LES of Turbulent Flows: Lecture 20

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Overview

1. *a priori* studies using Direct Numerical Simulation data

2. Experimental *a priori* studies
   - Laboratory experiments
   - Atmospheric boundary layer field experiments

a priori studies using Direct Numerical Simulation data

- Since shortly after the introduction of the **L**arge-**E**ddy **S**imulation (**LES**) technique by Deardorff (1970), experimental and **D**irect-**N**umerical **S**imulation (**DNS**) data sets have been used to test LES **S**ub**G**rid-**S**cale (**SGS**) models
- This type of model testing was termed *a priori* testing by Piomelli et al. (1988)

a priori studies using Direct Numerical Simulation data

- Many of these tests use data from low-to-moderate Reynolds number DNS of isotropic turbulence, turbulent channel flow, or mixing layer simulations
- These studies, and many others, helped to establish new SGS models, test existing models, and improve our understanding of the physics associated with grid scale energy transfers.

a priori studies using Direct Numerical Simulation data

- What follows is a brief literature review of *a priori* studies using DNS data
- We will cover different types of datasets and how they were used
- This will show you what has been done and perhaps give you ideas for your project related to your own research

a priori studies using Direct Numerical Simulation data

- Clark et al. (1979) - analysis of isotropic turbulence demonstrated the low correlation level between SGS stresses calculated from DNS and SGS stresses calculated from common (at the time) LES SGS models.
- Motivated by these results and the idea that near grid scale motions are the most significant for SGS energy transfers, Bardina et al. (1980) developed the similarity model.

a priori studies using Direct Numerical Simulation data

- Piomelli et al. (1988) used DNS of turbulent channel flow to show the link between the choice of filter type and SGS model type
- In another study, Piomelli et al. (1991) used DNS of channel flow to help establish the relative importance of backscatter events (an inverse-energy cascade from SGS to resolved scales) in LES

a priori studies using Direct Numerical Simulation data

- Domaradzki et al. (1993) used Taylor-Green vortex simulations to examine near grid cutoff scale energy transfers
- They observed inverse energy transfers (backscatter) centered around the filter cutoff scale supporting Bardina et al.'s (1980) hypothesis that the most active SGS are those close to Δ

a priori studies using Direct Numerical Simulation data

- Hartel et al. (1994) used results from DNS of low-Re number channel and pipe flow to examine SGS energy transfers in the near-wall region (buffer layer) – using conditional averaging, they found that backscatter could be associated with coherent structures in this region
- Vreman et al. (1995) - study of compressible mixing layer flow using DNS established the relative importance of the many SGS components that arise from filtering the compressible Navier-Stokes equation

a priori studies using Direct Numerical Simulation data

- A two-parameter dynamic mixed model was proposed by Salvetti and Banerjee (1995) and tested using DNS of channel flow and homogeneous compressible flow
- Salvetti and Banerjee (1995) compared their new model with the dynamic Smagorinsky model of Germano et al. (1991) and the dynamic mixed model of Zang et al., (1993)
- Their results showed improved correlations for their model over the other two

a priori studies using Direct Numerical Simulation data

- Menon et al., (1996) used isotropic turbulence DNS to examine scale similarity and one-equation SGS models
- They found that the one-equation models outperformed scale similarity models for poorly resolved simulations

a priori studies using Direct Numerical Simulation data

- Hartel and Kleiser (1997) studied the effect of different filter kernels on SGS energy transfers (Leonard, cross and SGS stress components)
- They found very little effect of the different types of filters provided that the decomposition was done in a Galilean invariant format – contradicting some earlier results

a priori studies using Direct Numerical Simulation data

- Salvetti and Beux (1998) focused on the relation between numerical discretization methods and implied implicit LES filters
- They looked at how different finite difference approximations effected the Leonard term and its correlation with the SGS stresses

a priori studies using Direct Numerical Simulation data

- Juneja and Brasseur (1999) used DNS data from simulations of isotropic turbulence and homogeneous buoyancy driven turbulence to study the effect of anisotropy and under-resolved turbulence on LES
- They found that SGS models with a direct coupling between the resolved and SGS could not properly account for SGS accelerations with direct implications for simulations of high-Reynolds number boundary layers
- This also suggested that stochastic SGS models (Mason and Thomson, 1992) may be appropriate

a priori studies using Direct Numerical Simulation data

- Shao et al. (1999) also examined SGS modeling of anisotropic flows but using mixing layer DNS
- They interpreted their results by separating the SGS stress tensor into parts that depend on the mean gradients and those that do not
- Their results showed that the SGS component that depends on the mean gradients is well represented by the eddy viscosity models while the part that does not can be represented by a similarity model for filters applied in physical space

a priori studies using Direct Numerical Simulation data

- More recently, Lu et al., (2007) used DNS of rotating turbulence to examine the effect of rotation on small scale turbulence and SGS models

Experimental *a priori* studies - Laboratory experiments

- In parallel to the numerical studies, many researchers have used experimental data with different instrumentation setups and various levels of approximation to examine the performance of LES SGS models in different flows
- This includes both laboratory studies and field studies in the atmospheric boundary layer (ABL)

Experimental *a priori* studies - Laboratory experiments

- Experimental studies are limited in their ability to collect 3D-unsteady flow fields
- However, they have the distinct advantage over DNS of allowing researchers to look at LES in more realistic flows and over a much larger range of Re – all the way up to ABL scales

Experimental *a priori* studies - Laboratory experiments

- Most lab experiments were conducted in wind tunnels and used either hot-wire anemometry or particle image velocimetry (PIV)
- In wind tunnel and field experiments, typically 1D or 2D data is collected
- This necessitates approximations for both filtering (i.e., using a 1D or 2D filter instead of a 3D filter to separate resolved and SGSs) and velocity gradients

Experimental *a priori* studies - Laboratory experiments

- Meneveau (1994), explored grid turbulence (the wind tunnel analog of isotropic turbulence) using a single hot-wire anemometer (a 1D approximation) with the goal of characterizing sufficient conditions for LES SGS models in terms of statistical moments of SGS quantities
- Also examined ν_T models and determined that while locally they have very little correlation with actual SGS dissipation rates, they do contain the correct physics (evaluated statistically) to generate acceptable energy spectra of the resolved LES flow field

Experimental *a priori* studies - Laboratory experiments

- Liu et al. (1994, 1995) used PIV measurements (a 2D approximation) to look at similarity SGS models in the far-field of a turbulent jet
- They verified earlier DNS results showing that the Smagorinsky model has poor correlation with the measured SGS dissipation rate and calculated SGS model coefficients by matching the average modeled and measured SGS dissipation rates

Experimental *a priori* studies - Laboratory experiments

- O'Neil and Meneveau (1997) also used a single hot-wire but measured wake flow behind a circular cylinder
- Confirming earlier results for eddy-viscosity and similarity models
- Showed that anisotropy contributes to changes in the Smagorinsky coefficient near the wake's edges and that coherent structures have a direct effect on the performance of SGS models
- Results support the idea that SGS models should 'learn' from the resolved scale motions (as in dynamic models)

Experimental *a priori* studies - Laboratory experiments

- Liu et al. (1999) studied the effect of rapid straining created by pushing two disks together in a water tank using time-resolved PIV measurements
- They found the rapid straining increased the correlation between measured and modeled SGS stress for the Smagorinsky model
- They also found opposite trends from typical steady-flow cases
- In the straining flow, the Smagorinsky (similarity) model under-predicted (over-predicted) SGS dissipation
- Results suggested that a linear combination of the two may be necessary for rapidly straining flows

Experimental *a priori* studies - Laboratory experiments

- Cerutti et al. (2000) performed one of the few experimental studies looking at spectral eddy-viscosity models using an array of X-wire probes (hot-wires that measure two velocity components) in a turbulent wake flow
- Marusic et al. (2001) used X-wires in conjunction with surface mounted shear stress sensors to do one of the first *a priori* studies of surface boundary conditions for turbulent boundary layer LES
- They found that common parameterizations were unable to reproduce the level of fluctuations in the wall shear stress
- Based on their results, they developed a new LES surface boundary condition

Experimental *a priori* studies - Laboratory experiments

- Tao et al. (2002) - one of the few (and first) studies to use holographic PIV (3D PIV) to examine SGS models – looked at the geometric relation between the SGS stress and strain in the core of a square duct
- Kang and Meneveau (2005) combined a hot-wire probe array with DNS data to look at the association between coherent structures and looked at filtered stress-strain geometric tensor alignment

Experimental *a priori* studies - Laboratory experiments

- Natrajan and Christensen (2006) - looked at the association of SGS models and coherent structures, with a focus on how backscatter events correlated with vortex packets in a wind tunnel boundary layer
- Hong et al., (2012) performed a similar analysis over a rough wall (pyramids) and examined the correlation between coherent structures and SGS fluxes with a focus on the association between roughness characteristics and inter scale energy transfer

Experimental *a priori* studies - Laboratory experiments

- Lastly, studies have looked at SGS modeling and spatially heterogeneous flows
- Carper and Porté-Agel (2008) used PIV measurements after a rough-to-smooth aerodynamic surface roughness transition to look at SGS physics and the trends in model coefficients downstream of the transition

Experimental *a priori* studies - ABL field experiments

- Shortly after major lab experimental efforts to study SGS models started, field experiments in the ABL began
- Taking measurements in the ABL allows researchers to look at SGS models and physics at Re numbers unattainable in a laboratory setting or by DNS
- In addition, the large scale of the ABL allows robust instrumentation to be used that is not as dependent on calibration procedures (sonic anemometers)

Experimental *a priori* studies - ABL field experiments

- One of the first of these studies was Porté-Agel et al. (1998).
- Used a sonic anemometer and 1D filtering approximations and focused on SGS heat flux and the Smagorinsky model
- Confirmed that the model could not reproduce SGS dissipation events, such as backscatter, associated with coherent structures (e.g., temperature ramps)

Experimental *a priori* studies - ABL field experiments

- Around the same time, Tong et al. (1999) used a 2D array to examine SGS stress in the ABL surface layer
- Shortly there after, Porté-Agel et al. (2001) extended the use of a 2D array to include two horizontal planes of sonic anemometers allowing them to measure all the components of the filtered strain rate tensor

Experimental *a priori* studies - ABL field experiments

- Higgins et al. (2003) looked at tensor alignment similar to the lab study of Tao et al. (2002) using ABL data and confirmed that the SGS stress and filtered strain rate tensors do not align in contradiction to the assumption of the Smagorinsky model
- Found that the mixed model formulation may be warranted for high-Re turbulence
- Many of the ABL studies mirrored the lab experiments in their quest to connect coherent structures with SGS physics using conditional averaging

Experimental *a priori* studies - ABL field experiments

- Carper and Porté-Agel (2004) used an array of sonics on the Utah salt flats (see Metzger 2002 for a description of the test location) to look at SGS dissipation events associated with 3D coherent structures
- Higgins et al. (2007) used a 4×4 array of sonics (also on the salt flats) to examine the effect of 2D versus 3D filtering

Experimental *a priori* studies - ABL field experiments

- Bou-Zeid et al. (2008) examined the scale dependence of SGS model coefficients in the ABL using sonic anemometers and found good agreement with published assumptions (i.e. power law dependence)
- More recently, several ABL researchers have started to examine SGS physics over complex surfaces including lakes and glaciers

Experimental *a priori* studies - ABL field experiments

- In many of the ABL studies, the ability of SGS models to account for buoyancy effects (an important factor in realistic ABL simulations) was studied
- Kleissl et al. (2003, 2004) found a clear dependence of the Smagorinsky coefficient on atmospheric stability
- Bou-Zeid et al. (2010) found a dependence of the SGS Prandtl number of stability