Modeling, Validation and Physics of Turbulent Flows: opportunities offered by petascale Direct Simulation

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Methodology & Tools

- Theory (model)
- Simulations
- Observations
- Truth...
- Lab. Exp.

Burgers - conference 2000
Large Eddy Simulation (GPU)  courtesy Jerome Schalkwijk
The convective boundary layer ...
\[
\frac{w_e}{w_\ast} = AR i^{-1}
\]
\[
A = 0.2
\]

Water Tank: Deardorff, Willis and Stockton, J FM 1980
Laboratory Experiments
(thermal convection tank)

Deardorff et al. water tank model of shear-free CBL (1960-80s)

Figure 7.10  Tank used by Deardorff (pictured above) and Willis in their laboratory experiments. (Deardorff and Willis.)


courtesy E. Fedorovich
Entrainment rate

\[ w_e = \frac{dz_i}{dt} \]

Deardorff, Willis and Stockton, JFM 1980
Multi-Scale Physics
Faculty of Applied Sciences
Experimental setup

- Fresh water
- Salt water
- Laser
- Water flow ($w_b$)
experimental results

\[ A \approx 0.2 \]

\[ A \approx 0.02 \]

factor 10 ??

1970-1980

J. Deardorff

Controversy ...

J.S. Turner

(normalised growth-rate) \( A \)

(inversion strength) \( Ri \)
### Governing equations

\[ \frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{1}{Re} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \theta \delta_{ij} \]

\[ \frac{\partial \theta}{\partial t} + \frac{\partial u_j \theta}{\partial x_j} = \frac{1}{Re Pr} \frac{\partial^2 \theta}{\partial x_j^2} \]

<table>
<thead>
<tr>
<th></th>
<th>atmosphere</th>
<th>tank (heat)</th>
<th>tank (salt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reynolds number</strong></td>
<td>( Re = \frac{w_* Z_i}{\nu} )</td>
<td>Re=10^8</td>
<td>Re=10^3</td>
</tr>
<tr>
<td><strong>Prandtl number</strong></td>
<td>( Pr = \frac{\nu}{\kappa} )</td>
<td>Pr=1</td>
<td>Pr=10</td>
</tr>
<tr>
<td><strong>Peclet number</strong></td>
<td>( Pe = Re Pr )</td>
<td>Pe=10^8</td>
<td>Pe=10^4</td>
</tr>
</tbody>
</table>
DNS

\[ \text{Cost} \sim N^4 \sim \text{Re}^3 \text{Pr}^2 \]

Re, Pr overview

saline tank

Deardorff tank

atmosphere
### DEI SA resource allocation:

2M cpu-hr

<table>
<thead>
<tr>
<th>Site</th>
<th>Architecture</th>
<th>cores used</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>SARA</td>
<td>IBM Power 6</td>
<td>1024</td>
<td>1024 x 1024 x 768</td>
</tr>
<tr>
<td>CINECA</td>
<td>IBM BCX/5120</td>
<td>2048</td>
<td>2048 x 2048 x 1024</td>
</tr>
<tr>
<td>LRZ</td>
<td>SGI Altix 4700</td>
<td>3072</td>
<td>1536 x 1536 x 768</td>
</tr>
<tr>
<td>Juelich</td>
<td>Bluegene</td>
<td>32,768</td>
<td>3072 x 3072 x 1536</td>
</tr>
</tbody>
</table>
\( N_x = N_y = 2048, \quad N_z = 1024, \quad p = 2048 \)
\( L_x = L_y = 3072m, \quad L_z = 1280m \)
\( \text{Re} = 30,000 \quad \text{Pr} = 1 \)

(potential) Temperature animation
The importance of large computations
The importance of large computations
The importance of large computations

Re number must be really large before fluid-properties can be neglected
Fortuity or talent?

Pr dependence (Re < 1000)

Deardorff tank

low Re and Pr-effects cancel out!

saline tank

DD tank
Methodology & Tools

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- Truth...

Methodology

- Theory
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Direct Simulation vs Understanding Turbulence

- DNS has now the ability to form the computational analog of laboratory experiments
- ‘interesting’ Reynolds numbers can be reached
- yields no immediate understanding
- ideal research tool (interactive)
- my impression: there seem a lack of hypotheses
Governing equations DNS

\[
\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = \frac{1}{\text{Re}} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \theta \delta_{i3} \\
\frac{\partial \theta}{\partial t} + \frac{\partial u_j \theta}{\partial x_j} = \frac{1}{\text{RePr}} \frac{\partial^2 \theta}{\partial x_j^2}
\]

Compare to a Reynolds-stress turbulence model

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} = \ldots \\
\frac{\partial \bar{\theta}}{\partial t} + \frac{\partial \bar{u}_j \bar{\theta}}{\partial x_j} = \ldots
\]

wouldn’t fit!
The Pr influence at large Reynolds numbers

Prandtl-number:
Large Reynolds/ Peclet limits

\[
\frac{w_e}{w_*} = f(Ri, Re, Pr) \quad \text{or} \quad \frac{w_e}{w_*} = f(Ri, Re, Pe)
\]

\[\text{Re} \rightarrow \infty \quad \text{or} \quad (\text{Pe} \rightarrow \infty)\]

\[
\frac{w_e}{w_*} = f(Ri, Pr) \quad \text{or} \quad \frac{w_e}{w_*} = f(Ri)
\]
LES of Stratocumulus

L = 25.6km  Dx = Dy = 100m

t = 1...16hr, liquid water path
Inverse Cascade?

2-D or not 2-D: that’s the question
Spectral variance budget

\[ c = \bar{c} + c_1 + c_2 + \ldots + c_n \]

\[ \frac{d}{dt} \bar{c}_\mu^2 = P_\mu - D_\mu + \sum_\lambda C_{\mu\lambda} \]

scale by scale variance budget
Scale Interaction Matrix $C_{\mu\lambda}$

16 sections

buoyancy field

source
sink
$P(\phi)$

upscale transfer

downscale transfer
Concluding remarks

- ‘Why modeling works’ - does it really work?

- Direct Simulation will soon become the ideal research tool for turbulence (direct interaction)

- Are we capable of defining the most pressing hypotheses in turbulence?