Large Eddy Simulations of an Idealized Hurricane

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Motivation

1. Intensity sensitivity to model resolution

2. Direct computation of effects of turbulence
Motivation 1: Resolution Sensitivity

Hurricane Katrina 2005
Forecasts start at 00Z August 27, 2005.

(Davis et al. 2008, MWR)
Motivation 1: Resolution Sensitivity

\[ \Delta=1.67\text{km} \quad \Delta=5\text{km} \]

Figure 4.4b. MM5 forecasted rainrate (mm h\(^{-1}\)) in Rita at 1115 UTC 22 September using 1.67-km (left) and 5-km (right) grid resolution. The model was initialized at 0000 UTC 20 September using the NOGAPS forecast fields as lateral boundary condition. The 1.67-km forecast shows a primary and secondary eyewalls as observed, whereas 5-km does not.

(HIRWG 2006, S. Y. Chen)
Motivation 2: Effect of Turbulence

ELDORA Reflectivity in Hurricane Rita (2005)
Courtesey Michael Bell

Hurricane Hugo (1989) Flight level data
Marks et al. (2008)
Regimes of Numerical Modeling (Wyngaard 2004)

\[ \Phi(\kappa) \]

Mesoscale limit

the "terra incognita"

LES limit

\[ 1/\Delta_{\text{meso}} \quad 1/l \quad 1/\Delta_{\text{LES}} \]
Model Setup

Idealized TC
f-plane
zero env wind
fixed SST

Nested Grids

WRF Model Physics
WSM3 simple ice
No radiation
Relax to initial temp.
Cd (Donelan)
Ck (Carlson-Boland)
Ck/Cd ~ 0.65
YSU PBL (Δ ≥ 1.67 km)
LES PBL (Δ < 1.67 km)

6075 km (Δ = 15 km)

1500 km (Δ = 5 km)
1000 km (Δ = 1.67 km)

333 km (Δ = 556 m)
37 km (Δ = 62 m)

111 km (Δ = 185 m)

50 vertical levels
Δz = 60 m ~ 1 km
Ztop = 27 km
Initial Condition

Initial sounding WRF neutral

$SST = 26.3^\circ C$

Initial vortex (m/s)

*After Rotunno and Emanuel (1987)*
Intensity Evolution

Instantaneous maximum 10-m wind

$(\Delta = 1.67 \text{ km})$
$(\Delta = 556 \text{ m})$
$(\Delta = 185 \text{ m})$
Surface Wind ~ Resolution

\((\Delta = 1.67 \text{ km})\)

\((\Delta = 556 \text{ m})\)

\((\Delta = 185 \text{ m})\)

\((\Delta = 62 \text{ m})\)

\(\text{max}=61.5\)

\(\text{max}=86.7\)

\(\text{max}=86.2\)

\(\text{max}=121.7\)
Eddy Kinetic Energy Spectra

LES

\[ \Delta = 1.67 \text{ km} \]
\[ \Delta = 556 \text{ m} \]
\[ \Delta = 185 \text{ m} \]
\[ \Delta = 62 \text{ m} \]
1-min Averaged Surface Wind

instantaneous

max=121.7

1-min average

max=78.8

37km

LES

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Max. Azimuthal-Mean Wind ~ Resolution

| Resolution | $<|u_{10}|>_{\text{max}}$ (m/s) |
|------------|---------------------------------|
| 1.67 km    | 53.4                            |
| 556 m      | 73.2                            |
| 185 m      | 77.1                            |
| 62 m       | 72.0                            |
Large Eddy Simulation

\[
\frac{\partial \overline{\theta}}{\partial t} = -\frac{\partial}{\partial x_i} \left( \overline{u_i \theta} \right) - \frac{\partial}{\partial x_i} \left( \overline{u_i' \theta'} \right)
\]

grid-scale \hspace{1cm} grid-scale \hspace{1cm} subgrid-scale

\[
\overline{u_i' \theta'} = -K_{LES} \frac{\partial \overline{\theta}}{\partial x_i} \ ; \ K_{LES} = (c_s \Delta)^2 |Def|
\]

When resolution increases (\(\Delta\) decreases)

- \(K_{LES}\) decreases => subgrid-scale flux decreases
- Grid-scale flux is small until the LES resolution threshold is crossed!
Lessons Learned from LES

- Modeled intensity increases with decreasing grid size (decreasing turbulent mixing length) until…

- LES threshold crossed, however…
  It’s not clear that $\Delta=62\text{m}$ is small enough for statistically converged result

- In high-resolution models treatment of turbulence as important as other factors (e.g. ocean coupling, ocean-wave drag, cloud physics, sea spray…)