LES of Turbulent Flows: Lecture 15
(ME EN 7960-008)

Prof. Rob Stoll
Department of Mechanical Engineering
University of Utah

Spring 2009

Evaluating Simulations and SGS models

- How do we go about testing our models? How should models be validated and compared to each other?
- Pope (2004) gives 5 criteria for evaluating SGS models:

  1. Level of description in the SGS model
  2. Completeness of the model
  3. The cost and ease of use of the model
  4. The range and applicability of the model
  5. The accuracy of the model

- Most of these criteria are related to the accuracy of simulation results:

  -**Accuracy**: Ability of the model to reproduce DNS, experimental or theoretical statistical features of a given test flow (or the ability to converge to these values with increasing resolution)

  An important aspect of this is **grid convergence of simulation statistics**. This is not always done but is an important aspect of simulation validation. Note that this convergence (especially in high-Re flows) may not be exact, we may only see approximate convergence.

Evaluating Simulations and SGS models

-**<u>Cost</u>**: When examining the above, it is important to include the cost of each model (and comparisons between alternative models).

-One model may give better results at a lower grid resolution (larger Δ) but include costs that are excessive:

Example: Scale-dependent Lagrangian dynamic model (Stoll and Porté-Agel, WRR, 2006):

38% increase in cost over constant Smagorinsky model

15% increase over plane averaged scale-dependent model

How much of a resolution increase can we get in each direction for a 30% cost increase?? Only a little more than 3% in each direction!

-**<u>Completeness</u>**: A "complete" LES and SGS model would be one that can handle different flows with simply different specification of BCs, initial conditions and forcings.

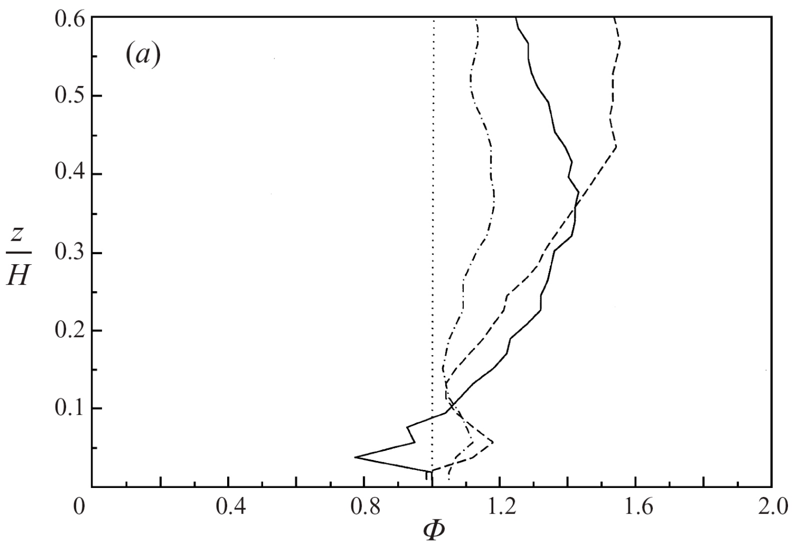
-In general LES models are not complete due to grid requirements and (possibly) ad hoc tuning for different flows.

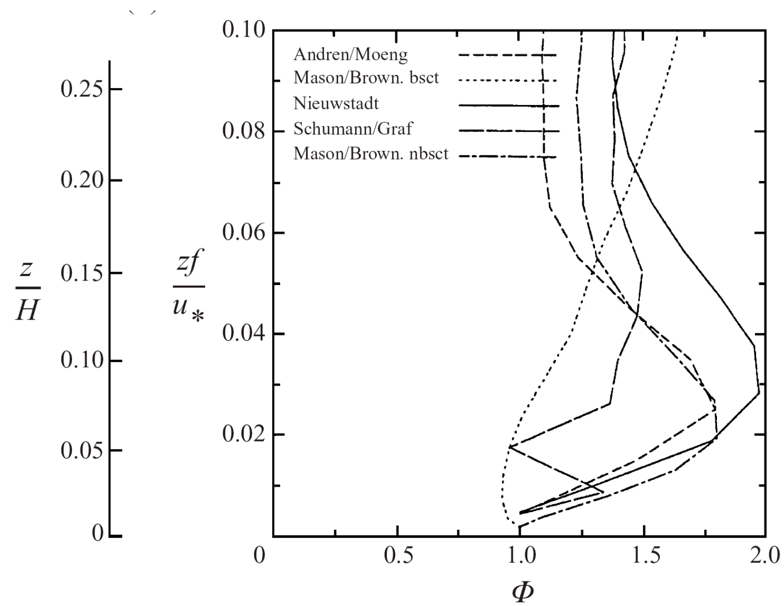
-Example from RANS: mixing length models are <u>incomplete</u> (different flow different *l*) while the k-ε model can be thought of as <u>complete</u> for RANS since it can be applied to any flow.

Accuracy of LES models

• Here we will look at some examples of different measurements of simulation accuracy and evaluation as well as a few common test cases for LES

• An example of the accuracy of LES models to predict flow statistics (from Porte-Agel et al, JFM 2000 and Andren et al., 1994, QJRMS):

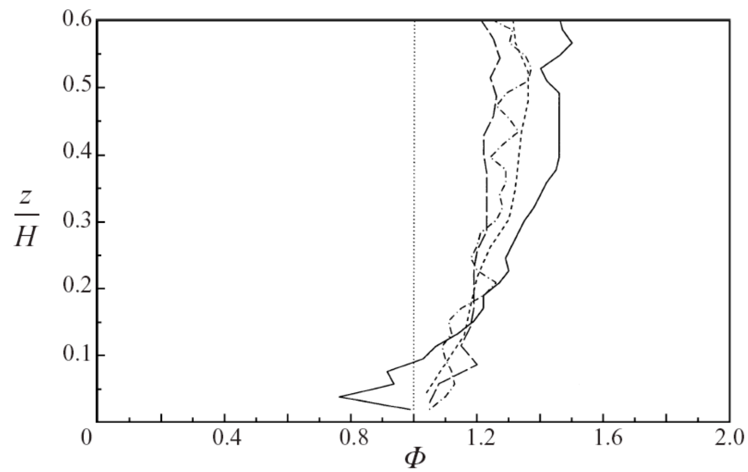




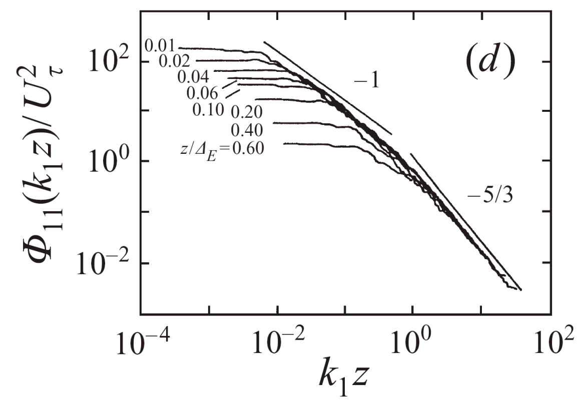
•Non-dimensional velocity gradient

Accuracy of LES models

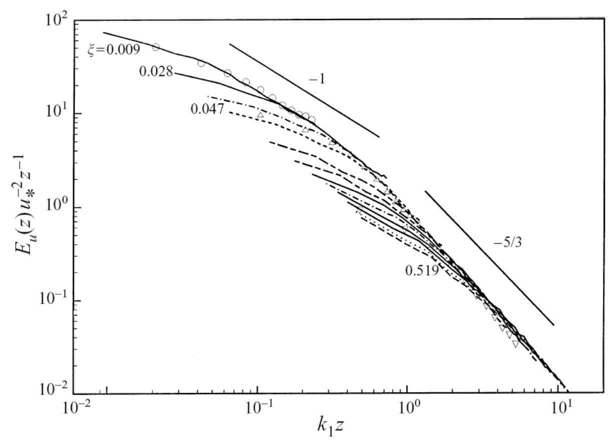
- An example of the accuracy of LES models to predict flow statistics (from Porte-Agel et al, JFM 2000)



•Non-dimensional velocity gradient



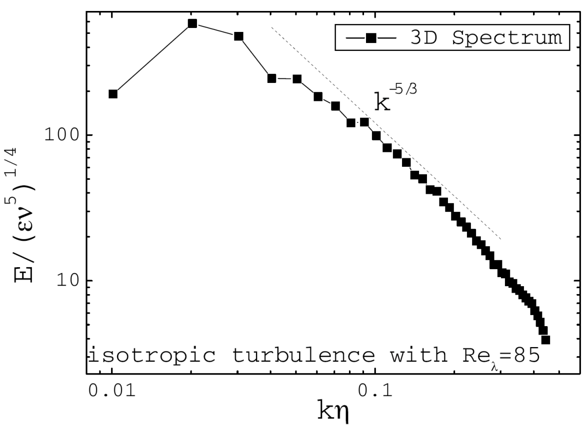
•Streamwise velocity spectra from Perry et al (1986)



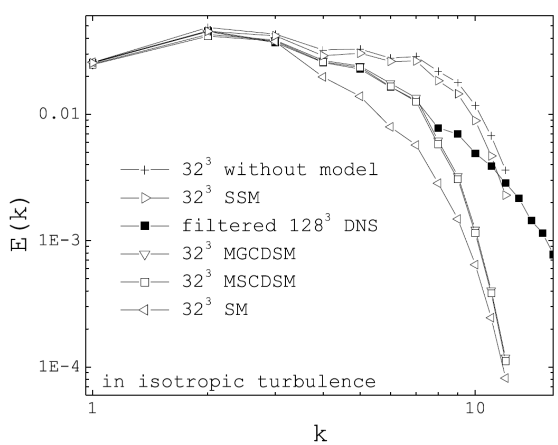
•Streamwise velocity spectra at two different resolutions

Test Case: Isotropic Turbulence LES

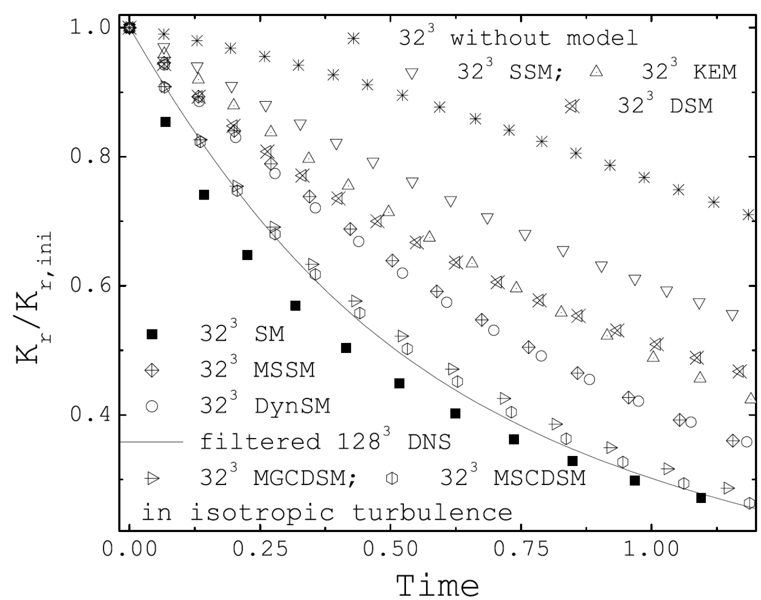
- An example from Lu et al, 2008



•Velocity spectra from DNS



•Velocity spectra from filtered DNS and LES



•Energy decay in isotropic turbulence

Test Case: Turbulent Boundary Layers

- An example from Guerts, 2004 of the effect of different SGS models on boundary layer development

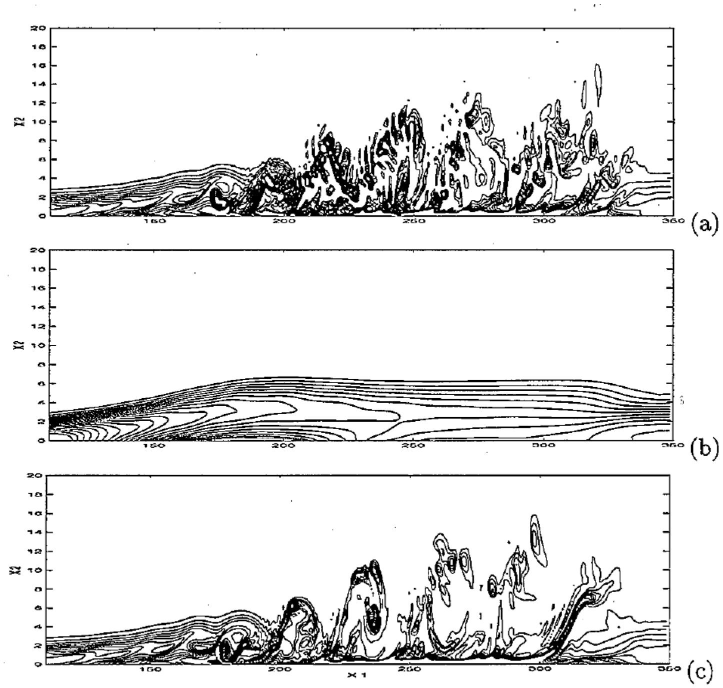


Fig. 8.15. Snapshot of the spanwise vorticity component: (a) DNS prediction, (b) LES with Smagorinsky's model and van Driest damping, (c) LES with dynamic eddy-viscosity model.

Test Case: Backward Facing Step

- An example from Cabot and Moin, 2000

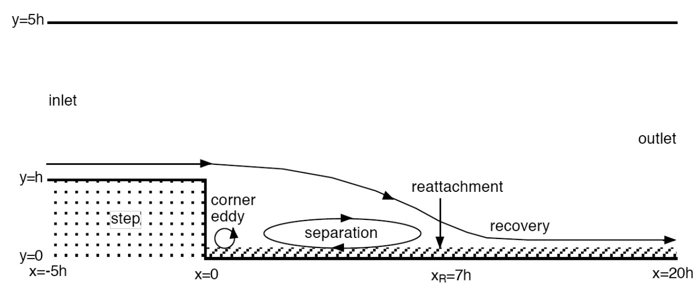


Figure 4. Sketch of the simulation domain for flow over a step of height h with an expansion ratio of 4 to 5. Wall stress models were used in the hatched region.

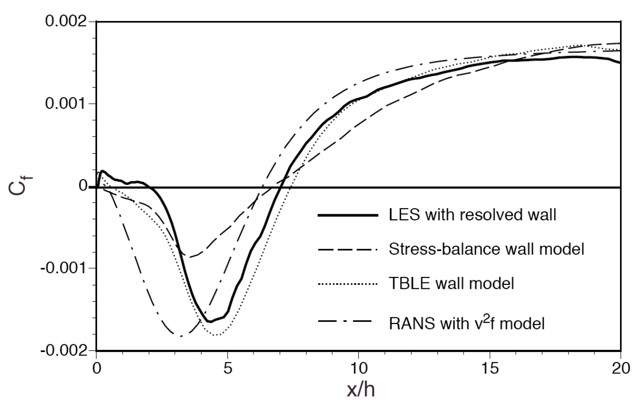


Figure 6. Friction coefficient on the bottom wall behind a step for the wall-resolved LES [2], wall stress models using stress balance and TBLE with a dynamic kappa in equation (5), and a global RANS $v^2 f$ model [18].

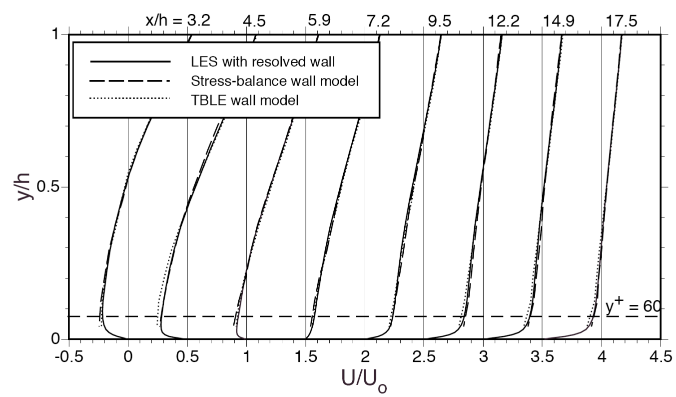


Figure 7. Mean streamwise velocity at different stations behind a step for the wall-resolved LES [2], and stress-balance and TBLE wall stress models. The dashed line is the height of the first computational cell, about 60 wall units near the exit.

LES Review Papers

- "**Large-Eddy Simulation: Acheivements and Challenges**", 1999, Piomelli, U, *Progress in Aerospace Science*.

  -A review paper outlining many different topics in LES starting from the basics of filtering. Many of the issues brought up in the paper are still must be fully addressed by the turbulence modeling community. It includes the basic classes of SGS models and issue relevant to compressible flow and acoustic simulations.

- "**Scale-Invariance and Turbulence Models for Large-Eddy Simulation**", 2000, Meneveau, Charles, and Katz, Joseph, *Annual Reviews in Fluid Mechanics*.

  -A very nice paper reviewing SGS models for incompressible turbulent flow. It also contains one of the few reviews to include experimental *a priori* studies in a review setting. Most of the main modeling techniques are present.

- "**Wall-Layer Models for Large-Eddy Simulations**", 2002, Piomelli, Ugo, and Balaras, Elias, *Annual Reviews in Fluid Mechanics.*

  -One of the few review papers to focus on LES off-wall boundary conditions. This doesn't contain issues related specifically to atmospheric flows but all the major techniques used in high-Re flows are present with the exception of local application of the log-law.

- "**Ten Questions Concerning the Large-Eddy Simulation of Turbulent Flows**", 2004, Pope, Stephen, *New Journal of Physics.*

  -A review of challenges and issues facing LES simulations and development. A nice read that can be helpful when determining what type of validations should be carried out. The paper stresses the need to examine grid convergence in simulation results.

Some Books on LES

- "**Elements of Direct and Large-Eddy Simulation**", 2004, Bernard J. Geurts.

  -A readable book covering everything from turbulence theory to LES subgrid scale models and numerical techniques. It contains mostly incompressible flow with some applications to compressible flow. While not as complete as some other books (measured by the number of different methods), this is a nice first book to go over.

- "**Large-Eddy Simulation for Incompressible Flows: An Introduction, 3rd Edition**", 2006, Pierre Sagaut.

  -Not really an introduction but more of a nice reference for LES SGS model techniques. It contains some turbulence theory but its best information is on filtering and SGS models. Probably the most complete collection of SGS models in any one place. It can be a difficult read due to the effort to include so many references.

- "**Turbulent Flows**", 2000, Pope, Stephen.

  -This book is not strictly speaking a book on LES. It is a book about incompressible turbulent flows that contains a very nice section on modeling. The modeling section includes a chapter on LES. The inclusion of general turbulence theory and LES together makes this book an ideal companion for texts that focus on LES and many times give brief or incomplete descriptions of the turbulent flow phenomena and mathematics the models are based on. Two related examples are isotropic turbulence theory (e.g., Kolmolgorov's hypothesis) and spectral analysis, both of which Pope gives excellent descriptions of.

Some Books on LES

- "**Mathematics of Large Eddy Simulation of Turbulent Flows**", 2006, Berselli, Luigi, Iliescu, Traian and Layton, William.

  -This book is a nice text on LES focused on the mathematics of LES. It is written in the style of a math text book (complete with theorems, Lemmas, proofs and remark statements throughout the text). The mathematical viewpoint makes several sections very strong (including those related to filtering and approximate deconvolution) but at the same time makes the text a somewhat incomplete viewpoint of LES. For example phenomenological modeling strategies are not discussed. Some important developments (e.g., dynamic modeling) are also missing from the textbook.

- "**Large-Eddy Simulations of Turbulence**", 2005, Lesieur, Marcel, Metais, Olivier and Comte, Peirre.

  -This is a shorter compact text on LES. Of the textbooks listed here, it contains one of the better descriptions of LES of compressible flow. It is also one of the better references for EDQNM (eddy-damped quasi-normal Markovian) theory, spectral LES and strucuture function SGS models. It is also the only text listed that explicitly discusses LES and atmospheric flows (although not in great detail).

- "**Implicit Large Eddy Simulation**", 2007, Grinstein, Fernando, Margolin, Len and Rider, William.

  -This book is a collection of papers on implicit LES techniques. The papers are logically chosen to give the reader a good overview of the development and motivation of this technique. This book is a nice starting point for a researcher interested in using ideas from researchers working in implicit LES. The first 2 chapters give a nice introduction to the technique and the motivations and historical developments.

- "**Large Eddy Simulation of Turbulent Flows: Analytical and Numerical Results for a Class of LES Models**", 2004, Volker, John.

  -A mathematically minded text this book contains a lot of information. It takes a similar approach to Berselli et al. but is harder to read. One unique feature is that it does contain a chapter devoted to testing many of the models discussed in the text in actual flows (2D and 3D mixing layers).