Upper-ocean response to Hurricane Ivan in a 1/25° nested Gulf of Mexico HYCOM#

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Ocean’s Response to a hurricane

Two stages [Price et al. 1994]

**Forced stage**: SST cooling, mixed-layer currents, surface heat fluxes mainly latent heat loss, geostrophic currents and associated sea level changes

**Relaxation stage**: Inertial-gravity oscillations excited by the storm.
Objectives

1. To assess the model’s ability to reproduce the observed behavior of the oceanic response to hurricane Ivan with and without data-assimilation.

2. To quantify the physical processes controlling the upper-ocean cooling during Ivan’s passage.
Outline

- Model description
  - Initial and boundary conditions
  - Data assimilation
  - Model experiments

- Results
  - Model-data comparison
  - Upper-ocean response to Ivan
  - Heat-budget
  - Sensitivity to initial conditions

- Conclusions
Model Description

**Model:** HYCOM

**Domain:** Gulf of Mexico (north of 18.1°N, west of 77.4°W)

**Horizontal resolution:** 1/25° (~4 km)

**Vertical:** 20 hybrid layers

**Vertical mixing scheme:** GISS level 2 [NASA Goddard Institute for Space Studies, Canuto et al. 2001, 2002]

**Surface forcing:** 1° NOGAPS [wind-speed, wind-stress, air-temperature, humidity, precipitation, surface shortwave and long-wave heat fluxes]

**Heat flux exchange coefficients:** Kara et al. [2002] formulation, latent, sensible heat fluxes are calculated using model SST
Boundary Conditions (BCs)

- 1/12° (~8 km) North Atlantic data-assimilative HYCOM system provides BCs [Chassignet et al. 2005]
- BCs are updated every day
- 1-10 days e-folding relaxation time
- 20 grid-points wide relaxation zone

Ivan: 14-16 Sept 2004 in GoM
Category 5 on 12 Sept

Maximum SST cooling occurred outside the WCE and LC regions

WCE -> Warm Core Eddy
LC -> Loop Current

2°x2° box 88°-86°W, 24°-26°N
Model Experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Model simulation</th>
<th>Period</th>
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</thead>
<tbody>
<tr>
<td>NAS</td>
<td>Non-assimilation</td>
<td>Jan-Dec 2004</td>
</tr>
<tr>
<td>AS</td>
<td>Assimilation</td>
<td>Jan-Dec 2004</td>
</tr>
</tbody>
</table>

Data Assimilation

- Assimilating daily operational Modular Ocean Data Assimilation System (MODAS) 1/4° SSH real-time altimeter observations
- *Cooper and Haines* [1996] technique is used to project the surface information to the interior of the ocean.
- Relaxation to the MODAS SST is **not included**
Impact of data-assimilation

- A comparison of zonal, meridional vel. and SSH

- Simulation with data-assimilation showed improved agreement with observations.

- WCE separation in NAS occurred in April instead of August as in AS which is consistent with observations.
A comparison with SEED ADCP data

14 acoustic Doppler current profilers (ADCPs) were deployed on the shelf and down slope, as part of the NRL Slope to Shelf Energetics and Exchange Dynamics (SEED) project.

- Ivan passed directly through the array.
- Currents in excess of 2 m/s were measured on the shelf.
Impact of data-assimilation

A comparison with SEED ADCP data (outer shelf)
Impact of data-assimilation

A comparison with SEED ADCP data (continental slope)

ZONAL VELOCITY (M S^{-1})

M13 (87.831°W, 29.156°N)  NAS  AS

DEPTH (m)  SEP  SEP  SEP
Upper-ocean response to Ivan

Simulated SST, MLD and SHF

- Pre-storm MLD of 10 m increased to 45 m during the storm and SST decreased from 28.5°C to 25°C in NAS
- Colder SST, shallower MLD and weaker surface heat loss in AS
- Post-storm warming due to surface heat gain by the ocean
Upper-ocean response to Ivan

surface currents and depth of 20°C isotherm

storm - wind-driven currents dominated the surface circulation

shallower thermocline in the assimilative run

depth thermocline in the LC and WCE regions
Upper-ocean response to Ivan

vertical temp. diffusion coefft. $\ln(K_T)$

- maximum vertical mixing occurred to the right of the storm
- lack of rightward bias in SST cooling was due to the underlying thermal structure of the water column
- vertical mixing occurred simultaneously with upwelling – shallow MLD and enhanced SST cooling
- vertical velocity of the assimilative run predicted slightly higher values
Upper-ocean response to Ivan

vertical temperature gradient and MLD

- **AS** – thin pre-storm ML and strong upper-thermocline temperature gradient enhanced upper-ocean cooling
- **NAS** – weak vertical temperature gradient resulted in less SST cooling

Box average 88°-86°W, 24°-26°N

What are the physical processes affecting the upper-ocean cooling?
Heat-budget analysis

Heat-budget terms can be written as

\[ Q_T = -Q_{U+V} -Q_W + Q_S + Q_{DV} + Q_{DH}; \]

- \( Q_T \) = rate of change of heat (\( dT/dt \))
- \( Q_{U+V} \) = horizontal advection
- \( Q_W \) = vertical advection
- \( Q_S \) = surface heat flux
- \( Q_{DV} \) = vertical diffusion
- \( Q_{DH} \) = horizontal diffusion (small, not included)
heat-budget terms averaged for 2°x2° box (88°-86°W, 24°-26°N)

<table>
<thead>
<tr>
<th>Date</th>
<th>September 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expts</td>
<td>NAS AS</td>
</tr>
<tr>
<td>$Q_T$ (W m$^{-2}$)</td>
<td>-1421 -2870</td>
</tr>
<tr>
<td>$Q_S$ (%)</td>
<td>2.4 -8.9</td>
</tr>
<tr>
<td>$Q_{DV}$ (%)</td>
<td>73.6 69.8</td>
</tr>
<tr>
<td>$Q_{U+V}$ (%)</td>
<td>16.1 16.0</td>
</tr>
<tr>
<td>$Q_W$ (%)</td>
<td>8.0 23.2</td>
</tr>
</tbody>
</table>

- surface heat-flux term was small
- wind-driven mixing dominated the cooling
- same horizontal advective cooling
- ~3 times vertical advective cooling in AS
Heat-budget terms at 50 m and 100 m (88°-86°W, 24°-26°N)
Sensitivity to initial conditions

- Storm-induced changes were insensitive to pre-storm conditions when assimilation is included.
- Simulation initialized with assimilation fields reproduced the observed changes in the upper-ocean reasonably well.
Conclusions

- A comparison of simulated zonal and meridional velocities using data assimilation showed improved agreement with ADCP observations.
- Model simulated amplitude of the cold wake (-6°C) compared reasonably well with the observed changes in SST.
- While the simulated location of WCE and LC in the assimilation run showed better agreement with satellite altimetry, the storm-induced SST cooling was 40-50% greater than the observed cooling.
- Overall, 72% of the upper-ocean cooling was due to wind-driven vertical mixing.
- There was a three-fold increase in the vertical advective cooling in the assimilative run.
- Surface heat-flux contribution to the mixed-layer heat budget was only ~4%. 
Nested (~1 km) model for the Persian Gulf region

northward intrusion of low-salinity water during summer
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