Multiscale flows in the Gulf of Mexico: from oil dispersion to coldwater coral evolution and carbon drawdown
Underlying Research Theme

Understand the interplay of **mesoscale and submesoscale circulations**, and their **seamless impact** at all temporal scales on the marine ecosystem and climate using modeling and (here indirect) observations.

- Ocean mesoscale: 10 km - 300 km; weeks – year
- Ocean submesoscale: 100m -10km (in this talk ≥1km); hours – days; prominent at vertical boundaries (ML – mixed layer, BBL – bottom boundary layer)
Oceanic space and time scales distribution

adapted from Chelton, 2001
Below ~3 km rotation and stratification are still important but are not asymptotically overwhelming

Ageostrophic motions cannot be neglected near vertical boundaries (surface, bottom)
The energy budget in the ocean
adapted from Wunsch and Ferrari, 2004

TIDES 3.5 TW
- INTERNAL TIDES 0.1 EJ
- SURFACE WAVES/TURBULENCE 11EJ (10^{18})
- INTERNAL WAVES 14EJ
- OPEN OCEAN MIXING
- BOUNDARY TURBULENCE
- SHELVES

WINDS ~21 TW
- UPPER OCEAN MIXING

HEATING/COOLING
- MESOSCALE EDDIES 13EJ
- LOSS OF BALANCE?

GENERAL CIRCULATION 20 YJ (10^{24})
- BOTTOM DRAG

E – P
- GEOTHERMAL

3D TURBULENCE/DISSIPATION MAINTENANCE OF ABYSSAL STRATIFICATION

2.6 TW
Observations in the Gulf of Mexico
MERCI MCI (Max. Chl Intensity)
Sargassum lines in 2005
(Gower et al., 2006)
Phytoplankton bloom around Antarctica

January 15, 2015. Modis AQUA
Photos taken by a commercial airline pilot between Canada and Greenland in early April, 2015.

The large eddy has a diameter of ~ 200 km.
• **Limited measurements** (in the Gulf of Mexico: Carthe – carthe.org – drifter experiments; Poje et al., 2014; D’Asaro et al., 2018 PNAS)

• Most progress through modeling using nested techniques to investigate finer and finer scales

• **Approaching the limits of hydrostatic models**
Why Submesoscale dynamics are prominent near the ocean vertical boundaries?

✓ Ocean interior: when a mesoscale circulation induces locally convergence through density gradients → an overturning circulation develops to smooth the density gradients and restore the geostrophic balance.

✓ Ocean vertical boundaries (surface and bottom): at convergence regions where waters with different densities meet, the overturning circulation is purely horizontal → the convergence of density surfaces accelerates → frontogenesis occurs, $R_o$ grows, upwelling and downwelling velocities on the sides of the front grow, submesoscale instabilities can develop.

See Levy et al., GRL 2012
1. PATTERN FORMATION AND SUBMESOSCALES: horizontal mixing and oil dispersion

At the surface \( w = \frac{D\eta}{Dt} \) only. Immediately below Ekman term (due to wind forcing), ageostrophic contributions, stretching and tilting terms reach their max values (Koszalka, Bracco et al., JGR 2009)

\[ \max \frac{\partial w}{\partial z} \]

max lateral convergence:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = - \frac{\partial w}{\partial z} \]

frontogenesis – but needs density gradients

\[ F = \frac{D|\nabla h\rho|^2}{Dt} = Q \cdot \nabla h\rho \]

\[ Q = (Q_1, Q_2) = -\left( \frac{\partial u}{\partial x} \frac{\partial \rho}{\partial x} + \frac{\partial v}{\partial x} \frac{\partial \rho}{\partial y}, \frac{\partial u}{\partial y} \frac{\partial \rho}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial \rho}{\partial y} \right) \]
SEASONAL DEPENDENCE
Instabilities

Four classes of instabilities generally implicated, often developing at fronts:

1. **Mixed-layer instability (MLI):** ageostrophic baroclinic instability that acts to constantly restatify the mixed-layer and develops at the scale of the local deformation radius. APE is needed, *strong seasonal cycling (parameterization available)*

2. **Gravitational instability:** may occur whenever the buoyancy frequency $N^2$ changes sign

3. **Symmetric instability (SI):** a change in sign of Ertel potential vorticity (EPV) is needed

4. **ageostrophic anticyclonic instability (AAI):** a change in sign of $(A-S)$ where $A$ is absolute vorticity defined as $A=f+\zeta$ and $S$ is strain rate is required
DENSITY GRADIENTS DEPENDENCE

Normalized relative vorticity ($\zeta/f$)

Sea surface salinity (SSS)

SSS lateral gradients

Normalized divergence ($\delta/f$)
IN THE ABSENCE OF RIVER INPUT

\[ F = \frac{D|\nabla_h \rho|^2}{Dt} = Q \cdot \nabla_h \rho \]

Luo et al., 2016 (see also Barkan et al., 2017)

AUG 2010 with river input

AUG 2010 without river input
The 2010 Deepwater Horizon oil spill
Sea of Marmara, Operational Land Imager on the Landsat 8
Phytoplankton bloom on May 17, 2015
2. PATTERN FORMATION AND SUBMESOSCALES:
Implications for vertical transport and carbon cycling
Modeling

• ROMS-Agrif at three different horizontal resolutions, 10 km, 5 km (all SCS) and 1 km (nested over 113°E–122°E, 17°N–25°N) split third-order upwind scheme, harmonic viscosity, linear bottom drag and KPP

• 6-hourly realistic forcing 2000-2008 (QSCAT/NCEP blended satellite wind and NCEP heat and fresh water fluxes 2000-2008); 20 yrs spin-up

• We find an eddy similar to that observed in January 2001
1km run

max for next high res. climate models

Zhong, Bracco et al, Scientific Reports, 2017
Standard deviation: modeled vs observed

Zhong, Bracco et al, Scientific Reports, 2017
Relevant for nutrient, carbon, oxygen uptake

Zhong, Bracco et al, Scientific Reports, 2017
Omand, D’Asaro et al., Science 2015 for observational evidence at high latitudes of POC export at eddy periphery. Estimated to contribute as much as ½ POC export in spring.
Implications for carbon cycling

Main point:
Large difference in POC flux between GC600 and AT357

Time series of POC flux collected from 2 sediment traps (black, GC600; green, AT357); Pink boxes indicate modeling periods, i.e., April/May; Sept/October 2012

Liu, Bracco, Passow, Elementa: Science of the Anthropocene, 2018
TOP: Sea surface height patterns from the Gulf of Mexico Coastal Ocean Observing System (GCOOS)

MIDDLE: Modeled sea surface height patterns

BOTTOM: Modeled surface salinity field

GC600 (black) and AT357 (green) sites are indicated. Major circulation features such as Loop Current and the (anticyclonic) Loop eddies are indicated.
\( \zeta/f \), averaged over the time over which the particles with various sinking velocities were at the surface.

See also: Omand, D'Asaro et al., Science 2015 for observational evidence at high latitudes of POC export at eddy’s periphery. Estimated to contribute as much as ½ POC export in spring.
Sinking time: Submesoscale convergence impacts

PDFs of the particles’ resident time in the water column, averaged on all ensemble members. Time required to reach traps along a straight line through sinking alone indicated by vertical lines.

PDF of flow vertical velocities at particles’ locations in upper 200 m for 30 md\(^{-1}\) case
3. PATTERN FORMATION AND SUBMESOSCALES: Transport near the ocean bottom

Near bottom normalized relative vorticity ($\zeta/f$)

Normalized near-bottom relative vorticity, $\zeta/f$. Instantaneous field

Bracco et al. Ocean Modelling 2016, 2018
Vertical velocities have to go to zero at the bottom -> horizontal shear layer near the bottom

Juxtaposition of along-slope frontal currents that are highly variable in speed and direction (very common in the Gulf of Mexico) -> lateral shear layers

The width of the layer depends on bathymetric slope; mostly unresolved at >= 5km horizontal resolution and partially resolved at ~ 1 km

Whenever high values of vorticity are achieved (\(\zeta/f >> 0.1\)) small scales eddies and filaments are generated through partially unbalanced instabilities

Bracco et al. Ocean Modelling 2016, 2018
Important differences in transport properties to the east and west of Mississippi Fan

Mean near bottom lateral speed

STD of near bottom lateral speed

Depth-integrated concentration of the tracer deployed at MC297 (black star) and GC600 3, 6 and 12 months after deployment. Note the different color scales! Implications for methane consumption confirmed by in-situ measurements over 6 years (Rogener, Bracco et al., Elementa 2018 in press)
Deep, cold water corals live at depths up to ~2,000 m. They are foundation species of the deep-sea benthos.
Leiopathes glaberrima: Genetic analysis over 10,000 generations: two sympatric lineages with restricted realized gene flow

Table 1. Comparisons of L. glaberrima population differentiation.

<table>
<thead>
<tr>
<th>A</th>
<th>Sum of Squares</th>
<th>Variance components</th>
<th>% variation</th>
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<tbody>
<tr>
<td>Among populations</td>
<td>101.04</td>
<td>0.48</td>
<td>13.57</td>
</tr>
<tr>
<td>Within populations</td>
<td>822.23</td>
<td>3.07</td>
<td>86.43</td>
</tr>
<tr>
<td>Total</td>
<td>923.27</td>
<td>3.55</td>
<td></td>
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Average Fst 0.136**

B

<table>
<thead>
<tr>
<th>GB299</th>
<th>GC140</th>
<th>VK826</th>
<th>VK906</th>
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<tbody>
<tr>
<td>0.000</td>
<td>0.012</td>
<td>0.169*</td>
<td>0.261*</td>
</tr>
<tr>
<td>0.136*</td>
<td>0.000</td>
<td>0.000</td>
<td>0.040*</td>
</tr>
<tr>
<td>0.212*</td>
<td>0.212*</td>
<td>0.000</td>
<td>0.000</td>
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Leiopathes glaberrima overall (A) and pairwise population differentiation (B) as estimated by an Analysis of Molecular Variance on Fst values in the northern Gulf of Mexico. P-values were estimated from 100 permutations and corrected for multiple comparisons (** p < 0.01).
Example of modeled connectivity for coral larvae of *Liopathes Glaberrima* at the four locations after 40 days and no mortality (TOP) and with a pelagic larval duration (PLD) of 20 days (BOTTOM).

Simulations help determining upper and lower limits of *Leiopathes glaberrima* larvae competency time - likely \(\approx 30\) days; definitively more than 10 days which is \(\sim\) larvae lifespan. This supports period of low metabolic activity (Graham et al., *Coral Reefs*, 2013).
**Callogorgia delta**

**PLD = 40 Days**

**Horizontal dispersal**

Bracco, Liu, Galaska, Herrera, Quattrini, In Prep.
Vertical dispersal

PLD = 40 Days
Genetic structuring with distance

Callogorgia delta
61,179 loci
Fst 0.0115-0.0691

Quattini et al 2015
Summary

Submesoscale circulations take **different shape and form** depending on mixed-layer depth, source of density gradients, near bottom circulation.

In the Gulf of Mexico they contributed to the oil convergence in 2010 + to the deep, narrow plume that formed at ~1,200 m depth, and to extremely patchy distribution of marine snow (impacts on corals). **SHORT TIME SCALES: HOURS TO MONTH**

Submesoscale induced vertical transport in eddies is much stronger if ageostrophic motions are accounted. With surface convergence has implications for ocean carbon and heat storage. POC sinking time can be significantly shorter than estimated by sinking velocities alone. Different submesoscale regimes in nearby regions along the continental slopes impact advection at the bottom.

**TIME-SCALE: YEARS TO DECADES**

Mesoscale/submesoscale mixing have contributed to the different evolution history of deep-water corals - and likely deep-water mussels (Faure et al., 2015) - along the continental slope in the Gulf of Mexico. No cosmopolitan distributions in this small, enclosed basin! Likely true for many coldwater mesophotic corals

**TIME SCALE: THOUSANDS OF YEARS**

Thank you

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