LES of Turbulent Flows: Lecture 10
(ME EN 7960-003)

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Eddy viscosity Models

- **Eddy Viscosity Models:** (Guerts pg 225; Pope pg 587)

-In Lecture 8 we said an eddy-viscosity models are of the form:

momentum: $\tau_{ij} = -2\nu_T \tilde{S}_{ij}$ ← filtered strain rate

↖ eddy-viscosity

scalars: $q_i = -D_T \frac{\partial \tilde{\theta}}{\partial x_i}$ where $D_T = \frac{\nu_T}{Pr_{sgs}}$ ← SGS Prandtl number

↖ eddy-diffusivity

-This is the LES equivalent to 1st order RANS closure (k-theory or gradient transport theory) and is an analogy to molecular viscosity (see Pope Ch. 10 for a review)

-Turbulent fluxes are assumed to be proportional to the local velocity or scalar gradients

-In LES this is the assumption that stress is proportional to strain: $\tau_{ij} \sim \tilde{S}_{ij}$

-The SGS eddy-viscosity ν_T must still be parameterized.

Eddy viscosity Models

-Dimensionally =>

$$\nu_T = \left[\frac{L^2}{T}\right]$$

-In almost all SGS eddy-viscosity models $\nu_T \sim u^* l^*$

velocity scale (u^*) — length scale (l^*)

-Different models use different u^* and l^*

-Recall from last time, we can interpret the eddy-viscosity as adding to the molecular viscosity so that the (dimensional) viscous term is:

$$\frac{\partial}{\partial x_j}\left[\left(\nu_T + \nu\right)\tilde{S}_{ij}\right]$$

What does the model do? We can see it effectively lowers the Reynolds number of the flow and for high Re (when 1/Re=>0), it provides all of the energy dissipation.

Most LES models use a nonlinear eddy viscosity. What happens if we use a constant?

- We effectively run the simulation at a different (lower) Re
- This has implications for DNS. If we try to use DNS at a lower Re to examine phenomena that happens at a higher Re, unless our low-Re is high enough that Re-invariance assumptions apply we can make the analogy between our DNS and an LES with a SGS model that doesn't properly reproduce the flow physics.

Smagorinsky Model

• **<u>Smagorinsky model</u>**: (Smagorinsky, MWR 1963)

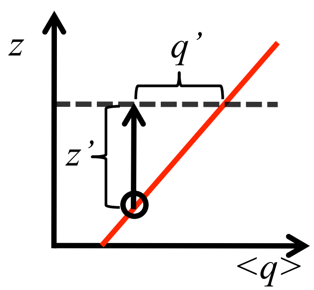
-One of the 1st and still most popular ν_T models for LES

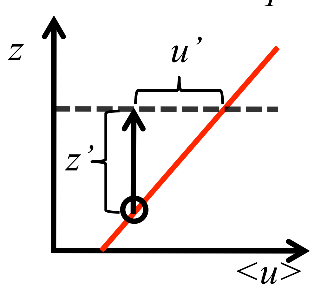
-Originally developed for general circulation models (large-scale atmospheric), the model did not remove enough energy in this context.

-Applied by Deardorff (JFM, 1970) in the 1st LES.

-Uses Prandtl's mixing length idea (1925) applied at the SGSs (see Pope Ch. 10 or Stull, 1988 for a full review of mixing length):

• In **<u>Prandtl's mixing length</u>**, for a general scalar quantity q with an assumed linear profile:





-A turbulent eddy moves a parcel of air by an amount z' towards a level z where we have no mixing or other change

-q' will differ from the surrounding by: $$q' = -\left(\frac{\partial\langle q\rangle}{\partial z}\right)z'$$

-ie it will change proportional to its local gradient

-Similarly, if velocity also has a linear profile:

$$u' = -\left(\frac{\partial\langle u\rangle}{\partial z}\right)z'$$

Smagorinsky Model

-To move up a distance z' our air parcel must have some vertical velocity w'

-If turbulence is such that $w' \sim u'$ then $w'=Cu'$ and we have 2 cases:

$$\frac{\partial u}{\partial z} > 0 \Rightarrow w' = -Cu'$$

$$\frac{\partial u}{\partial z} < 0 \Rightarrow w' = Cu'$$

-Combining these we get that: $$w' = C\left|\frac{\partial \langle u \rangle}{\partial z}\right| z'$$

-We q' and w' and now we can form a kinematic flux (conc. * velocity) by multiplying the two together:

$$\langle q'w' \rangle = -C\left\langle (z')^2 \right\rangle \left|\frac{\partial \langle u \rangle}{\partial z}\right| \frac{\partial \langle q \rangle}{\partial z}$$

-Where $(z')^2$ is the variance a parcel moves and C$(z')^2$ is defined as the mixing length ➔

$$\langle q'w' \rangle = -\ell^2 \left|\frac{\partial \langle u \rangle}{\partial z}\right| \frac{\partial \langle q \rangle}{\partial z}$$

-we can replace q' with any variable in this relationship (e.g. u')

Smagorinsky Model

•**Back to Smagorinsky model**:

-Use Prandtl's mixing length applied at the SGSs:

$$\nu_T = (C_S \Delta)^2 |\tilde{S}|$$

length scale → $(C_S \Delta)$; velocity scale → $|\tilde{S}|$

-Where Δ is the grid scale taken as $\Delta = (\Delta_x \Delta_y \Delta_z)^{\frac{1}{3}}$ (Deardorff, 1970 or see Scotti et al., PofF 1993 for a more general description).

-$|\tilde{S}| = \sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}}$ is the magnitude of the filtered strain rate tensor with units [1/T] and serves as the velocity scale (think $\frac{\partial \langle u \rangle}{\partial z}$ in Prandtl's theory) and $C_S \Delta$ is our length scale (squared for dimensional consistency).

-The final model is:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\,(C_S \Delta)^2\, |\tilde{S}|\tilde{S}_{ij}$$

-To close the model we need a value of C_s (usually called the Smagorinsky or Smagorinsky-Lilly coefficient)

Lilly's Determination of C_S

• Lilly proposed a method to determine C_S (IBM Symposium, 1967, see Pope page 587)

• Assume we have a high-Re flow => Δ can be taken to be in the inertial subrange of turbulence.

• The mean energy transfer across Δ must be balanced by viscous dissipation, on average (note for Δ in the inertial subrange this is not an assumption) .

$$\epsilon = \langle \Pi \rangle \quad \text{recall:} \quad \Pi = -\tau_{ij}\tilde{S}_{ij}$$

-Using an eddy-viscosity model $\nu_T \Rightarrow \Pi = 2\nu_T \tilde{S}_{ij}\tilde{S}_{ij} = \nu_T |\tilde{S}|^2$

-If we use the Smagorinsky model: $\nu_T = (C_S\Delta)^2 |\tilde{S}|$

=> $\Pi = (C_S\Delta)^2 |\tilde{S}|^3$

-The square of $|\tilde{S}|$ can be written as (see Pope pg 579 for details):

$$|\tilde{S}|^2 = 2\int_0^\infty k^2 \hat{G}(k)^2 E(k)dk$$

energy spectrum

filter transfer function

-Recall, for a Kolmogorov spectrum in the inertial subrange $E(k) \sim C_k \epsilon^{2/3} k^{-5/3}$

-We can use this in our integral to obtain (see Pope pg. 579): $|\tilde{S}|^2 \approx a_f C_k \epsilon^{2/3} \Delta^{-4/3}$

Lilly's Determination of C_S

- We can rearrange $|\tilde{S}|^2 \approx a_f C_k \epsilon^{2/3} \Delta^{-4/3}$ to get: $\epsilon = \left[\frac{\langle |\tilde{S}|^2 \rangle}{a_f C_k \Delta^{-4/3}} \right]^{\frac{3}{2}}$ (∗)
- Equating viscous dissipation and the average Smagorinsky SGS dissipation ($\epsilon = \langle \Pi \rangle$):

$$\epsilon = \langle (C_S \Delta)^2 \, |\tilde{S}|^3 \rangle$$

- if we now combine this equation with (∗) above and do some algebra…

$$C_S = \frac{1}{(C_k a_f)^{3/4}} \left(\frac{\langle |\tilde{S}|^3 \rangle}{\langle |\tilde{S}|^2 \rangle^{3/2}} \right)^{-\frac{1}{2}}$$

- we can use the approximation $\langle |\tilde{S}|^3 \rangle \approx \langle |\tilde{S}|^2 \rangle^{3/2}$ and a_f for a cutoff filter (see Pope)

=> $$C_S = \frac{1}{\pi} \left(\frac{2}{3C_k} \right)^{3/4}$$

- C_k is the Kolmogorov constant ($C_k \approx$ 1.5-1.6) and with this value we get:

$C_S \approx 0.17$