A Lagrangian Approach to Study the Gulf of Mexico's Deep Circulation:

Overview and Scientific Approach

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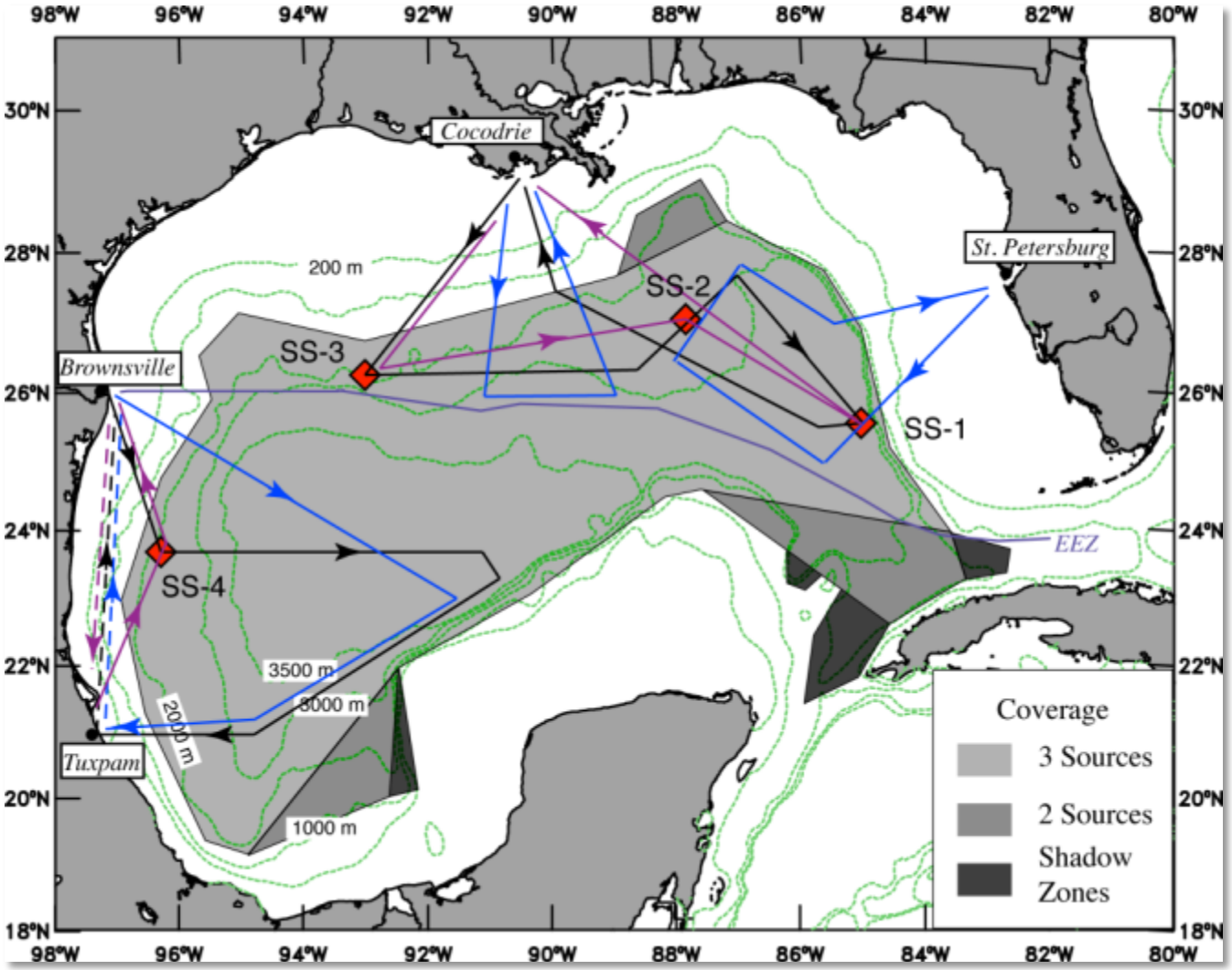
Program Objectives, Organization & Schedule

Program Objectives

Dynamics of the Deep Circulation of the Gulf using Floats

1. Deploy subsurface and profiling drifters over three years inside the Gulf of Mexico;
2. Analyze these data to produce maps of currents in the deep waters of the Gulf;
3. Estimate Lagrangian statistics of these current fields such as length and temporal scales;
4. Estimate particle horizontal dispersion and explore the feasibility of estimating vertical dispersion of pollutants and biological material; and
5. Provide information for BOEMRE to fulfill its regulatory mission and comply with NEPA requirements.

Study Region



Program Outline

Three-Year Field Study

1. Deploy & retrieve 4 sound sources
2. Deploy RAFOS Floats at 1,500 & 2,500 m on the following schedule – Gulf wide:
   - Year 1: 40 Floats – 10 surfacing after 1-year
     – 30 surfacing after 2-years
   - Year 2: 80 Floats – All surfacing after 2-years
3. Deploy 6 profiling APEX floats with CTD and optical sensors for 3 years
4. Collect satellite altimetry, SST, and ocean color to study and map surface layer circulation for the 3-year measurement interval.

Science Team

Dr. Amy Bower (WHOI) – RAFOS & Profiling Floats,
Statistical Analysis

Dr. Paula Perez-Brunius (CICESE) – RAFOS Floats
Chief Scientist, Mexican EEZ Cruises

Dr. Robert Leben (CCAR) – Remote Sensing and Altimetry

Dr. Peter Hamilton (SAIC) – Feature Models & Data Synthesis & Program Manager

Technical and Management Support

Mr. James Singer (SAIC) – Chief Scientist, US EEZ Cruises, Logistics

Mr. Paul Blankinship (SAIC) – Data Manager

Science Review Group

Dr. John Bane (University of North Carolina)

Dr. Joseph H. LaCasce (University of Oslo)

Dr. Susan Lozier (Duke University)

Tasks: Scientific advice and review to BOEMRE and PIs

- Post-award meeting
- Meeting to review data & analysis plans after Year-1 retrievals
- Review of final report

Schedule

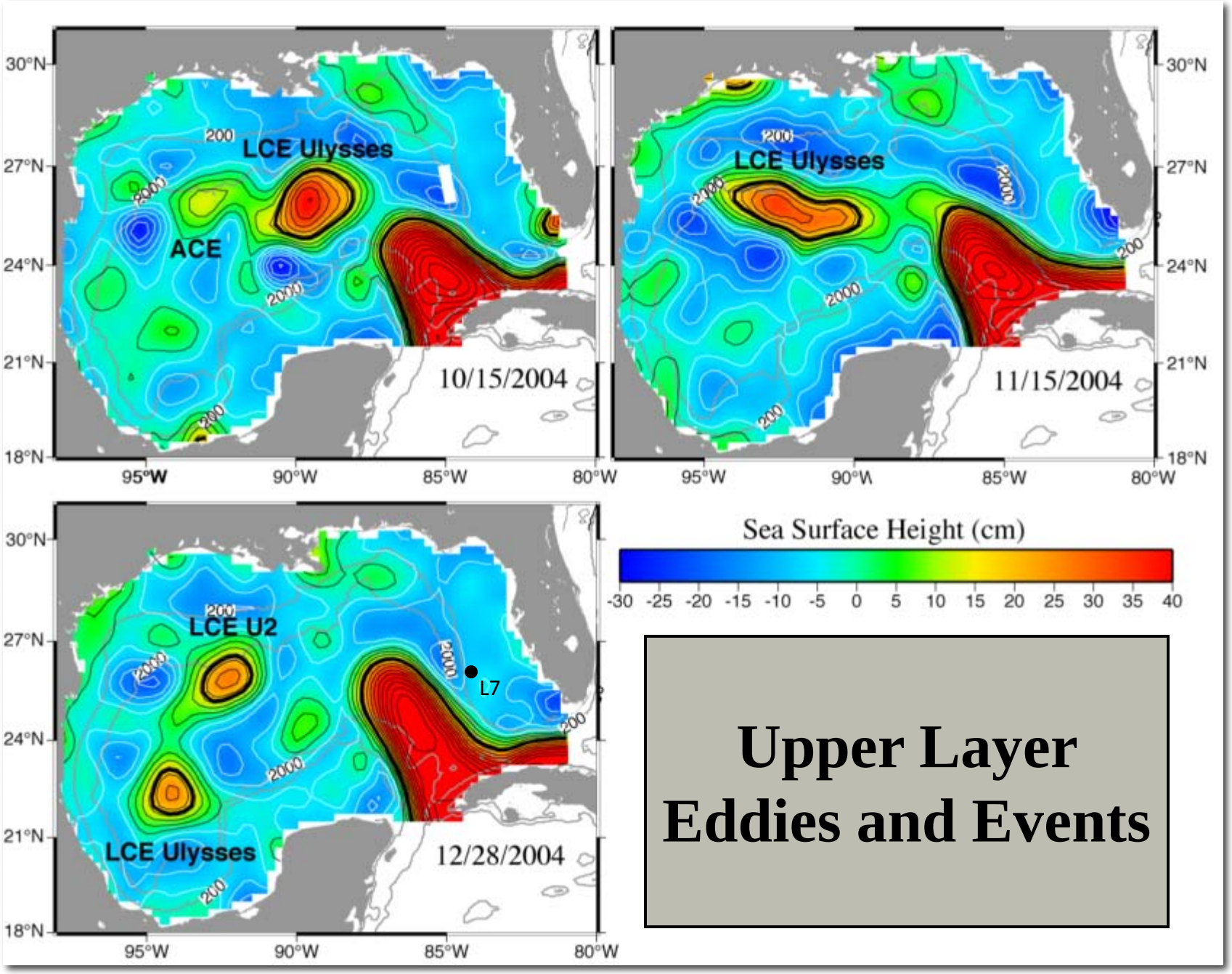
Field Program

1. July – August 2011: Deploy 4 Sound Sources, 40 RAFOS, & 6 APEX
2. July – August 2012: Deploy 80 RAFOS
3. August – September 2014: Retrieve Sound Sources

Analysis and Reports

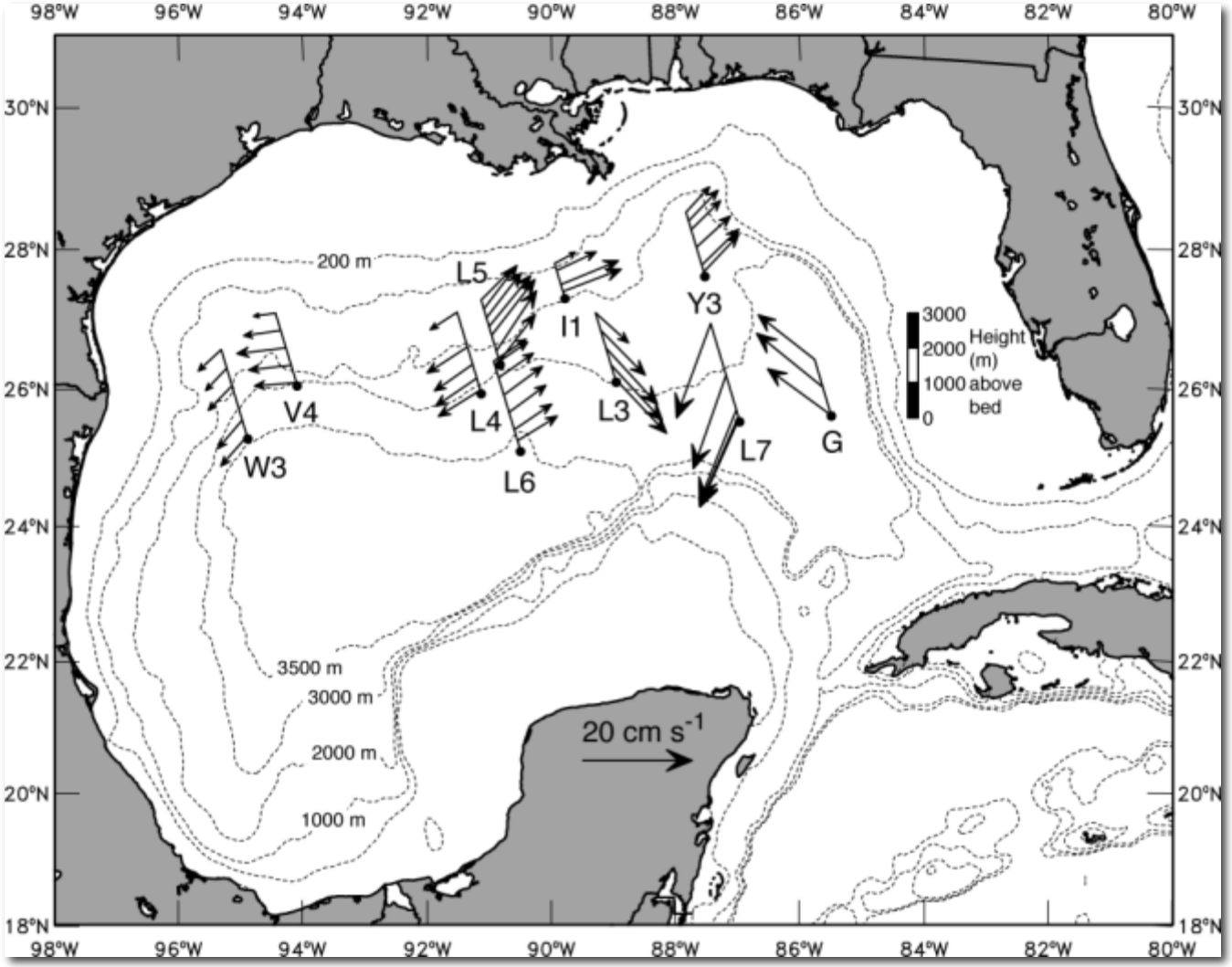
1. September → 6 APEX Profiling Data & Tracks
2. June 2012: 10 RAFOS Track Data
3. August 2013 → 40 RAFOS Track Data
4. August 2014 → 80 RAFOS Track Data
5. October 2015: Final Report

Experimental Design Considerations: Deep Gulf Circulation Features and Processes

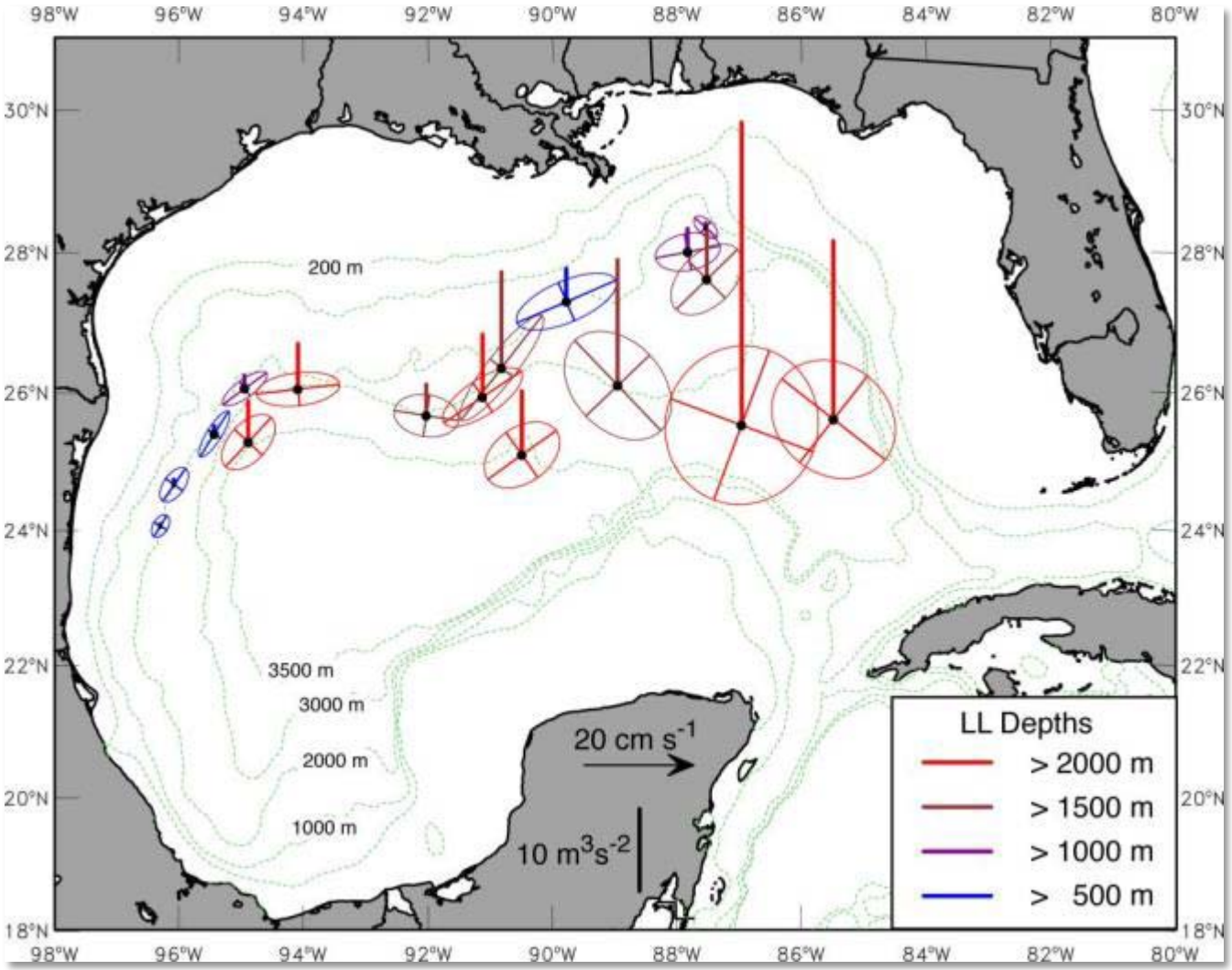


Upper Layer Eddies and Events

Depth Dependence of Lower-Layer Currents

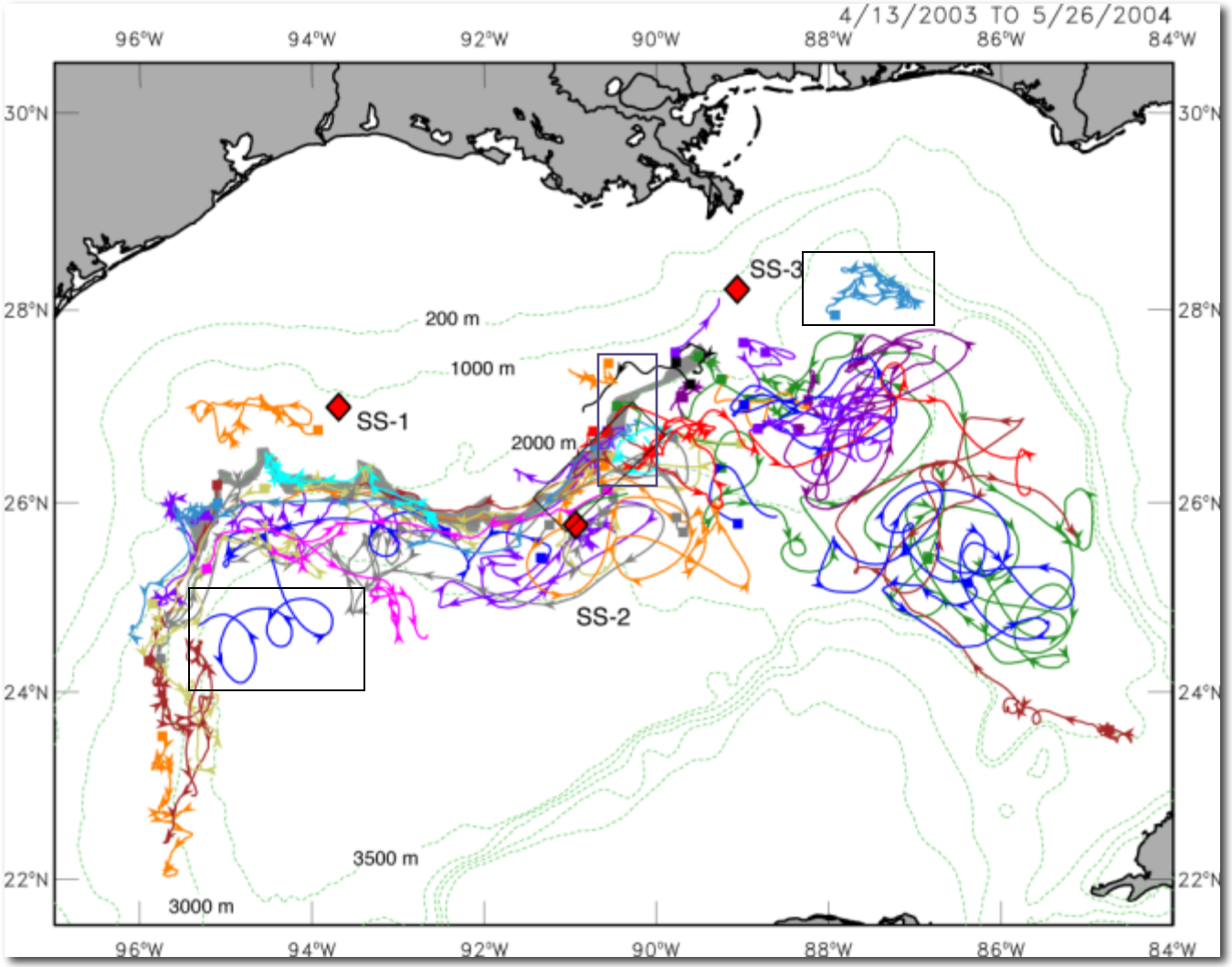


CEOF Mode 1 EKE for Lower Layer

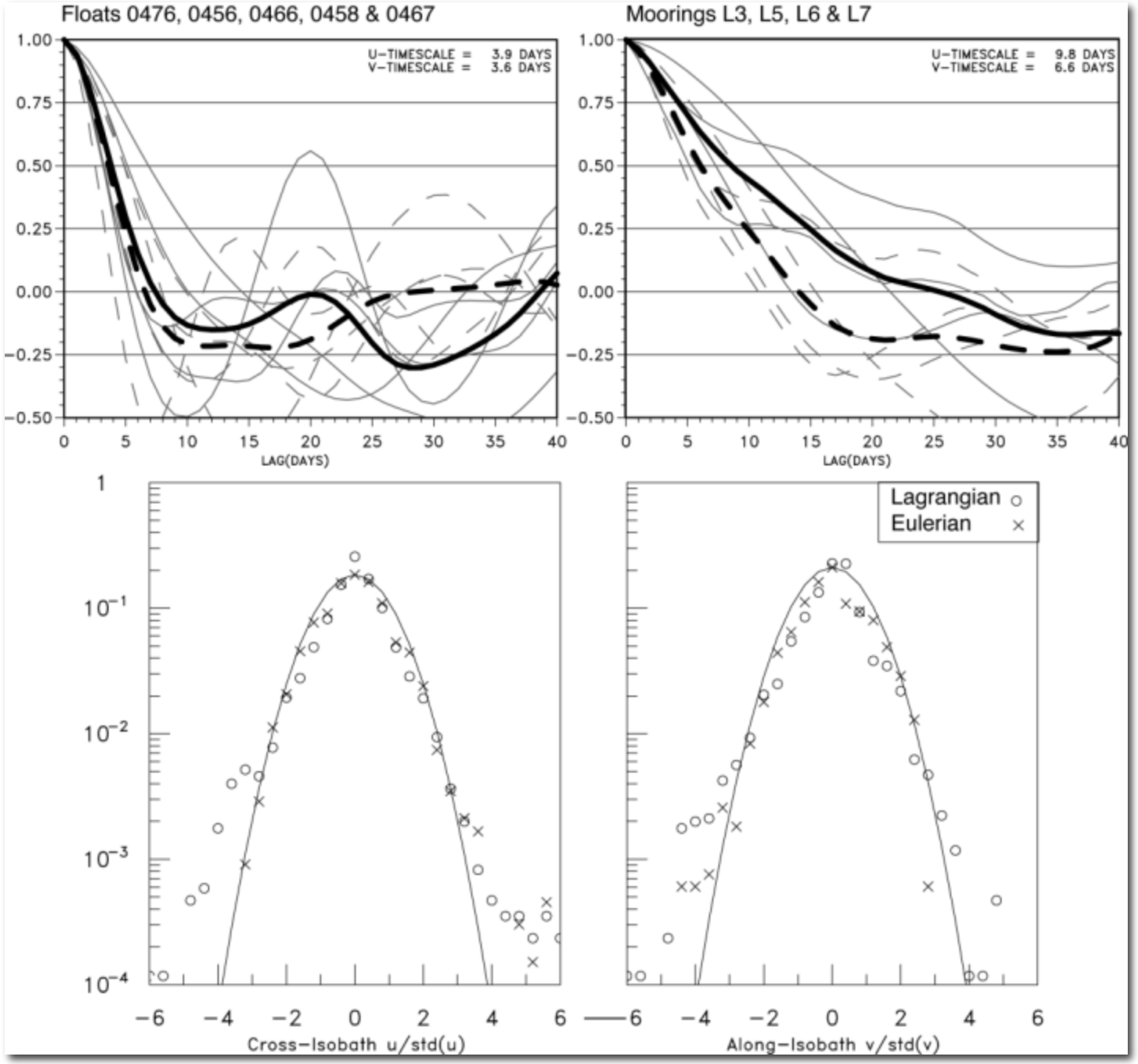


$$EKE_H = \tfrac{1}{2} < \int U^* U dz > \; = \tfrac{1}{2} \sum_n < A_n^*(t) A_n(t) > \int_{1000}^{H-50} e_n^*(z) e_n(z) dz$$

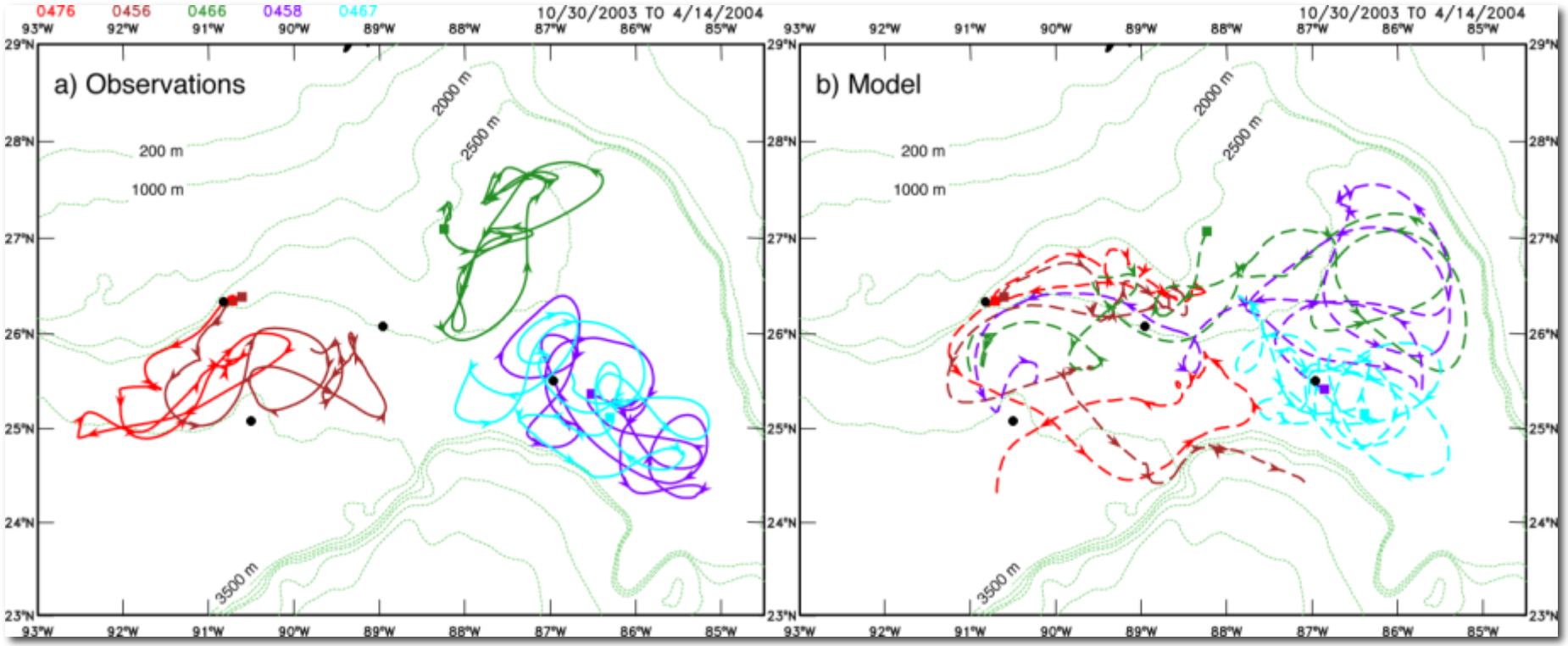
RAFOS Floats from the Exploratory Program



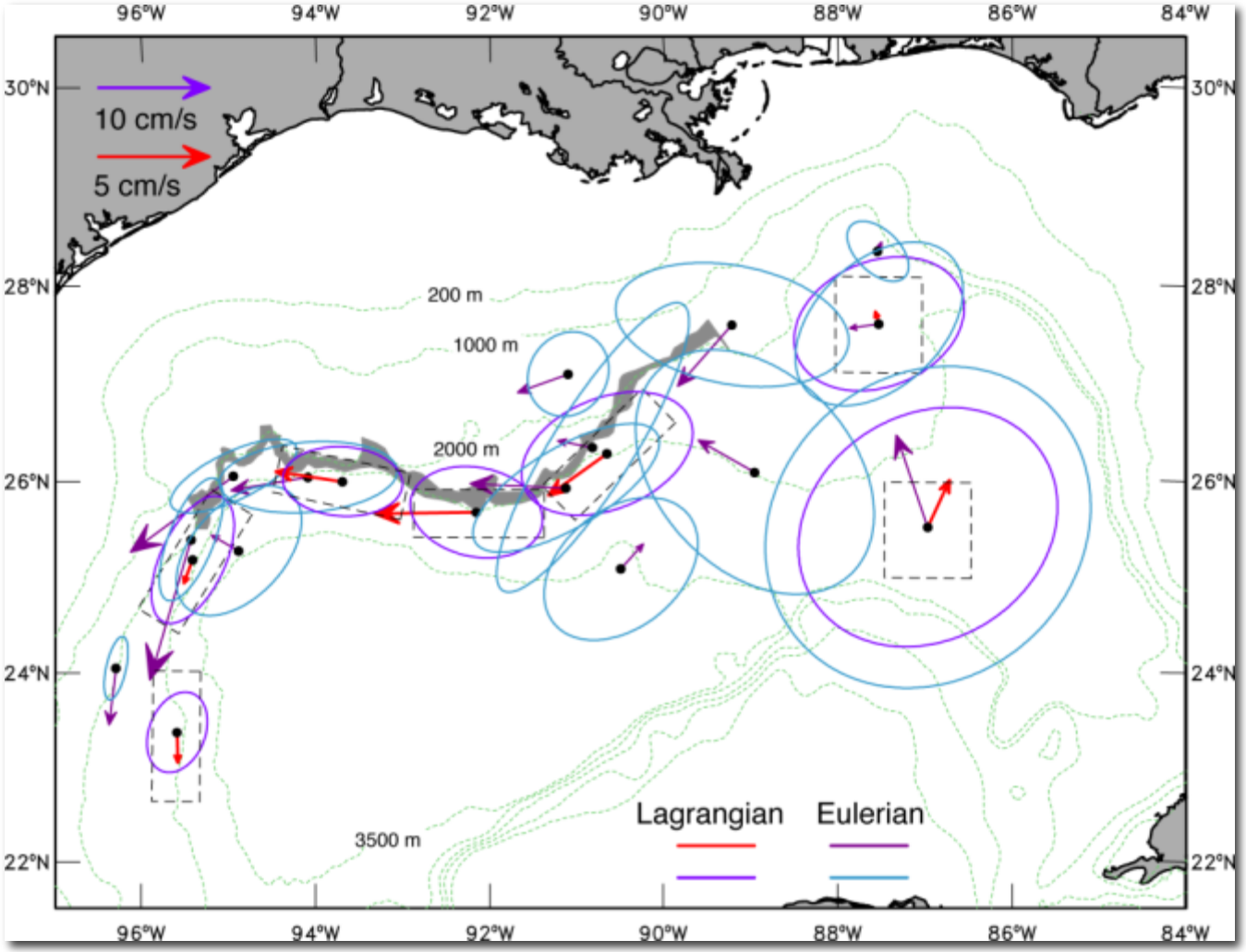
Lagrangian and Eulerian Auto-correlations and PDFs



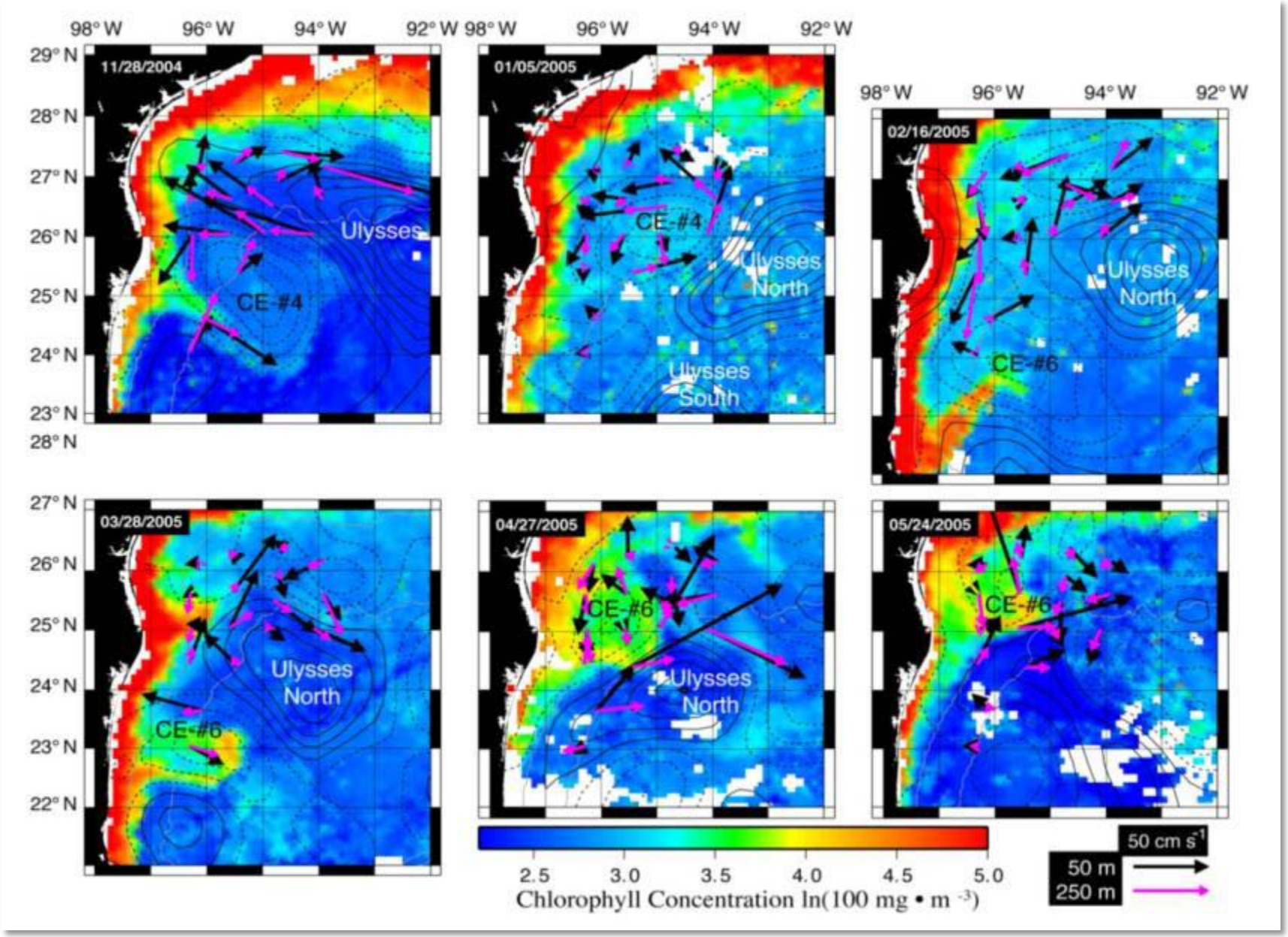
Comparison of Observed and Model Floats



Sigsbee Escarpment Boundary Current



Ulysses Interaction with the Western Slope



Summary

Two-Layer System

- Upper-Layer: Eddy Dominated with a Range of Scales
- Lower-Layer: TRW Dominated

Deep Sigsbee Escarpment Boundary Current

- Rectification of TRWs by Shoaling Topography

Loop Current is the Major Forcing for both Upper-Layer Eddies and Lower-Layer Waves

TRWs Could be Generated by Eddy-Eddy and Eddy-Topography Interactions throughout the Deep Gulf

Deep Eddies may Exist along with TRWs

- Lagrangian Observations in Western Gulf
- Produced by Models

Field Program

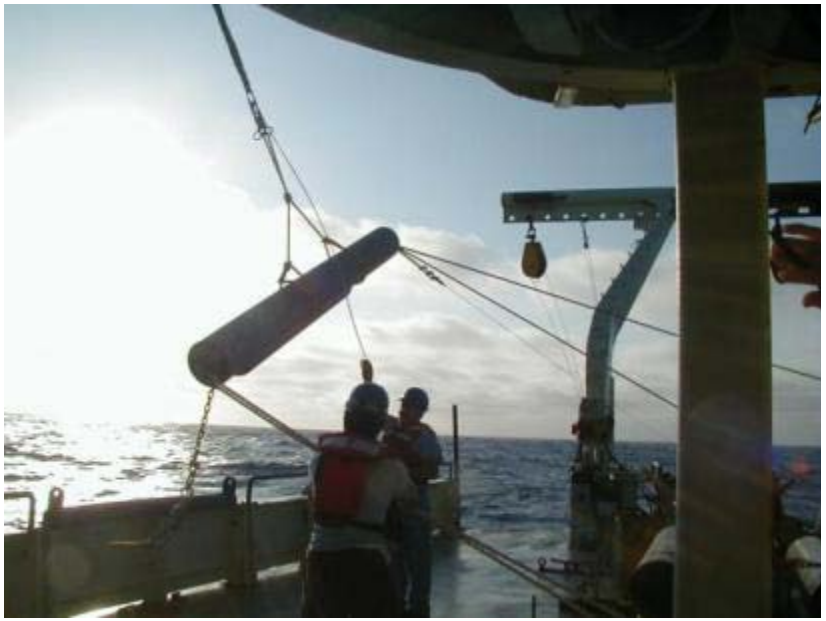
Designed to:

- Measure deep circulation Gulf-Wide with a high degree of statistical confidence,
- Advance understanding of deep circulation processes, & connections to surface layer eddies over a range of scales
- Generate an exceptional database for use by model and other studies

Components of the Field Program are:

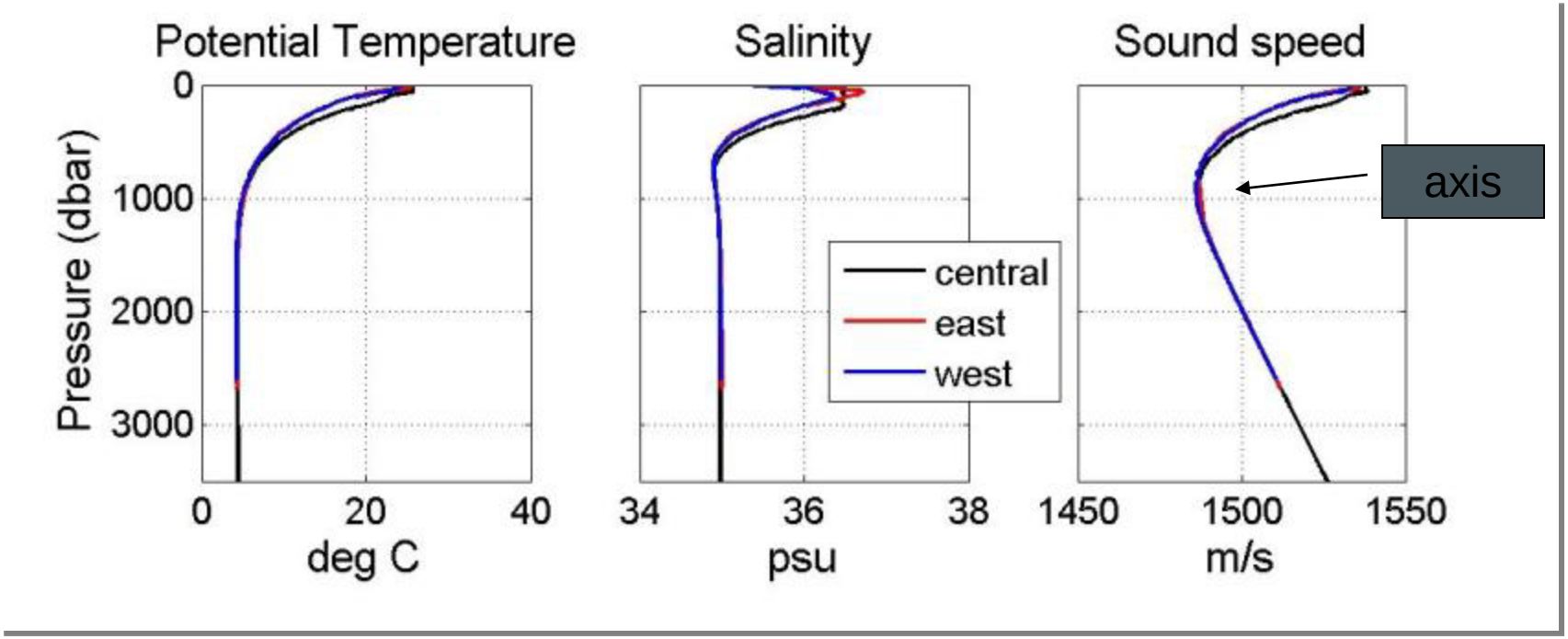
- Sound Sources
- RAFOS Deployments
- Profiling Float Deployments
- Remote Sensing

Sound Sources

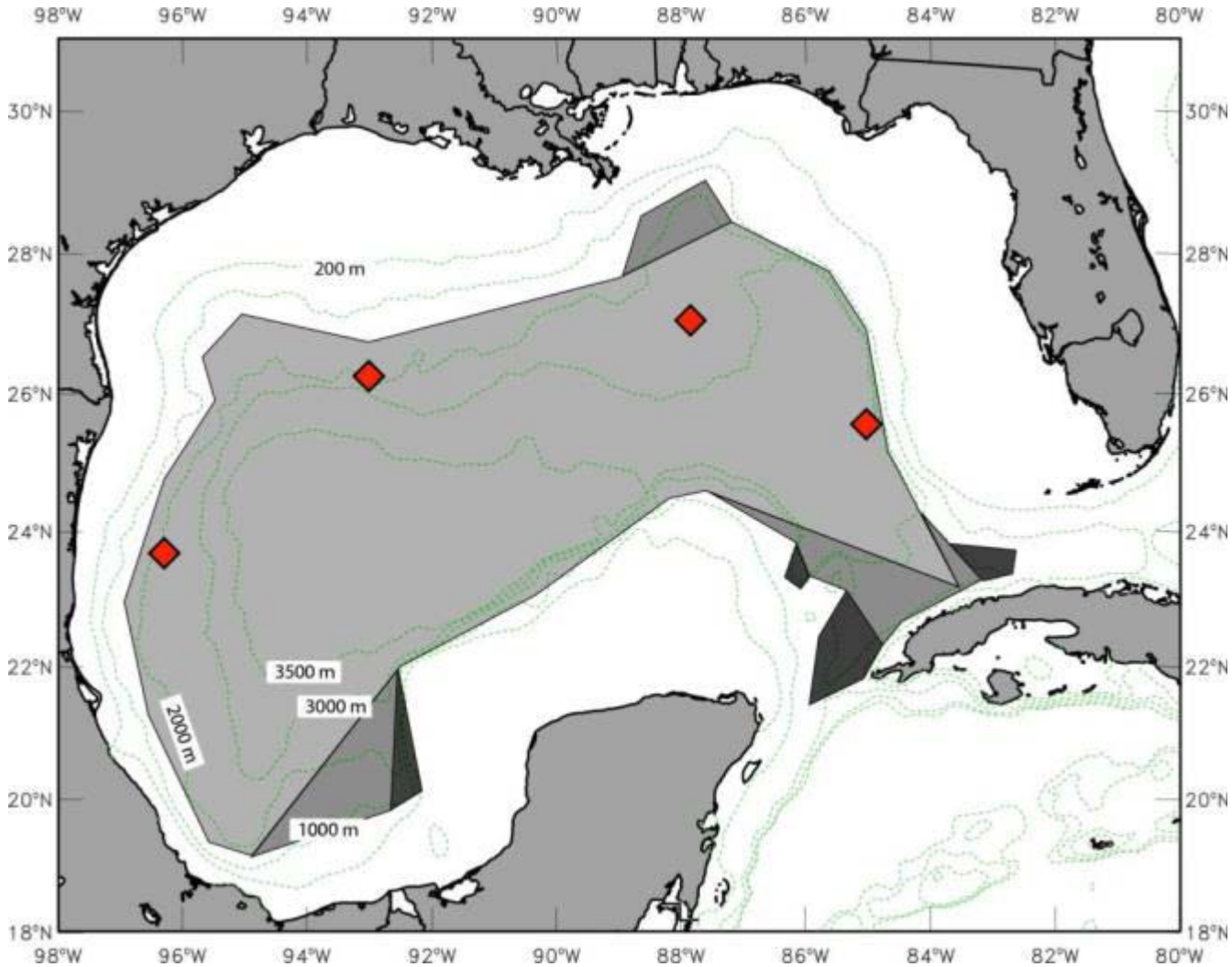


- Deploy total of 4 sound sources
  - Purchase 2 new from TWR
  - Build 1 at WHOI (URI design)
  - Refurbish 1 TWR source
- Standard 260-Hz RAFOS sources
- Lifetime of 4,000 pongs (3.7 years)

Sound Channel

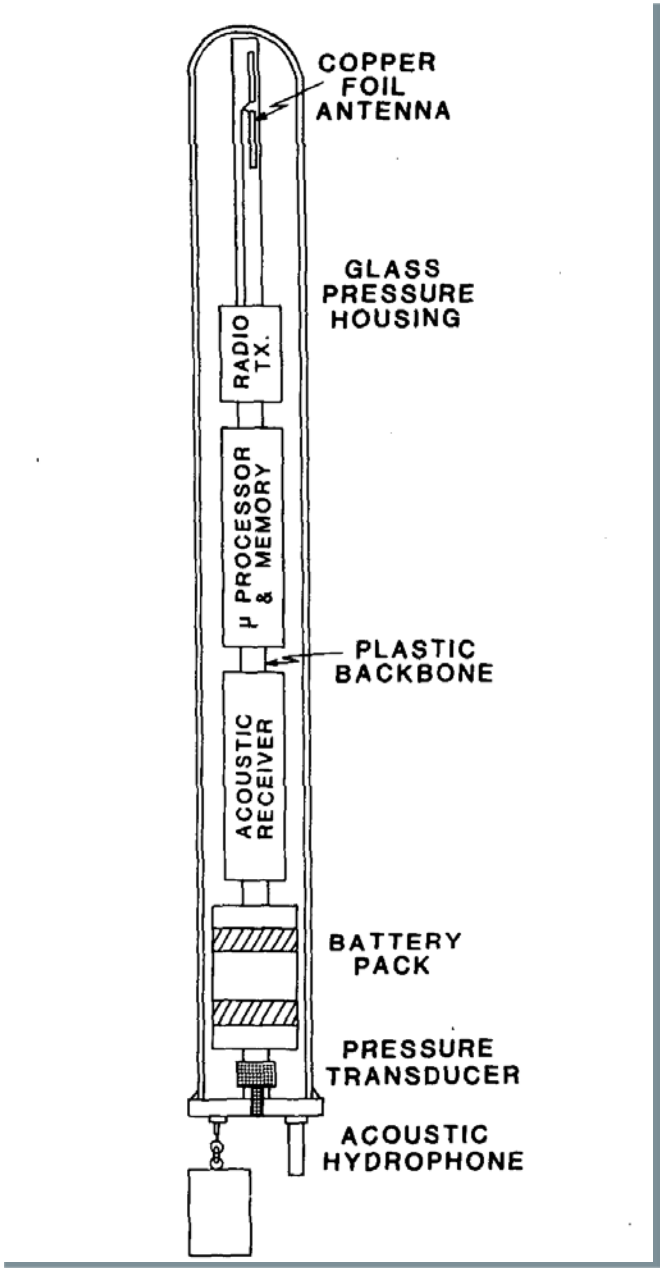


Source Deployment Positions



RAFOS Floats

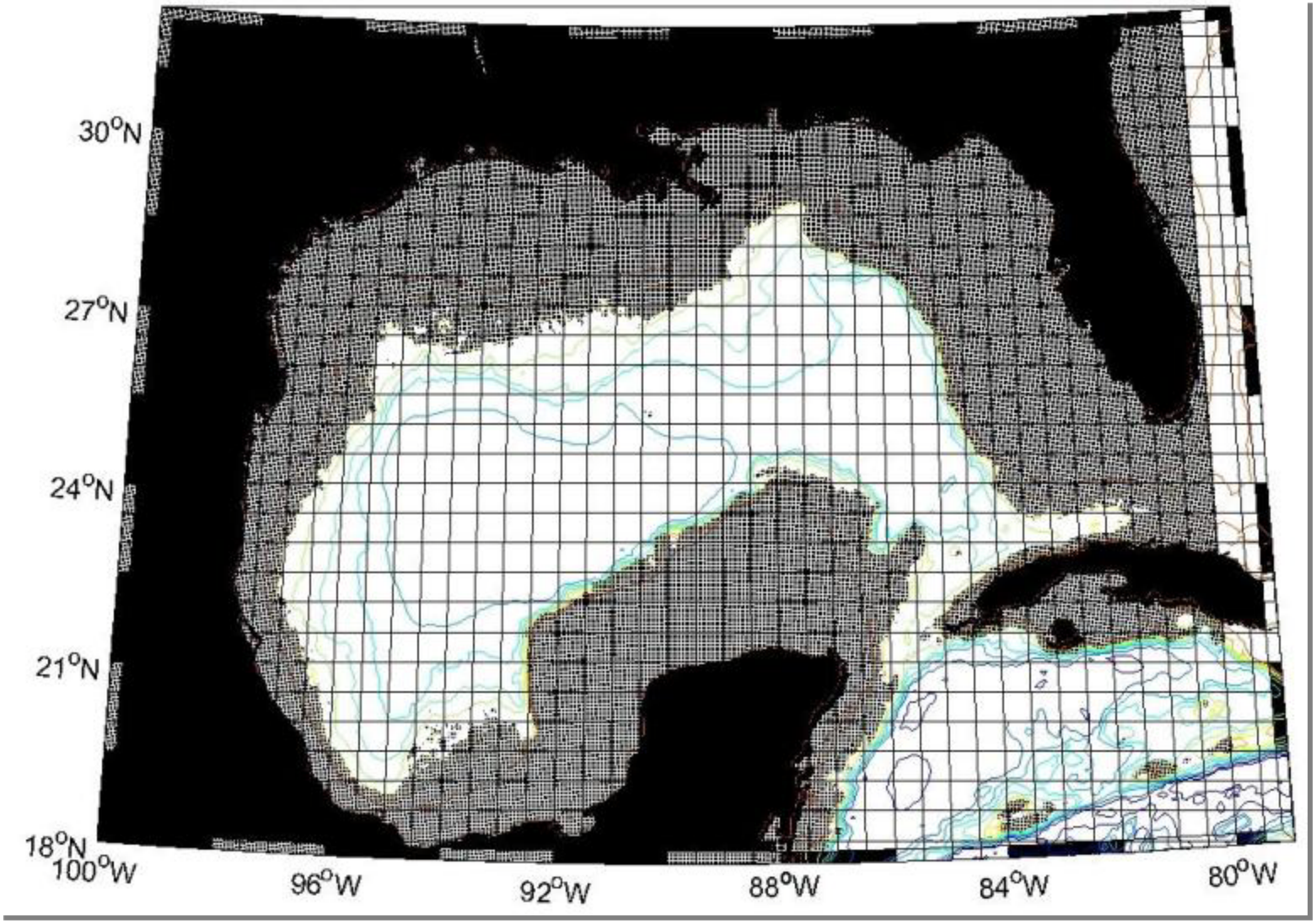
- tracked acoustically with sound sources
- measure temperature, pressure and acoustic travel times three times daily
- ballasted for 1,500 (80%), 2,500 (20%) meters
- 230 float-years of high-resolution trajectories
- Iridium telemetry



Initial RAFOS Deployments

- Spread along cruise tracks for water depths > 2,000 m
- 2,500 m deployment paired with a 1,500 m deployment
- Maximize the number of 1,500 m paired deployments (depends on sound source deployments)
- Deployment in escarpment boundary currents
- A few 1,500 m deployments made north of Sigsbee escarpment over northern slope

Spatial Data Coverage



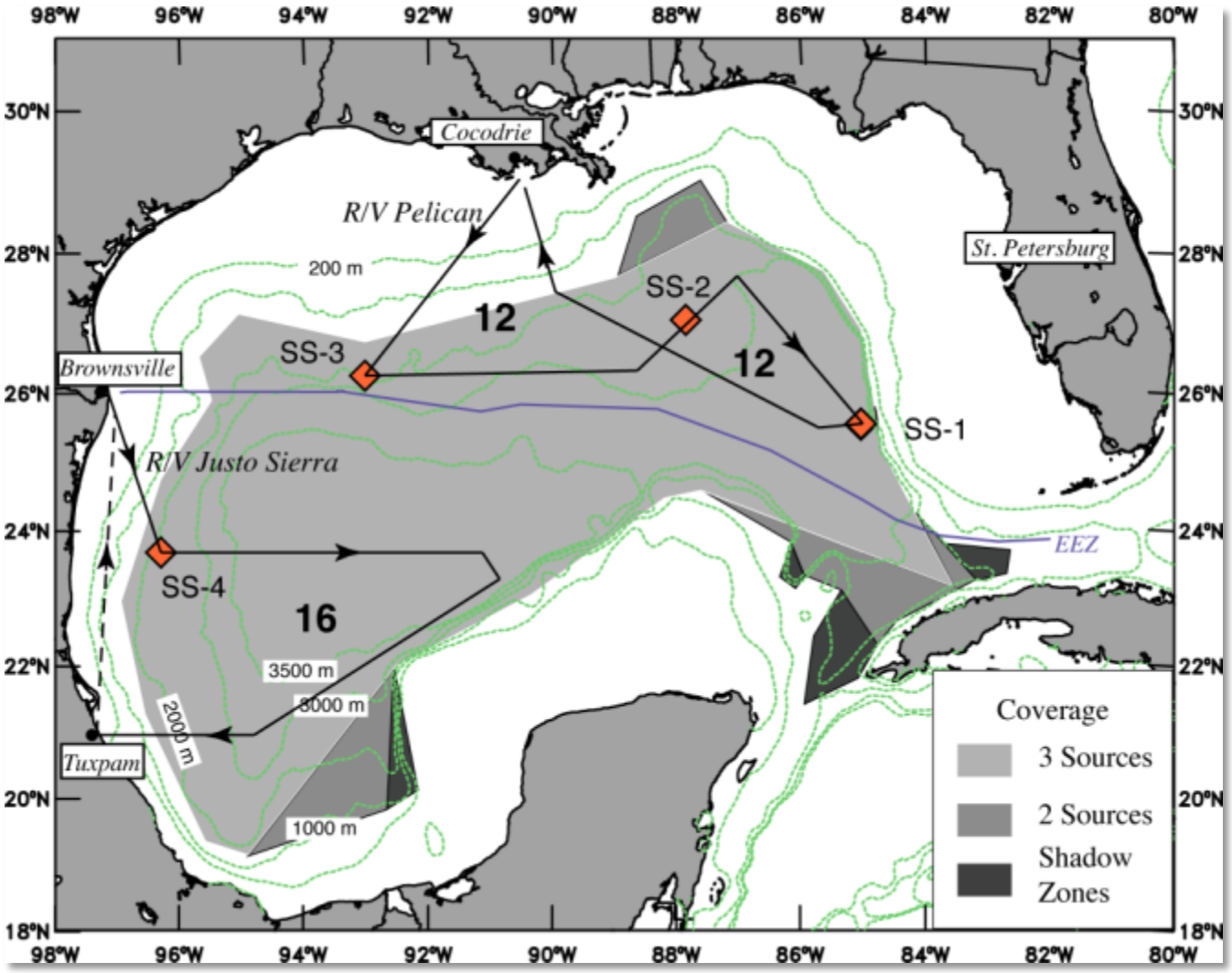
Estimate of Data Density

- 230 float-years with integral time scale of 3 days will provide ~27,500 independent velocity observations
- there are 224 1/2°x 1/2°boxes deeper than 1,500 m in the Gulf
- *if* float velocity observations distributed evenly over the Gulf, will obtain on average about 123 independent samples per box
- standard error of the mean would be [2, 1, 0.5 cm/s] for r.m.s. velocities of [20, 10,5 cm/s], representative of the range observed in the Gulf
- some uncertainties will be larger due to uneven float distribution and spatially coherent float tracks

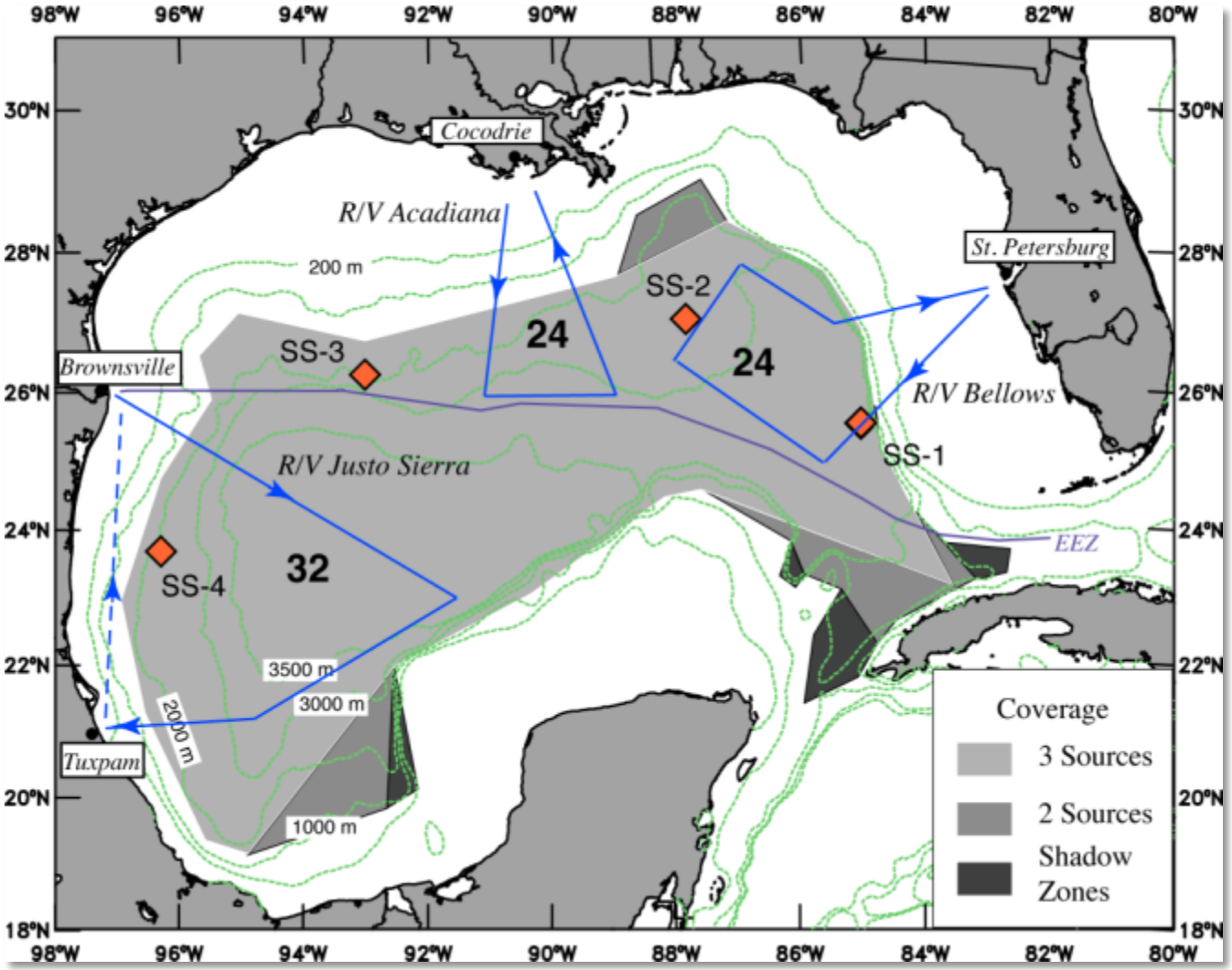
Summary of RAFOS Deployments

	Years 1 & 2		Year 2 & 3	
Deploy Length	24 (12) months		24 months	
Float Depths	1500 m	2500 m	1500 m	2500 m
Eastern Gulf	10 (3)	8	20	16
Central Gulf	10 (3)		20	
Western Gulf	12 (4)		24	
Totals by Depth	**32 (10)**	**8**	**64**	**16**
Totals	**40**		**80**	

Years 1: Sound Sources & 32 RAFOS @ 1,500 m
& 2: 8 RAFOS @ 2,500 m



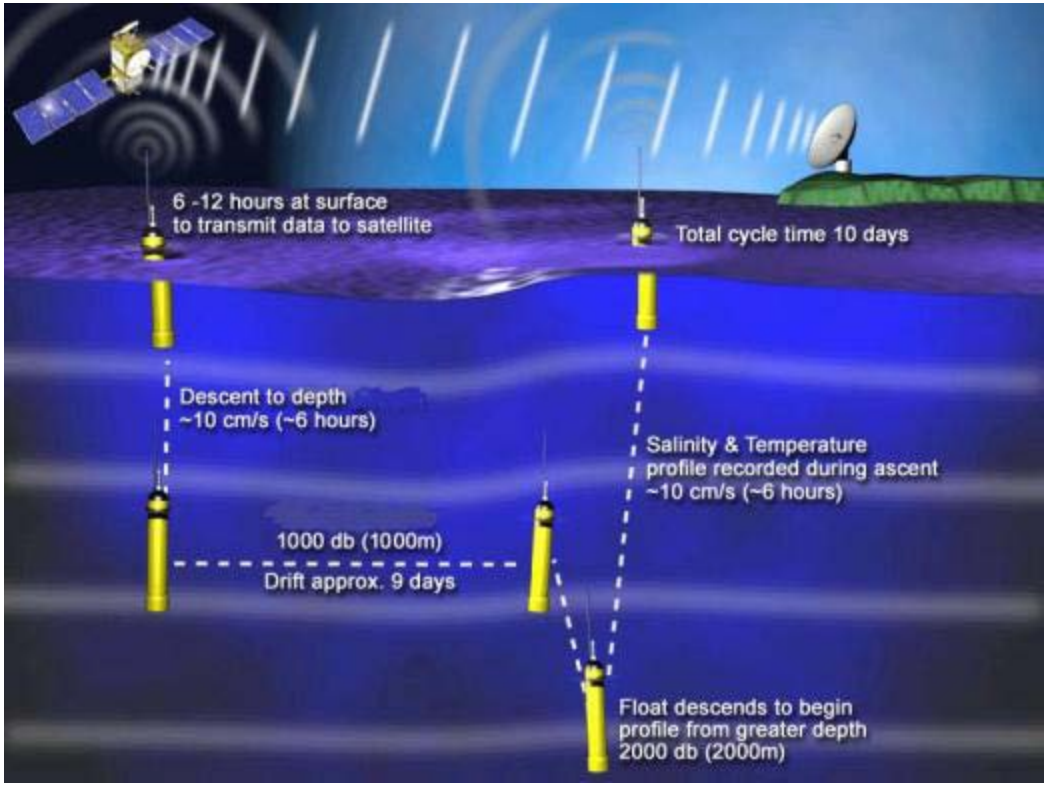
Years 2 & 3: 64 RAFOS @ 1500 m & 16 @ 2500 m



Profiling Floats

Profiling Floats

- Sea Bird CTD
- WET Labs Optical Sensor Package
- Iridium telemetry
- Acoustic receiver
- Lithium batteries
- Good for 150 profiles



Optical Sensors on Profiling Floats

- WET Labs optical sensor package
- Model FLbbCD
- Profiles of 3 biogeochemical parameters & hydrocarbons
  - phytoplankton abundance (chlorophyll fluorescence)
  - total particle concentration (backscattering)
  - dissolved organic matter (CDOM)

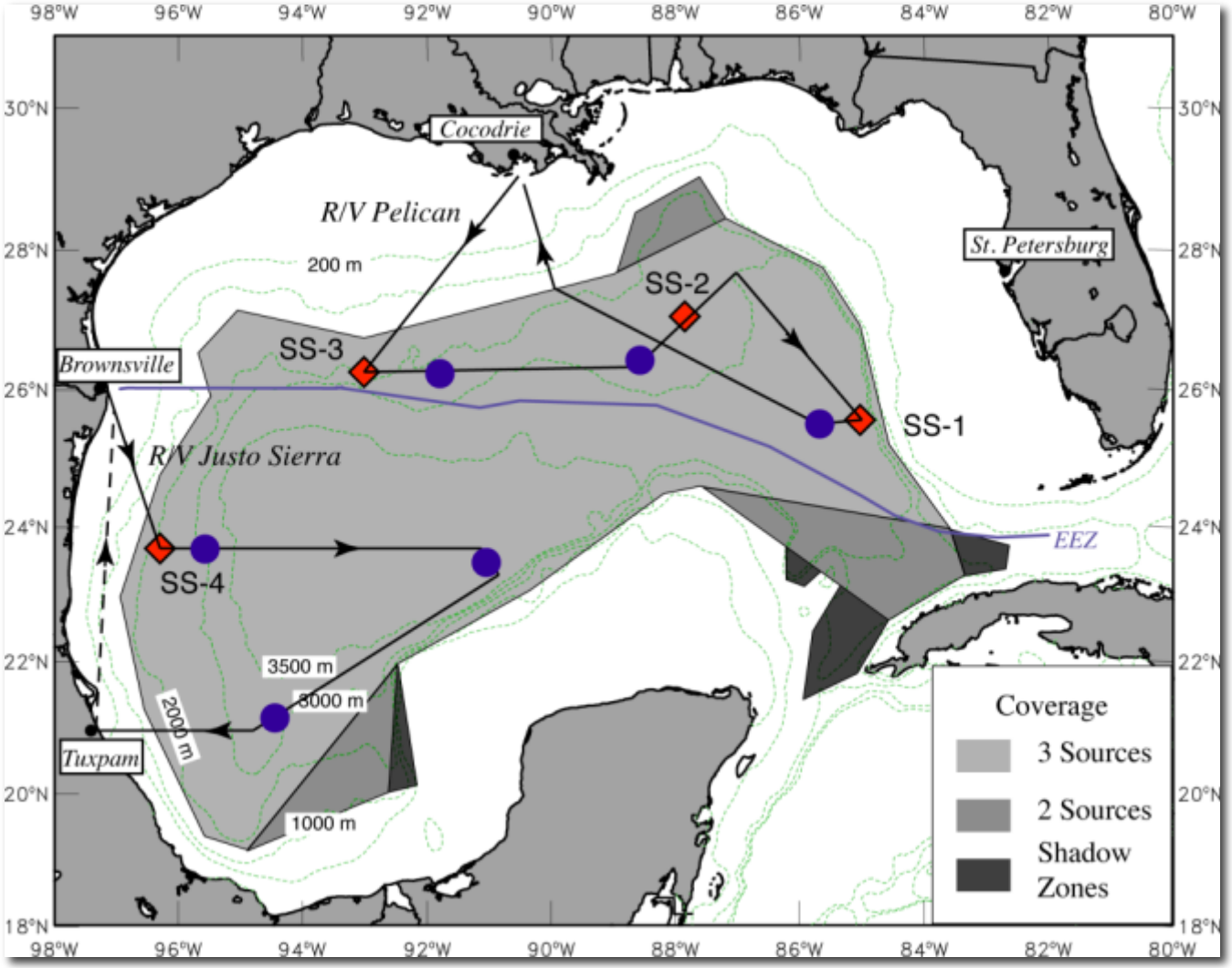
Sampling Scheme: Profiling Floats

- 6 APEX profiling floats released in year 1 for 3-year duration of field work
- 1,500-meter park depth
- profile temperature and salinity every 15 days, providing total of ~430 T/S profiles
- acoustically tracked while drifting, providing an additional 18 float-years of high-resolution trajectories
- rapid notification of sound source failure (less than one month)

Studies with Profiling Floats in the Gulf

	Deep Gulf (This Study)	Exploratory Program	Argo Global Program	NOPP Weatherly et al.
Number of Floats	6	6	~2-3000	17
Rest Depth (m)	1500	1000	2000	900
Profiling Depth (m)	1500	1500	2000	900
Cycle Time (days)	15	10	10-14	7
Profile Variables	T, S, Optical	T, S	T, S	T
Acoustically Tracked	Yes	Yes	No	No
Deployment Locations	Gulf Wide	Exploratory Array, North-Central Gulf	World Ocean, 3° lat-lon spacing	Northern Gulf
Coverage Aim	Uniform - Gulf	North-Central Gulf	Uniform –World Ocean	Gulf Wide
Time Interval	2011-2015	2003-2004	2001-2010	1998-2002
Number of Profiles in Gulf	~430	260	6 (in LC only)	1480

Profiling Float Deployment Locations

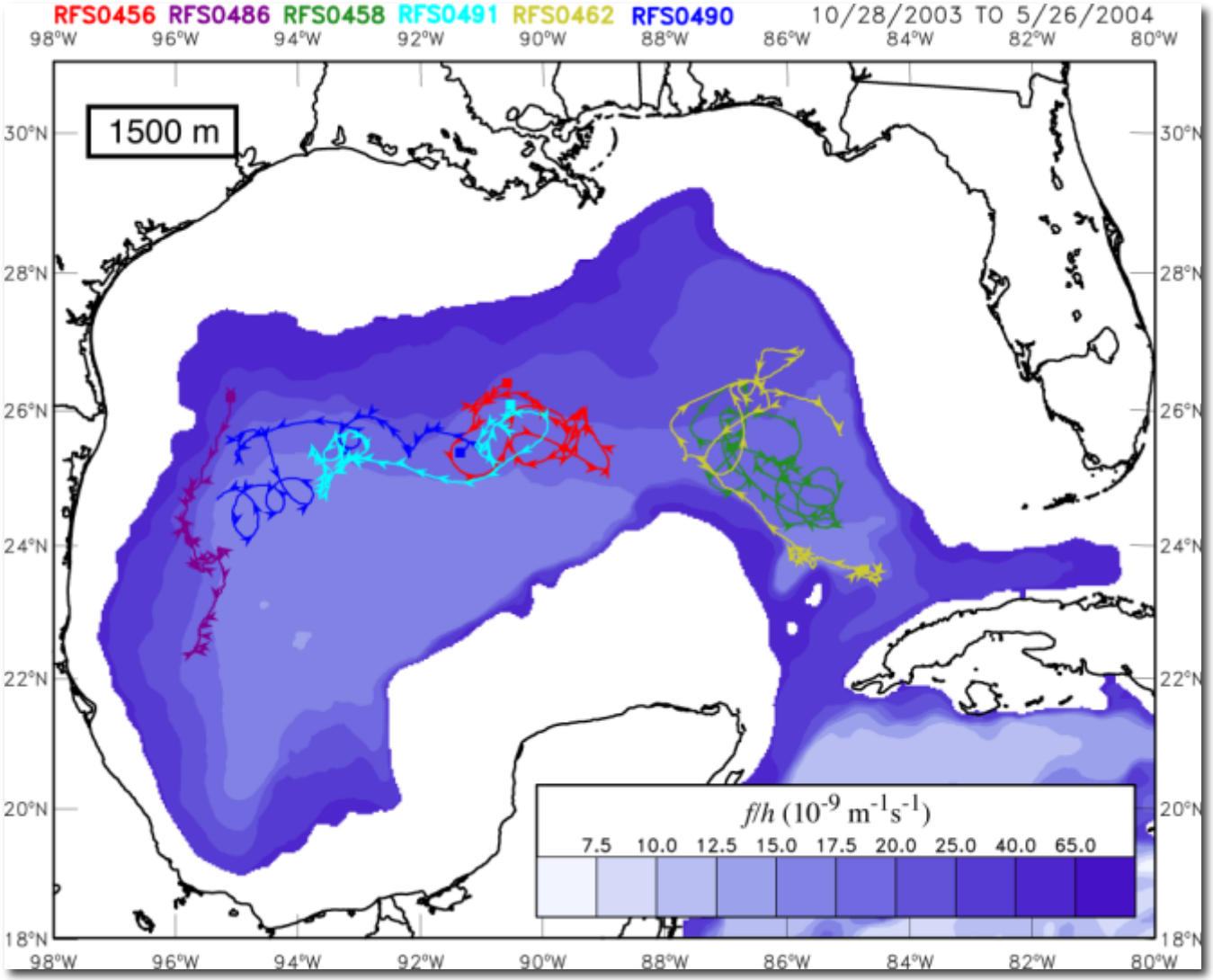


Lagrangian Statistics

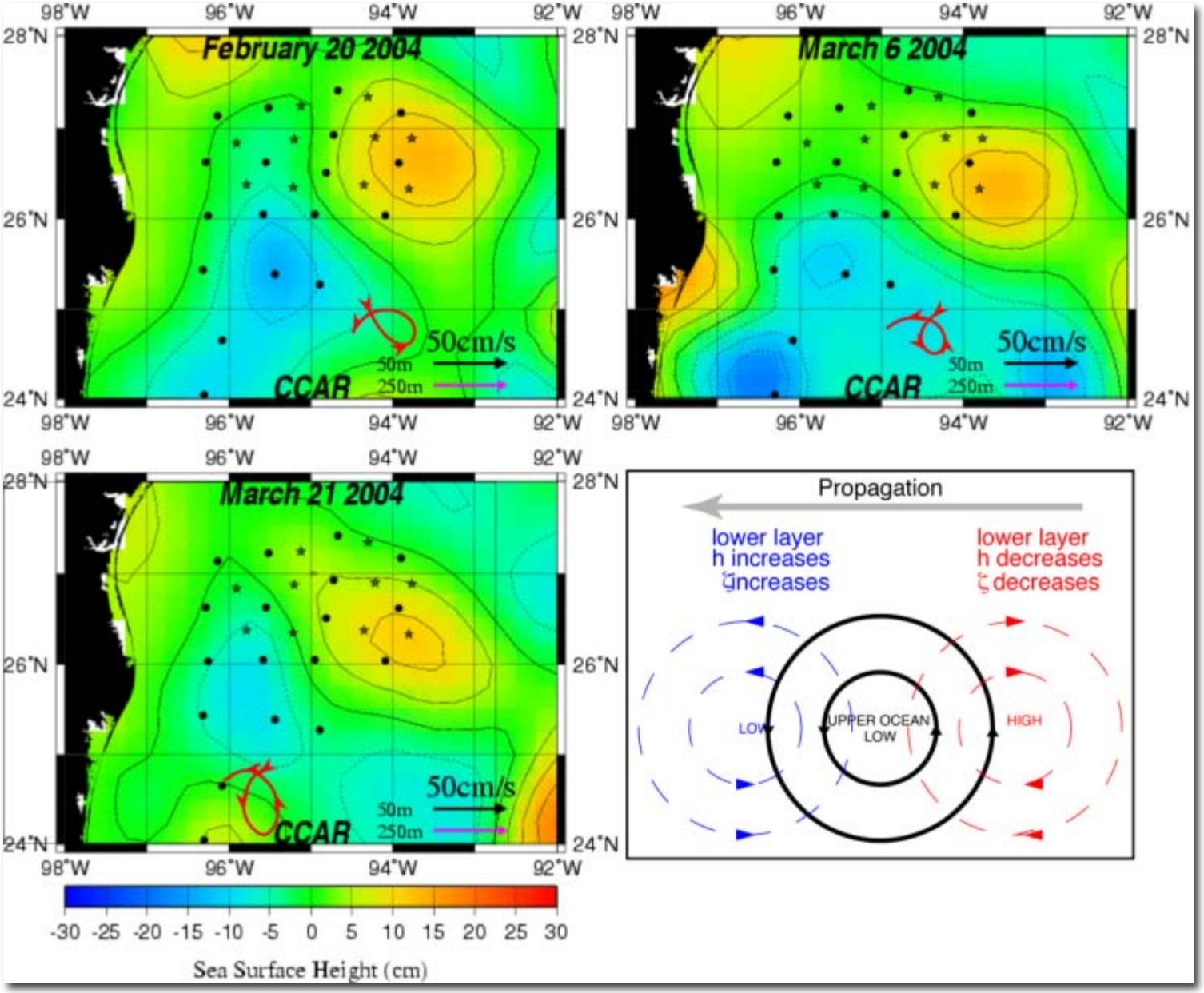
- Spatial Patterns
  - Mean Flows, Variances, EOFs, SOM
- Single Particle Statistics
  - Integral Time Scales, PDFs, Diffusivity
  - Time Series Analysis (Spectra, etc.)
- Multiple (usually 2) Particle Statistics
  - Relative Dispersion

    - Richardson, & Horizontal & Vertical Shear
  - Separation PDFs & Diffusivities
  - Clusters (≥ 3) - Divergence & Vorticity

Floats and *f/h* in the Gulf



Propagation of Deep Eddy into Western Slope



Ancillary Data

Surface-Layer Drifters of Opportunity

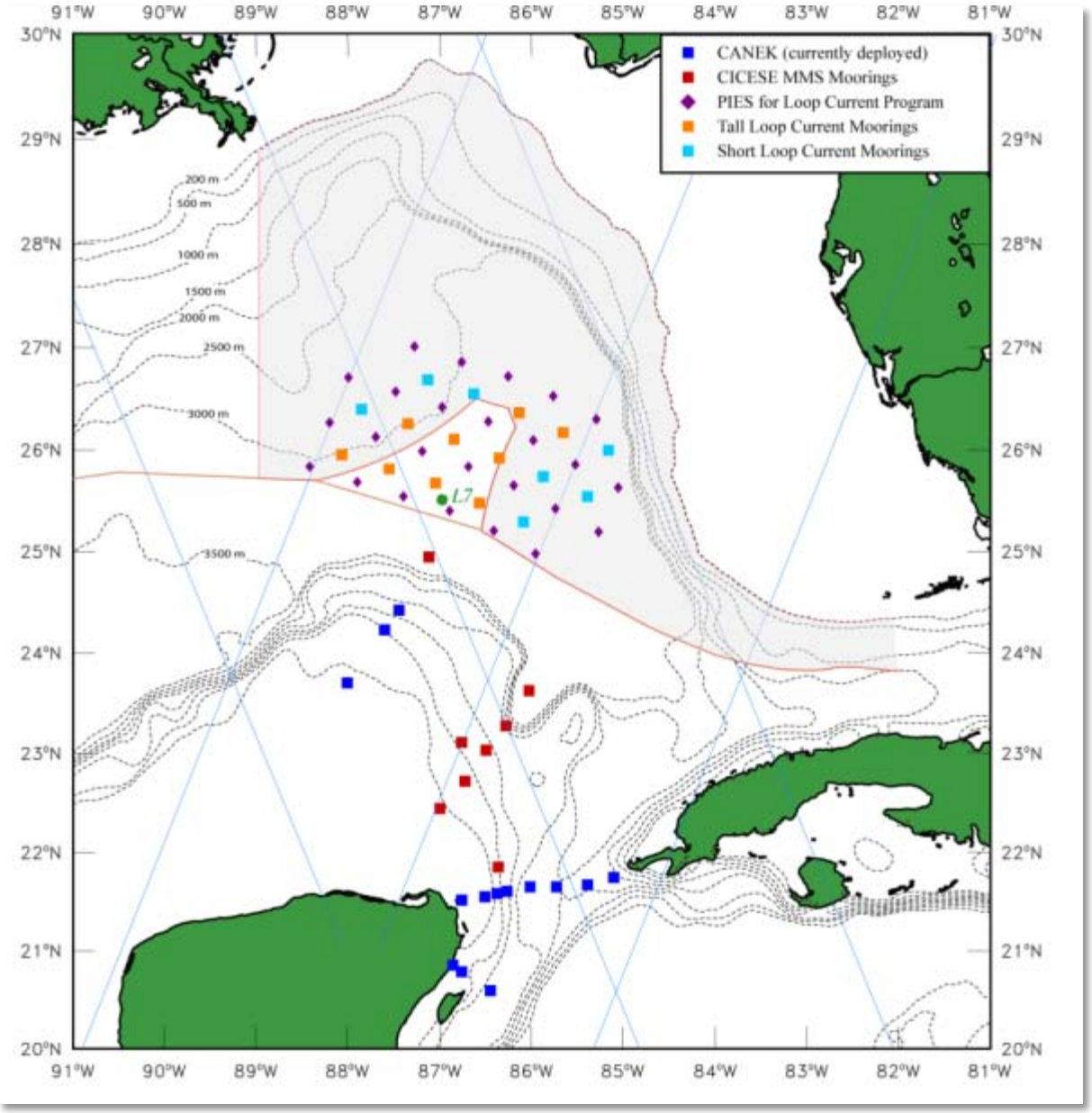
Profiling Floats of Opportunity

Deep Current Meter Moorings

- Loop Current Dynamics Study (BOEMRE)
- Deep-Water Horizon Arrays (NDBC/NMFS/BOEMRE)

Model Studies (BOEMRE/Industry/NOAA)

SAIC & CICESE Arrays for the Dynamics of the Loop Current Study



Remote Sensing

- Altimetry

  Capabilities: Satellite altimetry is the only “operational” satellite-based remote sensing technique that directly measures a dynamical variable of the ocean state – the sea surface height (SSH). Although the SSH is a surface measurement, it reflects the variation of density throughout the water column.

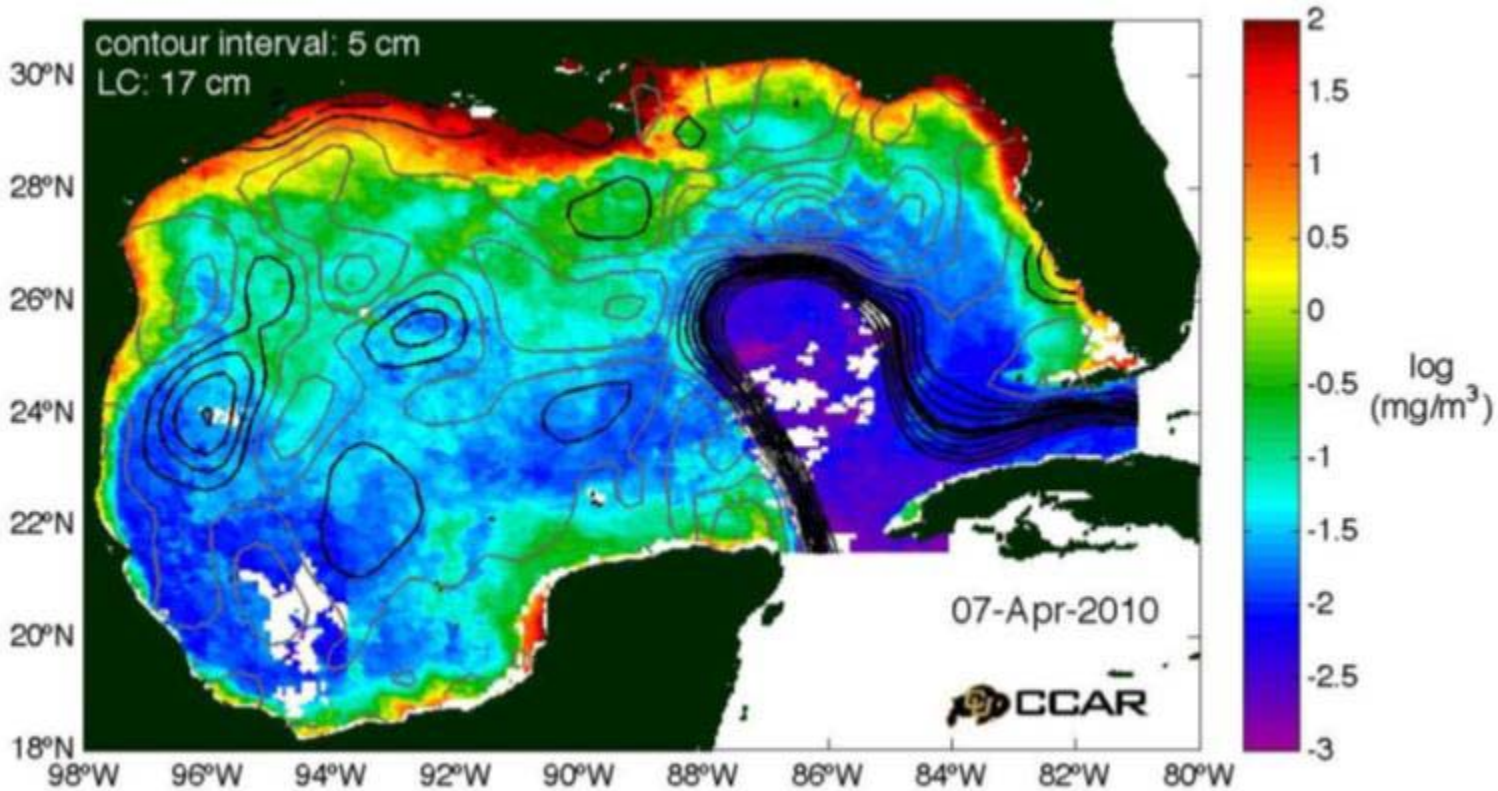
  Operational Missions: ESA ERS-2/Envisat, NASA/CNES Jason-1, OSTM/Jason-2.

  Research Missions: ESA Cryosat-2, AltiKa on CNES/ISRO SARAL Satellite.

- Radiometry

  GOES, G1SST, MODIS

SSH Overlaid on MODIS Ocean Color



Summary

An Exciting New Study using Lagrangian Floats to

Map Lower-Layer Deep Currents throughout the Gulf

Statistically Characterize these Currents

Generate Random Water Column Profiles for:

- Water Mass Characterization
- BioGeochemical Data in the Deep Basins

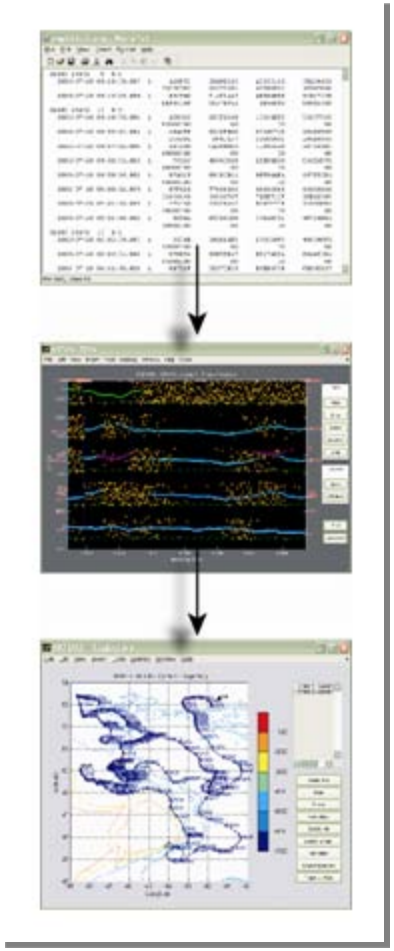
Investigate Deep Lagrangian Dispersion

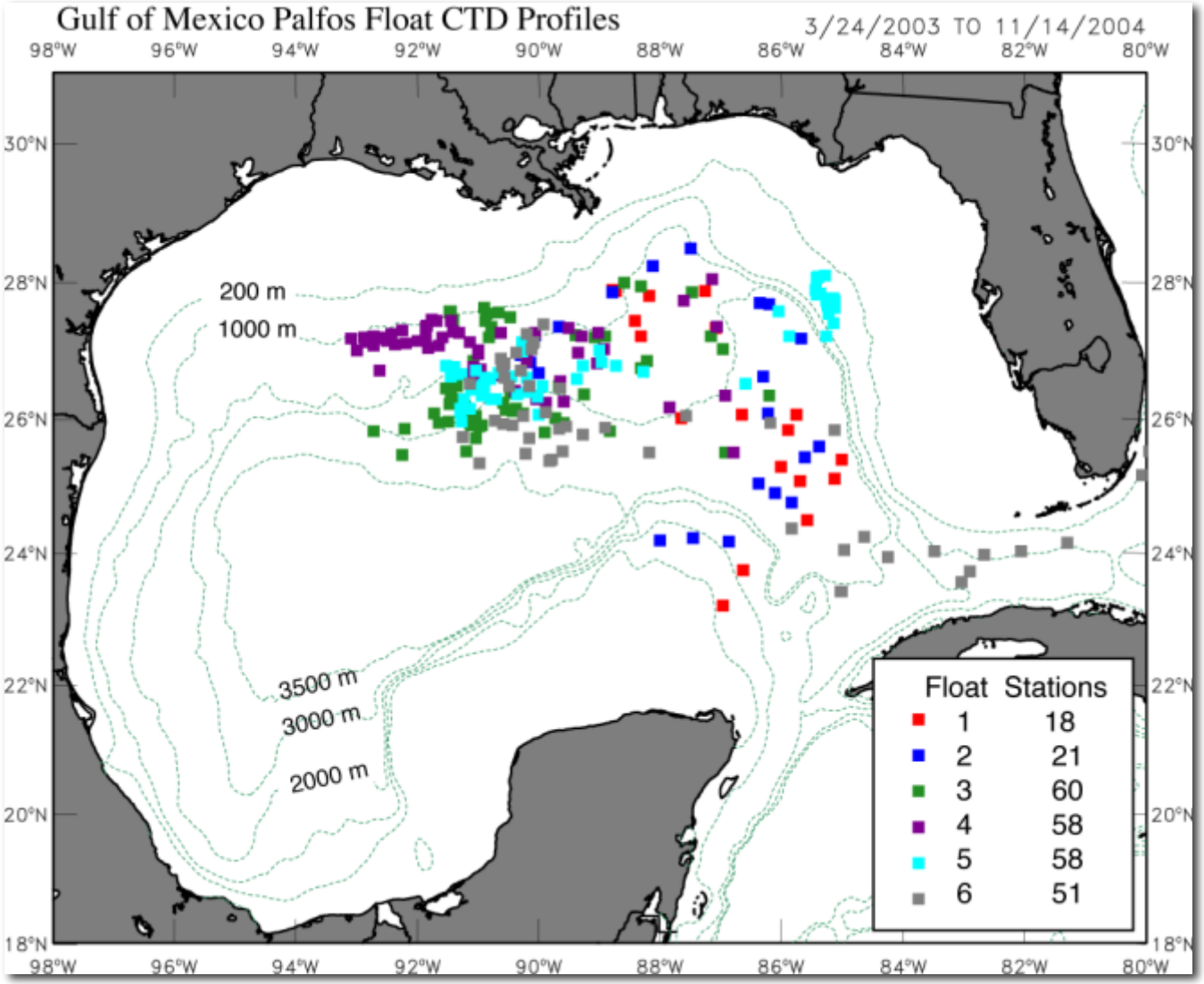
Investigate Upper-Lower Layer Coupling & Dynamics

Provide an Important Database for Model Studies

Float Data Processing

Profiles to 1,500 meters



- Raw (hex) data telemetered via Iridium.
- Satellite time used to calculate float clock corrections.
- Distance between sound sources and surface position of floats used in conjunction with last recorded times-of-arrival and sound velocity to calculate initial sound source clock corrections.
- TOAs and T/P edited for bad data; rollover corrections applied; floats tracked using a least squares method.
- Final source clock corrections; tracks corrected for sound velocity; interpolation between positions, if necessary.

Exploratory Program PALFOS Profile Locations