CFD Turbulence Simulations: Recent Developments and Future Directions

Sharath S. Girimaji
Ocean Engineering Department, Texas A&M University

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Outline

- Background
  - Modeling vs. computing
- Holistic modeling approach
  - Are we becoming too much of a *model du jour* culture?
- PANS paradigm and model development
- PANS results vs. LES, DES, URANS..

Challenges

Turbulence field = Method + Madness

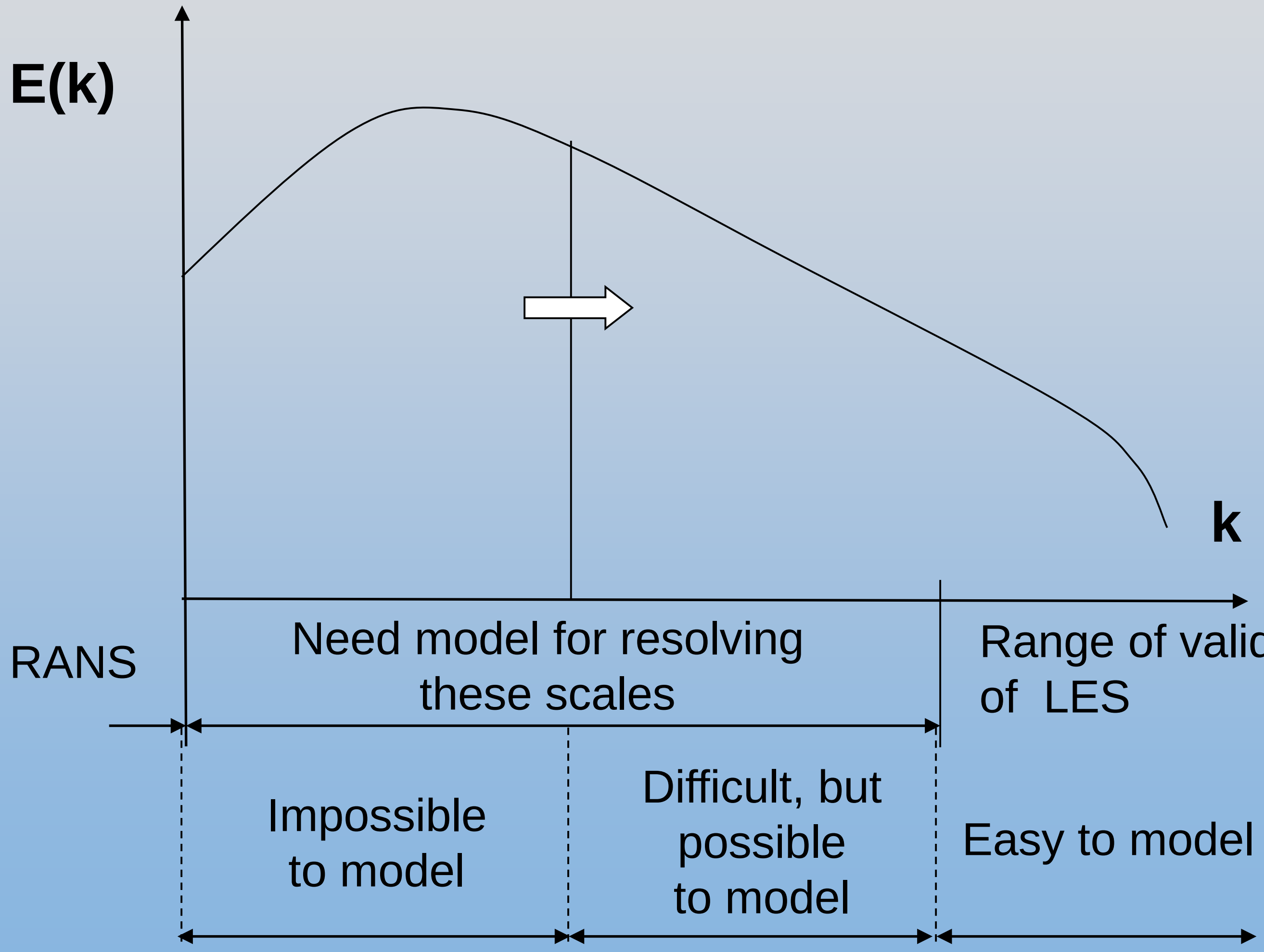
- **Method:**
  - Coherent structures, large-scale unsteadiness, flow dependent
  - Strong non-local effects, non-Markovian
  - Not easily amenable to one-point closure
  - Must be resolved, not modeled
- **Madness:**
  - Featureless, apparently chaotic
  - Dynamically passive, forward-cascading
  - Amenable to statistical stereotyping (one-pt. closure)
  - Can be modeled but judiciously

Comp. procedure must handle > method + madness

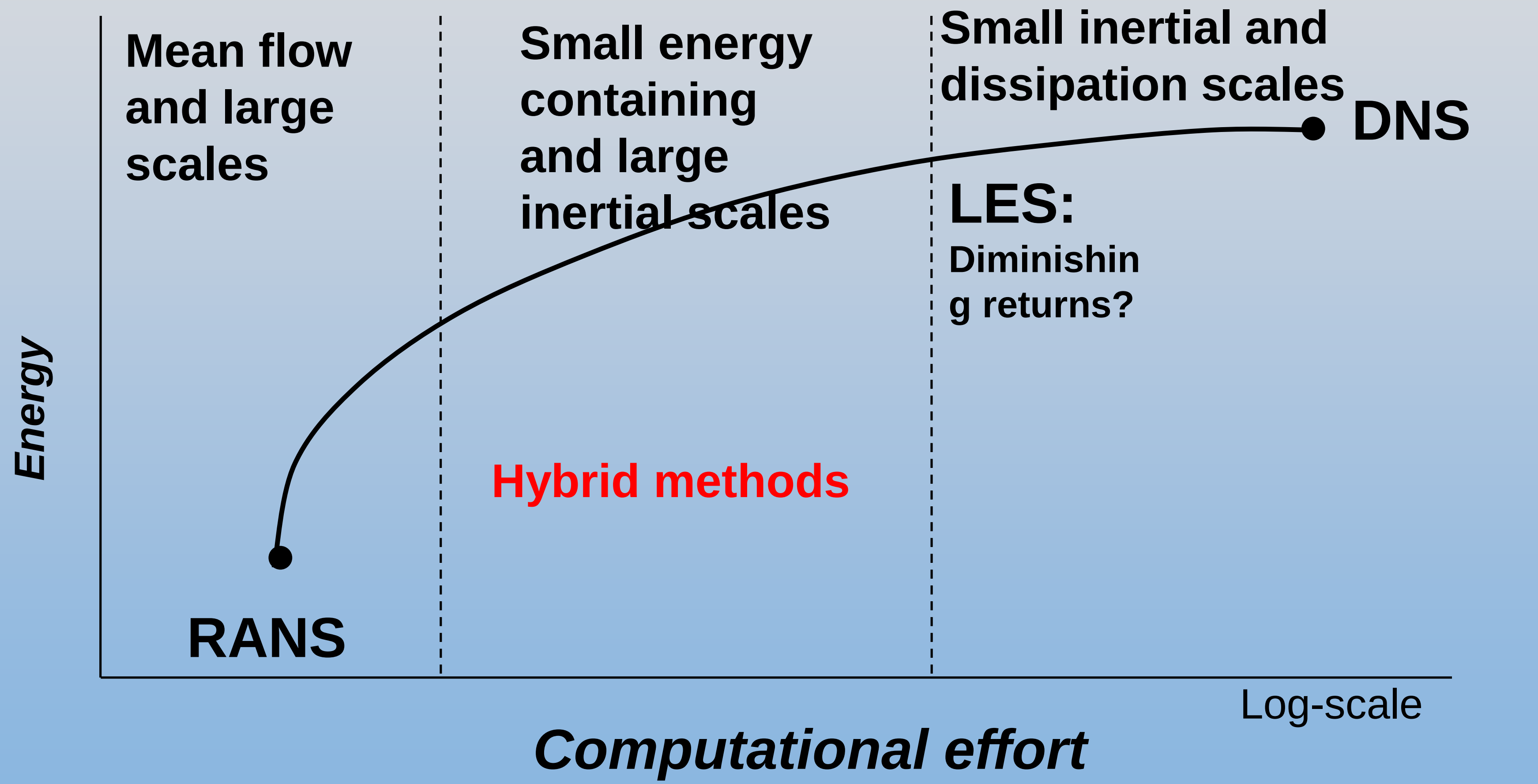
Traditional Approaches

- RANS
  - Attempts to model method and madness
  - Suffers from one-point closure limitations
- LES
  - Resolves energy-containing and inertial scales
  - Does not model even those scales amenable to modeling

RANS and LES


E(k)
k
RANS
Need model for resolving these scales
Range of validity of LES
Impossible to model
Difficult, but possible to model
Easy to model

Energy Resolved vs. Computational Effort



Problems cannot be solved at the same level of awareness that created them in the first place

-- *A. Einstein*

Context: Vision 2030

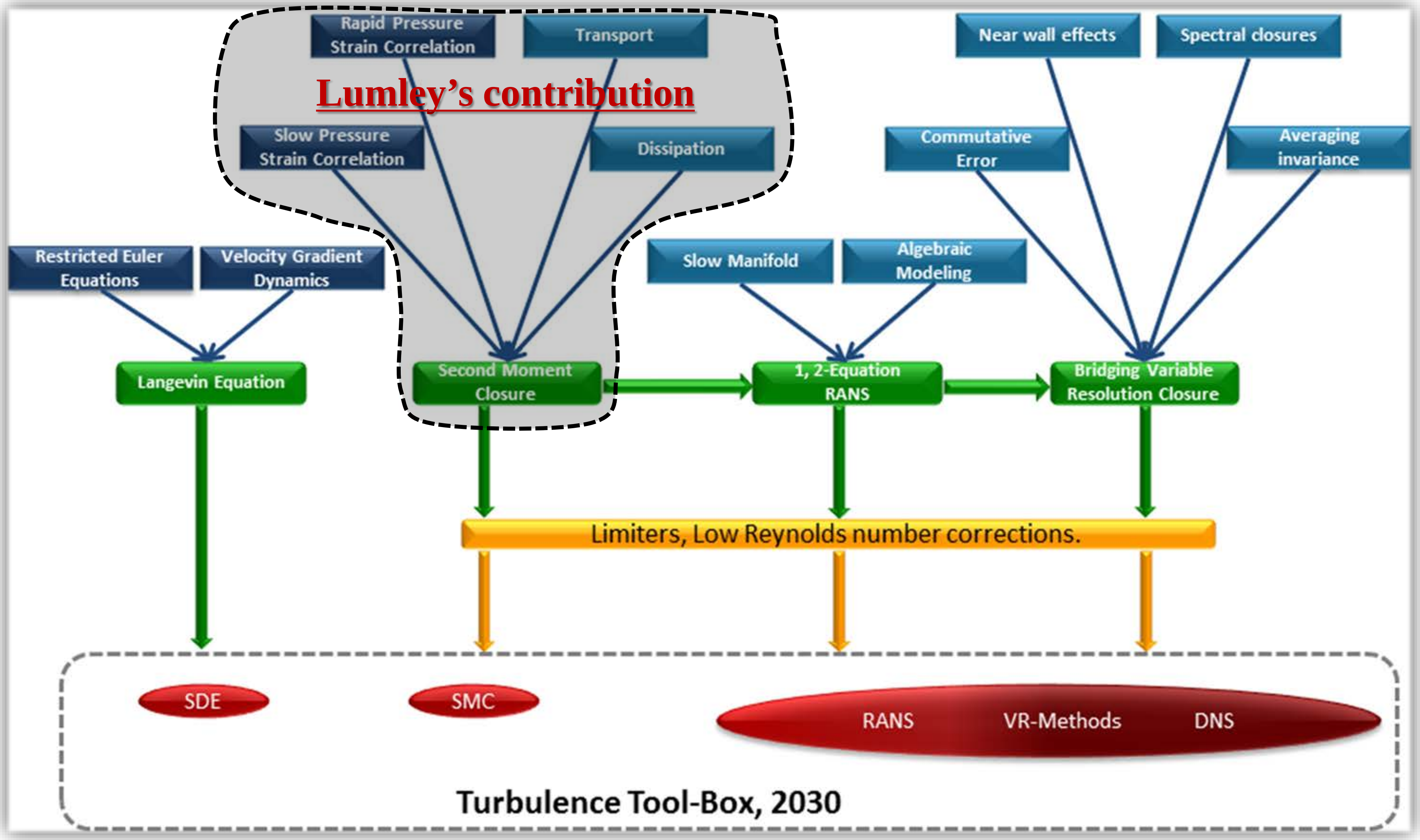
- *CFD at a crossroads … reliable use of CFD has remained confined to a small region due to the inability of current methods to reliably predict turbulent separated flows.*
  - RANS cannot overcome inherent difficulties → No *a priori* determination if a calculated flow is reasonable or spectacularly wrong
  - *Hybrid RANS-LES and wall-modeled LES offer the best prospects … although significant modeling issues remain.*

The VISION (The model we wish for)

A knowledge-based vision of the required capabilities of state-of-the-art CFD in the notional year 2030:

- **Centered on physics-based predictive modeling**
- **Automated management of errors and uncertainties (Error management)**
- **Able to effectively leverage the most capable HPC hardware of the day**
- **Enables complex multidisciplinary analyses and optimizations**

The vision and the Roadmap



SRS: Theoretical Foundation

	RANS	Constant Resolution PANS	Variable Resolution PANS
7 Equation Model	1. RDT 2. Equipartition of Energy 3. Realizability 4. Streamline Topology	1. Kolmogorov 0th Hypothesis 2. Spectral Partition Analysis 3. Low-RE Effects ($f_\varepsilon \neq 1$)	1. Commutation Residue Analysis 2. Total Energy Conservation $(\kappa_r+\kappa_u):f_{\kappa_1} = (\kappa_r+\kappa_u):f_{\kappa_2}$
2 Equation Model	1. Two-time Scale Analysis 2. Representation Theory 3. Extended Thermodynamics		
Boundary Layer	Equilibrium Analysis $P = \varepsilon \rightarrow \sigma_\kappa, \sigma_\varepsilon$	Partial Equilibrium Analysis $P_u \approx \varepsilon_u \rightarrow \sigma_{\kappa_u}, \sigma_{\varepsilon_u}$	Commutation Residue Analysis
Grid Adaptation		1. Scale-similarity of Governing Equation 2. 'Dynamic' or In Situ Adaptive Schemes	
Uncertainty Quantification		1. Comparison of apriori and aposteriori f_κ 2. Convergence with $f_\kappa \rightarrow 0$ 3. Theory of Randomized Algorithms	

March toward 2030 bridging model goals

`Best' variable- resolution hybrid method –

multi-step development overcoming one challenge at a time

1. Derive: Closure model for a `fixed' intermediate resolution
2. Derive: Eqbm. BL behavior for fixed intermediate resolution
3. Demonstrate: Improved resolution → improved resolution
4. Demonstrate: Fluctuating field is physical
5. Derive: Low-Re effects as a function of resolution
6. Derive: Closure model for resolution variation – Commutation residue
7. Develop: Error management strategy for unsteady flows
8. Develop: Dynamic optimization scheme
9. Develop: Stress transport equations

Systematic model development and clear avenues for future improvements

PANS SRS method

- **G1-PANS Equations**

$$\frac{DU_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_k}\left[(\upsilon + \upsilon_u)\frac{\partial U_i}{\partial x_k}\right]$$

$$\frac{\partial k_u}{\partial t} + U_j\frac{\partial k_u}{\partial x_j} = P_U - \beta^* k_u \omega_u + \frac{\partial}{\partial x_j}\left(\frac{\upsilon_u}{\sigma_{ku}}\frac{\partial k_u}{\partial x_j}\right)$$

$$\frac{\partial \omega_u}{\partial t} + U_j\frac{\partial \omega_u}{\partial x_j} = \alpha\frac{P_u \omega_u}{k_u} - \beta' \omega_u^2 + \frac{\partial}{\partial x_j}\left(\frac{\upsilon_u}{\sigma_{\omega u}}\frac{\partial \omega_u}{\partial x_j}\right)$$

$$\sigma_{\varepsilon u} = \frac{f_k^2}{f_\varepsilon}\sigma_\varepsilon \qquad \sigma_{ku} = \frac{f_k^2}{f_\varepsilon}\sigma_k \qquad \beta' = \alpha\beta^* - \frac{\alpha\beta^*}{f_\omega} + \frac{\beta}{f\omega}$$

1. **Const. f_k ; $f_e = 1$**
2. **Correct BL equilibrium for any f_k**