High-resolution Regional Climate Modeling

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Variability in tropical storm numbers

Most severe hurricane category

Tropical Storm
Category 1
Category 2
Category 3
Category 4
Category 5

Data: http://www.aoml.noaa.gov/hrd/hurdat/hurdatTAB.txt
IPCC AR4 Projection of Global Surface Temperature (2090-2099) for A1B “business as usual” Scenario

Global mean warming = 2.8°C
Climate Change and Hurricanes
Emanuel (2005), Holland and Webster (2007)

Figure 1. Tropical cyclone occurrence (dots indicate annual totals and the black line is a 9-year running mean) in the North Atlantic together with East Atlantic sea surface temperature (SST) anomalies for the hurricane season (grey line) from 1855 to 2005. TC1–TC3 refer to climate regimes discussed in the text.
Atlantic Ocean

Low wind shear (Average year)
- Storm's latent heat is focused over small area.

High wind shear (El Niño year)
- Storm's latent heat is focused over larger area.
Increased Tropical Atlantic wind shear in model projections of global warming

Vecchi & Soden, GRL (2007)
The Gulf Stream’s Pathway to Impact Climate

Graphic representation of the Gulf Stream surface current speeds in blue-white (white is the fastest) and upward wind velocities in yellow-red (red for stronger winds), along with land-surface topography of eastern North America. Image, courtesy of Fumiaki Araki and Shintaro Kawahara at JAMSTEC, was made for cover of Nature issue.

Minobe et al. (2008)
Computer Models of Climate
Coupled Regional Climate Model Domain
Atmospheric component:
Weather Research & Forecasting Model (WRF)

Developed at NCAR
- 27-km/9-km horizontal resolution, 35 vertical levels
- Timestep $\Delta t = 90$ Seconds

NCEP-NCAR reanalysis for boundary conditions and initial conditions

Physics parameterizations:
- WSM 3-class simple ice (Microphysics), RRTM (LW-Radiation),
- Goddard SW-Radiation, YSU PBL scheme,
- Kain-Fritsch cumulus convection scheme
Oceanic component:
Regional Ocean Modeling System (ROMS)

- Developed at Rutgers University/UCLA
- 9-km Horizontal Resolution & 30 levels for the Atlantic Basin
- $\Delta t = 10$ minutes. Boundary conditions derived from Levitus observational data.
Coupling strategy

- Atmosphere and ocean exchange fluxes of momentum, energy, and freshwater

- Atmosphere and ocean model on same spatial grid
  - 27 km and 9 km grids

- Coupling every hour
Computational performance on Ranger (TACC)

**WRF 30 km (460x466x28 grid)**

<table>
<thead>
<tr>
<th>CPUs</th>
<th>Wall clock hrs for 1 yr run</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>57</td>
</tr>
<tr>
<td>256</td>
<td>36</td>
</tr>
<tr>
<td>384</td>
<td>28</td>
</tr>
</tbody>
</table>

*The ocean model is about 20 times faster than the atmospheric model, for the same grid!*
WRF on High Performance Systems

- Community model designed for HPC
  - Keys are performance and portability
  - Multi-level domain decomposition supports both shared and distributed memory parallelism
  - WRF software framework portable over range of system architectures

WRF 2.5km CONUS Benchmark
http://www.mmm.ucar.edu/wrf/WG2/bench

John Michalakes
WRF Scaling

- WRF Nature Run
  - 2 billion cell hemispheric run at 5km
  - 50 TF/s on 150K cores (Cray XT5)
  - Weak scaling; low simulation rate
- Current work on Blue Gene/P
  - 12km/4km/1.3km Hurricane Bill
  - ~1000km square moving nest covering entire storm
  - 4K nodes/16K processors
  - Simulation rate is about 15:1
- Need to look at node-speed for strong scaling

courtesy Peter Johnsen, Cray
Annual mean bias: Uncoupled 9 km ROMS forced with CORE2 fluxes

SSH

T

S

Surf. velocity

ROMS9km/MY25 vs SODA [surface, Annual mean]
MAM Precipitation and wind bias: 27km WRF coupled with 9km ROMS vs. Global CGCMs

Regional Model

Global Model

Coupled

Uncoupled

Coupled-Obs.
CRCM simulation: Tropical cyclone tracks
Barrier Layer (BL) in the ocean:
Isothermal layer deeper than mixed layer

Typical vert. profile

Vert. profile with a Barrier Layer

\[ BLT = D_{T-0.2} - D_{\sigma} \]
\[ \Delta_{\sigma} = \sigma_{\theta}(T_{10} - 0.2, S_{10}, P_0) - \sigma_{\theta}(T_{10}, S_{10}, P_0) \]
Barrier Layers and tropical cyclones

\[ V_{max} = \sqrt{\frac{C_k}{C_d}} \frac{(T_s - T_0)}{T_0} (K_s - K_d) \]  
Emanuel, 1986

Surface SST cooling: Negative feedback factor

McPhaden et al., 2009

Ffield., 2006
Comparison of SST response for cases with and without a BL

Typical case: Without a BL

Temperature profiles: Before (blue), After (red)

Atypical case: BL with an inversion

Temperature profiles: Before (blue), After (red)
PDF of SST change for cases with(red) and without(blue) BLs

mean $\Delta SST_{BL} = 22\%$ of mean $\Delta SST$
Observational analysis


Hurricane tracks: NOAA-AOML

Monthly maps of BLT: SODA 2.0.4

mean $\Delta SST_{BL} = 51\%$ of mean $\Delta SST$
Conclusions

- Coupled regional climate model produces hurricane-like vortices

- Ocean mixing in the hurricane wake is quite sensitive to vertical stratification
  - occasionally the mixing can lead to warming!

- Ocean mixing in the hurricane wake does not contribute significantly to poleward oceanic heat transport
Coupled Regional Climate Model (CRCM)

• Regional atmospheric model coupled to regional ocean model
• Lateral b.c. from global coupled model or reanalyses
Environmental precursors for hurricane genesis
Gray (1968, 1979)

- **Sea surface temperatures > 26 degrees C**
  - Sufficiently deep mixed layer (> 50m)
- **Deep conditional instability**
  - Cooling with height, mid-tropospheric moisture
- **Low values (< 10 m/s) of vertical shear between 850 hPa and 200 hPa**
- **Sufficiently removed from equator for Coriolis effect**
- **Pre-existing disturbance with cyclonic vorticity**
Research Domain

Hurricane genesis in Atlantic basin from 1958 to 2008
Space: Tropical Atlantic
Main Development Region (MDR): 8N - 20N, 20W - 65W
Time: Hurricane season (July - October)
Coupled Regional Climate Modeling in the Atlantic Sector
Texas A&M University

- Atmospheric model: WRF (27km)
- Ocean model: ROMS (27km and 9km)
- Both models use the Arakawa C-grid
- Atmospheric and oceanic lateral b.c. from global reanalyses/models

- Objectives
  - Address tropical biases in coupled models
  - Study air-sea interaction at very high resolution

- Analysis
  - Surface flux imbalance and model bias
  - Hurricanes and air-sea interaction
Outline:

- Tropical cyclones and climate change
- Time-slice experiments and air-sea coupling
- Coupled regional climate model
- Ocean mixing and the barrier layer
- Conclusions
Cold water wake of Hurricane Dean 8/26/07
Some Results

• Need higher ocean resolution to simulate Gulf Stream separation
  – 27km WRF coupled to 9km ROMS
  – Better load balancing: WRF 60%, ROMS 40%

• Hurricanes and oceanic Barrier Layers
  – Usually a hurricane leaves cold SST wake
  – But Barrier Layers can reverse this effect!

• Surface flux imbalances
  – What the ocean wants vs. what the atmosphere provides
  – Largest errors in tropical SST still found near the coastal upwelling regions
BL formation in the wake of tropical cyclones

Framework of study

Regional Coupled Model (RCM)

ROMS(27 km) - WRF (30 km)

Initial and boundary conditions derived from NCEP re-analysis and Levitus data