Idealized LES of a TC-like boundary layer...

and WRF-LES of Hurricane Katrina (2005)

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Tropical Cyclone Boundary Layer (TCBL)

• Emanuel’s PI theory: TC is like Carnot engine
  – Enthalpy input from warm oceans ($C_k$)
  – Momentum lost to ocean surface ($C_D$)

• Why is TCBL so important?
  1. BL communicates information between surface layer and free atmosphere: impacts TC intensity and structure (and thus predictability)
  2. We live in boundary layer: want to know about mean wind and turbulent gusts

Emanuel (1986; 1995a,b)
Part 1: Idealized Large Eddy Simulation of TCBL

• What is the simplest configuration of LES that can represent key features of a TCBL?
• According to Nakanishi and Niino (2012):
  – Periodic lateral boundary conditions
  – Incompressible barotropic flow with extreme winds (35 m s\(^{-1}\)) forced by constant horizontal PGF
  – Some representation of centrifugal force (v/R)
  – No surface heat flux, clouds, or radiation
• But is this too simple?
Consequences of NN12 LES configuration

• Periodic LBCs + constant horizontal PGF: **effectively simulates turbulent statistics** at a single vertical column

• Simulation of single column w/ periodic LBCs:
  – Fixed radius from TC center can represent centrifugal force \((V/R)\) **in Cartesian coordinates**
  – Surface heat flux = 0
  – Incompressible: no mean vertical velocity (becomes important close to TC eyewall)
Problem with NN12 LES setup

• NN12 represent centrifugal force as v/R
  – Yields barotropic instability (their Appendix A)
  – Their workaround: change v/R to <v>/R
    (\(<v>\) = horizontal average v at each vertical level)

• To make a 3-month-long story short:
  – Unphysical barotropic instability introduced by improper “small angle” approximation in conversion from cylindrical to Cartesian coordinates
  – Our solution: Change reference frame to rotate with TC – replace Coriolis parameter f with “effective” Coriolis: \( f^* = f + 2V_g/R \)
LES momentum equations

- Coded in Cartesian coordinates (R is constant)

\[
\begin{align*}
\frac{Du}{Dt} &= -\frac{1}{\rho} \frac{\partial p}{\partial x} + f^* (v - V_g) - \frac{\partial \tau_{x,j}}{\partial x_j} \\
\frac{Dv}{Dt} &= -\frac{1}{\rho} \frac{\partial p}{\partial y} - f^* u - \frac{\partial \tau_{y,j}}{\partial x_j}
\end{align*}
\]

\[f^* = f + 2 V_g / R\]
Our idealized LES setup

• NCAR LES

• Properties unchanged between LES runs:
  – Incompressible, periodic LBCs, constant $V_g$
  – Grid mesh: $\Delta x = \Delta y = \Delta z = 40$ m
  – Domain size: $(L_x, L_y, L_z) = (20$ km, 20 km, 4 km)
    (500x500x100 grid points)
  – Time: 40,000 sec (11.11 hr); $\Delta t = 0.1$ sec
  – Dry, no radiation, no surface heat flux
  – Initial $\theta$ profile: $\theta = 300$ K at sfc, $d\theta/dz = 4$ K km$^{-1}$
Configuration of different LES runs

- Default (CNTL) LES: $R = 60$ km, $V_g = 35$ m s\(^{-1}\), $C_D$ (via $z_0$) follows Donelan et al. (2004)

- Test sensitivity to...
  - $f^*$ (via $R$): $R = 30, 60, 120$ km [R30, CNTL, R120]
  - $V_g$: $V_g = 17.5, 35, 70$ m s\(^{-1}\) [V17.5, CNTL, V70]
  - Surface drag (via $z_0$) at $V_g = 70$ m s\(^{-1}\):
    - $C_D$ is flat above 33 m s\(^{-1}\) (Donelan et al. 2004) [V70]
    - $C_D$ increases monotonically w/ wind [Charnock70]
    - $z_0 = 0.1$ m (strong friction over land) [Land70]
\[ v' = v - \langle v \rangle \text{ (m s}^{-1}\text{)} \text{ at } z = 100 \text{ m} \]
Normalized profiles of mean $K_m$

- $K_m = \text{vertical component of eddy viscosity}$
  - Solid: Resolved-scale
  - Dashed: Subgrid-scale
- All runs (except V17.5) are clearly in LES range
- Normalized $K_m$ increases with $R$ (decreases with $f^*$)
- Normalized $K_m$ curves collapse for fixed $R$ and $V_g \geq 35 \text{ m s}^{-1}$

Averaged over last 3 h of each run
Normalized profiles of mean v

- \( \langle v \rangle / V_g > 1 \) is characteristic of all rotating (Ekman) flows
- Invites comparison with linear theory of Kepert (2001, K01)
  - Areas of agreement:
    - Increased \( R \) (decreased \( f^* \)) = higher, stronger overshooting jet
    - Increased \( C_D \) = higher, stronger jet
    - Weak jet: LES and K01 neglect vertical advection of \( u \) (Kepert and Wang 2001)
  - Areas of disagreement (due to \( K_m \)):
    - Increased \( V_g \) = higher, weaker jet

Averaged over last 3 h of each run
Conclusions (Idealized LES)

- Incompressible Cartesian LES w/ periodic LBCs severely constrains modeling TCBL
  - Change $f$ to $f^*$ (to account for TC’s rotation)
  - Neglect mean vertical advection
  - Result: Ekman layer with extremely fast rotation, can be compared with linear analytic model of Kepert (2001)

- LES agrees with K01 linear model, except when nonlinear effects of $K_m$ overwhelm and counteract effects of $V_g$
Part 2: WRF-LES of Hurricane Katrina (2005)

• Limitations of Part 1 motivate new approach
• Use WRF model to nest down from mesoscale
  – Non-periodic LBCs
  – Compressibility
  – Moist physics and radiation
• Problems: High computational/memory requirements
  – Short integration time (4-6 hours)
  – Infrequent output (every 1 hour)
  – Coarser grid mesh (1/3 km, 1/5 km, 1/9 km)
Experimental setup

• Run WRF simulations of Hurricane Katrina (Aug. 05)
  – Spinup: EnKF assimilation of airborne Doppler velocities
  – Deterministic run from 00Z/26 to 12Z/28 with $\Delta x = 3 \text{ km}$

• Integrate until 18Z/28 using following 1-way nested, fixed meshes:
  – $\Delta x = 1 \text{ km}$ (YSU and MYNN PBL schemes)
    • $\Delta x = 333 \text{ m}$ (YSU PBL scheme and no PBL scheme)
      – At 14Z, nest down to $\Delta x = 111 \text{ m}$ (no PBL scheme)
    • $\Delta x = 200 \text{ m}$ (no PBL scheme)
Simulated visible satellite (SWDOWN field), valid 18Z/28 for 111 m simulation
Preliminary results: Katrina LES

Diagnosed SGS fluxes from nonlinear backscatter and anisotropy (NBA) scheme

Finer mesh = weaker, more shallow SGS fluxes (good)
Preliminary results: Katrina LES

- Plots of 10-m wind speed at 18Z/28
- PBL scheme appears to discourage very strong local wind maxima
- Polygonal eyewalls
- Compare with Fig. 2 of Rotunno et al. (2009)
Preliminary conclusions (Katrina LES)

• $\Delta x$ between 100 m and 1 km give very different results
  – $\Delta x = 333$ m appears to be in “gray zone” or “terra incognita” for LES
  – $\Delta x = 111$ m is much more acceptable for TC LES
  – May be necessary to nest a LES mesh inside a “gray zone” mesh: don’t use gray zone only!

• LES of real TC cases is not quite ready yet for “prime time” – much more testing needed (see next slide)
What needs to be done going forward?

• For idealized LES of TCBL
  – Look at turbulence structure & higher-order moments
  – Add surface heat flux w/ strong capping inversion
  – Use compressible, non-periodic LBC LES
  – Heterogeneous surface drag: coastline

• For LES of TCs: Testing with quasi-idealized vortex
  – Various subgrid-scale parameterizations
  – 1-way vs. 2-way nesting
  – Size of < 1 km meshes (absolute, and relative to size of TC vortex)
  – Longer integration time: how is practical predictability limited?
References


Extra/Backup slides
Normalized profiles of mean u

- \( \langle u \rangle / V_g < 0 \) is characteristic of all rotating (Ekman) flows
- Compare with K01 linear theory
  - Areas of agreement:
    - Increased \( R \) (decreased \( f^* \)) = deeper inflow layer
    - Increased \( C_D \) = deeper inflow layer
  - Areas of disagreement (due to \( K_m \)):
    - Increased \( V_g \) = deeper inflow layer

Averaged over last 3 h of each run
Compare with Rotunno et al. (2009)

Rotunno et al. (2009)
- Two-way nesting
- 50 vertical levels
- Idealized vortex
- Sizes of sub-km meshes:
  - 556 m: 333 km x 333 km
  - 185 m: 111 km x 111 km
  - 62 m: 37 km x 37 km

Present work
- One-way nesting
- 83 vertical levels
- Hurricane Katrina
- Sizes of sub-km meshes:
  - 333 m: 816 km x 816 km
  - 200 m: 471 km x 471 km
  - 111 m: 278 km x 278 km
• Simulated IR (OLR field), valid 18Z/28 for 200 m simulation
Background: Boundary layer modeling

1. Mesoscale simulations
   – Parameterize all BL turbulence

2. Large Eddy Simulation (LES)
   – Explicitly resolve energy-containing eddies
   – Parameterize small dissipative eddies

3. Direct Numerical Simulation (DNS)
   – Resolve all turbulence (way too expensive)
Tropical Cyclone Boundary Layer (TCBL)

• Emanuel’s potential intensity theory: TCs are like Carnot engines
  – Enthalpy input from warm oceans ($C_k$)
  – Momentum lost to ocean surface ($C_D$)

• BL communicates information between surface layer and free atmosphere

Emanuel (1986; 1995a,b)
Why is TCBL so important?

1. Impacts TC intensity/structure (and thus predictability)

2. We live in the boundary layer... want to know about mean wind and turbulent gusts
Results: Time series of $u_*$

- Adjustment oscillation has period very close to $2\pi/f^*$ (inertial period)
- $u_*$ increases slightly with $f^*$ (decreases slightly with $R$)
- $u_*$ impacted much more by $V_g$ and surface drag (increased $V_g$, $C_D = \text{increased } u_*$) – no surprise
Background

• Emanuel’s potential intensity theory for TCs

\[
V_{\text{max}}^2 = \frac{C_k}{C_D} \left( \frac{1 - 0.25r_0^2}{1 - \gamma \frac{C_k}{2C_D}} \right)
\]

\[
P_{\text{min}} \approx - \frac{V_{\text{max}}^2 (1 - 0.5AH) - 0.25r_0^2}{1 - AH}
\]

• Increase \( C_k \) and/or decrease \( C_D \) = stronger TC (faster winds and deeper central pressure)

• Problem: uncertainty/error in \( C_k \) and \( C_D \) parameterizations = error in TC forecasts

Emanuel (1986; 1995a,b)
$C_D$ and $C_k$ in an atmosphere-only model

- In similarity theory, $C_k$ is a function of $C_D$ (scalar flux proportional to momentum flux)
  \[-\tau/\rho = u_* \times u_* = C_D U(\Delta U) = u_* \times C_D^{1/2} U\]
  \[-H/(c_p \rho) = u_* \times \theta_* = C_k U(\Delta \theta) = \theta_* \times C_D^{1/2} U\]
  \[-E/(L_v \rho) = u_* \times q_* = C_k U(\Delta q) = q_* \times C_D^{1/2} U\]

- This means $\alpha$, $V_c$, and $m$ also impact $C_k$!
Hot off the supercomputer! LES of Katrina

• Max. $V_{10}$ extremely sensitive to $C_D$ formula
  – Donelan $C_D$: 98 m s$^{-1}$
  – Charnock $C_D$: 77 m s$^{-1}$

• Horizontal grid:
  – Spacing = 333 meters
  – Size: 816 km x 816 km
    (2448 x 2448 points)

• 85 vertical levels
• Run for 6 hours
Future work

• Move to Very Large Eddy Simulation (VLES)
  – The new “gold standard” of TC simulations
  – How does turning off PBL scheme impact results?

• Test $C_D$ independent of $C_k$ (Smith et al. 2012)
  – Goes against similarity theory and WRF
  – But can shed more light on problem

• Incorporate parameter estimation into Penn State’s WRF-EnKF system
  – Especially for $\alpha$, the multiplicative parameter in $C_D$
  – Requires more near-surface observations