An Introduction to Remote Sensing of the Gulf of Mexico
SSH Overlaid on Chl and SST Imagery
This talk is focused on Gulf of Mexico mesoscale circulation driven by the Loop Current and its associated eddy field that is resolved by multi-satellite sampling provided by the current generation of multiple nadir satellite altimeters.

4 Introduction to satellite altimetry

4 Several applications in the Gulf of Mexico
   Off shore oil and gas exploration and production
   Hurricane intensification
Deepwater Ocean Circulation: Satellite Altimetry
Satellite Altimeter Coverage in LC Study Area

BOEM “Dynamics of the LC Study” Moorings

<table>
<thead>
<tr>
<th>Satellite(s)</th>
<th>Repeat Period</th>
<th>Cross Track Spacing (degrees)</th>
<th>Cross Track Spacing (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T/P, Jason, &amp; OSTM</td>
<td>10 days</td>
<td>2.83°</td>
<td>285 km</td>
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<tr>
<td>GFO</td>
<td>17 days</td>
<td>1.47°</td>
<td>148 km</td>
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<td>ERS-1&amp;-2, Envisat</td>
<td>35 days</td>
<td>0.72°</td>
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<td>OSTM/Jason Interleaved</td>
<td>10 days</td>
<td>1.42°</td>
<td>143 km</td>
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Schematic of Altimeter System
Schematic of Corrections

Atmospheric Refraction Corrections
- dry gases
- water vapor
- ionospheric electrons

Instrument Corrections
- tracker bias
- waveform sampler gain calibration biases
- antenna gain pattern
- AGC attenuation
- Doppler shift
- range acceleration
- oscillator drift
- pointing angle/sea state

Sea-State Bias Corrections
- EM bias
- skewness bias

External Geophysical Adjustments
- geoid height $h_g$
- ocean tidal height $h_T$
- atmospheric pressure loading $h_a$

$$h = H - R$$
$$h_d = h - h_g - h_T - h_a$$

Sea Surface
Reference Ellipsoid
Bottom Topography
Sample along track SSH anomaly

TOPEX/ERS-2/GFO Apr 1 2001 - Apr 30 2001

Sea surface height (cm)
Mapped SSHA plus model mean
GOM SSH Anomaly 10/22/2003
Altimetry Blended SSH
SST/SSH Overlay October 22, 2003
Altimetric Tracking of the LC and LCEs

4 The 17-cm LC tracking contour is used to objectively track the LC and LCEs and identify LCE separation events.

4 The day that the breaking of the LC tracking contour occurs is identified as the nominal “time” of LCE separation.

4 Sometimes a detached eddy will reattach to the LC. In those cases, the time associated with the final detachment of the LCE from the LC is referred to as the LCE separation time.

4 A total of 30 separation events were observed in the altimetric record from January 1, 1993 through December 31, 2012.
Loop Current (LC) metrics are computed using the 17-cm sea surface height contour as a proxy for the high velocity core of the LC in the eastern Gulf of Mexico.

This proxy allows objective computation of LC metrics such as:

4 Maximum northward and westward extent of LC penetration.
4 Length
4 Area
4 Circulation
4 Volume
Westward Propagation of a Loop Current Eddy
Fate of Eddy “Zorro”
20-Year Altimetric Record of LCE Separation Events
LC Retreat Animation

Sea Surface Height (cm)

Separation Period (days)

Retreat Latitude

LCE #1
Retreat Latitude Following Separation

![Graph showing retreat latitude following separation over separation period (months) with three lines representing different records: 34-year record, pre-altimeter record only, and altimeter record only.](image-url)
Pre-Altimetry Record
The combined time series of Seasat altimetry, ocean color and SST images, and HMI/EddyWatch charts were used to manually identify LC separation events and LC retreat following separation.

Satellite coverage was sufficient to determine that there were no separation events in 1979. A separation event was identified in 1978 that was observed by an industry drifter. The retreat can now be estimated from Seasat altimetry.

A total of 19 separation events and retreats have been identified in the “pre-altimetry” record spanning July 1978 through 1991.
Seasat Jul-Aug 1978: Loop Current and Eddy
Pathfinder AVHRR
Sample HMI Eddy Watch Report
LCE Separation & Retreat Latitude: 34-year Record

Pre-Altimetry

Altimetry

Table 1. Loop Current eddy separation period and retreat latitude from the pre-1992 observational record.

<table>
<thead>
<tr>
<th>Year-Letter</th>
<th>Industry Name</th>
<th>Source* and Separation Date</th>
<th>Separation Period (days)</th>
<th>Retreat Latitude (^N)</th>
<th>Confirmation Datasets</th>
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<tr>
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<td>D 15-Jul-78</td>
<td></td>
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<td>Seasat/Drifter</td>
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<td>2</td>
<td>1980a</td>
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<td>C 16-May-80</td>
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<td>4</td>
<td>1980c</td>
<td>C 08-Aug-80</td>
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<td>5</td>
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<td>25.50</td>
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<td>9</td>
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<td>Arnold H 28-Aug-84</td>
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*Source Key: D – Drifter, C – color, A – AVHRR SST, H – HMI/EddyWatch

Table 3. Loop Current eddy separation period and retreat latitude from the altimetric record – 1992 through June 2012.

<table>
<thead>
<tr>
<th>Year-Letter</th>
<th>Industry Name</th>
<th>Separation Date</th>
<th>Separation Period (days)</th>
<th>Previous Retreat Latitude</th>
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<td>Icarus</td>
<td>Feb-12</td>
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34-Year LCE Separation Monthly Histogram
Circular Statistics 2-Mean Cluster Analysis
Randomization Significance Test

Altimeter Record: 30 Separation Events
Remote Sensing for Off Shore Oil and Gas Industry
Loop Current and Drilling Platform
Deepwater Horizon Rig

A sister rig, the Nautilus, being transported on a Heavy-Lift vessel

L and R, the Deepwater Horizon on location in better days
True Color MODIS Image: May 17
Deep Water Horizon Oil Spill

4 On April 20, 2010 the Macondo Prospect oil well experienced a massive blowout, causing the explosion and collapse of the Deepwater Horizon oil rig, 77 km southeast of the Mississippi River Delta, Louisiana in 1667 meters of water.

4 17 workers are injured and 11 workers go missing and are presumed dead.

4 The oil gushed into the Gulf from 22 April to 15 July, releasing approximately 800 million liters of oil to which BP added 1.84 million gallons of dispersant.

4 Real-time satellite imagery using visible, infrared and radar measurements were essential for tracking the dispersed surface oil across large areas of the Gulf of Mexico (GOM) as well as the ocean currents impacting its motion.
GOES Movie: April 26 through May 28
Horizon Deepwater Oil Spill

Estimated Total Spill
- 5 million barrels
- 800,000 m$^3$… or just 1/30 sec of LC flow assuming a transport of 24 Sverdrups.
- Animation on upper right is from New York Times.
- Animation on the lower right shows particles released at the spill site and advected by surface geostrophic flow calculated from near real-time SSH maps.
Simulated Oil Particle Tracking

4 Daily gridded velocity fields were obtained from hindcast gridded SSH maps using a geostrophic flow approximation on an $f$-plane with central finite differencing.

4 Velocities needed to compute the particle paths were interpolated from the gridded velocity fields using tricubic interpolation in lat, lon, and time.

4 The particle positions were integrated through time using a second order Runge-Kutta (RK2) method.

4 Twenty five particles were seeded in a patch 0.2 x 0.2 degrees centered on the oil leak every hour over the integration period.
Simulated Spill using Altimetry
Hurricane Intensification
Rapid Hurricane Intensification

Rapid hurricane intensification occurs in the Gulf of Mexico because of deep layers of warm current associated with the Loop Current and Loop Current eddies.

Suspected in the 1969 Hurricane Camille.

Observed and verified by modeling studies of the 1995 Hurricane Opal.

Satellite altimetry estimates of “heat potential” associated with subsurface warm layers were used operationally during Katrina, Rita and Wilma by the National Hurricane Center.
A tale of three storms … or why is the Loop Current important?

- **Four** land-falling Gulf coast hurricanes in 2005 with damages totaling in excess of $100 Billion.

- The only Atlantic season on record where three Cat 5 hurricanes occurred in a single season.
The 2005 hurricane season was the most costly on record with estimated damages in the U.S. of over $100 Billion:

- Dennis $2.2 Billion
- Katrina $80 Billion
- Rita $9.4 Billion
- Wilma $14.4 Billion
GOES-12 SST Composite with SSH Overlaid

Katrina Path

Maximum sustained winds (mph)
CCAR SSH Map Overlaid with Katrina Path/Sustained Winds
Before Katrina, Hurricane Camille was the hurricane by which all Gulf-coast hurricanes were measured:

Category 5 at landfall with 190 mph maximum sustained winds.
Landfall pressure was 909 mbar. Only the Labor Day Hurricane of 1935 was lower (895 mbar).

Over 20 foot storm surge from Pass Christian to Biloxi, the highest storm surge ever measured until Katrina.

At least 150 dead in Mississippi. Another 150 killed in flooding caused by Camille in Appalachian Mountains.
1969 Hurricane Camille

- Category 5 at landfall near Pass Christian on August 18, 1969.
- Hindcast 1-D modeling studies implicates Loop Current in the rapid intensification and severe strength.

From *Divine Wind: The History and Science of Hurricanes* by Kerry Emmanuel
Tropical Cyclone Heat Potential: Sept 22, 2005

Image Credit: Gustavo Goni, NOAA
Rita Wednesday 9/21 10 AM CDT

CU/CCAR Sea Surface Height(cm) 09/20
NWS Forecasted Hurricane Rita Track 10 AM CDT Wed 9/21
Sustained Wind Speeds in MPH
Rita Thursday 9/22 4pm CDT
Rita Friday 9/23 10am CDT
Rita Friday 9/21 4pm CDT

CU/CCAR Sea Surface Height(cm) 09/22
NWS Forecasted Hurricane Rita Track
Location at 4 PM CDT Fri 9/23
Sustained Wind Speeds in MPH

Eddy Vortex
Loop Current

Colorado Center for Astrodynamics Research
University of Colorado at Boulder

ATOC Ocean Seminar
November 11, 2013
Rita Friday 9/23 10pm CDT
Thanks!