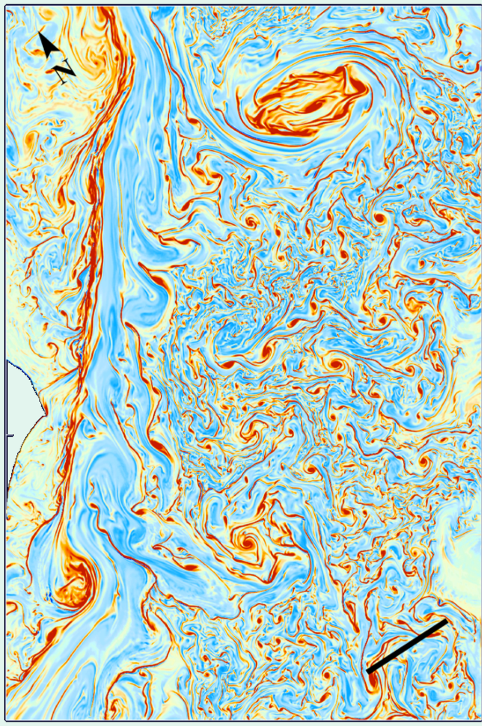
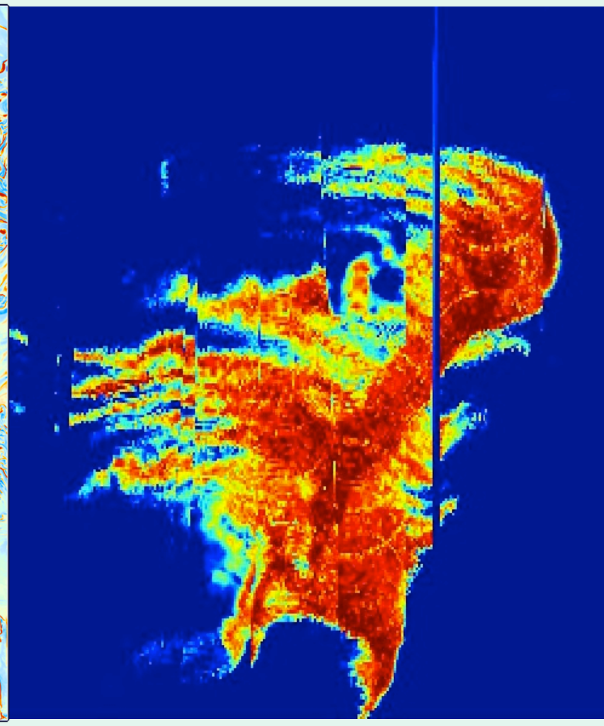
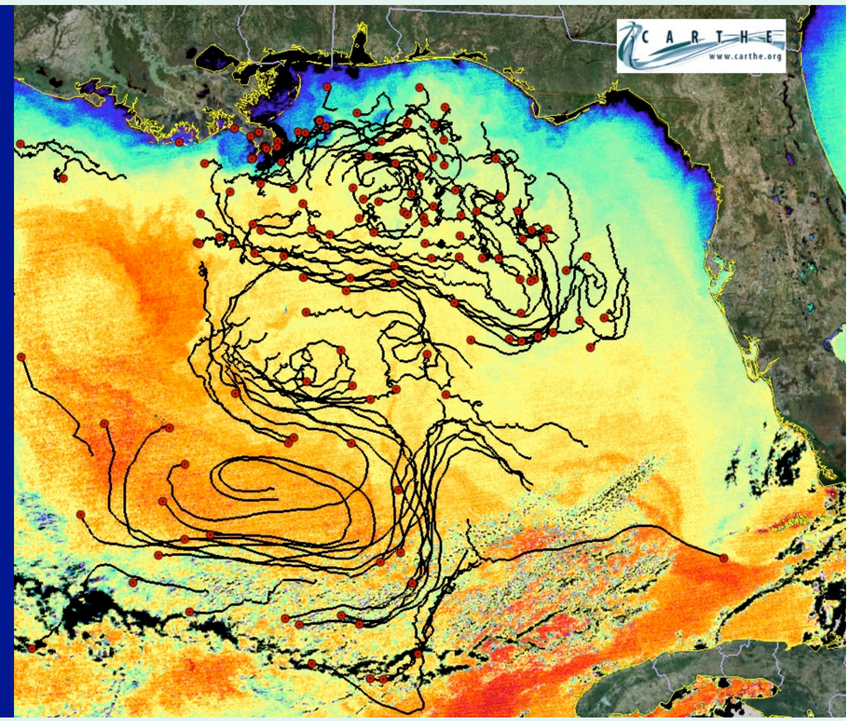
A Summary of Recent Submesoscale Programs: Lateral Mixing (LatMix) and Grand LAgrangian Deployment (GLAD)



ROMS submesoscale soup (Molemaker, McWilliams)



Air-borne LIDAR observation of dye (Concannon, Ledwell, Sundermeyer)

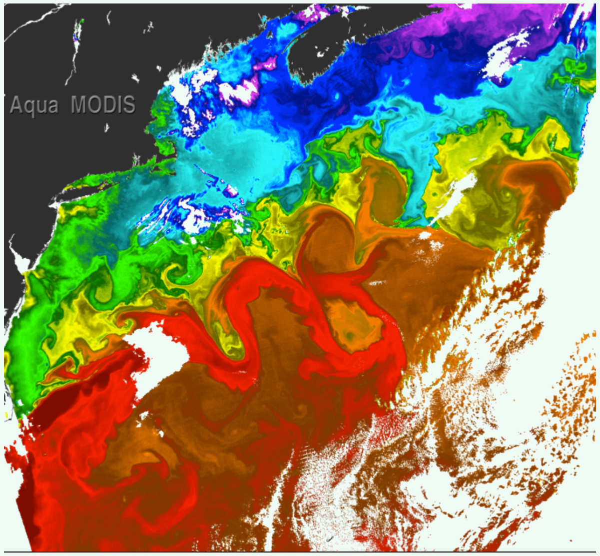


GLAD drifters in the GoM (Özgökmen and CARTHE)

Tamay Özgökmen, University of Miami

CLIVAR Summit, Annapolis, July 2013

A Dilemma of Geophysical Turbulence:



- Strongly-rotating, high aspect ratio flows: ~2D
- 2D energy cascade is mostly backwards (upscale)
- How do mesoscale features access dissipation?
  What is in between mesoscale and 3D small scales,
  100 m to 10 km? (McWilliams, 2000, 2008)
- How are *submesoscale* flows generated?
  What do they do? Are they important wrt mesoscale
  features? How do multi-scale interactions work?

Why are submesoscale flows important?

1) Energetics of ocean circulation: important for long-term computations; climate community.

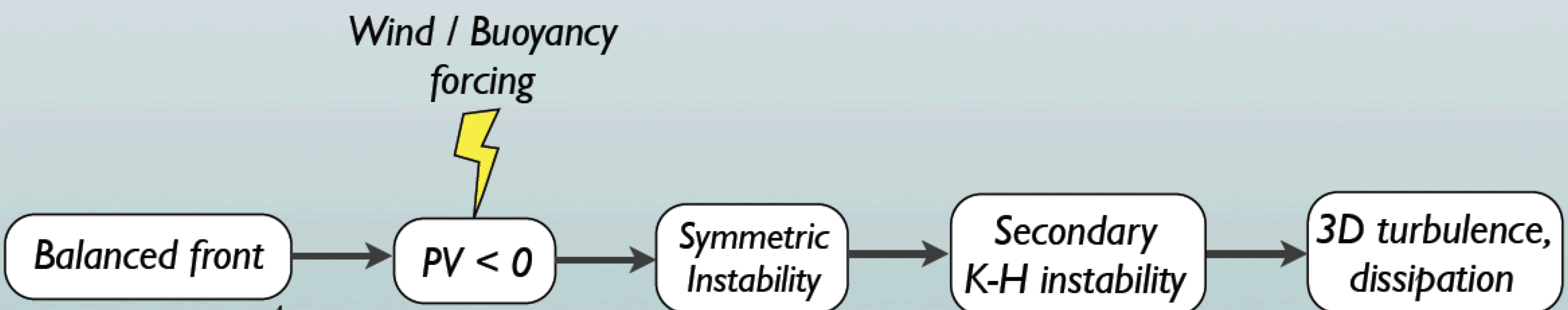
2) High vertical velocities induced by submesoscale processes affect vertical transport of biogeochemical tracers (Mahadevan and Tandon, 2006; Klein and LaPeyre, 2009); NSF/NASA.

3) Rapidly-evolving (hours) submesoscale flows may have a direct effect on naval operations (acoustics, submerged vehicles, mines and sensors), thus ONR interest.

4) Surface pollutant transport, e.g. DwH and predictive capability for response; oil spill community and GoMRI.

Upper Ocean Energy Budget

- Eddy stirring generates sharp density fronts (frontogenesis)
- Fronts can become unstable (baroclinic, symmetric instabilities)
- 3D turbulence feeds off of the frontal energy and mixes passive scalars



$$PV \simeq fN^2 - \frac{M^4}{f}$$

Taylor + Ferrari, 2010, JPO, **40**, 1222

What Physics Govern Lateral Mixing for 100 m to 10 km?

LatMix DRI Hypotheses:

Null Hypothesis: *Shear dispersion by inertia gravity waves.*

Hypothesis 1: *Vortical modes – coherent cortices formed by gravity wave breaking does the main stirring.*

Hypothesis 2: *Geostrophic turbulence – mesoscales generated by baroclinic instability dictate stirring over the submesoscale (non-local).*

Hypothesis 3: *Mixed layer instabilities (Fox-Kemper et al., 2008...) – ageostrophic submesoscale motions driven by mixed layer fronts.*

Two Major LatMix Experiments:

Summer cruise in 2011, three ships, Sargasso Sea

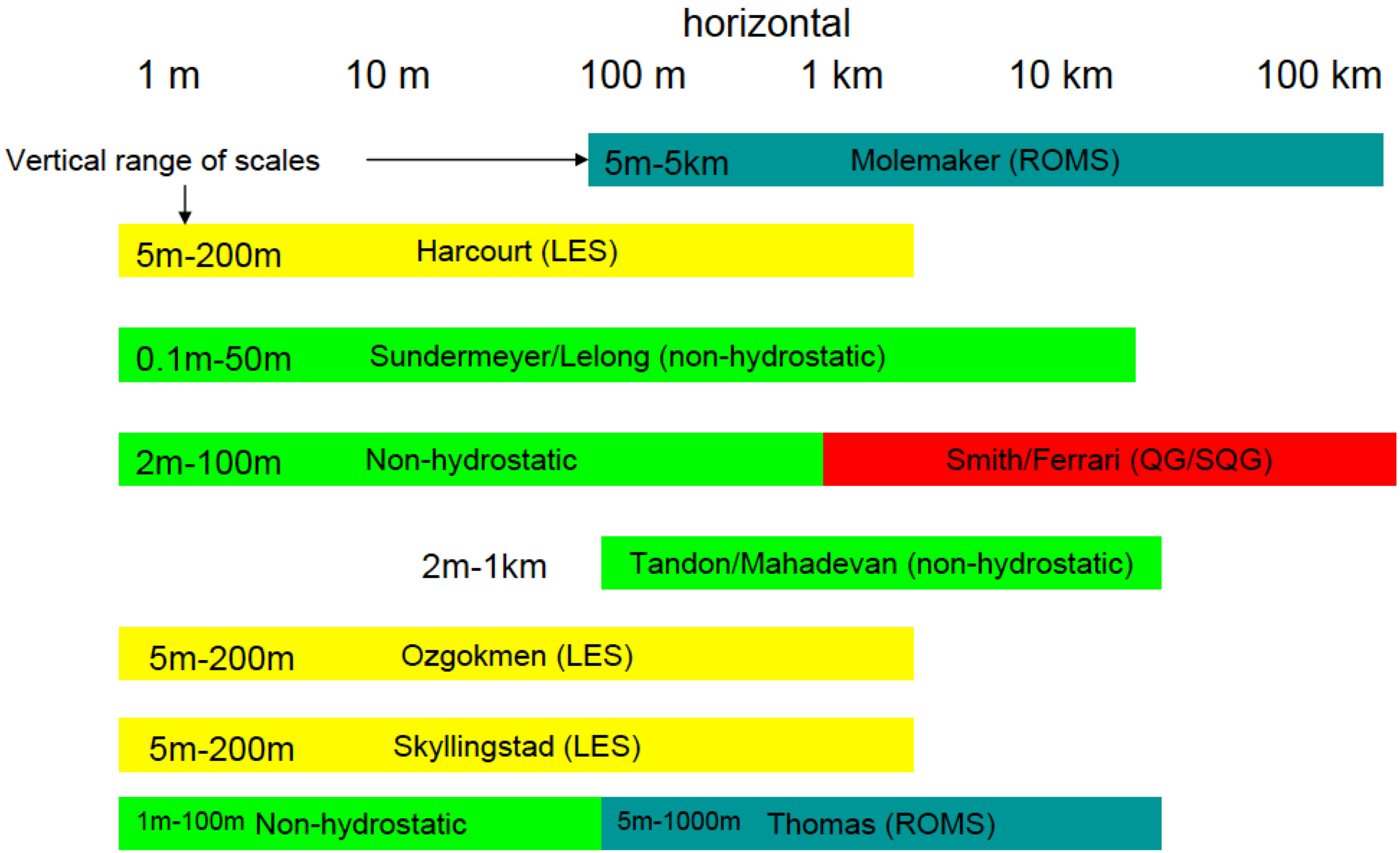
Winter cruise in 2012, two ships, Sargasso Sea and northern wall of the Gulf Stream

Observational Capabilities: Who & What

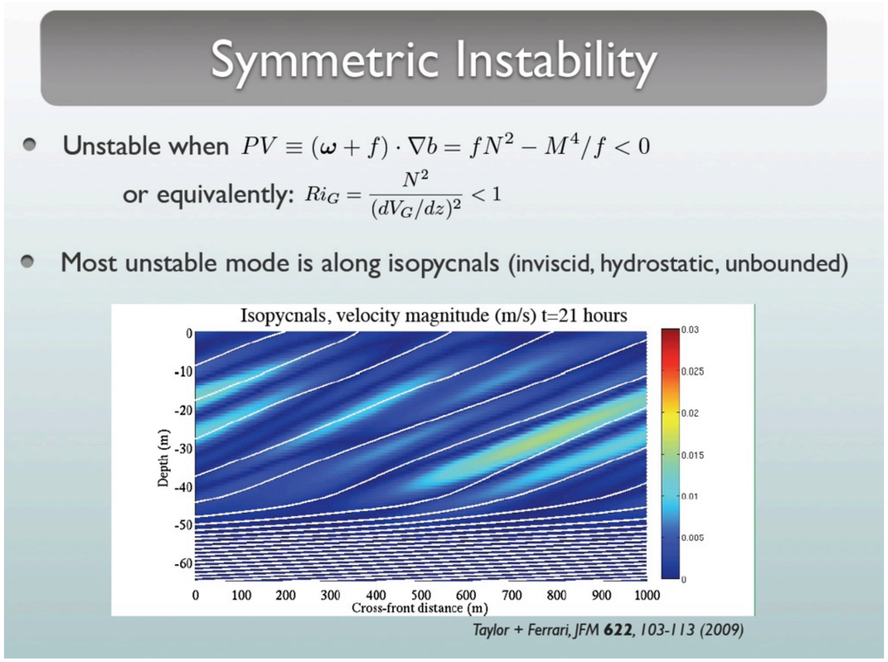
WHO	Platforms	Measurements	Resolution	Tow Speed	Notes
Ledwell Sundermeyer	Acrobat, drifters	T, S, N^2, dye	?	<4 kts	winch?, small boat sampling
Terray Concannon	LIDAR	dye	3 m along, 200 m swath, vert?	90 kts	
Levine	MVP, injection apparatus	T, S, N^2, dye	0.25–1.5 km along, vert?	6–12 kts,	winch
Klymak	MVP	T, S, N^2, DO, dye	1.5 km along, vert?	10 kts	winch
Lee	Triaxus	T, S, **u**, N^2, shear, dye	0.3-3.0 km	4-8 kts	winch
Kunze	Hammerhead	T, S, **u**, N^2, shear, χ, dye, obs, chl	100-200 m along, 10 m depth range	3-4 kts	winch
Sanford	20 EM/APEX floats	T, S, **u**, N^2, shear, χ, dye	100-m @ 10 cm/s 45 min return	~Lagr	Small boat recovery/deploy
D' Asaro	Lagrangian float	T, S, N^2, shear, w, w_z, dye	Isopycnal	~Lagr	Acoustic tracker on ship
Goodman	T-REMUS	T, S, **u**, N^2, shear, ε, χ, dye, obs, chl	25-200 m along, 0.5-1 m vert	2-5 kts	Small boat for recovery/deploy
Shearman Nash	4 Gliders	T, S, **u**, N^2, shear, ε, χ, dye, obs, chl	0.25 – 1.25 km along, 0.25 m vert	0.5–1 kts	

Modeling efforts in LatMix DRI

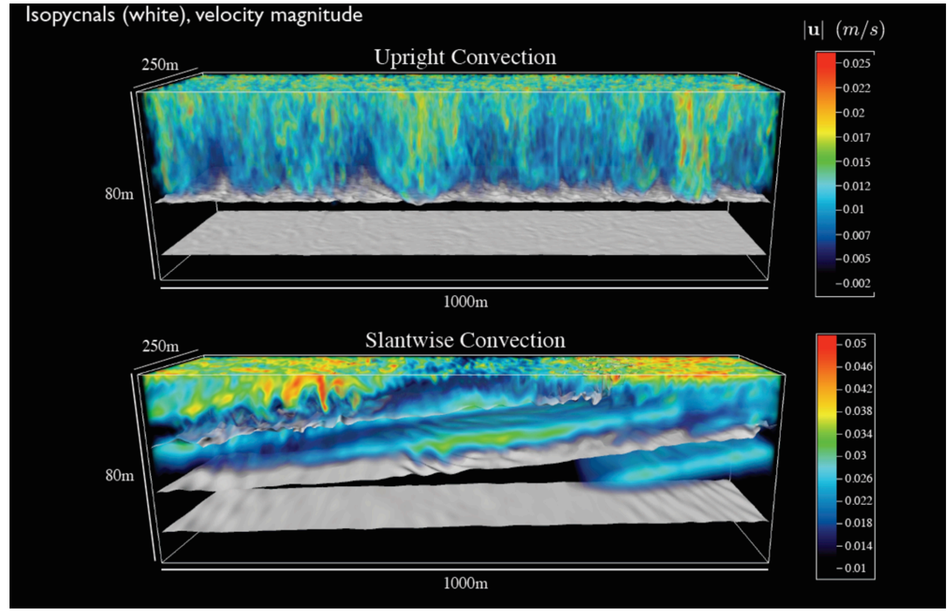
- Range of scales and models used:



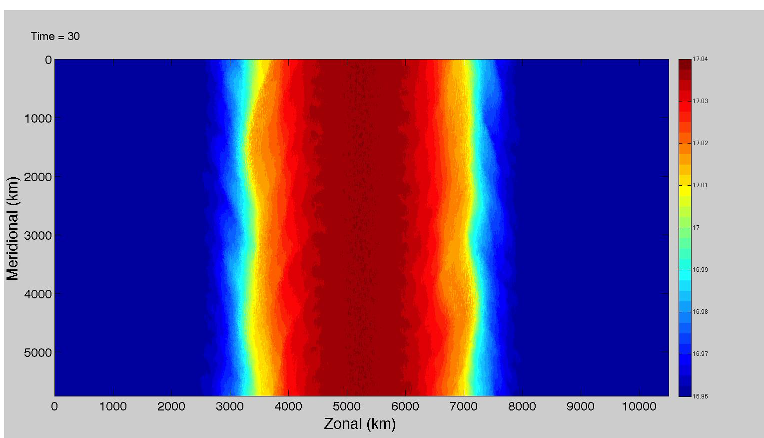
Examples of Nonhydrostatic Process Modeling:



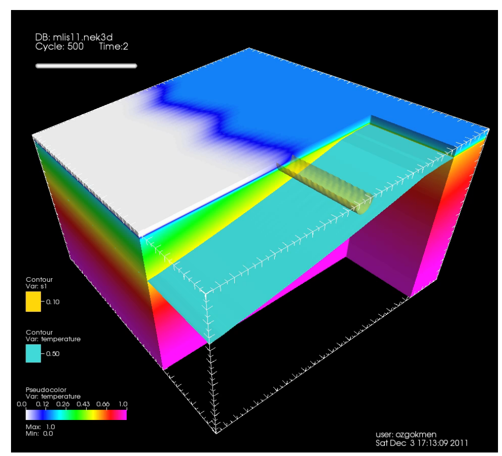
Symmetric instability: Taylor, Ferrari, Thomas



Multi-process LES: Filament with winds + Langmuir forcing (Skyllingstad & Samelson)

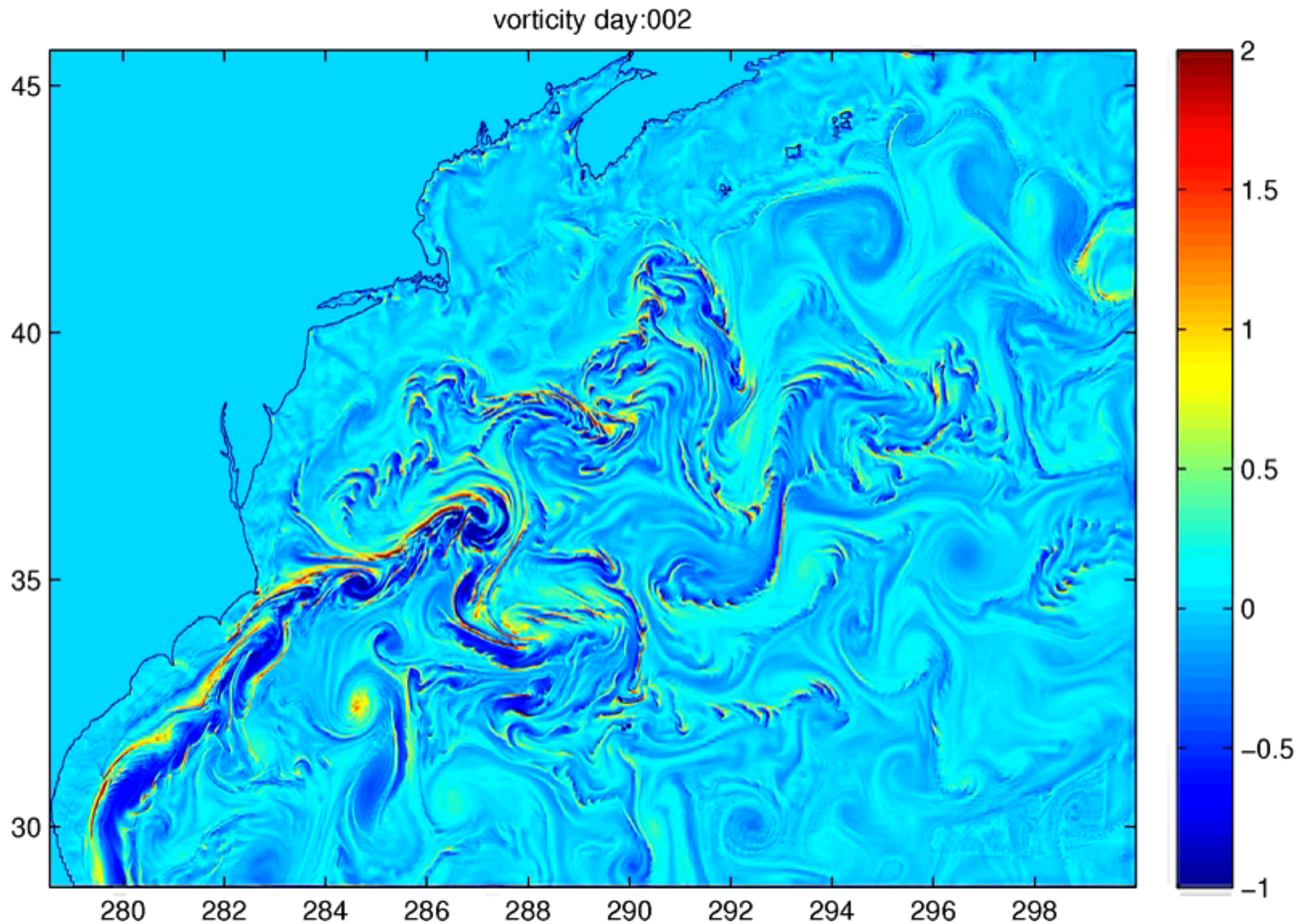


Multi-process LES: Mixed layer and deep baroclinic instability (Özgökmen)

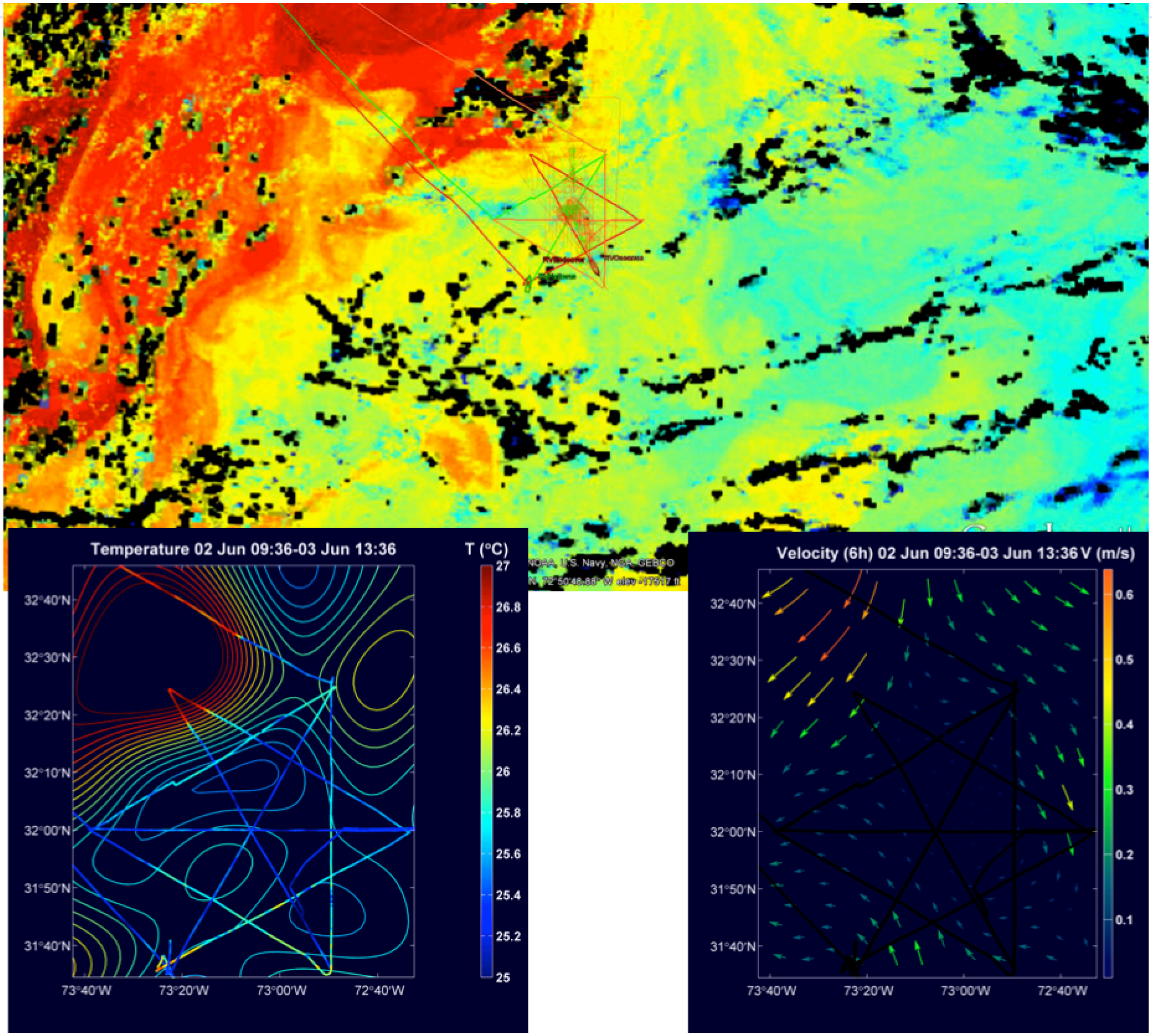


On the seasonality of submesoscales:

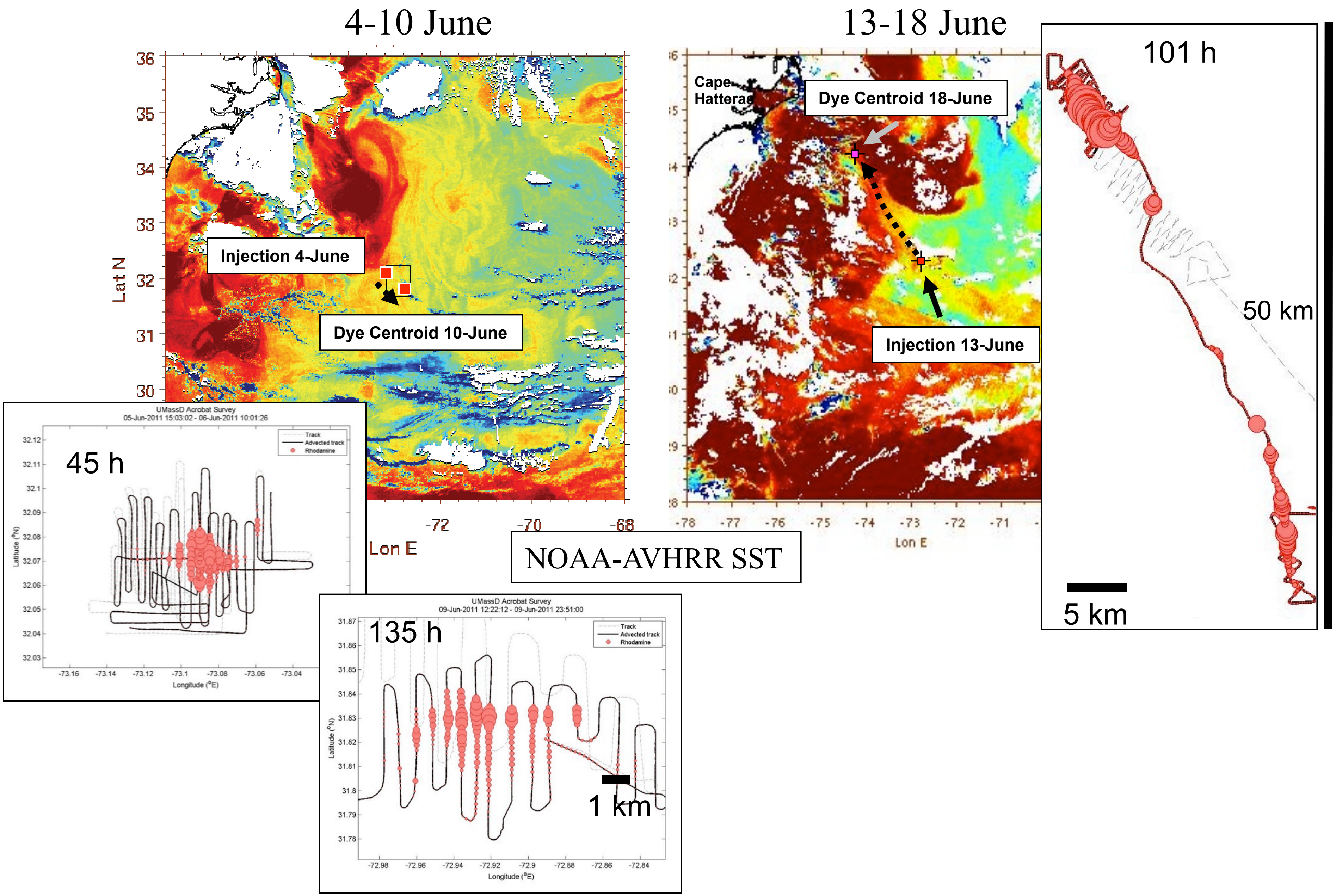
from 1/48 degree HYCOM (Mensa, Griffa, Özgökmen, 2013, in press)



Site 1 - Big Nothing: large-scale survey

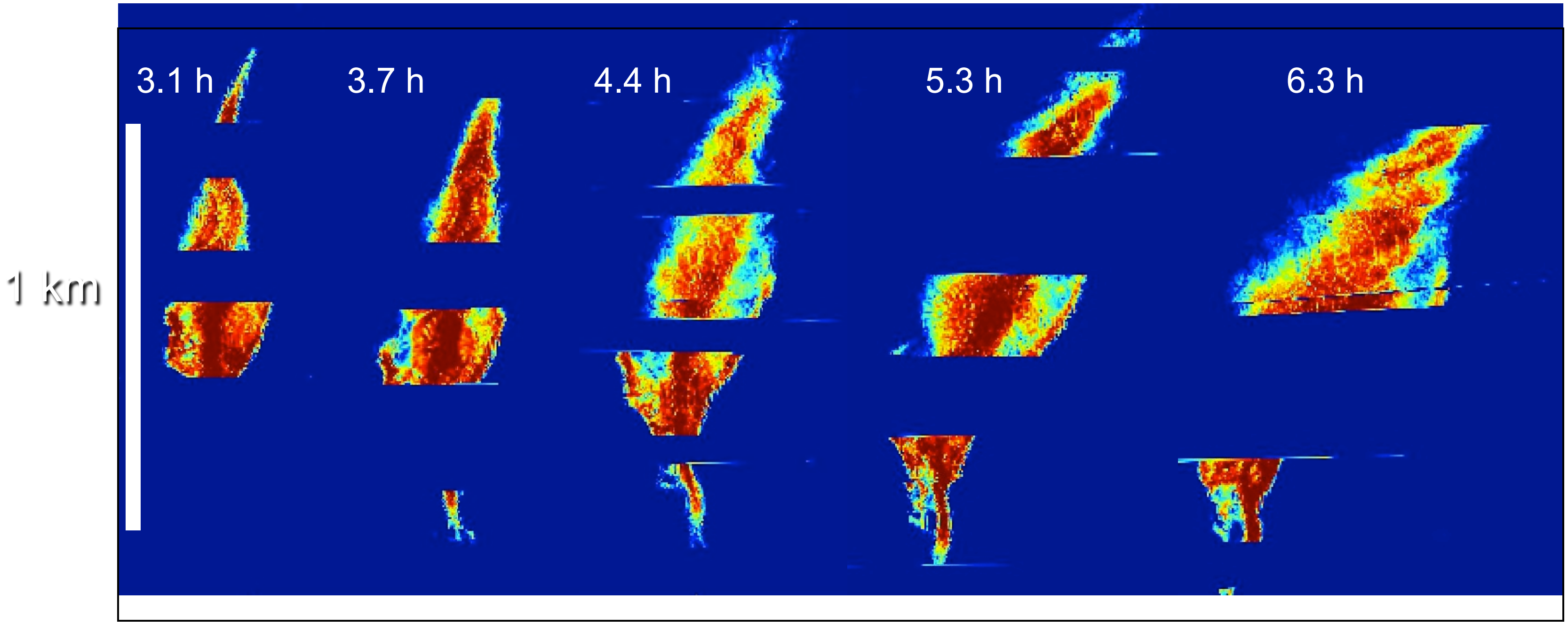


Ship-Based Dye Sampling for Summer 2011 Experiment (Ledwell, Sundermeyer, Levine)

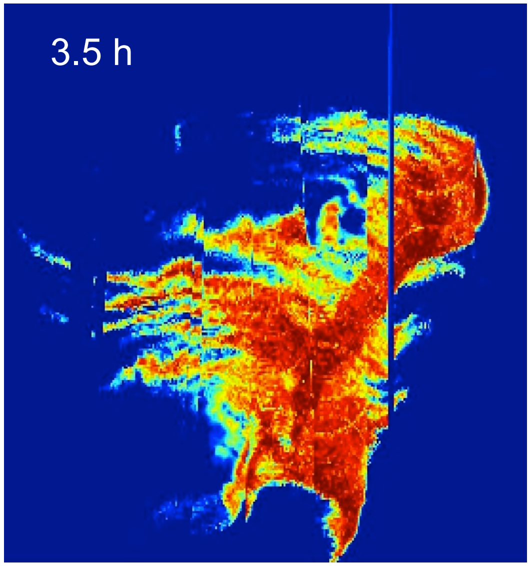


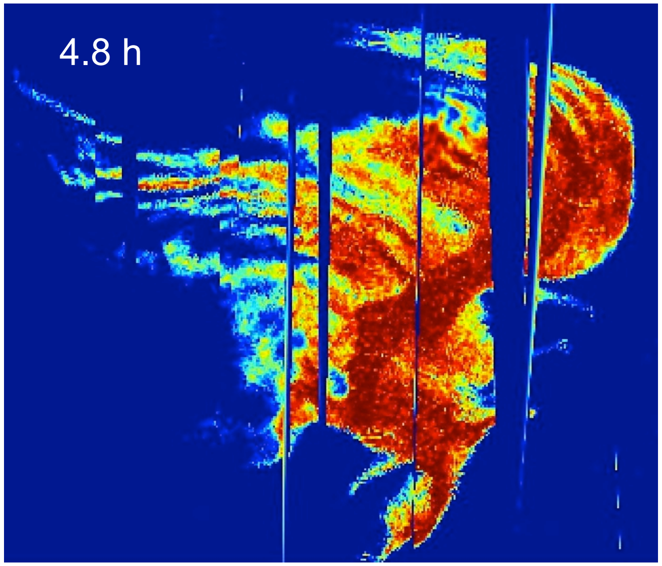
LatMix 2011 – June 10, Lidar Obs

Credit: Concannon, Ledwell, Sundermeyer

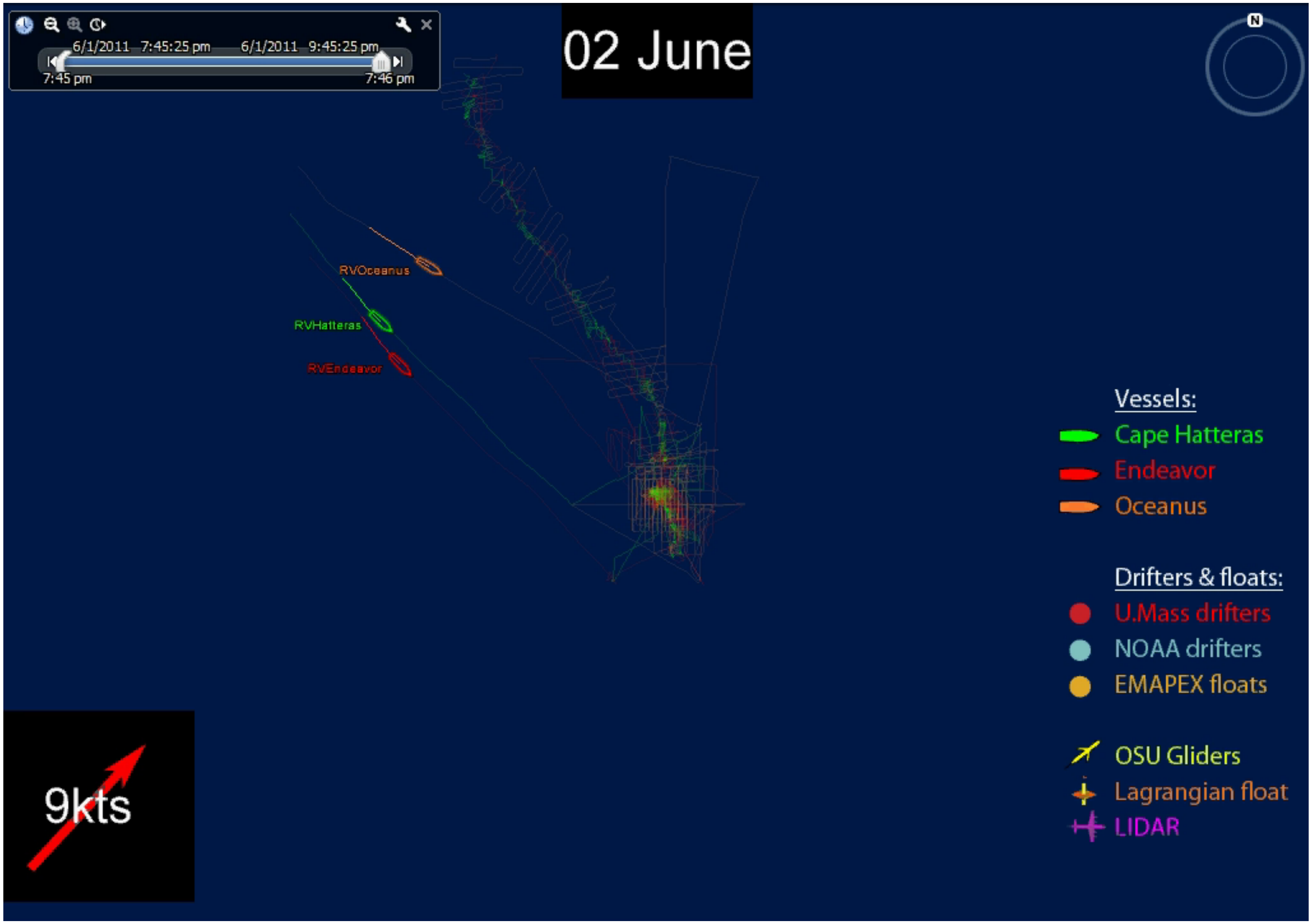


LatMix 2011 – June 15, Lidar Obs



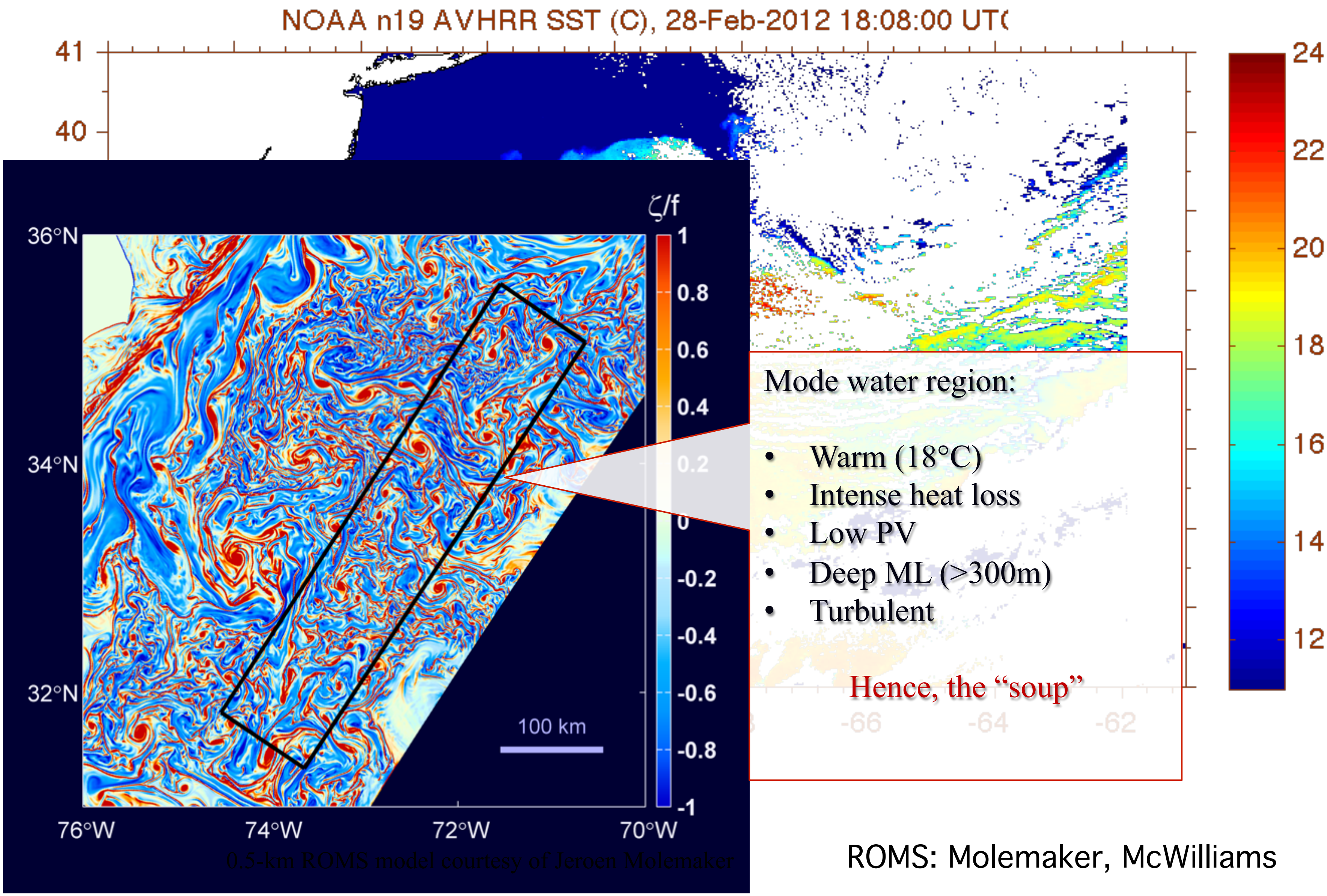


2011 Summer Latmix Expedition: 3 weeks in 60 secs



Credit: Andrey Shcherbina, Eric D'Asaro

LatMix 2012 Winter Expedition:
Fully developed submesoscale “soup” in Mode Water region?



Mode water region:

- Warm (18°C)
- Intense heat loss
- Low PV
- Deep ML (>300m)
- Turbulent

Hence, the “soup”

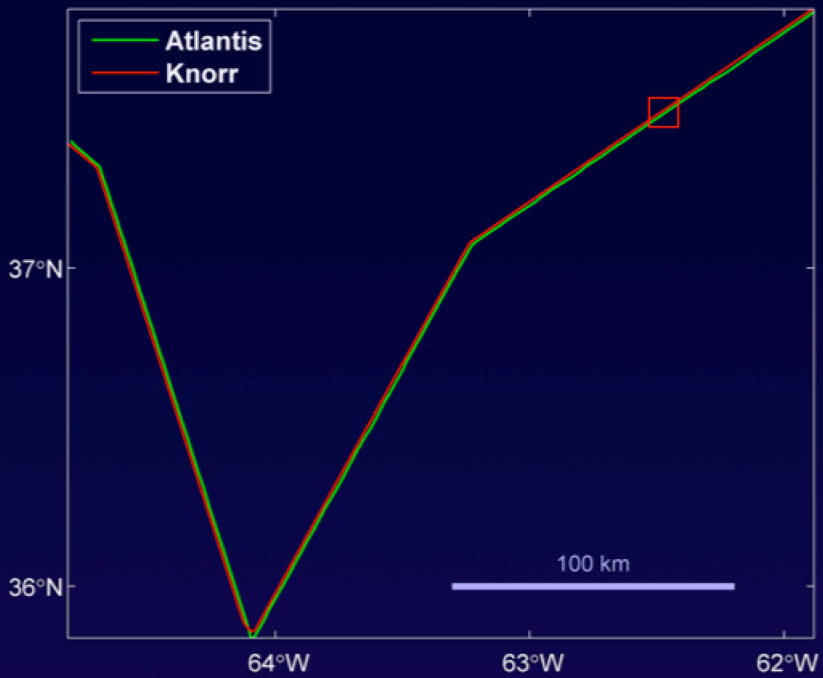
ROMS: Molemaker, McWilliams

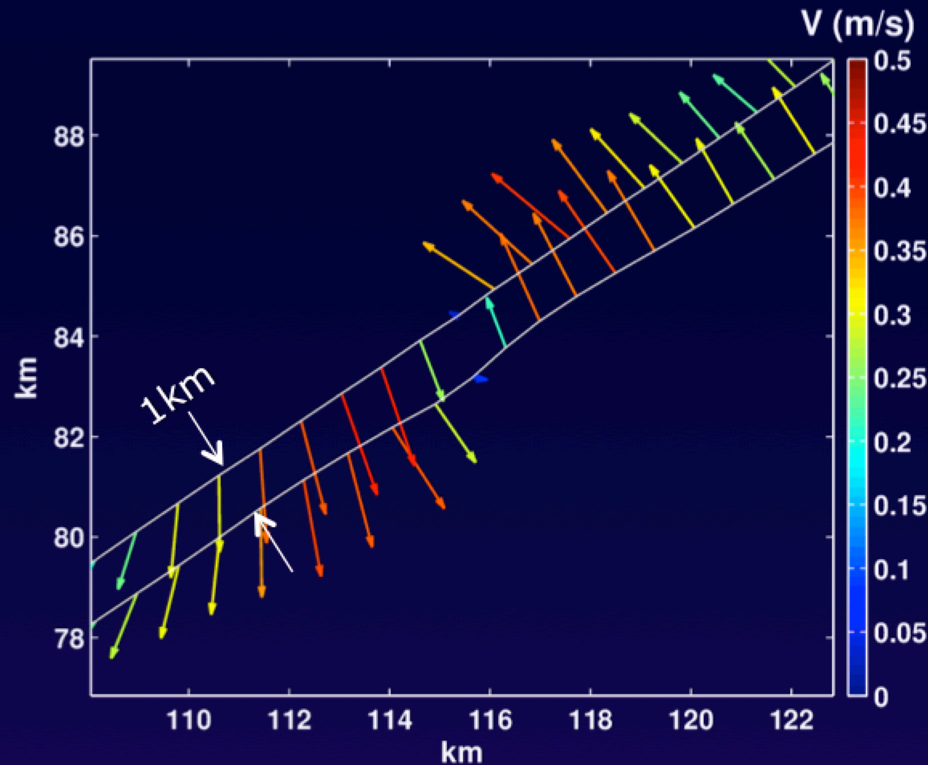
The "soup" in LatMix 2012

"I don't care if it exists or doesn't exist.
The question is whether we could detect it if it were there."
– Eric

First ever (?)
500-km long,
2 vessels, 2 towed-bodies,
full vorticity survey,
resolving at ~1km

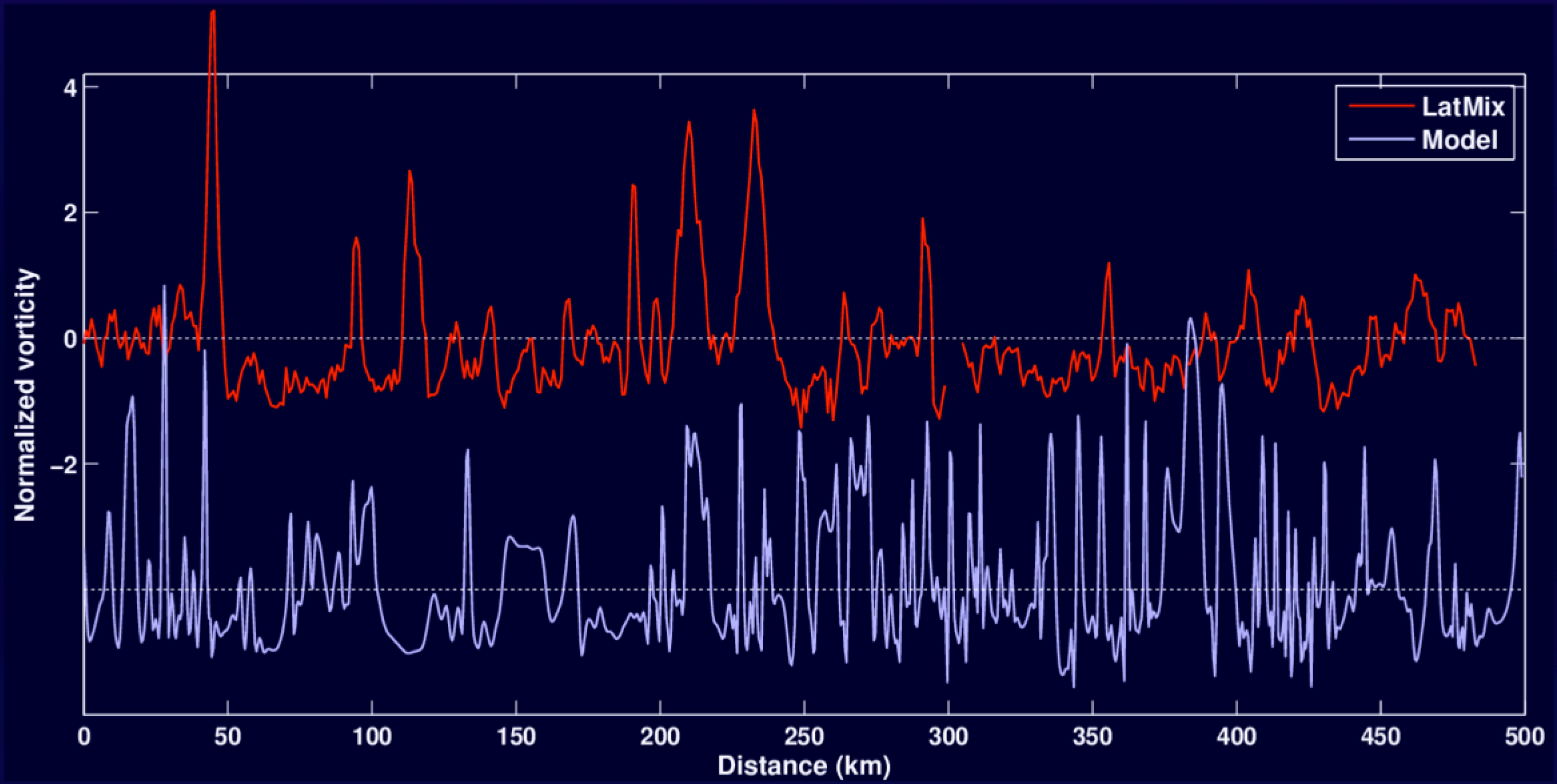
Credit: Shcherbina, D'Asaro, Lee, Klymak, Molemaker, McWilliams





Mixed layer vorticity

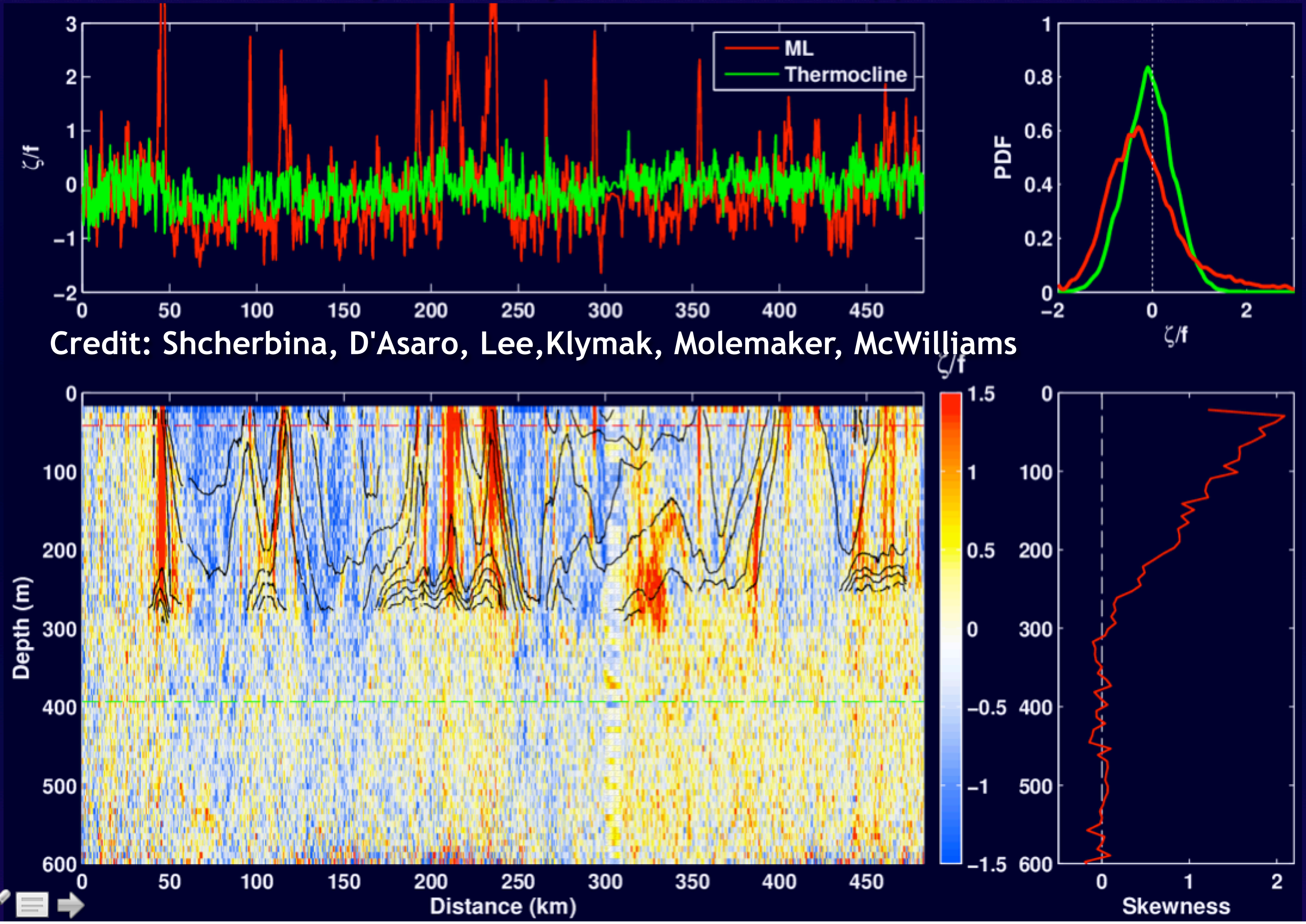
More intermittency in real life



Credit: Shcherbina, D'Asaro, Lee, Klymak, Molemaker, McWilliams

Details of vorticity distribution

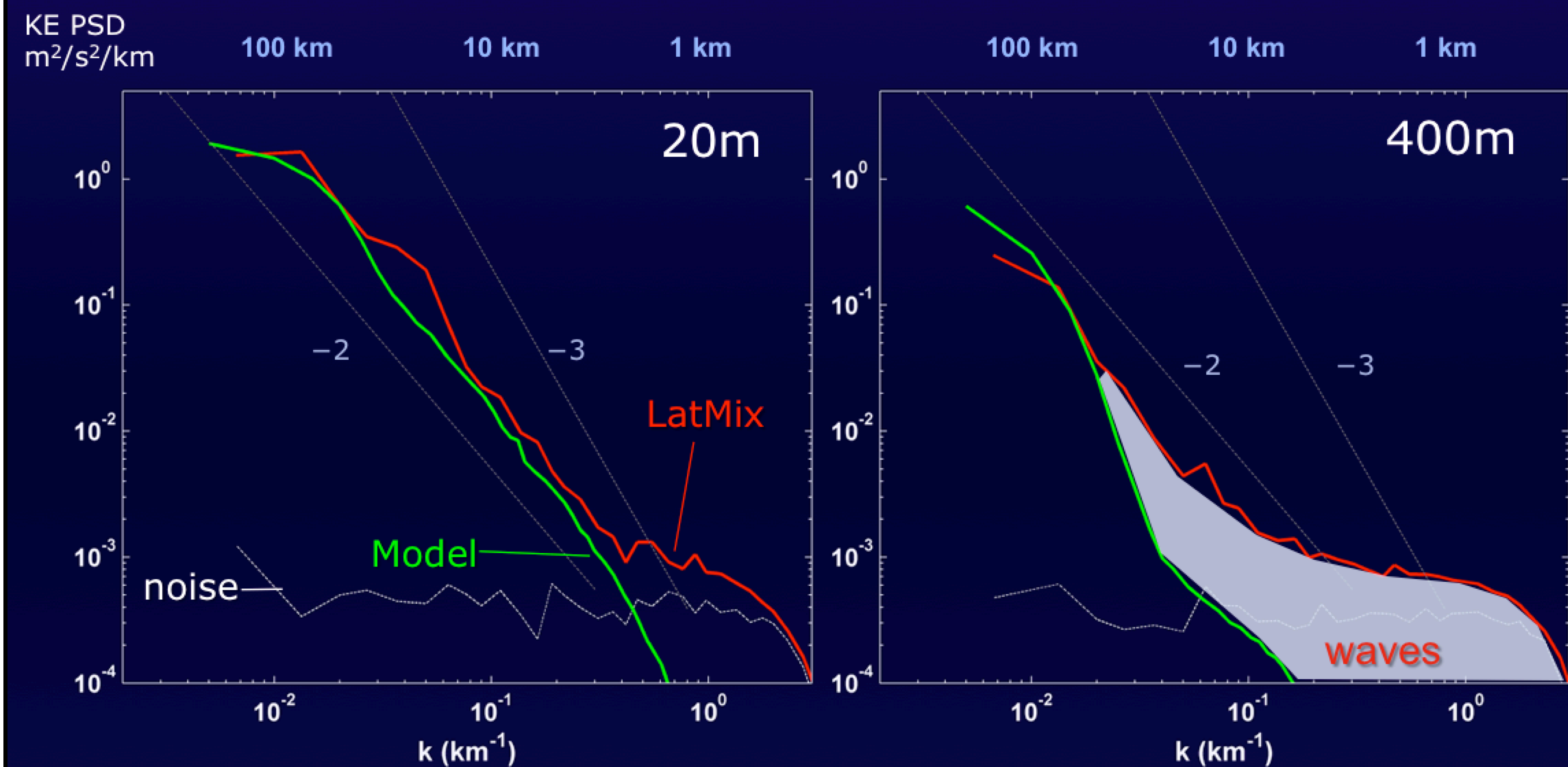
Vorticity variability confined to the upper 300m



Credit: Shcherbina, D'Asaro, Lee,Klymak, Molemaker, McWilliams

Kinetic energy spectra

Good agreement with the model (except internal wave contribution).

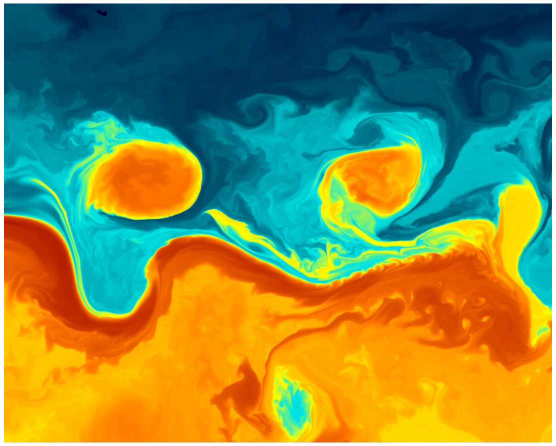


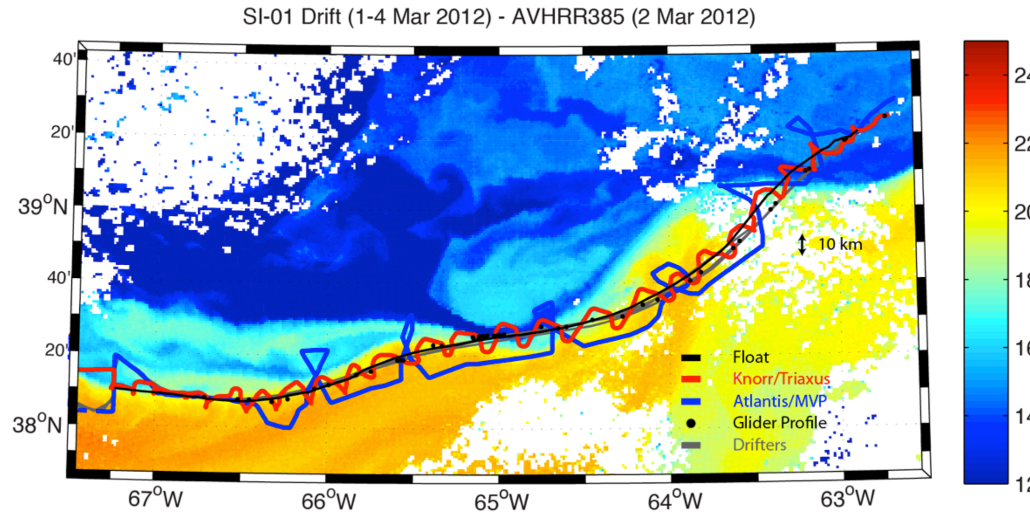
Credit: Shcherbina, D'Asaro, Lee, Klymak, Molemaker, McWilliams

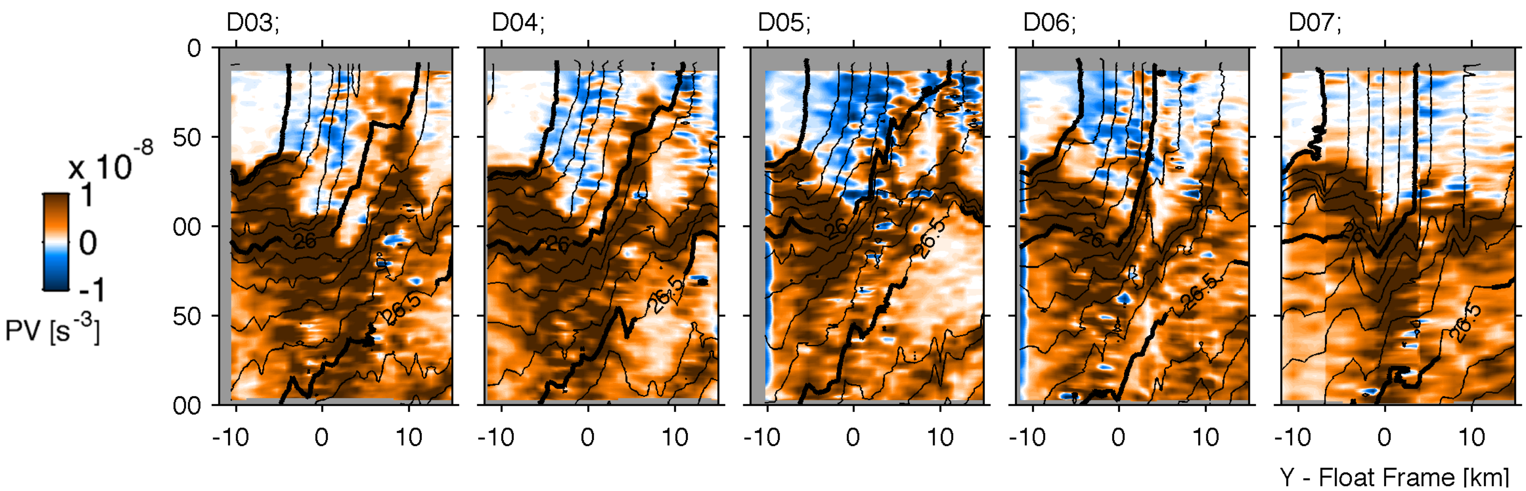
Model: 0.5-km ROMS (Jeroen)

Symmetric instability along Gulf Stream Northern Wall
Credit: Thomas, Lee

ROMS of GS north wall (Gula)







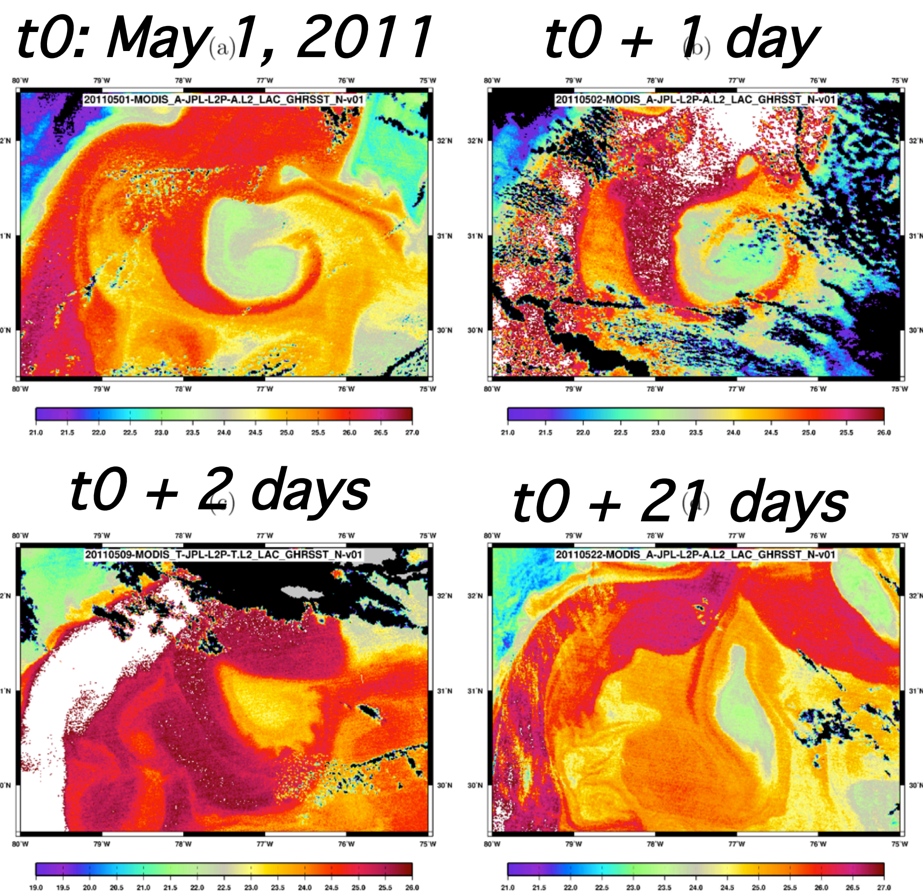
- The stratification in the boundary layer was stable, yet the Ertel potential vorticity:

$$PV = (\boldsymbol{\omega} + \mathbf{f}) \cdot \nabla b < 0$$

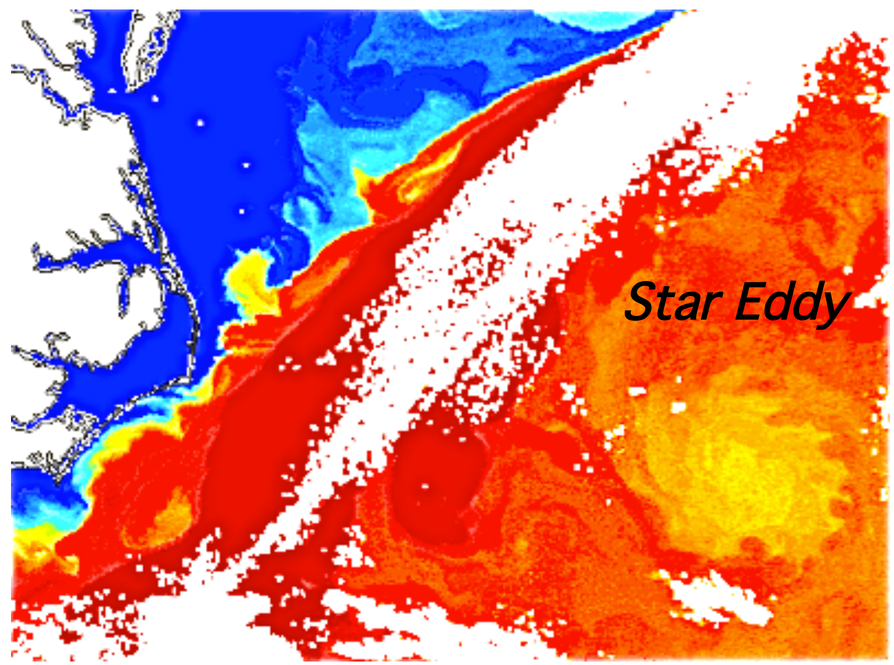
was negative; the flow satisfied the necessary conditions for symmetric instability.

Other Interesting Phenomena Encountered – Star/Wonder Eddies:

2011 Summer Cruise:

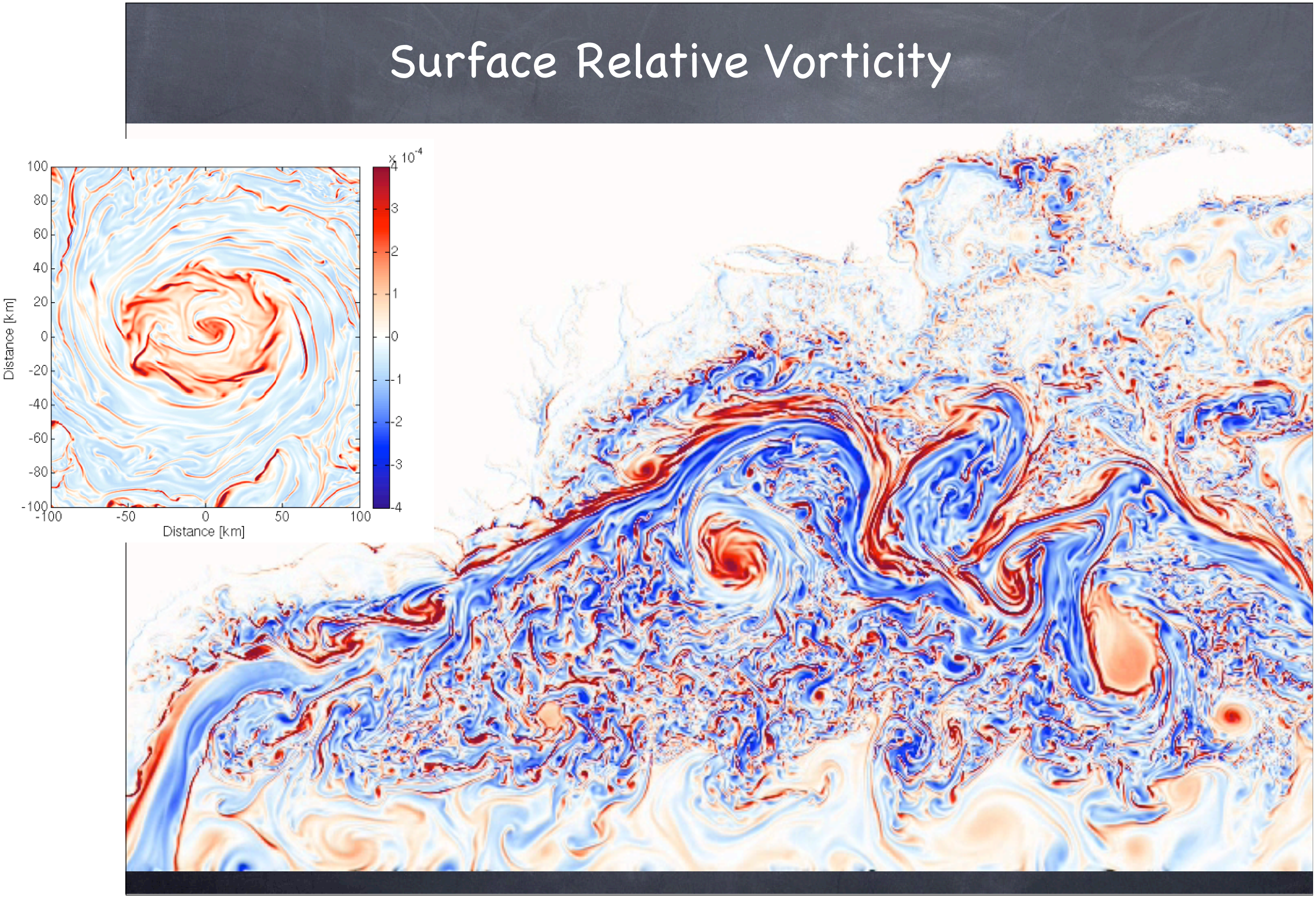


2012 Winter Cruise:



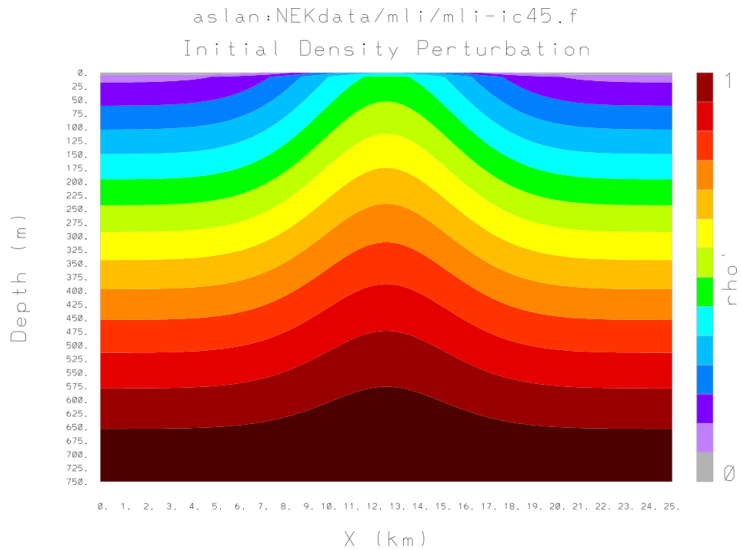
Credit: Hartcourt

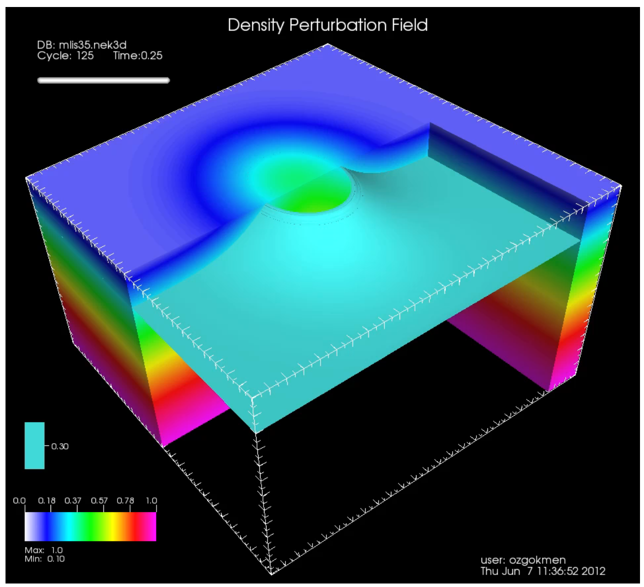
ROMS simulation (Molemaker, McWilliams)



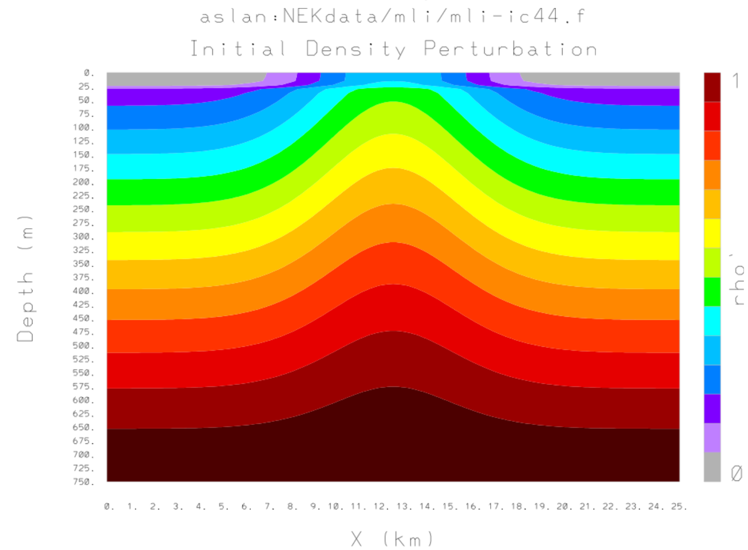
A Cyclone Protruding into the Mixed Layer: (Özgökmen)

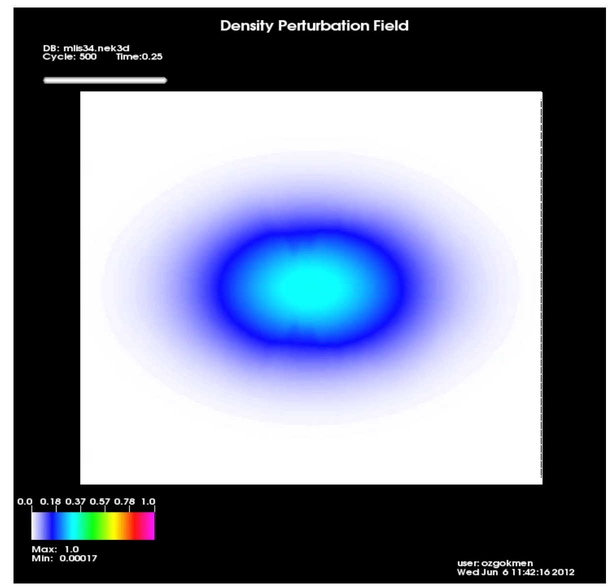
MLD=0 m



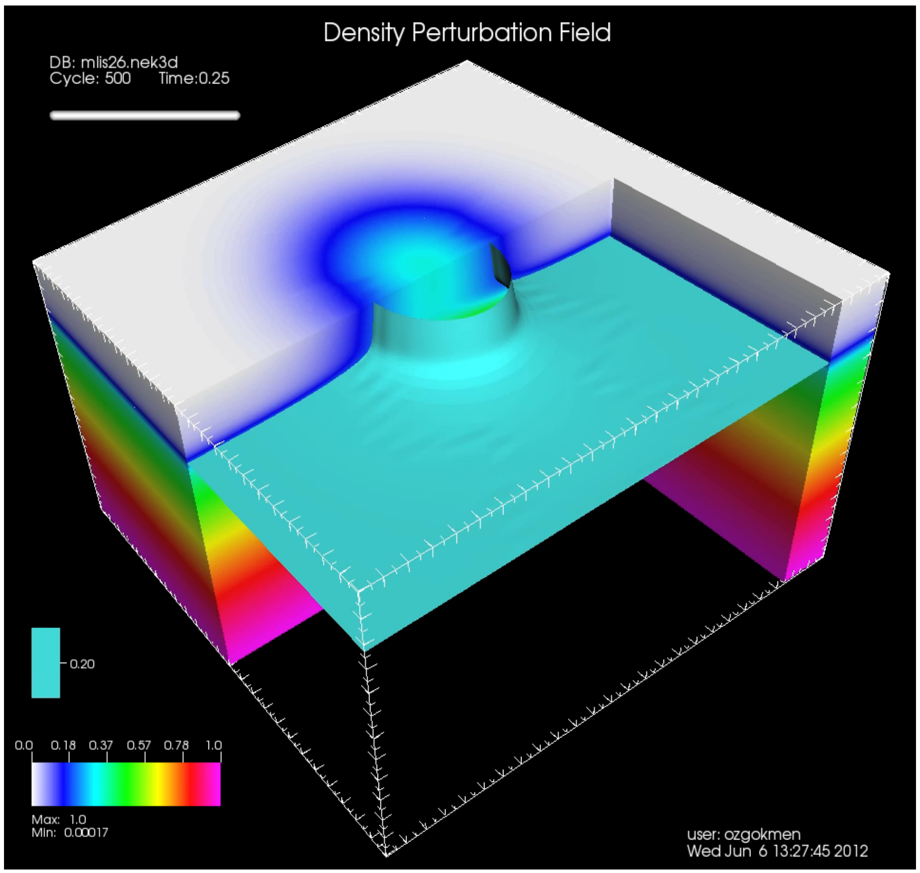


MLD=25 m

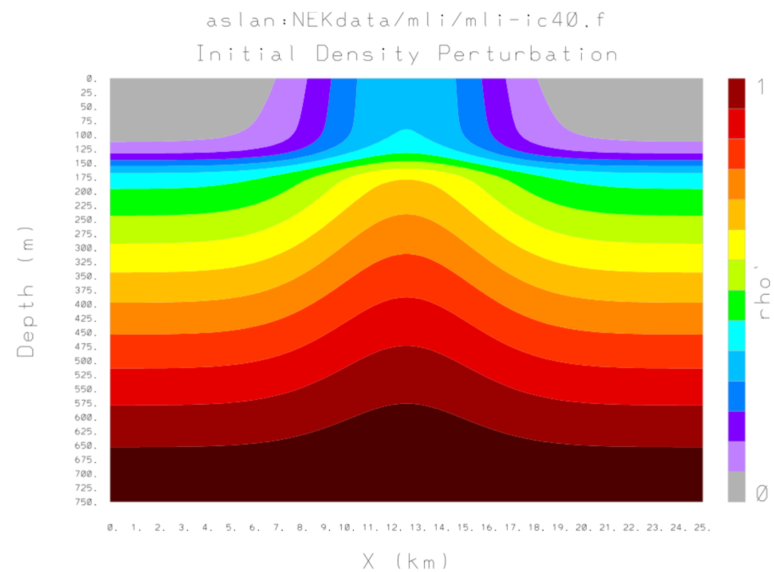




Deeper Mixed Layer for Stronger Submesocales:



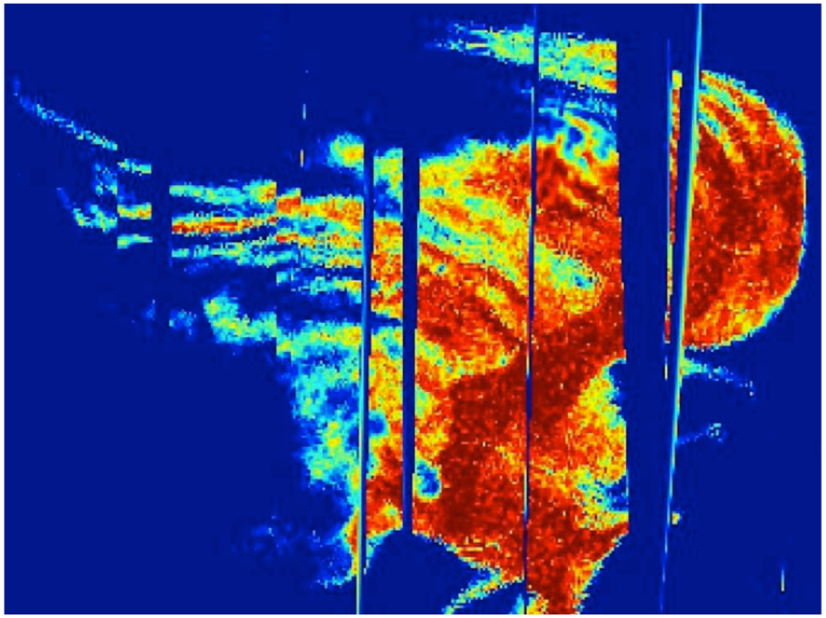
MLD=150 m



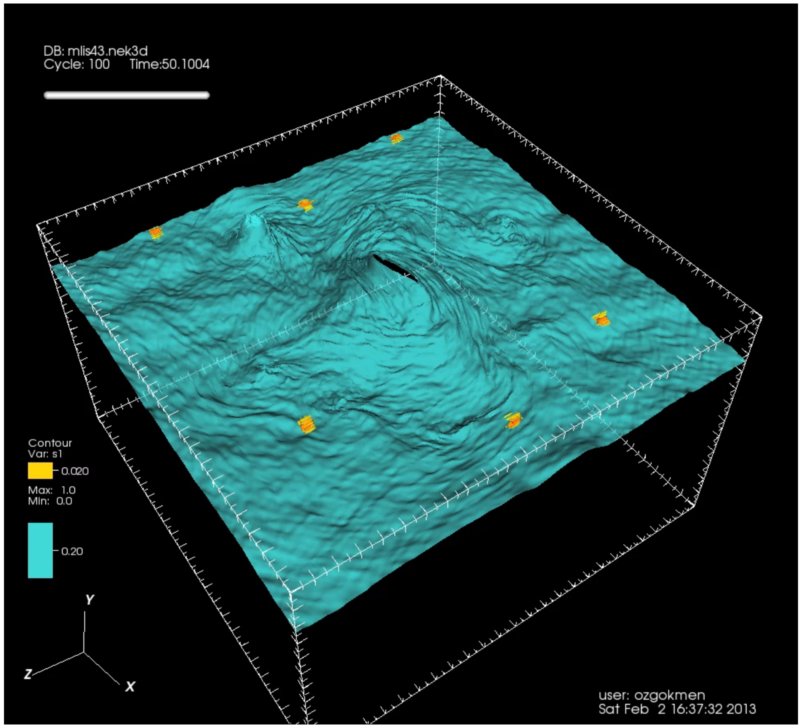
(Özgökmen)

Inertia Gravity Waves Below the Mixed Layer:

LIDAR Image of Tracer Patch Injected Just Below the Mixed Layer
(Ledwell, Sundermeyer, Concannon)



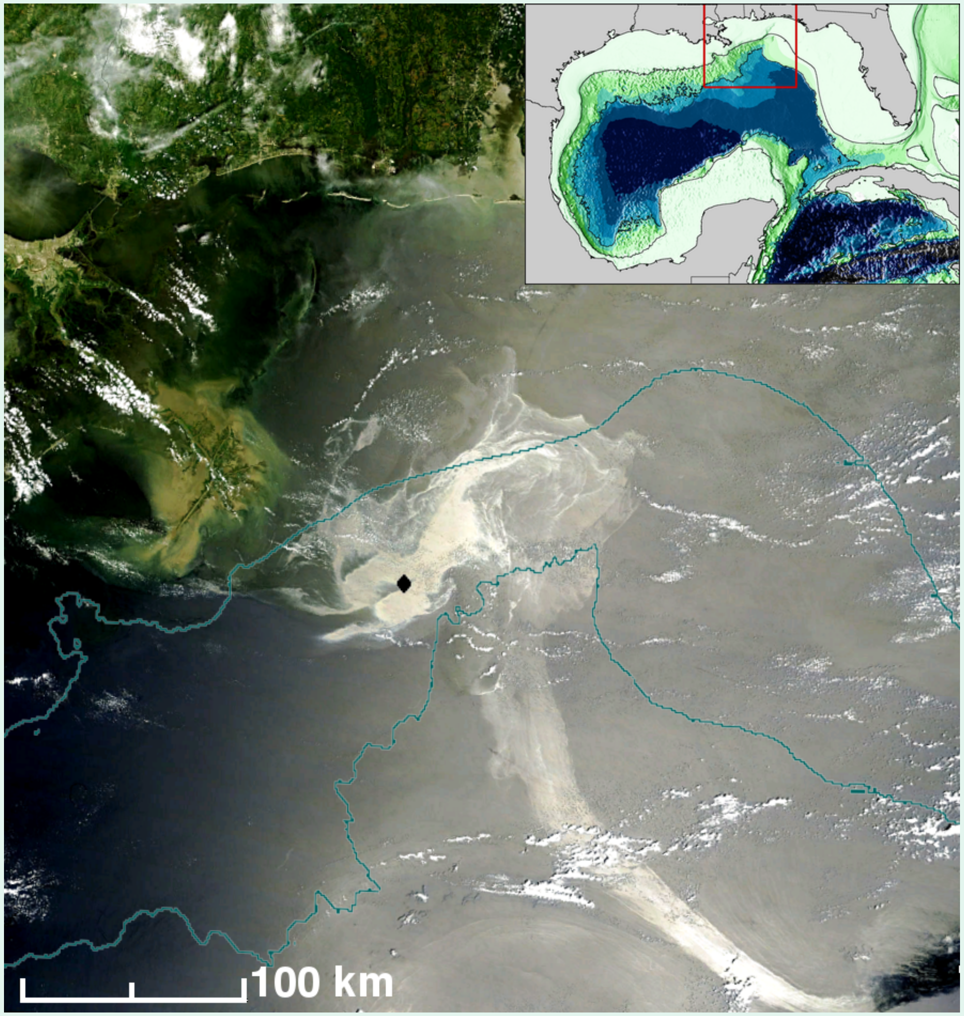
Are these filaments IGW driven?

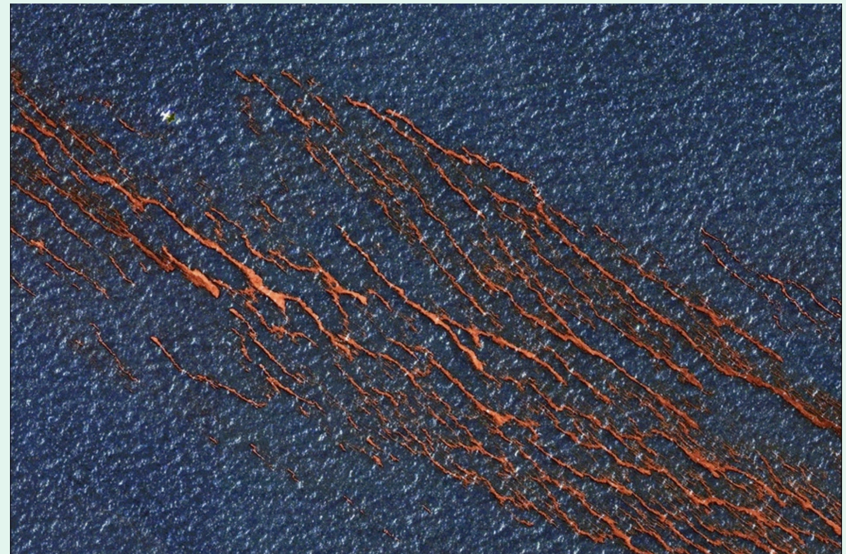


(Özgökmen)

Spin-off Research Programs – GLAD in the GoM:

Oil reveals multi-scale nature of the ocean's surface flows





GLAD objective:

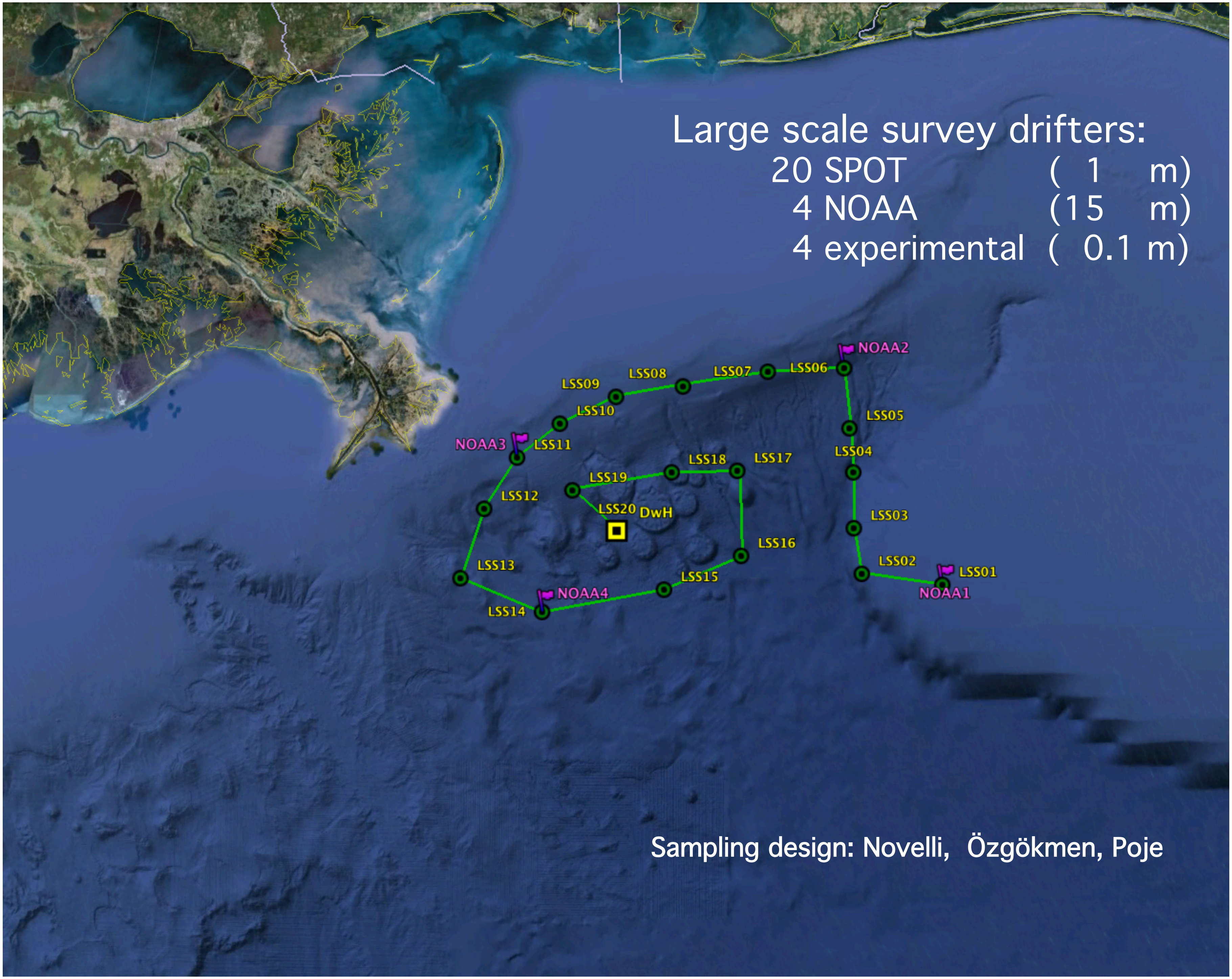
Do submesoscales influence surface transport near the DwH region?

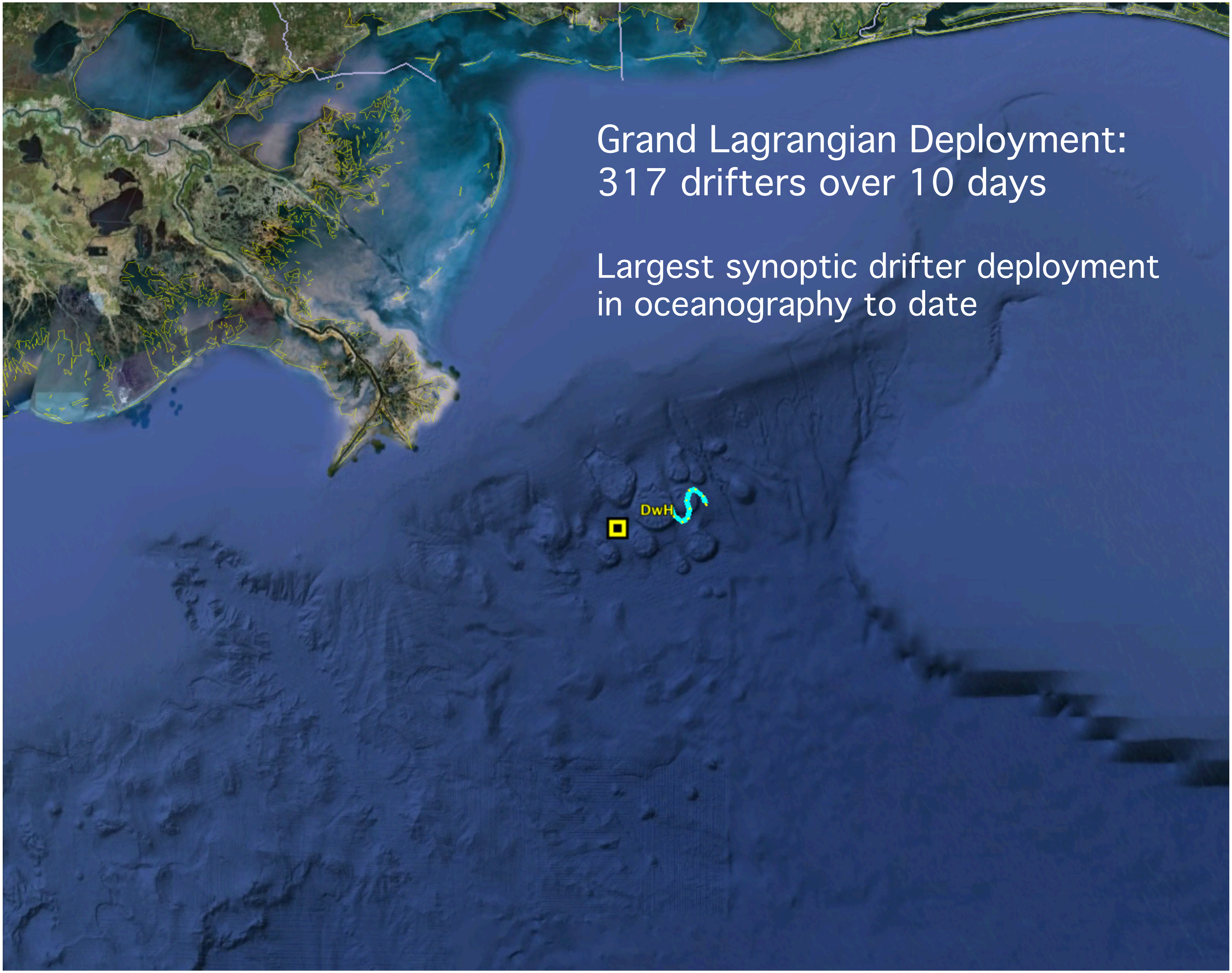
Grand Lagrangian Deployment (GLAD):

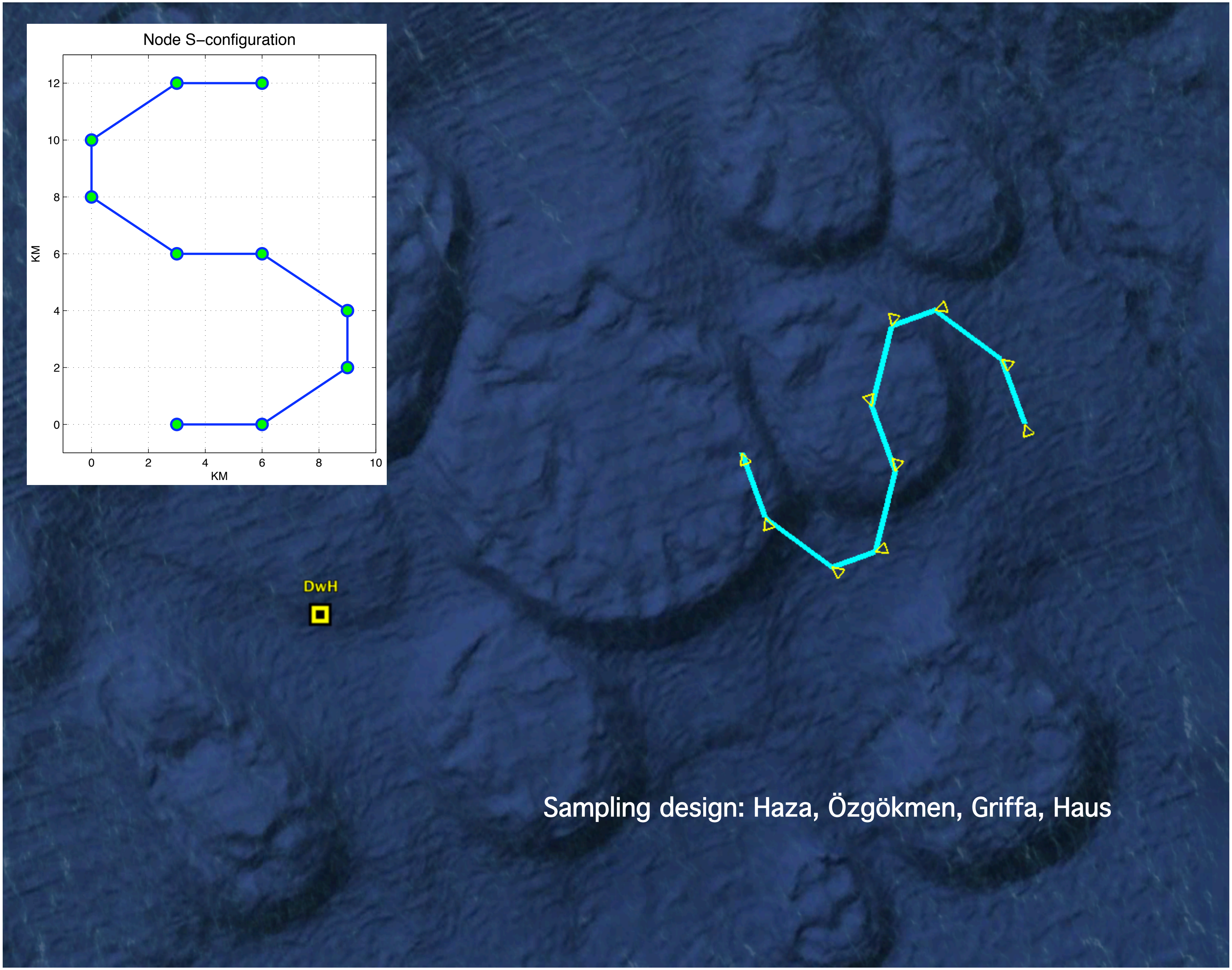
Borrowed several successful practices from LatMix, such as virtual experiments, large scale surveys and multi-scale sampling

Involved heavy operational GCM modeling; *40 realizations of HYCOM and NCOM at 1 km and 3 km with 72 hour forecasts have been provided starting 7 weeks in advance, as well as wave and atmospheric/storm forecasts.*

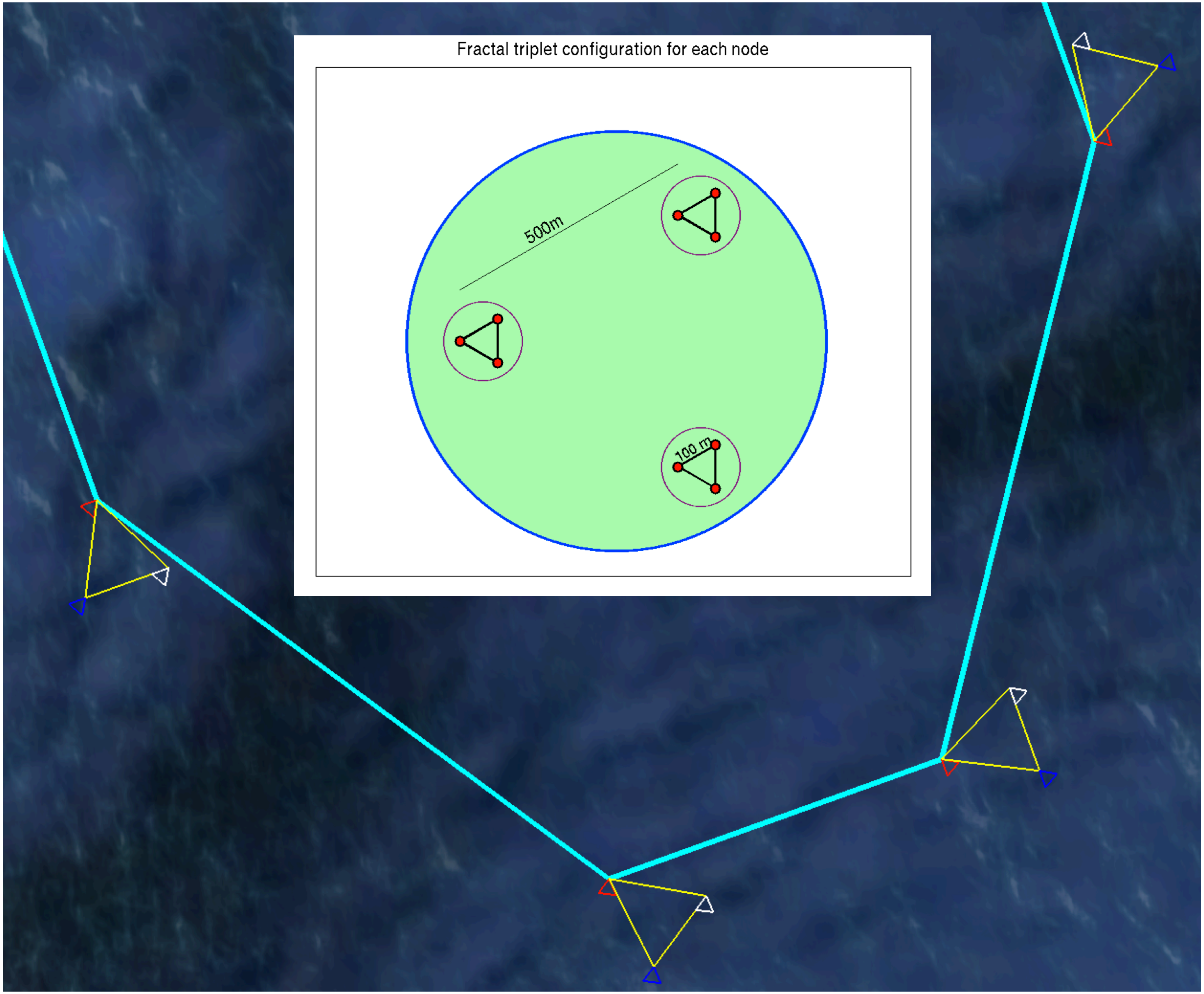
GLAD focused narrowly on multi-scale deployments of a ***single instrument, surface drifters****, which were considered suitable for high-accuracy (5 mins, 5 m), long term (up to 6 months) sampling of rapidly-evolving surface flows for transport calculations in the Lagrangian framework in the DwH oil spill region.*

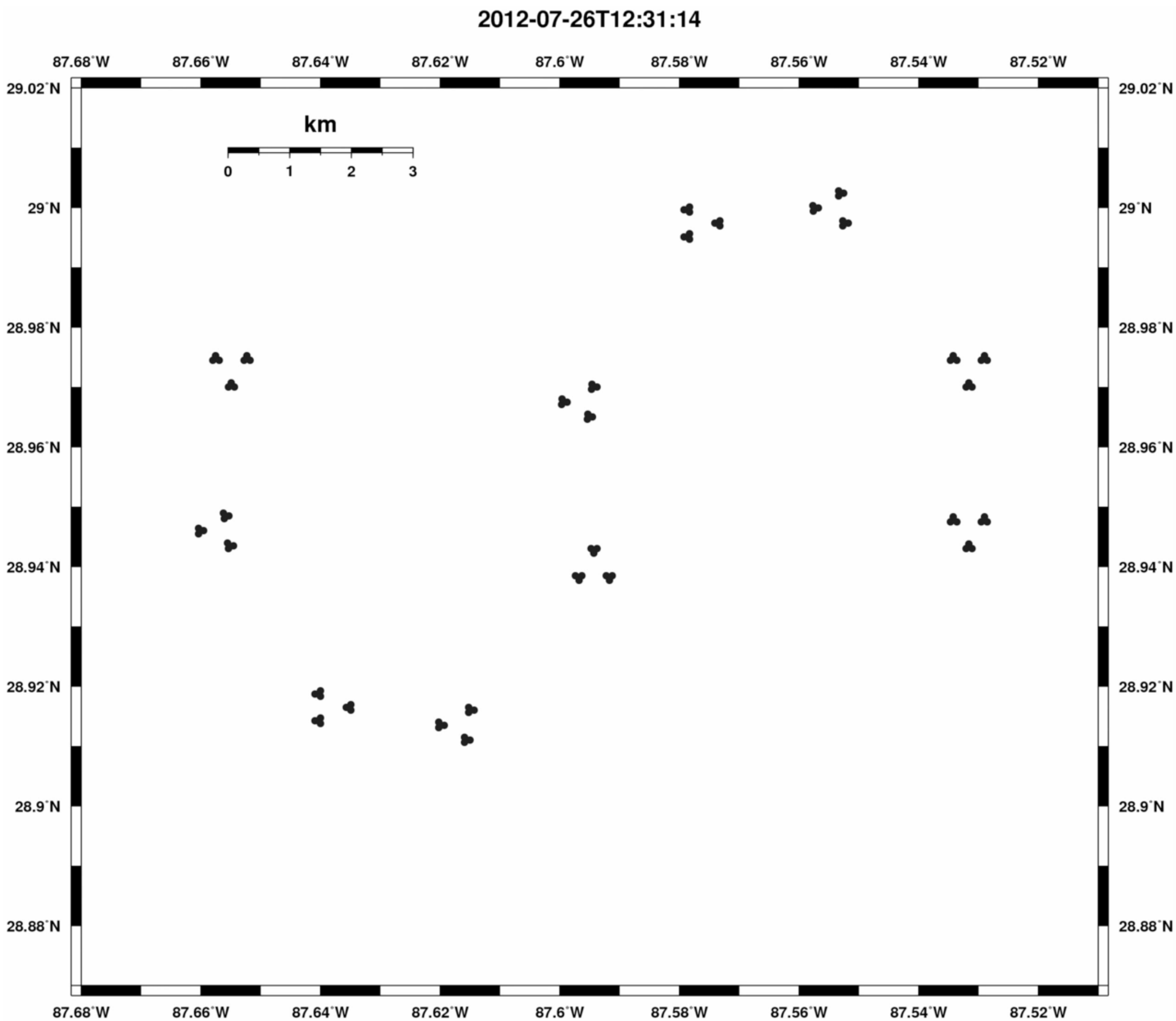

Large scale survey drifters:
20 SPOT (1 m)
4 NOAA (15 m)
4 experimental (0.1 m)
NOAA2
LSS06
LSS07
LSS08
LSS09
LSS10
LSS05
NOAA3
LSS11
LSS04
LSS18
LSS17
LSS19
LSS12
LSS20
DwH
LSS03
LSS16
LSS13
LSS02
LSS01
LSS15
NOAA4
NOAA1
LSS14
Sampling design: Novelli, Özgökmen, Poje


Grand Lagrangian Deployment:
317 drifters over 10 days
Largest synoptic drifter deployment
in oceanography to date
DwH



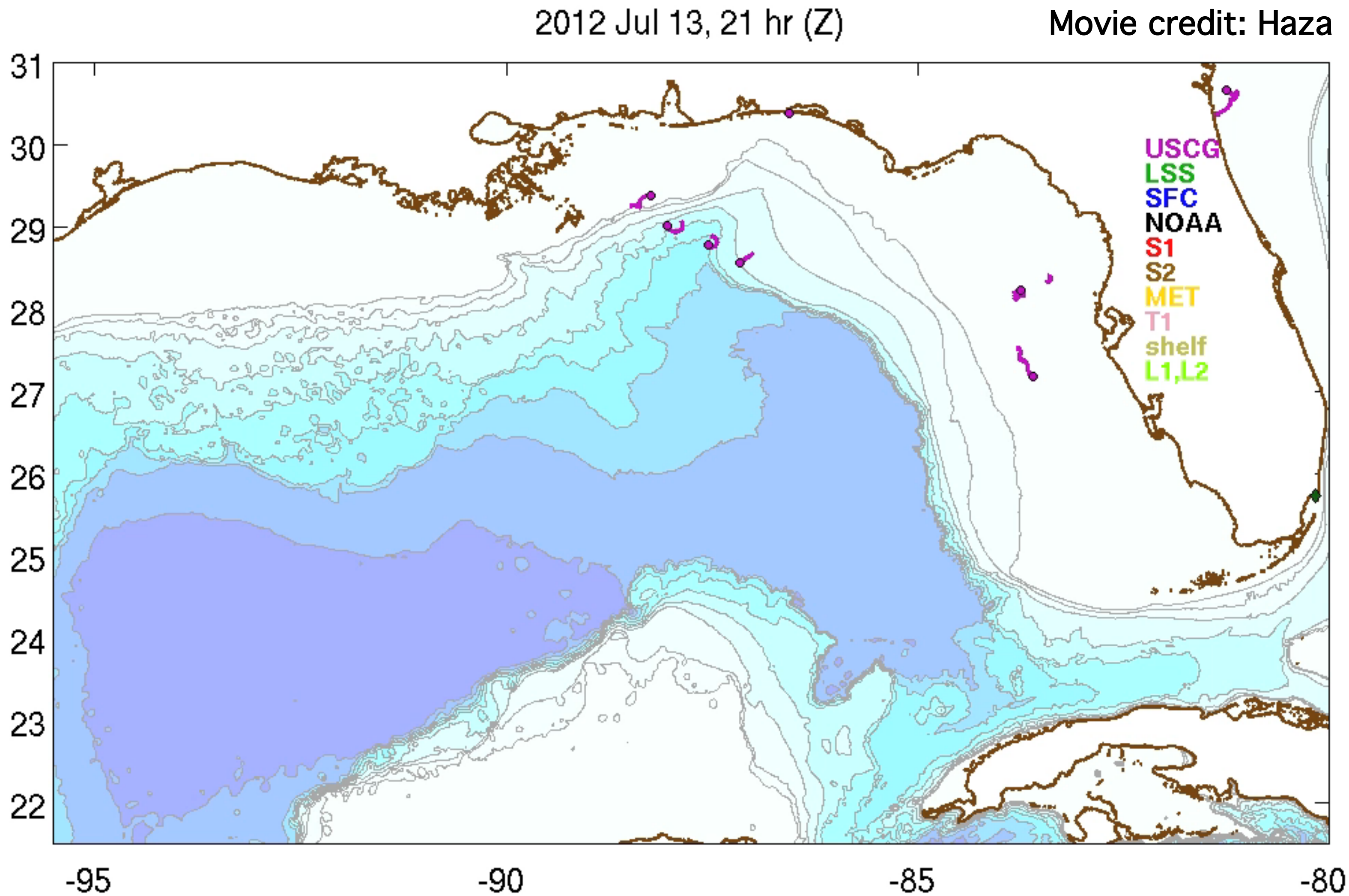
Node S−configuration
KM
KM
0
2
4
6
8
10
12
DwH
Sampling design: Haza, Özgökmen, Griffa, Haus


Fractal triplet configuration for each node
500m
100 m



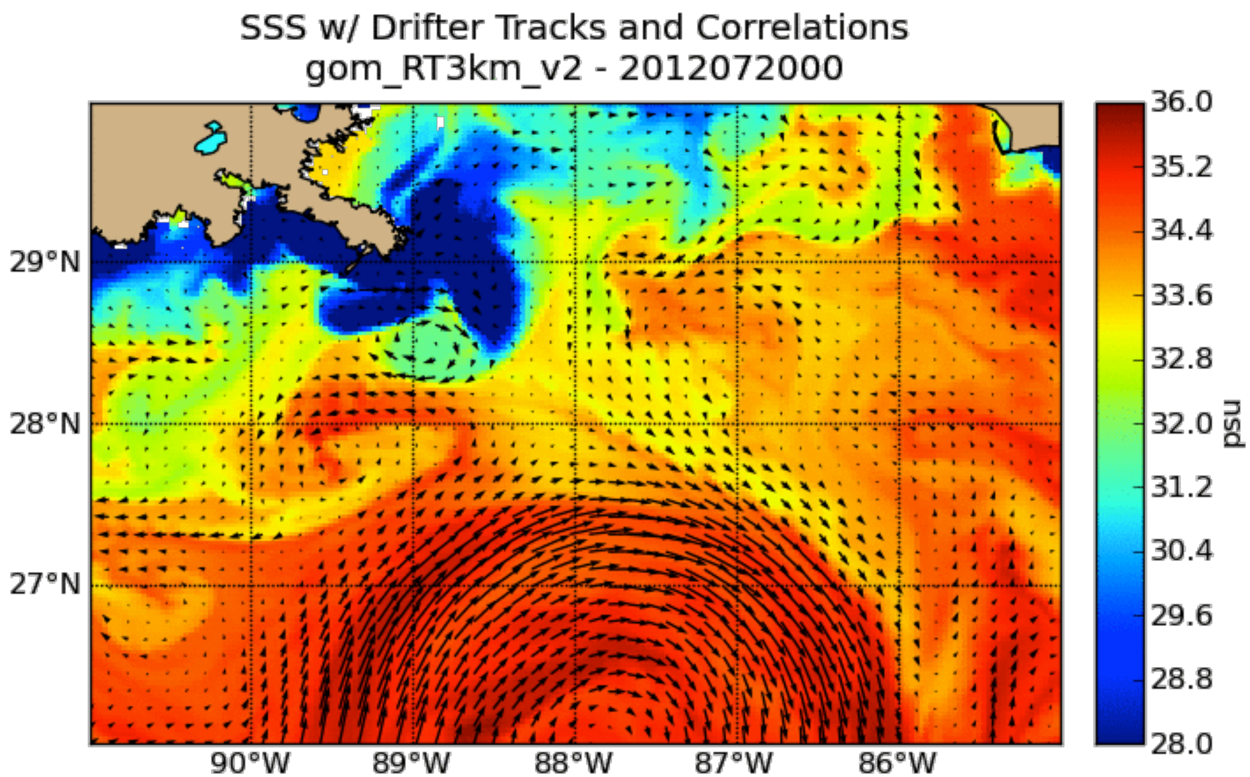
55 cm/s or 1.1knot Inertial Currents...

Entire GLAD Data Set of 317 Drifter Deployments



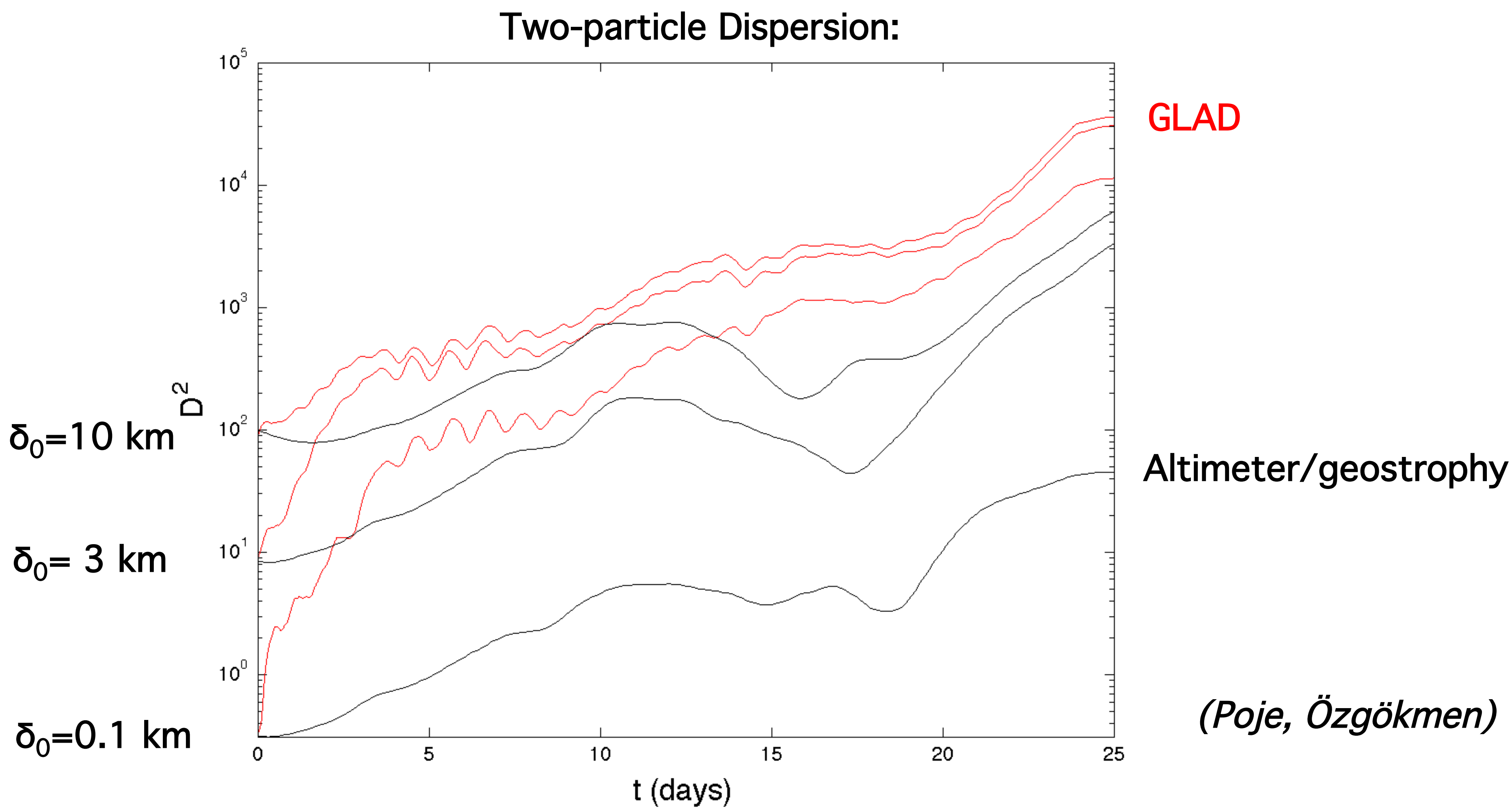
5.7 million data points obtained in total

Realistic Modeling by the Naval Research Laboratory Prediction Group:



- NRL has carried out 72 hour forecasts for GLAD using 3 km and 1 km models with up to 40 ensembles during June – September, 2012.

Do Submesoscales Matter for Surface Dispersion? (YES!)



(Poje, Özgökmen)

High dispersive energy in the submesoscales is severely underestimated by altimeter-derived geostrophic flows – local dispersion regime.

Conclusions:

LatMix 2011 Summer Experiment:

- Involved two 6-day experiments, one in a weak front and the other in a moderately strong front SE of the Gulf Stream with ML depth of 10 to 20 m. Dye patches were released just below the mixed layer at 30 m.

- Lateral spreading of both patches can be described by an effective diffusivity of 1 m^2/s.

- Analysis of dye and ADCP data (Birch), Lagrangian float data (D'Asaro) indicate that shear dispersion (null hypothesis) cannot account for the lateral observed spreading. It is not known what process is responsible.

- Air-borne LIDAR measurements (Concannon) have yielded stunning images of the isopycnal/lateral spreading of dye below the mixed layer. These patterns appear to be very challenging to reproduce by any of the models & modelers.

- Dye (Ledwell, Sundermeyer, Levine) as well as ROV microstructure (Goodman) and the swarm of EM-APEX floats (Sanford, Lien) yielded very low diffusivities of $1x10^{-5}$ m^2/s and low dissipation rates.

Conclusions:

LatMix 2012 Winter Experiment:

- *Parallel two-ship sampling (D'Asaro, Lee, Klymak) has convincingly demonstrated that submesoscale soup exists in the Sargasso Sea with increasing intensity above 300 m depth (within the winter mixed layer), in agreement with predictions by ROMS (Molemaker, McWilliams) and other (HYCOM, Mensa et al.) models of the region for winter (deep mixed layer) conditions.*

- *The contrast between Summer 2011 and Winter 2012 experiments imply a seasonality of the submesoscales with in the mixed layer.*

- *Symmetric Instability was identified at the North Wall of the Gulf Stream (Thomas, Lee)*

GLAD:

- *Large surface drifter deployments (CARTHE) showed conclusively that lateral spreading near the DwH region for scales smaller than 20 km is controlled locally, i.e. by submesoscale processes. Exact mechanisms (MLI, Langmuir, or other) are yet to be identified.*

Submesoscales exist & matter for near-surface transport in the ocean.

What is the connection to climate/CLIVAR?

- These processes are part of the real ocean... are they part of ocean/ climate models?
- Submesoscales matter for passive tracer transport; do they matter for heat transport?

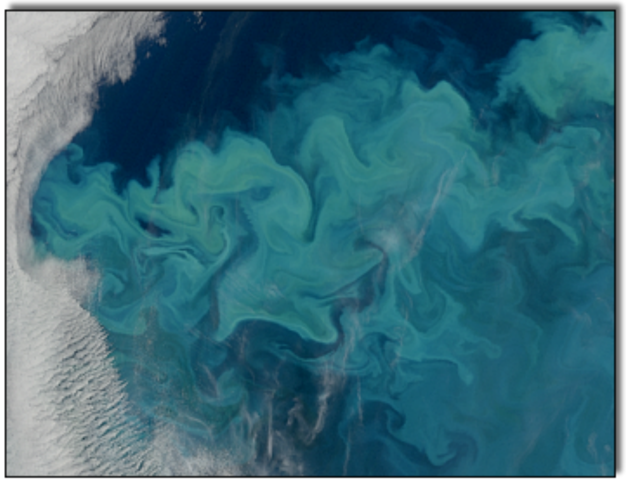
Outstanding Issues:

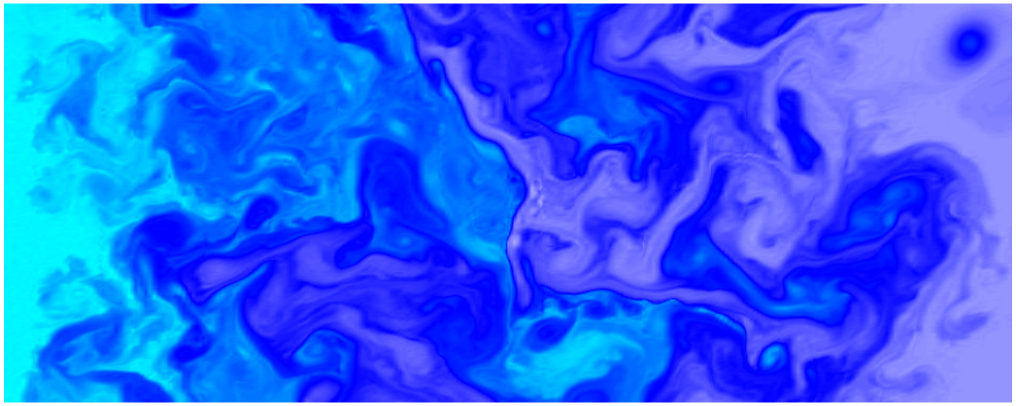
- Overall energetics unclear from observations
- Summer mixed layer not well sampled
- LIDAR tracer patterns cannot be explained yet using models
- IGWs hard to investigate due to dispersion issues in hydrostatic models, and overall, resolution.
- Interaction of mesoscale and submesoscale impacts transport in the horizontal and vertical; mostly unresolved
- Interaction of mixed layer with deeper ocean is not well understood
- 3D transport patterns inside submesoscale and mesoscale eddies are not well known
- Individual processes and their interactions are yet to be sorted out; MLI and symmetric; MLI and Langmuir; MLI and IGWs; etc.
- Almost all models (LES, OGCMs) resolve only 2 processes at this point; must chose which ones; how to go wider scale is a major issue
- Atmospheric forcing, and waves
- Ocean's upper boundary layer is a happening place!

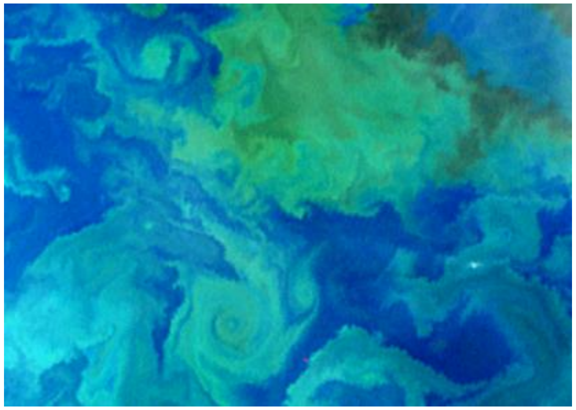
Extra slides

Which One is the Model ?

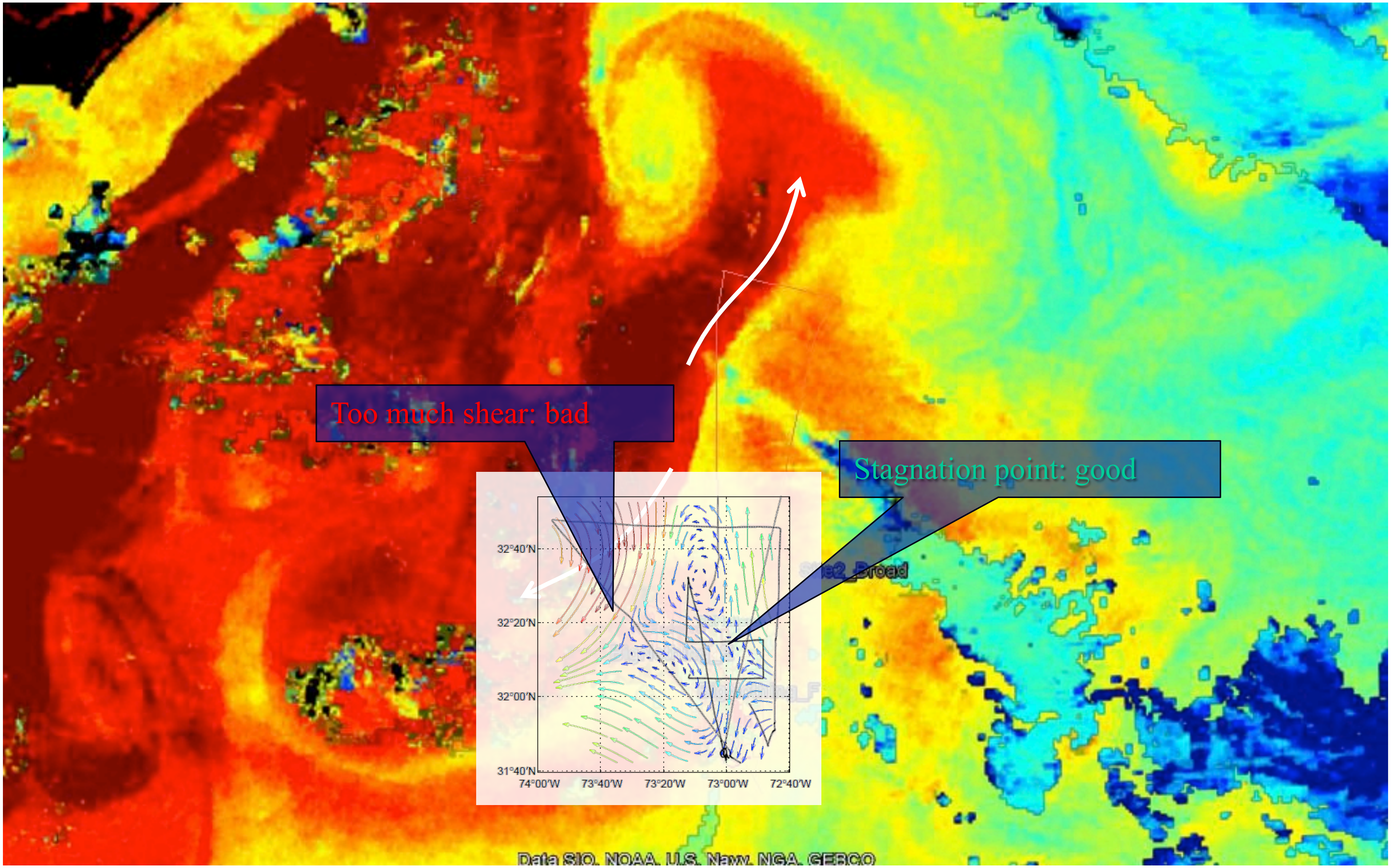
3 Chlorophyll Images From Remote Sensing vs Long-term MLI Computation



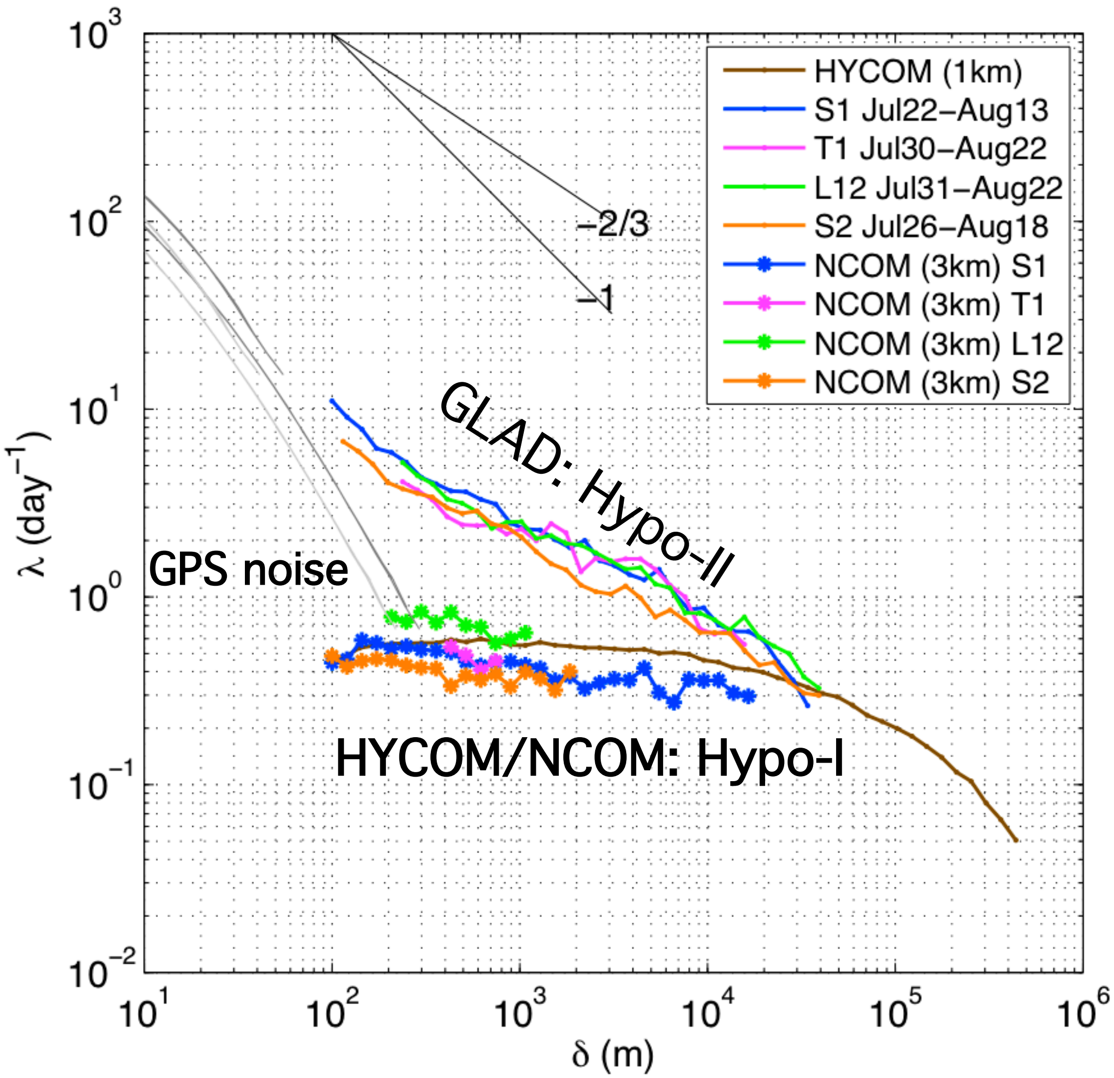




Site 2 Selection



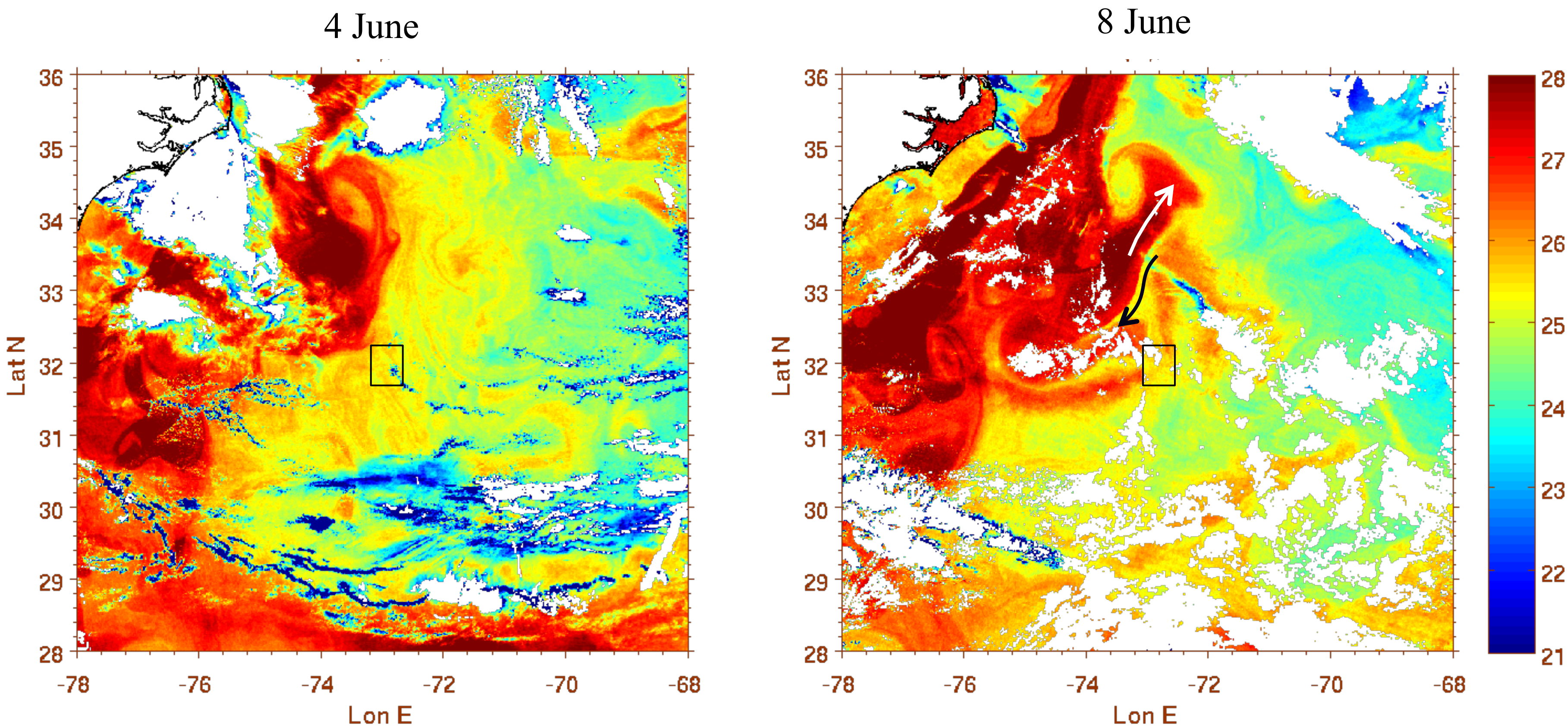
What Does GLAD Show: Hypothesis-I or Hypothesis-II?



Richardson scaling from 100 m to 20 km; ***submesoscales affect transport for δ<20 km***

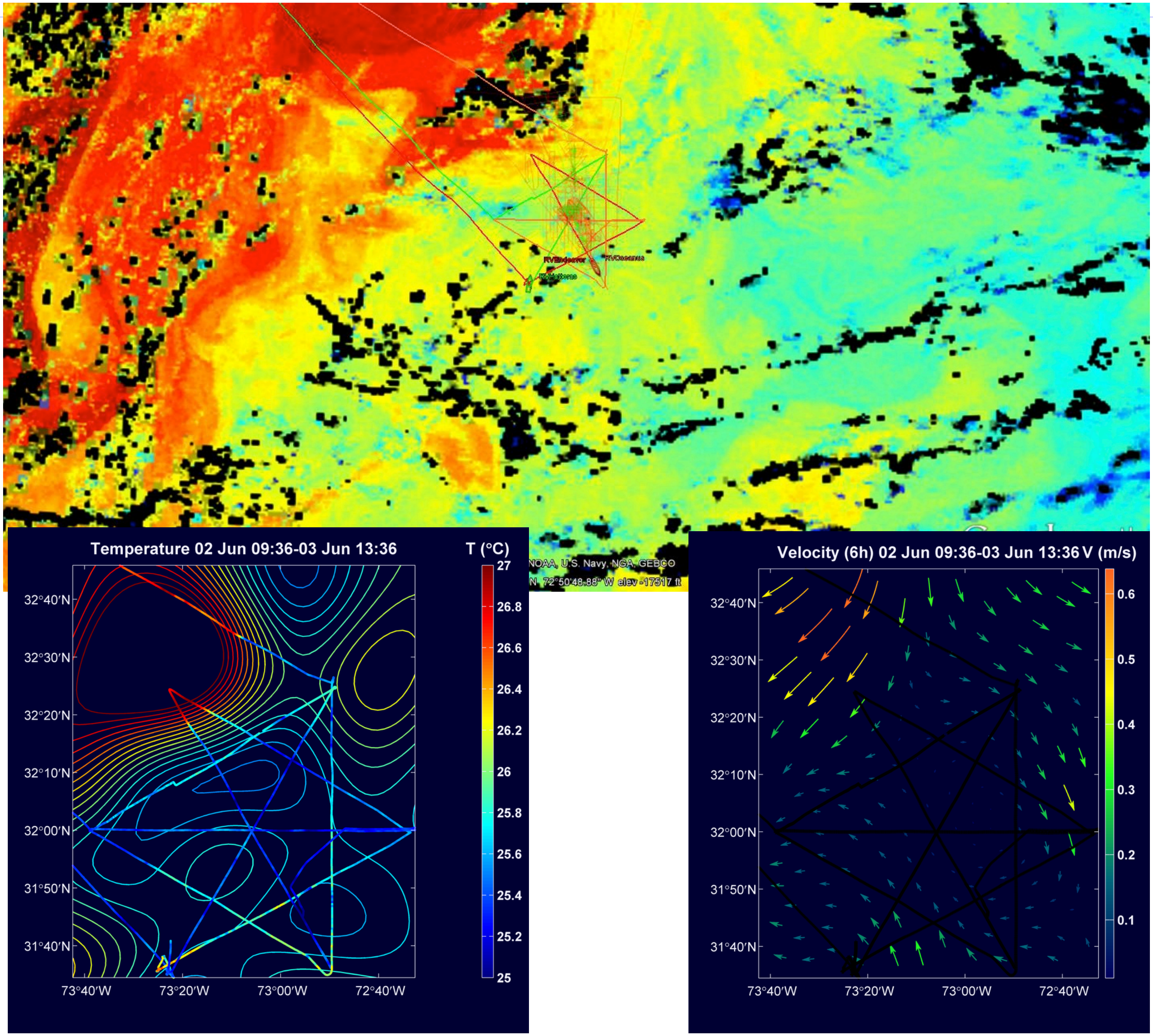
Parameterizations by Haza et al. (2012) can be applied to fix the dispersion deficit in OGCMs now that the truth is known.

Site Selection for Summer 2011 Experiment - Big Nothing:



NOAA-AVHRR SST

Site 1 - Big Nothing: large-scale survey



2011 June Cruise Movie:

Credit: Andrey Shcherbina, Eric D'Asaro

Why Drifters?

* Moored instruments: too little coverage

* Towed profiling instruments:
compromise between horizontal and vertical coverage; multiple ships

* Satellite remote sensing:
SST impeded by cloud cover; SSH mesoscale; velocity field from geostrophy
SAR breaks down under moderate winds, no velocity field

* Gliders:
too slow, too few, aliasing, no velocity field, expensive

* Tracers with airborne laser tracking:
good for observing shapes, no velocity field; expensive; untraceable within mixed layer

* HF/VHF radars:
excellent for velocity field, but surface and coastal locations only

* *Lagrangian drifters in massive clusters:*
inexpensive, accurate, deployable anywhere, capture net dispersive effect of all processes down to drifters size (~ 1m) ✔ ✔ ✔ ✔
Grand Lagrangian Deployment - GLAD!