CARTHE CONSORTIUM
for ADVANCED RESEARCH on TRANSPORT of HYDROCARBON in the ENVIRONMENT

The Road to GLAD: A Perspective

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Much thanks to

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- Tamay Özgökmen - RSMAS

Duality of Nature

- Field (wave) view – Eulerian
- Particle view – Lagrangian
- But Euler responsible for both

Euler – Lagrange in Fluid Mechanics

Batchelor: "The Lagrangian type of specification is useful in certain special contexts, but leads to rather cumbersome analyses and in general is at a disadvantage in not giving directly the spatial gradients of velocity. We shall not need to use it in any systematic way…"

Lamb: 12 chapters, 730 pages, 385 sections. 2 sections over 3 pages discuss Lagrangian fluid mechanics.

Euler – Lagrange in Fluid Mechanics

Pedlosky: Assumes Eulerian description at outset. Gives Ertel/Rossby theorems in Lagrangian form, but makes no fundamental use of formalism.

Gill: Oblique references to Lagrangian description on pages 64 & 98.

Kundu & Cohen: "Classical mechanics has two alternate descriptions… Most of this book is written in the field description but it is frequently useful to express a particle derivative in the field description."

History Lessons

- Fluid Mechanics written by “Eulerian bigots” – M. Toner
- Meteorology – Parcel methods pushed in early days of numerical weather prediction, but most of user community wants to know if it will rain on their parade.
- Oceanography – Most of user community wants to know where did crap come from and where is it going

Time Line for Lagrangian Oceanography

- PreCambrian (1872-1927) – Began with Challenger Expedition, ended with Meteor Expedition
- Paleozoic (1927 – 1973) – Ended with IDOE meteor
- Mesozoic (1973 – 1993) – Ended with arrival of ETs at Little Compton Meeting
- Cenozoic (1993 – 2010) Ended with Deepwater Horizon meteor
- Post Deepwater Horizon – Name? **Brave New Era**

PreCambrian

- Era of grand "expeditions"
- Constancy of Composition & definition of salinity in terms of Cl equivalents

. . . The moisture and varying temperature of the land depends largely upon the positions of the currents in the ocean, and it is thought that when we know the laws of the latter we will, with the aid of meteorology, be able to say to the farmers hundreds of miles distant from the sea, 'you will have an abnormal amount of rain during next summer,' or 'the winter will be cold and clear,' and by these predictions they can plant a crop to suit the circumstances or provide an unusual amount of food for their stock. . . . From a study of these great forces, then, we derive our greatest benefits, and any amount of well-directed effort to gain a complete mastery of their laws will revert directly to the good of the human race.

Lt. John E. Pillsbury, 1891
from *The Gulf Stream*

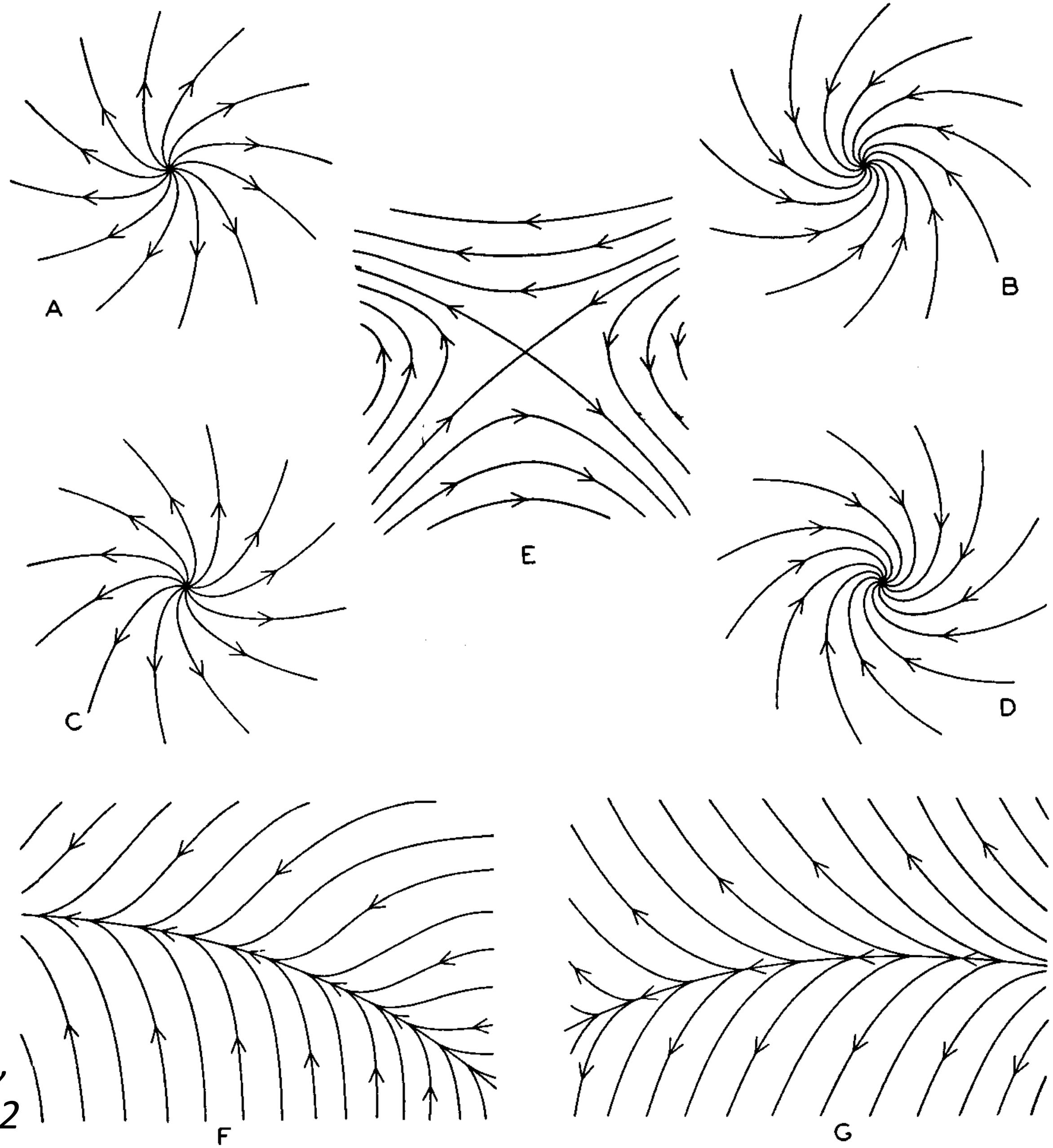
Paleozoic

Eulerian

- Mainstream Oceanography was Eulerian – streamlines **are** trajectories – Geostrophy rules
- Emergence of classical turbulence theory

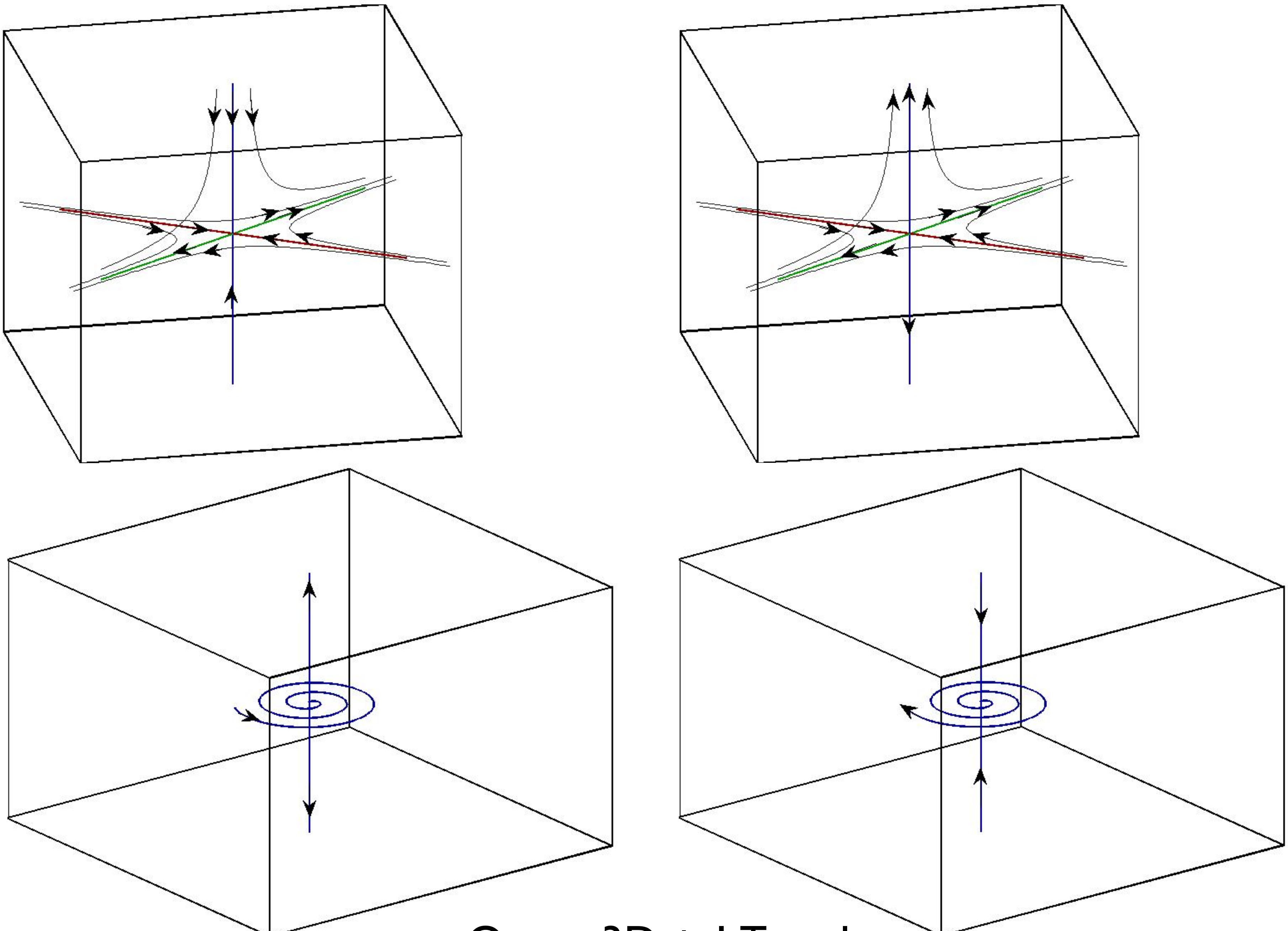
Lagrangian

- Difficulty reconciling particle statistics with concentration measurements
- L. F. Richardson – Neighbor Diffusion – 1929
- Richardson & Stommel (J. Met 1949) Observations of parsnip pairs "confirm" 1.4 or 4/3 law in atmosphere & ocean.
- John Swallow and his floats



The Oceans
Sverdrup, Fleming,
and Johnson - 1942

Fig. 96. Singularities in a two-dimensional vector field. *A* and *C*, points of divergence; *B* and *D*, points of convergence; *E*, neutral point of first order (hyperbolic point); *F*, line of convergence; and *G*, line of divergence.



Ocean 3D + 1 Template

Mesozoic Era: POLYMODE to Little Compton

Meteor: International Decade of Ocean Exploration

1968 State of Union: “I have instructed the Secretary of State to consult with the other nations on the steps that could be taken to launch an historic and unprecedented adventure – an International Decade of Ocean Exploration for the 1970’s.”

MODE/POLYMODE Circa 1975

MODE/POLYMODE - Essentially Eulerian Experiments with a goal of benchmarking numerical models

- High failure rate of moorings
- Mesoscale variability obviated much of hydrography
- But Rossby SOFAR floats saved the day!

SOFAR FLOAT
700 - 2000 m

McWilliams Streamfunction Maps

JPO 810 - 827, 1976
JPO 828 - 846, 1976

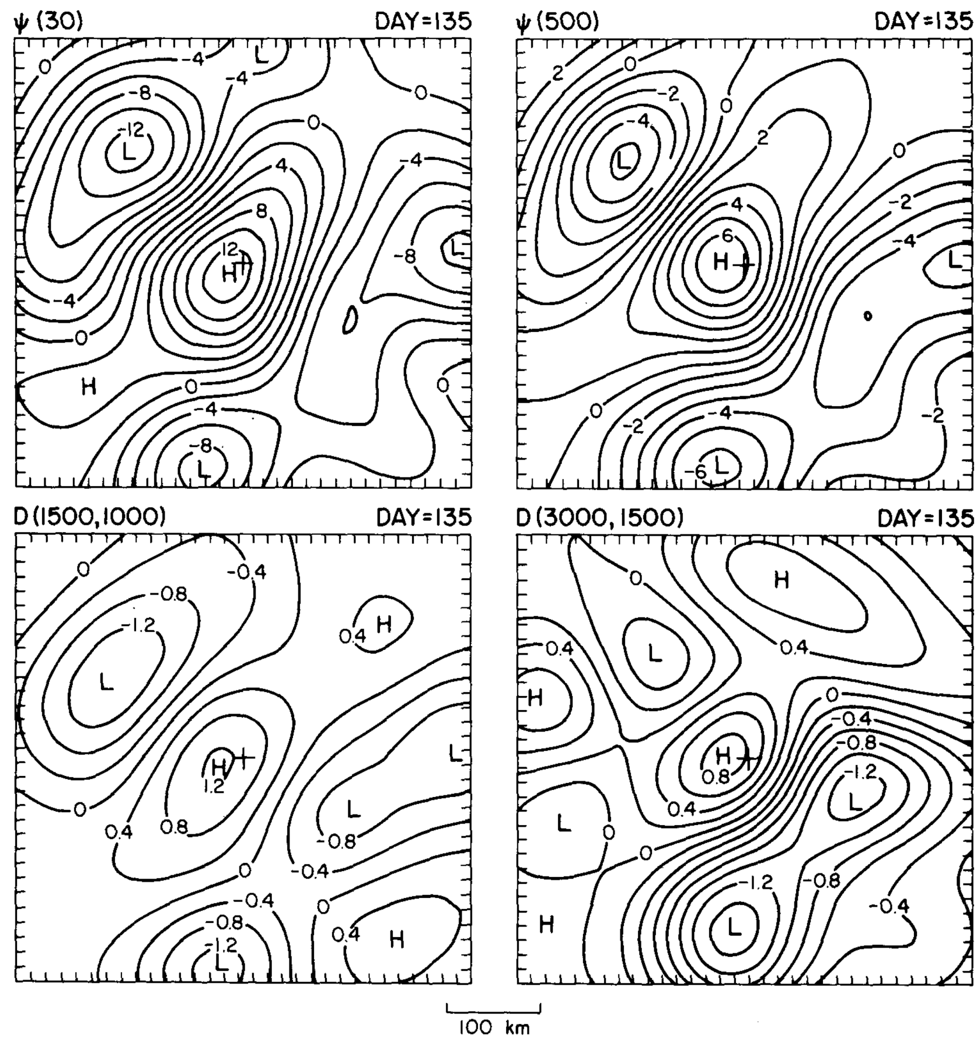


FIG. 3. Maps of the vertical increment in streamfunction on day 135 in different depth regimes: near surface, thermocline, sound channel and deep ocean. [Actually, $D'(1500, z)$ is represented here by $\psi(z)$ for the upper two regimes.]

Anomaly Dynamics Study - North Pacific Circa 1975

938 JOURNAL OF PHYSICAL OCEANOGRAPHY VOLUME 8

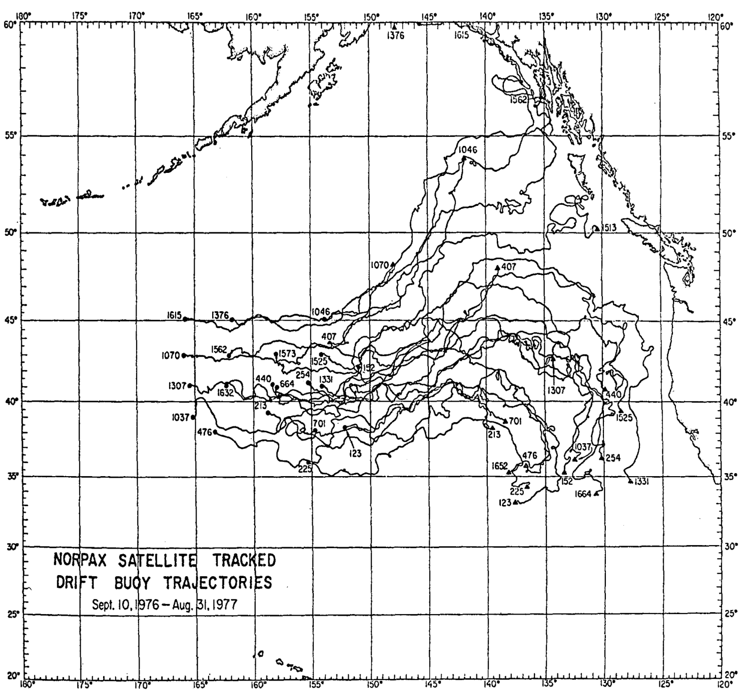


FIG. 1. A composite of the trajectories of 22 drifters deployed during the ADS I and II. The trajectories are from positions fixed by Nimbus 6 during the period 10 September 1976 through 31 August 1977.

508 MCNALLY ET AL: CURRENTS OF NORTH PACIFIC

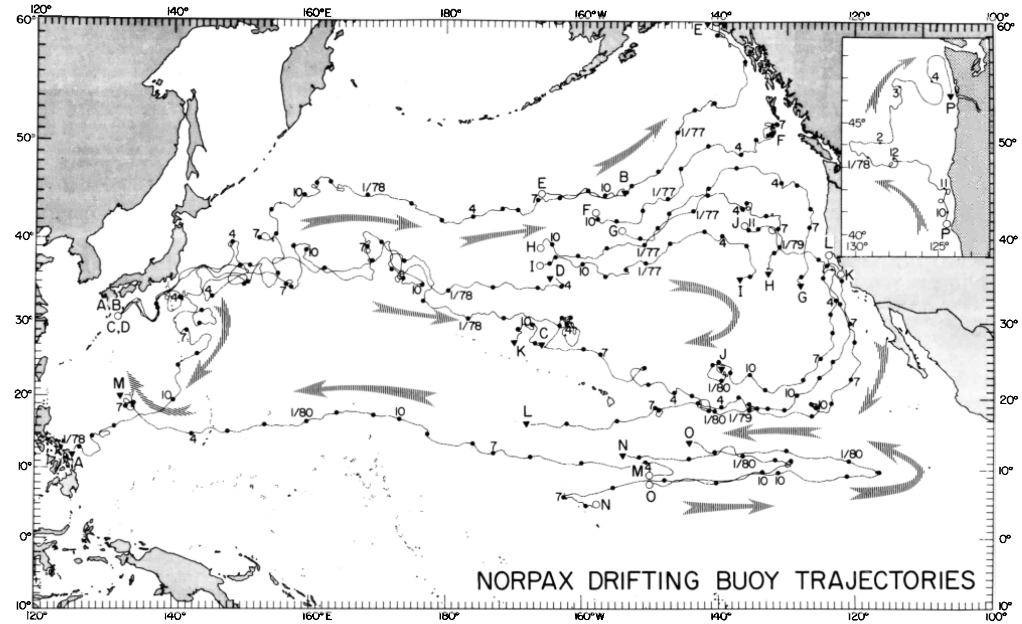


Fig. 1. Trajectories of 16 satellite-tracked drifting buoys deployed from 1976 through 1980 during various experiments. Open circles indicate the deployment locations, solid circles indicate the first day of each month, and triangles indicate the last reported locations. The large stippled arrows show the directions of the trajectories. See Table 1 for detailed information.

Real Ocean is Filled With Mesoscale Eddies

Trajectories of 35 Surface Drifters

Richardson (1981)
J Phys Oceanogr, 11, 999-1010

Mesozoic Era: POLYMODE To Little Compton 1993 – Rise of the Mesoscale

Eulerian

- Experimental - Extensive mooring programs
- Rise of numerical models

Lagrangian

- Focus on mean and mesoscale currents, dispersion, simple process models
- Okubo criterion DSR 1970, 1976
- Experimental
  - Subsurface “floats” tracked acoustically.
  - Surface “drifters” tracked by satellite
  - Satellite remote sensing

Aref, 1984, JFM

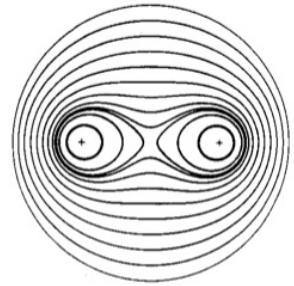


FIGURE 3. Streamlines for a device with two fixed agitators operating continuously. Agitators (indicated by crosses) are at $z = \pm 0.5a$, where a is the tank radius.

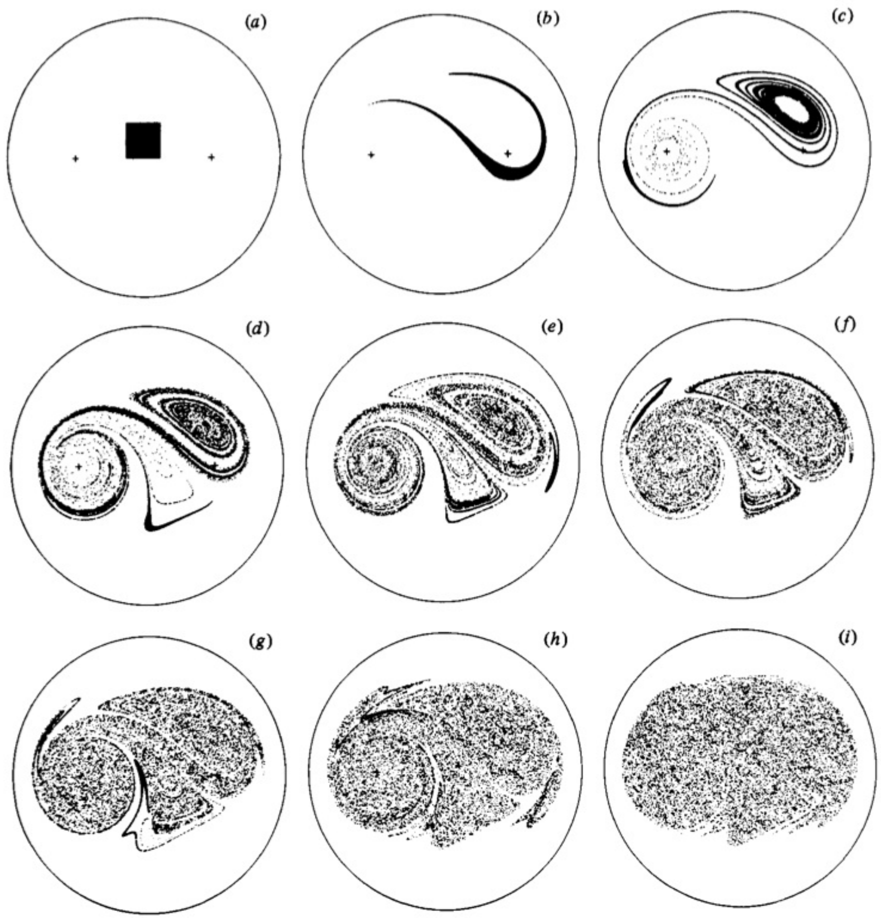


FIGURE 4. Phases in the stirring of an initially square array of particles. Parameters are $\beta = 0.5$, $\mu = 1.0$. Panels shown are at times (*a*) $t = 0$; (*b*) 1; (*c*) 2; (*d*) 3; (*e*) 4; (*f*) 5; (*g*) 6; (*h*) 9; (*i*) 12.

Cenozoic Era 1993 - 2010

- Starts with ONR sponsored meeting in Little Compton RI – brought together DST theorists and oceanographers
- Recognition of large Lagrangian user community in oceanography
- Rapid development of GPS technology & computing power
- Emergence of Lagrangian data assimilation

Lagrangian Coherent Structures

Defined by Haller (2000) in terms of FTLE

Other LCS characterizations

FSLE	Joseph & Legras (2002)
Minimal Trajectories	Mancho & Mendoza (2010)
Mesohyperbolicity	Mezic et al (2010)
Complexity	Rypina et al (2011)
Geodesics	Haller & Boron-Vera (2012)
Koopman Operator	Mezic (2012)

Most GFD studies restricted to 2D velocities

Theory applies to R^n

Are LCS important in GFD?

MODE/POLYMODE (circa 1975): Mesoscale eddies transport heat, salinity, and momentum. Yet…..

- How do eddies form?
- How many eddies are there?
- How do eddies exchange heat, etc. with environment?

Since MODE/POLYMODE

- Growing Lagrangian user community
- Dramatic increase in computing power and submesoscale data
- Dramatic oil spills, i.e. Deepwater Horizon

Little Compton meeting: DST methods applied to 2D mesoscale transport

To date: Kinematic descriptions

Cenozoic Era 1993 -2010 – Rise of Lagrangian Experiments & Lagrangian Data Assimilation

- SCULP– 750 drifters released 1993 – 1998 in Northern GoM
- ALACE and SOLO floats in North Atlantic
- Basin & Global synthesis
- LIDEX, MREA, & REP in Med

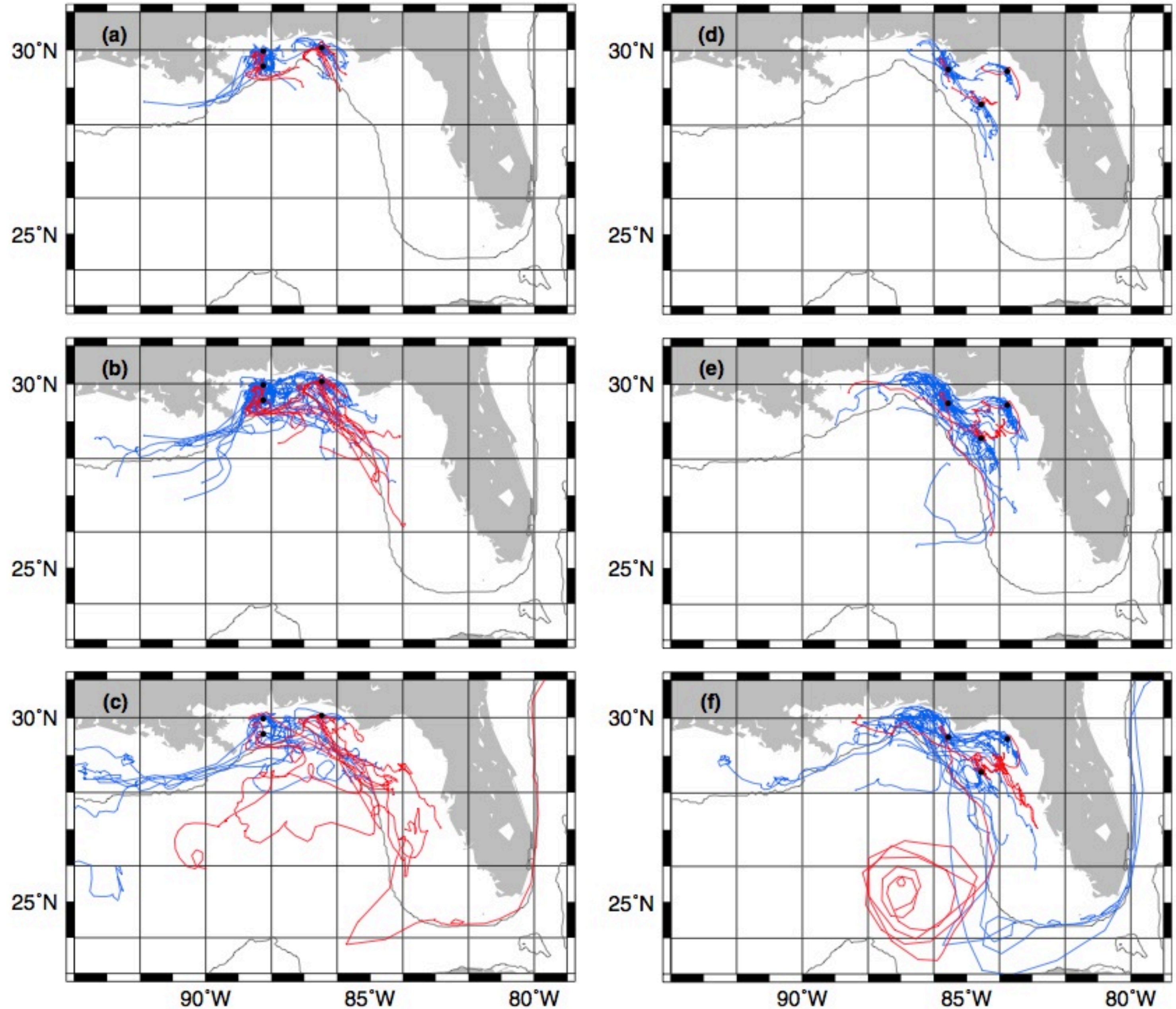


Fig. 5. As in Fig. 4 for drifters on the northwest Florida shelf that travel for (a) 10 days (84 tracks), (b) 30 days (74 tracks), and (c) 90 days (21 tracks) after passing within 5 km of 88.25°N, 29.97°W; 88.25°N, 29.57°W; or 86.47°N, 30.06°W; and travel for (d) 10 days (59 tracks), (e) 30 days (57 tracks), and (f) 90 days (25 tracks) after passing within 5 km of 83.75°W, 29.45°N; 84.55°W, 28.56°N; or 85.50°W, 29.50°N.

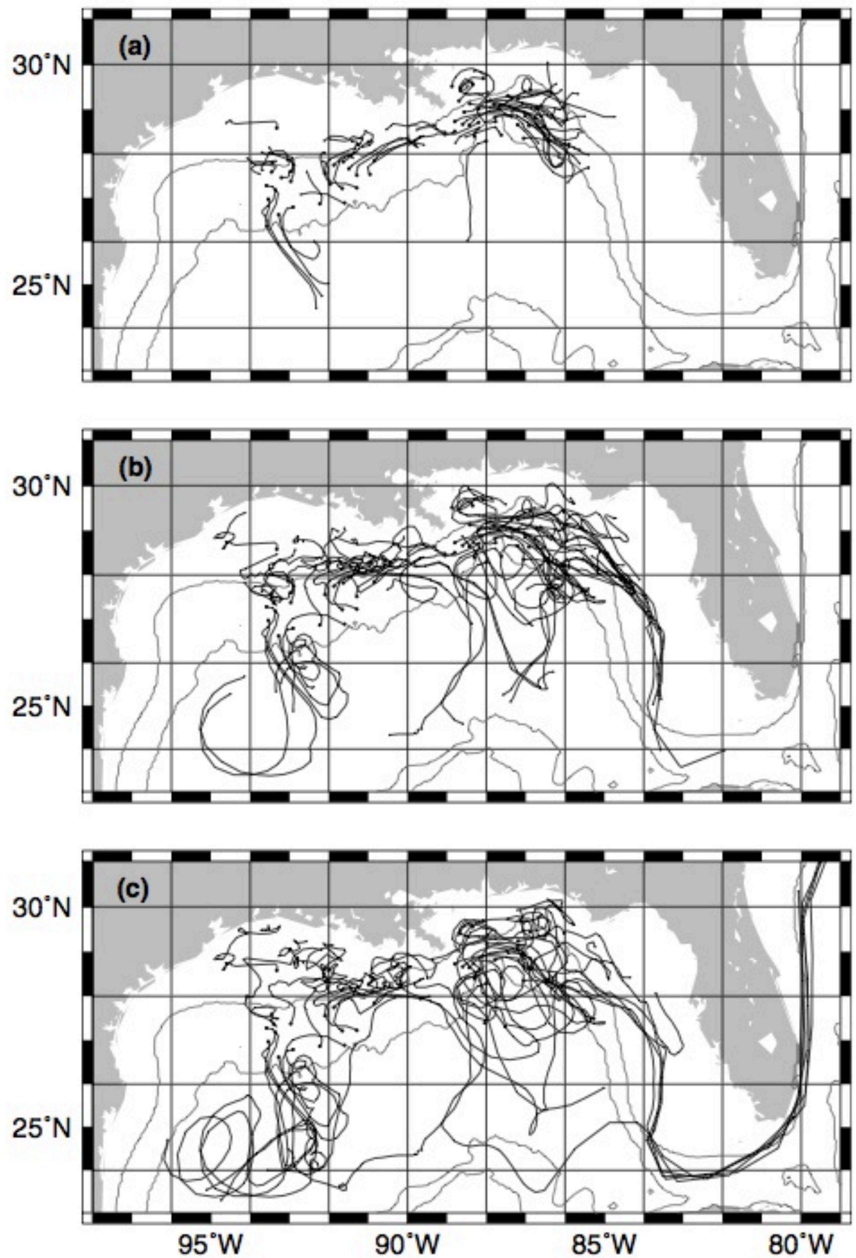


Fig. 6. Tracks of drifters deployed within specific eddy features during the SCULP-III experiment. Trajectories during the first (a) 10 days (61 tracks), (b) 30 days (52 tracks), and (c) 50 days (31 tracks) days after deployment are shown.

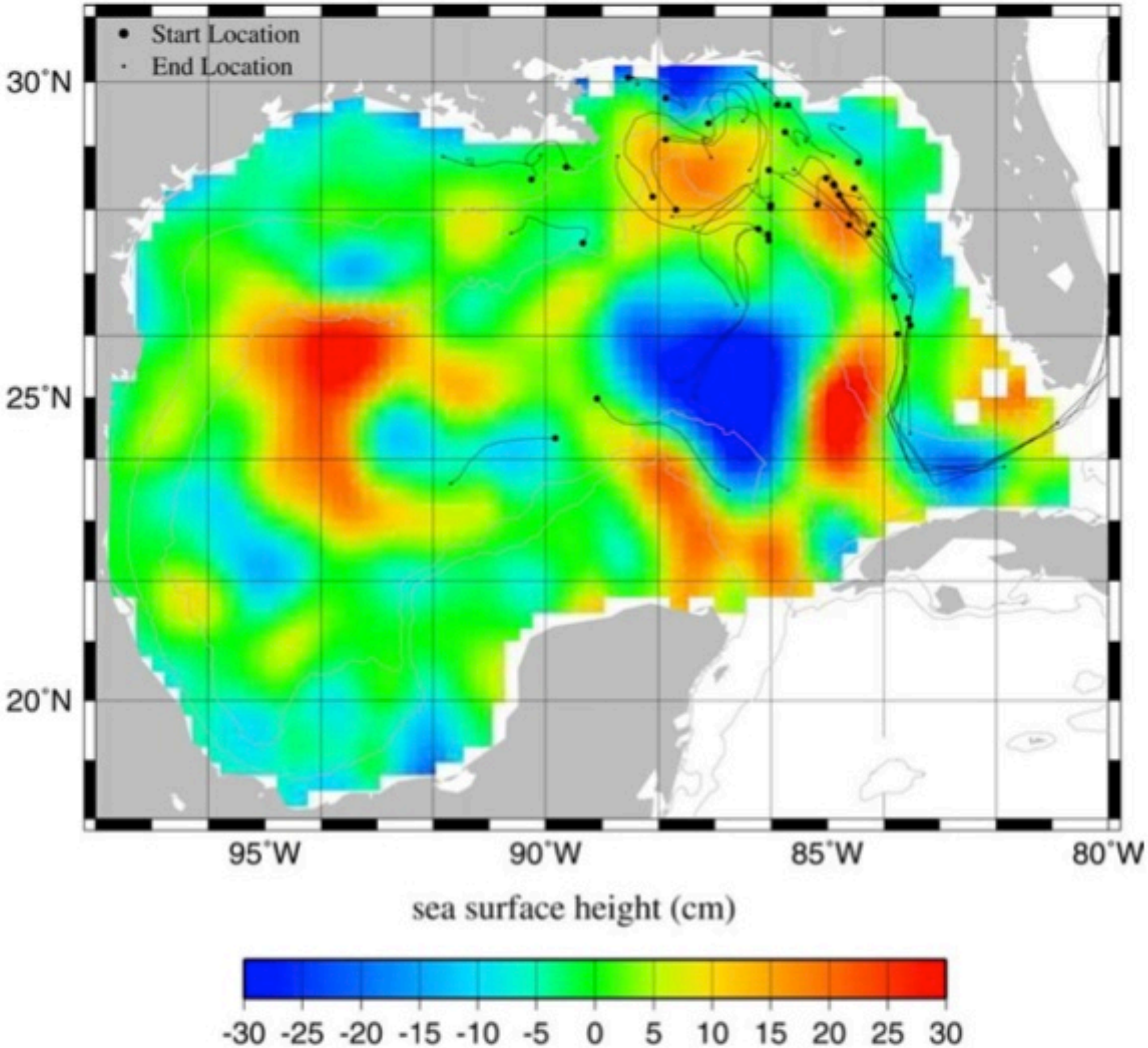
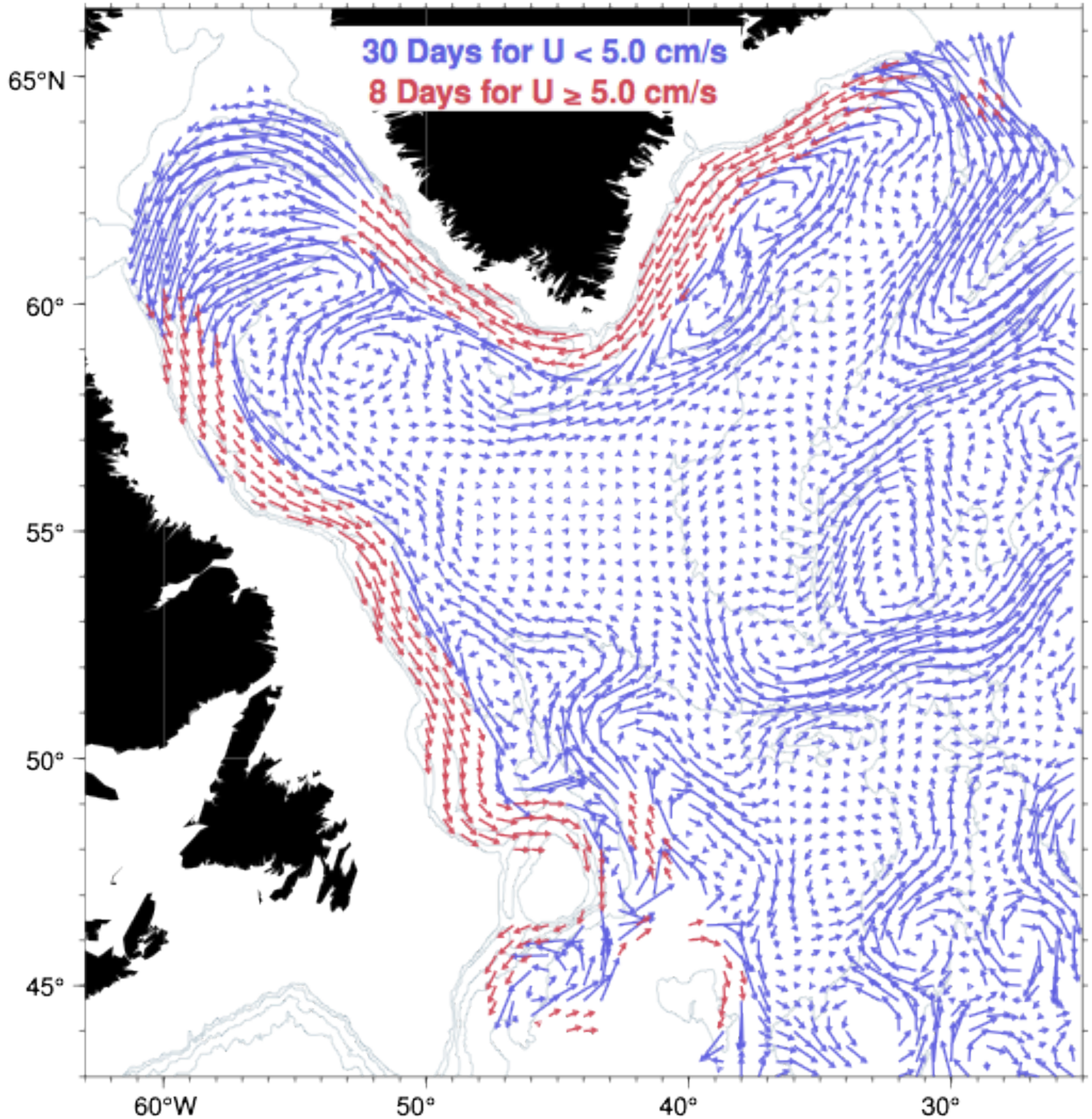


Fig. 20. As in Fig. 19 with altimetry data for 23 August, 1998, and drifter trajectories recorded from 16 through 31 August, 1998.

Mapped displacements at 700 m



Mean circulation of the Labrador Sea and Irminger Basin as determined from ALACE and SOLO floats, plotted as displacements. (Lavender et al. 2000)

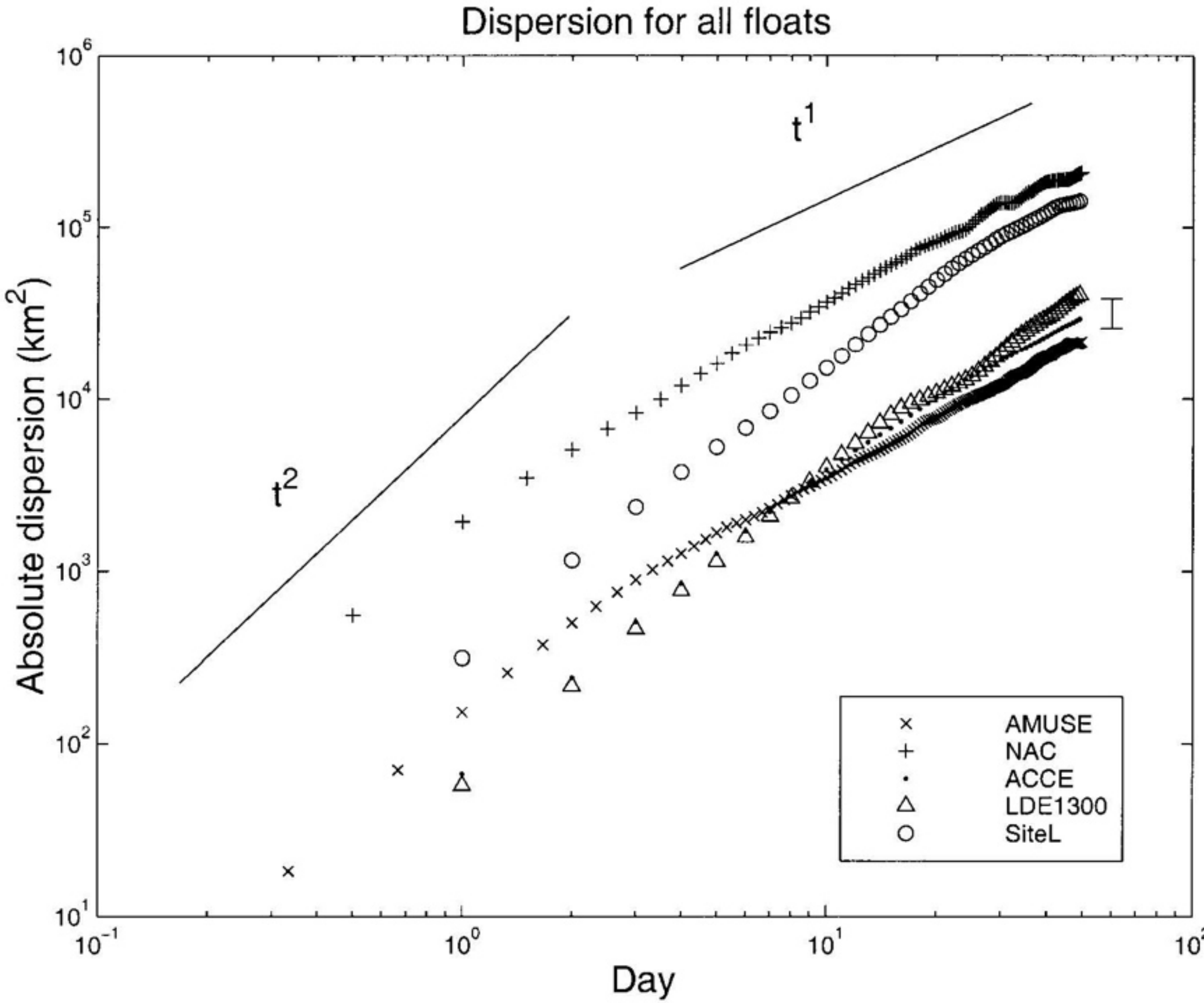


Figure 9. The single particle dispersions for all floats in the respective regions. The trajectories have been cut into 50-day segments for this calculation. Note the sample sizes are greater in this case, which is reflected by the smaller (ACCE) error bars.

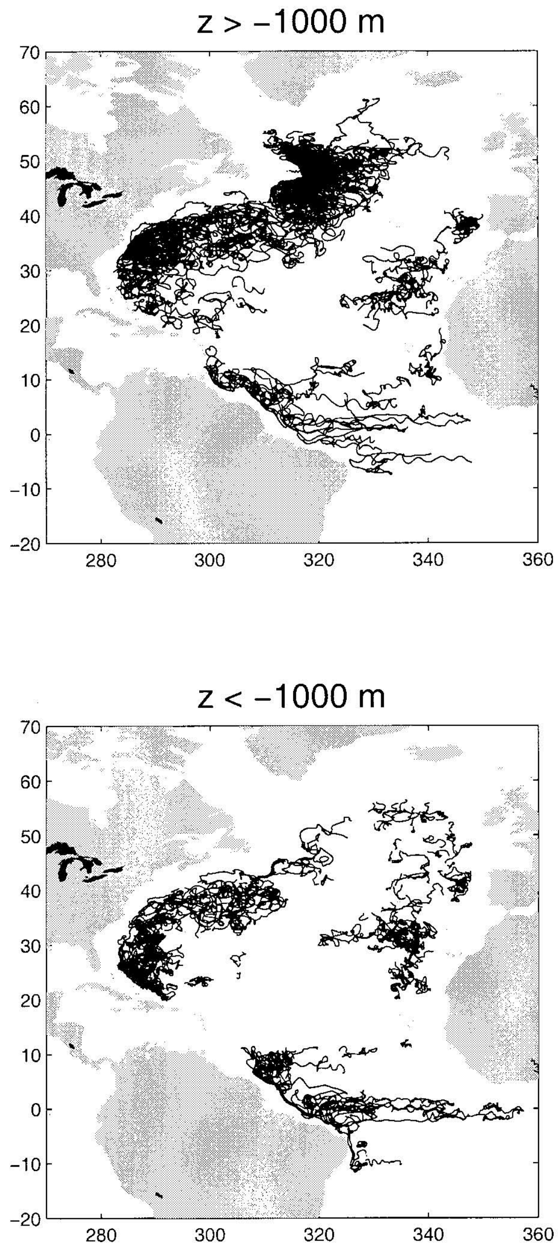


FIG. 1. Trajectories of the floats used in this study. Floats above 1000 m are at the top, and the deep floats at the bottom, as indicated.

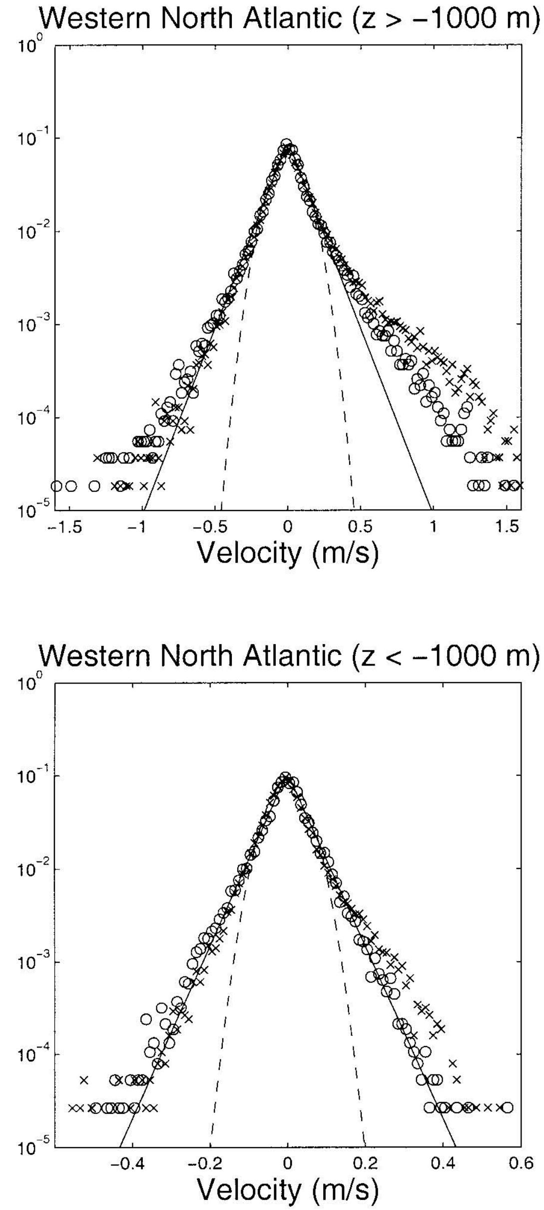


FIG. 2. The probability density functions for the velocities in the western Atlantic. The PDFs for the zonal velocities are indicated by (×), and for the meridional velocities by (○). Also shown are the least squares best fit Gaussian curves (dashed lines) and exponential curves (solid lines).

JGR 2003

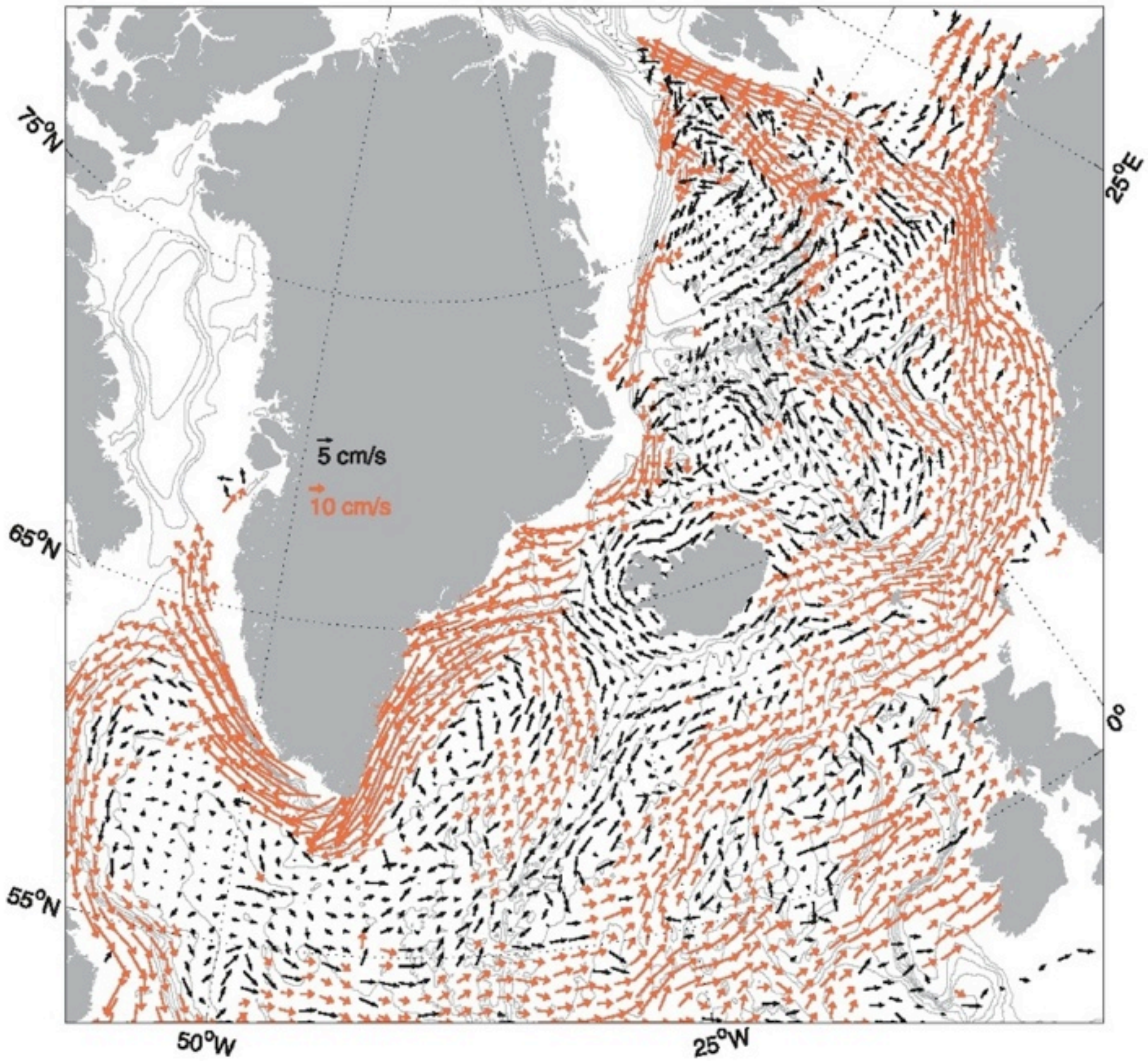
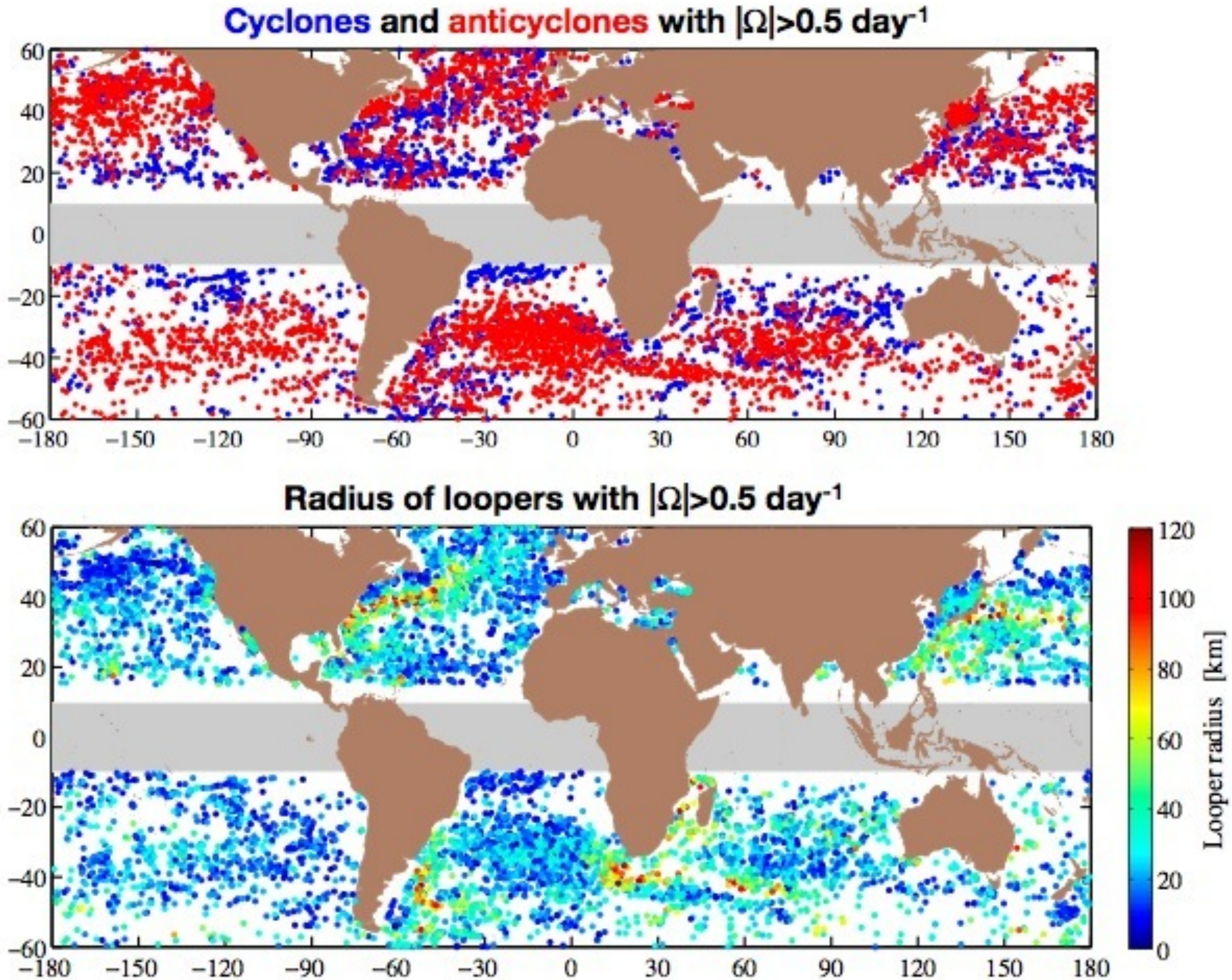


Figure 5. Quasi-Eulerian current vectors derived from 18 day low-passed filtered trajectories and averaged in overlapping 1° latitude × 2° longitude boxes. See text for details of the data treatment. Note the different scales for low-velocity (black arrows) and high-velocity currents (red arrows). Bottom topography at 500 m intervals is shown as gray lines.

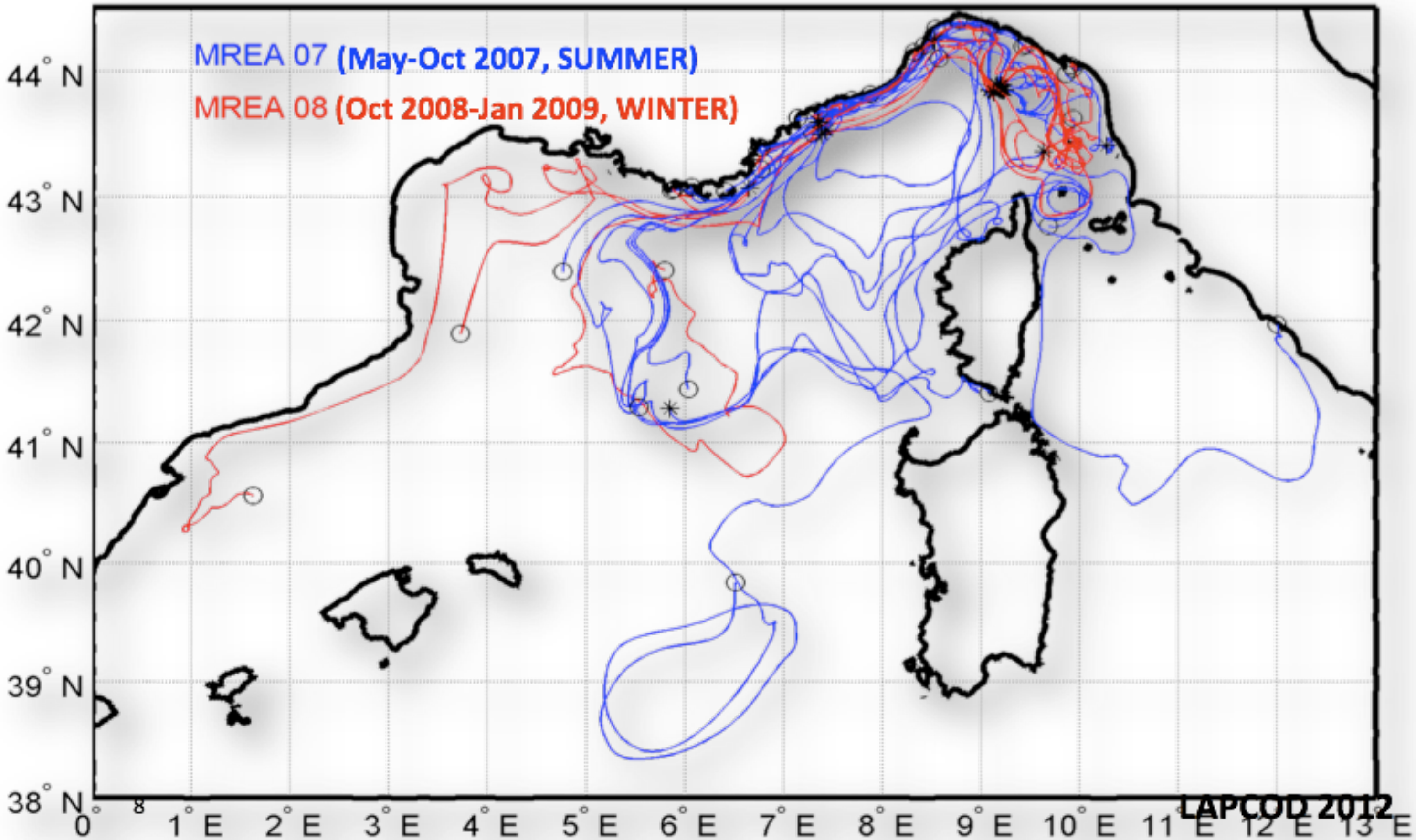


Griffa et al, GRL, 2008

General description of the observations

The Northern Current (NC) and the **general cyclonic circulation** is evident in both years

Complex circulation patterns prevailed in the **eastern Ligurian Sea**, before the drifters eventually joined the NC in the coastal area off Genoa



SUMMER
Closed cyclonic gyre in the Ligurian Sea

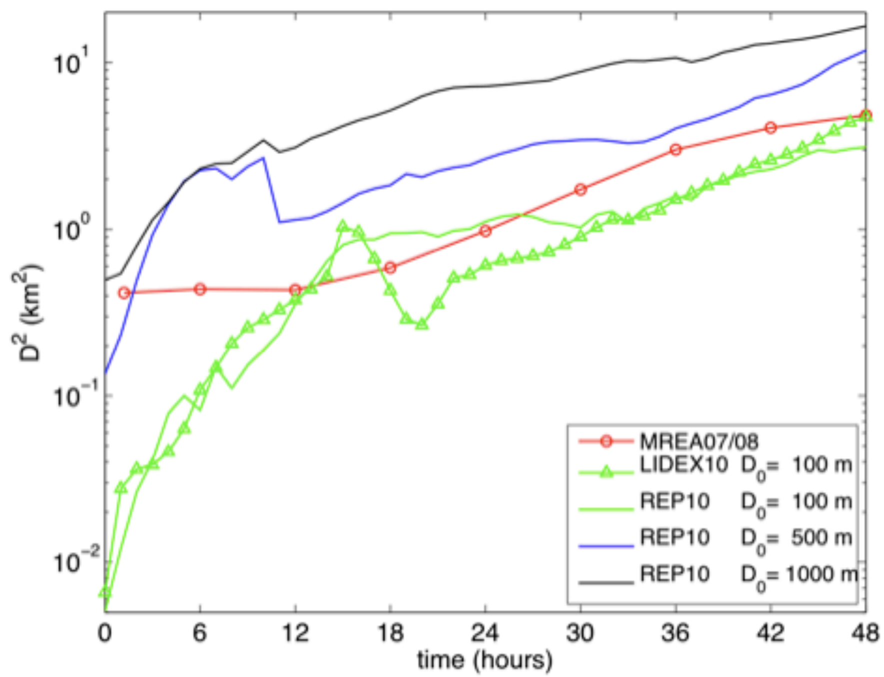
WINTER
Not a closed gyre, drifters follow the continental slope towards the Catalan Sea

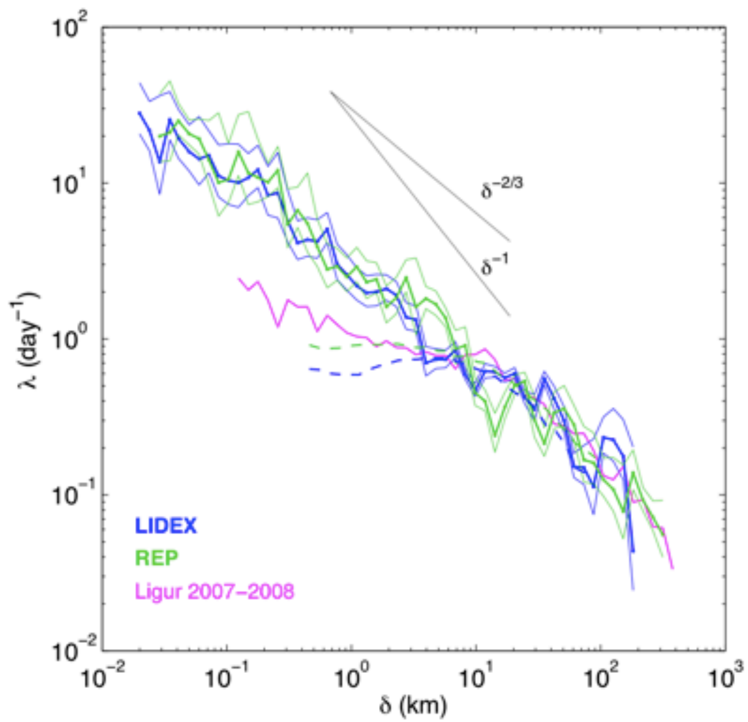
Relative dispersion results

- $D^2(t)$ and FSLEs are consistent for LIDEX and REP and they show that:

• values of Lambda max reach 20 d^{-1} at scales of the order of 100 m, one order of magnitude higher than the ROMS model and MREA results

• relative dispersion at scales 100 m - 1 km appears local (no exponential flattening), and it is likely due to active submesoscale motions.

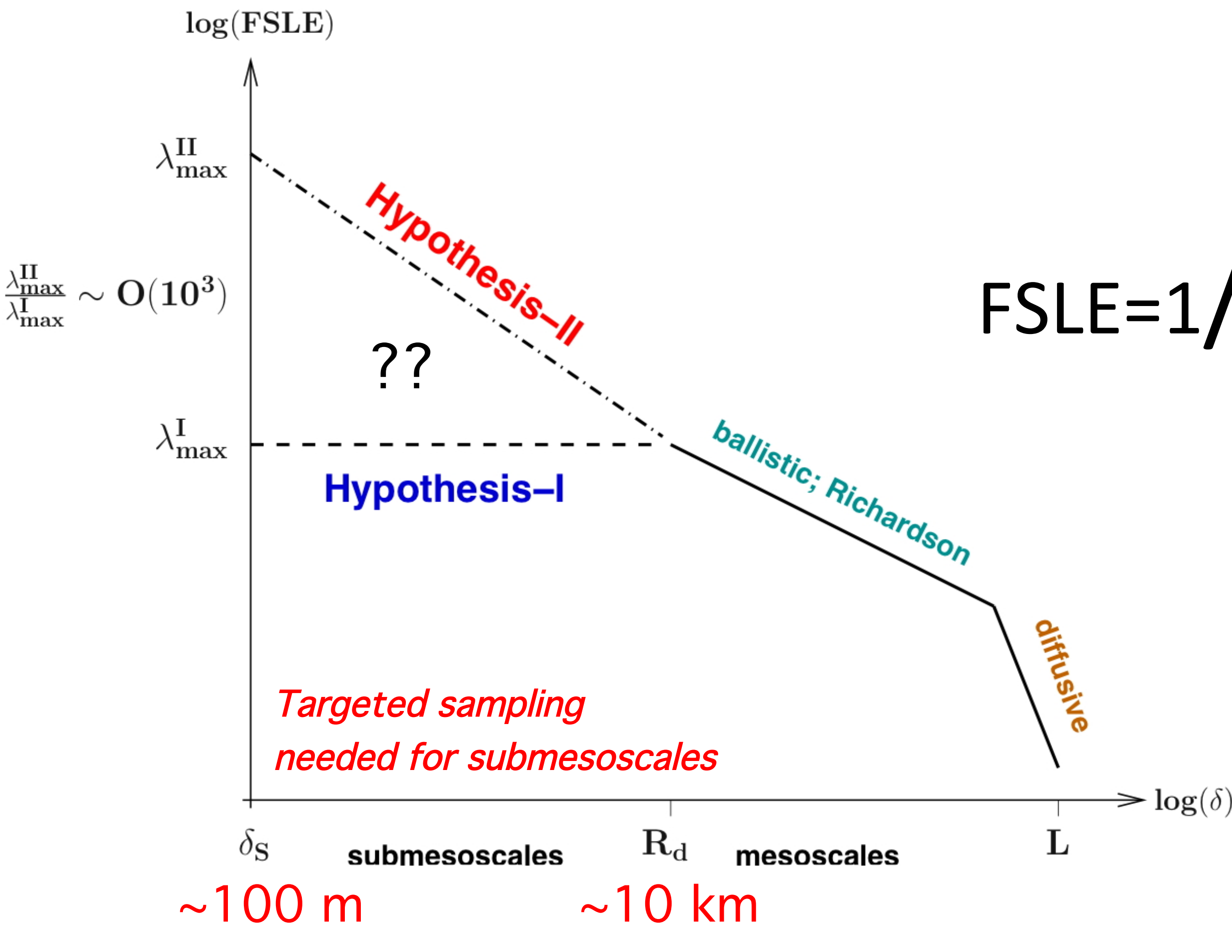




L'Europe en Méditerranée
Europe in the Mediterranean
LAPCOD 2012
Programme cofinanced by European Regional Development Fund (ERDF)
Programme cofinancé par le Fonds Européen de Développement Régional (FEDER)

Griffa

A Scale-Dependent Lagrangian Measure of Ocean Transport



FSLE=1/τ

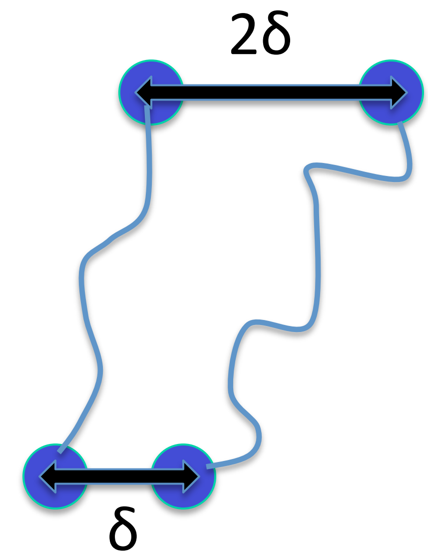


Image credit: Özgökmen & Poje

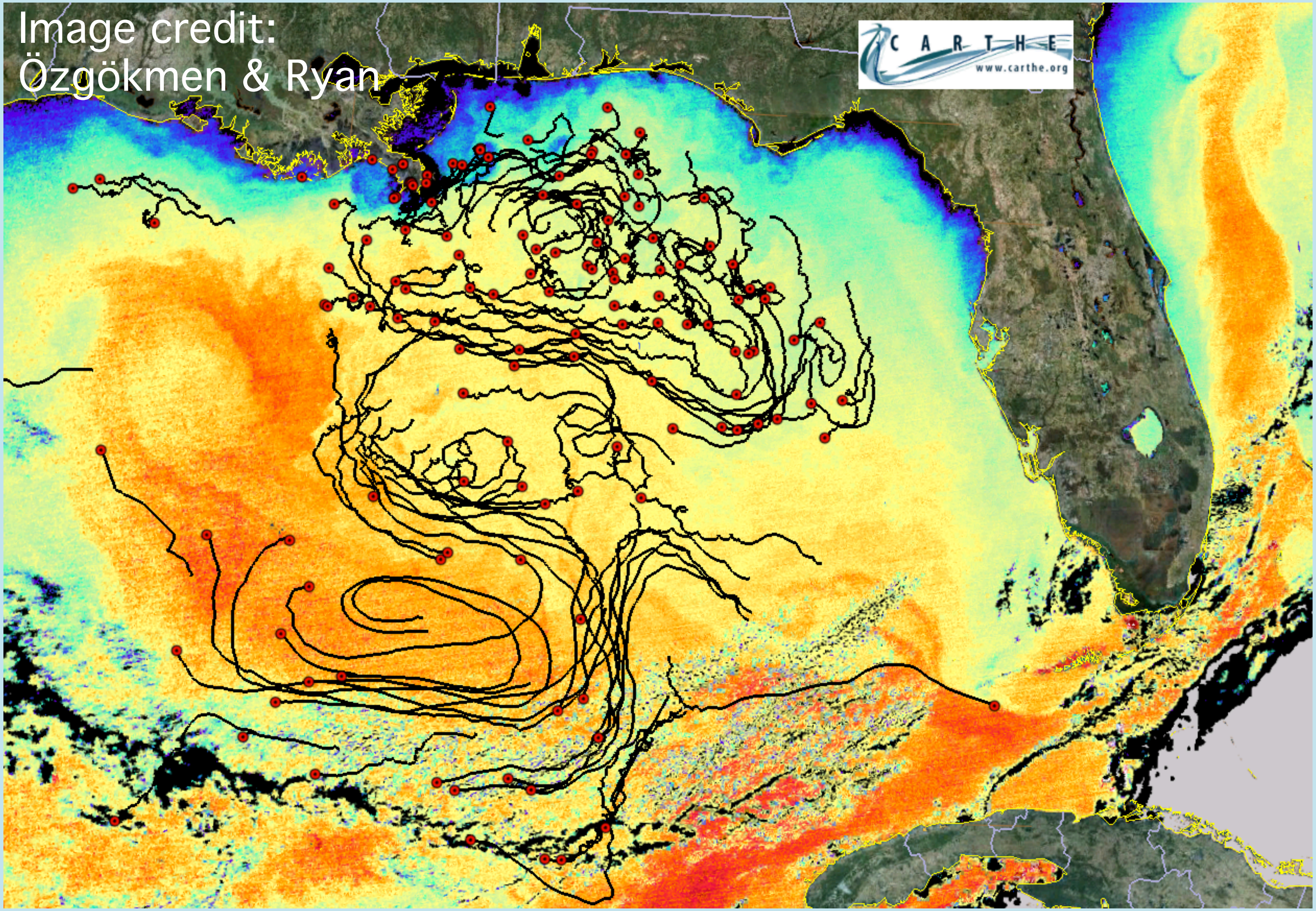
Hypothesis-I: energetic and slowly-evolving turbulent features in control, ***data-assimilating OGCMs adequate for good predictions***

Hypothesis-II: rapidly-evolving small scales dictate relative dispersion at submesoscales, ***parameterizations of submesoscale processes needed in OGCMs***

2010 - Deepwater Horizon Meteor

Post DeepWater Horizon Era – What has been achieved?

Grand Lagrangian Deployment (GLAD) in the GoM



Designed based on LES and NRL/OGCM studies: 317 drifters with 100 m to 10 km spacings, 5-15 mins position transmission, 5 m position accuracy, > 2 months tracking, largest ever synoptic drifter deployment *(GoMRI supported)*

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

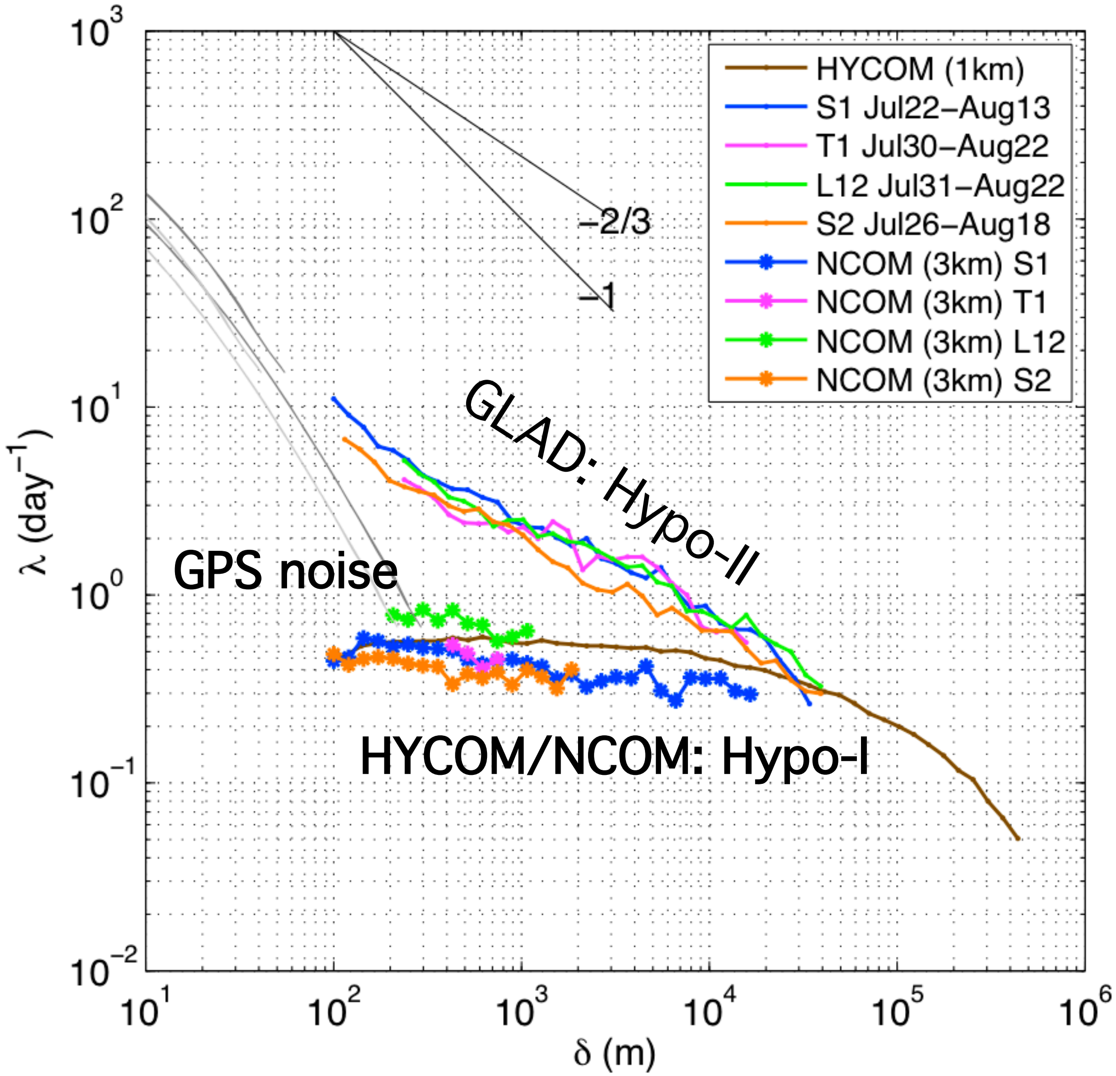


Image credit: Haza

Richardson scaling from 100 m to 20 km; ***submesoscales affect transport!***
(similar to results from Ligurian Sea experiments)

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

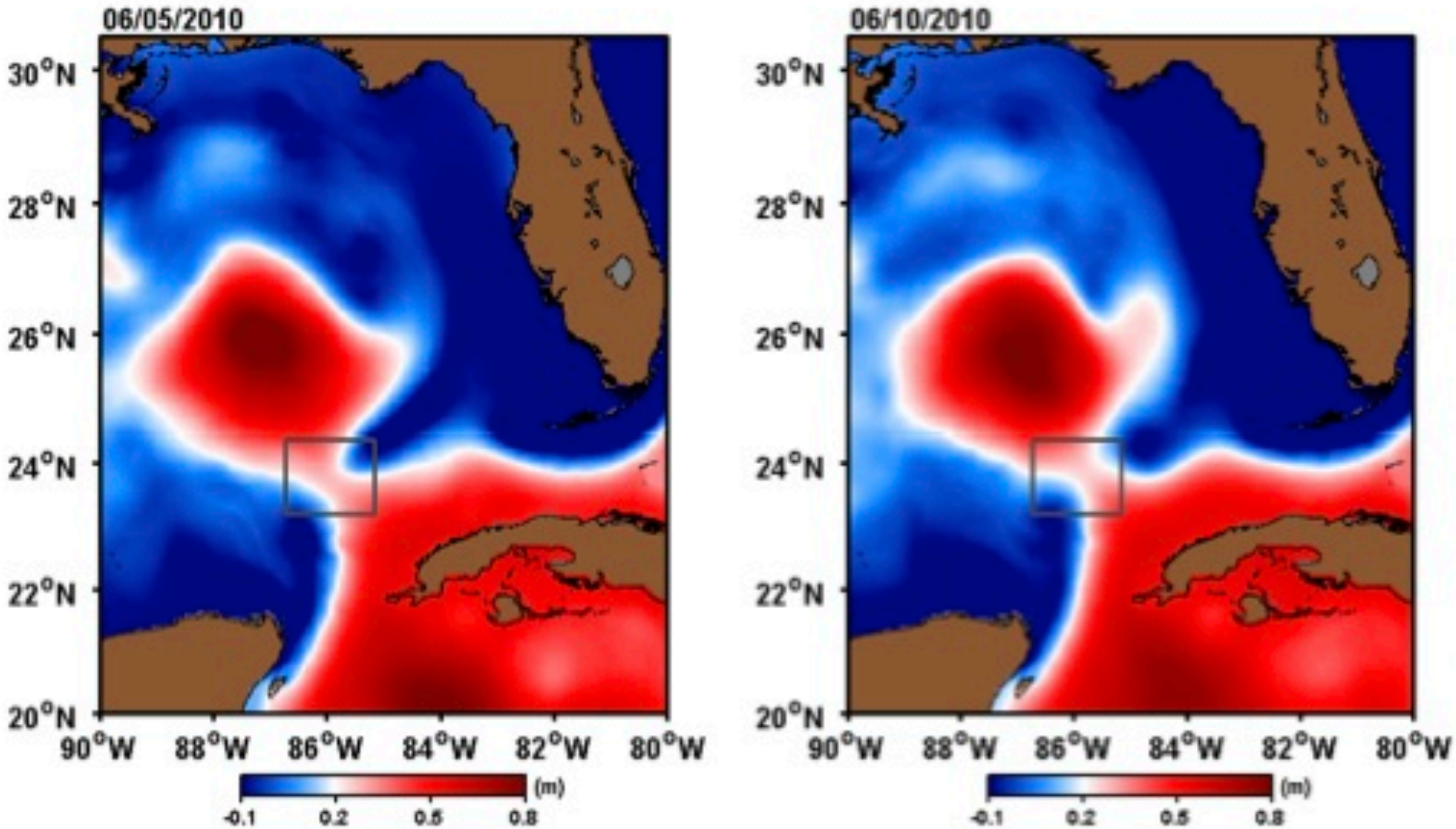
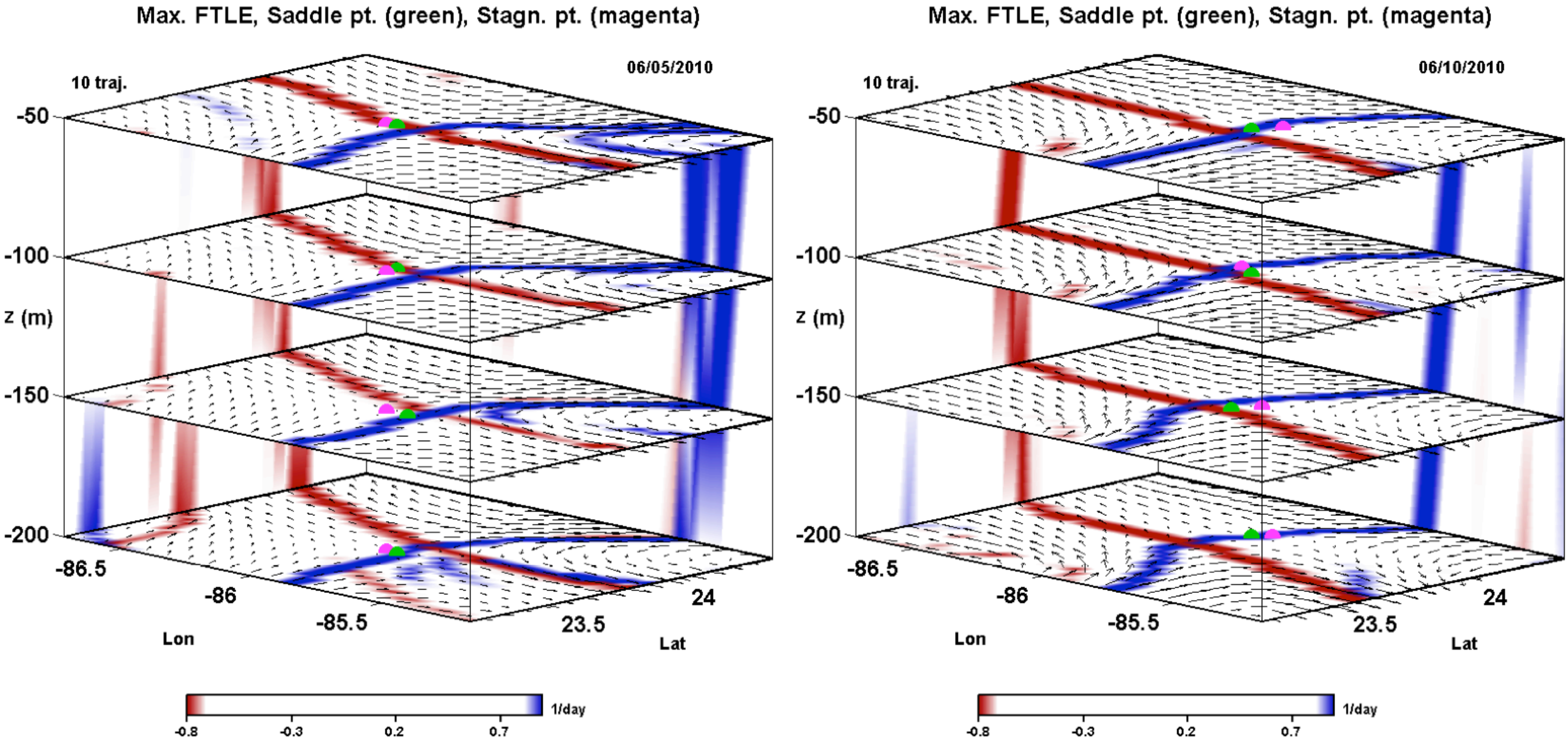


Fig. 1. Sea surface height anomaly (SSHa) of the Loop Current in the Gulf of Mexico during a ring formation event in June 2010. The left panel shows SSHa on 5 June and the right panel shows SSHa five days later on 10 June. The saddle region in the small box is the focus of this study.

Ocean 3D +1 Mixing Boundaries

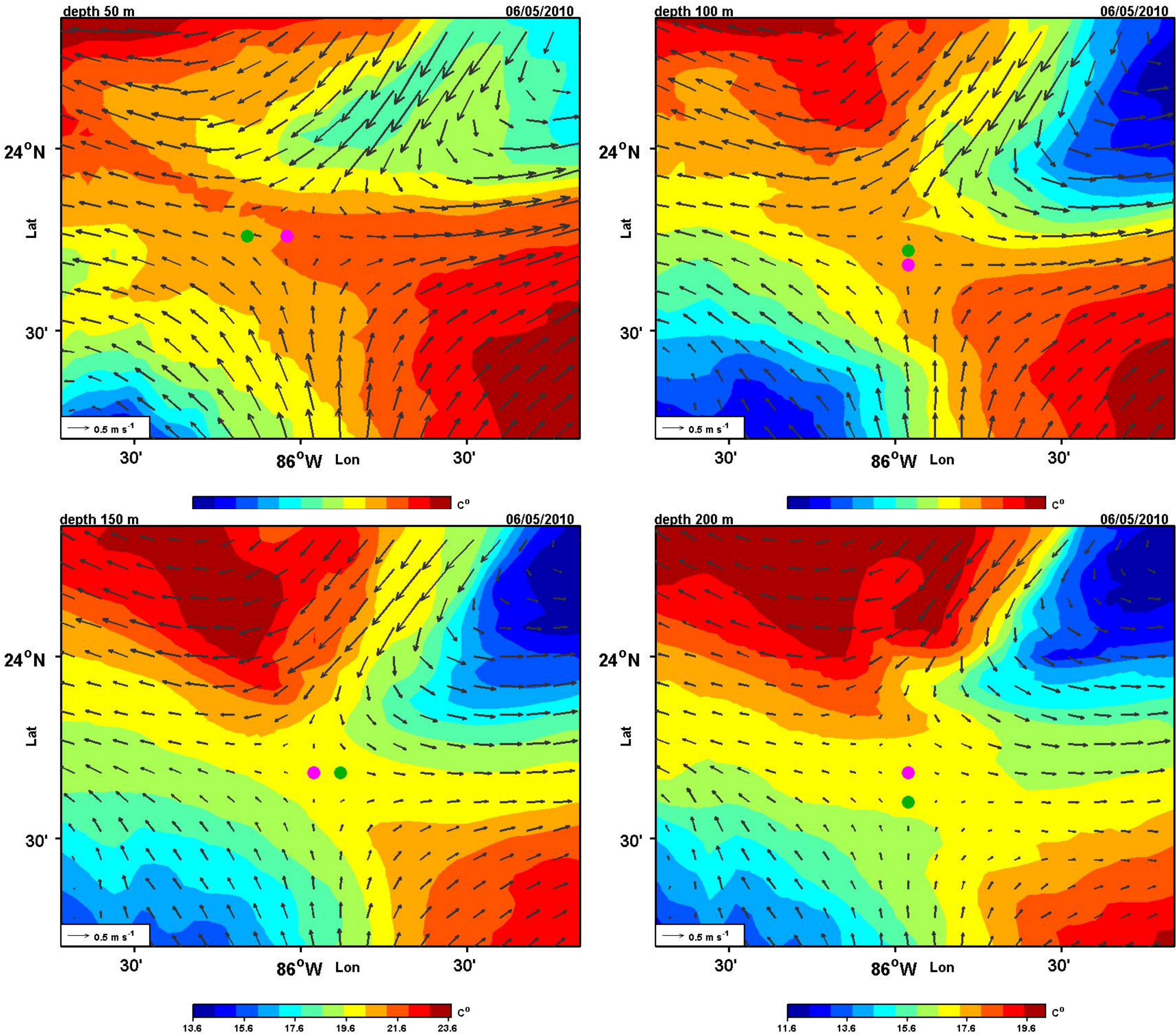
5 June 2010 ← 25 Kilometers → 10 June 2010



Stagnation Point

Saddle Point

Note Temperature Saddle Point diagnoses critical region



Prediction is hard, especially about the future – Y. Berra

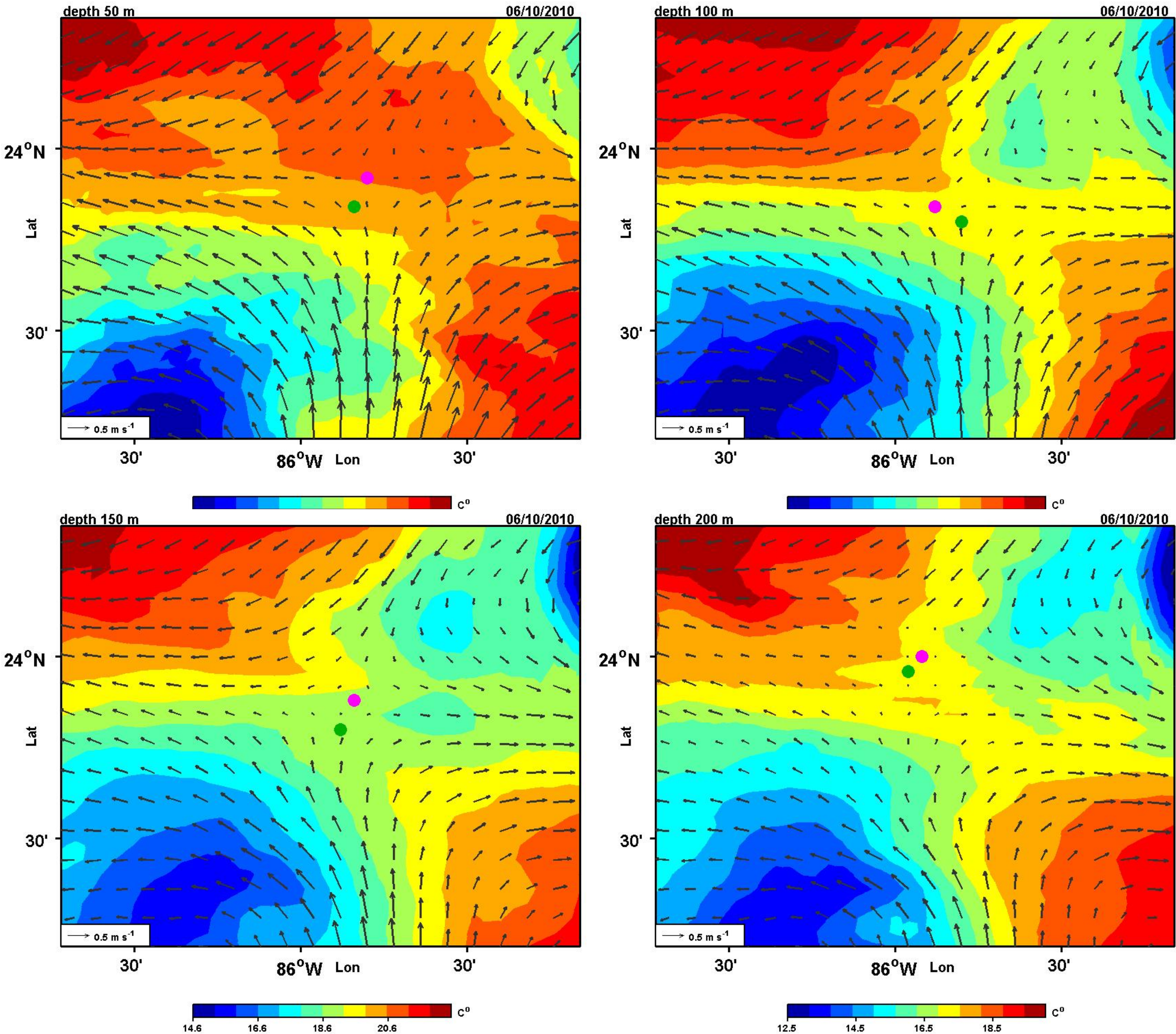
The New Era

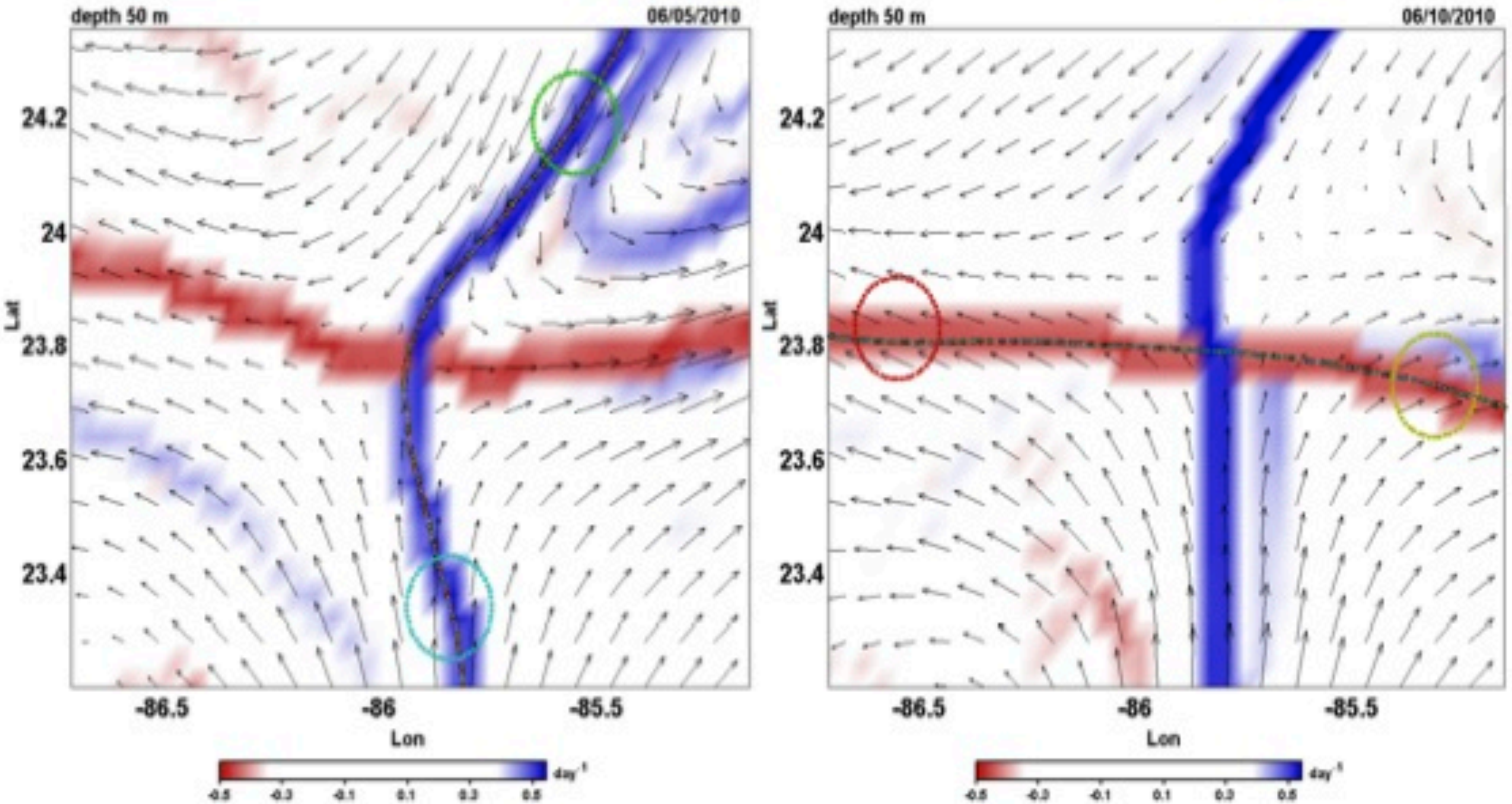
- IDOE ⟷ GoMRI, POLYMODE ⟷ CARTHE
- Trends
  - Continued growth of Lagrangian user community
  - 3D +1 Ocean
  - Focused "Lagrangian" experiments coupled with model developments – a la GLAD
  - Submesoscale – the new frontier
  - Lagrangian data assimilation
- Prediction
  - Turbulence from Lagrangian View
  - The last kilometer – ocean to land

Stagnation Point

Saddle Point

Note Temperature Saddle Point diagnoses critical region





(a) (b)

Fig. 6. Plots of FTLE ridges at depth 50 m for (a) 5 June 2010 (b) 10 June. The green and aqua circles in panel a denote the fluid blobs that were advected forward 5 days and shown in the curve lying in the unstable (red) FTLE on 19 June. Similarly the red and yellow circles in panel b were advected backwards 5 days and shown in the curves lying in the stable (blue) FTLE on 5 June.

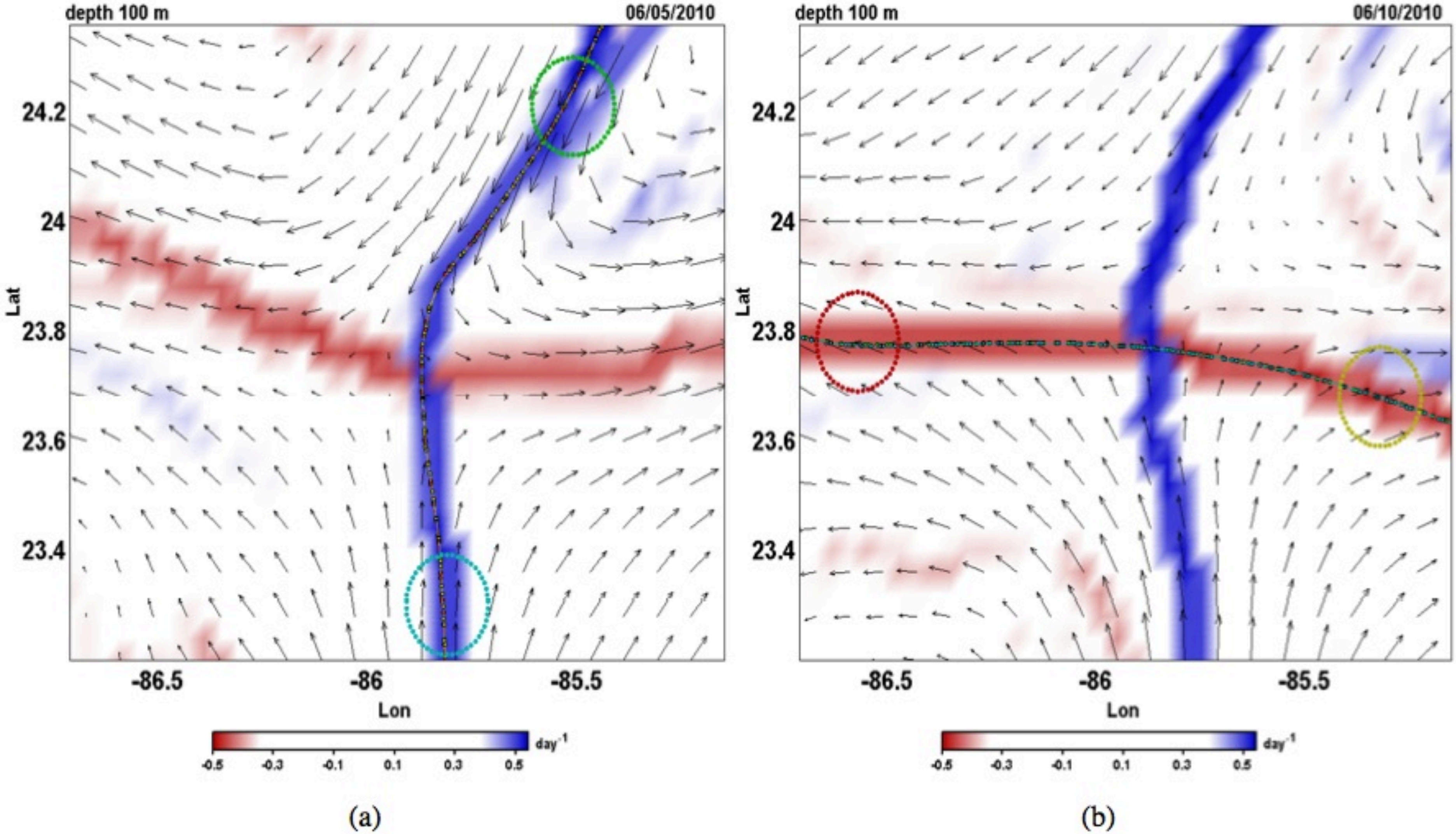


Fig. 7. Same as figure 6 except at 100 m.

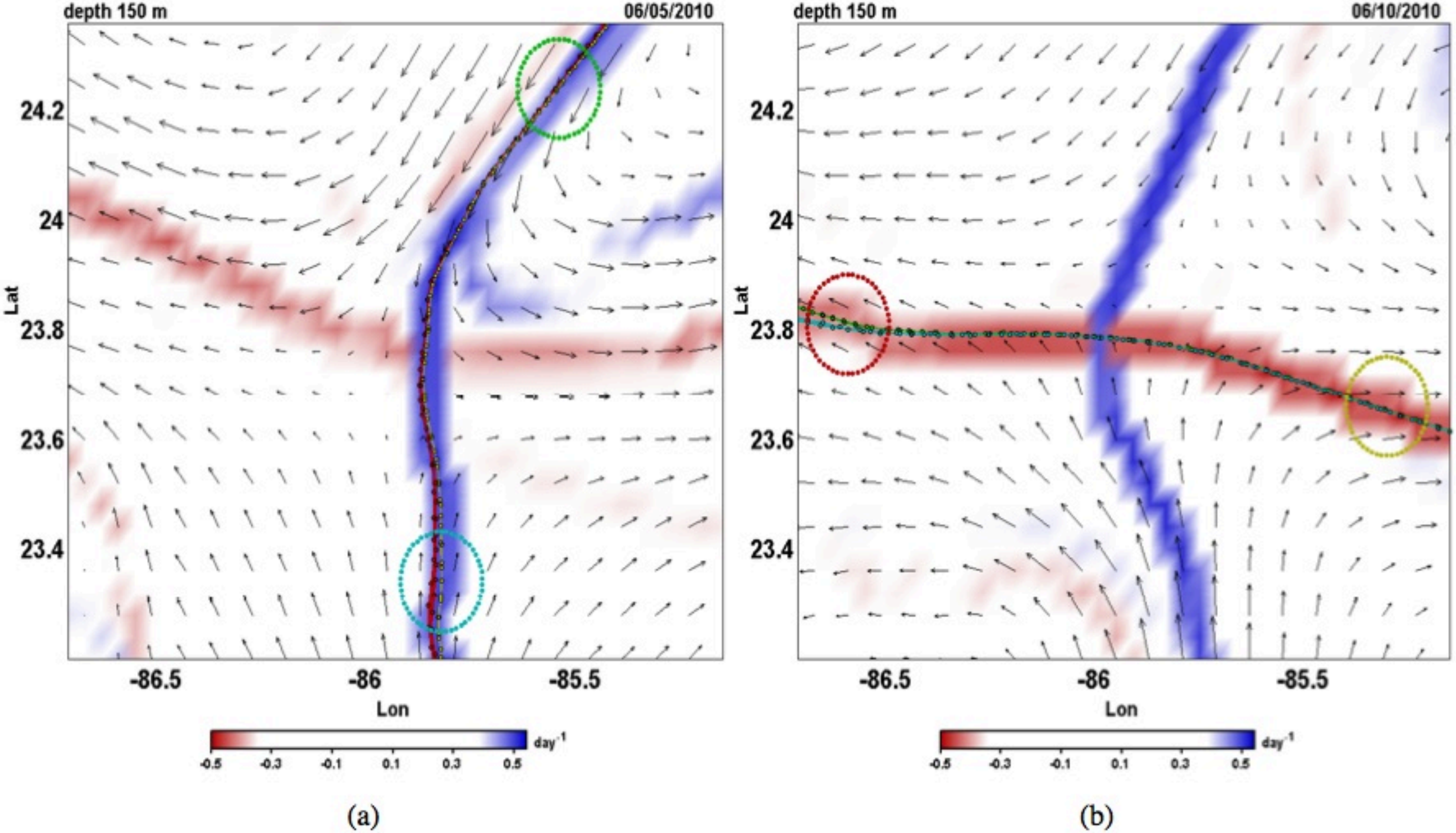


Fig. 8. Same as figure 6 except at 150 m.

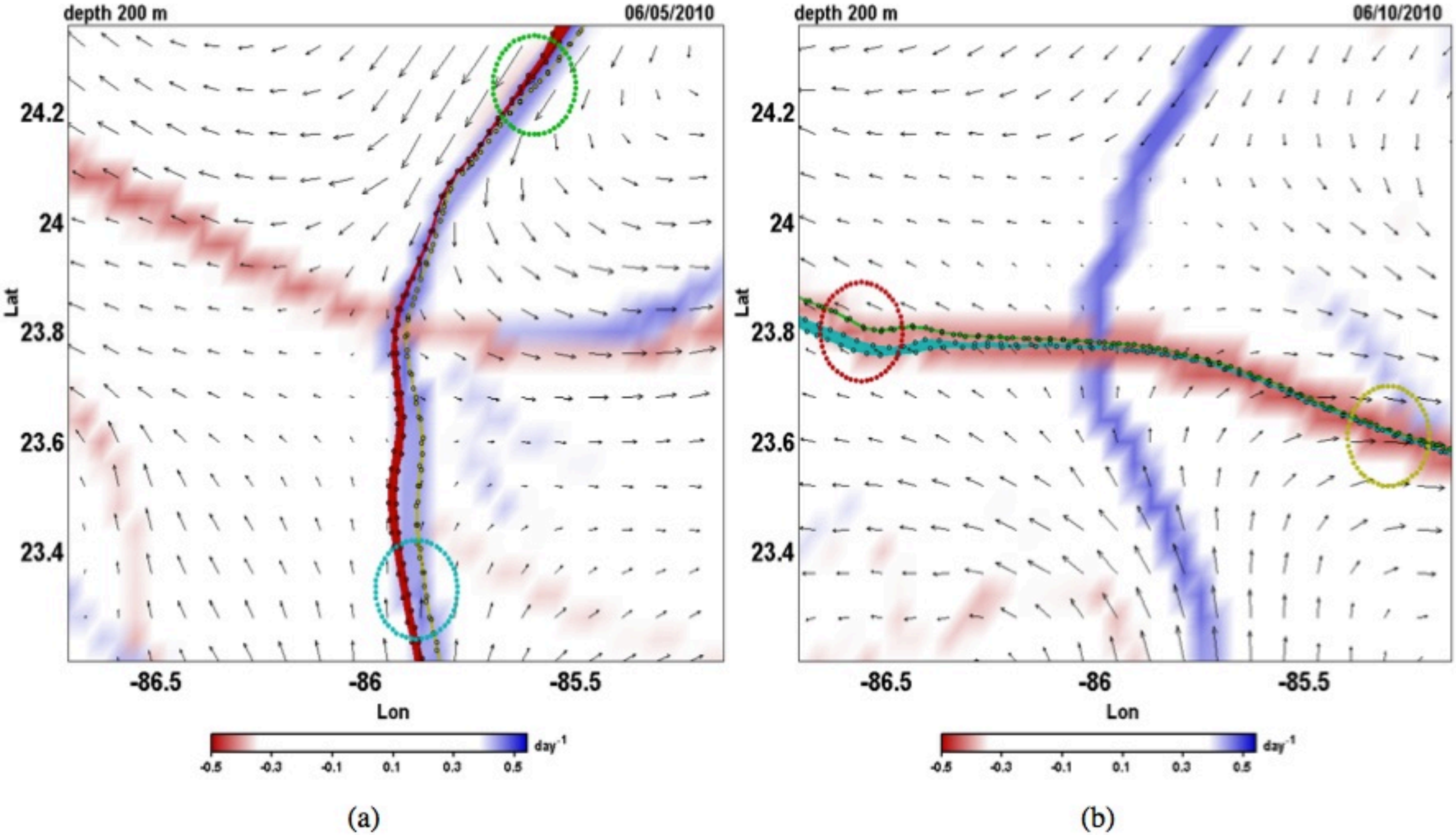


Fig. 9. Same as figure 6 except at 200m.