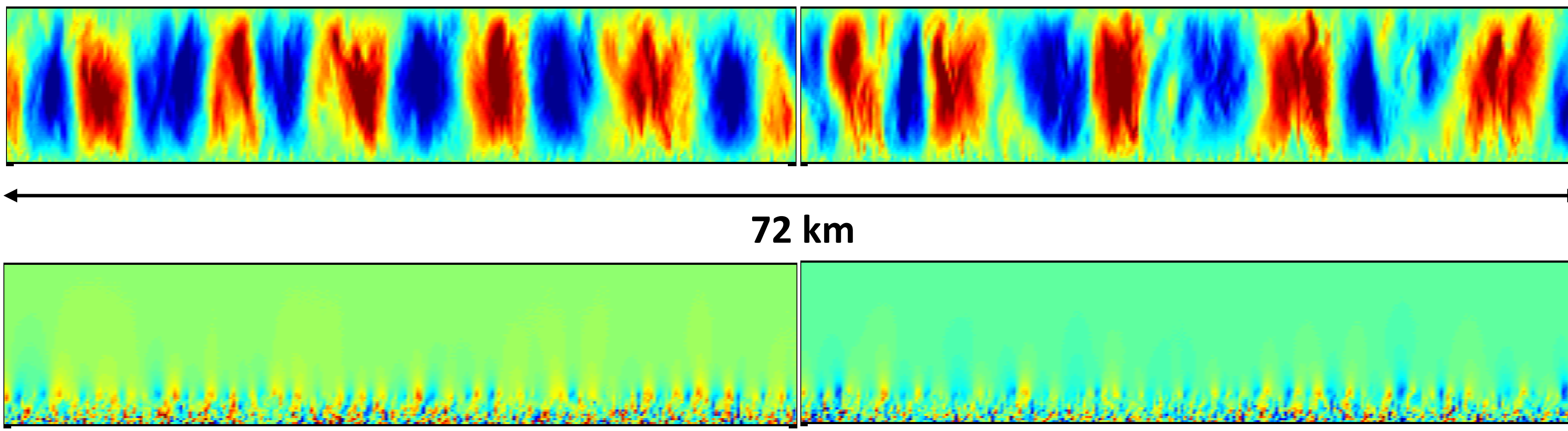
Flow structure: *The equator (5 deg. Latitude)*

E-W wind (180 deg.)



W-E wind (0 deg.)

Red – upward velocity; blue – downward velocity

At the low latitudes, the EBL turbulence is organized in the rolls only in the E-W flow; streaks could be identified in W-E flow.

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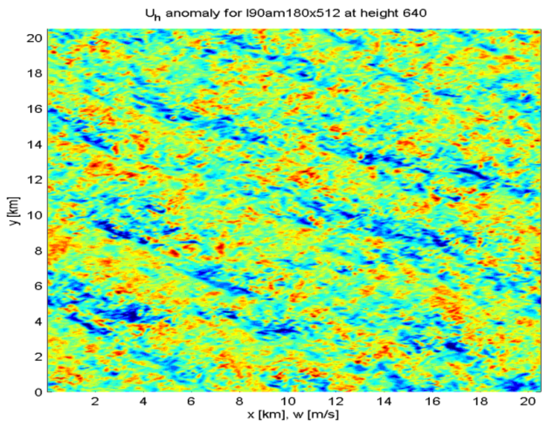
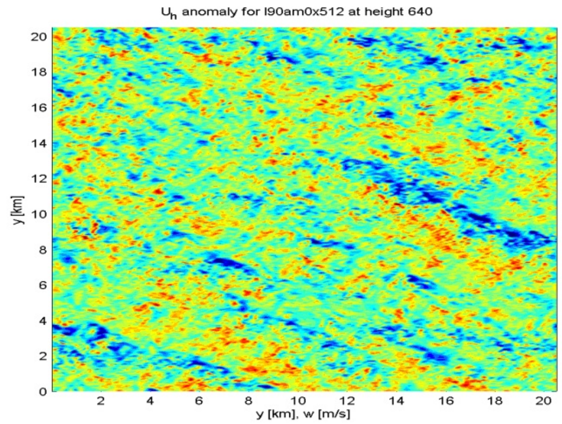
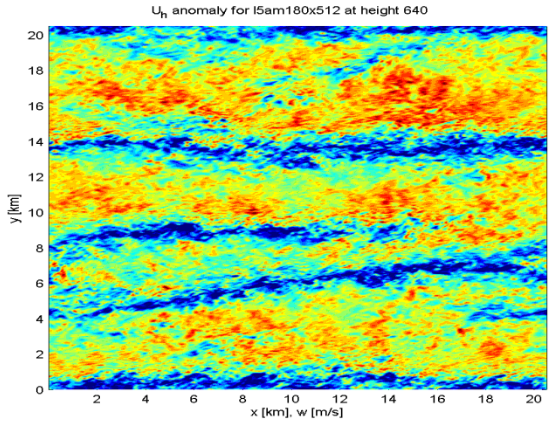
3D EBL simulations (PALM)

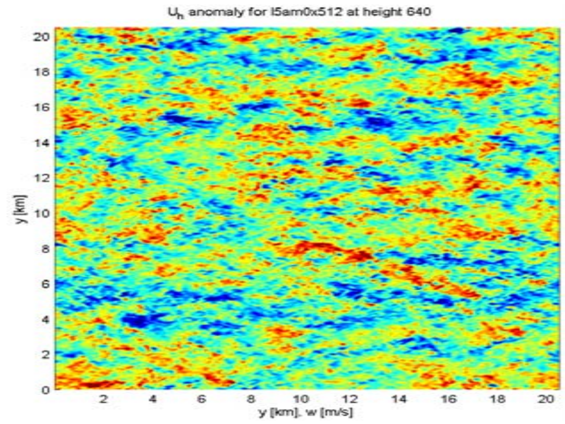




<u>EBL at the Pole</u>
Left: East-to-West flow
Right: West-to East flow

Streaks?





<u>EBL at the Equator (5N)</u>
Left: East-to-West flow
Right: West-to East flow

Definitely rolls!

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Effects of Large-Eddy Concept: Surface Boundary Layer

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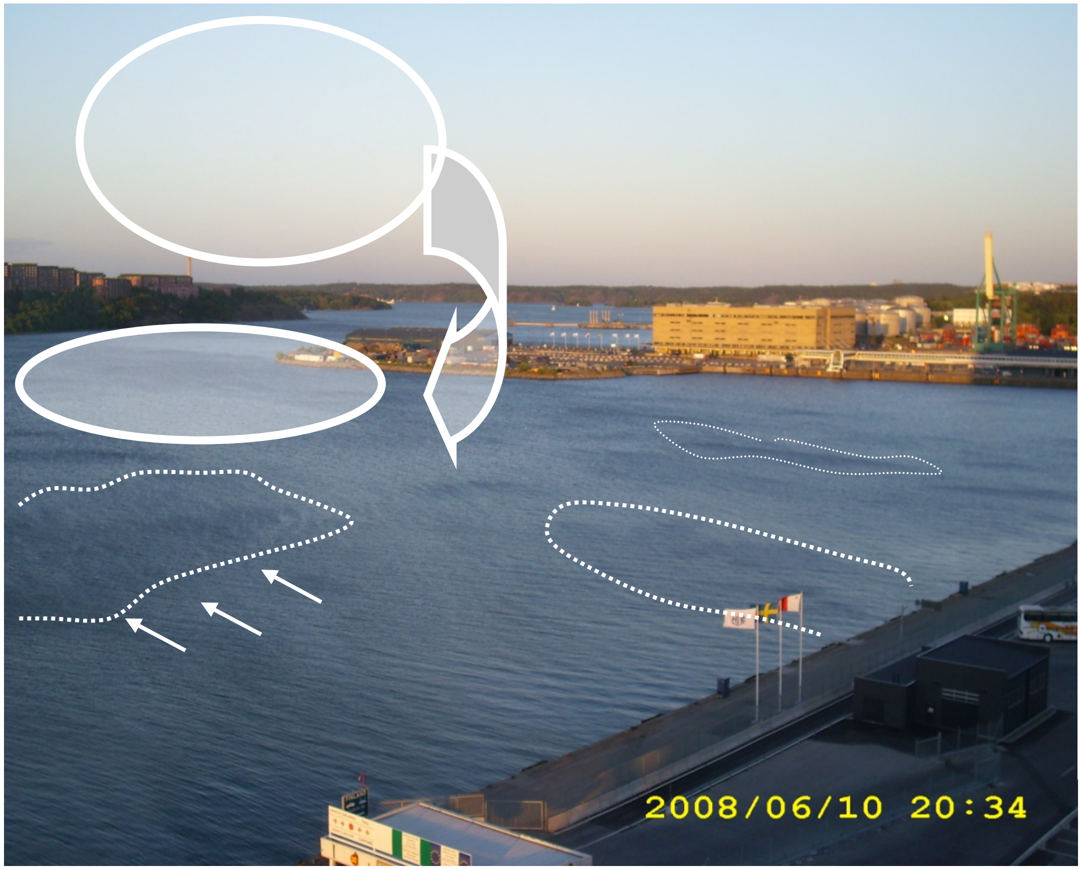
Turbulence generation in high Re PBL



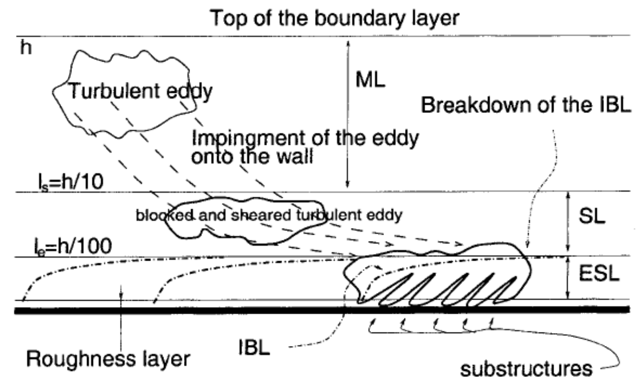
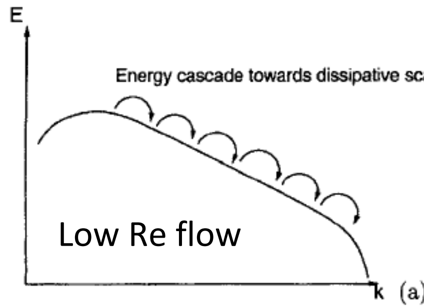
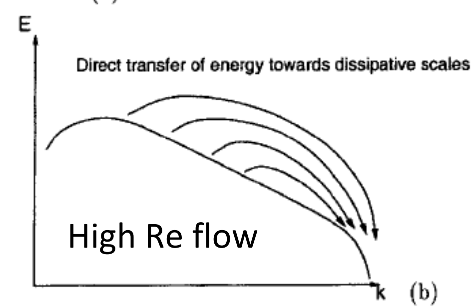


Figure 1. Sketch of a typical high Reynolds number boundary layer; $h \approx$ 1–2 km, $\ell_s \approx$ 100–200 m, $\ell_e \approx$ 10–20 m, the roughness length z_0 is less than 0.1 m over a field, less than 1 m over a typical city.





Photo, I.Esau from Stockholm.
Concept after J.C.R. Hunt and others (2000-2006)

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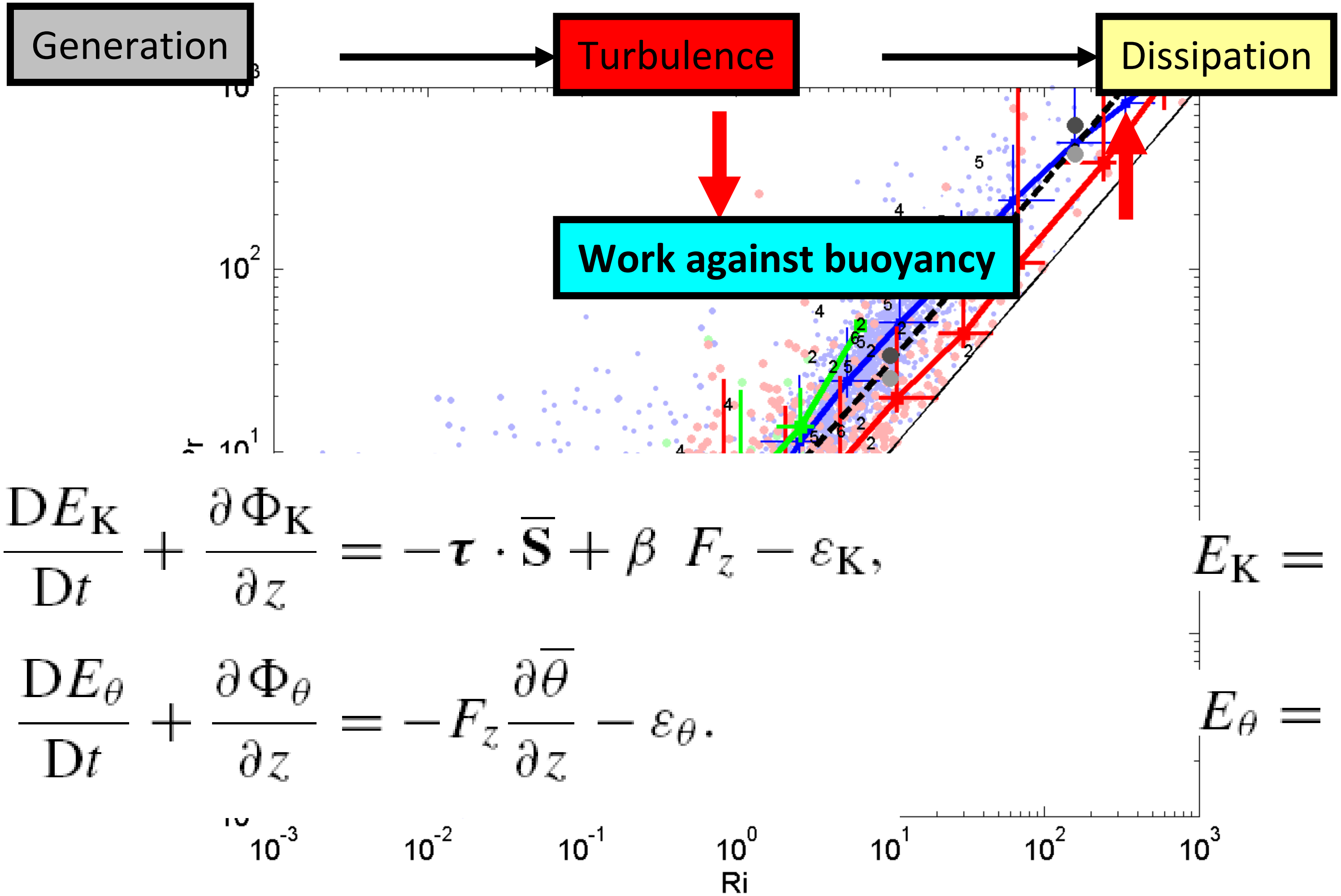
Total turbulence energy and inherent link between mixing properties and MO-similarity



$$\frac{DE_K}{Dt} + \frac{\partial \Phi_K}{\partial z} = -\boldsymbol{\tau} \cdot \bar{\mathbf{S}} + \beta\ F_z - \varepsilon_K, \qquad E_K = 1/2\overline{u_i u_i}$$

$$\frac{DE_\theta}{Dt} + \frac{\partial \Phi_\theta}{\partial z} = -F_z \frac{\partial \bar{\theta}}{\partial z} - \varepsilon_\theta. \qquad E_\theta = 1/2\overline{\theta'^2}$$

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Toward Culture of Simulations

Most results obtained to date have been encouraging …. However, there are some counter examples of incorrect prediction … in regions where LES matches to boundaries …

P.J. Mason, *Large-eddy simulation: A critical review of the technique*. Quart. J. Roy. Meteorol. Soc. 120 (1994) 1–26.

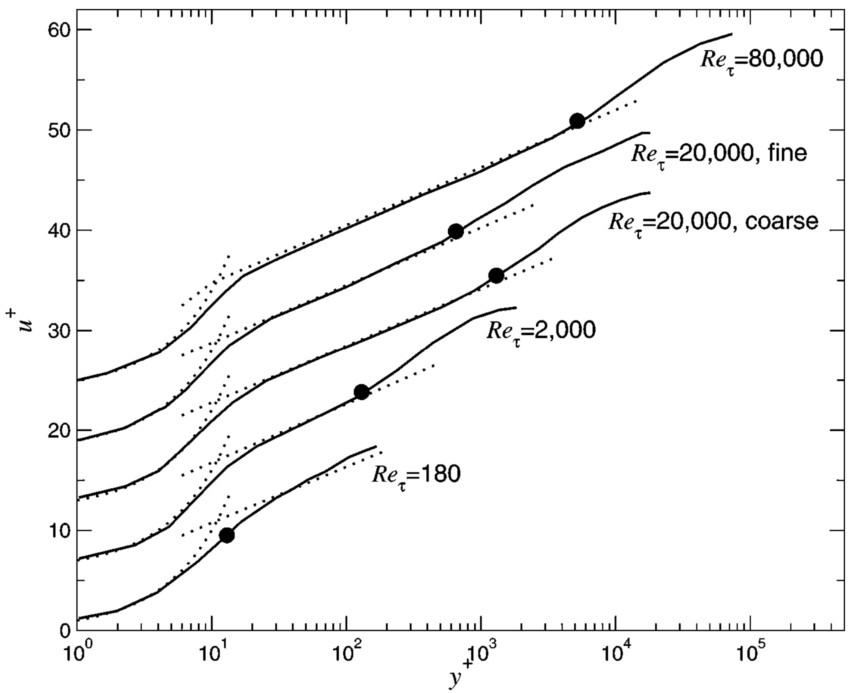
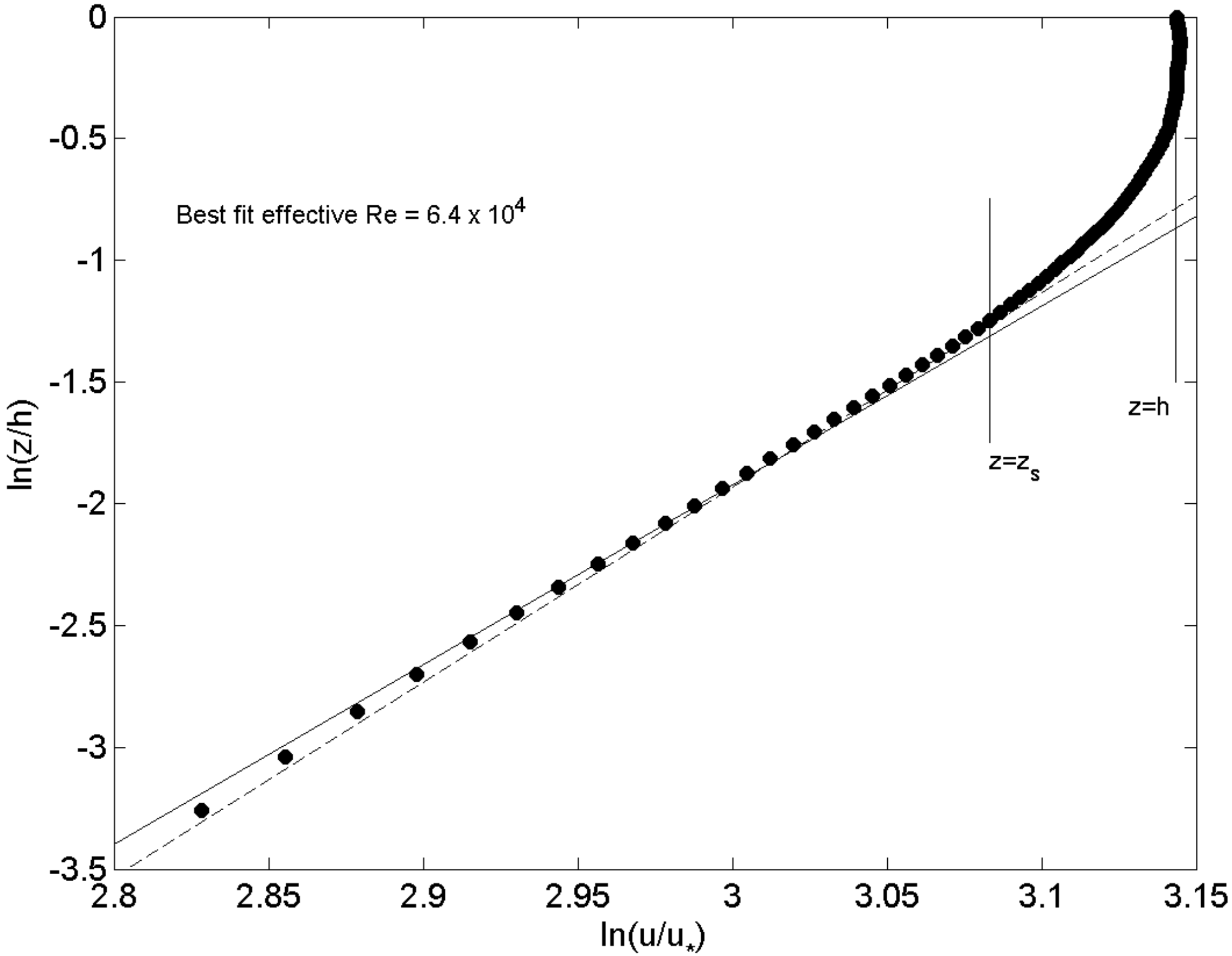


Figure 10 Mean velocity profiles in plane channel flow. DES-based wall-layer model (Nikitin et al. 2000). Each profile is shifted by 6 units in the vertical direction for clarity, and a bullet shows the interface between the RANS and the LES regions.

LES are incorrect only when assumed to have infinite Re

Effective Re in LES



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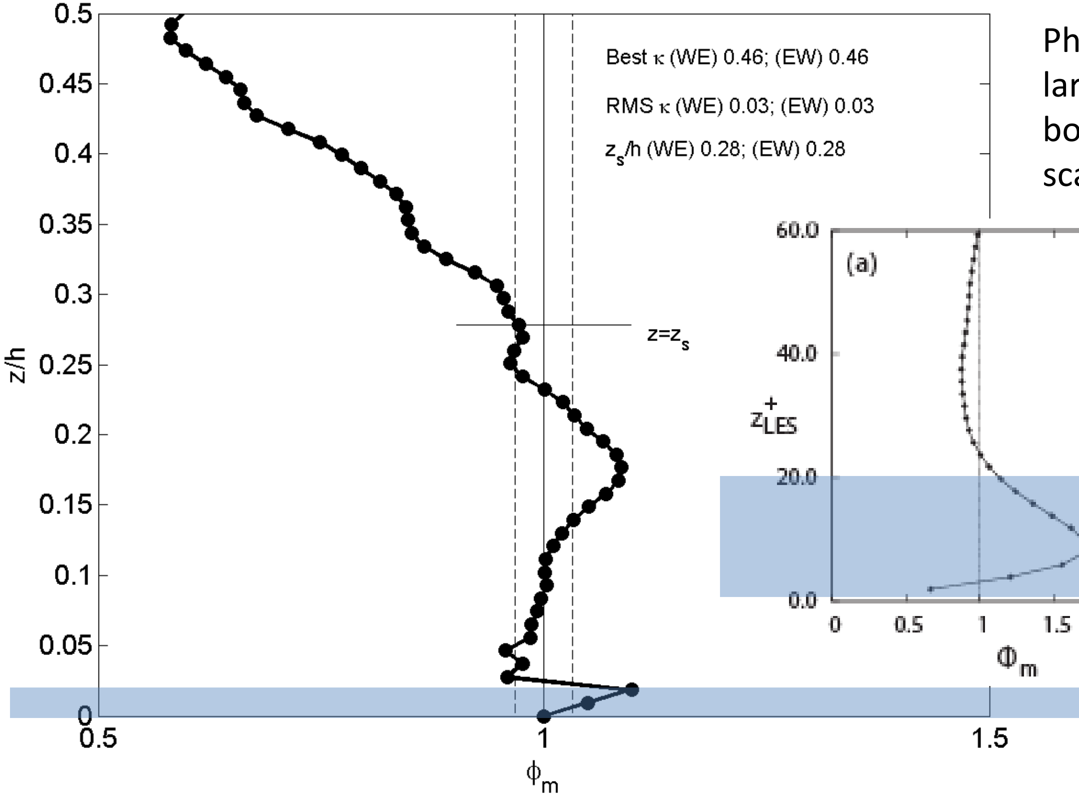
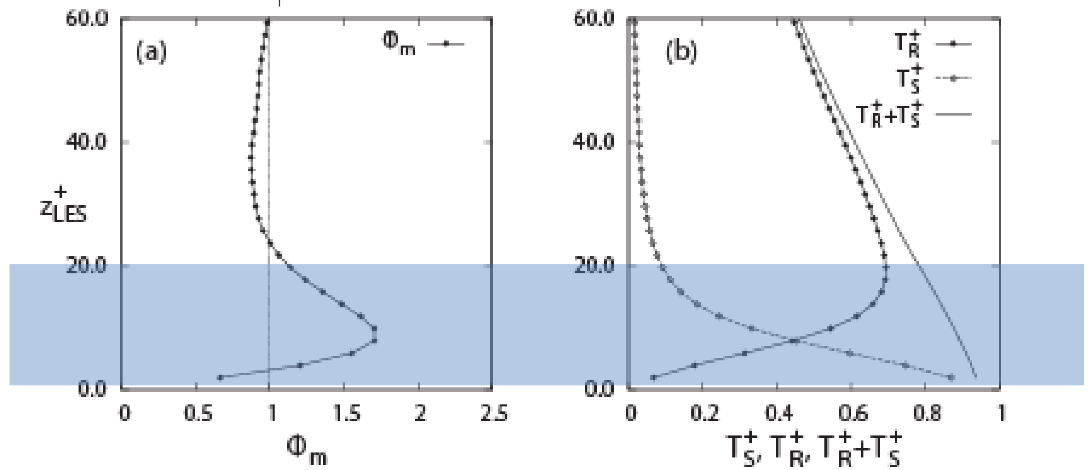
Identification of simulated surface layer by Brasseur and Wei

Phys. Fluids 22, 021303 (2010); Designing large-eddy simulation of the turbulent boundary layer to capture law-of-the-wall scaling by James G. Brasseur and Tie Wei





Overshoot in LES of the neutral ABL using the Smagorinsky model (C_s = 0.2) and a 128×128×128 grid. (a) Φ_m vs *z*LES+. (b) Wall normalized mean resolved and SFS shear stress *TR*+ and *TS*+ plotted against *z*LES+ and its sum. κ = 0.4 is assumed in forming Φ_m. κ = 0.4 is assumed in forming Φ_m.

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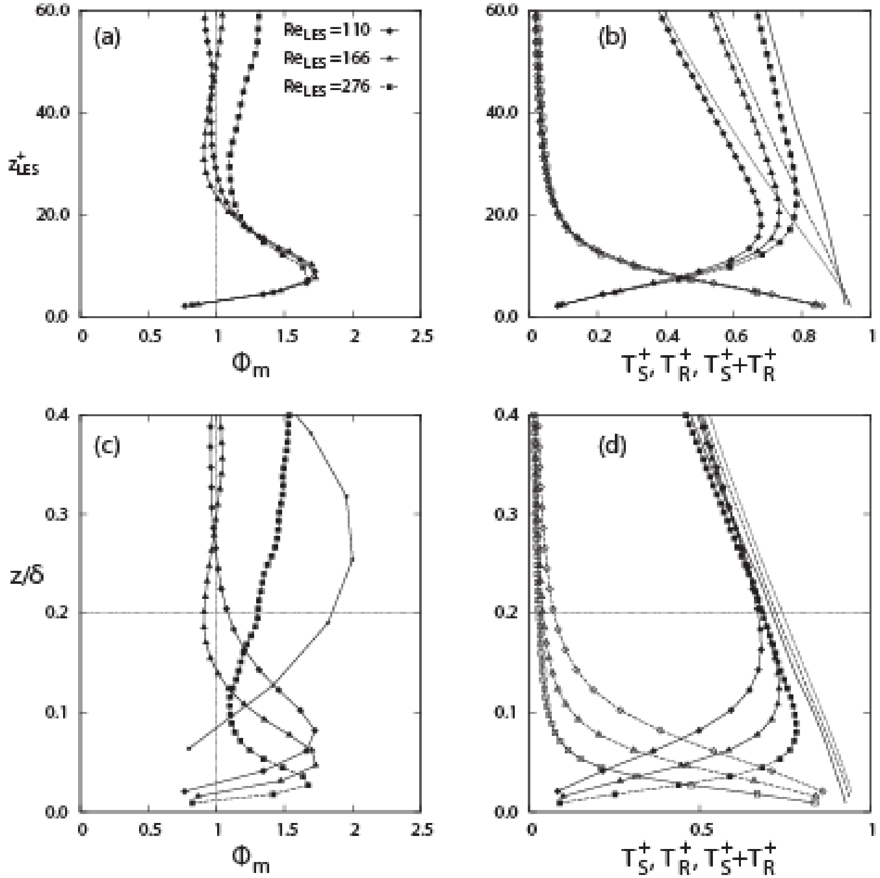
Relationship to LES resolution



Overshoots in LES of the neutral ABL. (a) Φ_m vs zLES+. (b) Normalized resolved Reynolds stress *TR*+ (filled symbols) and mean SFS shear stress *TS*+ (open symbols) vs zLES+. Dotted, dashed, and thin lines are the sum of resolved and SFS stress from low to high LES Reynolds number. (c) Φ_m vs z/δ, where δ is defined as the height where Φ_m = 0. (d) *TR*+ (filled symbols) and *TS*+ (open symbols) vs z/δ. The LES Reynolds numbers of the simulations are shown in (a). In order of Re_{LES}, the Smagorinsky constants and grids were (C_s = 0.1, 42×42×96), (C_s = 0.2, 192×192×128), and (C_s = 0.1, 128×128×256). The thin black line in (c) is a simulation with such low Re_{LES} that turbulence is barely sustained (C_s = 0.2, 42×42×32 and Re_{LES} = 38). The horizontal dotted lines in (c) and (d) indicated the upper margin of the surface layer where LOTW should be predicted. κ = 0.4 is assumed in forming Φ_m.

Culture of Simulations

Reflection in Model Development

As it usually happen, at the beginning, nobody thought much about foundations making ungrounded statements

$$\partial_t u + (\nabla \times u)\times \bar{u} + \nabla\left(p + \frac{1}{2}u^2\right) = \bar{f} \qquad \bar{u} = (I - l_{cut}^2\Delta)^{-1} u$$

Leray (1934) based NS-alpha model

$$\begin{cases} \partial_t \bar{u} + \bar{u}\cdot\nabla\bar{u} = \nabla\cdot(-pI + T), \nabla\cdot\bar{u} = 0, \\ T = 2l_{cut}^2(\partial_t S + \bar{u}\cdot\nabla S + S\Omega - \Omega S), \\ S = \frac{1}{2}(\nabla\bar{u} + (\nabla\bar{u})^T), \quad \Omega = \frac{1}{2}(\nabla\bar{u} - (\nabla\bar{u})^T). \end{cases}$$

$$\partial_t u + u\cdot\nabla u + \nabla\cdot(pI - T^*) = \bar{f} \qquad u\cdot\nabla u = \nabla(\bar{u}\otimes\bar{u}) + \nabla(u\otimes u - \bar{u}\otimes\bar{u})$$

Ladyzenskaja-Kaniel (1969) based eddy-viscosity model

$$\begin{cases} \partial_t \bar{u} + \bar{u}\cdot\nabla\bar{u} = \nabla\cdot(-\bar{p}I + (\bar{u}\otimes\bar{u} - \overline{u\otimes u}) - T^*), \\ \nabla\cdot\bar{u} = 0, \\ T^* = 2l_{cut}^2|\bar{S}|\bar{S} \end{cases}$$

S

Dissipaters, filters and symmetries

Model Type	Translations	Rotations and reflections	Scaling transfor mations*	Material indiffer ence**
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.

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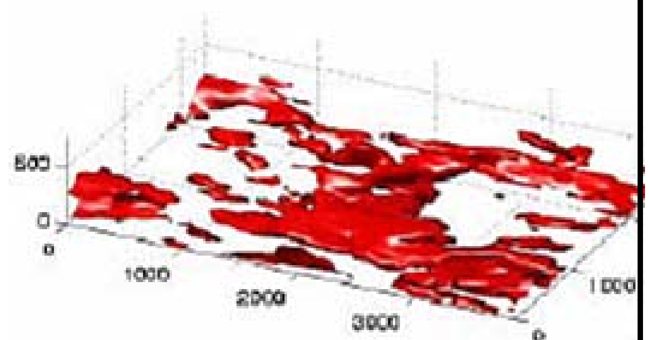
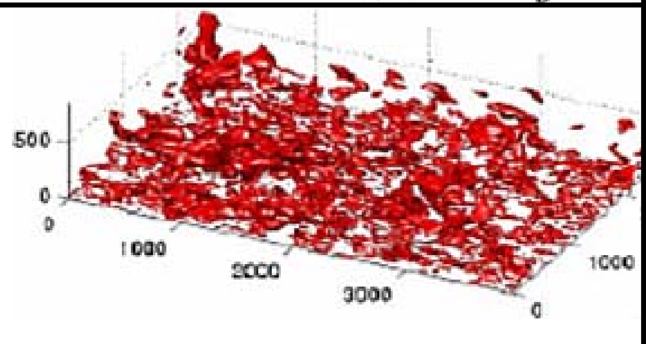
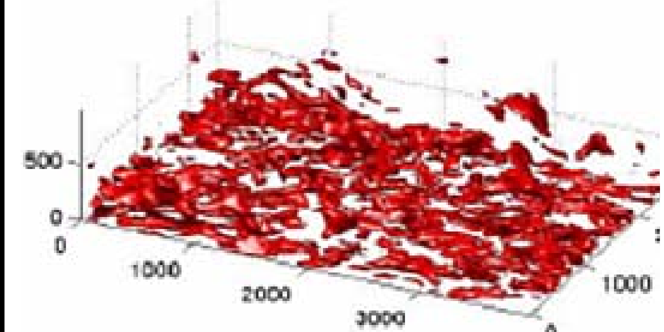
Practical implications

LES mesh	Dynamic-mixed LESNIC	Static Smagorinsky LESNIC, $C_s = 0.17$
32^3		**No turbulence develops, laminar flow**
128^3		

Instant fluctuations of the flow velocity in stably stratified LES runs for Beare et al. (2006) study. Data computed with the LESNIC code (Esau, 2004).

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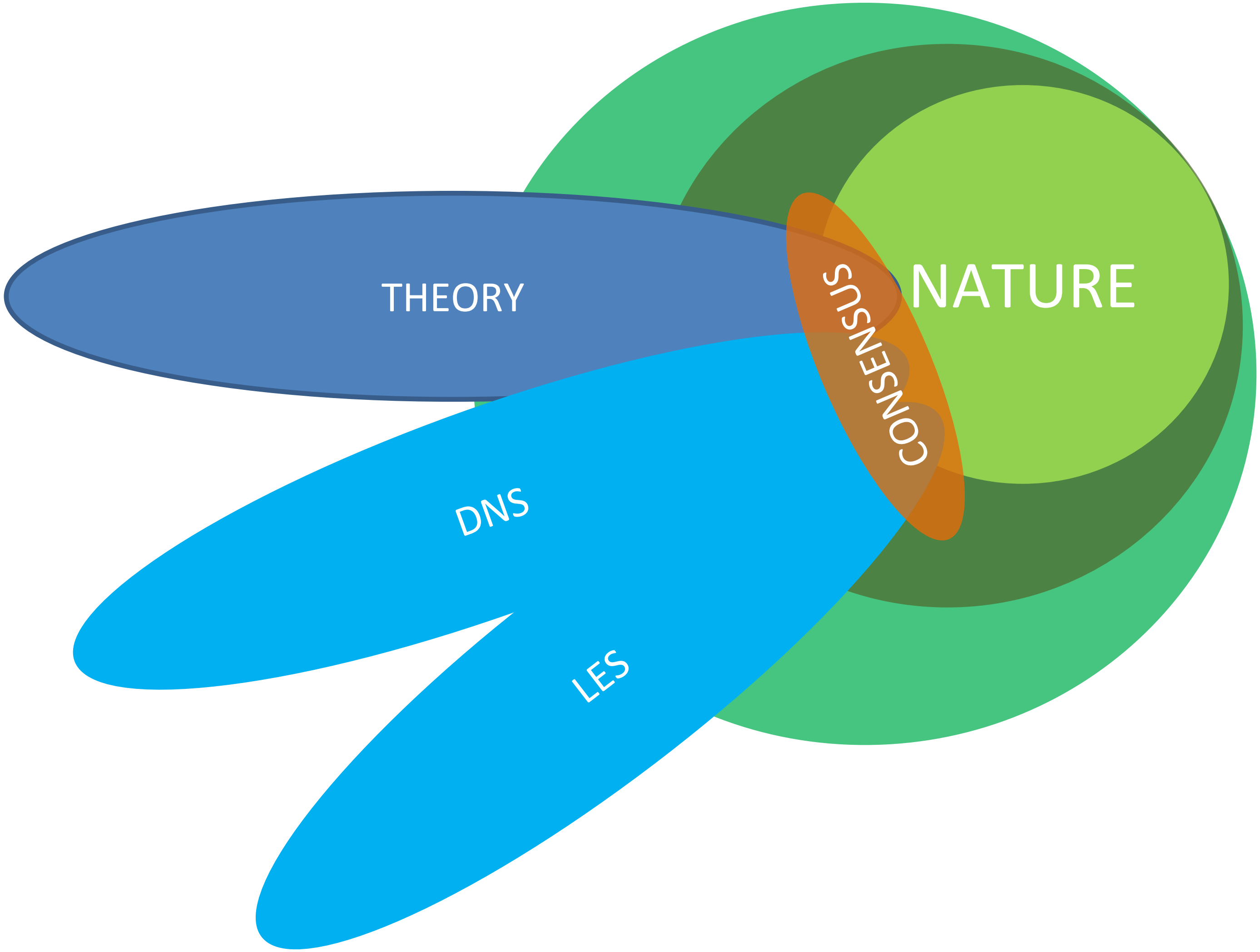
Part III and the last:
Adopting Culture of Simulations



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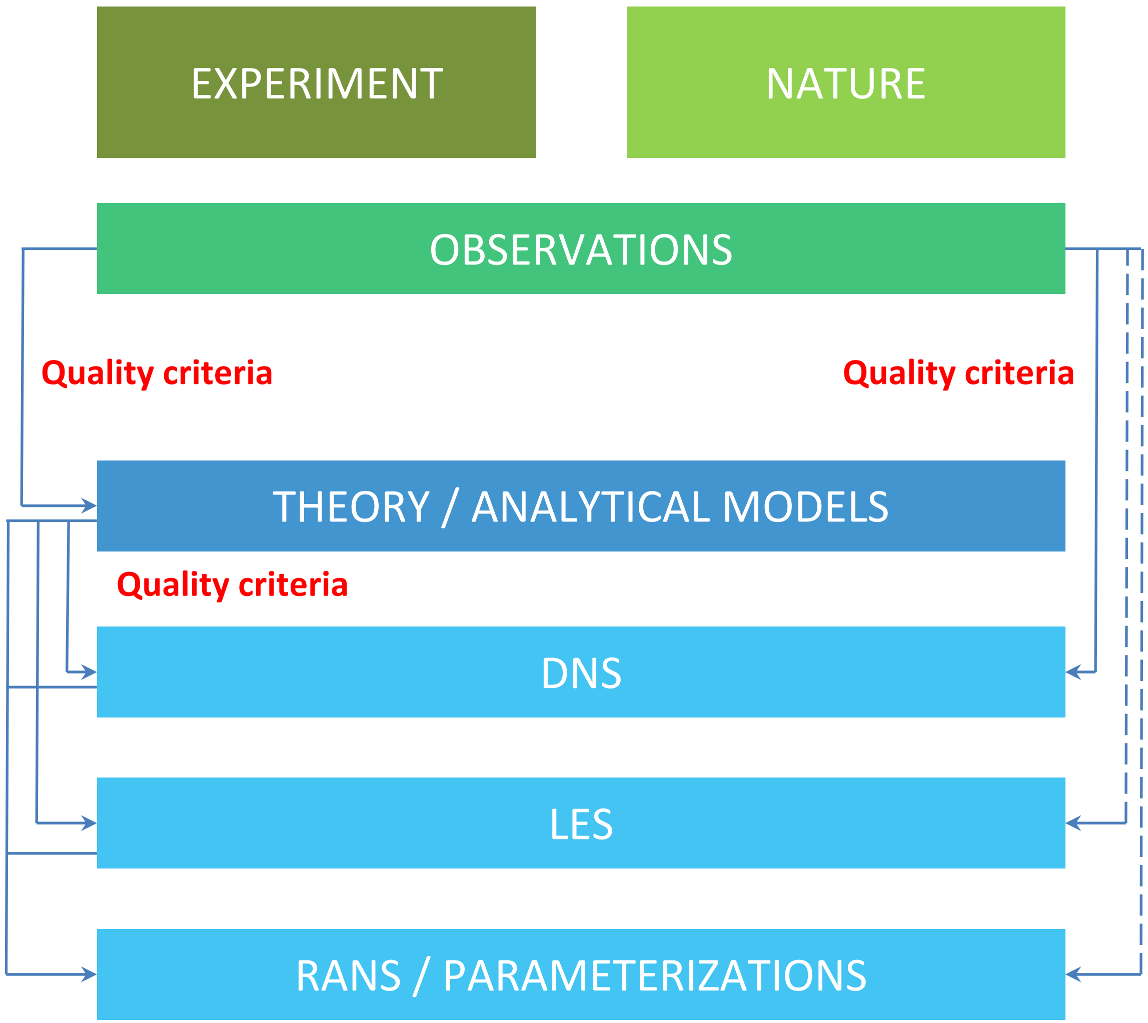
Turbulence Model Hierarchy



EXPERIMENT may not characterize NATURE
e.g. sophisticated experiments with active turbulence control

OBSERVATIONS can be uncertain, incorrect and incomplete

THEORY can be non-unique, non-representative and incorrect

MODELS are constraint by OBSERVATIONS, THEORIES and higher MODEL in hierarchy but ad hoc (non-observable, e.g. mixing length) parameters cannot be constraint

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Simulations determine Experiments
HATS (Horizontal Array Turbulence Study)

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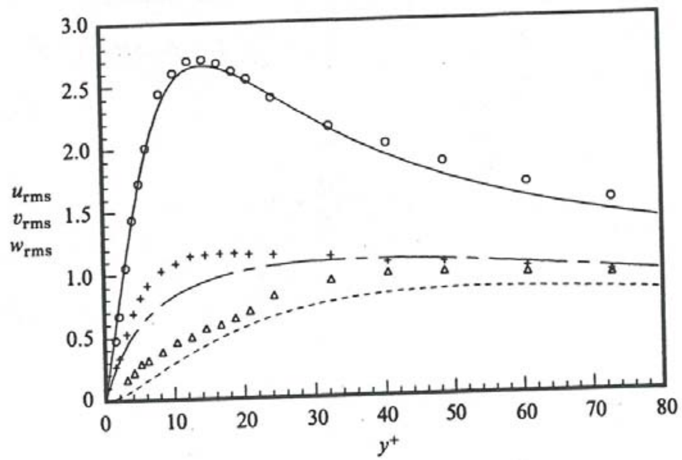
Non-trivial step is that the needs of models, not those of theory, determines the experiment

We begin to move from calculations to simulations considering the model as independent entity

Simulations correct Experiment



142 J. Kim, P. Moin and R. Moser

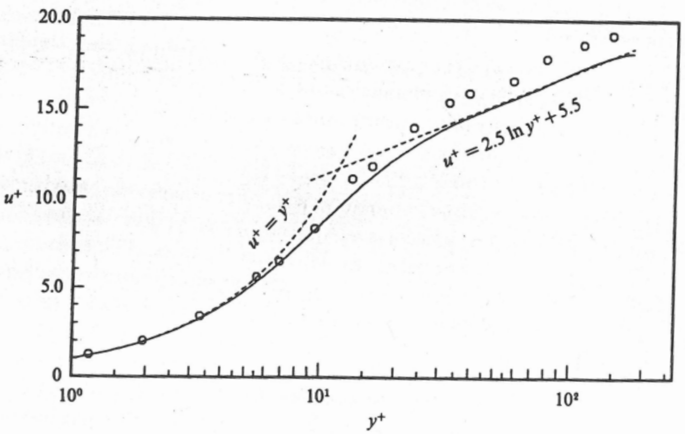
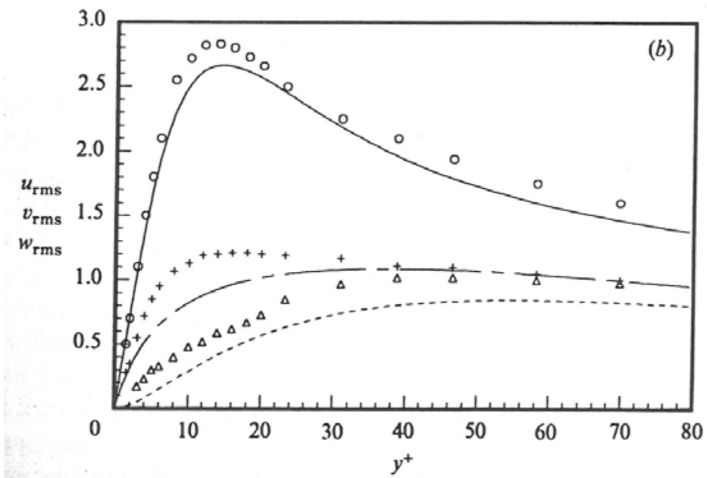
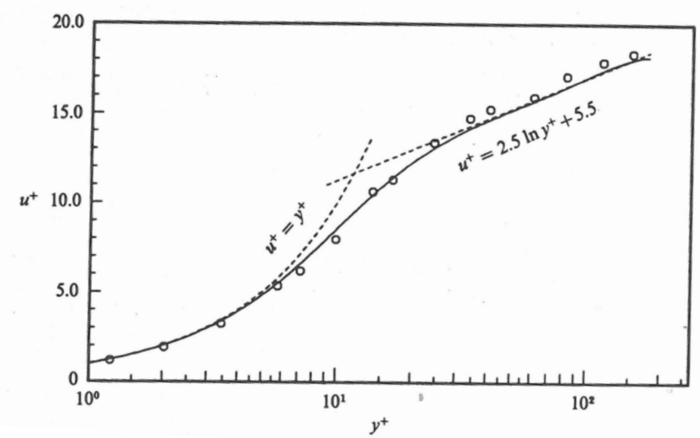


FIGURE 4. Mean-velocity profiles: ——, upper wall; – – –, lower wall (masked by solid ○, data from Eckelmann (1974); ----, law of the wall.

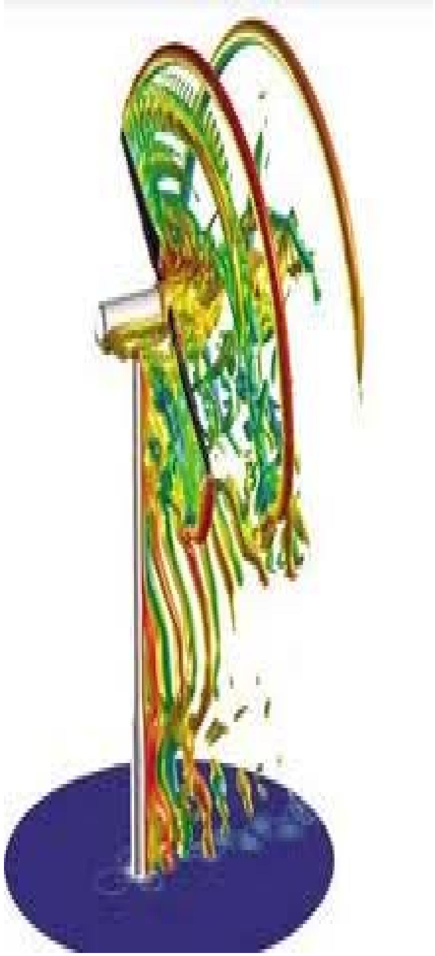




S Kim, J., Moin, P. and R. Moser, 1987: Turbulence statistics in fully developed channel flow at low Reynolds number, J. Fluid Mech., 177, 133-166

Summary

- Turbulent models were traditionally considered as affirmative quantitative tools to calculate numbers for pre-existing theories within their range of calibration (e.g. J. Lamley)
- They are largely still are, e.g. wind turbine, car, bridge etc engineering
- But turbulent models increasingly become effective tools for production new knowledge (e.g. P. Moin)
- To use opportunities provided by turbulence modeling, critical shift of paradigm is required
- From modernism and positivism (K. Popper and T. Kuhn) to post-modernism and post-positivism (I. Lacatos, Fantoviz and Ravitz)
- In new model hierarchy, the better models should reproduce not the larger range of scales but the larger range of yet unobserved or unrecognized facts



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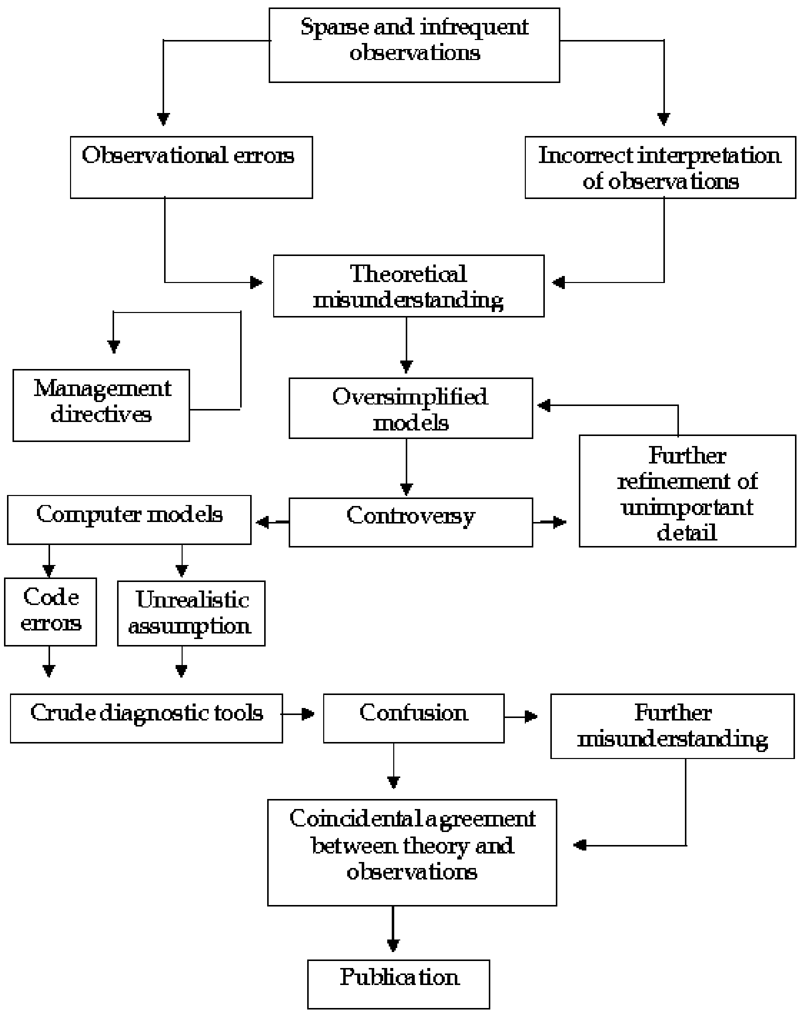
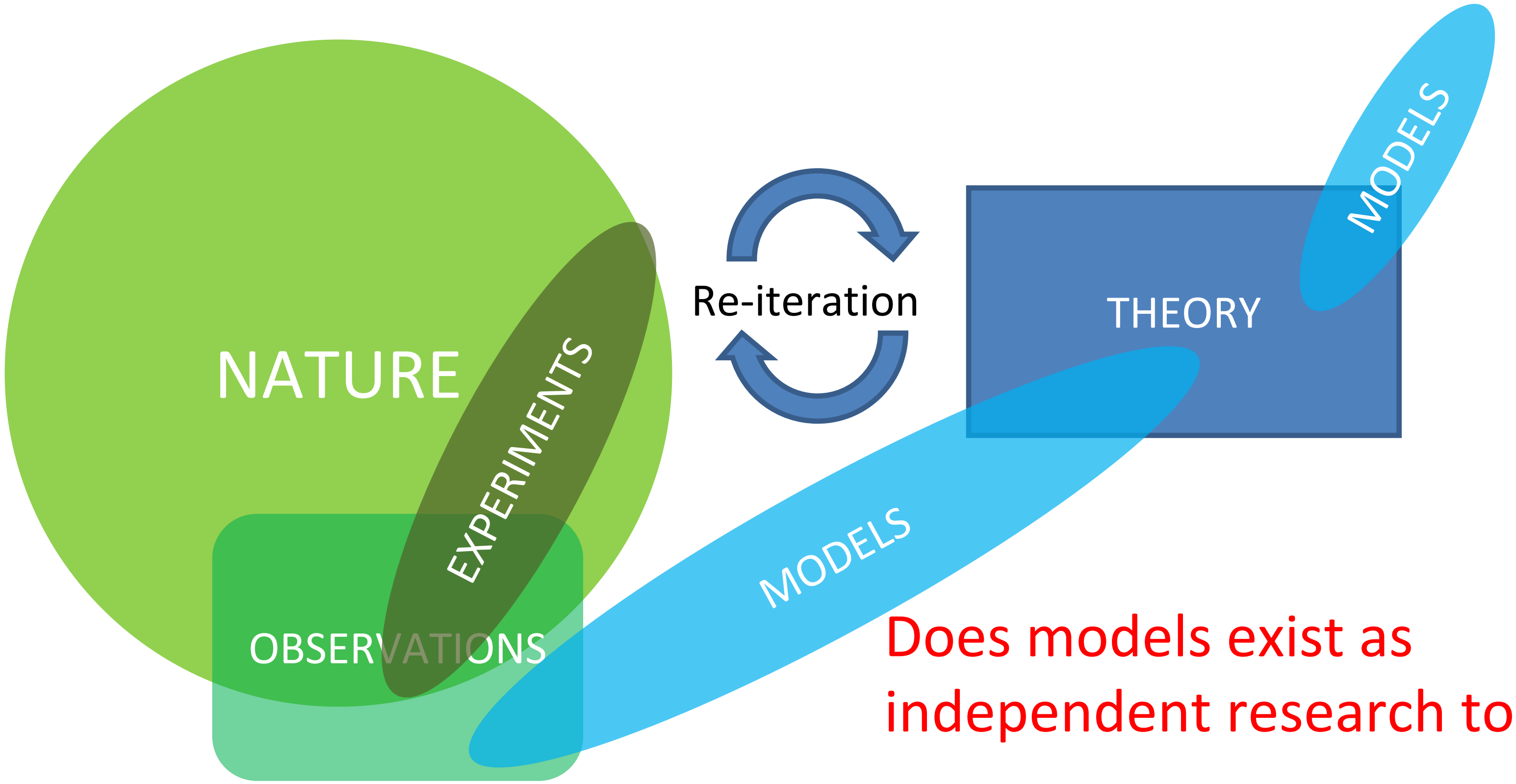
Thank you



Sparse and infrequent observations
Observational errors
Incorrect interpretation of observations
Theoretical misunderstanding
Management directives
Oversimplified models
Further refinement of unimportant detail
Computer models
Controversy
Code errors
Unrealistic assumption
Crude diagnostic tools
Confusion
Further misunderstanding
Coincidental agreement between theory and observations
Publication

F

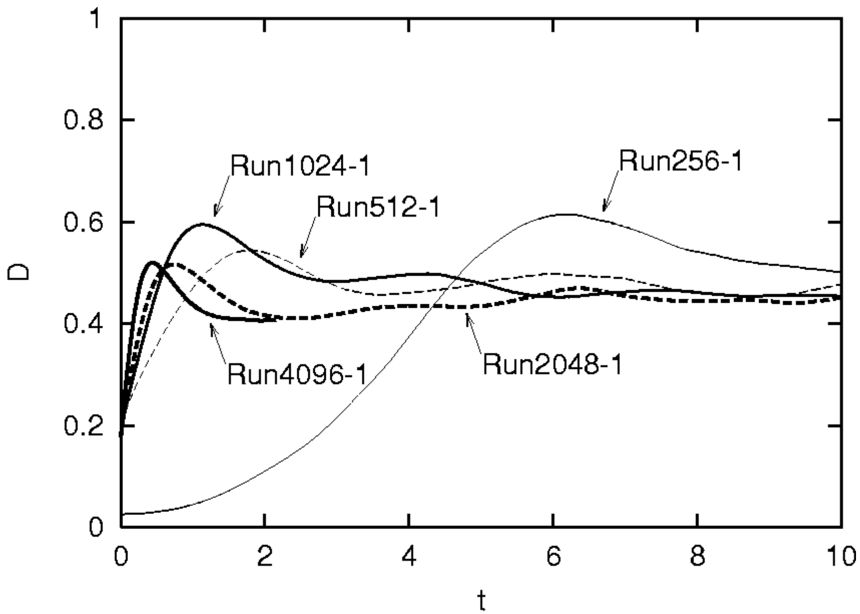
Research of Open Systems

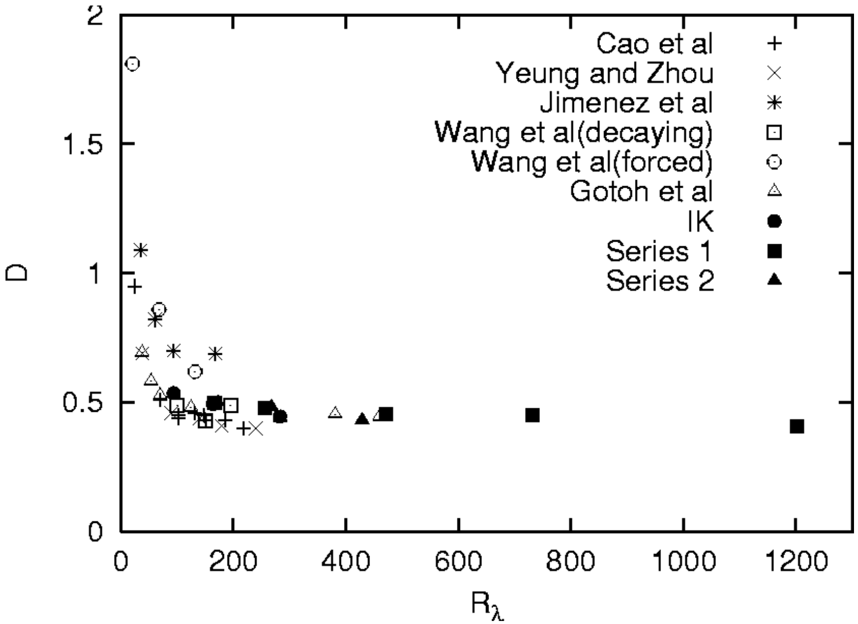


Does models exist as independent research tool?

Observations – sample a small fraction of nature and not necessarily readings are relevant
Experiments – essentially a part of nature but not necessarily relevant or observed
Theory – reiterates with but not necessarily based on nature via observed evidences
Models – based on both observations and theory but not necessarily compatible with

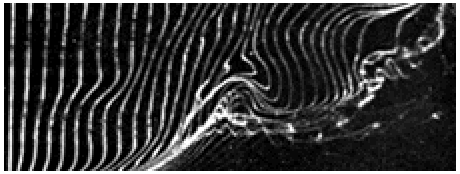
Kaneda, Y, Ishihara, T., Yokokawa, M., Itakura, K. and A. Uno, 2003: Energy dissipation rate and energy spectrum in high resolution direct numerical simulations of turbulence in a periodic box, Physics of Fluids, 15(2), L21-L24





Neither different runs of one DNS nor different DNS are sufficiently consistent to supplaunt nature

DNS by J. Kim and P.Moin
http://www.stanford.edu/group/ctr/articles/tackle_sidebar1.html



Observations in experiment by S. Kline

- Data can be generating and re-generating unlimited times under specified, controllable conditions
- Model databases can be analyzed at cheap cost by diverse discipline researchers
- New ideas and theories can be tested, iterated and calibrated

Affirmative Research

- Research strategy designed to confirm pre-concieved conclusions, simplifications etc.