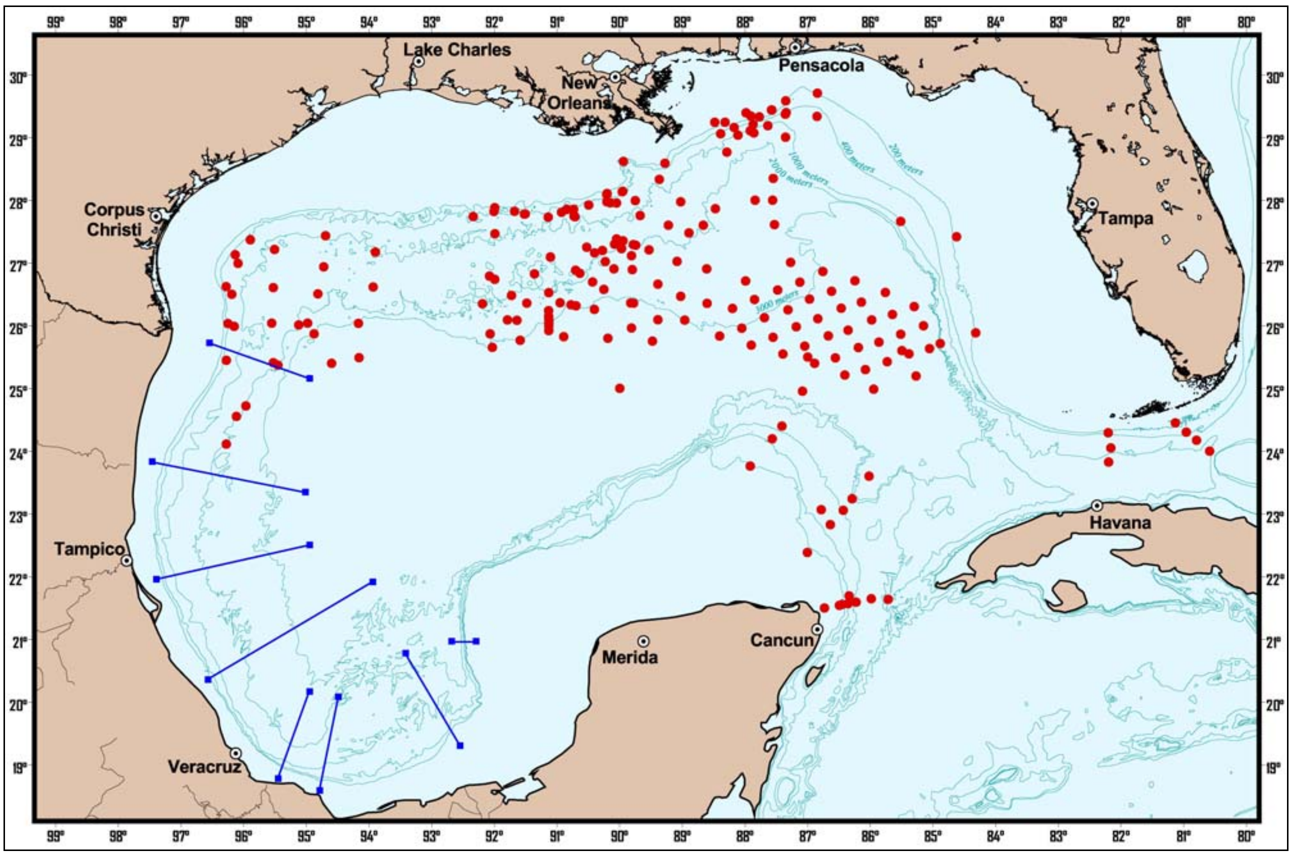
OCS Study
MMS 2010-001

Proceedings: USA-Mexico Workshop on the Deepwater Physical Oceanography of the Gulf of Mexico

June 2007



U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

OCS Study
MMS 2010-001

Proceedings: USA-Mexico Workshop on the Deepwater Physical Oceanography of the Gulf of Mexico

June 2007

Editors

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EXECUTIVE SUMMARY

The MMS has led the USA's physical oceanography studies of the Gulf of Mexico for over 30 years. Consequently, observational and numerical modeling studies of the Gulf of Mexico circulation have advanced rapidly. Now the challenge is to pursue, together with Mexican colleagues, progressive, coordinated observational and modeling studies of the deep Gulf of Mexico.

Accordingly, fifty-seven American and seven Mexican colleagues gathered for two and one-half days in June 2007 to review the present understanding of the deepwater physical oceanography of the Gulf of Mexico, and to consider scientific, technological, and logistical opportunities to further advance that understanding. For example, recent time series results from moored current meter arrays and satellite radar altimetric sea surface height maps, on one hand, and numerical simulations of the Gulf's circulation, on the other hand, were presented, suggesting a high potential for better integrated modeling and observational studies in the near future. Further, newly developed instrumentation for free-fall or autonomous vertical profiling observations, as proven in other regions of the ocean, were introduced for potential application in future Gulf studies. A combination of invited plenary talks, participatory breakout groups, and final plenary discussions was used to develop a consensus. To focus the deliberations, a **proposed MMS/PEMEX Gulf of Mexico Long-Term (*viz.*, decadal) Goal was interjected: Establish a scientifically credible Gulf of Mexico (model-based) analysis/re-analysis system that will foster and facilitate diagnostic studies of the circulation and related topics**.

Such a long-term goal immediately gives rise to several questions; e.g.,

1. What process and sensitivity studies are needed?
2. What observing subsystem network design strategy is needed?
3. What modeling subsystem validation and verification strategies are needed?

These and related questions led to the consideration of metrics for the assessment of model skill, and, for that matter, of observing network adequacy. The potential scientific and pragmatic value is high for strongly coordinated (i.e., more than has been the case heretofore) observational and modeling studies, involving both American and Mexican colleagues, focused on the long-term goal of evolving a circulation analysis/re-analysis capability for the circulation of the Gulf of Mexico and its application to ecosystem and other studies.

INTRODUCTION

The activities of the offshore oil & gas industry in the Gulf of Mexico have intensified and extended further offshore in recent decades, creating new challenges for marine resource and environmental management and new opportunities for marine scientific research. These opportunities include the study of the circulation of the Gulf of Mexico in its full glory of powerful mean current jets, fronts, and mesoscale eddies and their interactions with steep bottom topography; the Mississippi-Atchafalaya River plume; and the passage of tropical cyclones in the summer and cold fronts in the winter. Observations and numerical modeling of the Gulf's circulation suggest that observations and models must be linked to generate sound estimates of the spatially complex and temporally variable circulation. American and Mexican offshore oil & gas exploration and production has spread from the inner continental shelf regions to the continental slope and now to the deep Gulf. In recent years, both American and Mexican scientific investigations of the circulation have extended into deeper waters, too. Hence, American and Mexican offshore industries, environmentalists, and research scientists share an interest in a comprehensive description, understanding, and predictive capability for the Gulf circulation. With both the USA and Mexico planning further extensive field and modeling studies in the near-future, it was thought timely to conduct a workshop to discuss recent results and coordinate plans, with the hope that more of the space-time variability could be characterized than otherwise would be possible by either country alone.

PROGRAM

26 JUNE 2007

0730 Breakfast

0800 Prof. Chris Mooers, RSMAS/UM

Opening Remarks

0805 Dr. Guillermo Pérez Cruz, PEMEX

Pemex´s Metoceanic Plans for the Gulf of Mexico

0820 Dr. Alexis Lugo-Fernández, MMS

MMS Objectives and Expectations

Invited Talks

0830 Dr. Peter Hamilton, SAIC

An Overview of Deep Circulation Processes in the Gulf Using Moored and Lagrangian Observations

0855 Drs. Randy Watts and Kathy Donohue, URI

Synthesis of Bottom Pressure/Inverted Echo Sounder (PIES) Data from MMS Studies in the Gulf of Mexico

0940 Dr. Leo Oey, PU

A Modeler's Quest to Probe the Deep Unknowns

1025 Break

1040 Dr. Julio Candela, CICESE

CANEK: Ten Years of Current Measurements in the Northwestern Caribbean

1120 Dr. Julio Sheinbaum, CICESE

Numerical Models of the Gulf of Mexico and Caribbean Sea: the CICESE Experience

1200 Lunch

1300 Dr. Robert Leben, CU

Upper Ocean Circulation in the Gulf of Mexico Deepwater: A Remote Sensing Perspective

1415 Dr. Peter Hamilton, SAIC

Upper Layer Subsurface Jets and Inertial Currents in the Northern Gulf

1440 Dr. Dong-Shan Ko, NRL

IAS/NFS: An Operational Nowcast/Forecast System for the Intra-Americas Sea (IAS)

0315 Break

0330 Dr. John Toole, WHOI

New Technologies/Approaches (w/audience participation)

1630 General Discussion Led by Chair and Co-Chairs

1715 Organization of Breakout Sessions (Chair)

1730 Adjourn

27 JUNE 2007

0800 Breakfast

0830 First Breakout Sessions

S-1 Observational Plans and Needs for Modeling Information in USA Waters

(Co-Chairs, Steven DiMarco, TAMU and Antonio Badan, CICESE; Rapporteur, Walter Johnson, MMS)

S-2 Modeling Plans and Needs for Observational Information in USA Waters

(Co-Chairs, Robert Weisberg, USF and Julio Sheinbaum, CICESE; Rapporteur, Carole Current, MMS)

1000 Break

1030 S-1 and S-2 (continued)

1200 Lunch

1330 Second Breakout Sessions

S-3 Observational Plans and Needs for Modeling Information in Mexican Waters

(Co-Chairs, Antonio Badan, CICESE and Steven DiMarco, TAMU; Rapporteur, Walter Johnson, MMS)

S-4 Modeling Plans and Needs for Observational Information in Mexican Waters

(Co-Chairs, Julio Sheinbaum, CICESE and Robert Weisberg, USF; Rapporteur, Carole Current, MMS)

1500 Break

1530 S-3 and S-4 (continued)

1700 Adjourn

1730 "Social Hour"

28 JUNE 2007

0800 Breakfast

0830 Breakout Session Summaries (Co-Chairs and Rapporteurs)

1000 Break

1030 Overall Summary/Follow-up Plans (Chair and Co-Chairs; Rapporteurs, Carole Current)

(Workshop report with studies recommendations/short report for OS/etc.)

1200 Adjourn

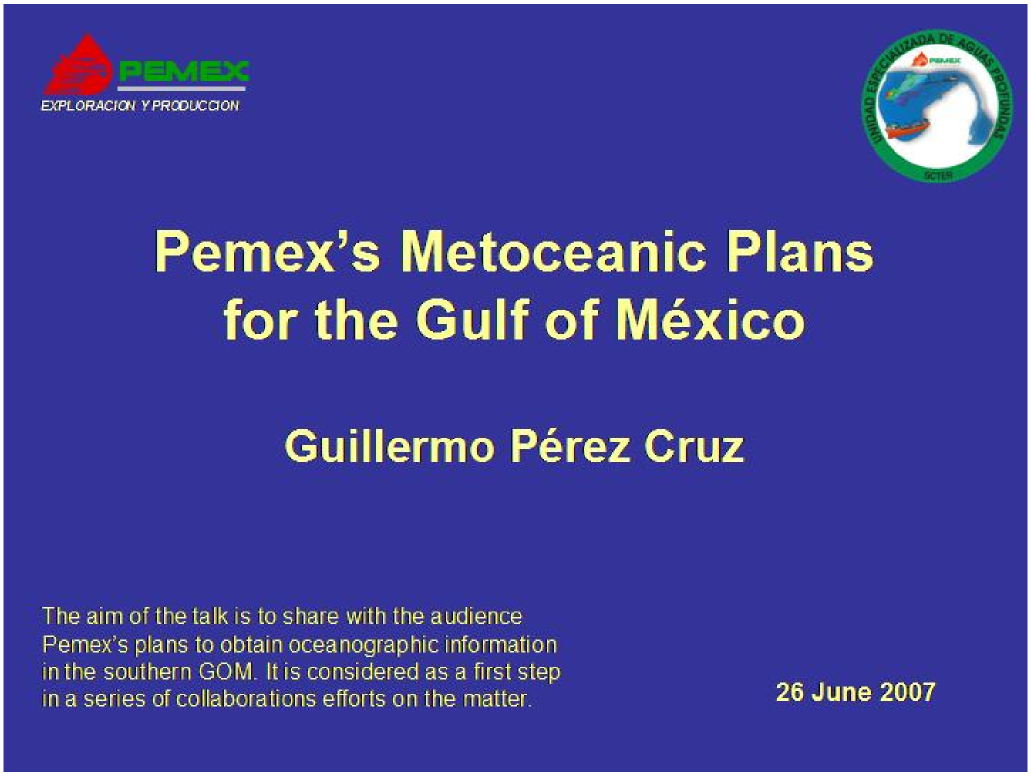
1200 to 1400 Lunch meeting for Convener, Chair, Co-Chairs, Rapporteurs, et al. to plan follow-up

INDIVIDUAL PRESENTATIONS

PEMEX'S METOCEANIC PLANS FOR THE GULF OF MÉXICO

Guillermo Pérez Cruz, Pemex

Slide 1



Slide 2

PEMEX EXPLORACION Y PRODUCCION

Outline

- Background
- Summary of E&P Recent Activities
- Program 2007–2012
- Implementation
- Remarks

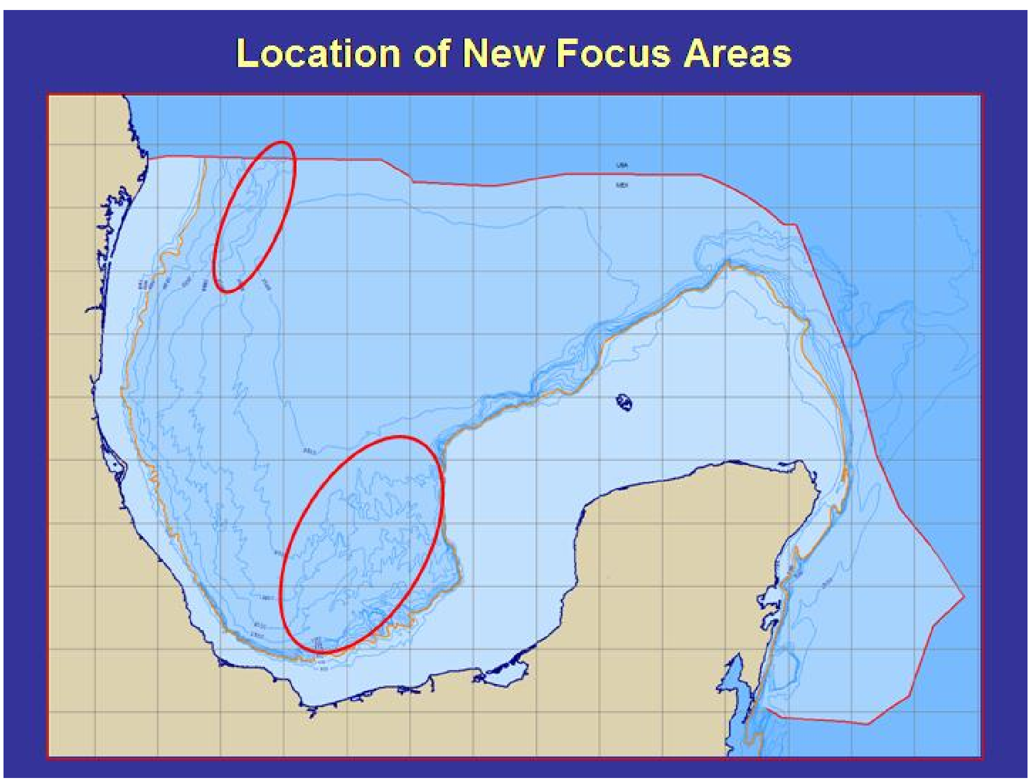
Slide 3

Background

- Pemex has conducted operations to explore and produce hydrocarbons in the southern GOM since the late 70s.
- Numerous fields were discovered and went into production; most of them still produce.
- The infrastructure to produce ~2.8 bbd consisting of platforms, pipelines and other facilities, lies in water depths no greater than 100 m.
- Operations are being supported by weather and hurricane surveillance reports that provide information about: winds, wave heights, temperature, pressure, among other meteorological data and ocean conditions.
- During that period Pemex has operated within international standards of safety and environmental protection.

Slide 4

Slide 5



Slide 6

Summary of Recent Activities

- Pemex formally started exploratory activities in deep waters of the GOM in 2002.
- Since then, valuable information has been acquired, processed and interpreted, particularly ~25,000 sq km of 3D seismic and hundreds of sea-floor piston cores.
- As a result of this initial campaign, the assessment of the prospective resources in deepwater GOM is supported by a more reliable data base, new reserves have been added, and areas where the exploratory effort need to be focused in the following years are clearly identified.
- Plans and programs to continue exploring, developing, and producing the discovered reserves are now in progress.
- To become a reliable operator in the deepwater arena, Pemex needs to comply with safety and environmental regulations and develop a way to understand and predict ocean behavior.

Slide 7

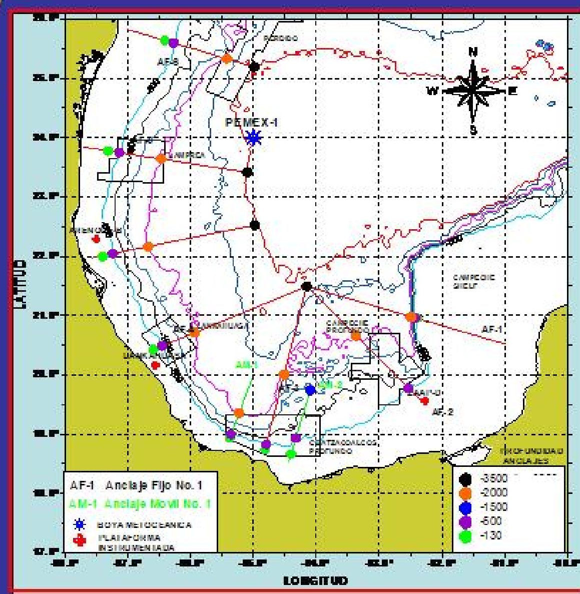
Program 2007–2012

- To design a program to obtain oceanographic information in the GOM, Pemex conducted a series of workshops with participation of scientists from various oceanographic institutions.
- The objectives of the program are to compile existing data and models, acquire new data, and integrate all of them to produce nowcast/forecast of currents and other ocean properties, as well as to make the results available in real time for the Pemex operations in the deepwater GOM.
- Our aim is to deploy and operate an extensive distribution network from the shelf to the deepwater environments to make *in-situ* observation, complemented with remote sensing data.
- Information generated from observational data and models output will be stored within a large mass storing system and distributed to users.

Slide 8

Program 2007–2012

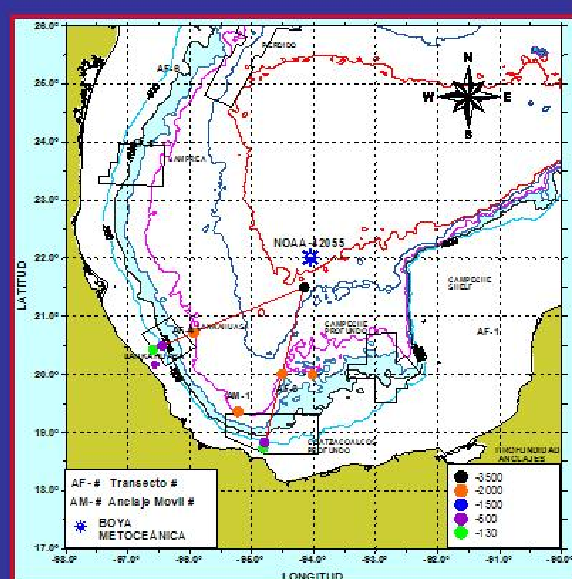
- **33 Mooring Systems**
  Currents and other properties along the water column (130-3500 m)
- **1 Buoy Metereologic Station**
  Currents, waves and weather conditions
- **6–10 Surface Drifters**
  Shallow currents and eddy's trajectories
- **3 Mooring Systems tied to production platforms**
  Currents, waves and other meteorologic parameters
- **Satellite Data**
- **Historical Data and Models**
- **Processing Center**
  Store, process and distribute



Slide 9

Program 2007

- **9 Mooring Systems**
  Currents and other properties along the water column (130-3500 m)
- **2 Surface Drifters**
  Shallow currents and eddy's trajectories
- **1 Mooring Systems tied to production platforms**
  Currents, waves and other meteorologic parameters
- **Satellite Data Set**
- **Historical Data and Models**
- **Processing Center**
  Store, process and distribute



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Implementation

- Pemex is relying on CICESE to gather, process and interpret its oceanographic data. CICESE will be responsible for model building, data management, and data supply.
- The Mexican Petroleum Institute (IMP) will act as a link between Pemex and CICESE and will assure proper delivery of data for reliable support of Pemex operations.
- The IMP will also serve as the link between Pemex and oceanographic institutions, as well as government instances to establish collaboration agreements for joint efforts and to prevent unnecessary duplications.

Slide 11

Final Remarks

- Pemex acknowledges the importance of a reliable oceanographic data base to support its operations and to define criteria for infrastructure design in deepwater.
- The program is believed to be a good starting point to address Pemex's mid- and long-term needs.
- The program is a good starting point for collaboration with oceanographic institutions and government agencies.
- The resulting information and models eventually will be the source for research programs that not only will benefit the scientific and industry communities but also society in general.

MMS OBJECTIVES & EXPECTATIONS FOR U.S.-MEXICO DEEPWATER WORKSHOP

Alexis Lugo-Fernández, Minerals Management Service

Slide 1

Slide 2

Outline

- Objectives & Expectations
- GOM Existing Current Database
- FY08 Study: "Dynamics of the Loop Current"
- Upcoming Highlights

Slide 3

Objectives of this Workshop

- Review current ideas of deepwater physical oceanography in U.S. and Mexican waters;
- Develop recommendations for a coordinated plan of physical oceanography research in U.S. and Mexican waters;
- Suggest coordination of physical oceanographic and interdisciplinary research between U.S. and Mexican researchers; and
- Prepare and publish workshop proceedings.

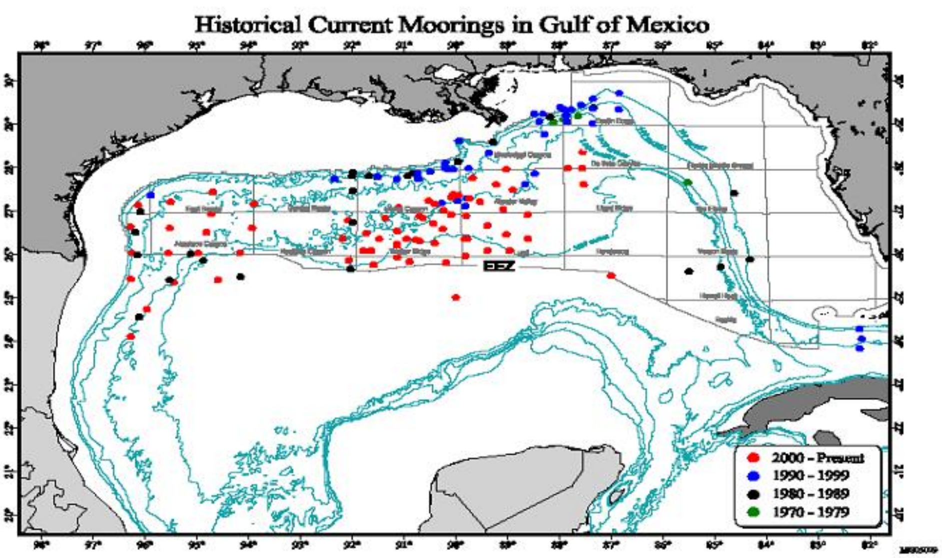
Slide 4

Workshop Expectations

- Recommendations to develop next phase of U.S. deepwater studies.
- Recommendations for better integration of field and modeling research.
- Suggestions for new technologies to conduct future research.
- Suggestions for PEMEX to refine, implement, and conduct their future program.
- Recommendations on how to coordinate U.S. and Mexican research.
- Proceedings report that will guide next phase of MMS research.

Slide 5

MMS Gulf's Database of Currents



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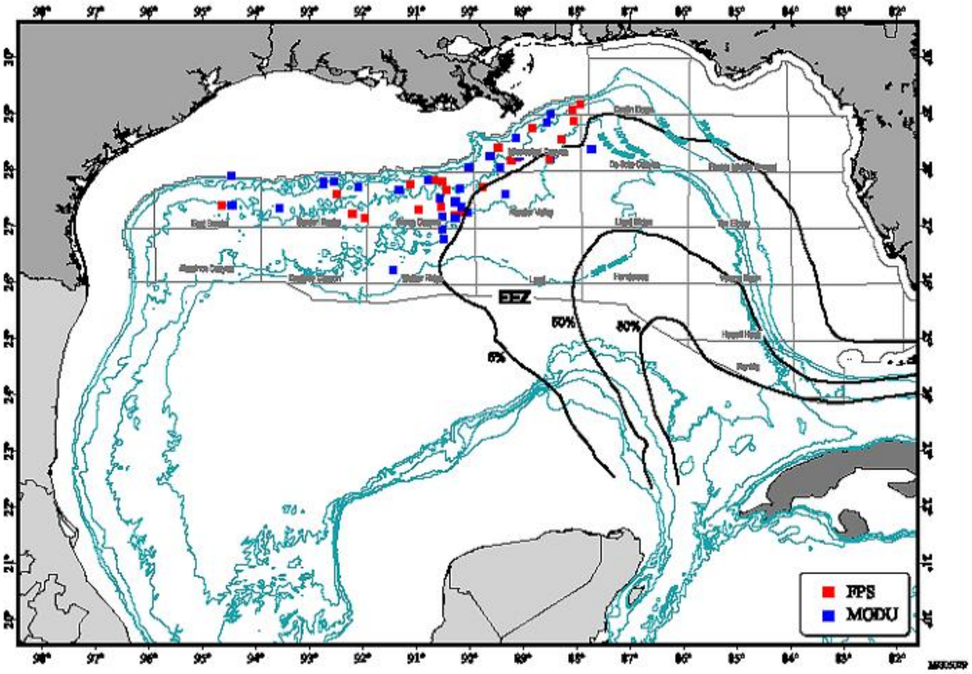
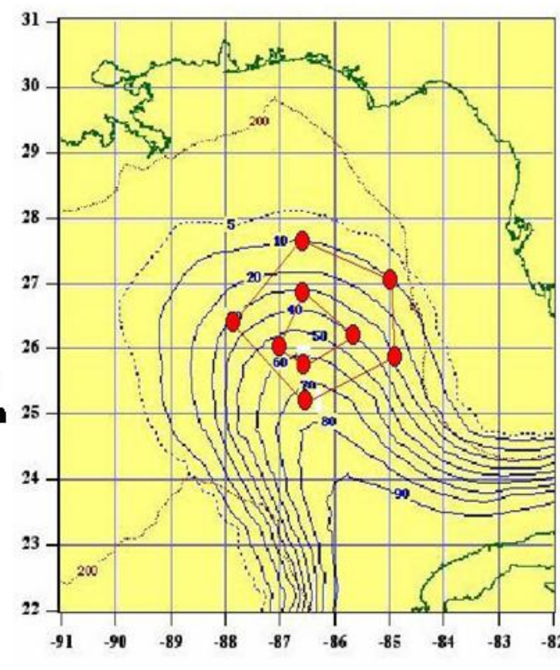
Stations from MMS NTL



Slide 7

FY08: "Dynamics of the Loop Current in U.S. Waters"

- **Loop Current affects both upper and lower layer dynamics.**
- **Few long-term measurements on this current, especially during eddy shedding.**
- **Full depth moorings, PIES, ADCP, satellite altimetry, hydrographic surveys to be deployed.**
- **Three years of observations**
- **Study effects of shedding on lower layer dynamics, Rossby waves, coupling of upper and lower using vorticity dynamics.**
- **Collaboration with Mexican oceanographers?**



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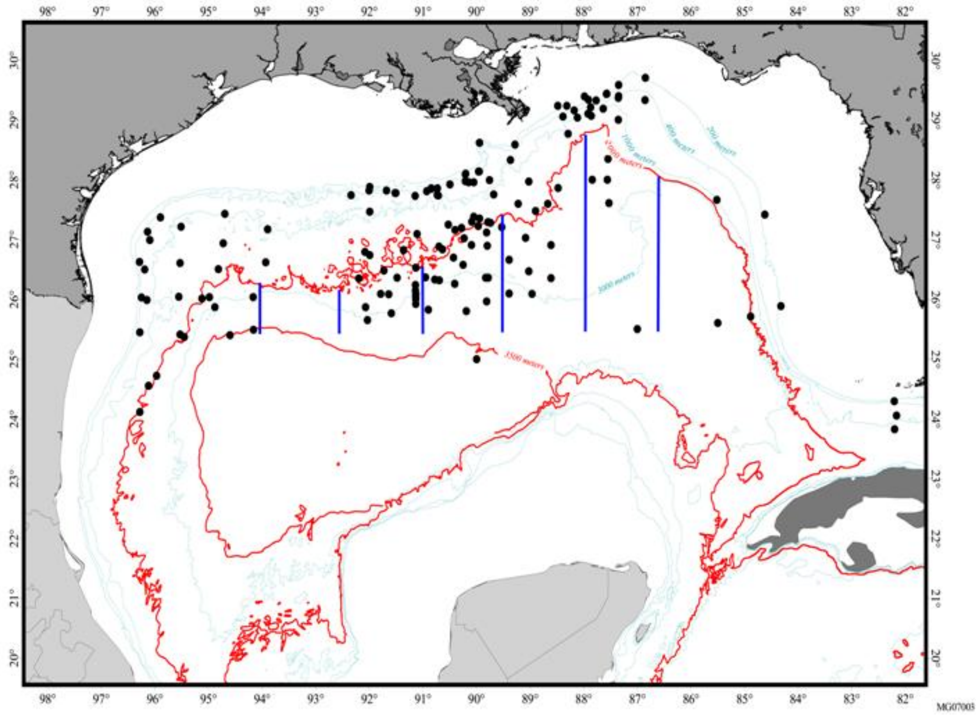
MMS Transect Study



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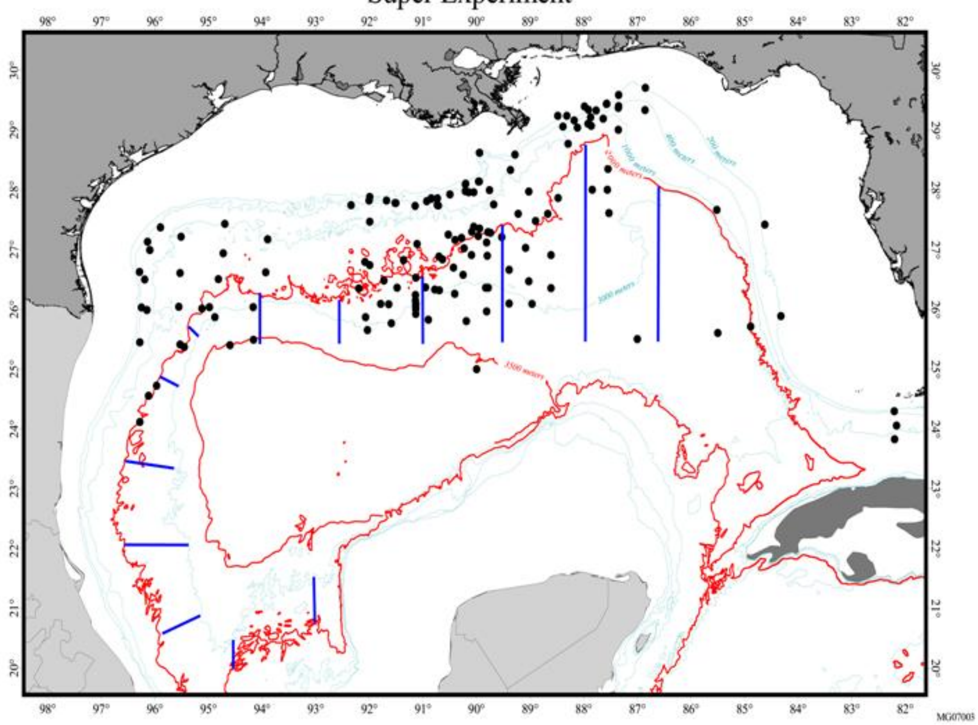
Super Experiment



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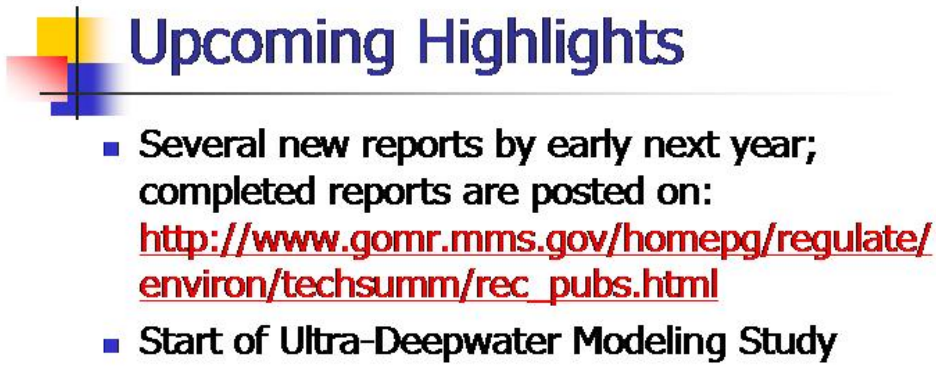
Upcoming Highlights
Several new reports by early next year; completed reports are posted on:
http://www.gomr.mms.gov/homepg/regulate/environ/techsumm/rec_pubs.html
Start of Ultra-Deepwater Modeling Study

AN OVERVIEW OF DEEP CIRCULATION PROCESSES IN THE GULF USING MOORED AND LAGRANGIAN OBSERVATIONS

Peter Hamilton, Science Applications International Corporation

Introduction

The database of deep current observations has had recent major additions from several MMS studies over the lower slopes and abyssal depths of the northern Gulf. The mooring positions are given by the dots in Figure 1 with the indicated studies being the Eastern Gulf (*E*: 4 moorings, January 2005 – January 2006), Exploratory Program (*X*: 19 moorings, March 2003 – April 2004), Northwestern Gulf (*W*: 13 moorings, April 2004 – June 2005), Mexican sector (*C*: 1 mooring in the central Gulf, May 2003 – August 2004, and 5 moorings in the western Gulf, September 2004 – November 2005), and Western Loop Current (*L*: 1 mooring, April 2003 – June 2004). The exploratory program also deployed deep RAFOS Lagrangian floats at depths below 1000 m. In the central and western Gulf, the moorings have shown that there are bottom intensified low-frequency fluctuations with periods of ~ 10 to 60 days that are highly coherent in the vertical for depths greater than ~ 800 – 1200 m. These motions are characteristic of Topographic Rossby waves (TRWs) as shown by Hamilton (1990), Hamilton and Lugo-Fernández (2001), and Hamilton (2007). Analyzed wavelengths are generally in the range of ~ 70 to 200 km and group speeds of order 10 to 20 cm/s are prevalent. Modeling studies (Oey and Lee 2002) indicate that energetic fluctuations in the lower layer are generated by Loop Current (LC) fluctuations, and also westward translating anticyclones (LC eddies) shed from the LC. However, the mechanisms for the generation of TRWs by the LC or LC eddies have not yet been clearly observed or elucidated from model and theoretical studies. Model studies have also shown that westward translating LC eddies may generate a companion lower-layer cyclone/anticyclone pair that remain coherent into the far western Gulf (Welsh and Inoue 2000). These lower layer eddy-like circulations have not yet been observed, and present indications from the observations are that if such deep eddies are generated by a LC eddy shedding event, then they may disperse into more rapidly propagating TRWs.

Statistics

Figure 1 shows the mean and standard deviation ellipses calculated for 40-HLP current records at generally 100-m above the bottom, where the water depth is greater than 1000 m. Records are at least one-year long with the western Gulf having ~ 15-month durations. There are some locations where the height above the bottom is 500 m; however, these are all in water depths greater than 2000 m, and because the currents are nearly depth independent in the lower part of the water column, the statistics are not significantly affected when compared with the 100 m above the bottom level. Means are generally anticlockwise with enhanced flows at the base of the slope ~

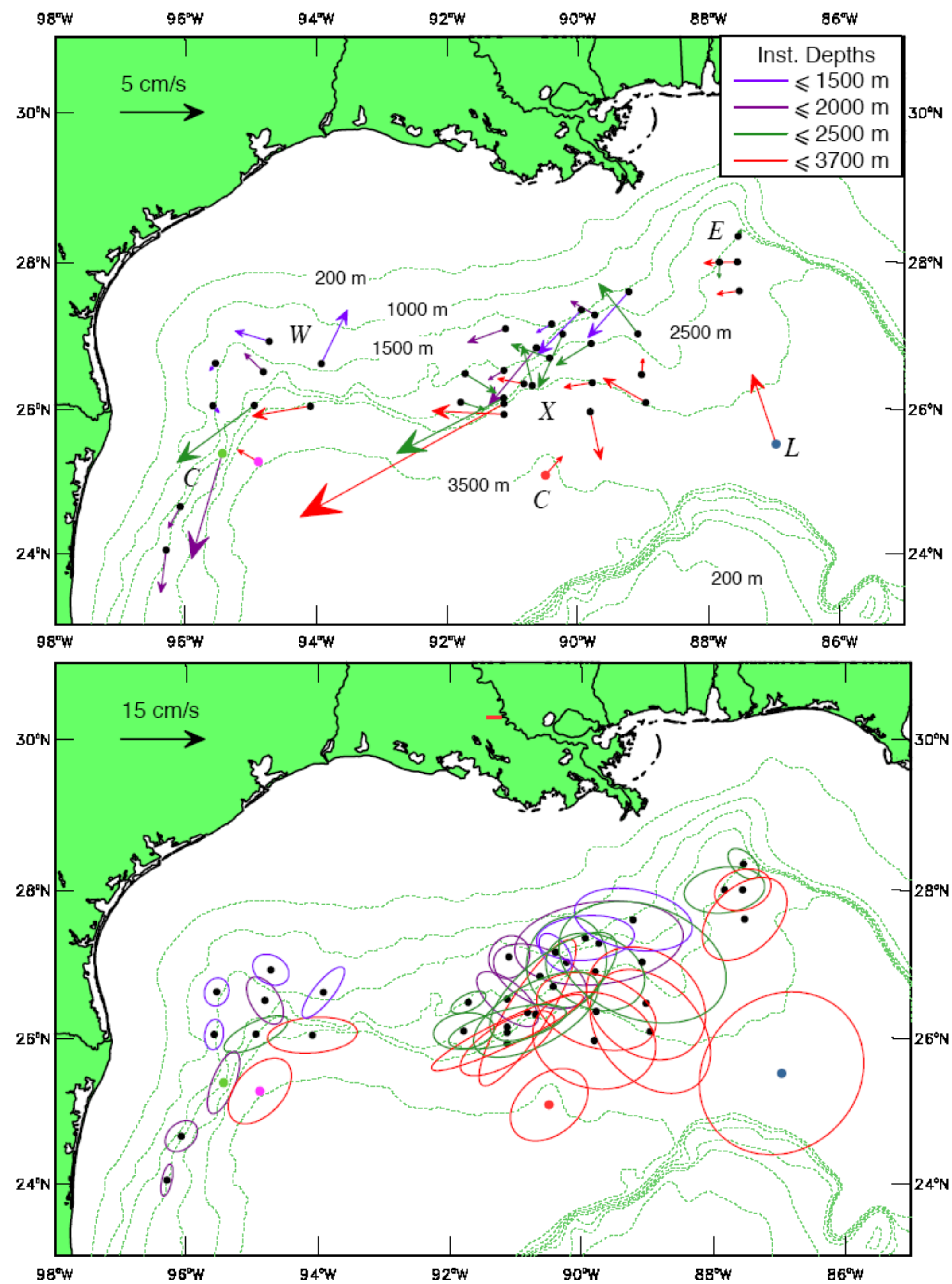

Figure 1. Mean (top) and standard deviation ellipses (bottom) of 40-HLP currents at 100 to 500-m above the bottom from recent MMS studies (see text). The mooring locations marked by a color (not black) dot are used in Figure 4.

2000 – 2500 m where the topographic slope is steep. This generally corresponds to the base of the Sigsbee Escarpment in the central and western Gulf. In the central Gulf, there is a strong mean jet directly above the steepest part of the escarpment slope around 91°W, where maximum speeds are ~ 12 cm/s. This is the only location, to date, where an array of bottom-current meter moorings was placed across the escarpment (the SEBCEP array, which was industry's contribution to the Exploratory program). Most of the other moorings were above or below the escarpment. Nevertheless, it is clear there is an enhanced clockwise flow in the central and western parts of the northern Gulf along the escarpment. The means also indicate that flows converge towards the escarpment, particularly on the deeper basin side both for the Exploratory and Western Gulf studies. The enhanced escarpment mean flows are also observed in the float trajectories. Away from the escarpment, the deep floats tend to oscillate around in the same general area. If they go close to the escarpment, then they move rapidly to the west. Thus, fluctuating TRW flows, which are energetic below the escarpment, have some of their energy converted to mean flows by the reflection mechanism of Mizuta and Hogg (2004) through topographic rectification by the shoaling topography (DeHaan and Sturges 2005).

The eddy kinetic energy, represented by the standard deviation ellipses (Figure 1), has a high degree of spatial variability. The largest magnitudes are on the west side of the LC, represented by "L" and the southeastern part of the exploratory array. Energy decreases from this region in all directions, including south. The Eastern Gulf array, "E," was situated on the northern edge of the LC front for most of the deployment interval, yet the energy levels are less than for the observations immediately to the west. In the central Gulf below the escarpment, variance decreases towards the west, and there is a further small decrease in the western array, where the highest energies are in the northwest corner for the moorings deeper than 2000 m. There is a sharp reduction in variance above, compared to below the escarpment in both the central and western Gulf. Thus in both the western and central Gulf arrays, there are similar patterns with energy highest at the upstream (in the sense of TRW propagation with shallower water on the right) end with decreasing energy levels in downstream direction and a sharp reduction in energy in the shallower water above the steep topographic feature. Otherwise, the ellipses have their major axes nearly aligned with the topography, particularly where the slope is steep. This is consistent with TRW dynamics.

Figure 2 shows the tracks of two RAFOS floats below the LC. The LC during this period, was extended and in the process of shedding eddy Titanic. The floats are below any direct LC flows. Both floats have both cyclonic and anticyclonic loops, and remain in the same general area for the six-months of the record, neither migrating to the western basin nor to the west Florida slope under the east side of the LC. It could be argued that these types of water parcel displacements are characteristic of TRWs, which, to first order, transport momentum but not mass, unlike a true eddy with a closed-core circulation. The velocities of the drifters are compared with the nearest deep current meter, where the records overlap, and they are quite similar in magnitude with the floats having more high frequency content than the velocities from the mooring. This is an indication of non-linear nature and spatial in-homogeneity of the wave field.

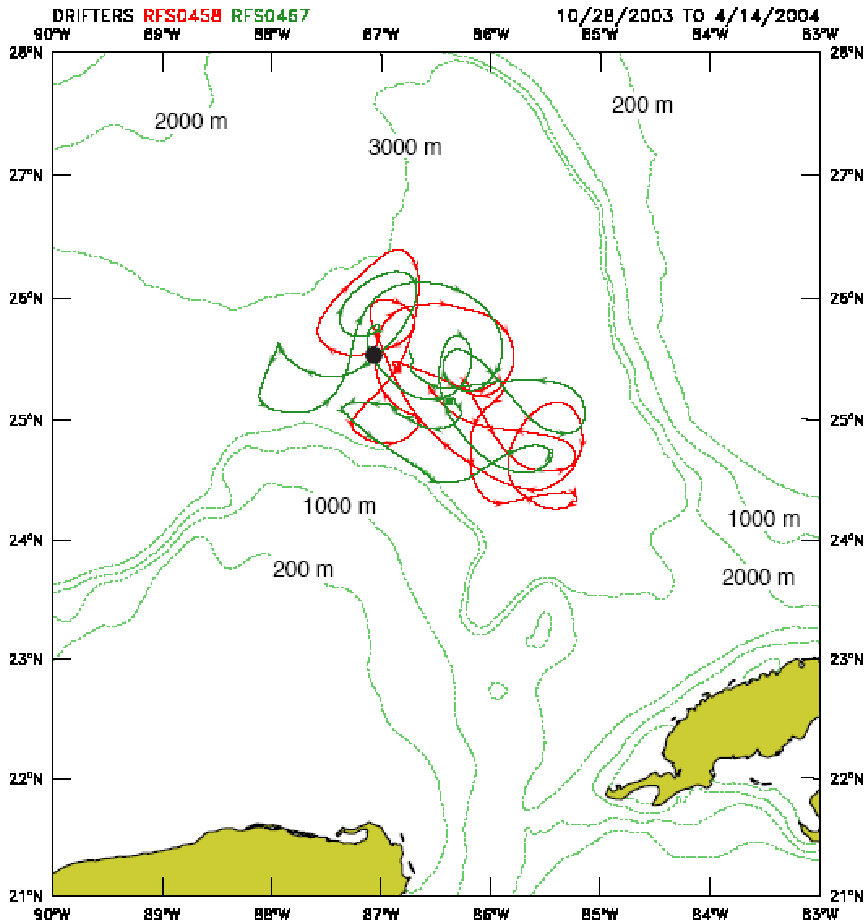

Figure 2. Smoothed lagrangian drifter tracks from two Exploratory RAFOS floats at 1500 m. Arrow heads at five-day intervals. The black dot is the position of the LSU mooring L07.

In the exploratory program, 36 RAFOS drifters were deployed at depths greater than 1000 m. Most of the drifters had tracks similar in character to Figure 2 in that the oscillations were fairly rectilinear with no preferred direction of rotation and the floats remained relatively localized for periods of up to six months. Exceptions were if the float ventured near to the escarpment: then they were transported westward along the escarpment by the large deep mean flows found there (see Figure 1). Of the 36 drifters deployed, only one showed the consistent kinematics of a translating eddy. This was near the western Mexican slope, and the drifter made three circuits just before it surfaced at the end of the deployment (Figure 3). There appears to be no obvious connection with the upper-layer eddy field, though it does approximately precede a westward translating upper layer cyclone that in turn precedes a LC anticyclone.

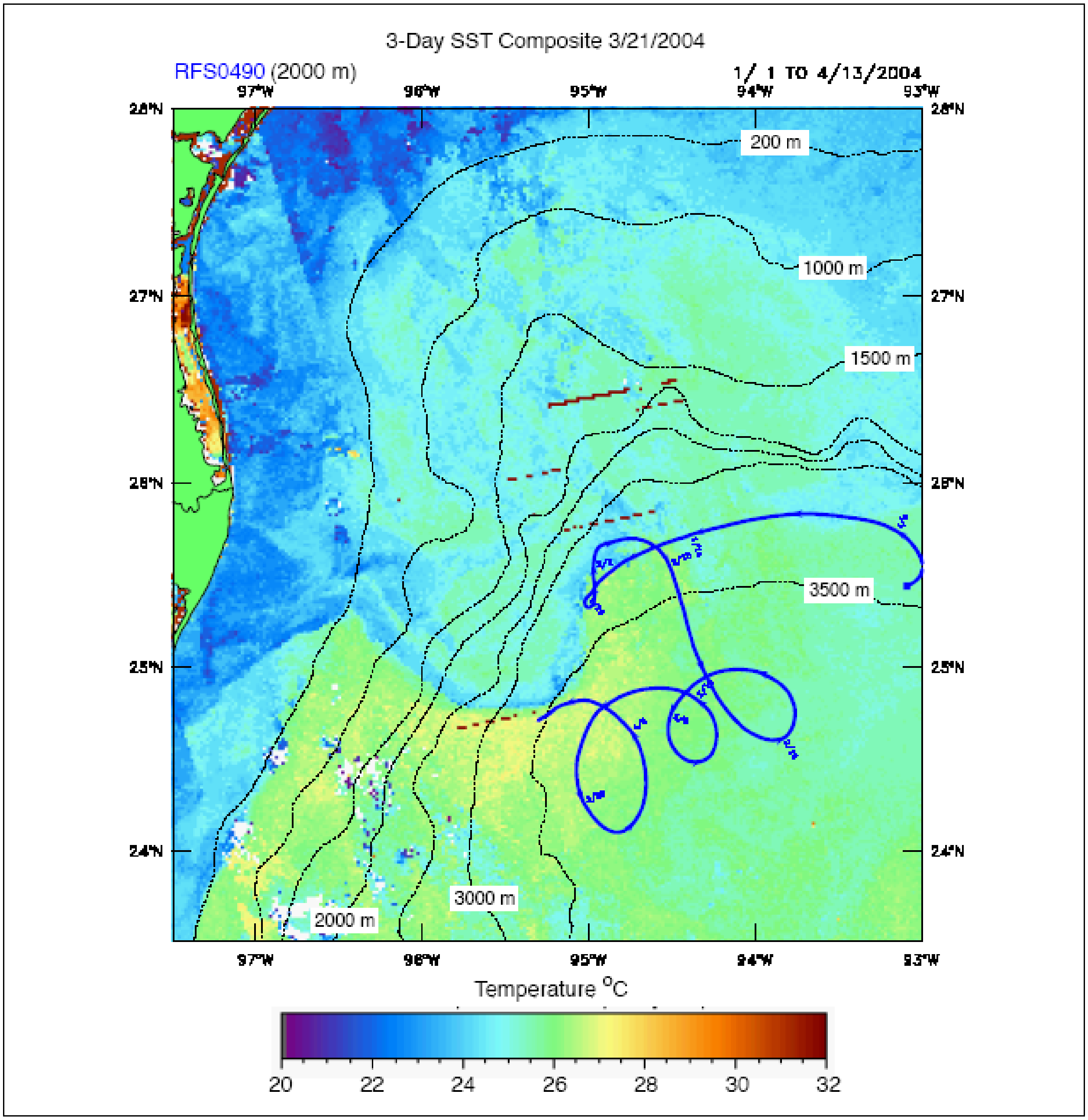

Figure 3. Smoothed track of RAFOS float RFS0490 at 2000 m for the indicated time interval. Arrow heads are at 5-day intervals and dates (mm/dd) are the positions at 0000 GMT. The overlaid satellite image (courtesy JHU-APL) of SST is a 3-day composite center around 21 March 2004.

Spectra

As an illustration of the decay of EKE from east to west, the KE spectra are shown for four moorings (see Figure 1 for locations) that are in the deepest water except for the far western one, with the two central ones (L6 and W3) being approximately on the 3500 m isobath. Note the

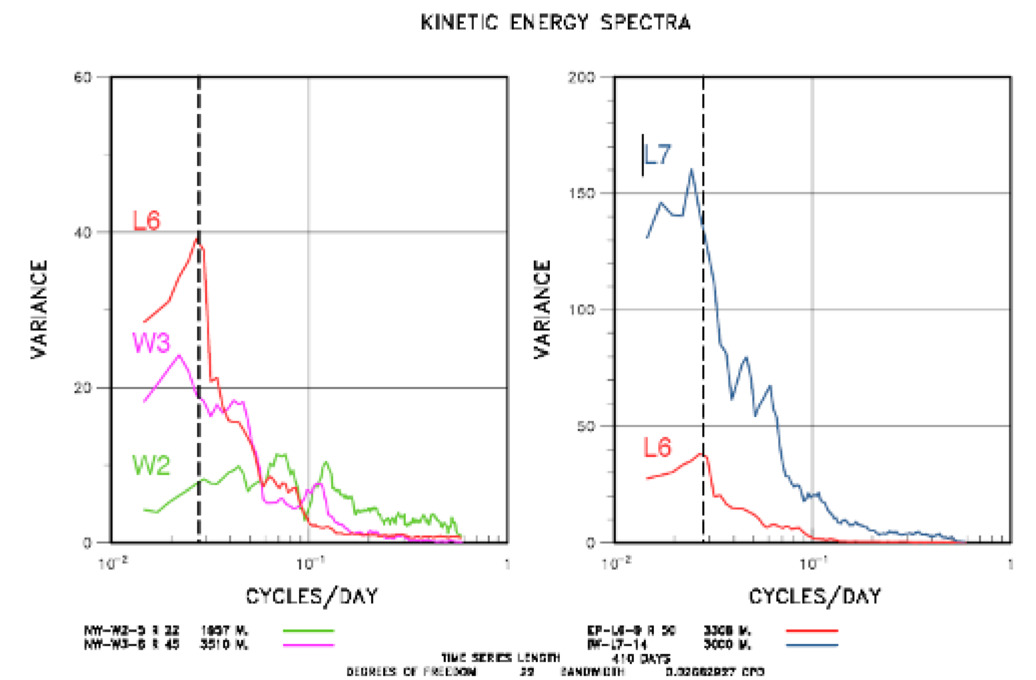

Figure 4. Kinetic eddy spectra in variance preserving form for the near-bottom current records across the center of the Gulf. The mooring locations are color coded the same as plot lines on Figure 1.

change of scale between the two plots with the L6 spectra being repeated as a reference. L7 on the west side of the LC has the highest energy levels with prominent peaks at 30- and 50-day periods. L6 and W3 have similar spectral content but much lower energy levels. However, the decrease between L7 and L6 is much greater than between L6 and W3. W2 is at the bottom of the steep Mexican slope and has a peak at 12-14 days. The shifting of spectral peaks with location was noteworthy for the exploratory currents below the escarpment, with highly energetic high frequency motions (~ 10 days) in the northeast section, lower frequency motions (~ 60 days) in the southwest part of the array with relatively smooth changes between the two along the escarpment. The southeast corner of the array had energetic motions at most of the frequencies observed in the rest of the records. It appears that, in the central Gulf, incoming TRWs from the east and southeast with a range of frequencies are reflected and refracted by the escarpment topography which acts as a kind of filter, trapping the 10-day fluctuations in the northeast and allowing the longer period fluctuations to propagate out towards the deeper water in the western part of the Gulf.

Much remains to be explored in developing an understanding of how TRWs propagate through the Gulf and where are the preferred generation zones. The connections to LC and surface layer eddy variability at various scales have yet to be determined. Developing the correct physics of these generation and propagation processes is going to be crucial for nowcast and forecast numerical predictions of deep currents in the Gulf.

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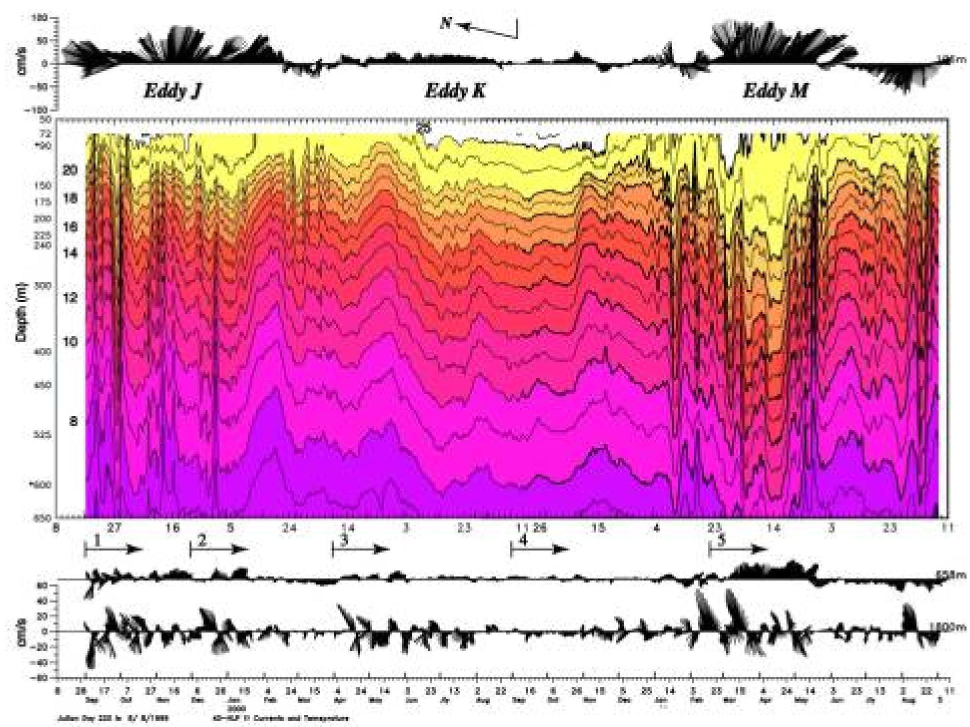
Dr. Peter Hamilton is a Senior Oceanographer with Science Applications International Corporation, a position he has held since 1979. He has served as a Principal Investigator on many MMS programs in the Gulf of Mexico and other coastal seas. He received his Ph.D. from the University of Liverpool (U.K.) in 1973, and followed this with a postdoctoral position at the University of Washington.

Slide 1

Slide 2



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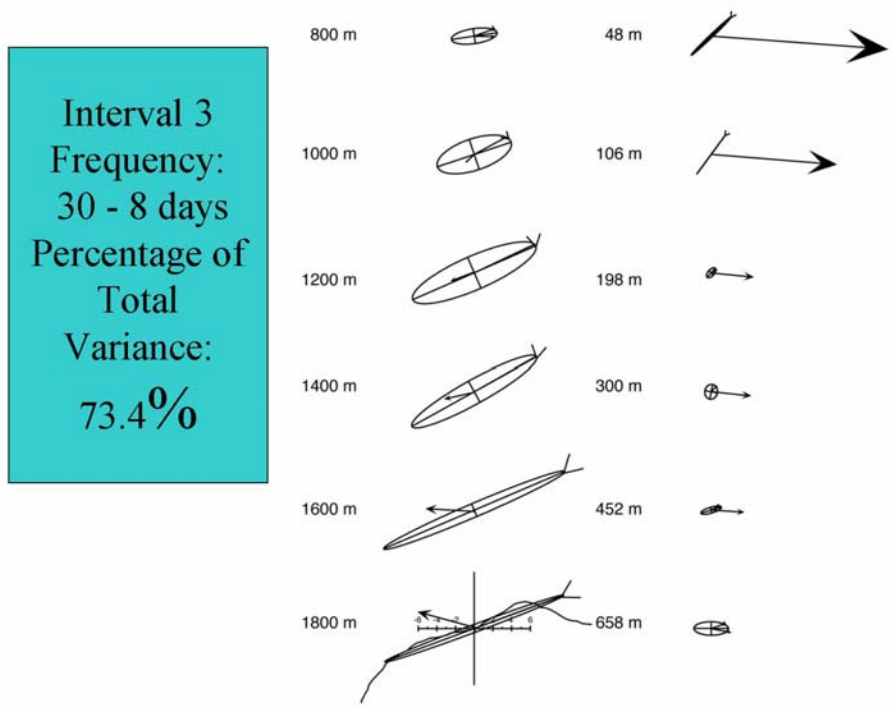

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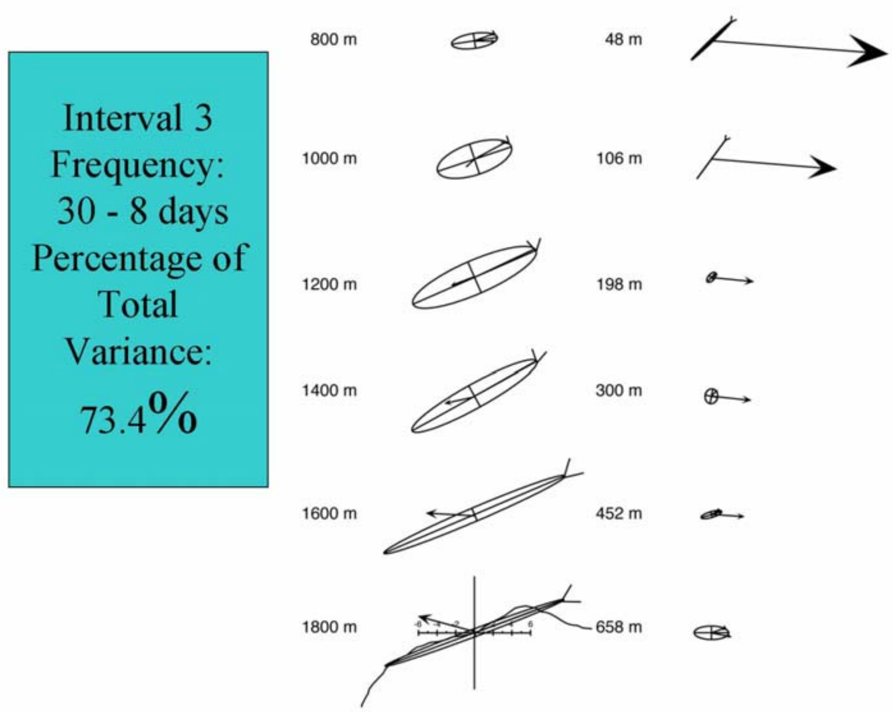

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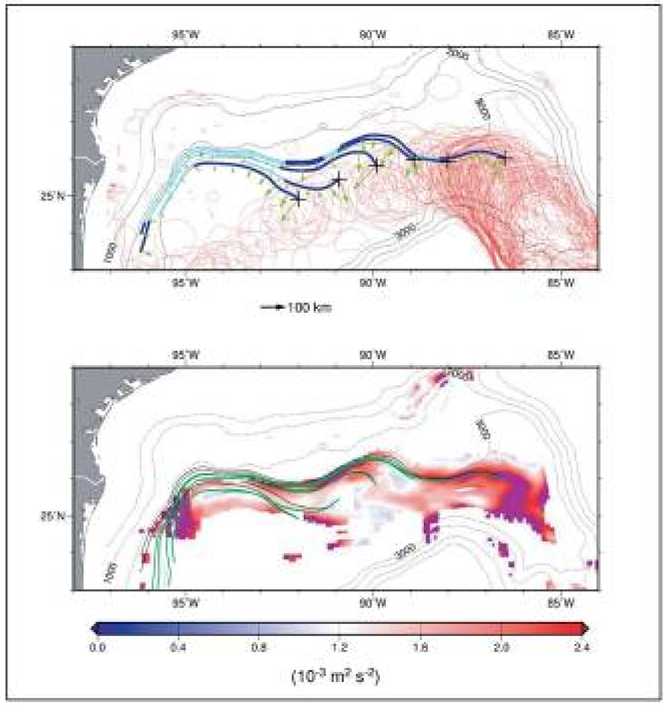
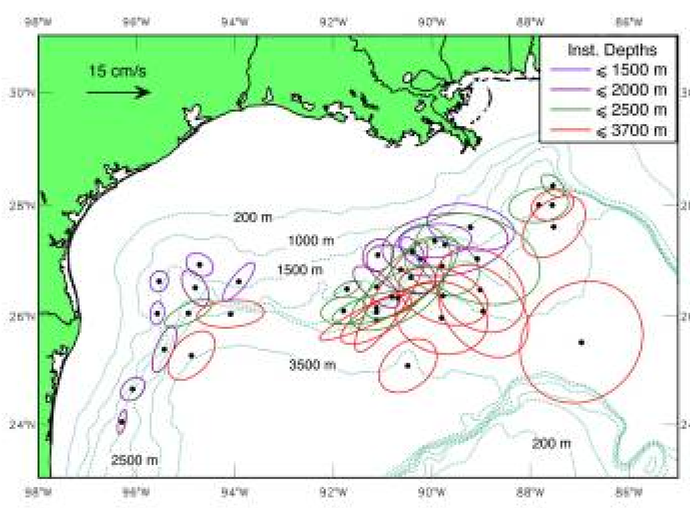
Bottom
20 - 100 day EKE
with
TRW Ray Paths
from
Numerical Model
(Oey & Lee,
2002)



Slide 6

Standard Deviation Ellipses ~ 100-500 mab



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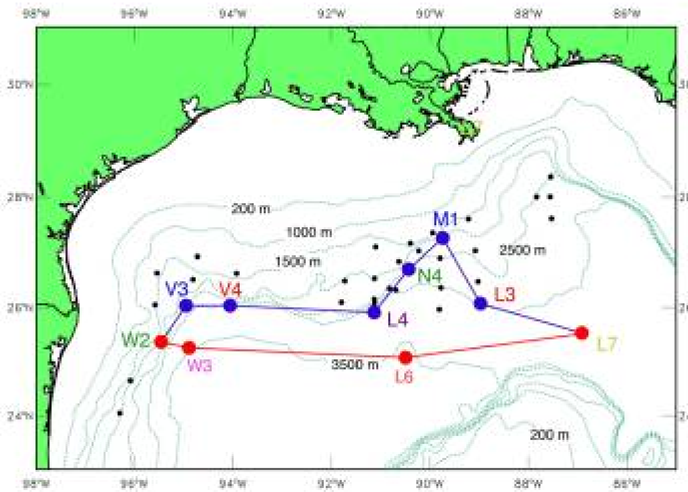
Map of KE Spectra Locations



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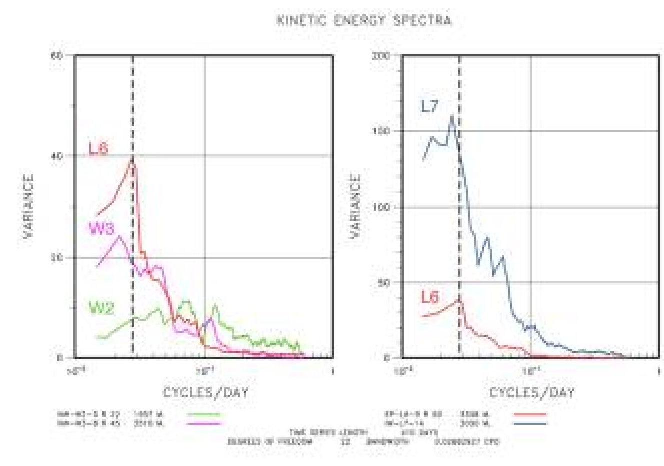
KE Spectra across the Gulf - 1



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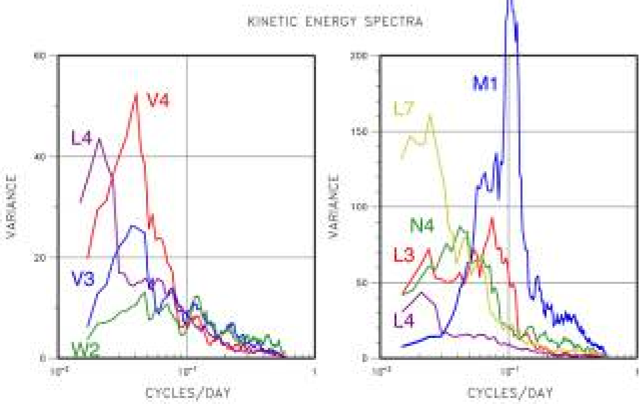
KE Spectra across the Gulf - 2



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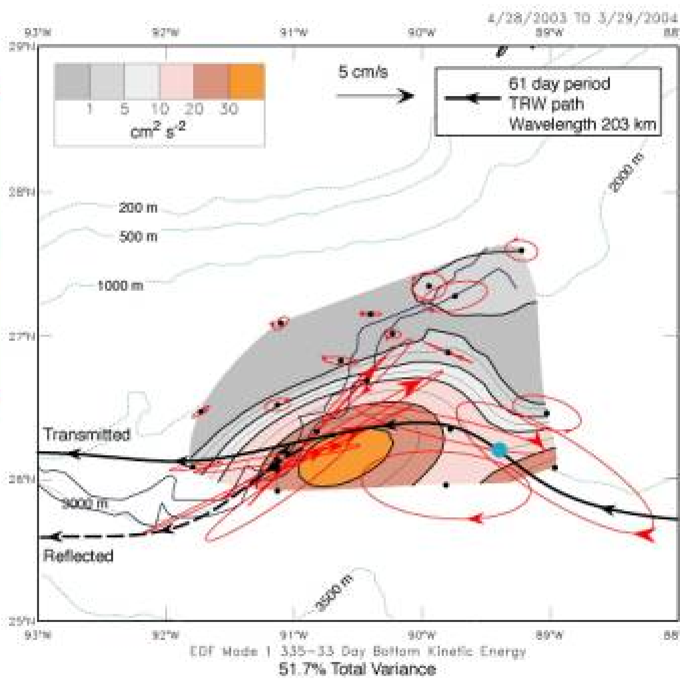
335-33 Day Variability and TRW Path



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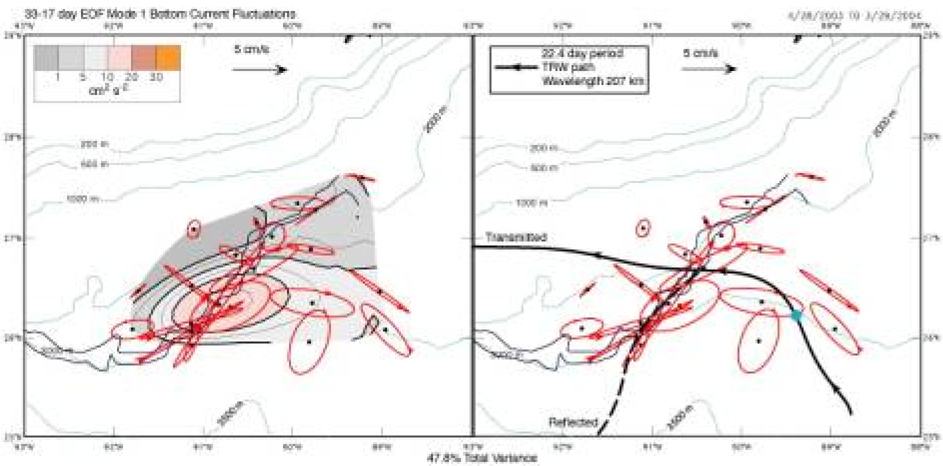
33-17 Day Variability & TRW Path



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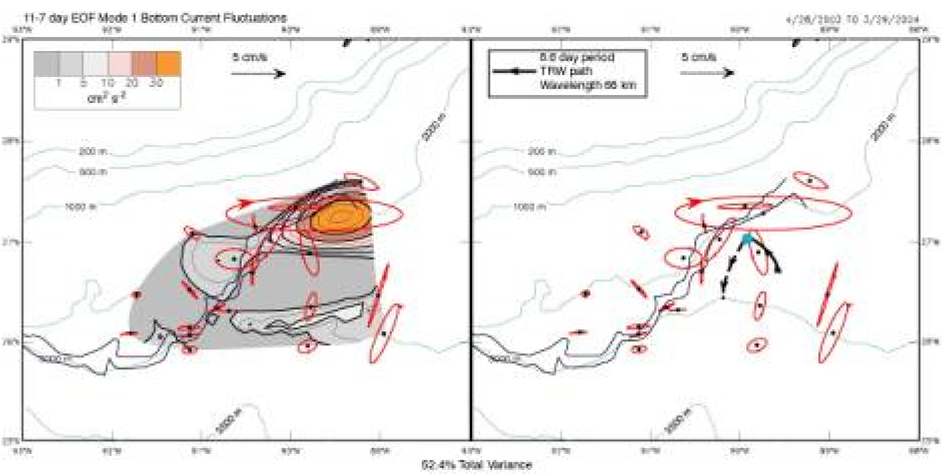
11-7 Day Variability & TRW Path



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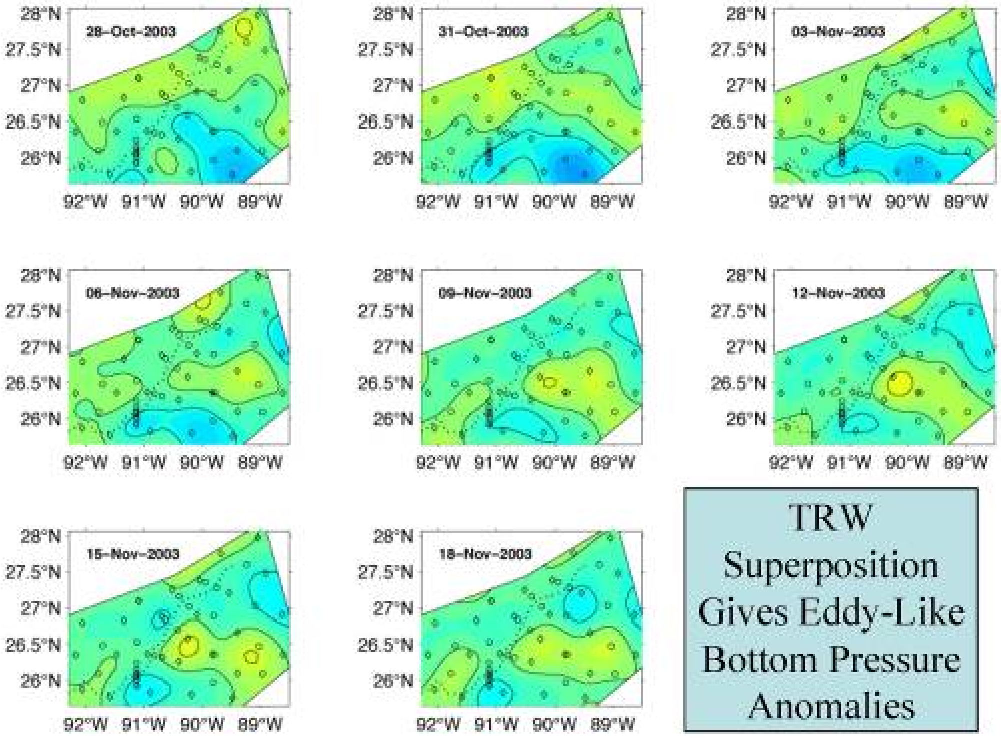
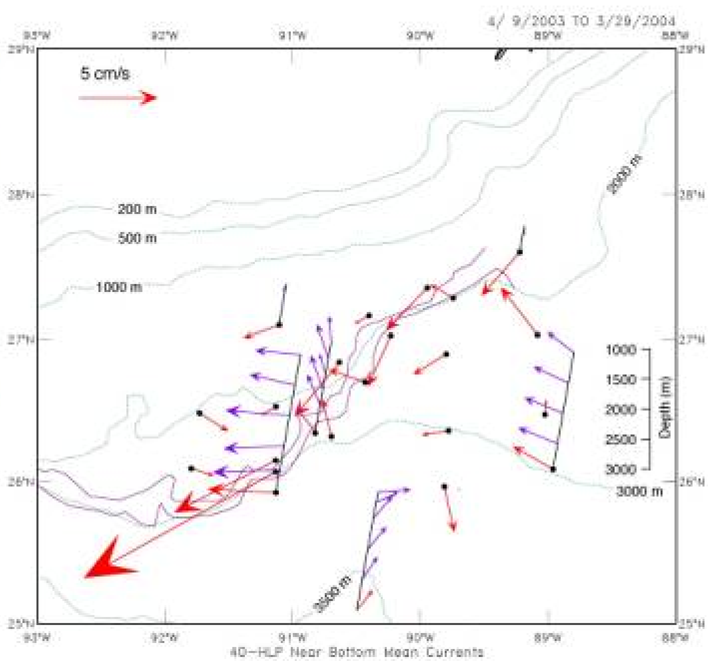


Slide 14

Sigsbee Escarpment Lower Layer Mean Currents



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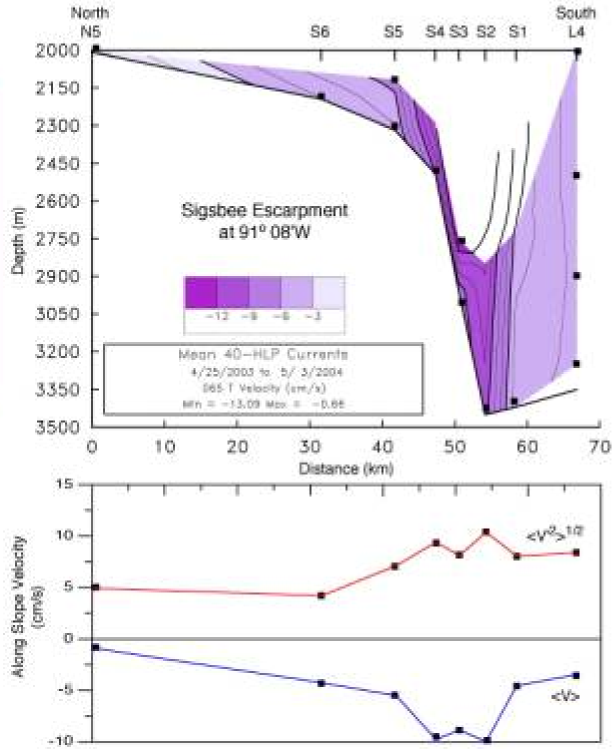
Mean Along-Slope Currents across the Escarpment



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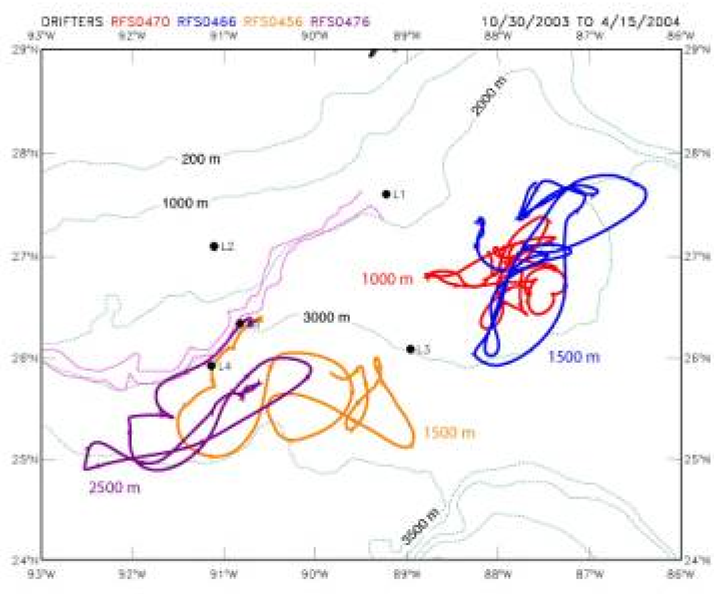
North Central Gulf RAFOS Float Trajectories



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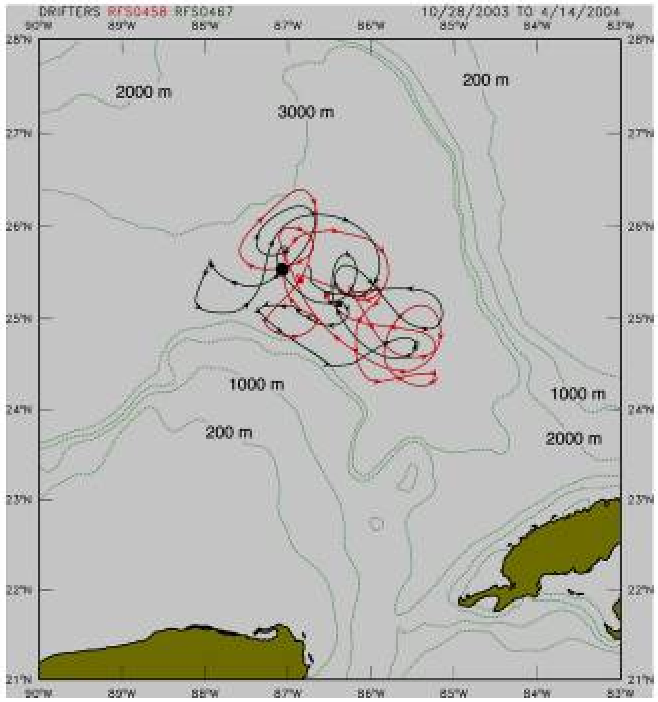
RAFOS Floats at 1500 m under the Loop Current



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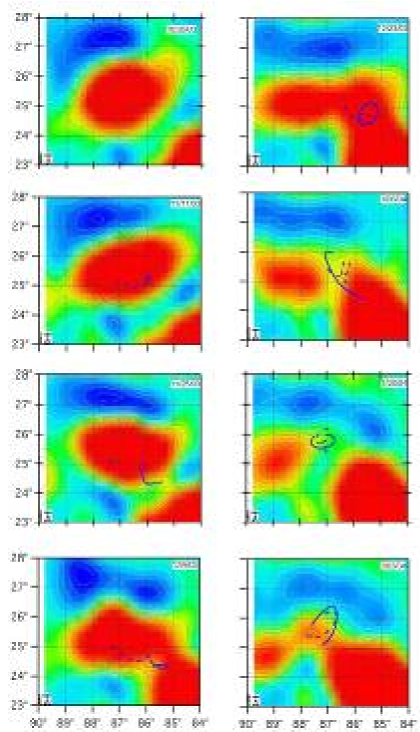
Floats below LC and Eddy Titan



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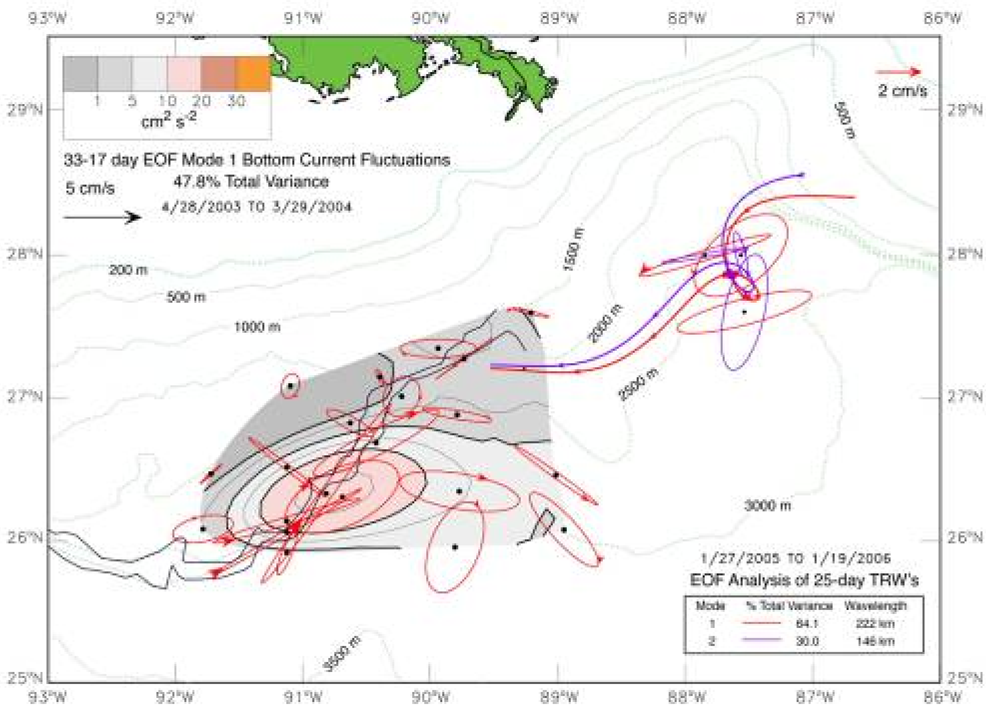

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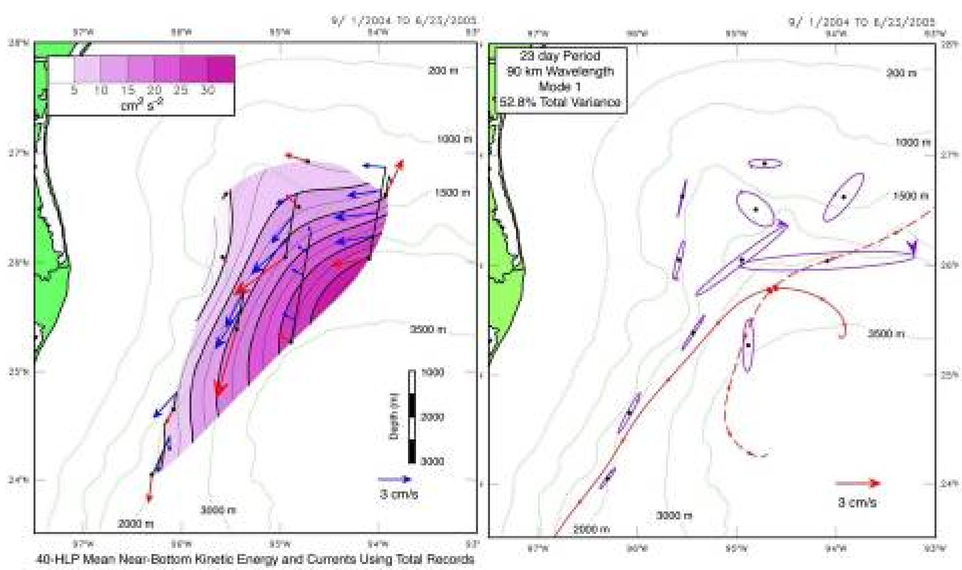
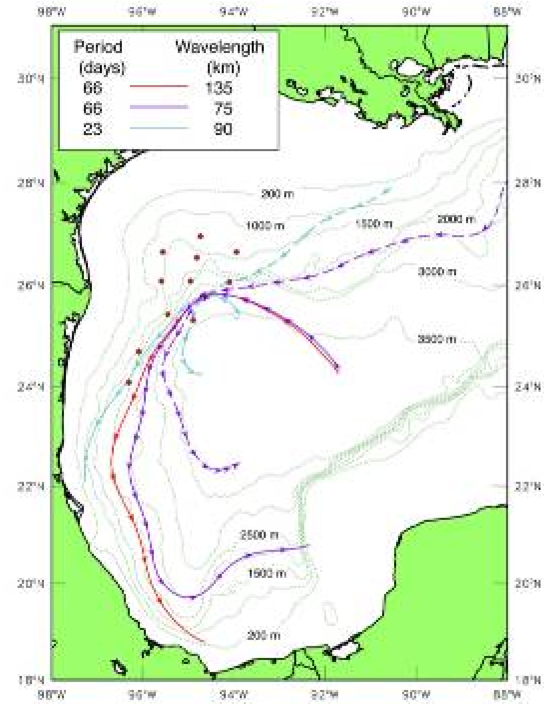
Lower Layer Mean Current Profiles & 23 day TRW



Slide 21

Western Gulf TRW Ray Traces



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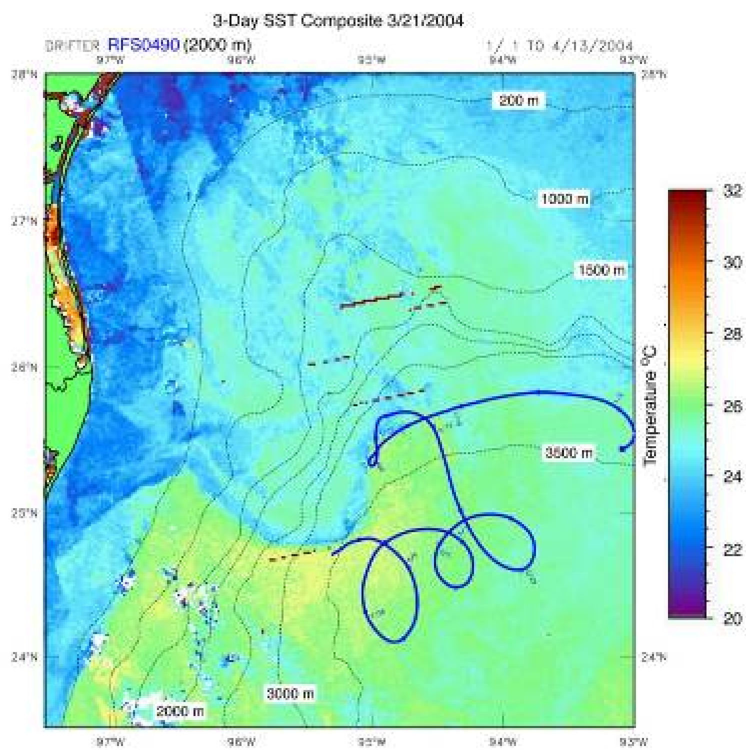
Deep Cyclonic Eddy



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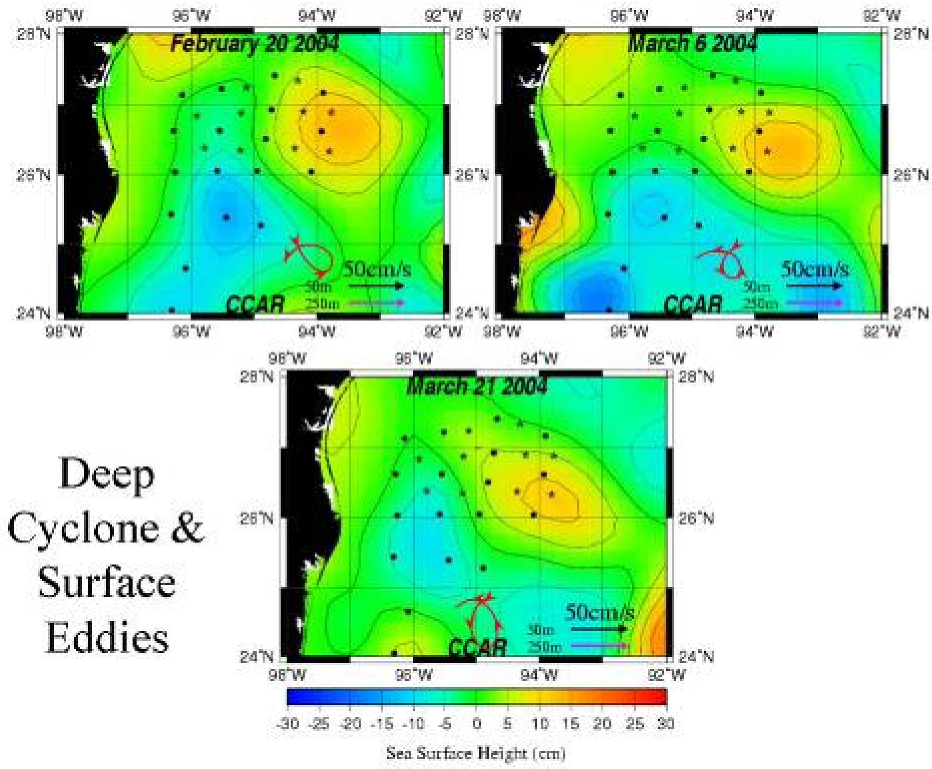

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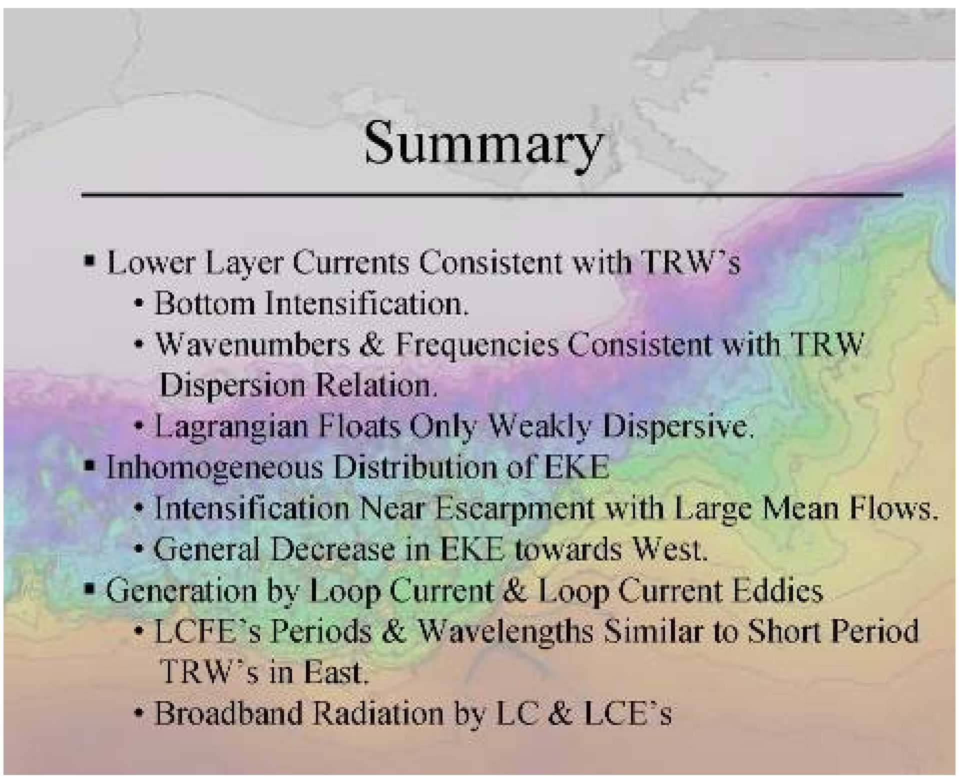

PRESSURE-RECORDING INVERTED ECHO SOUNDER (PIES) STUDIES IN THE GULF OF MEXICO

Kathleen Donohue and D. Randolph Watts, University of Rhode Island

Introduction

Three arrays of pressure-recording inverted echo sounders (PIES) and current meter moorings were deployed in waters deeper than 1000 m in the Northern Gulf of Mexico to measure and coherently map currents and eddies daily through the full water column with mesoscale resolution (Figure 5). The Exploratory Array in the north central Gulf was deployed in March 2003 and recovered April 2004. The Northwest Gulf array was deployed October 2004 to August 2005, and the Northeast Gulf array in December 2004 to January 2006. Science Applications International Corporation (SAIC) led the Exploratory and Northwest Gulf projects while Evans Hamilton Inc. led the Northeast Gulf project. Mineral Management Services funded all three projects.

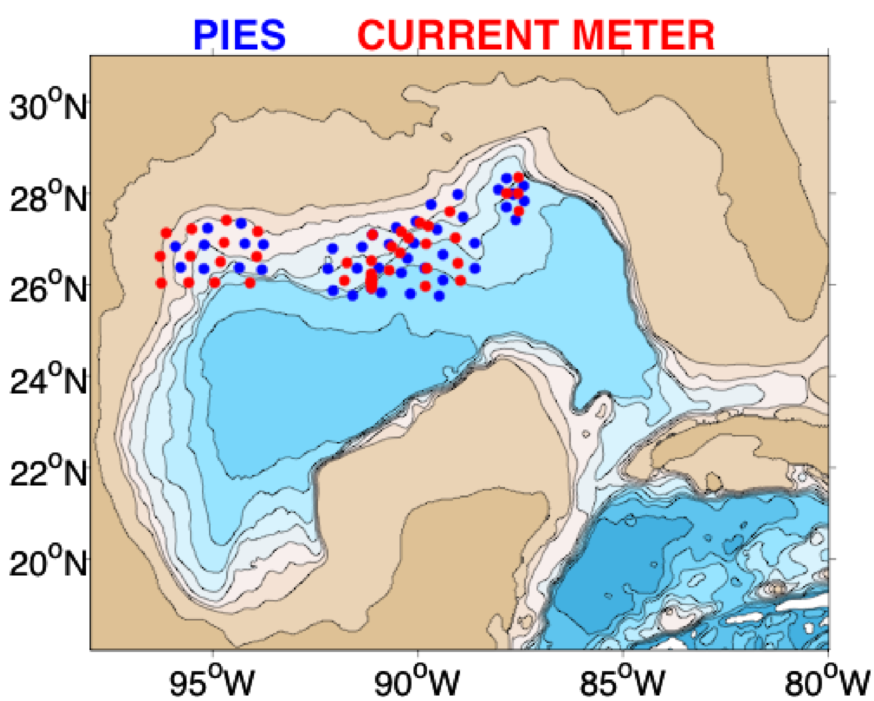

Figure 5. Map of the three MMS-sponsored arrays of pressure-recording inverted echo sounders (PIES, blue dots), and current meter moorings (red dots) deployed in the northern Gulf of Mexico. Bathymetry contoured every 1000 m depth.

PIES Methodology

Within each of the three arrays we produced 4-D maps of temperature, salinity, density, and velocity. Round-trip acoustic travel time measured by the inverted echo sounder allowed estimates of vertical profiles of temperature, salinity, and density, utilizing empirical look-up tables based upon historical hydrography for the region. Estimated horizontal density gradients were mapped to estimate baroclinic shear profiles. Pressure fields were leveled via geostrophy using mean current measurements. By referencing the baroclinic velocity profiles with deep velocities from the mapped pressures and currents, the absolute profiles of geostrophic velocity were obtained. Maps were produced with optimal interpolation techniques adapted from Bretherton et al. (1976) and outlined in Watts et al. (2001).

Tall moorings provided independent measurements to evaluate our PIES-derived fields of temperature and velocity in each experiment. Comparisons between PIES-estimated and directly-measured mooring temperatures indicate that the empirical relationship holds well in the Gulf of Mexico, and demonstrated that the variance explained in the thermocline is approximately 85%. A more stringent test of the PIES methodology and mapping is the comparison against measured velocities, and the agreement between measured and PIES-estimated series was excellent. The rms differences in velocity were less than 10 cm/s near 200 m depth, 6 cm/s near 700 m, and 4 cm/s at depths below 1500 m.

Currents and Eddies across the Gulf of Mexico

The majority of mesoscale eddy variability in the deep-water northern Gulf of Mexico is related to the Loop Current, Loop Current Eddies, and frontal eddies. The energy distribution is strongly affected by the topography of the deep continental slope, especially the Sigsbee Escarpment (Figure 6a). In each of the three arrays, the strongest surface currents and eddies outside the Loop Current itself were in Loop Current Eddies. Only the periphery of the Loop Current entered these arrays during these observations. In the North Central Gulf two Loop Current Eddies, Sargassum and Titanic, entered the eastern portion of the array and passed directly through the region to the southwest. The resulting eddy kinetic energy (EKE) was high in the eastern portion and diminished to the west. EKE is defined as $(1/2)\ [\ (u')^2 + (v')^2\ ]$, where $u' = (u - U)$, $v' = (v - V)$, $(U, V) = ([u], [v])$, and [ ] indicates the average over the observation period. In the Northwest Gulf one Loop Current Eddy, Ulysses, entered its eastern portion while other smaller and weaker cyclones and anticyclones appeared. The resulting EKE was high in the eastern portion and diminished to the west. Loop Current and Loop Current Eddies skirted the southwest corner of the Northeast Gulf array, so surface EKE was not as high as the other experiments.

The strongest deep currents and eddies among these three experiments were found in the North Central Gulf array (Figure 6b). Deep eddies entered from the southeast and translated west and northwest to impinge upon the Sigsbee Escarpment and track along it.

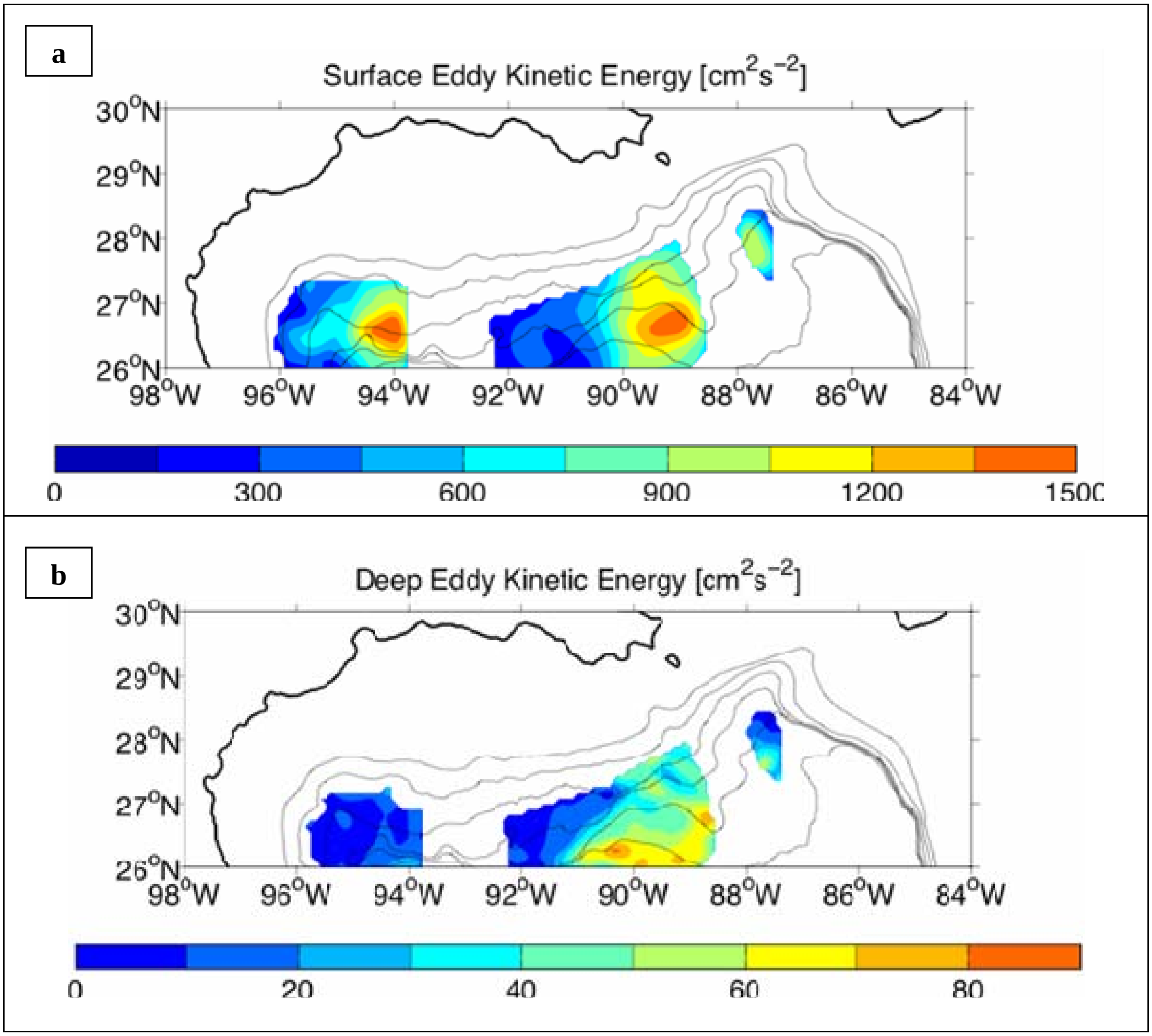

Figure 6. Surface and deep eddy kinetic energy determined from the three PIES arrays in the northern Gulf of Mexico. Bathymetry is contoured every 1000 m depth.

The deep currents became concentrated along the steep Sigsbee topography, especially near 90^{o}-91^{o}W. Most eddies in the deep Gulf remain south of Sigsbee and do not enter into the region to its northwest. We note that region is distinct from the shallower-yet continental shelf. In the Northwest Gulf the deep eddies were much weaker, but they too were partly steered along the topography. Compared within the Northwest Gulf array, the deep eddies were more energetic offshore of the 2000 m isobath. Deep eddies entered the Northwest Gulf region from the east and did not appear to originate locally. In the Northeast Gulf, five strong deep eddies passed through the southern deeper portion of the array. The deep eddies were episodic, associated with intervals when upper-layer Loop Current and Loop Current Eddies swept southeast through the array.

Diagnostic Studies of Vertical Coupling Between Upper and Deep Circulation

The Central and Northeast Gulf Arrays exhibited several examples of interaction between the upper and deep ocean: blocking, joint propagation of upper and lower layers, and baroclinic instability. Upper and lower layers are dynamically coupled when their motions stretch or squeeze the opposite layer. The lower-layer response to vortex stretching/squeezing tends to produce respectively positive/negative relative vorticity to balance the changes in thickness. Figure 7 illustrates such a case in the Northeast Gulf Array, in which a deep anticyclone led and deep cyclone trailed as the Loop Current or Loop Current Eddy swept southeast through the array. This pattern repeated itself five times in 2005.

Note that the above description of local vertical coupling is highly idealized: we have neglected the effects of topography, a spherical earth, and lower-layer advection of a background potential vorticity gradient, for example. We refer the reader to Cushman et al. (1990) for a more in-depth discussion, and we point out that Welsh and Inoue's (2000) modeling study reveals the joint spin-up of lower layer eddies beneath strong translating upper-ocean features. The lower layer potential vorticity (PV) can be diagnosed as follows, where PV = $(f + \zeta)/H$, and f = Coriolis frequency (planetary vorticity), ζ = relative vorticity, and H = lower layer thickness from the sea floor to the base of the thermocline (6^{o}C isotherm depth). Figure 8 shows the time series of terms contributing to the PV balance at a point where the deep eddies spun up and passed repeatedly. The local PV was not constant but varied through a range of about 25%, and this variation, PV tendency ∂ PV/∂t, was balanced by PV advection, u (∂ PV/∂x) + v (∂ PV/∂y).

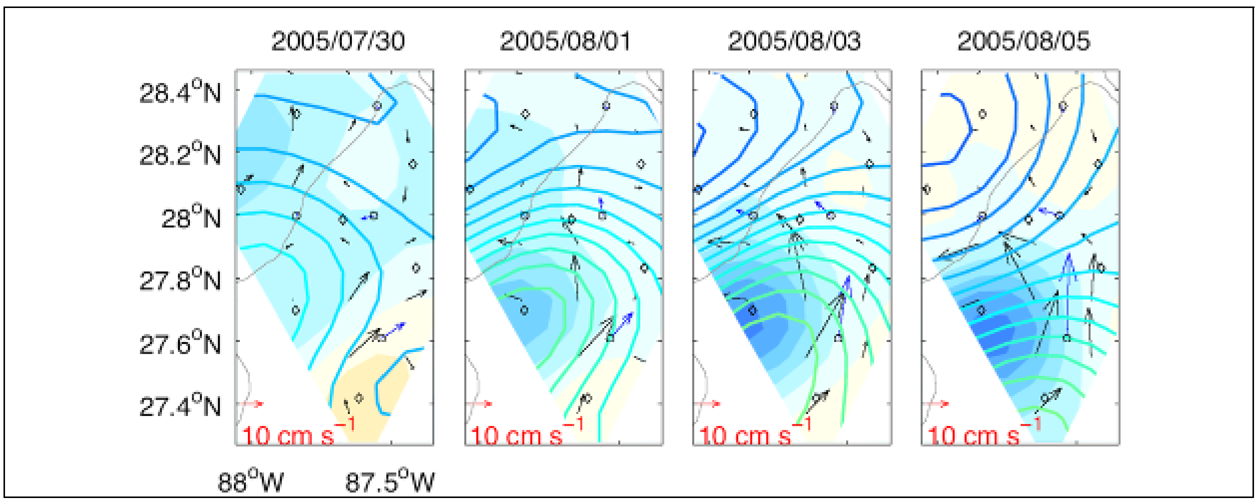

Figure 7. Case study of a lower-layer cyclone leading an upper-ocean cyclone [30 July – 05 August 2005] as the crest of the Loop Current withdraws southeastward in the Northeast Gulf array. Maps of surface streamfunction (bold contour lines) superimposed upon shaded contours of pressure at 1500 m depth for four separate days. In both fields highs are represented by red hues and lows represented by blue hues. Bathymetry contoured every 1000 m depth is denoted by the gray lines. PIES sites indicated by diamonds; current meters by circles.

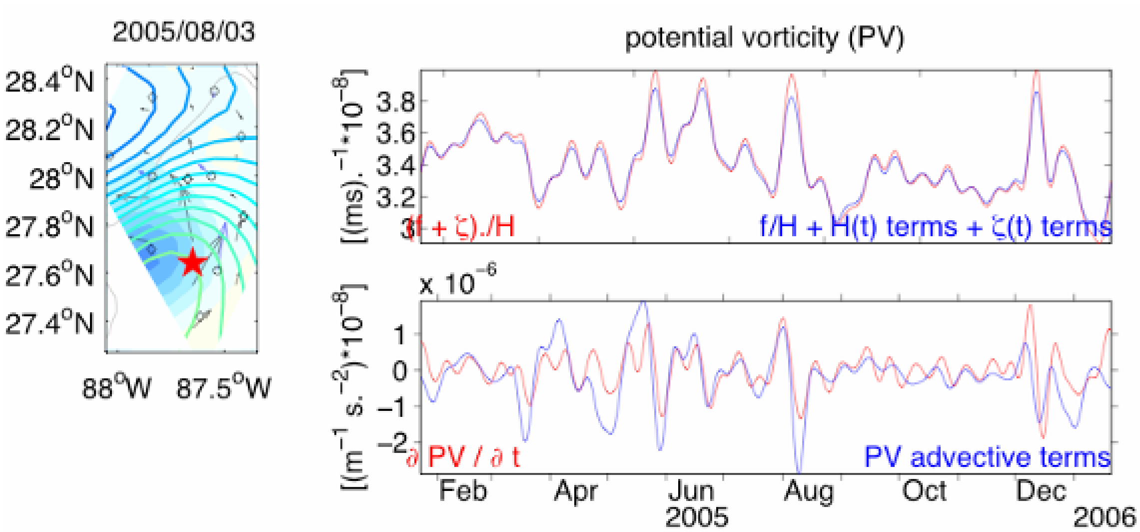

Figure 8. Potential vorticity terms are diagnosed as time series at the location within the Northeast Gulf array indicated by the red star. As the cyclone of Figure 7 passed in July-August a local peak PV can be seen in the upper panel. The PV tendency is balanced by PV advection, as shown in the lower panel.

In events where deep eddies are vertically coupled to the upper loop current, an array like this allows diagnosis of dynamical balances. The time scales, spatial scales and PV balances of deep eddies all support that they exhibit the dynamics of topographic Rossby waves (TRWs).

Future Observational Work

A current meter option has been added to the PIES, called CPIES, because many PIES applications also required deep current measurements. The CPIES includes the Doppler current-sensing head of the Aanderaa RCM-11, buoyed 50 m above the PIES to be out of the bottom boundary layer. It now includes acoustic release, a 4+ years deployment capability, and acoustic telemetry capability. Two experiments funded by ONR and NSF in the Kuroshio and Kuroshio Extension successfully deployed and recovered arrays of CPIES.

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Cushman-Roisin, B., E.P. Chassignet and B. Tang. 1990. Westward motion of mesoscale eddies. Journal of Physical Oceanography 20:758–768.

Welsh, S.E. and M. Inoue. 2000. Loop Current rings and the deep circulation in the Gulf of Mexico. Journal of Geophysical Research 105(C7):16951–16959.

Watts, D.R., X. Qian, and K.L. Tracey. 2001. Mapping abyssal current and pressure fields under the meandering Gulf Stream. Journal of Atmospheric and Oceanic Technology 18:1052–1067.

Kathleen Donohue received a Ph.D. degree in oceanography from the University of Rhode Island in 1995. In 2000, after a post doctoral appointment at the University of Hawaii, she returned to the University of Rhode Island where she worked as an assistant Marine Research Scientist from 2000 to 2006 and presently has an ADVANCE research professor position. Kathleen is a physical oceanographer whose research interests include describing the global ocean velocity structure with particular focus on western boundary current regimes.

D. Randolph Watts is a Professor of Oceanography at the University of Rhode Island. His current research interests are dynamic and descriptive physical oceanography, with emphasis on dynamics and energetics of strong current systems and their large scale eddies.

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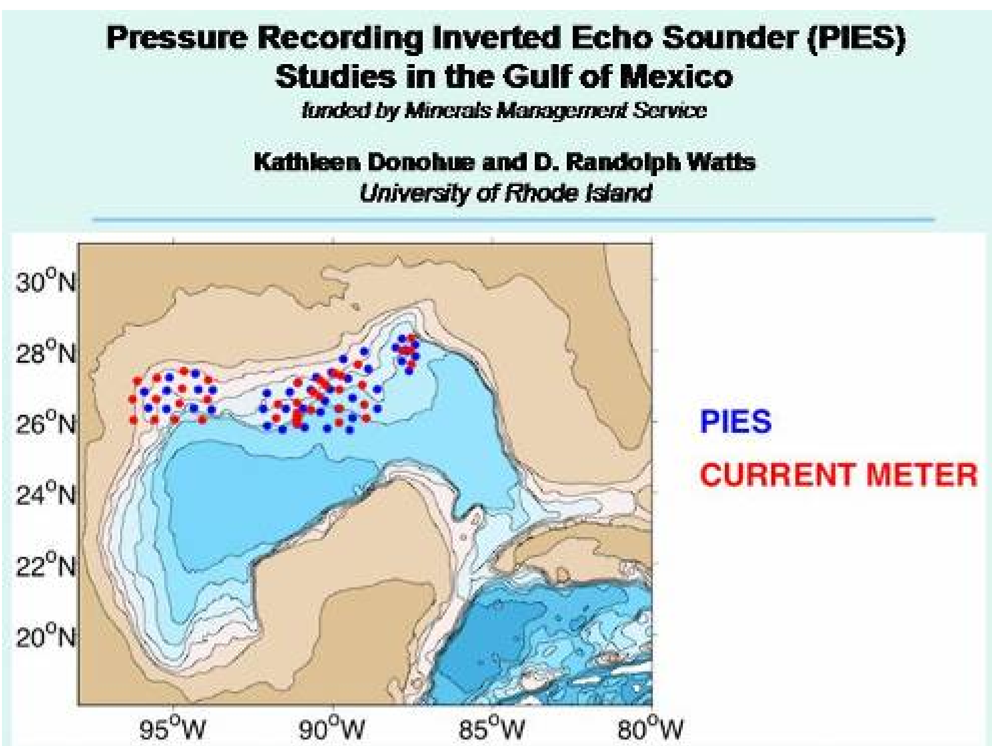
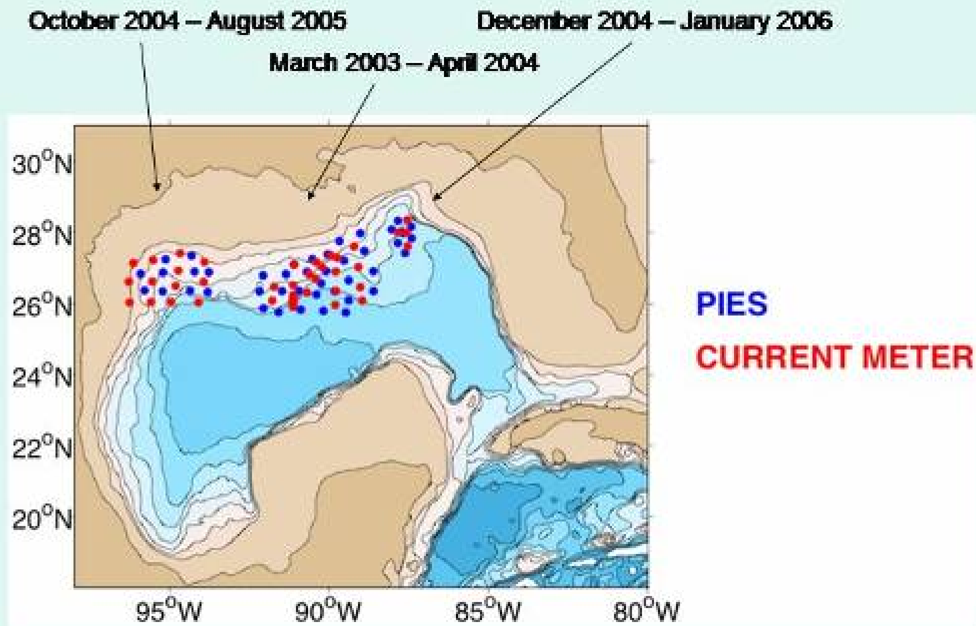


Slide 2

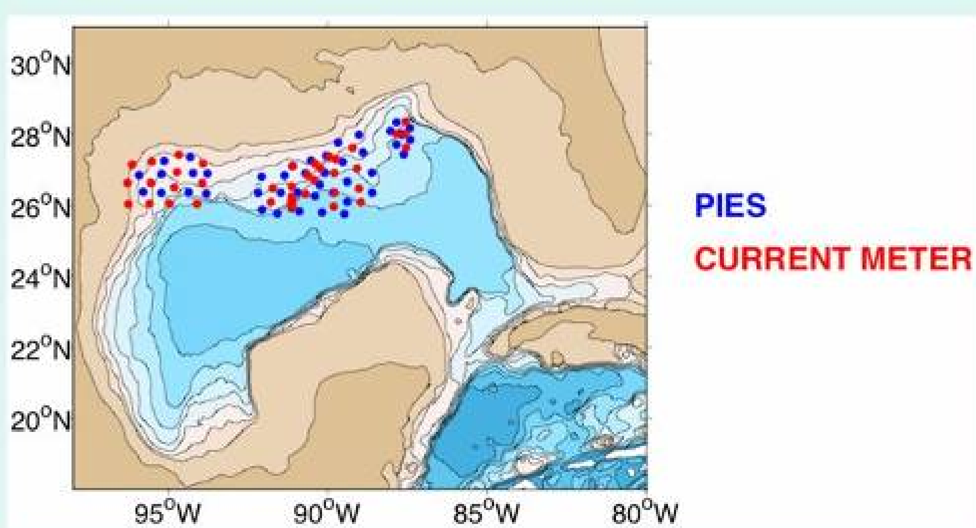
Three Programs Funded by MMS to SAIC and EHI



Slide 3

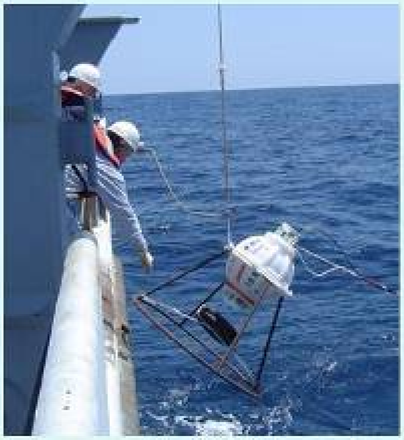
These three arrays map the currents throughout the water column.

Mesoscale resolution allows the diagnosis of dynamical quantities.



Slide 4

PIES: Pressure Recording Inverted Echo Sounder

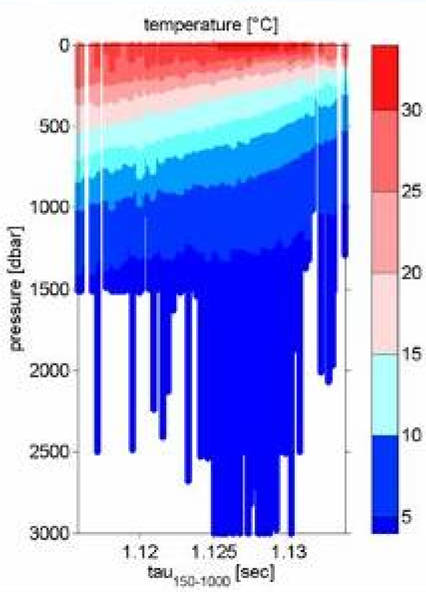


- Sits at the ocean bottom.
- Emits 12kHz sound pulses.
- Measures round trip travel times of acoustic pulses to sea surface and back.
- Measures bottom pressure.

Round trip travel time is a proxy for vertical profiles of temperature and salinity.

Slide 5

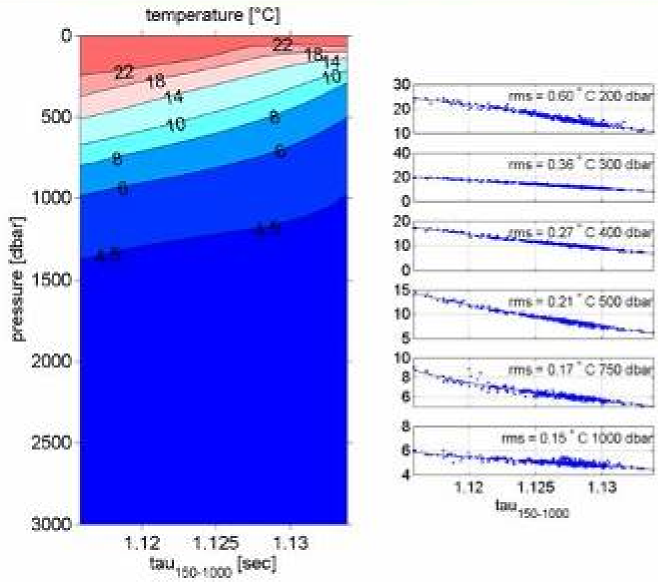
Hydrography establishes the proxy relationship between temperature and round trip travel time.



- Hydrographic data sorted by round-trip travel time index, tau.
- A relationship exists between the integrated variable $tau_{150-1000}$ and vertical profiles of temperature.

Slide 6

Cubic smoothing splines fit create a gridded look-up table.

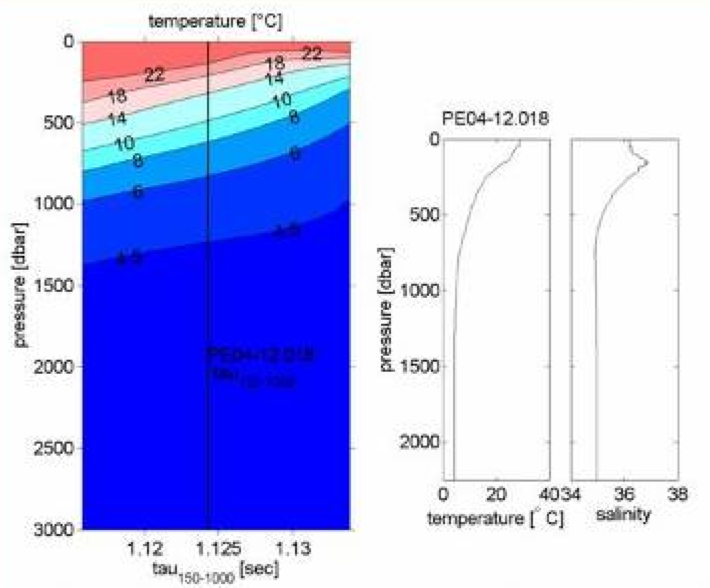


RMS indicates the departure any individual profile might have from the look-up fit.

RMS are .25C within the main thermocline and decrease with increasing pressure.

Slide 7

Example: Look-up a temperature profile, given $tau_{150\text{-}1000}$ from a cast.



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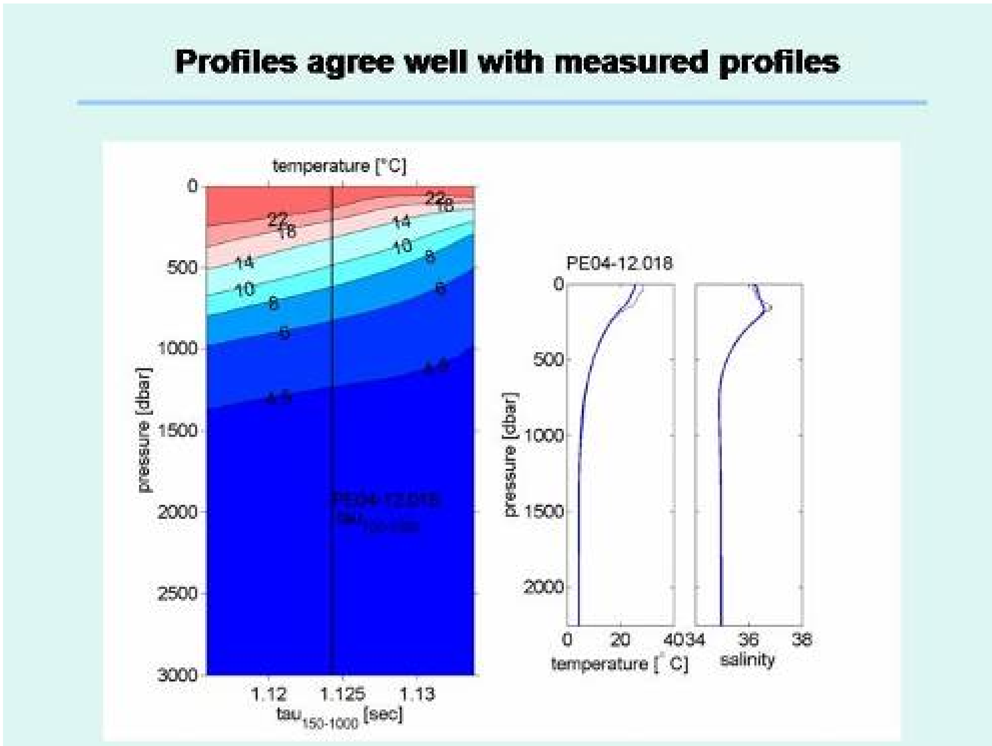

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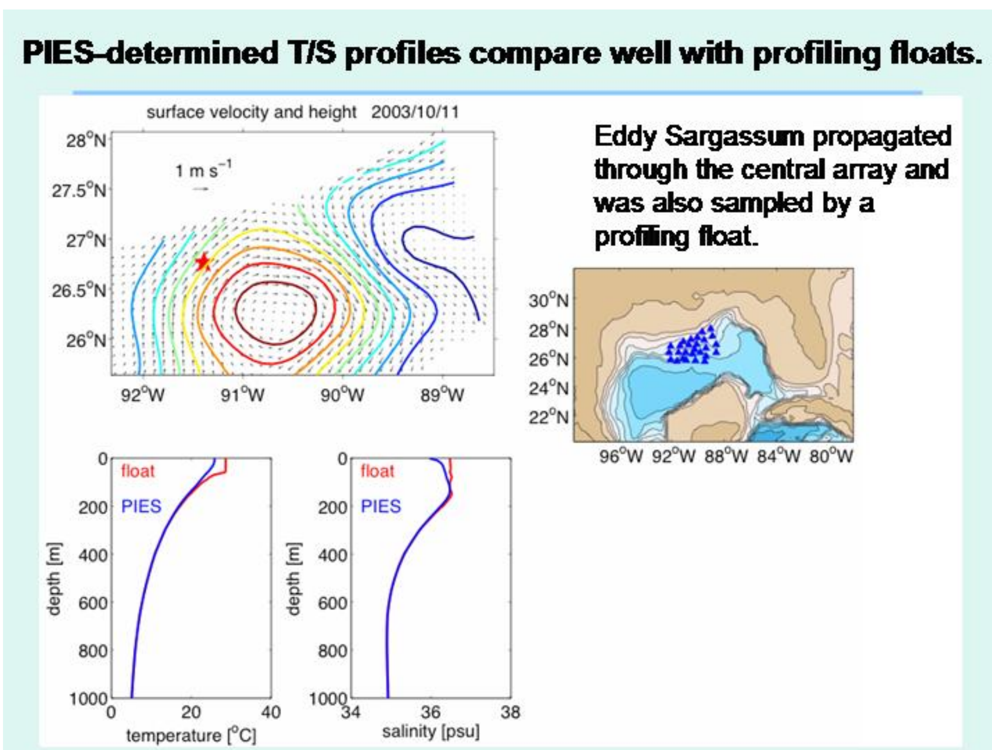
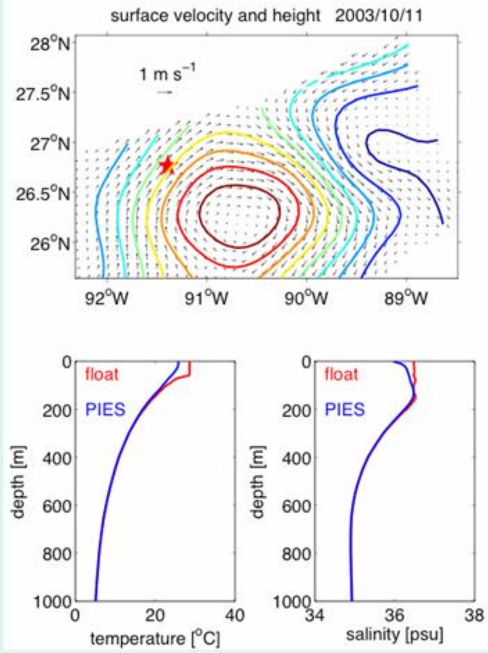
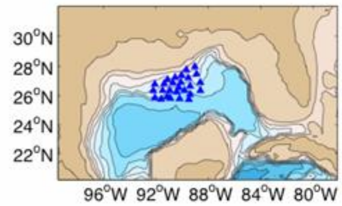


Slide 10

PIES-determined T/S profiles compare well with profiling floats.

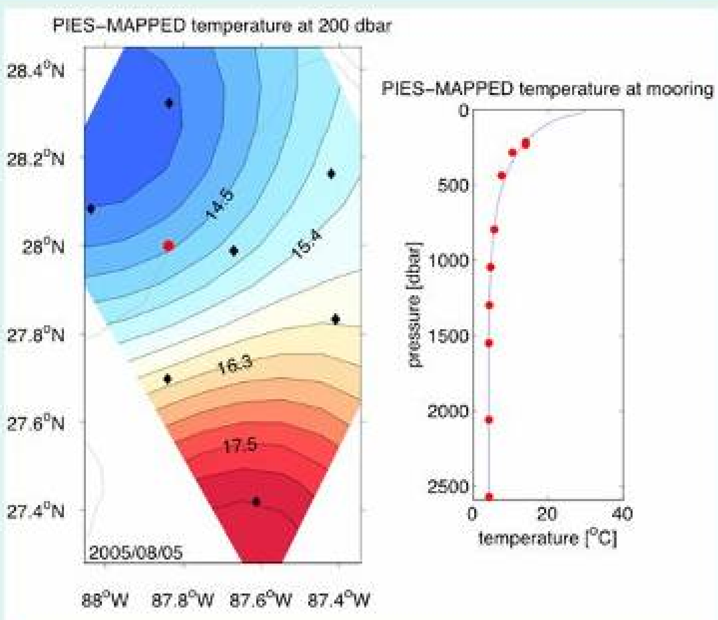


Eddy Sargassum propagated through the central array and was also sampled by a profiling float.



Slide 11

Northeast Gulf PIES array successfully maps temperature



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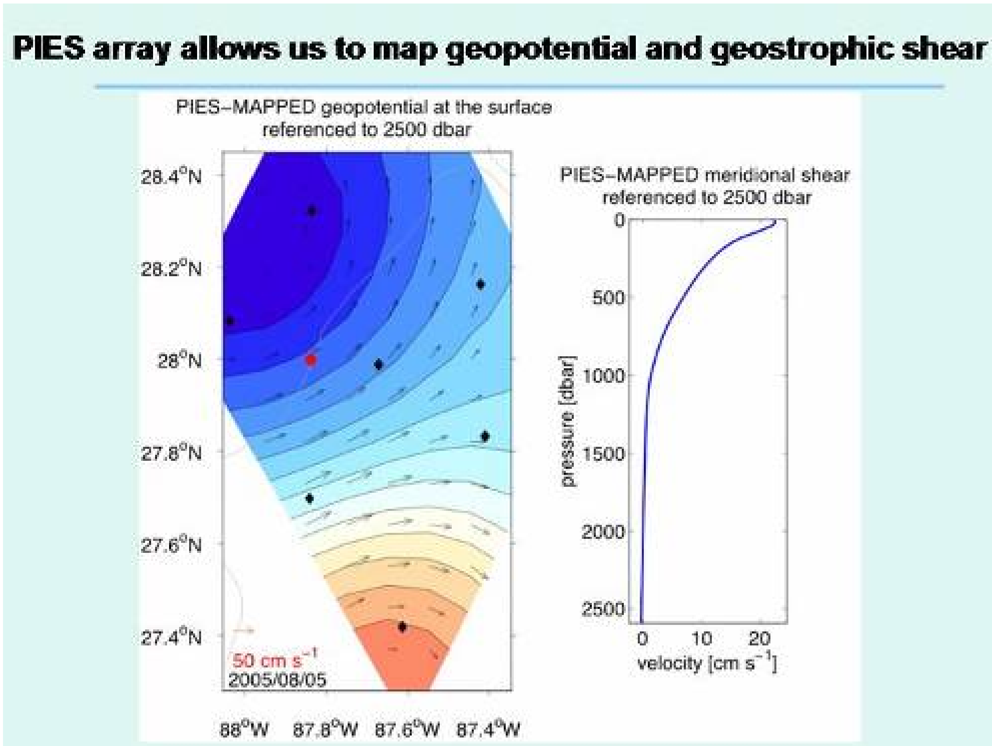

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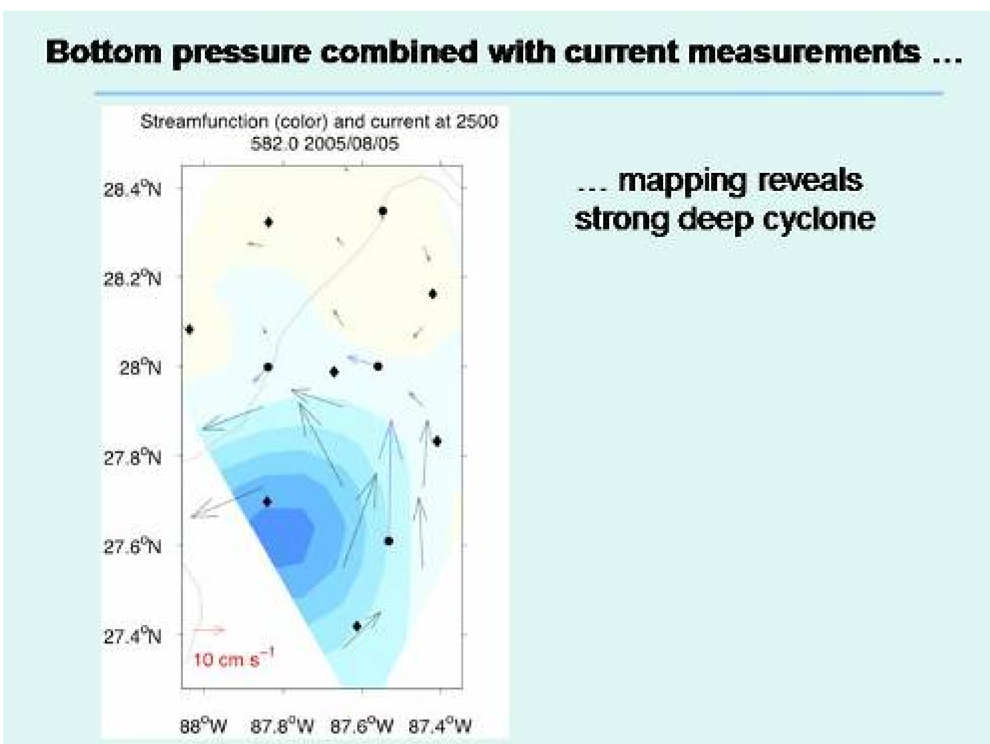
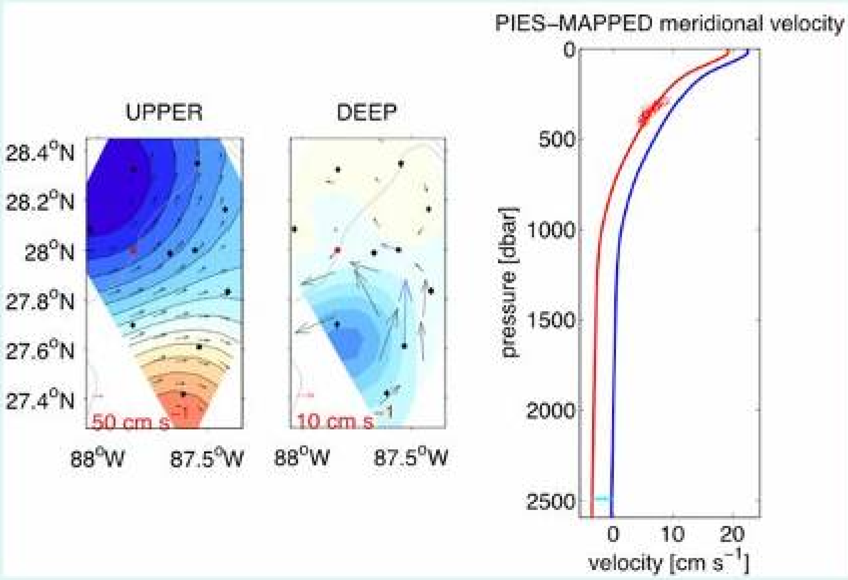


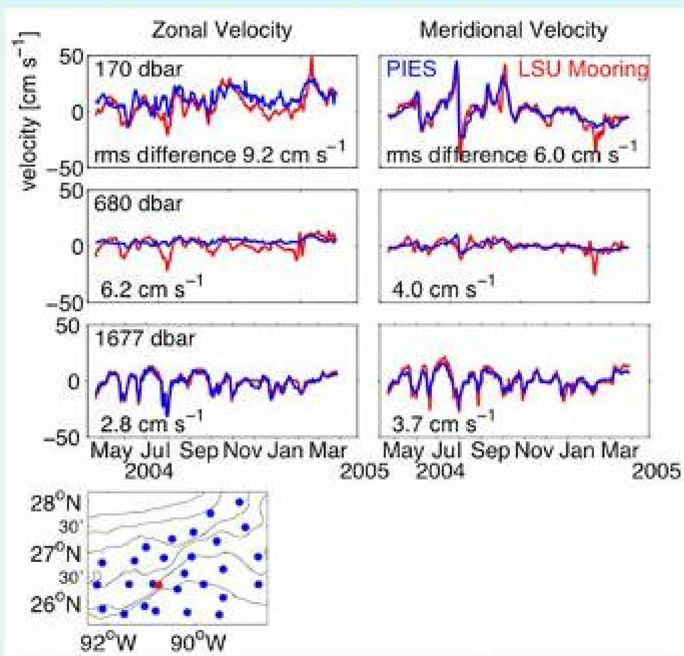
Slide 14

PIES array allows us map full water-column circulation



Slide 15

Excellent agreement between mapped and measured velocity.



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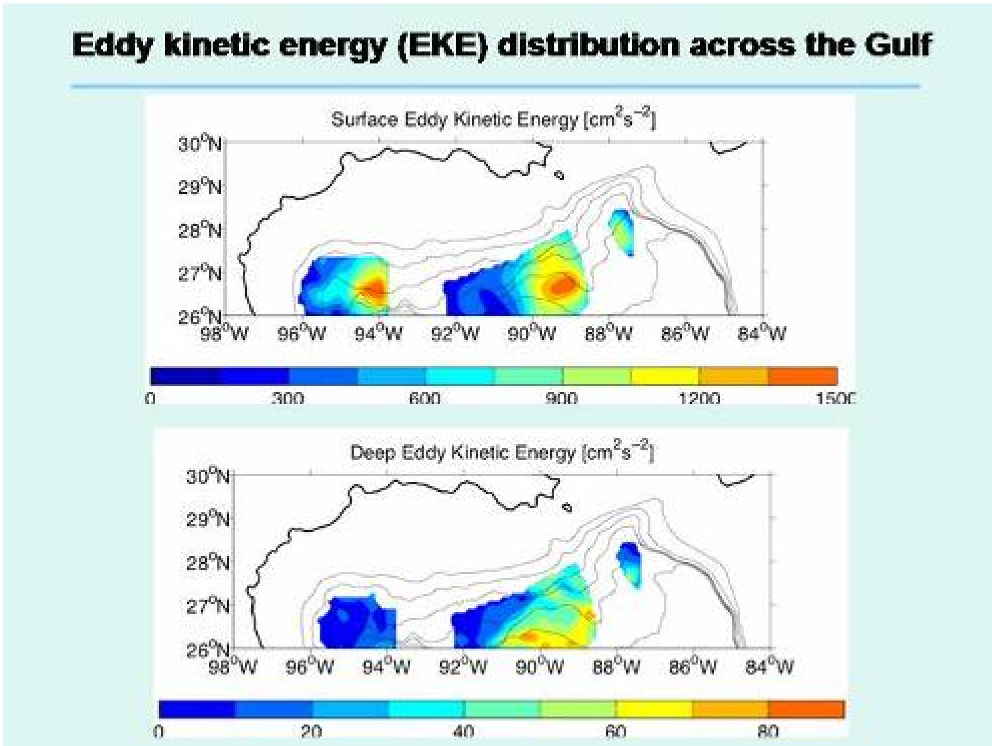

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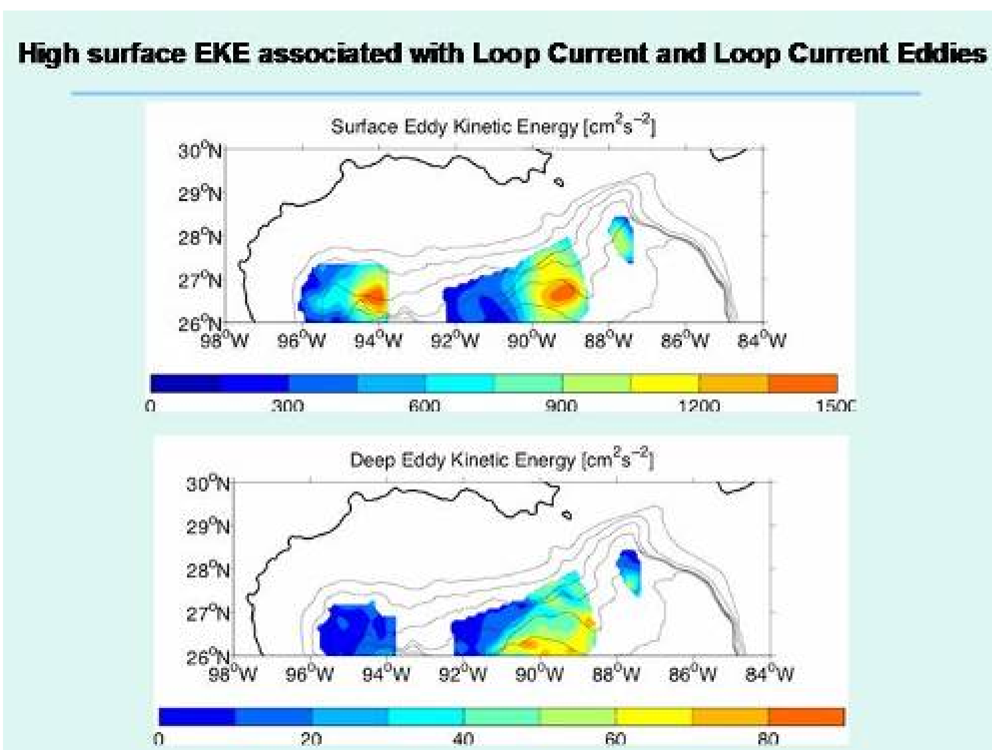
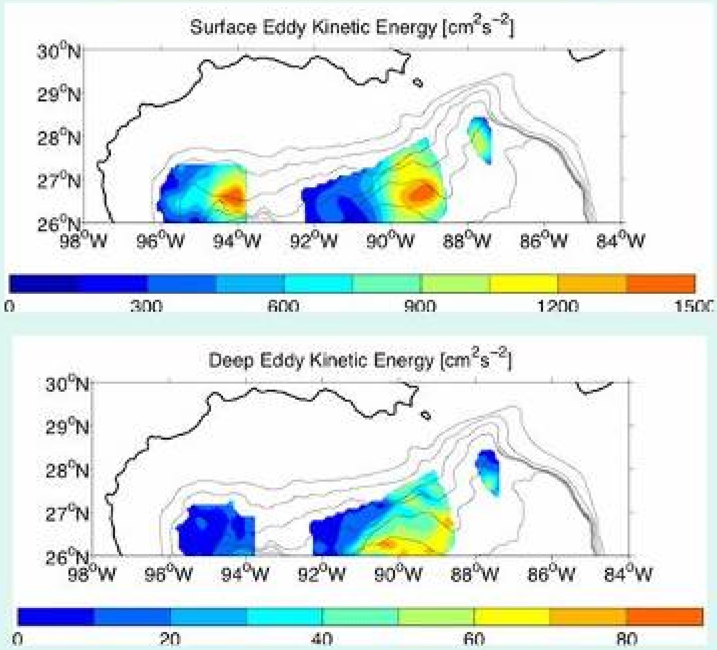


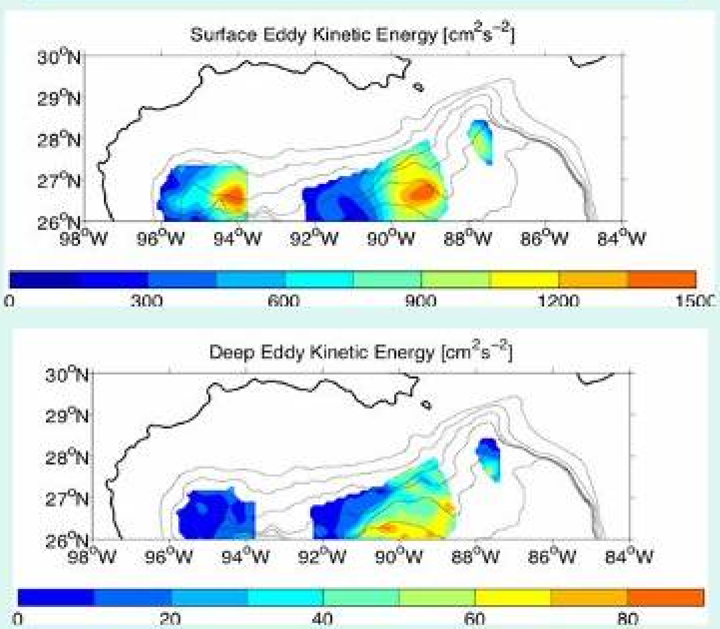
Slide 18

Strong deep EKE found in northeast Gulf and south of the Sigsbee escarpment with lowest EKE in the northwest Gulf.



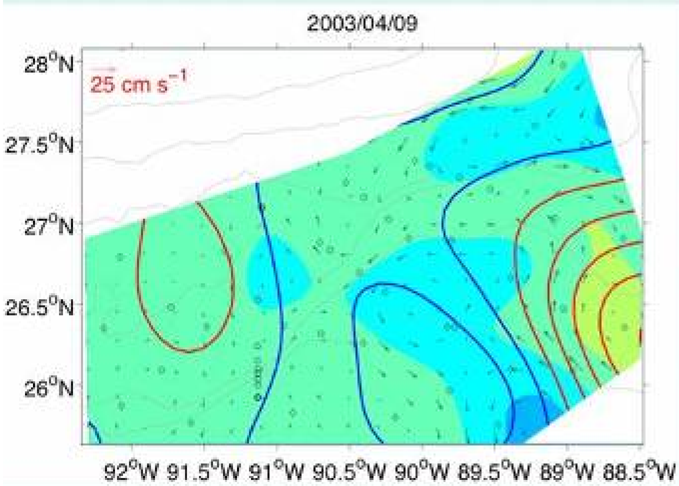
Slide 19

Deep eddies are steered by topography.
Open question – How does the upper ocean steer deep flow?



Slide 20

Movie of circulation in the central Gulf



Colored lines – Sea Surface Height

Filled contours – Deep streamfunction

Vectors – Deep currents

Red hues denote highs.

Blue hues denote lows.

Slide 21

Deep eddies steered by topography

- Cyclones approach Sigsbee Escarpment and deflect westward.
- Anticyclones approach Sigsbee Escarpment, stall and weaken.
- This behavior results from complimentary (cyclones) or competing (anticyclones) effects of dipole self-advection and topographic beta.

Slide 22

Deep eddies steered by topography

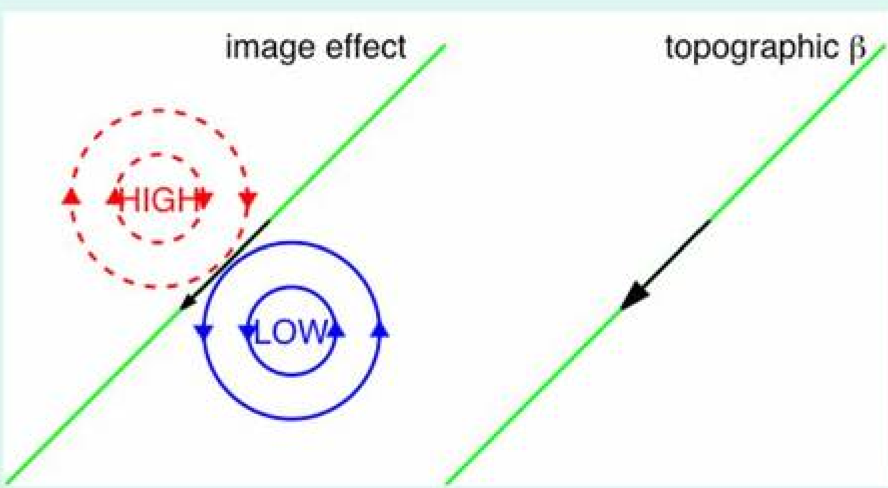
•Cyclones approach Sigsbee Escarpment and deflect westward.

•Anticyclones approach Sigsbee Escarpment, stall and weaken.

This behavior results from complimentary (cyclones) or competing (anticyclones) effects of dipole self-advection and topographic beta.

Slide 23

Cyclone: dipole self advection and topographic beta reinforce each other.



Slide 24

Examples of interaction between upper and deep circulation.

Blocking: The propagation of a deep cyclone is temporarily halted when it encounters Eddy Sargassum.

Joint propagation of upper and lower layers: The lower-layer responds to vortex stretching/squeezing by upper ocean.

Baroclinic Instability

Slide 25

Examples of interaction between upper and deep circulation.

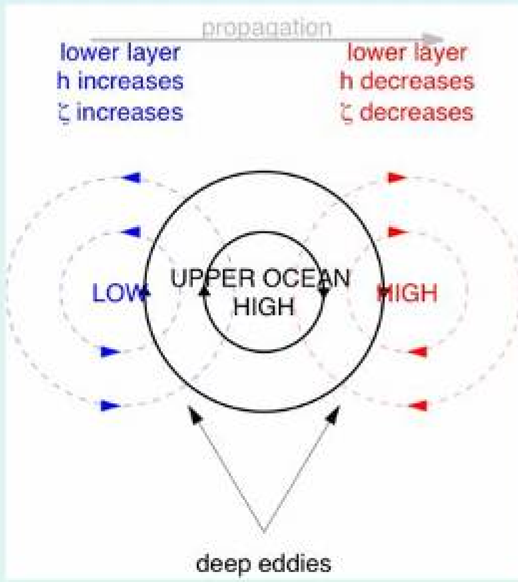
Blocking: The propagation of a deep cyclone is temporarily halted when it encounters Eddy Sargassum.

Joint propagation of upper and lower layers: The lower-layer responds to vortex stretching/squeezing by upper ocean.

Baroclinic Instability

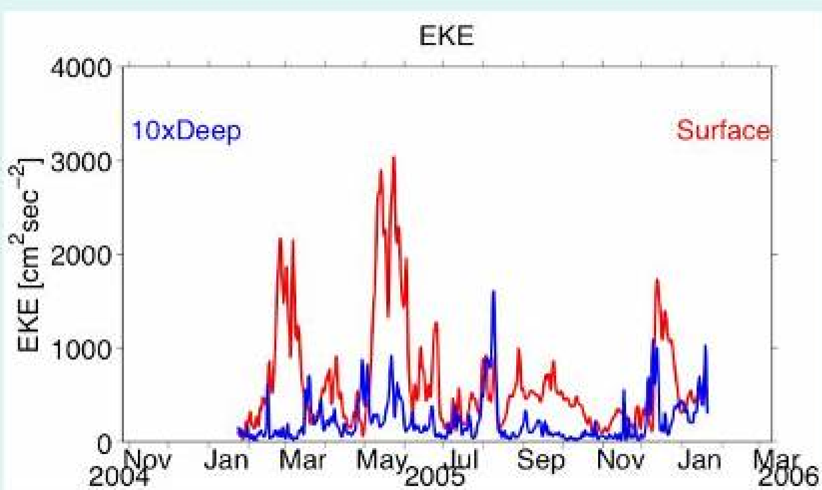
Slide 26

Propagating strong upper-ocean features stretch/ squash lower layer and spin up deep eddies.



Slide 27

Northeast Gulf: Deep eddy events often associated with upper Loop Current or Loop Current Eddy. Coincidence or Coupling?



Slide 28

Diagnose lower-layer potential vorticity to determine whether there is local vertical coupling.

$$PV = \frac{f + \zeta}{H}$$

f = Coriolis parameter

ζ = lower - layer relative vorticity

H = lower - layer thickness (6 degree isotherm to bottom)

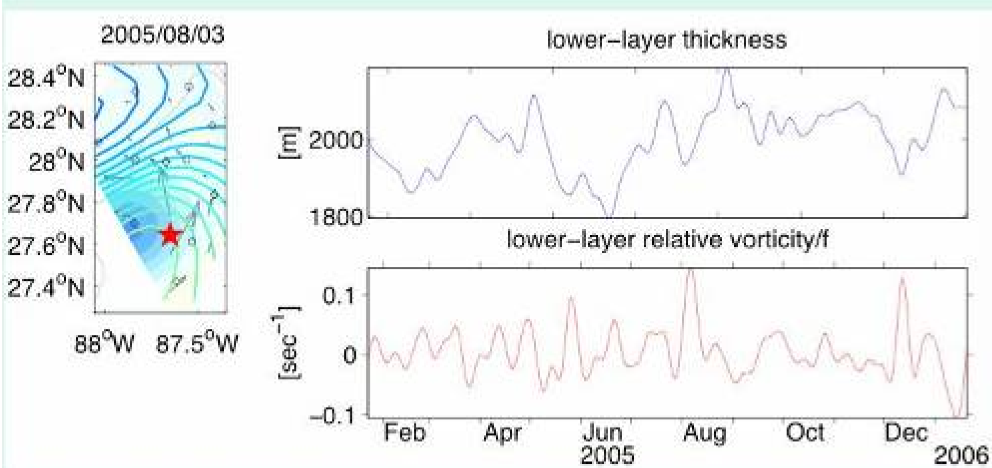
Assume

$$\frac{DPV}{Dt} = 0$$

$$\frac{\partial PV}{\partial t} + u\frac{\partial PV}{\partial x} + v\frac{\partial PV}{\partial y} = 0$$

Slide 29

Examine lower-layer thickness and relative vorticity ...



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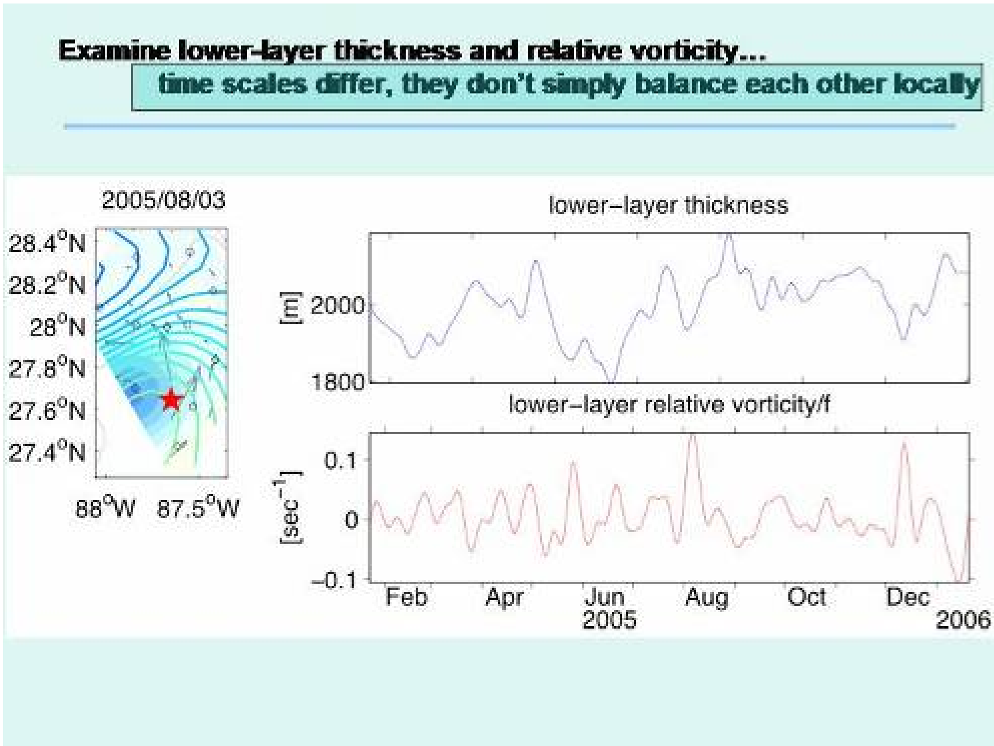

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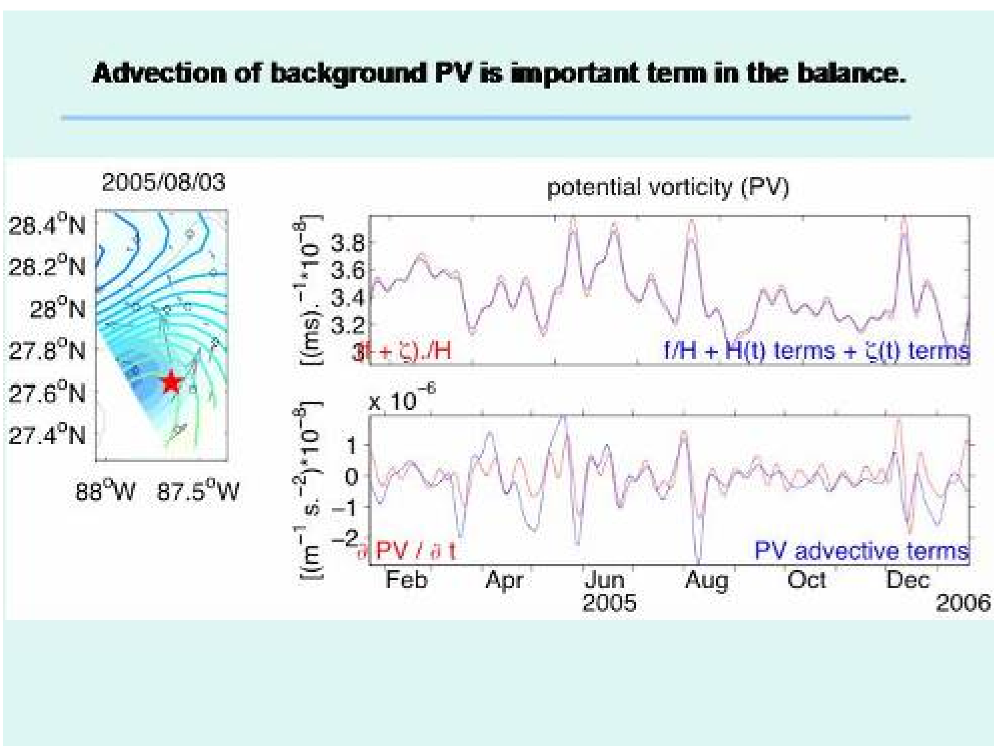
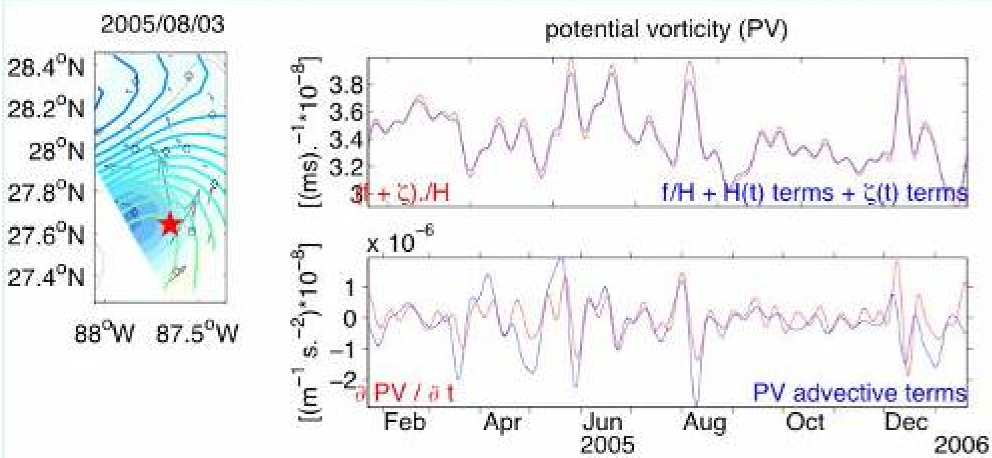


Slide 32

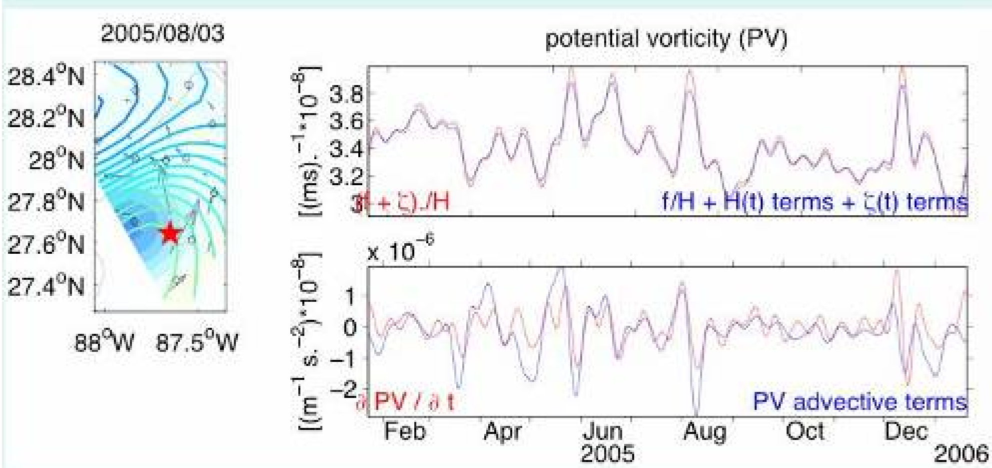
Advection of background PV is important term in the balance.



In events where deep eddies are vertically coupled to the upper loop current, an array like this allows diagnosis of dynamical balances.

Slide 33

Advection of background PV is important term in the balance.



The time scales, spatial scales and PV balances of deep eddies all support that they exhibit the dynamics of TRWs.

Slide 34

Conclusions and looking to the future

- Arrays of PIES and current meters with mesoscale resolution successfully map the full-water column circulation.
- Deep eddies are strongly steered by topography.
- Potential vorticity analysis useful to diagnose upper-deep coupling (two-way).

- Successful experiments with array of CPIES ...

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CPIES:
current and pressure recording inverted echo sounder

Measures bottom current.
(50 m off bottom)

Measures bottom pressure.

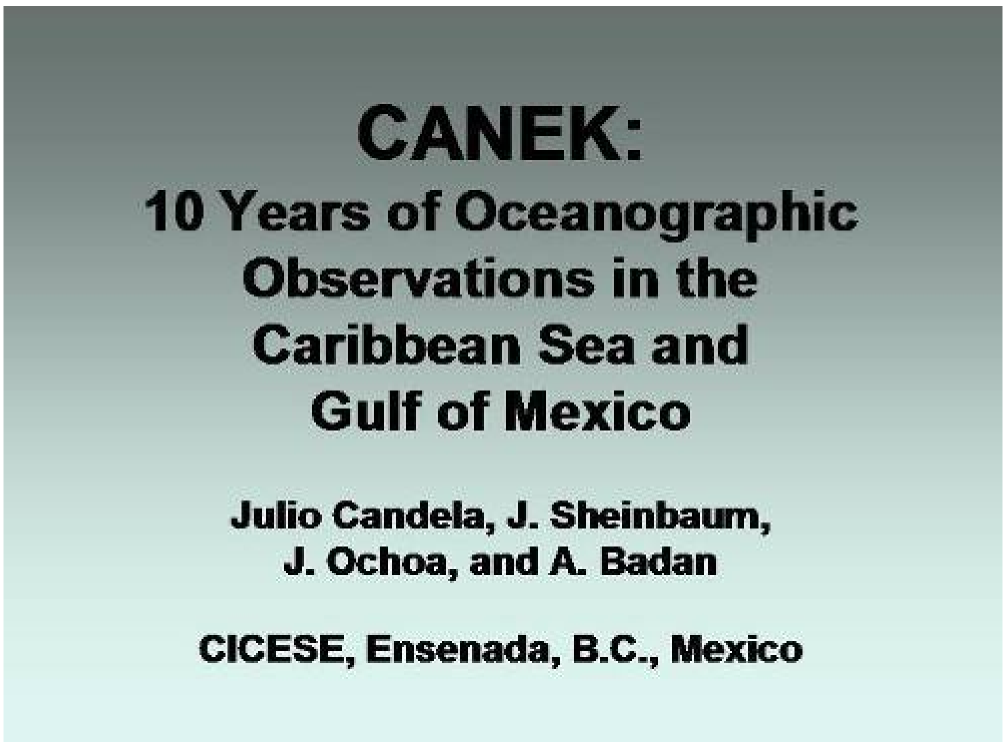
Emits 12kHz sound pulses.
Measures round trip travel times of acoustic pulses to sea surface and back.

Successful deployment and recovery in Kuroshio and Kuroshio Extension experiments

CANEK: 10 YEARS OF OCEANOGRAPHIC OBSERVATIONS IN THE CARIBBEAN SEA AND GULF OF MEXICO

Julio Candela, J. Sheinbaum, J. Ochoa, and A. Badan, CICESE

Slide 1

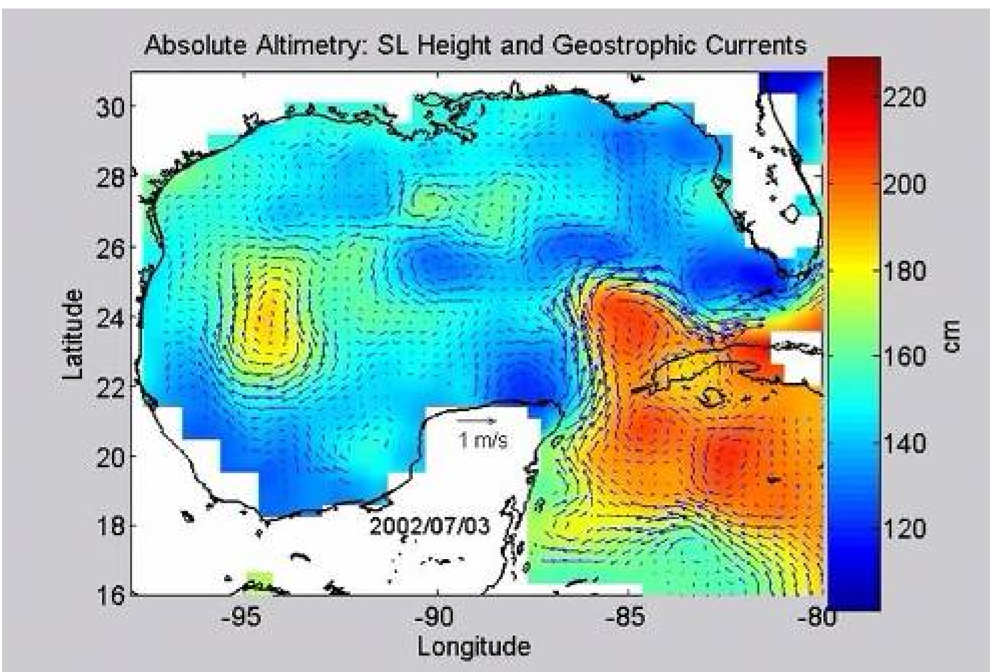


Slide 2

Topics:

- Measurements in Yucatan Channel and the Caribbean Coast of Mexico: The CANEK Program.
- Transports in Yucatan Channel.
- Relation of the flow in Yucatan Channel with the Loop Current behavior in the Gulf of Mexico.
- Eddies in the western Gulf of Mexico.
- Circulation in the Mexican Caribbean Coast.
- Response of the Mexican Caribbean to the passage of Hurricane Wilma.

Slide 3



AVISO

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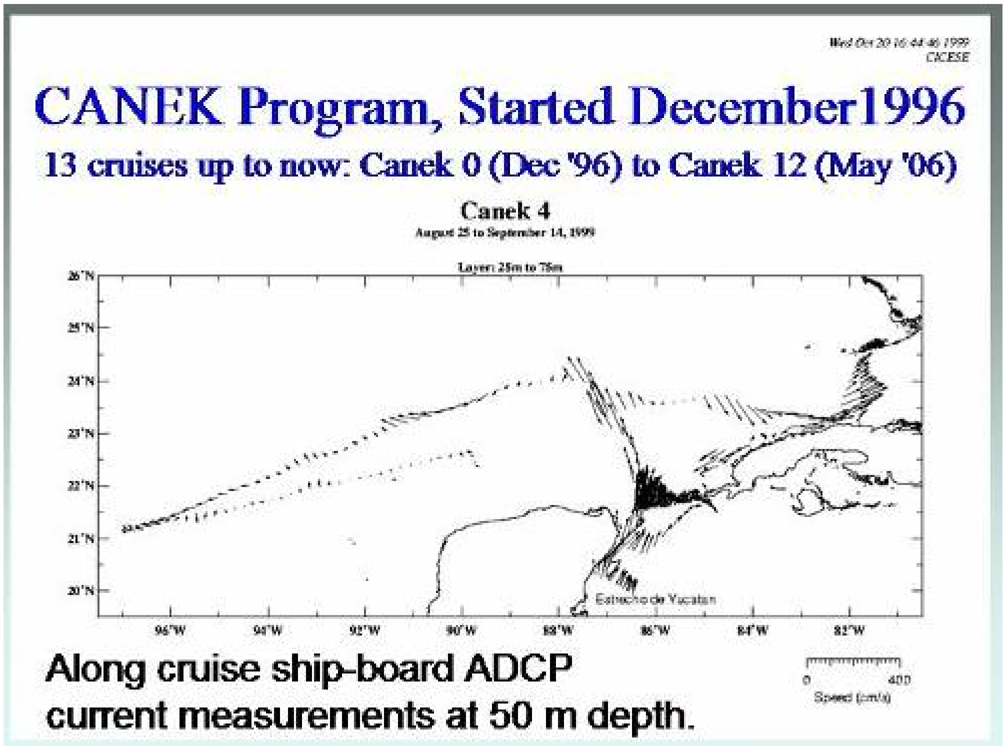

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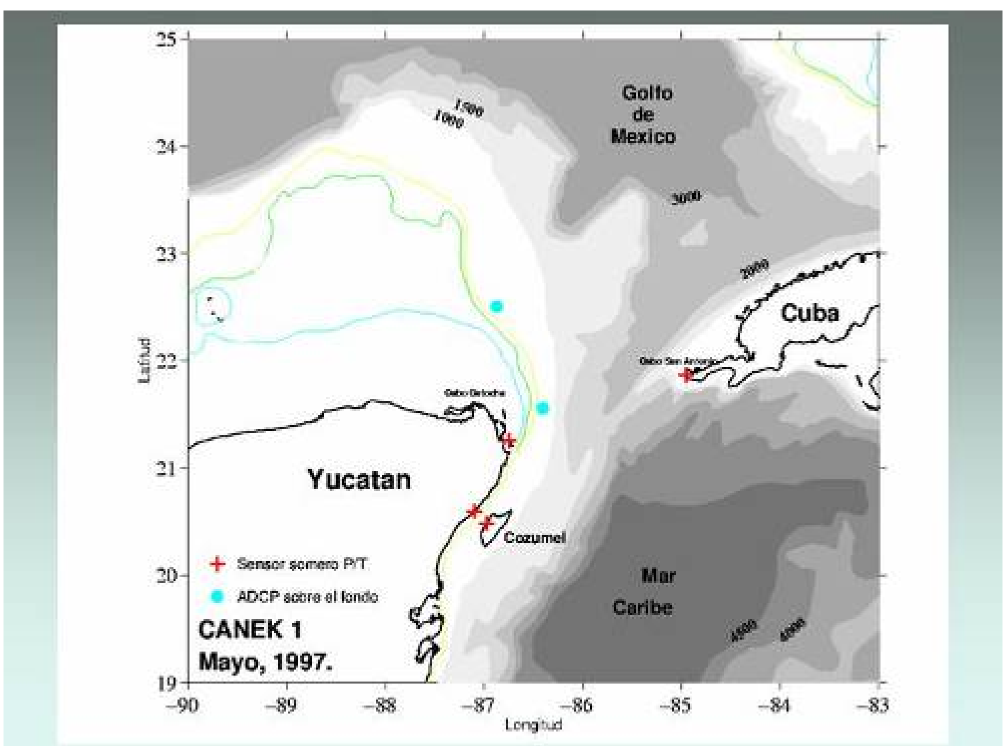

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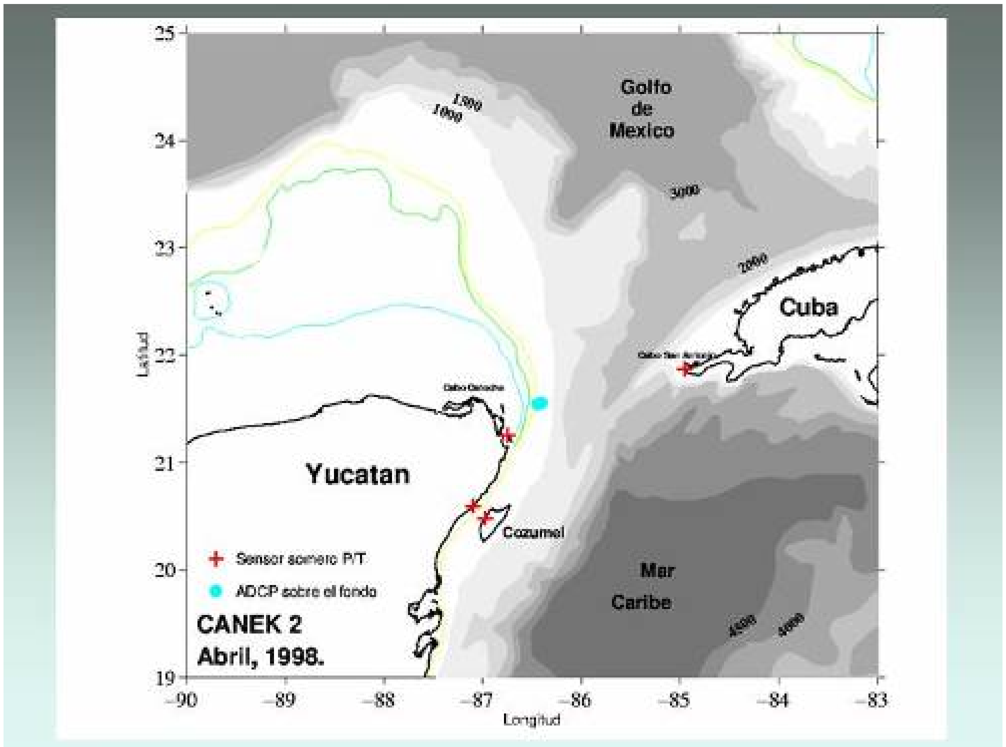

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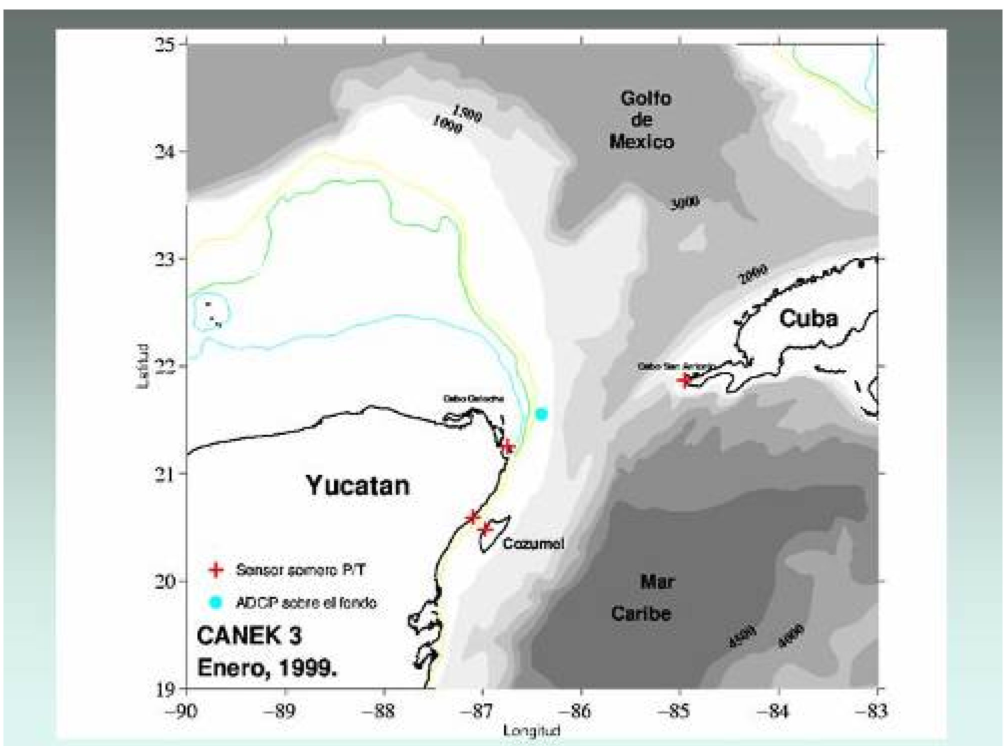

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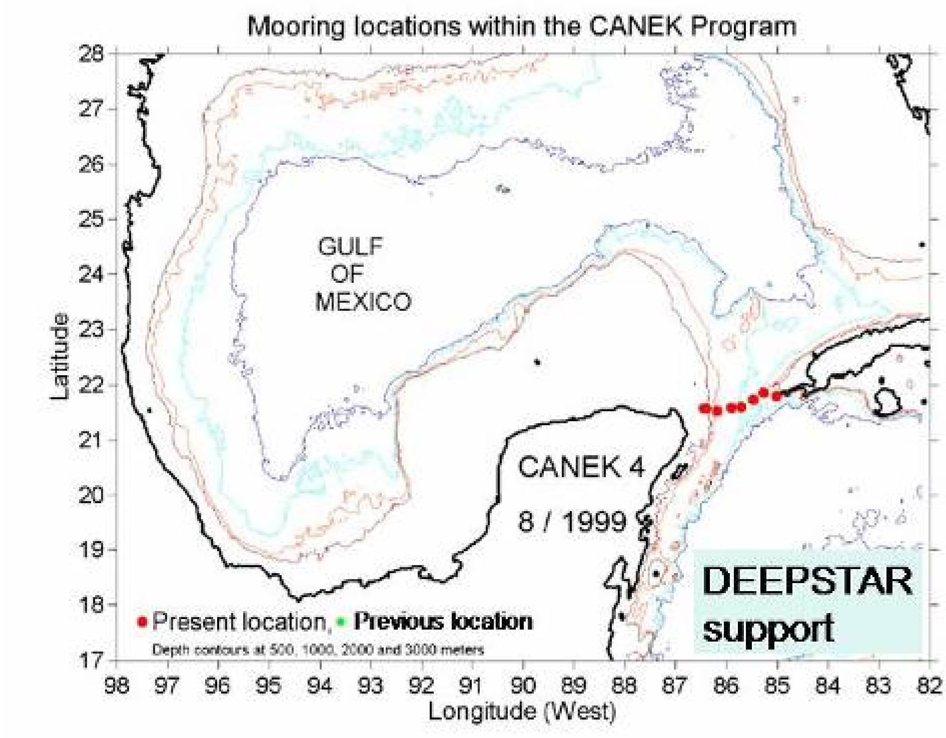

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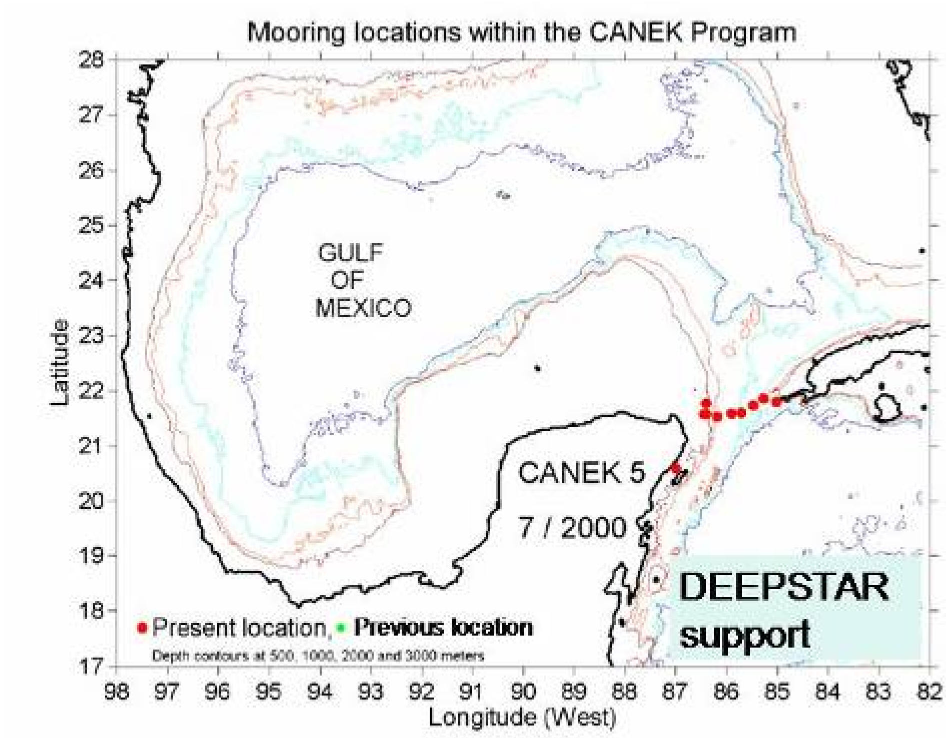

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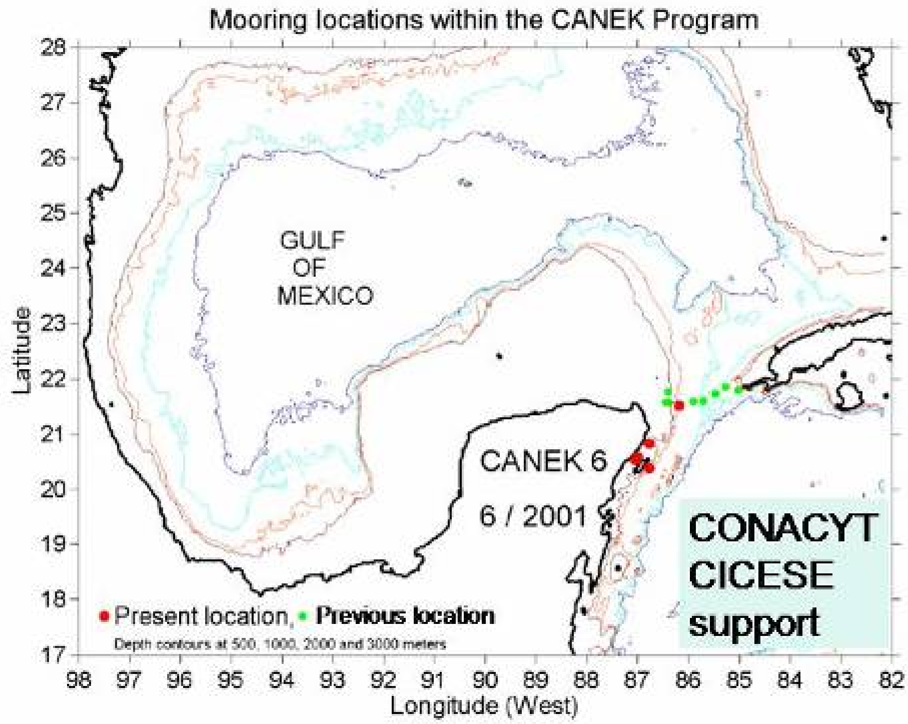

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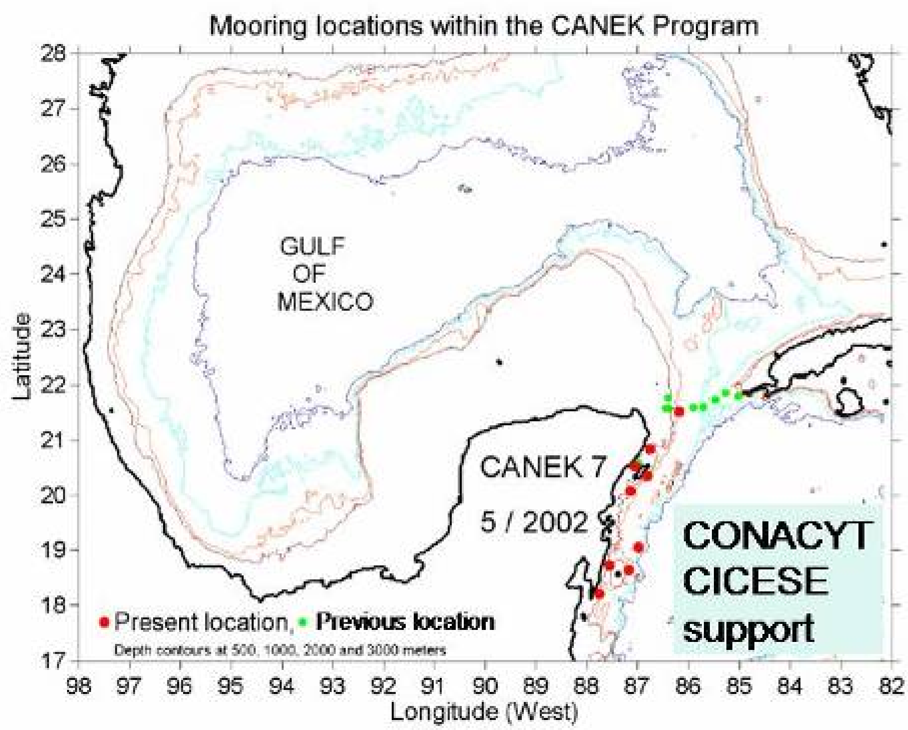

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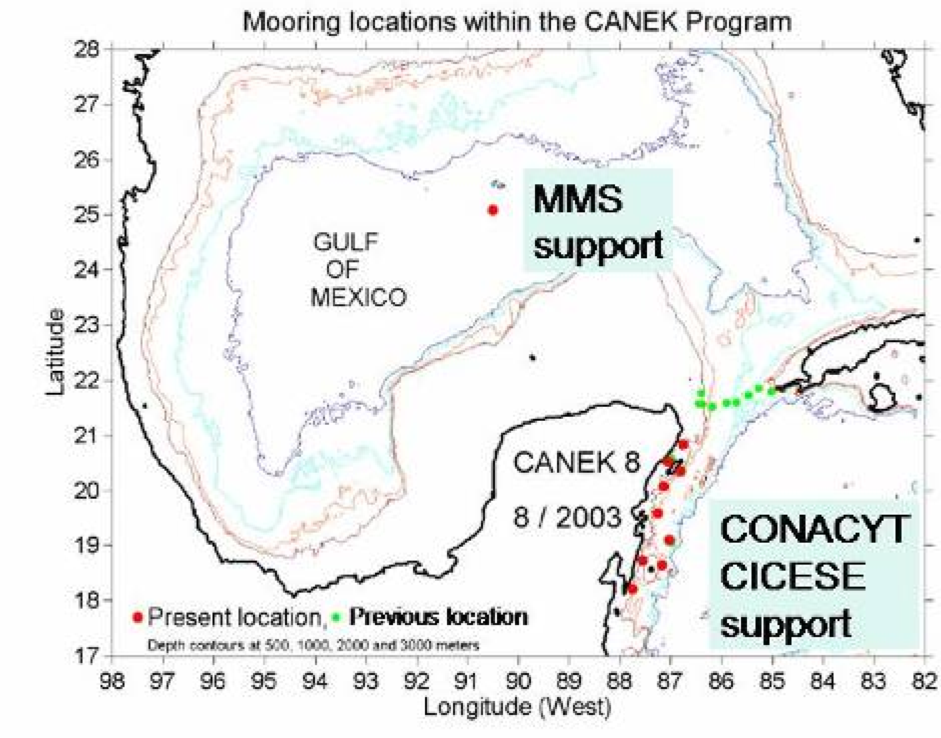

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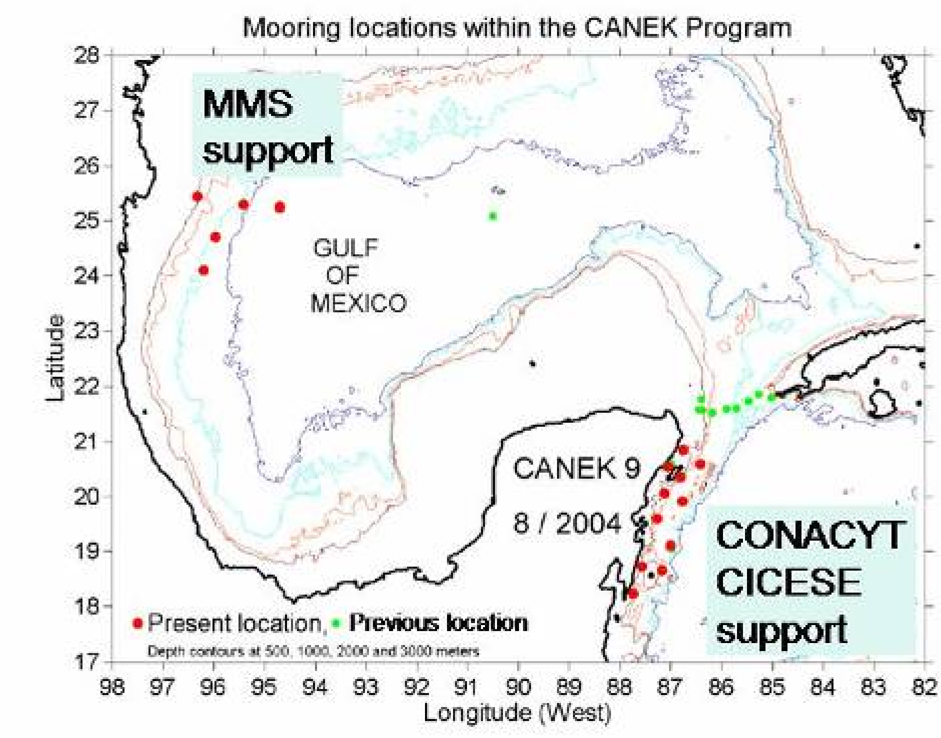

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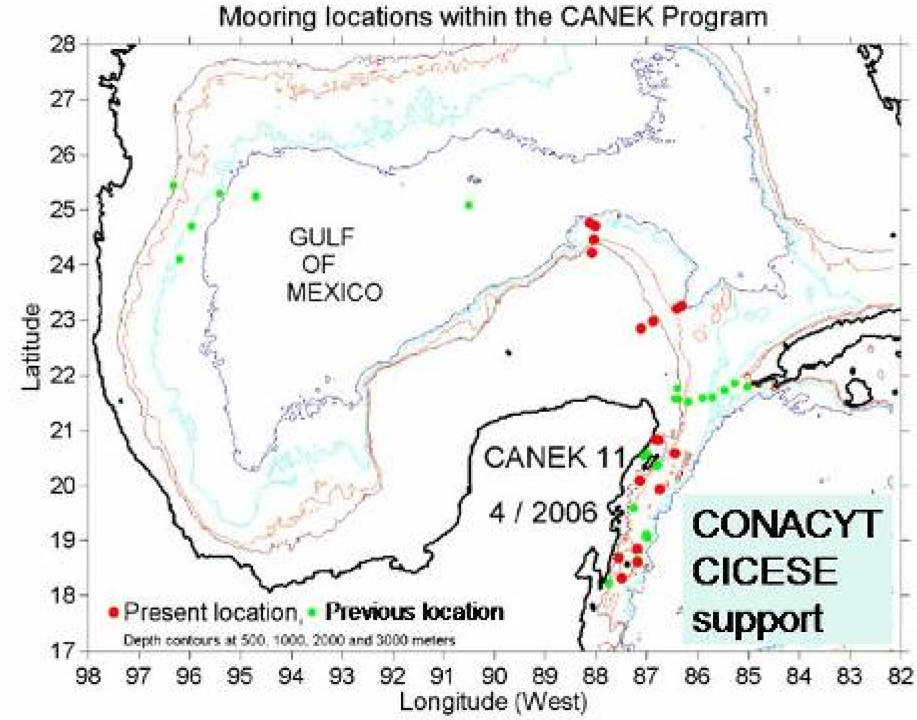
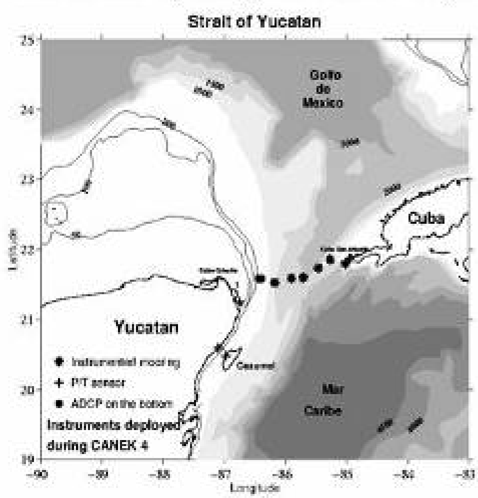
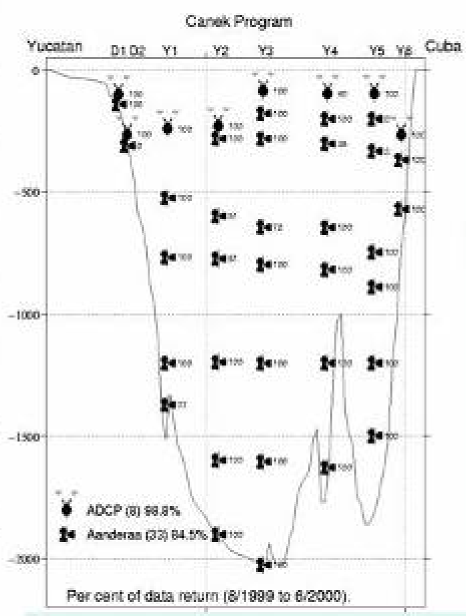


Slide 15

CANEK 4, August 1999 Deployment in Yucatan Channel



Measurements from 8/1999 to 7/2001



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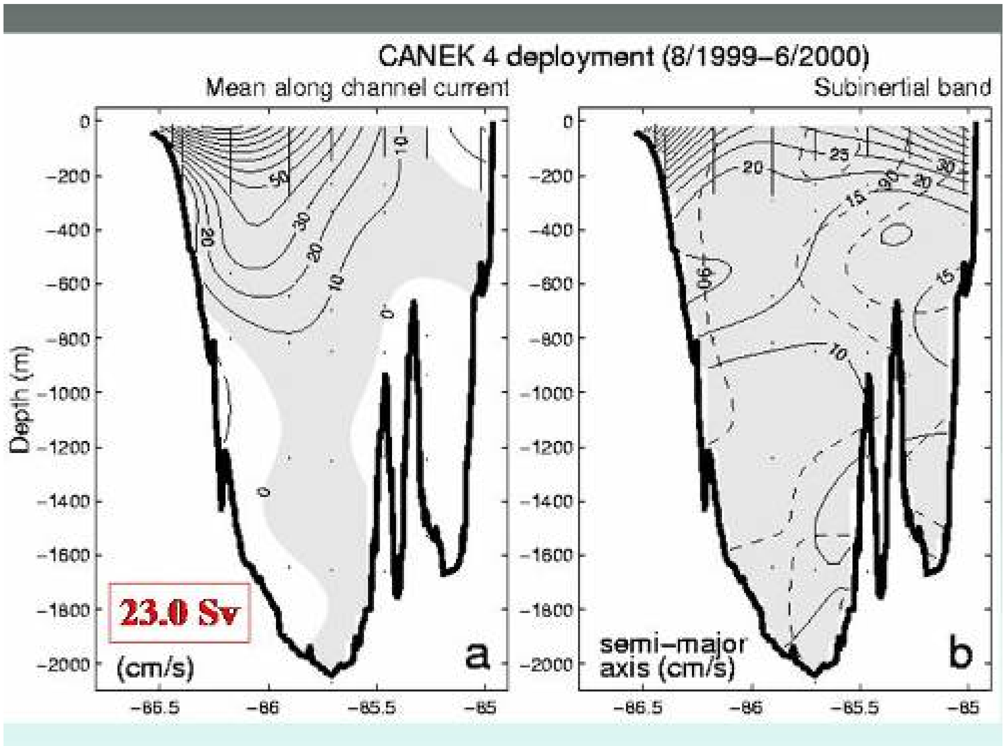

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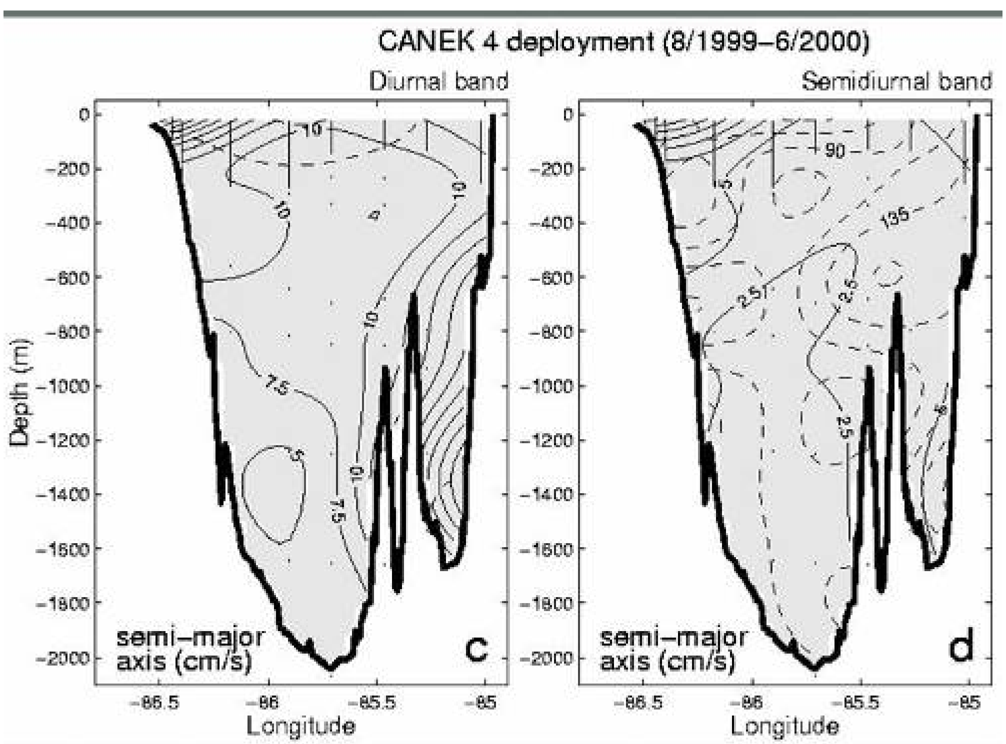

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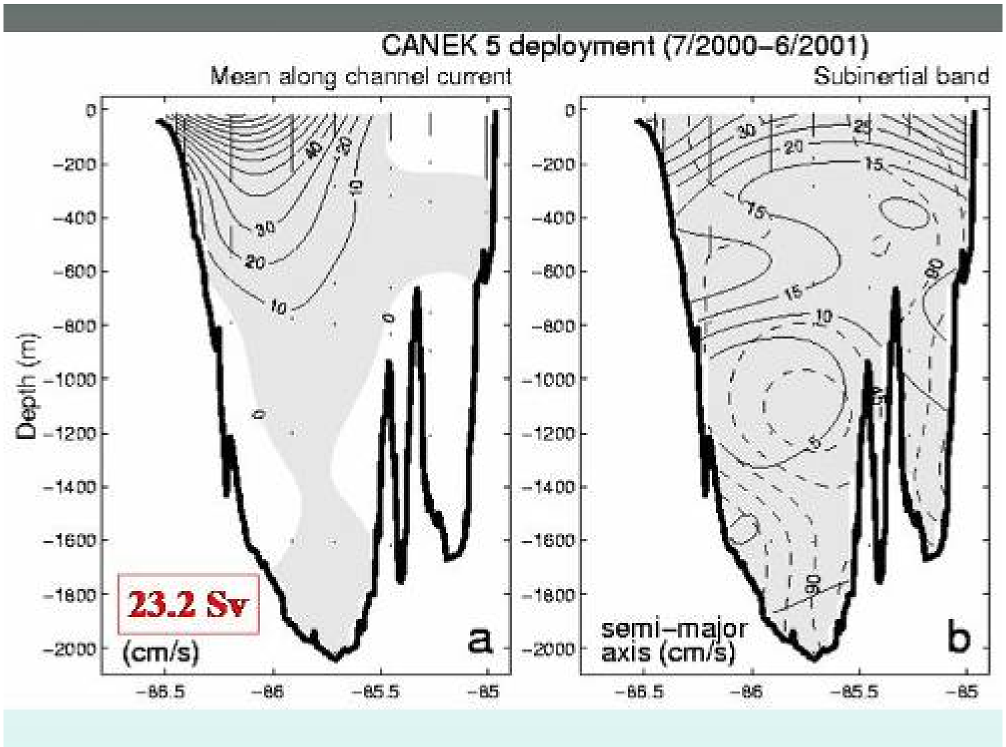

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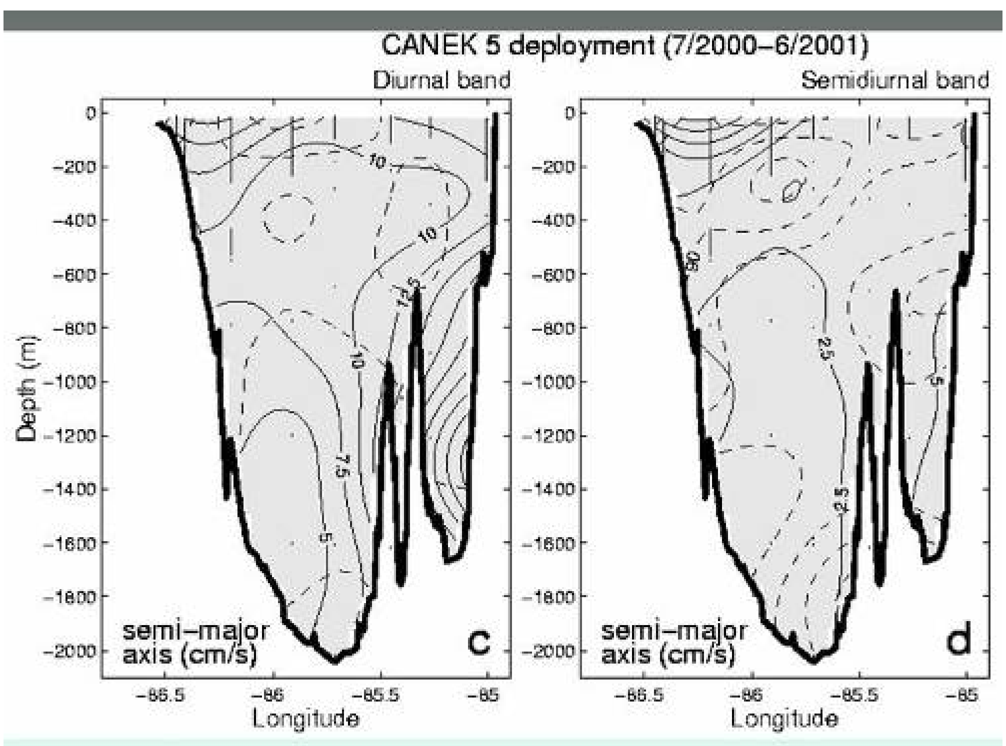

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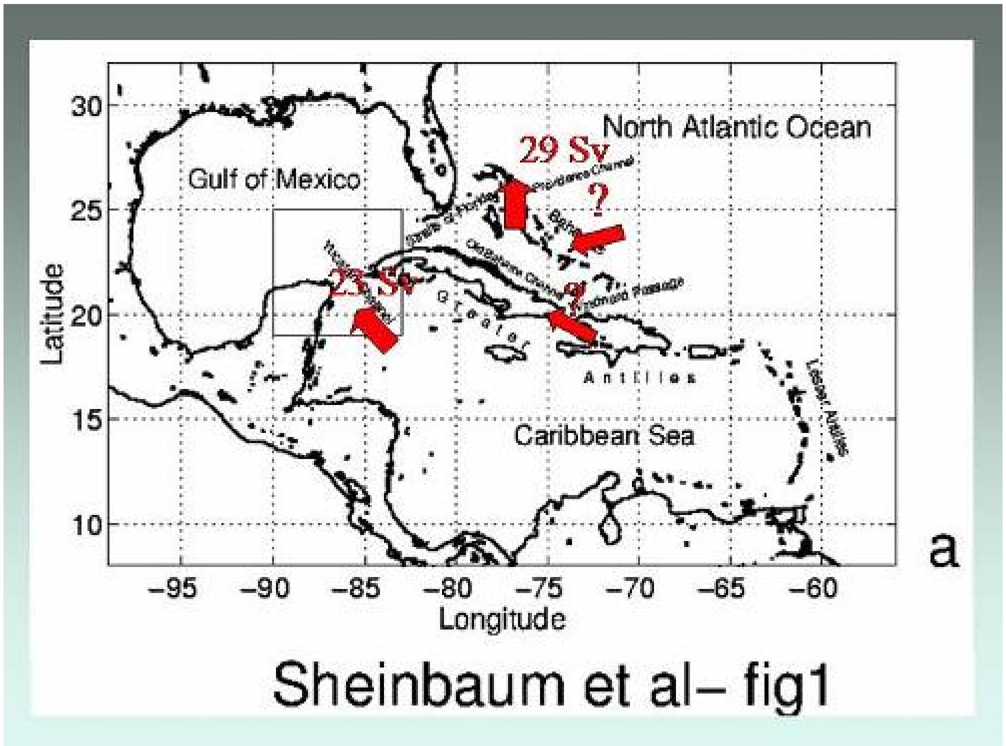

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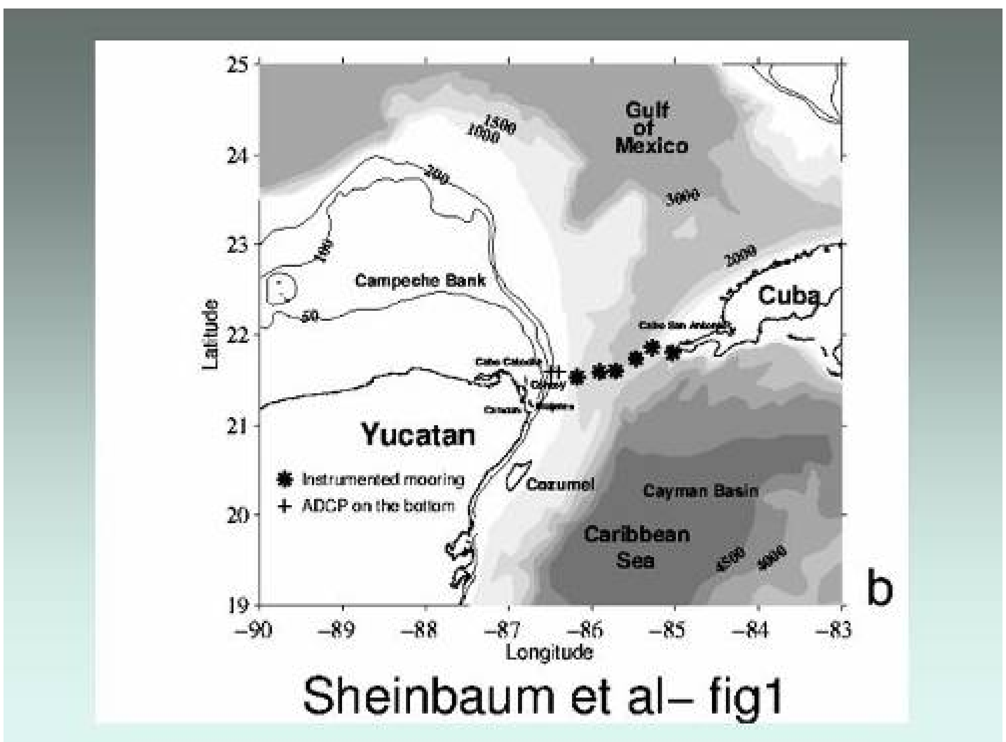

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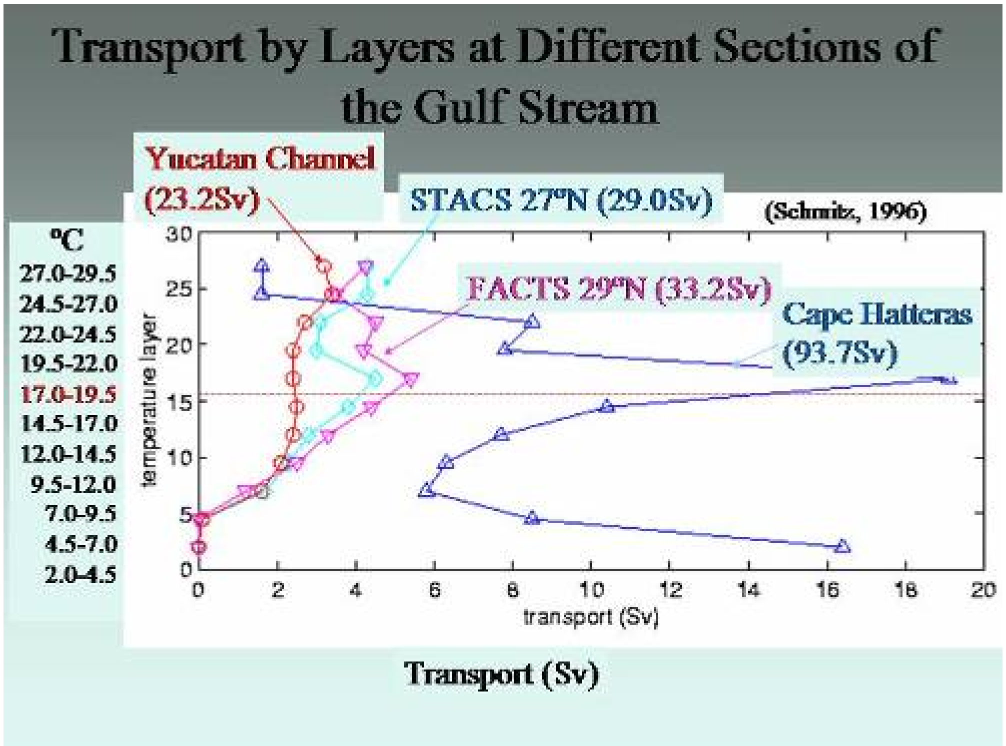

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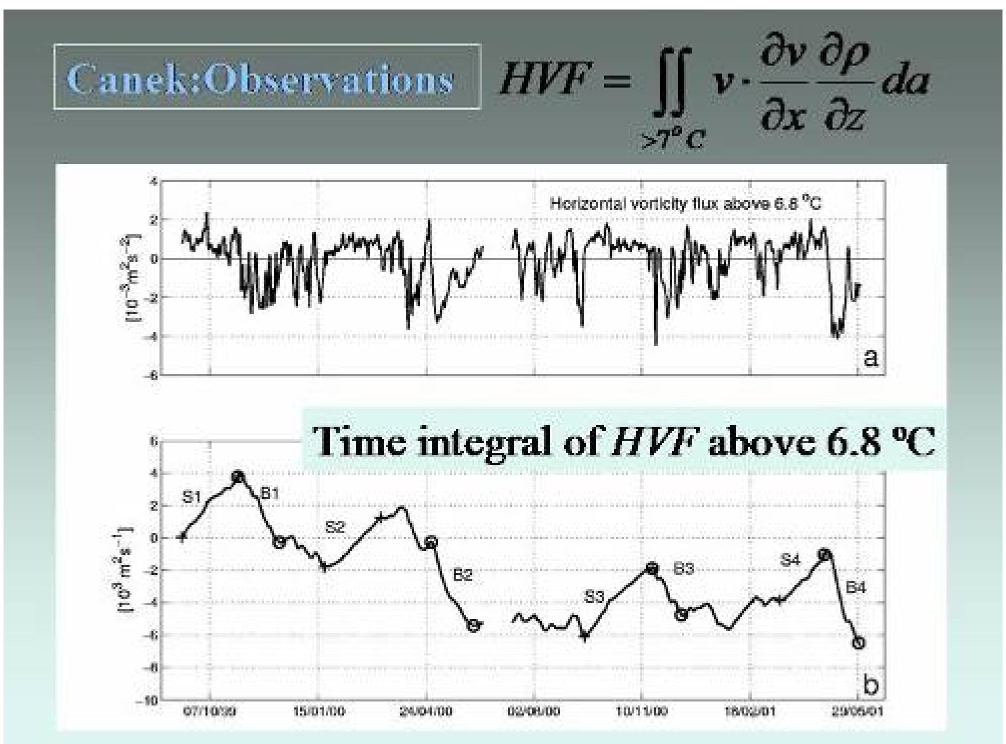

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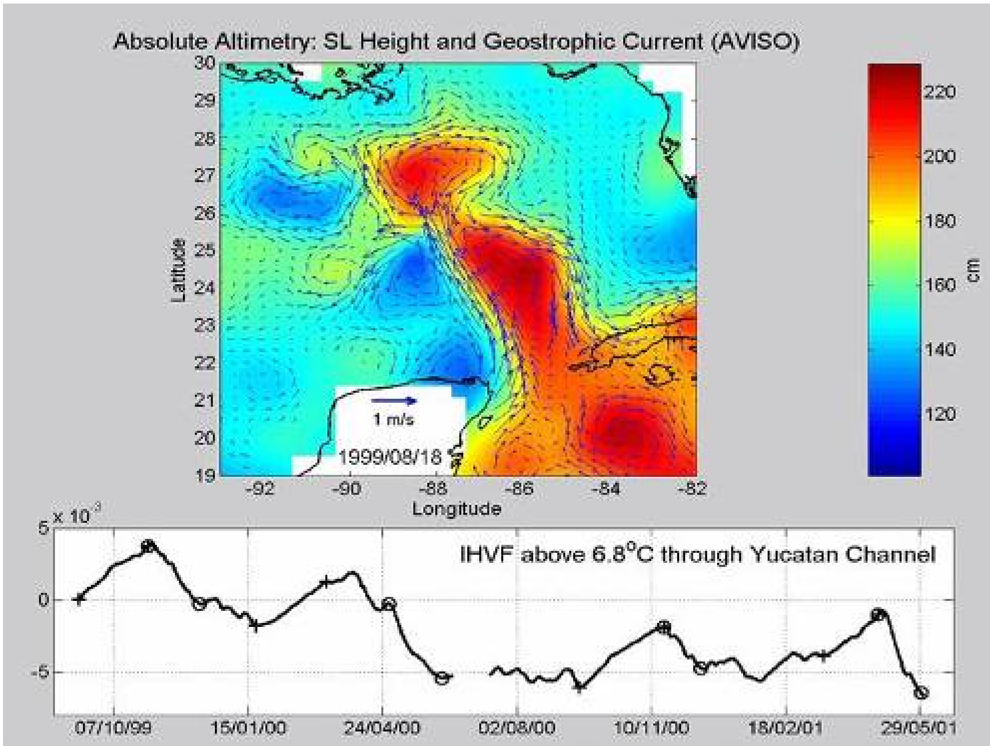

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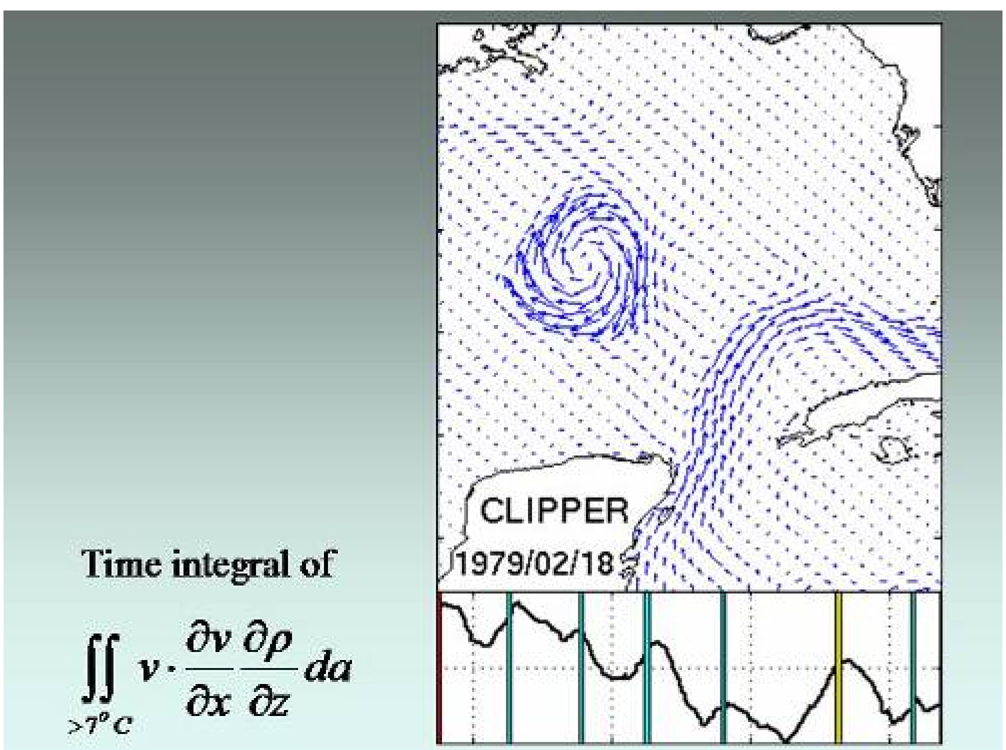

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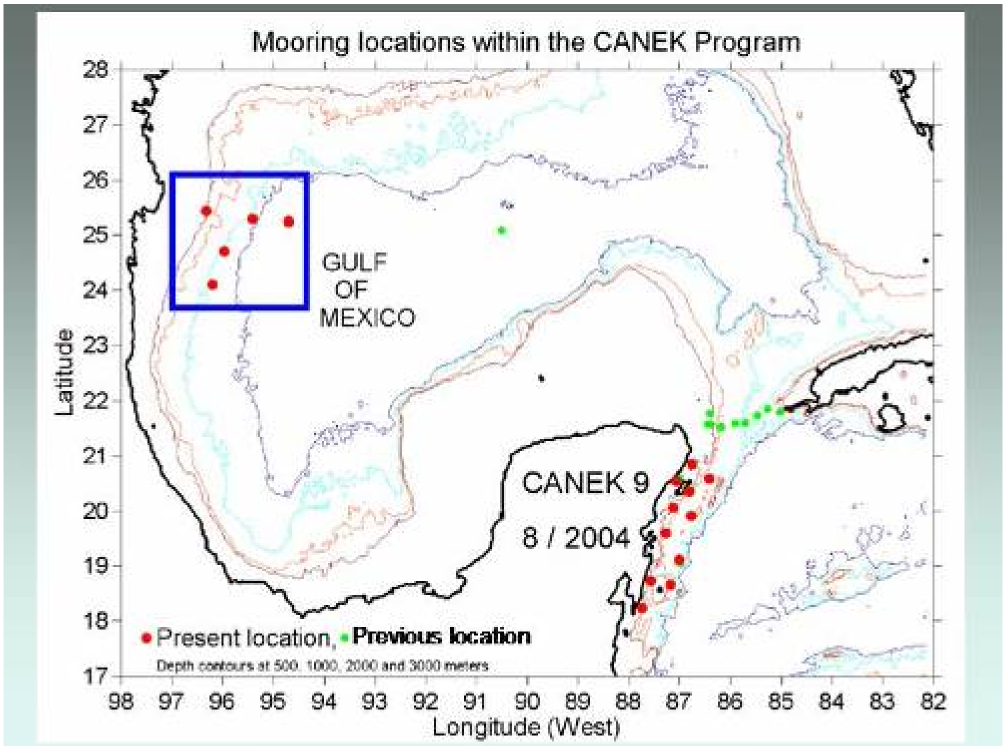

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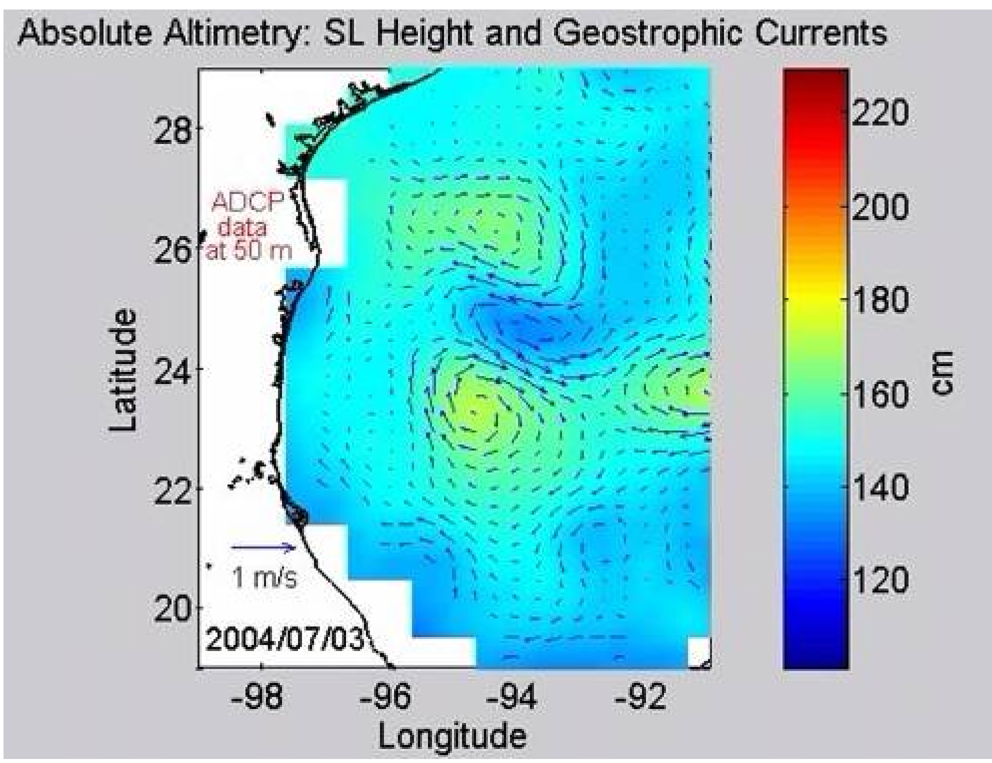

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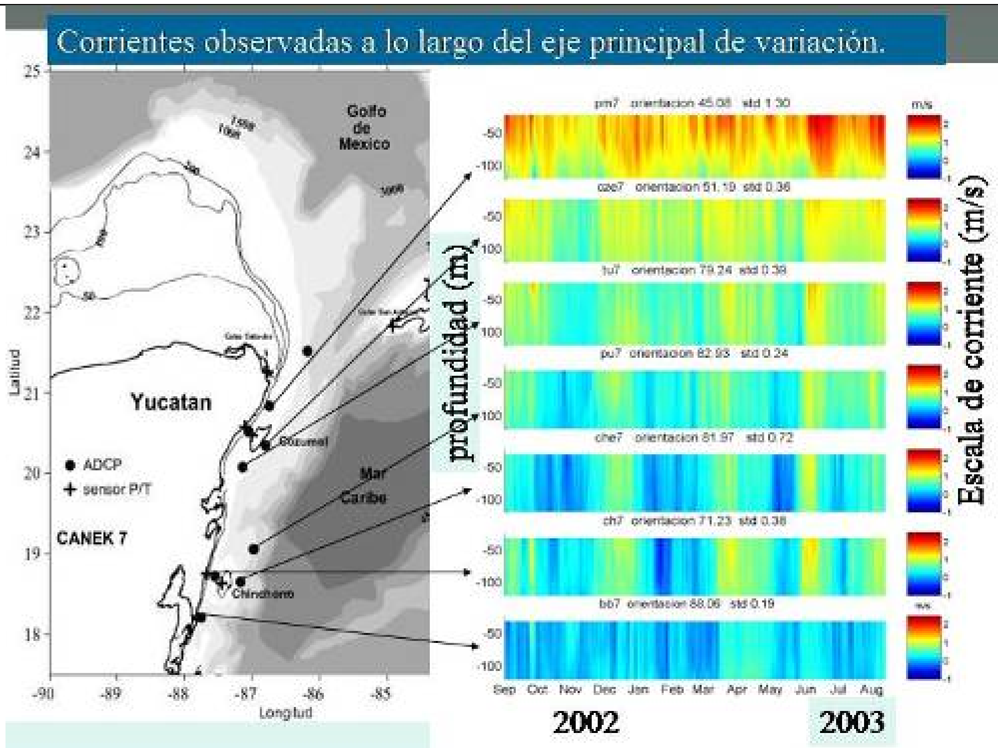

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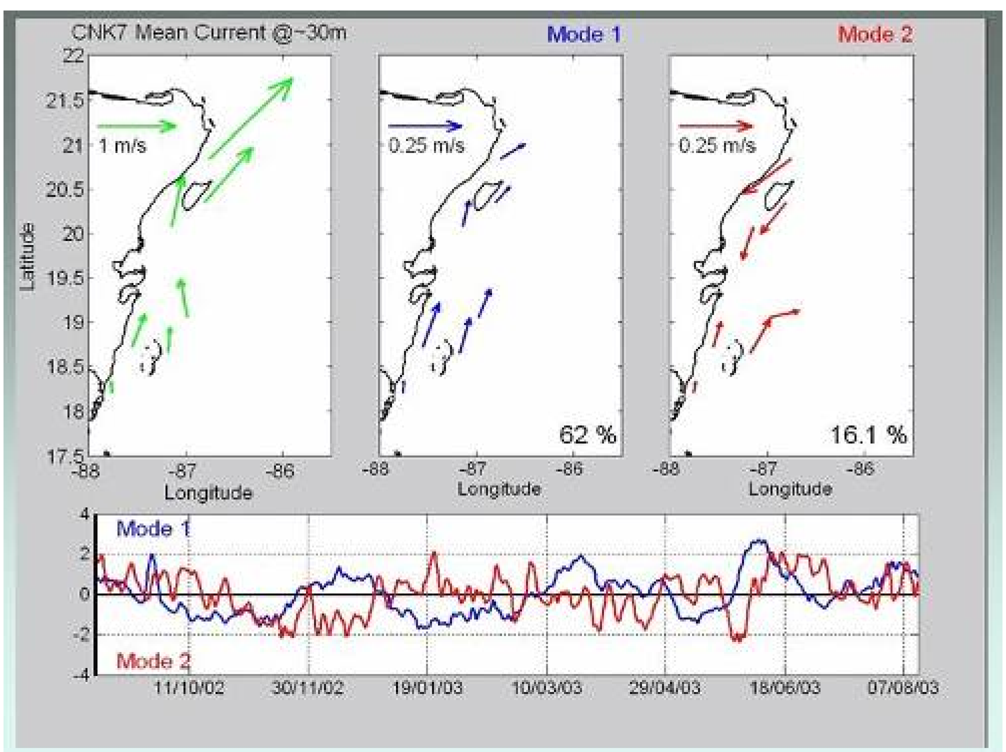

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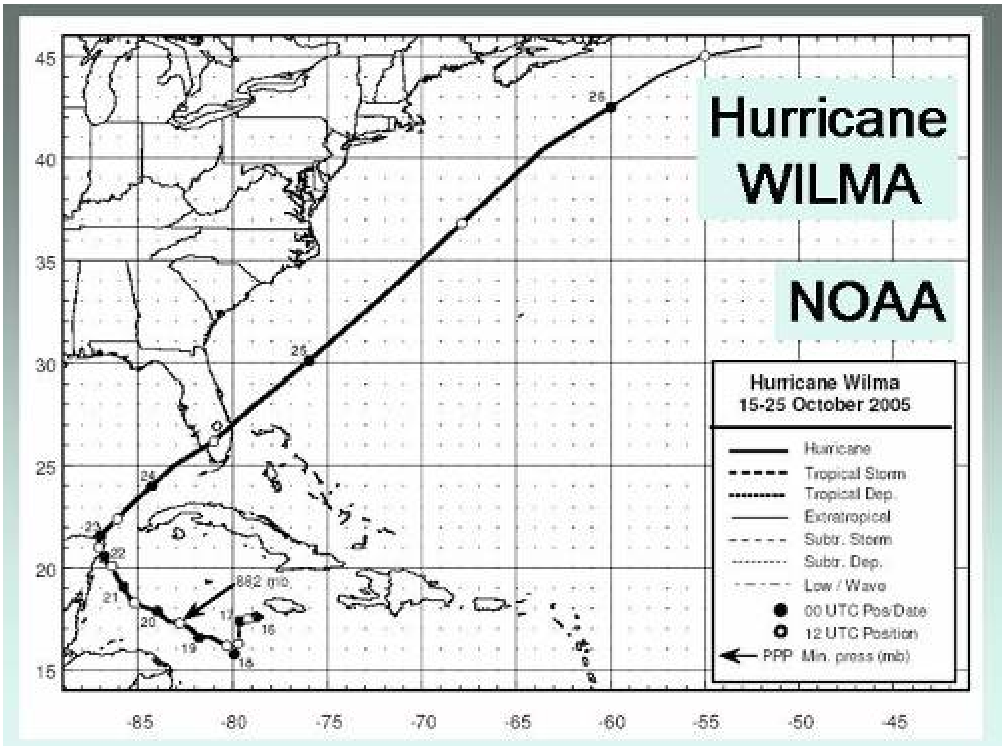

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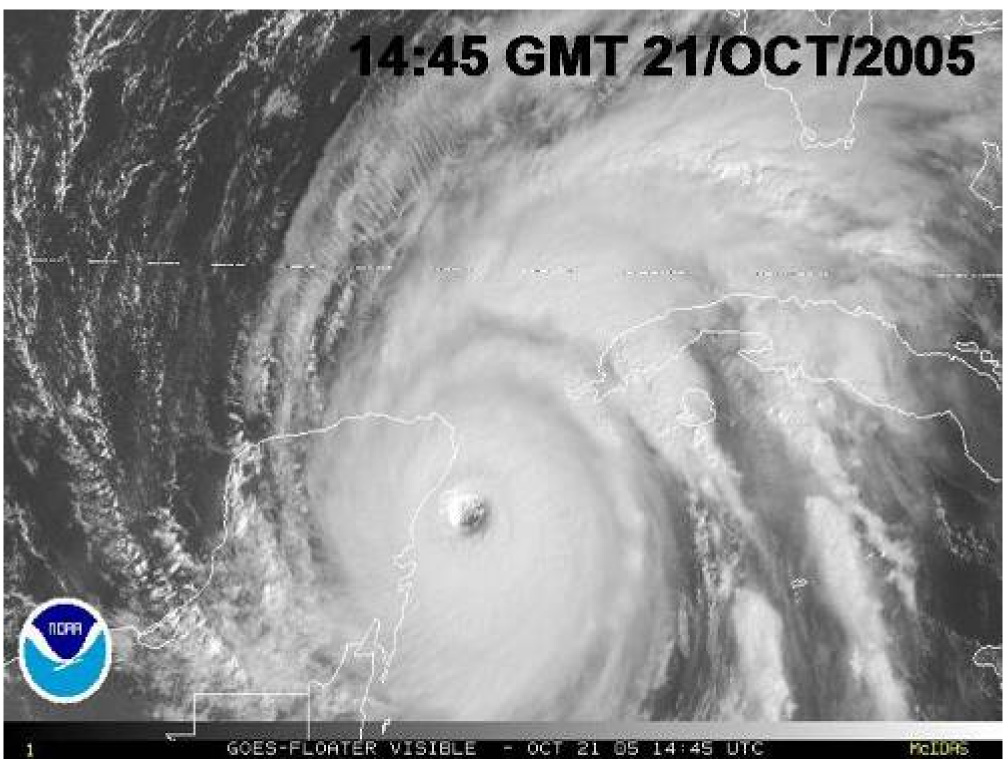

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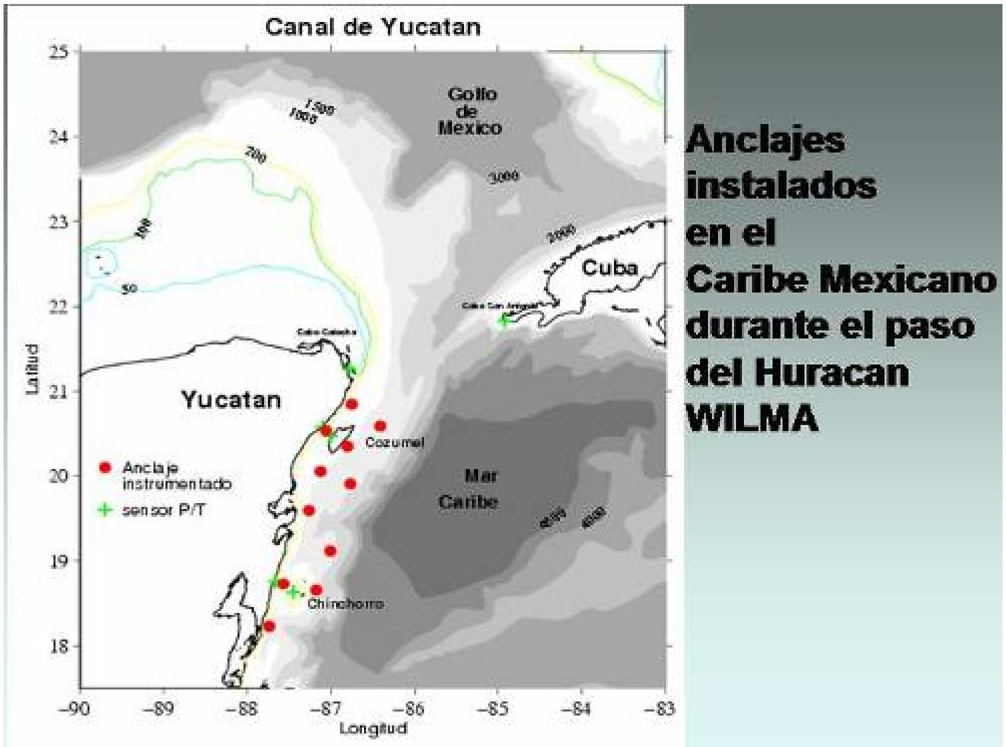

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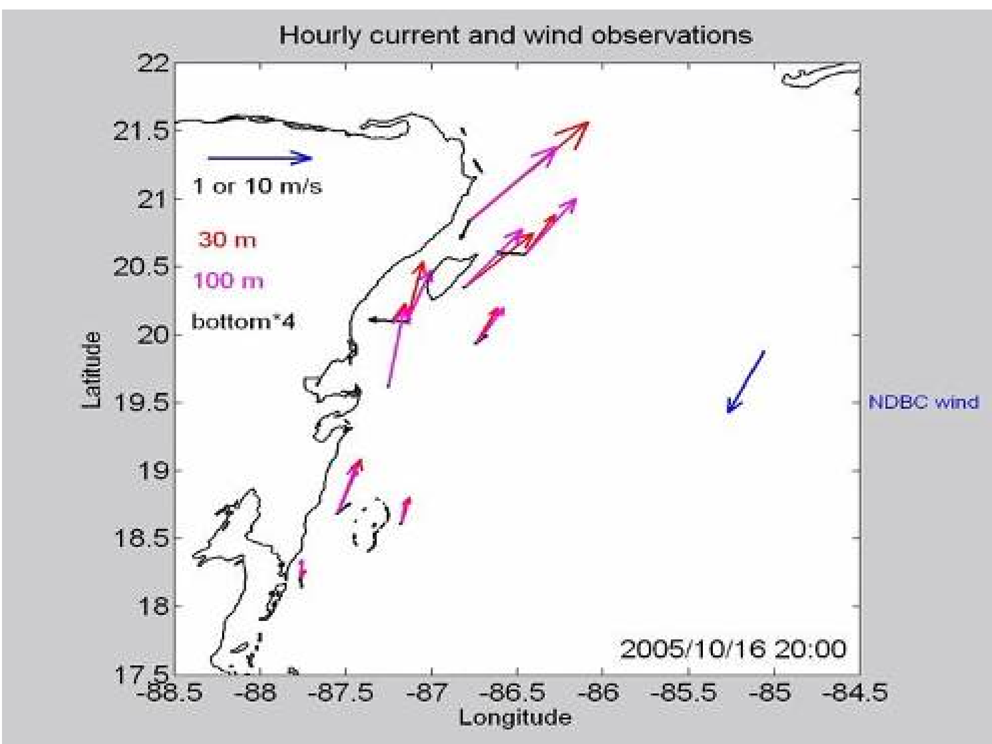

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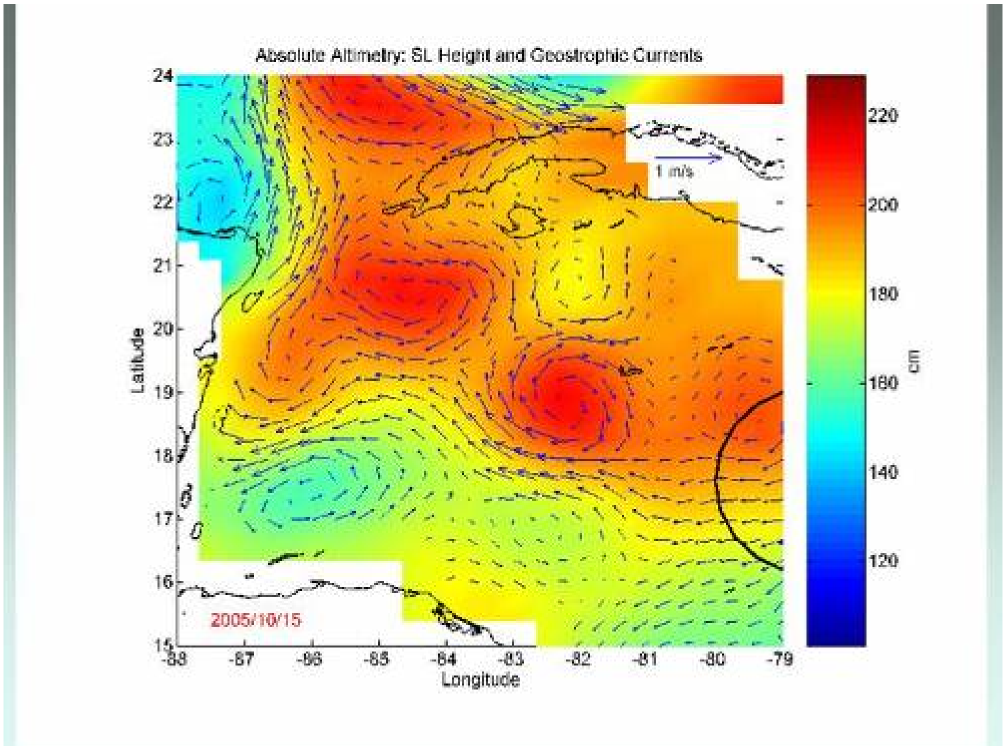

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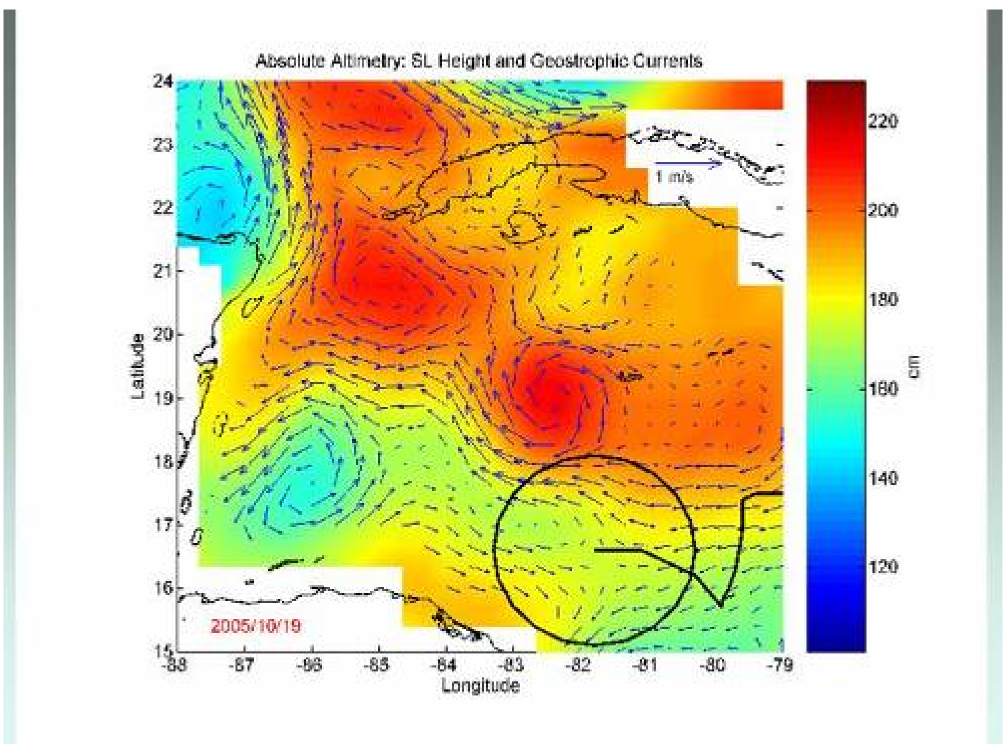

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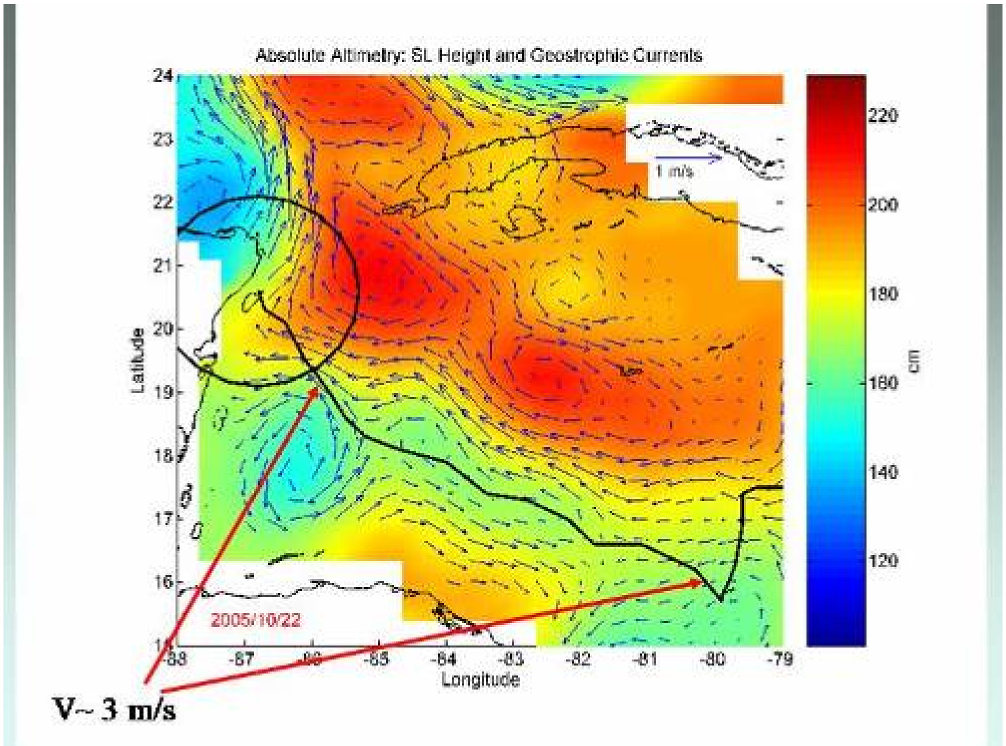

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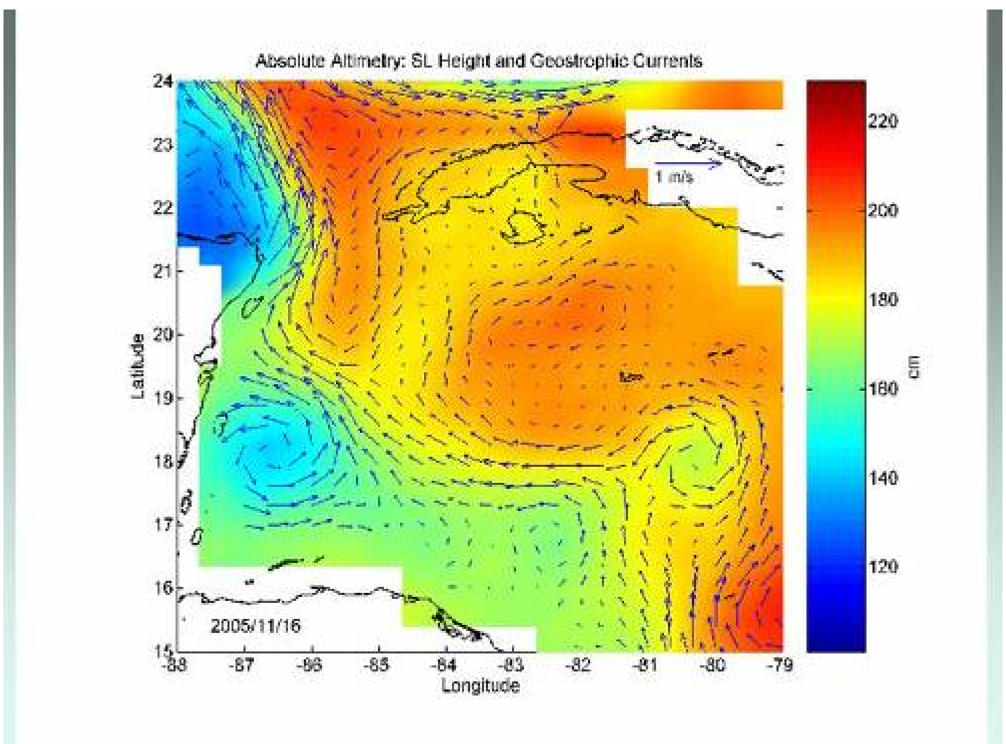
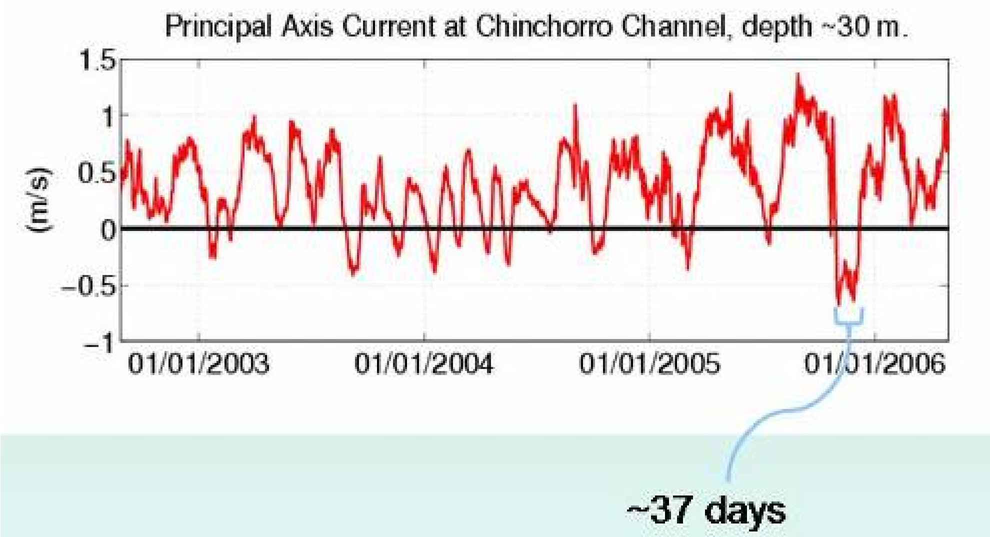


Slide 38

Principal Axis Current along Chinchorro Channel at 30 m depth

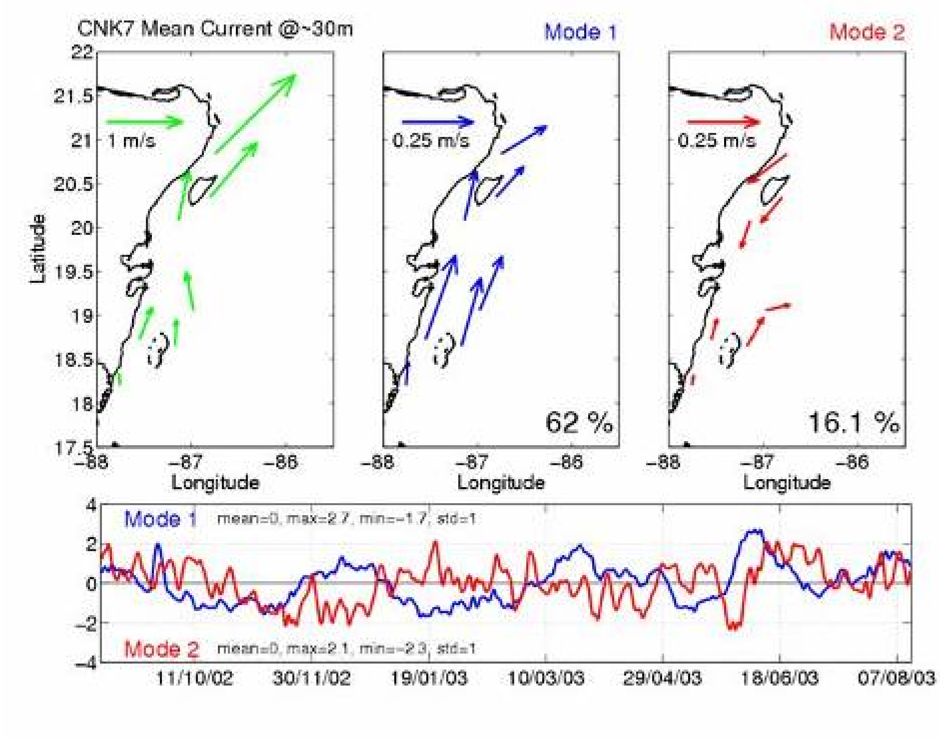


Slide 39

Final Remarks:

- From CANEK we have now a better picture of the Yucatan Current structure and variability.
- The discrepancy between transports in Yucatan and Florida needs to be resolved.
- The vorticity flux through Yucatan is linked with the Loop Current behavior in the Gulf of Mexico.
- The flow along the Caribbean Coast of Mexico is dominated by the Yucatan Current and is strongly modulated by the passage of meso-scale eddies.
- Notably, Hurricane Wilma affected the ocean instantly under its path to depths of 500 to 1000 m.
- Some hurricane perturbations, like the reversal of the flow in Chinchorro Channel, lasted for over a month after Wilma's passage.

Slide 40



CNK7 Mean Current @~30m
Mode 1
Mode 2
1 m/s
0.25 m/s
0.25 m/s
62 %
16.1 %
Latitude
Longitude
Longitude
Longitude
Mode 1 mean=0, max=2.7, min=-1.7, std=1
Mode 2 mean=0, max=2.1, min=-2.3, std=1
11/10/02
30/11/02
19/01/03
10/03/03
29/04/03
18/06/03
07/08/03

UPPER LAYER SUBSURFACE JETS AND INERTIAL CURRENTS IN THE NORTHERN GULF

Peter Hamilton, Science Applications International Corporation

Inertial Currents

Inertial period fluctuations of the currents dominate the high frequency (periods of less than 40 hours) part of the spectrum in the upper layer of the slope and deep basin. Diurnal and semi-diurnal tidal currents are essentially negligible even though diurnal surface tides are evident in sea level and the inertial period ($= 2\pi/f$, where f is the Coriolis parameter) of ~ 26 hours over the northern Gulf slope is close to that of the diurnal tide. Clockwise rotary motions (viewed from above) characterize inertial-internal waves. Inertial motions are primarily forced by variable surface winds. This includes winter and tropical storms. The inertial wake in deep water, with stronger oscillations on the right hand side compared to the left of a hurricane track have been extensively studied and modeled (Price 1981; D'Asaro et al. 1995). Inertial currents may also be generated by geostrophic adjustment processes and thus may be generated by eddy-eddy and eddy-topography interactions.

The relative vorticity of the background flow affects the frequency of the inertial response such that anticyclones and cyclones lower and raise the effective Coriolis parameter, f_e. An example of this is given in Figure 9 where two adjacent ADCP moorings in the NW Gulf show different frequency responses that are shifted by the vorticity of the cyclonic and anticyclonic eddies in which they were located for most of the month of May, 2004. Anticyclonic eddies can trap inertial oscillations because f_e increases with depth and in the cyclonic zones on the outer edges of the eddy, and internal-inertial waves cannot propagate with intrinsic frequencies lower than the local f. In Figure 9, the kinetic energy increases with depth between 35 and 125 m for location U3 in the anticyclone. Kunze (1986) discusses enhanced inertial oscillations just above the thermocline in a warm-core ring, and similarly Donohue et al. (2006) show strong subsurface inertial currents, with a central frequency ~ $0.9f$, within eddy Sargassum, which detached from the Loop Current in August 2003.

In May 2005, an isolated cold front crossed from the NW Texas coast to the SE over the NW Gulf moored array (see Figure 9 for locations). Ten out of the 13 moorings had upper-layer 75 kHz ADCP's that spanned 40 to 420 m depths. Thus, the response of the upper-layer to relatively uniform isolated strong wind impulse could be investigated. The results suggest that there was some zonal uniformity of response that was banded meridionally with alternating high and low inertial amplitudes with the highest energies on the northern edge of the array. Because the group velocity of internal-inertial waves is at a declination to the horizontal and directed towards region of lower f, i.e., southwards, the implications are that north-south banded nature of the amplitude response could be the result of destructive interference with the horizontally propagating waves.

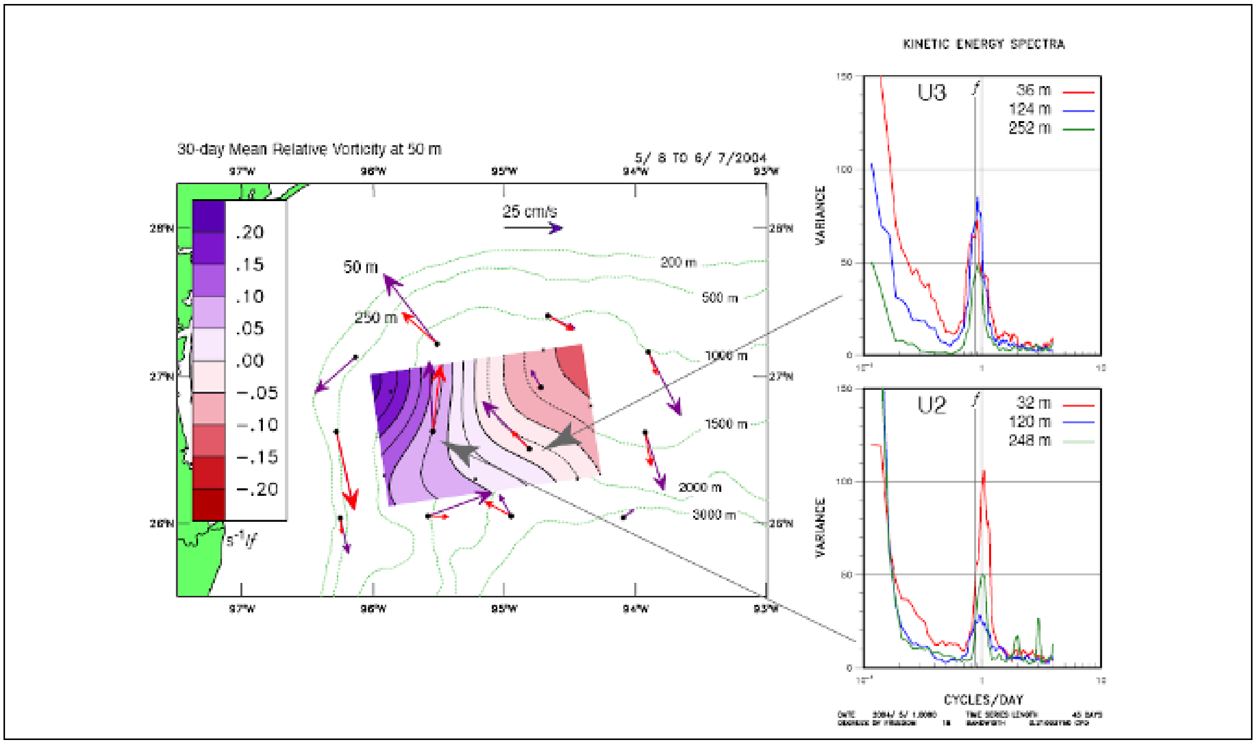


Figure 9. RH panels show the kinetic energy spectra, in variance preserving form, for currents at 3 depths at U3 and U4 moorings. The spectral peaks are shifted from the local *f* by the background relative vorticity (units fractional f) contoured in the LH panel, which also shows the 30-day mean 40-HLP currents at two depths.

There was no obvious relationship of the spatial variability of the inertial currents to the underlying eddies. Similar results were found for a sequence of winter storms for the same array.

Subsurface Jets

DiMarco et al. (2004) discuss the possibility that high-speed subsurface currents, with speeds > 50 cm/s, can occur between 150 and 350 m depth, while surface currents were weak. Drilling operators had reported cases of shutdowns caused by such high-speed subsurface flows, which have become known as jets. However, the available database was plagued with instrumentation problems and results were inconclusive on whether such phenomena could occur in deep water. Vertically propagating inertial-internal waves could produce higher speeds at depth than at the surface, and DiMarco et al. (2004) cite the case of Hurricane Georges where deep inertial energy occurred over the DeSoto slope several days after the passage of the storm. However, the available database, after excluding inertial events, suggested that if such jets occur, then they seemed to be associated with the edges of anticyclones that were possibly interacting with an ADCPs in the upper 400 to 500 m of the water column might have a chance of capturing such a adjacent cyclone or frontal eddy. Only moorings that had continuous current profiles from subsurface jet. For six such moorings in the central Gulf that give a total of ~ seven years of

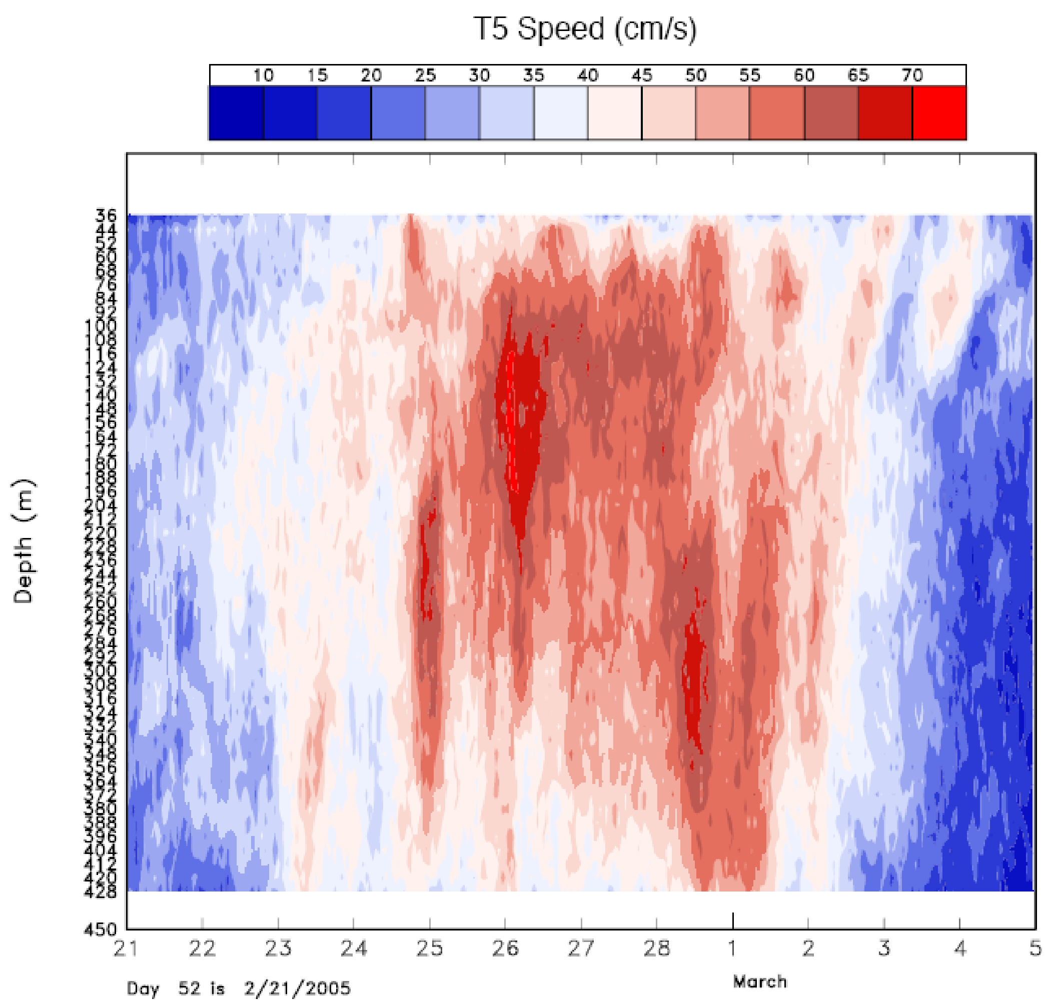


Figure 10. Unfiltered speed from the 450 m ADCP at T5 for the indicated interval.

measurements, no significant jet-like events were found. However, in the NW Gulf upper-layer ADCP records, a number of subsurface jets that fit the criteria of maximum speeds > 50 cm/s occurring between 150 and 350 m depth with lesser speeds near the surface, have been found. Of the 17 subsurface jet events identified in the 450-m ADCP records, 10 are considered to be primarily inertial events, and seven are non-inertial. Other than having more 450-m ADCP years (14) in the western Gulf than in the central Gulf, it is not yet clear why the NW part of the slope has more subsurface jet events than the central or eastern parts of the slope.

Figure 10 shows the current speeds in the upper 450 m of the water column at mooring T5 in the NW Gulf (see Figure 11 for location). This clearly fits the criteria for a subsurface jet with speeds exceeding 70 cm/s around 150 m depth, with much lower speeds at the surface (~ 40 cm/s). The time series of upper-layer temperatures for this event show the coldest water arriving

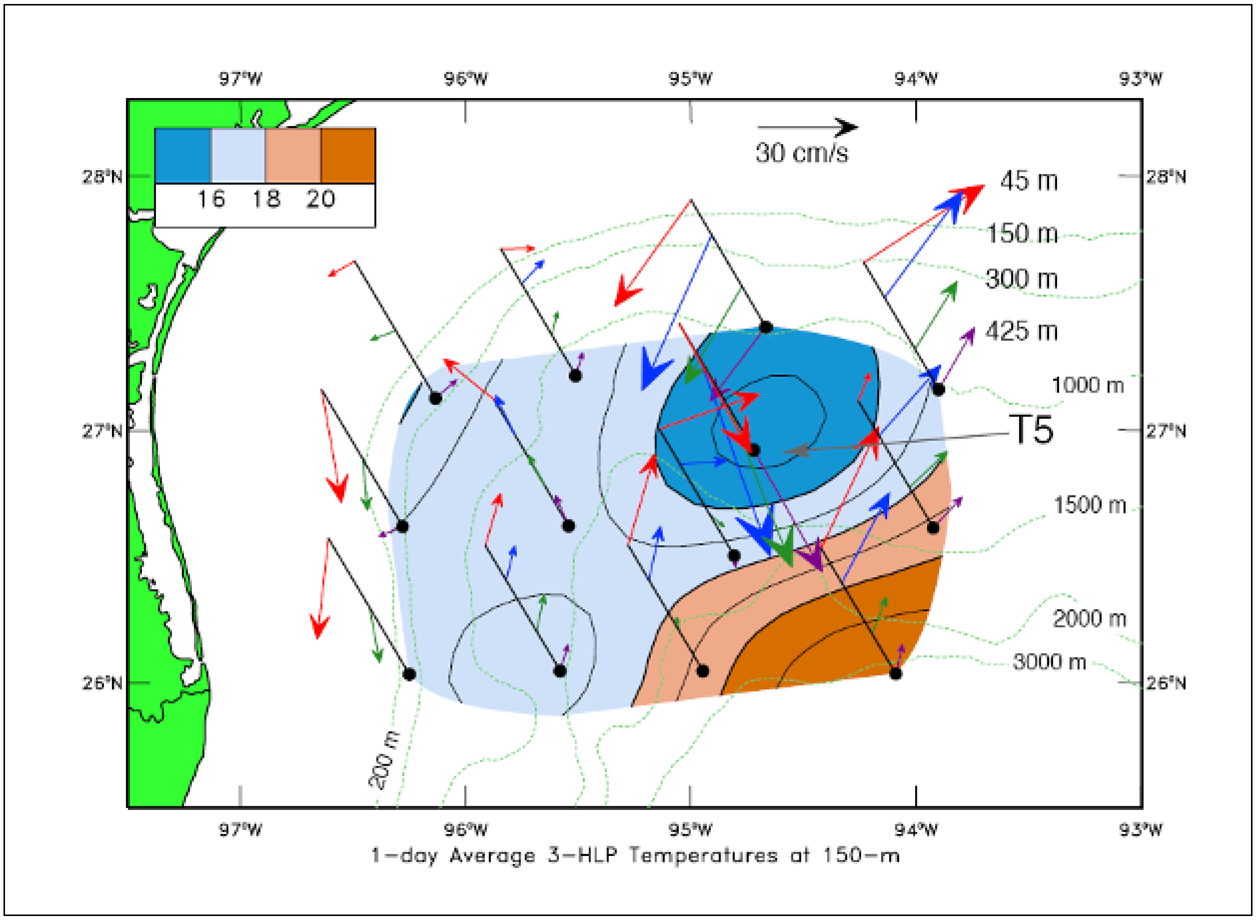


Figure 11. 1-day mean 3-HLP temperature at 150 m and currents at selected depths for 26 February 2005, 0000 GMT. The currents are plotted as 3D pseudo profiles. The location of the T5 mooring is noted by the gray arrow.

at 250 m, one to two days before it arrives at 75m, which implies reversing horizontal thermal wind gradients above and below the jet. This indicates that this event is primarily geostrophic. Maps of the horizontal temperature and velocities (Figure 11) show that T5 was located in a cold cyclone, which was interacting with a larger warm anticyclone to its south. The interaction causes the vertical center axis of rotation of the cyclone to be tilted towards the anticyclone, and it is this distortion of the density field that causes diverging isotherms that support a geostrophic subsurface jet. A number of other similar cases that also involve cylone-anticyclone interactions occur in this NW study.

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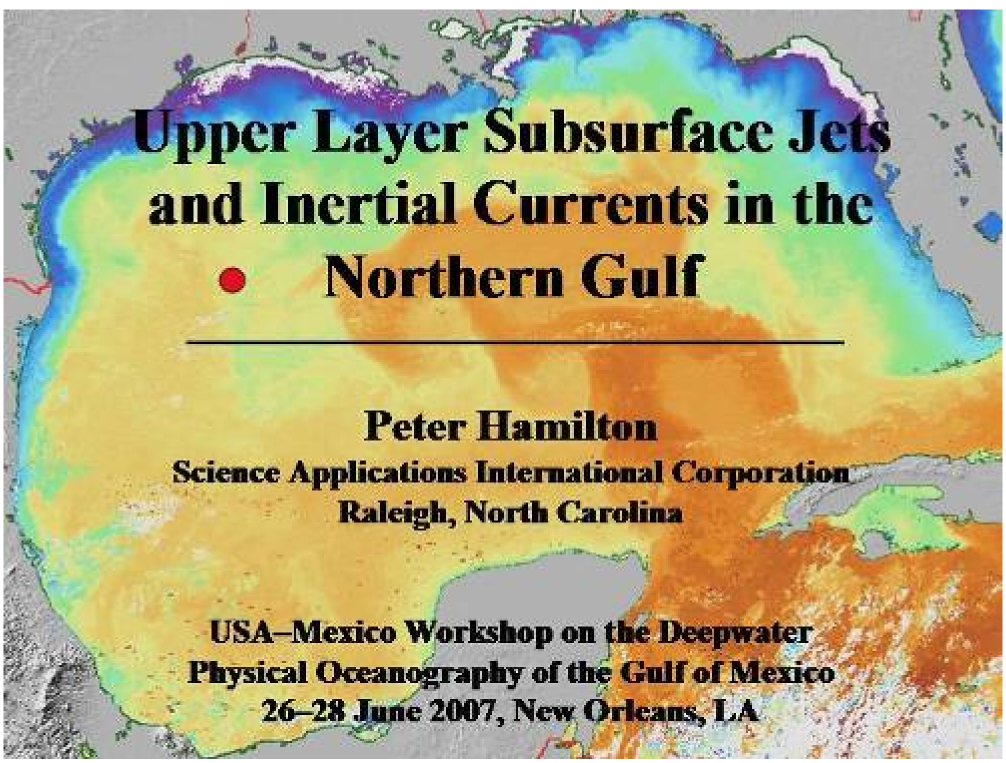
Slide 1



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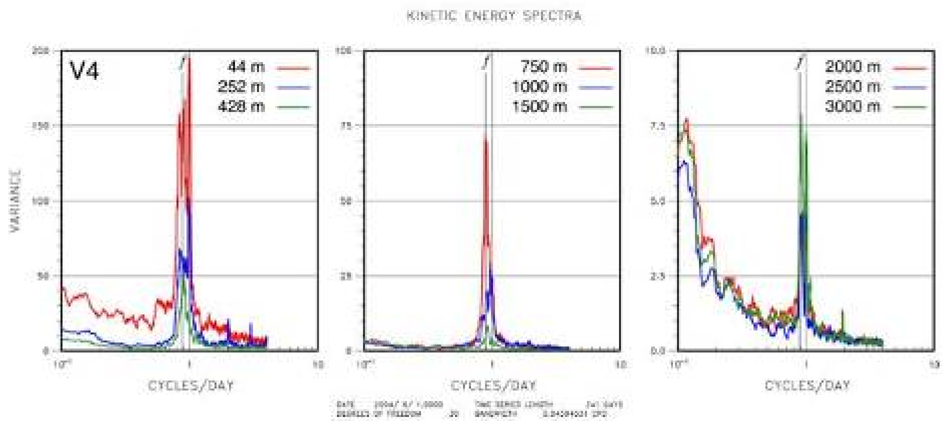
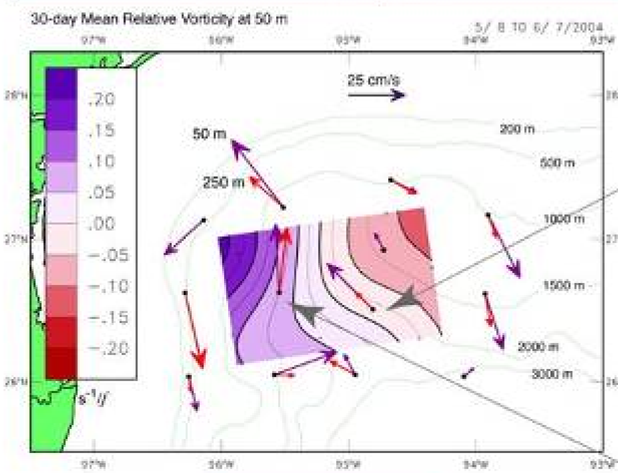
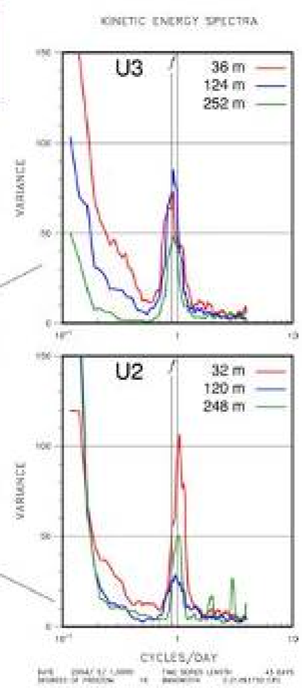
High Frequency Spectra Dominated by Inertial Motions in Deep Water



Slide 3

Relative Vorticity Effects on Inertial Response

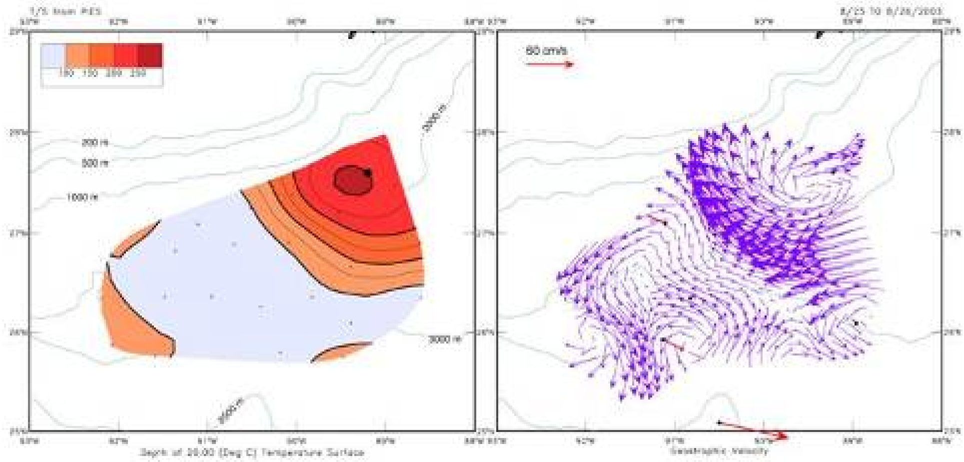




$$f_e = f + \zeta/2$$

Slide 4

Eddy Sargassum Inertial Event



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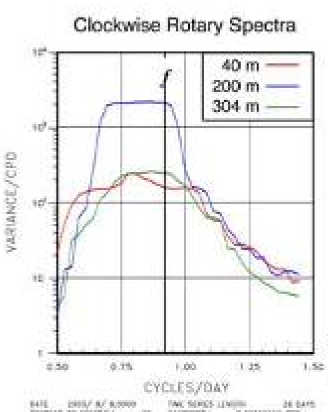
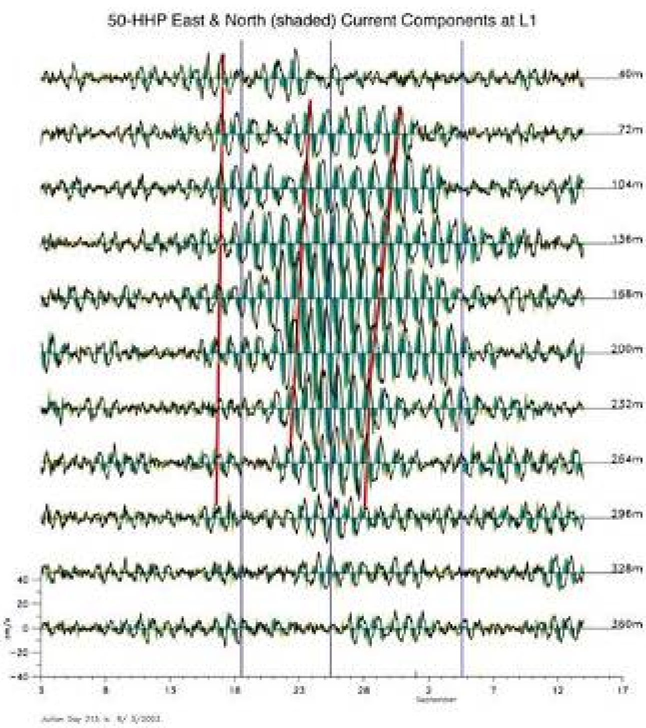
Sargassum Inertial Currents





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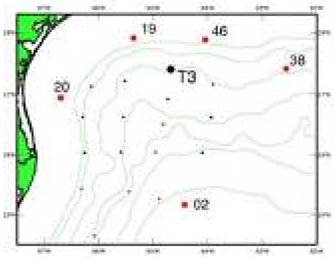
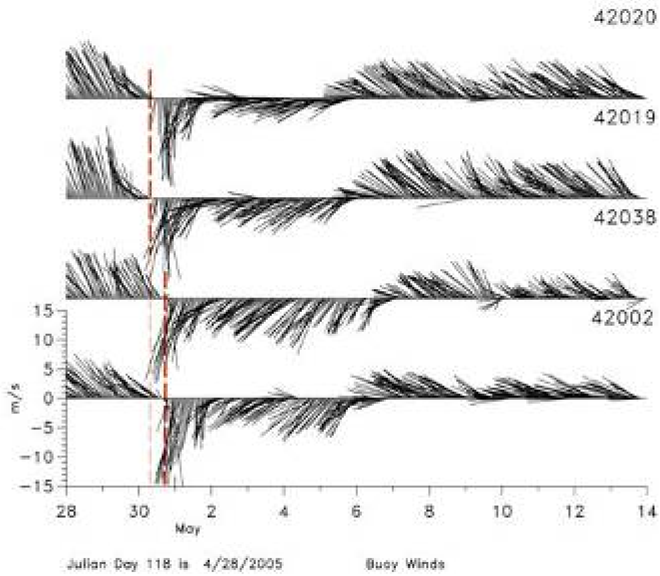
May 2005 Cold Front Winds





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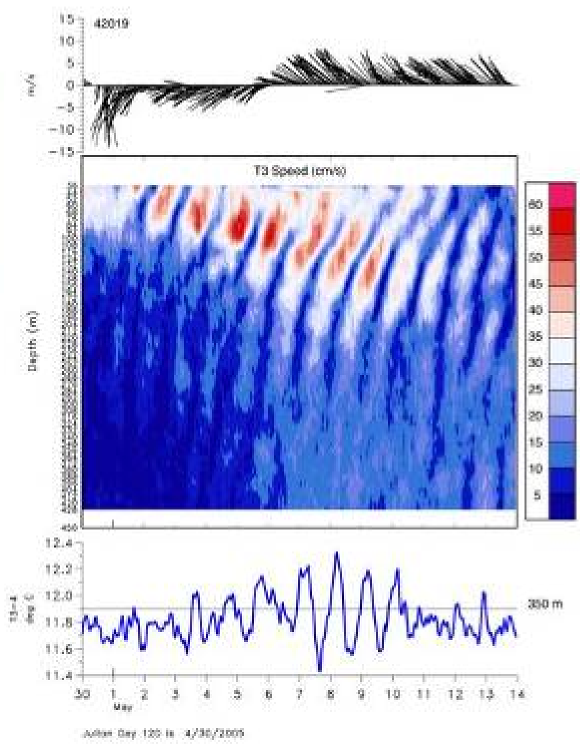
Inertial-Internal Wave Response at T3



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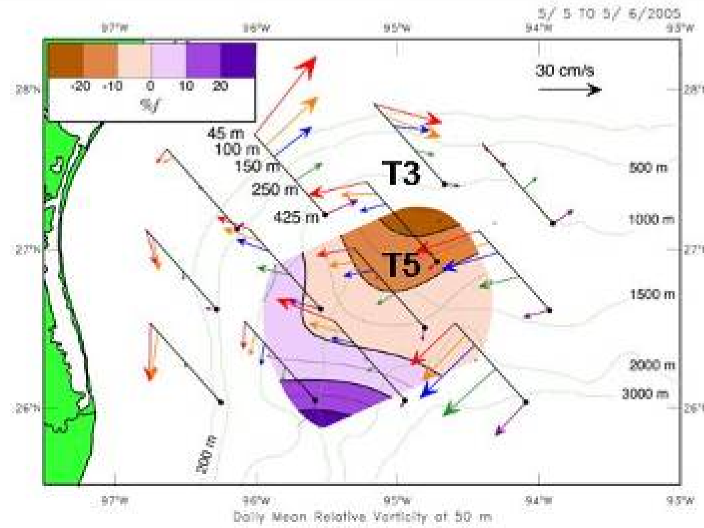
Relative Vorticity and Daily Mean Currents for May Inertial Event



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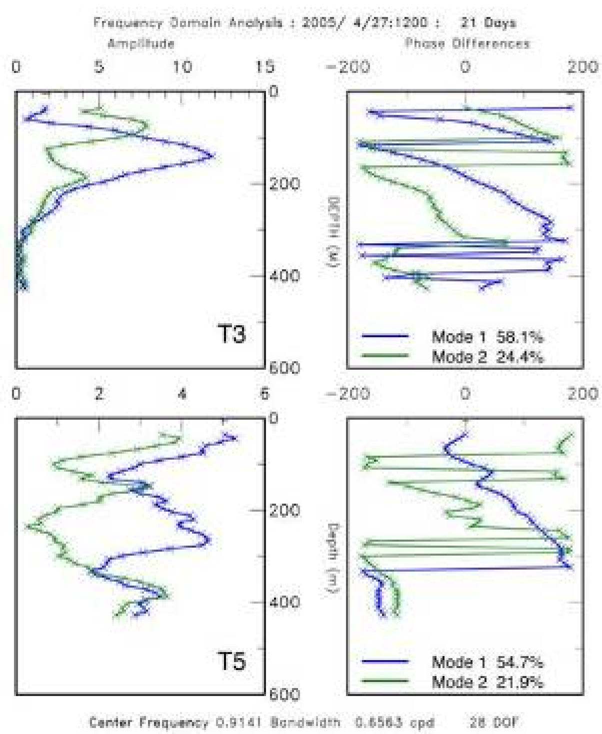
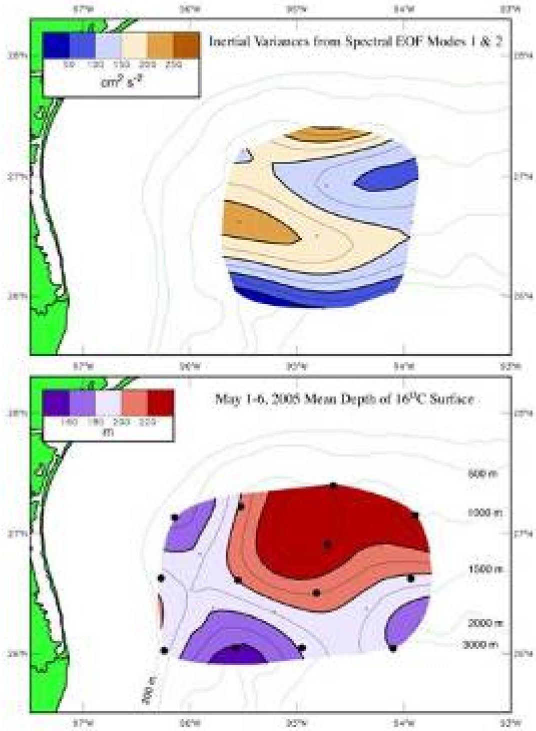
Inertial Band Clockwise Rotary Current EOF Modes for the Surface Layer



Slide 10

Inertial Band
40 – 450 m
Water Column
Variances from
EOF Modes



Slide 11

Inertial Currents: Summary

- High Frequency Dominated by inertial period currents.
- Eddy field vorticity affects response period
  - Cyclones raise f_e
  - Anticyclones lower f_e
  - Major LC eddies can trap inertial energy
- Primarily horizontal inertial oscillations in the near-surface convert to vertical oscillations at depth.
- Meridionally inhomogeneous response to single wind event across NW Gulf slope.
- Generation by:
  - Storms, hurricanes, geostrophic adjustment

Slide 12

Subsurface Jets

Industry reports of effects on deepwater rigs of apparent strong subsurface flows while near-surface is quiescent.

DiMarco et al. (2004) investigated ~ 10 historical observations of subsurface jets. Results were inconclusive primarily because of measurement issues.

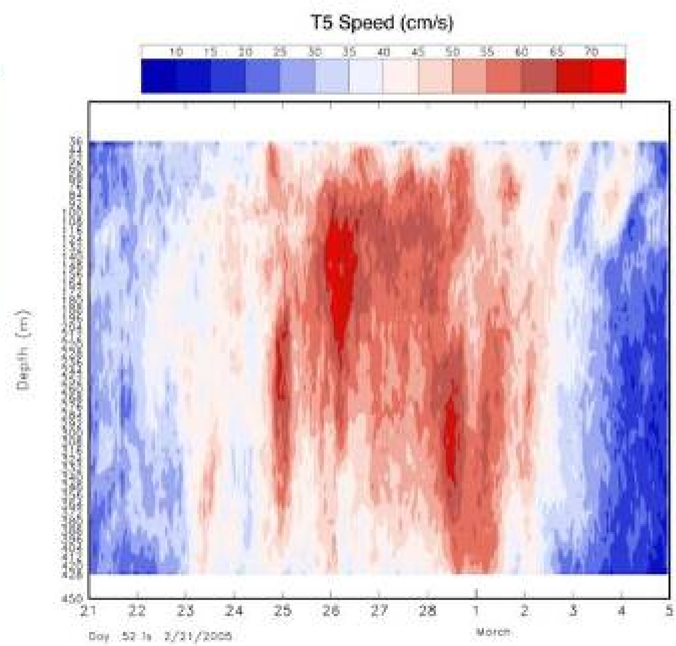
Vertically propagating inertial-internal waves can produce subsurface flow maxima (e.g., the T3 inertial event).

Using 75kHz ADCPs deployed at 450 to 500 m, non-inertial subsurface current maxima between 150 – 350 m have been found:

- Central Gulf: 7-years from 5 moorings: 0 jets
- NW Gulf: 14-years from 10 moorings: 7 jets

Slide 13

Subsurface Jet Event at T5 in February 2005



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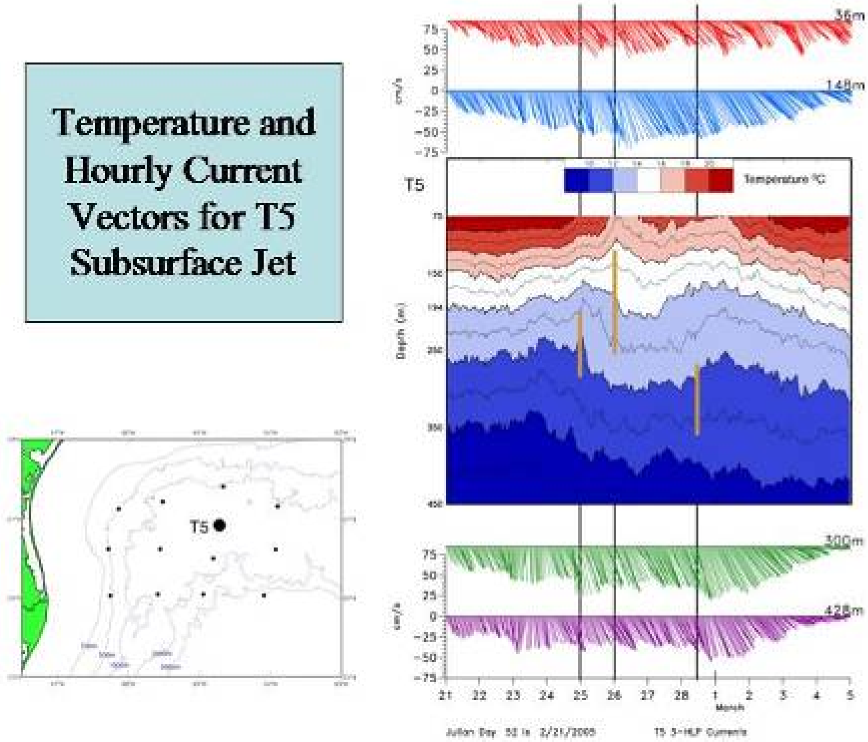

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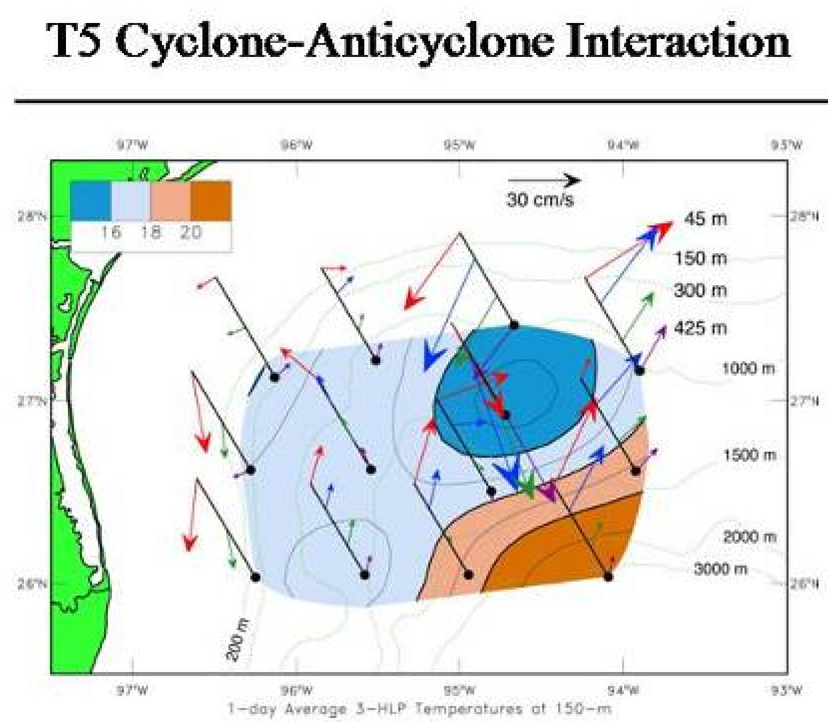

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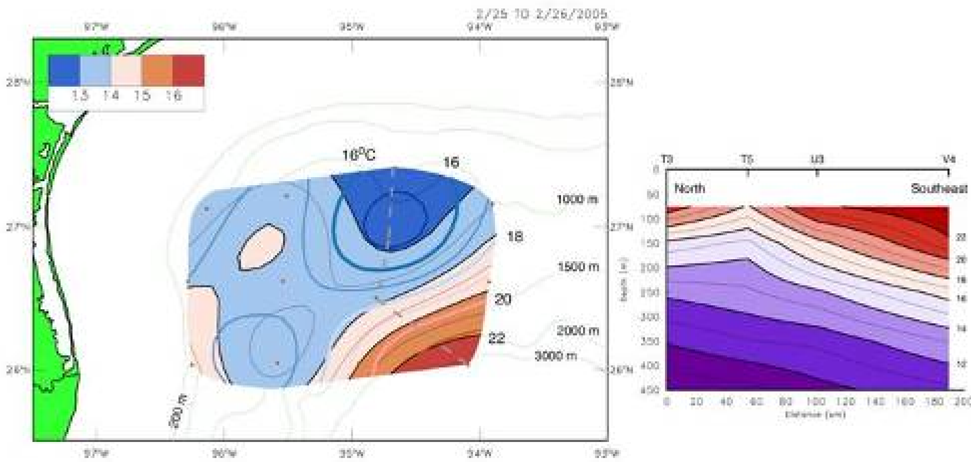
Tilt of Cyclone Vertical Axis Towards Anticyclone



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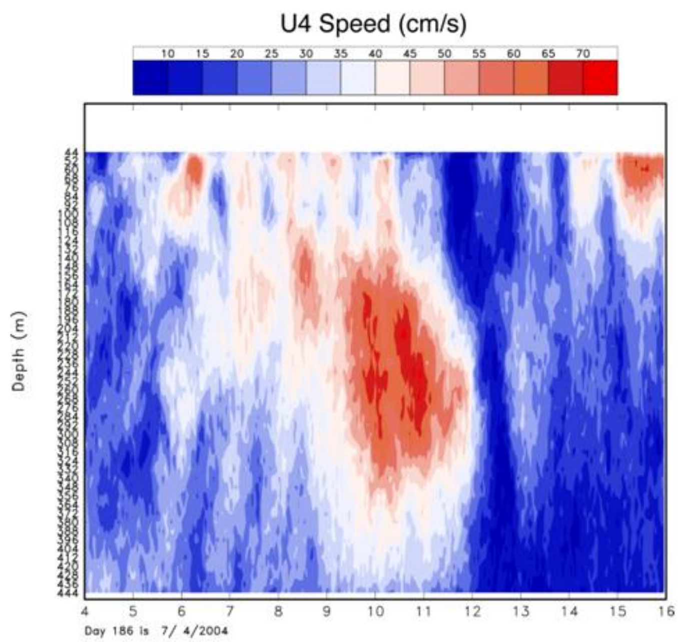
Subsurface Jet Event at U4 in July 2004



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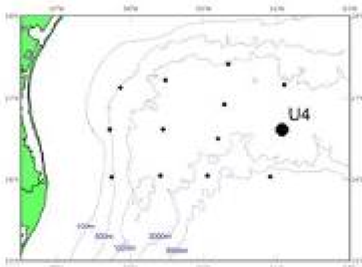
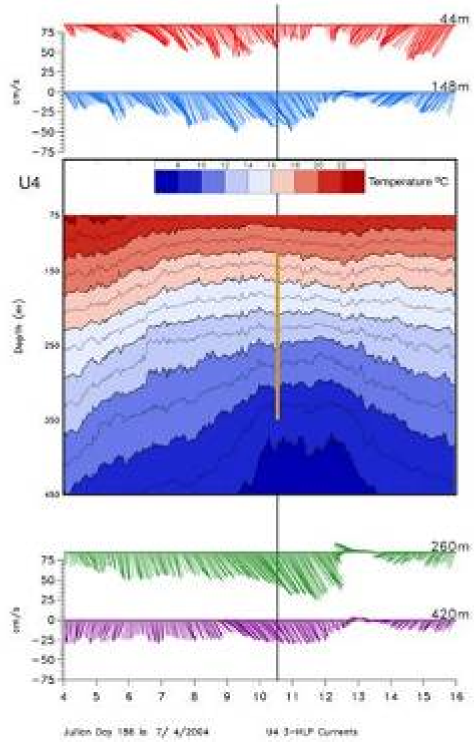
Temperature and Hourly Current Vectors for U4 Subsurface Jet





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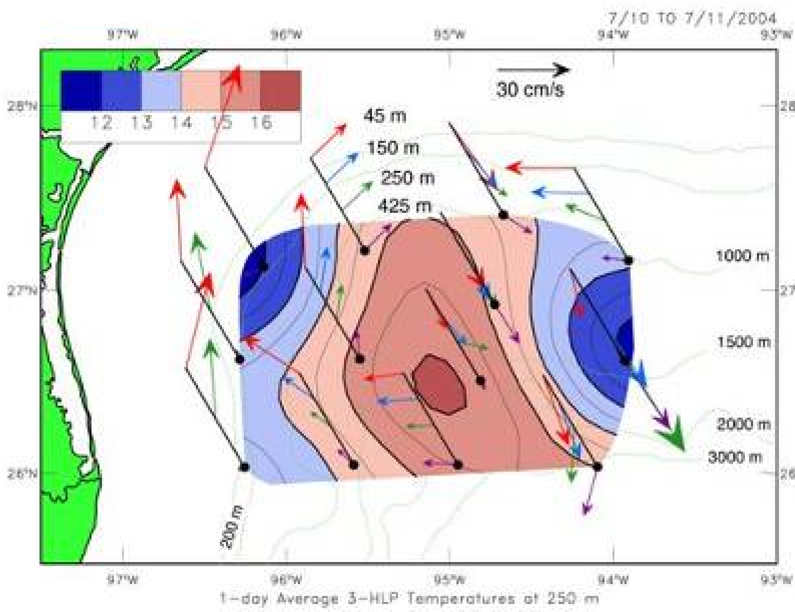
U4 Cyclone-Anticyclone Interaction



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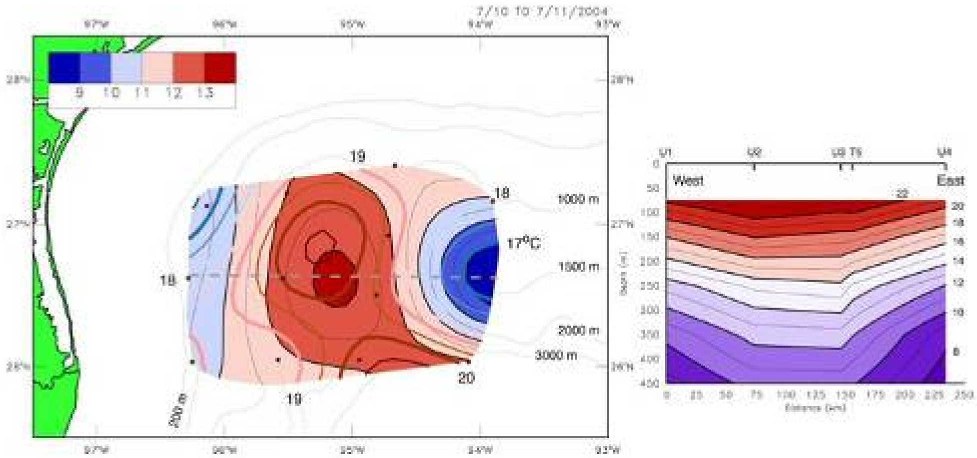
Tilt of Anticyclone Vertical Axis



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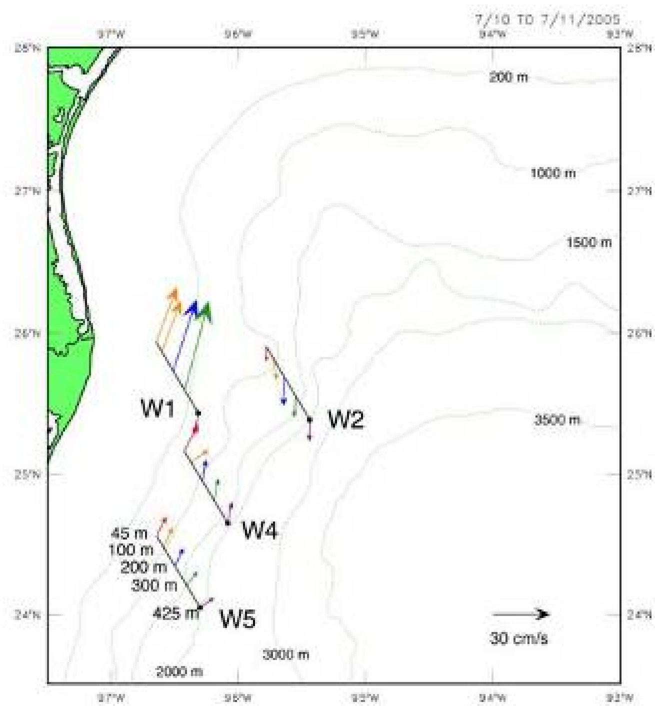
Subsurface Jet Against the Mexican Slope



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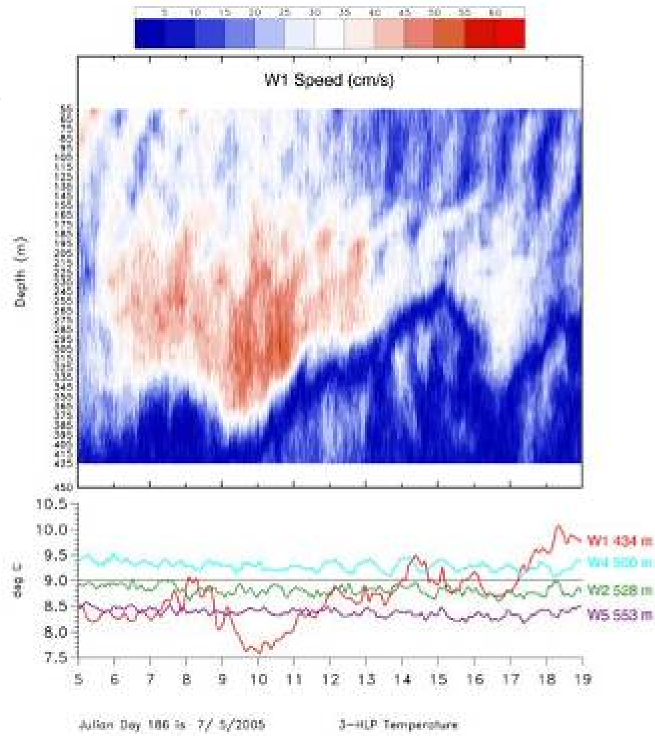
Subsurface Jet Event at W1



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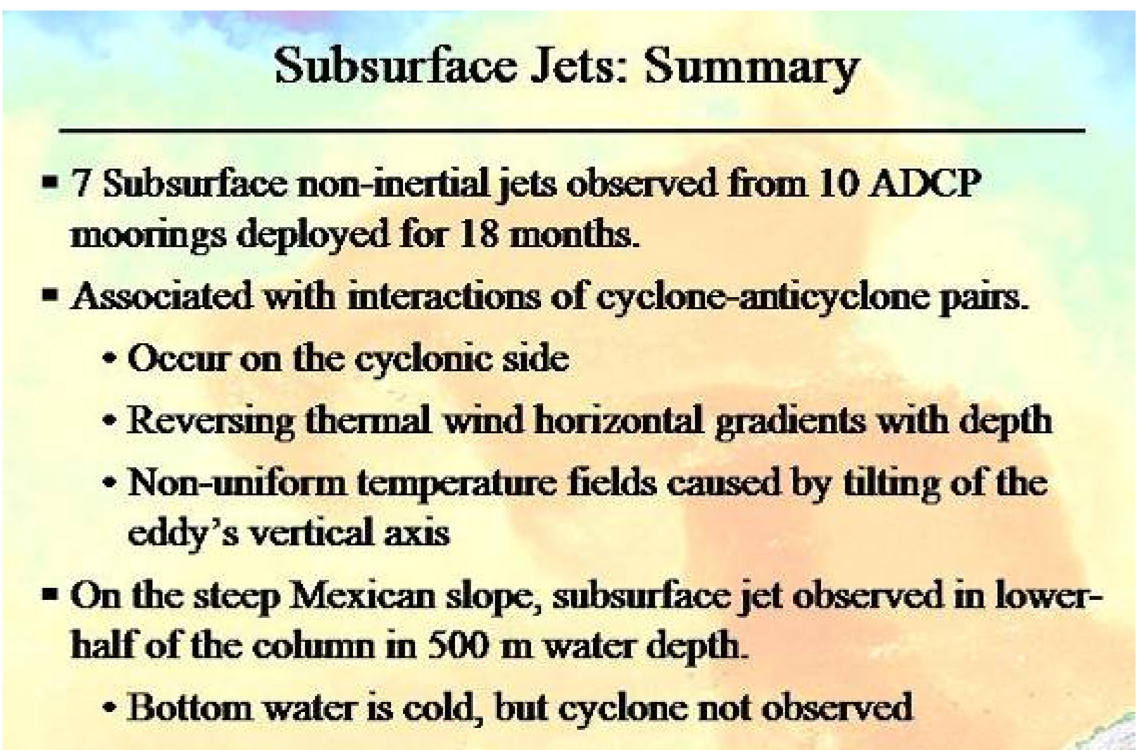

INTRA-AMERICAS SEA OCEAN NOWCAST/FORECAST SYSTEM (IASNFS): AN OPERATIONAL REAL-TIME NOWCAST/FORECAST SYSTEM FOR INTRA-AMERICAS SEA

Dong S. Ko, Naval Research Laboratory

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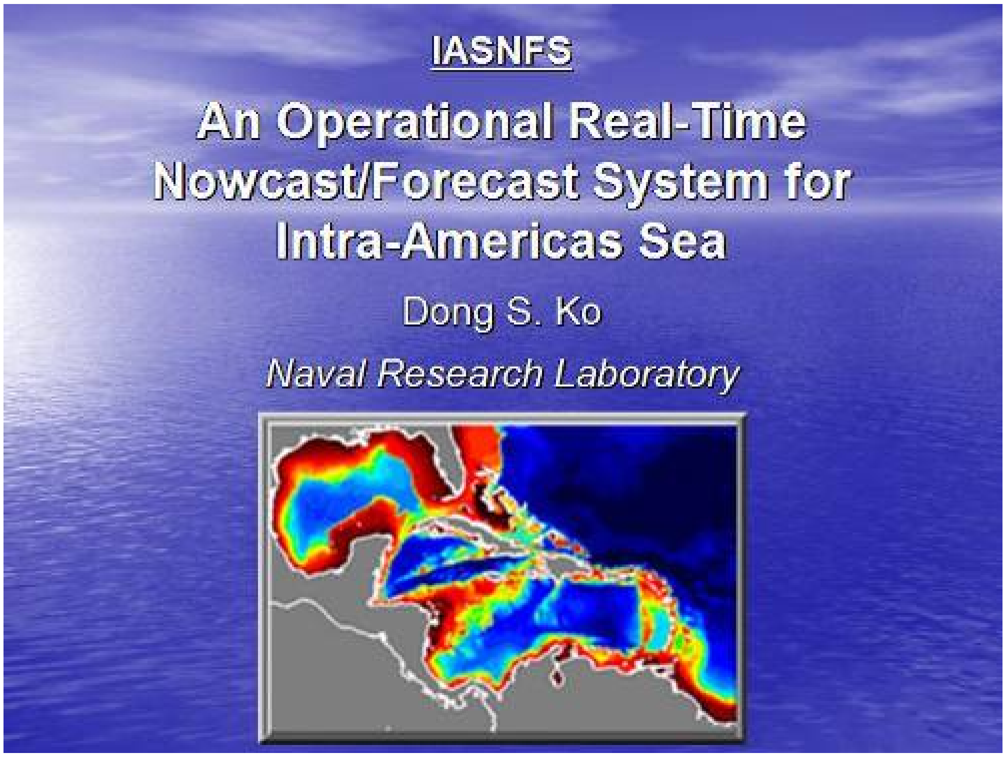

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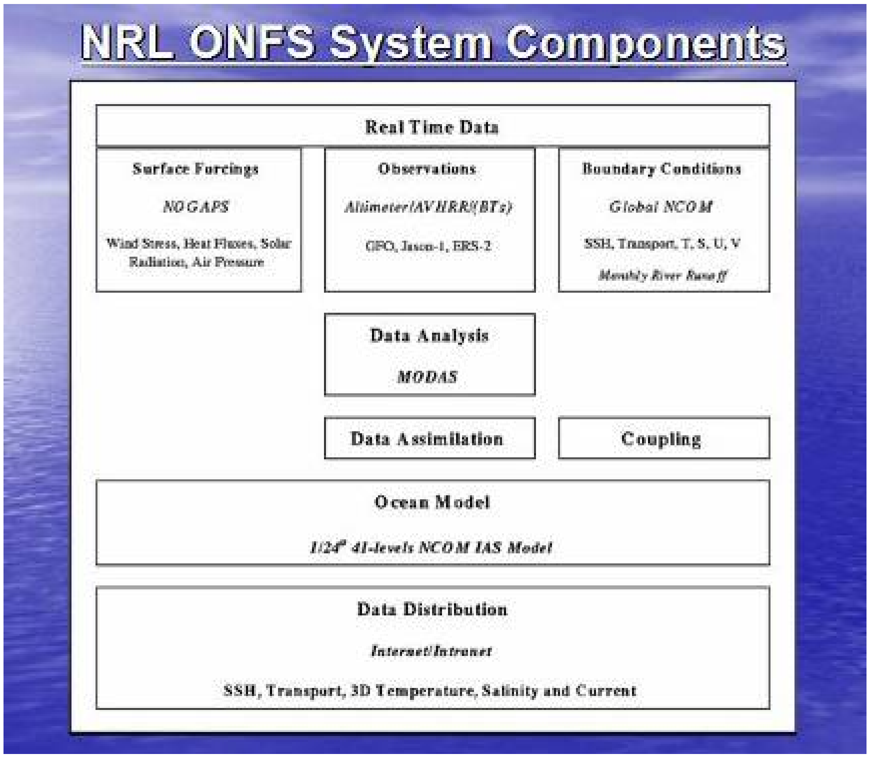

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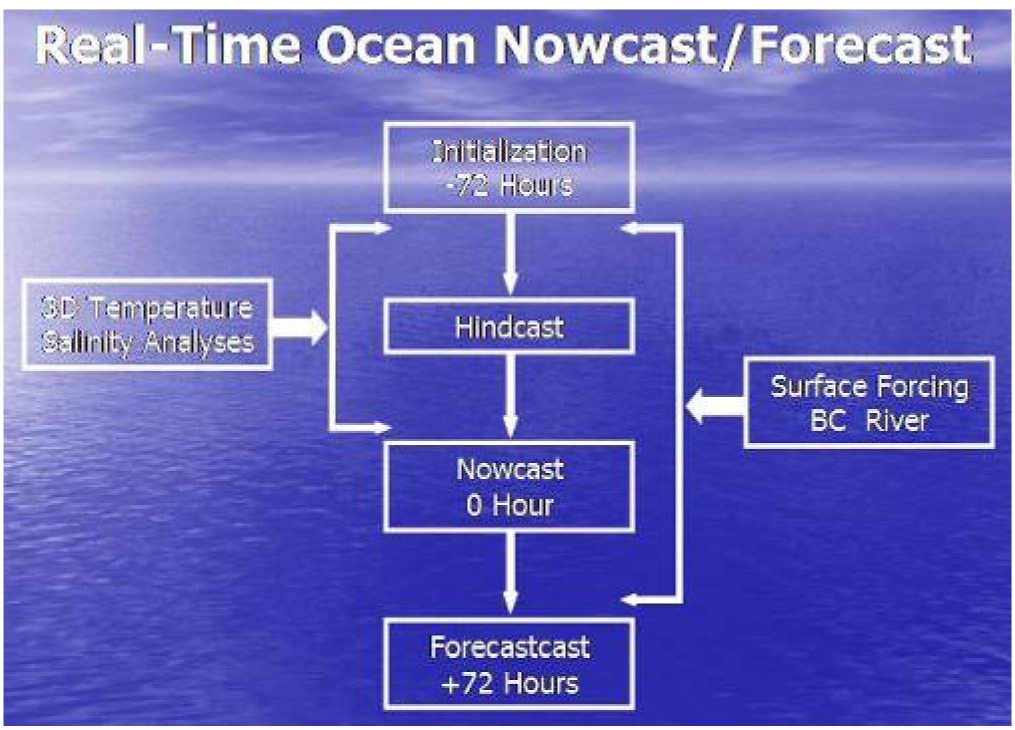

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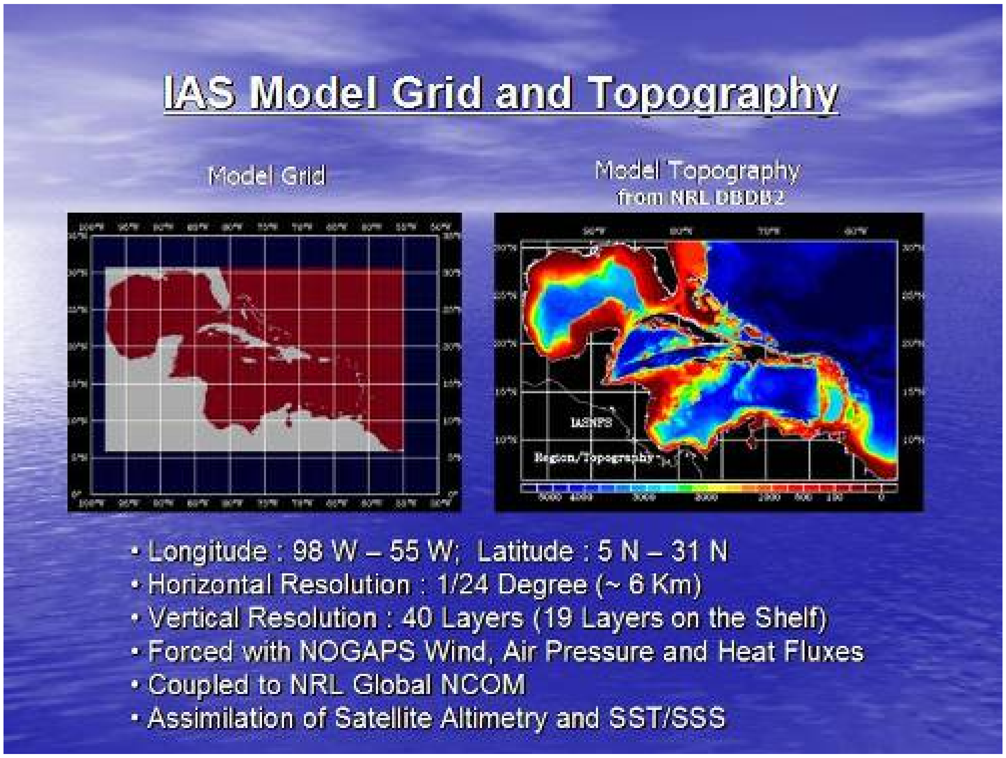

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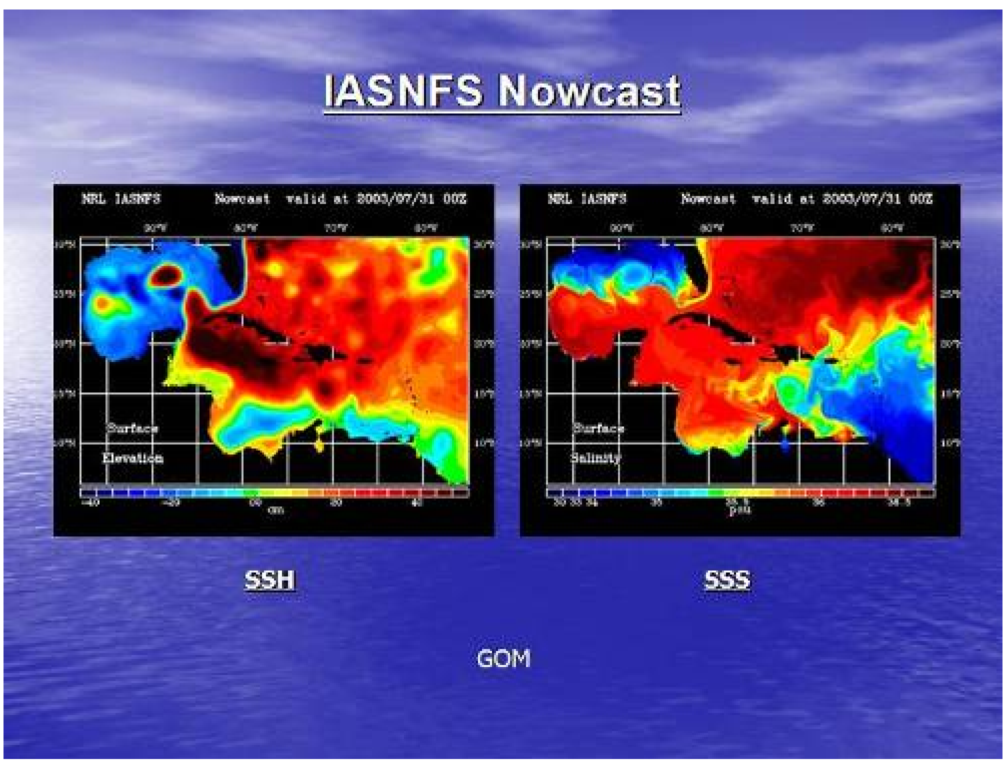

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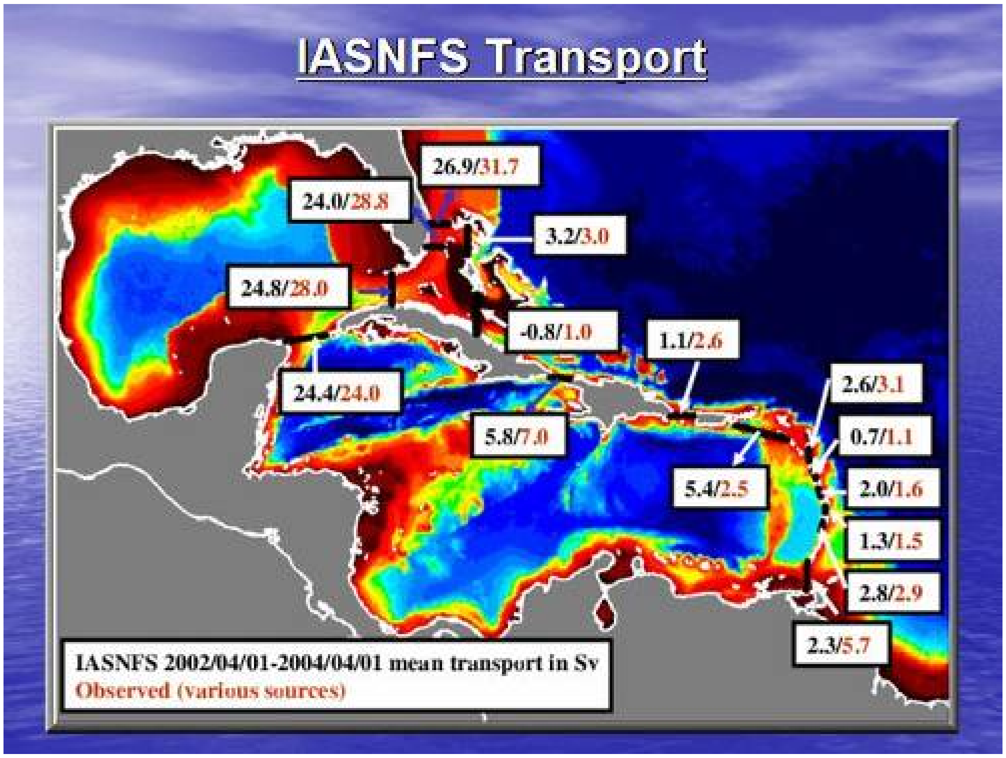

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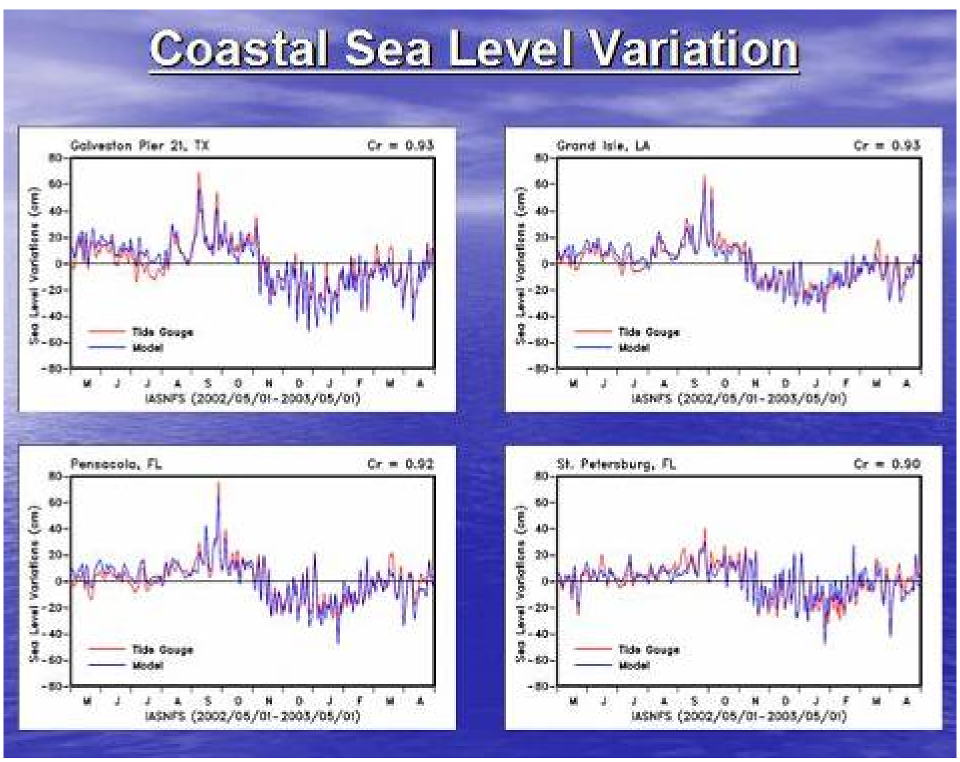

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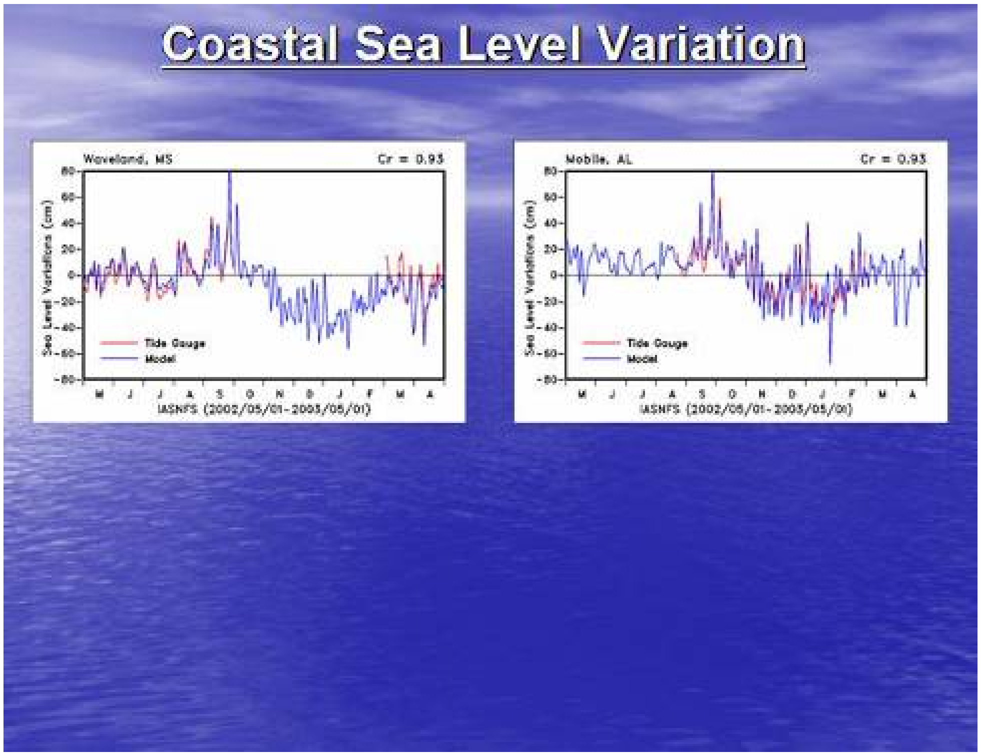

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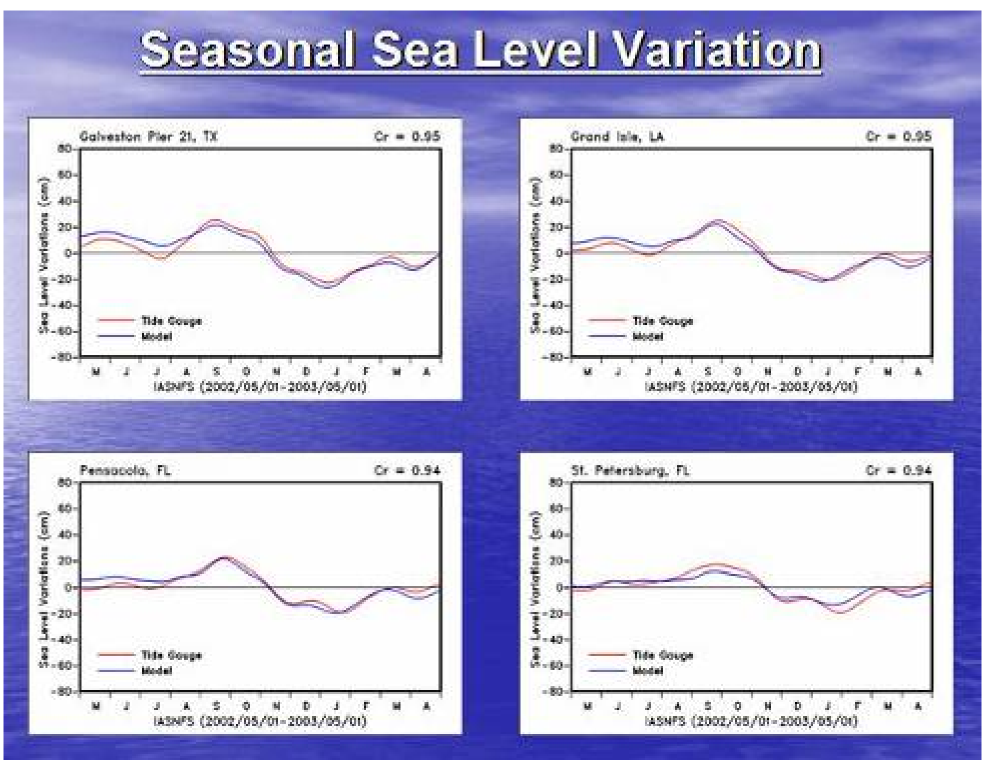

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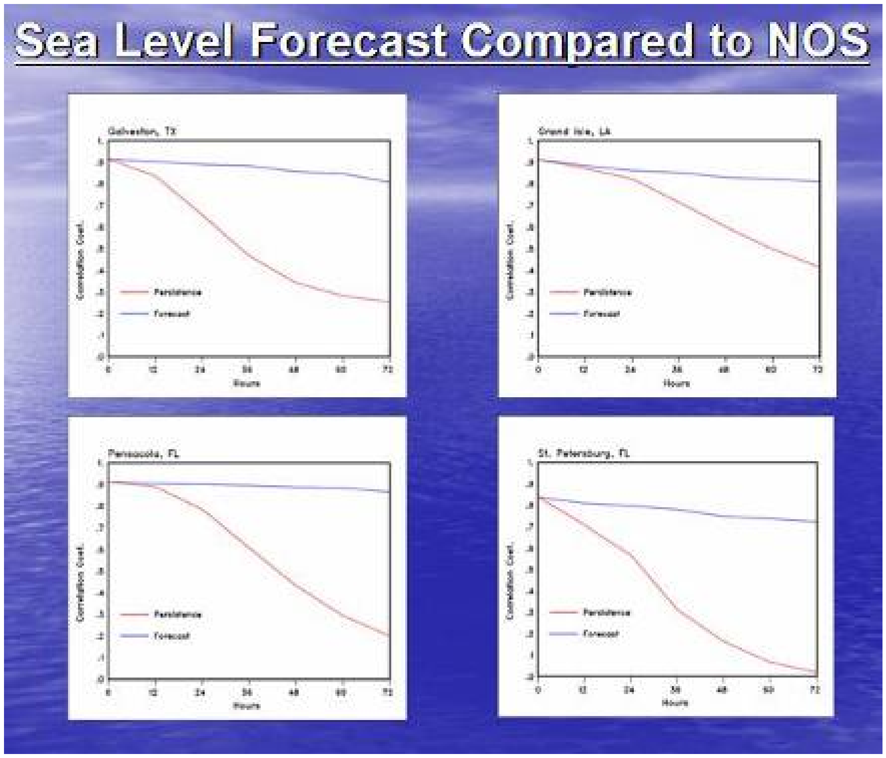

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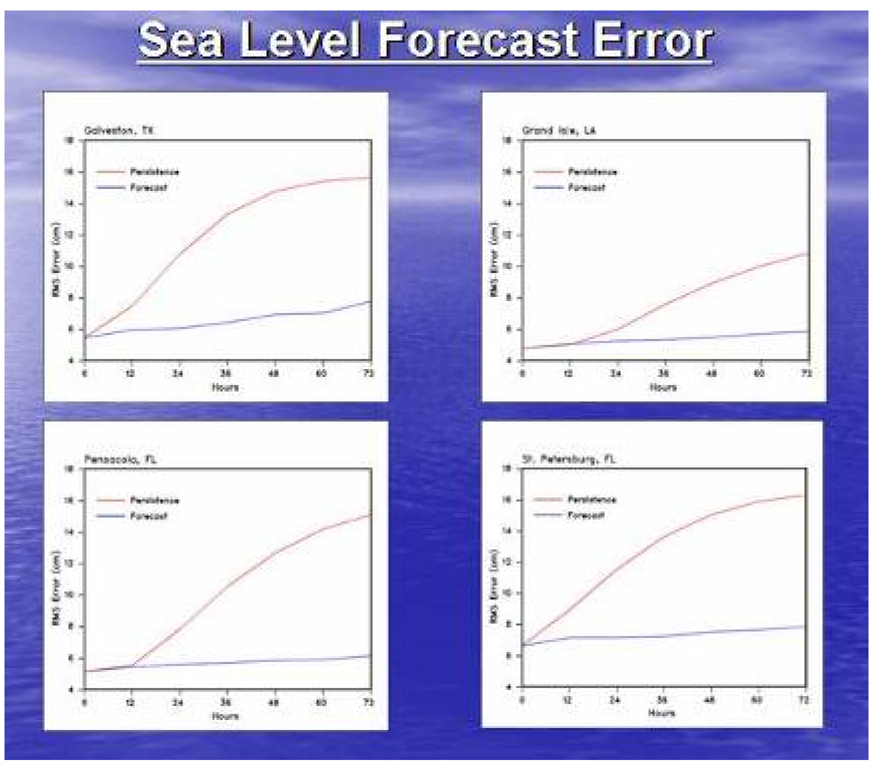

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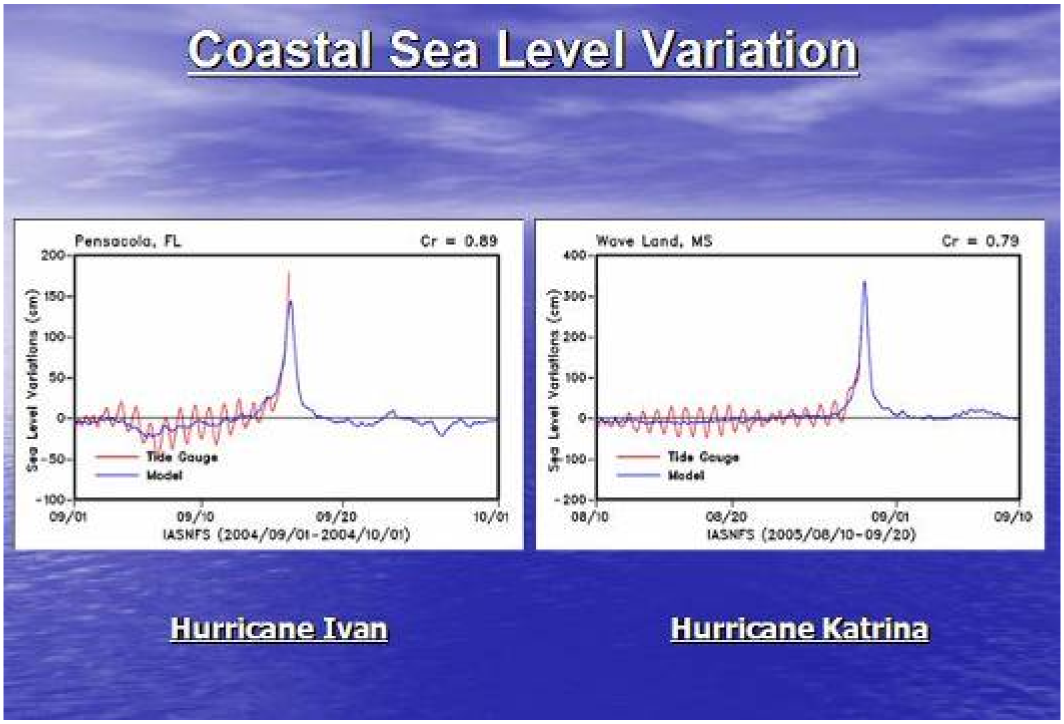

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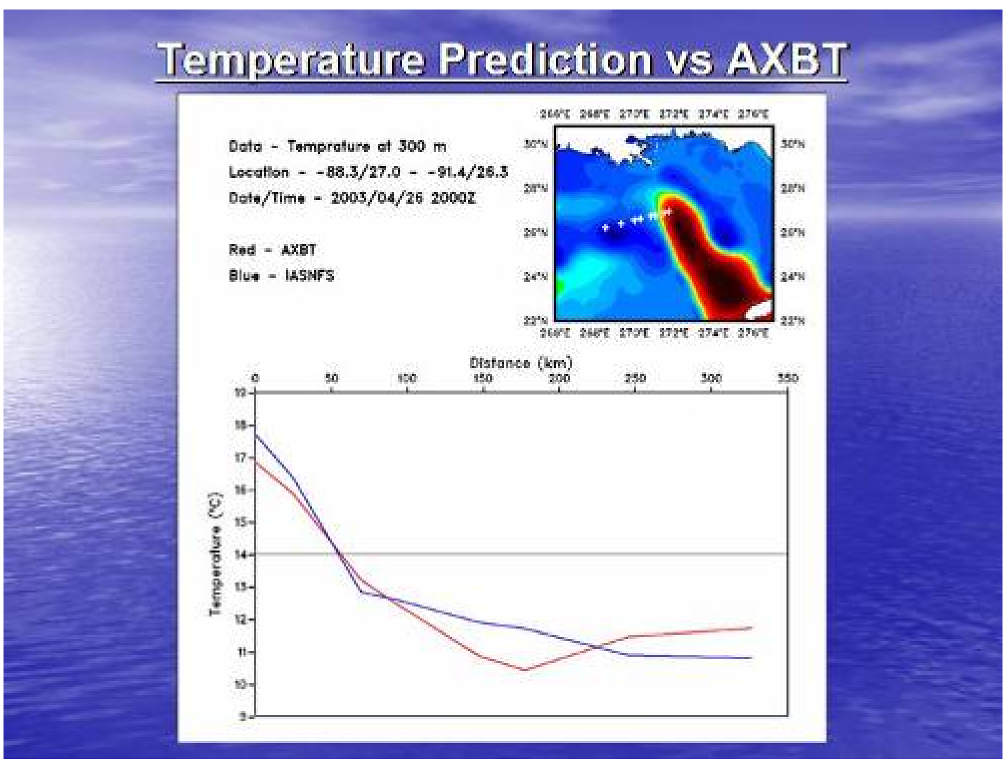

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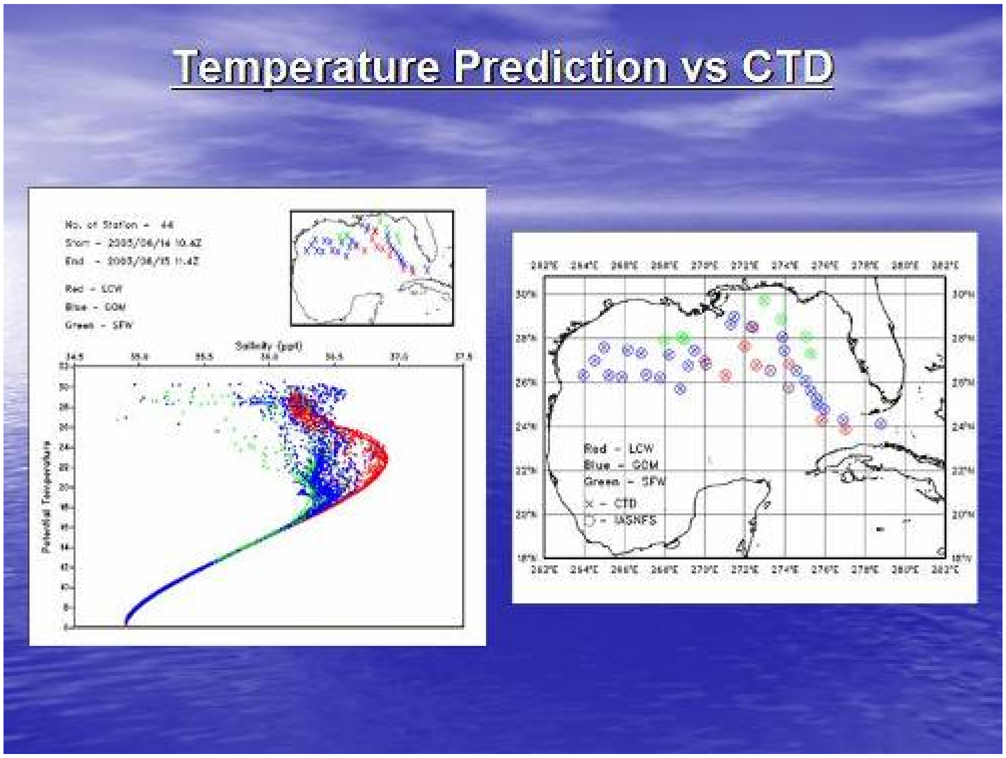

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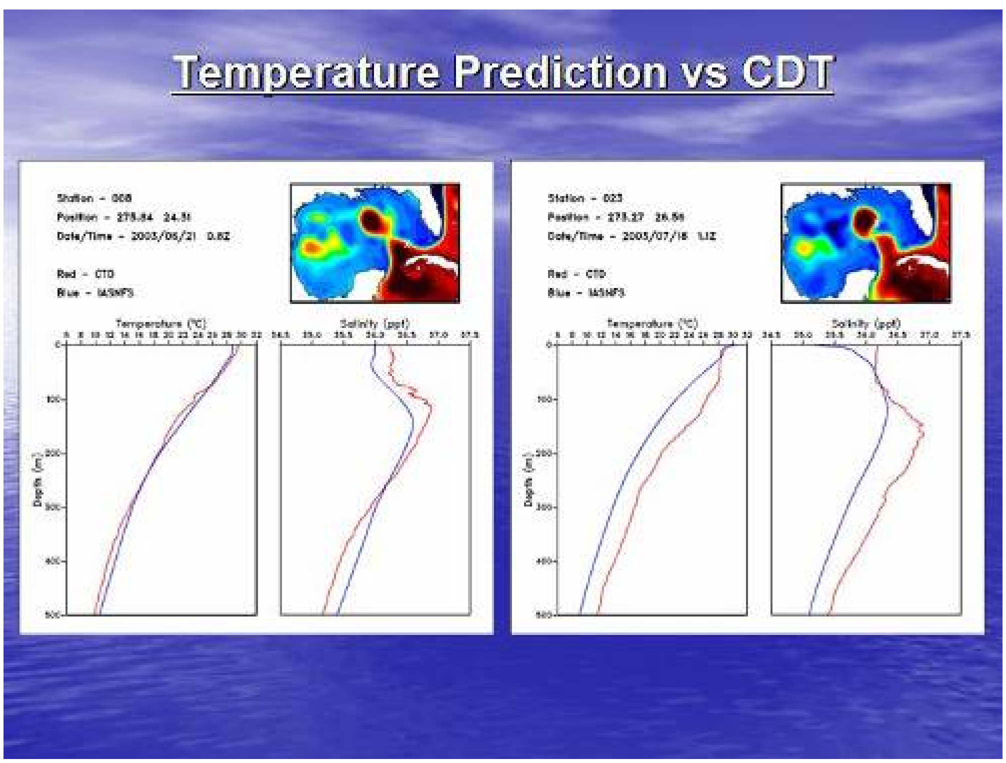

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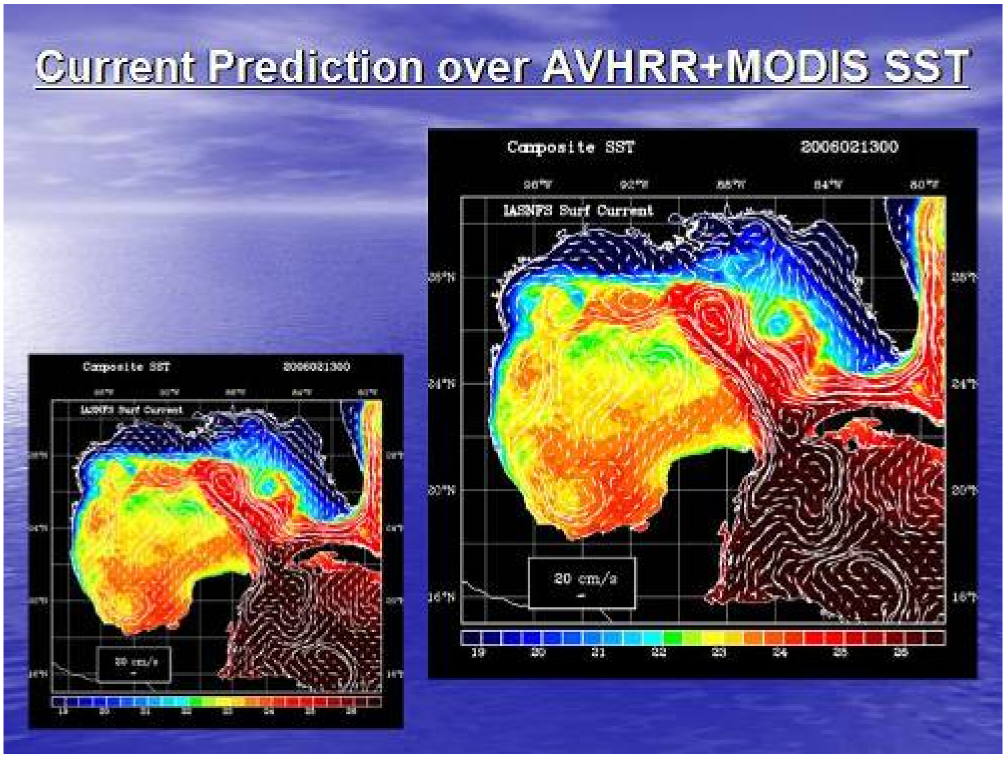

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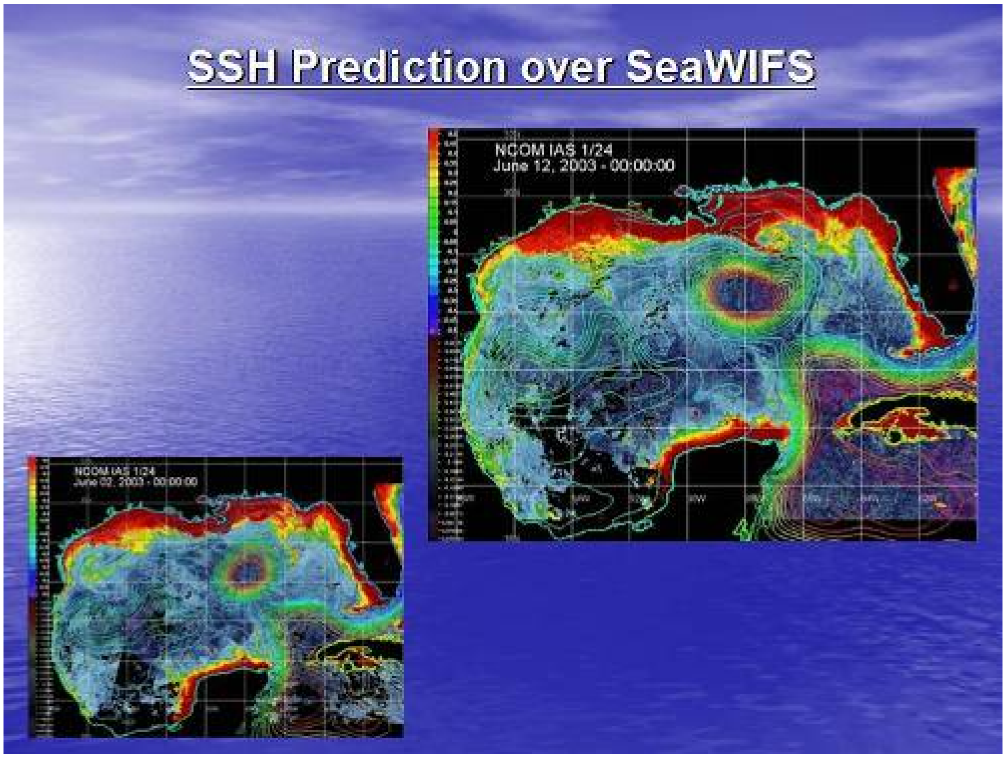

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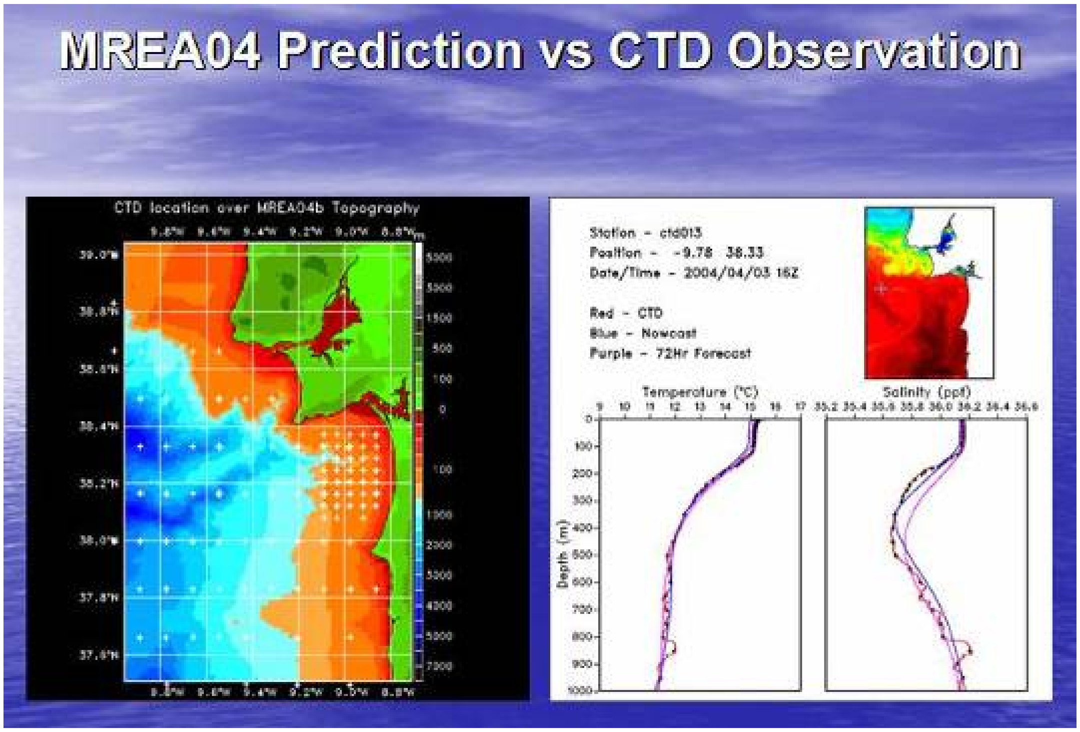

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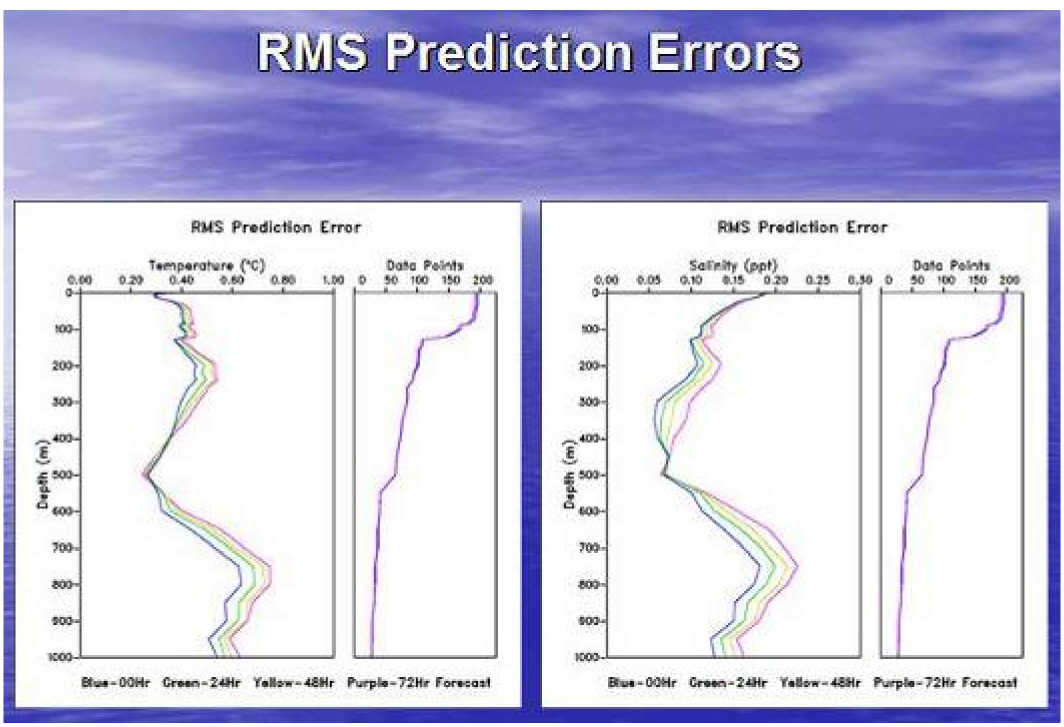

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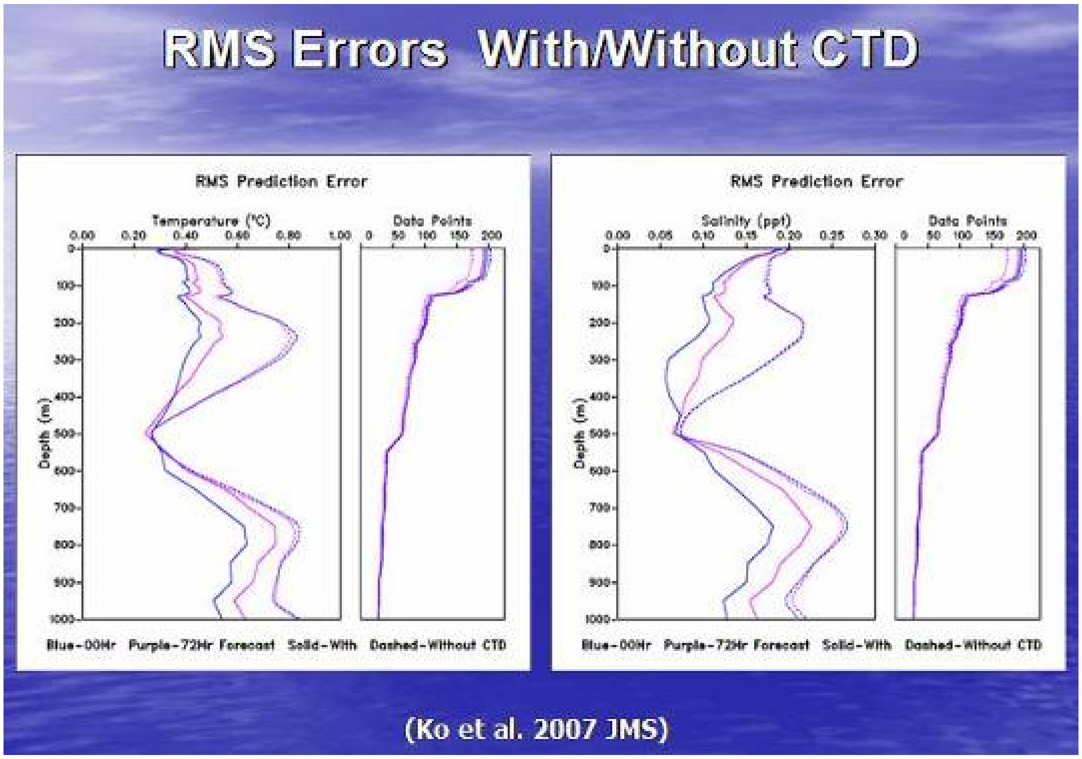

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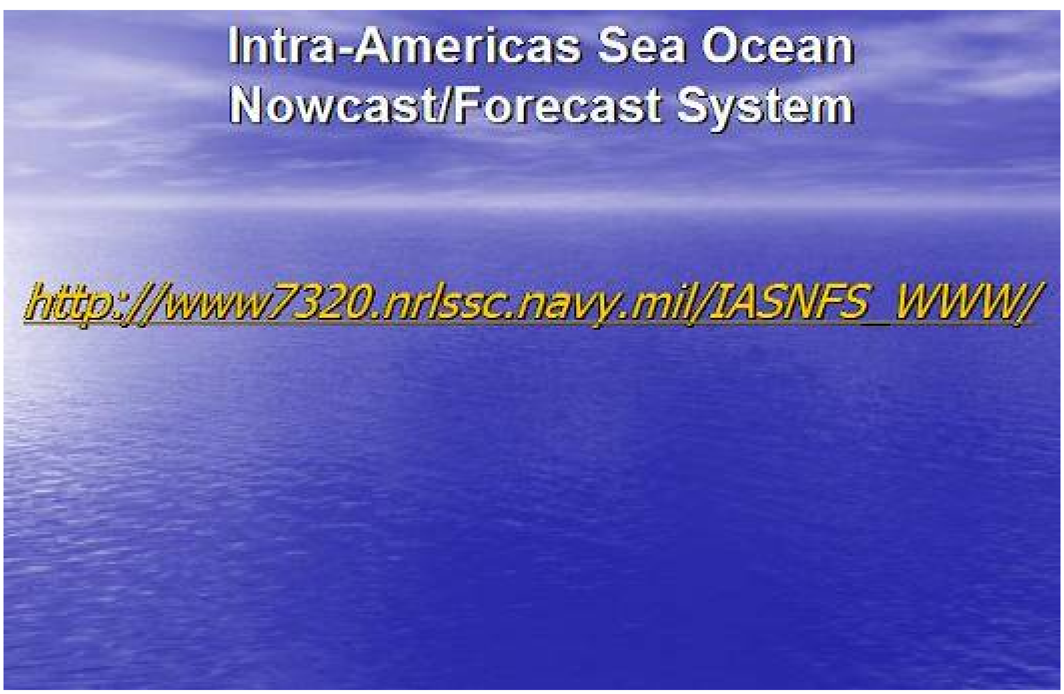

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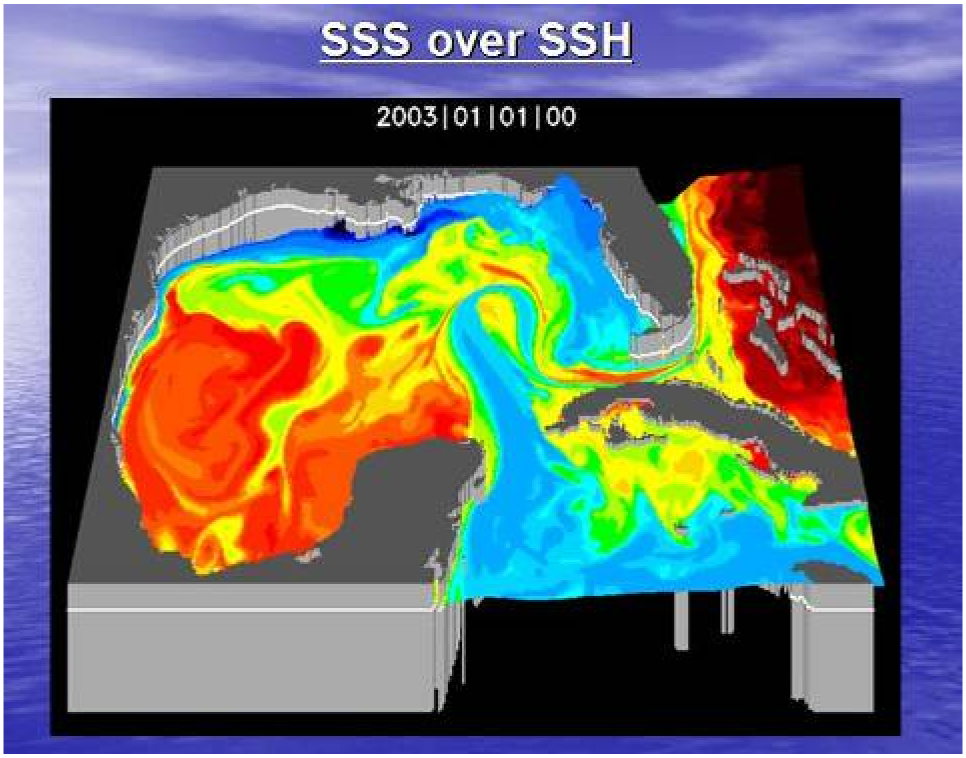
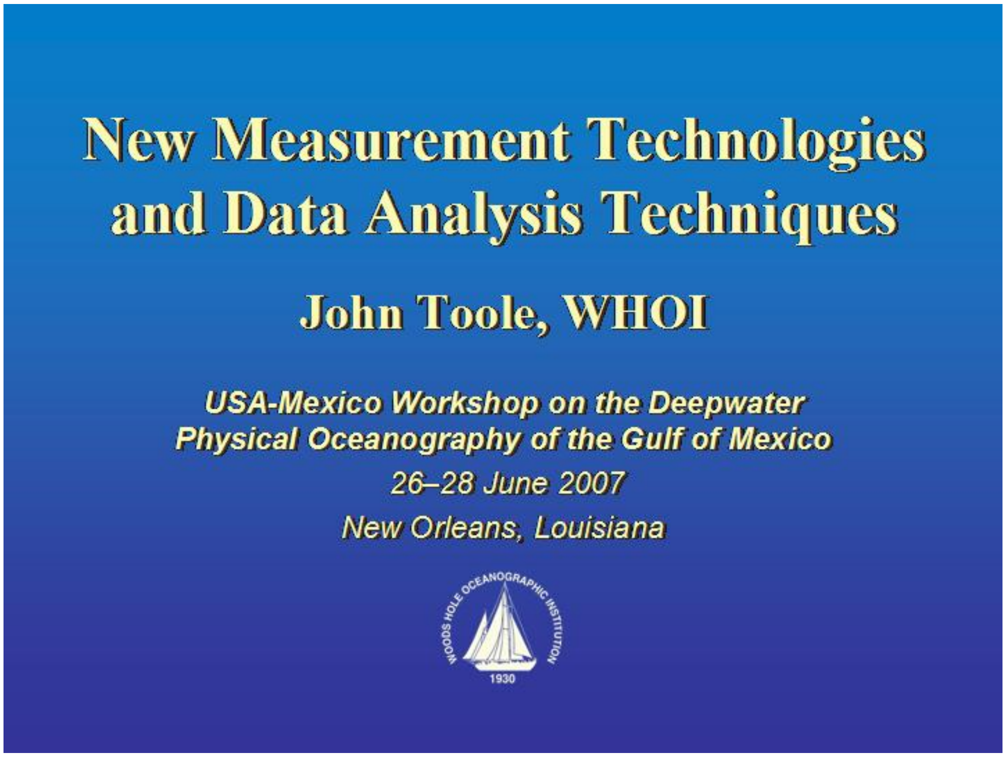


NEW MEASUREMENT TECHNOLOGIES AND DATA ANALYSIS TECHNIQUES

John Toole, Woods Hole Oceanographic Institution

Slide 1



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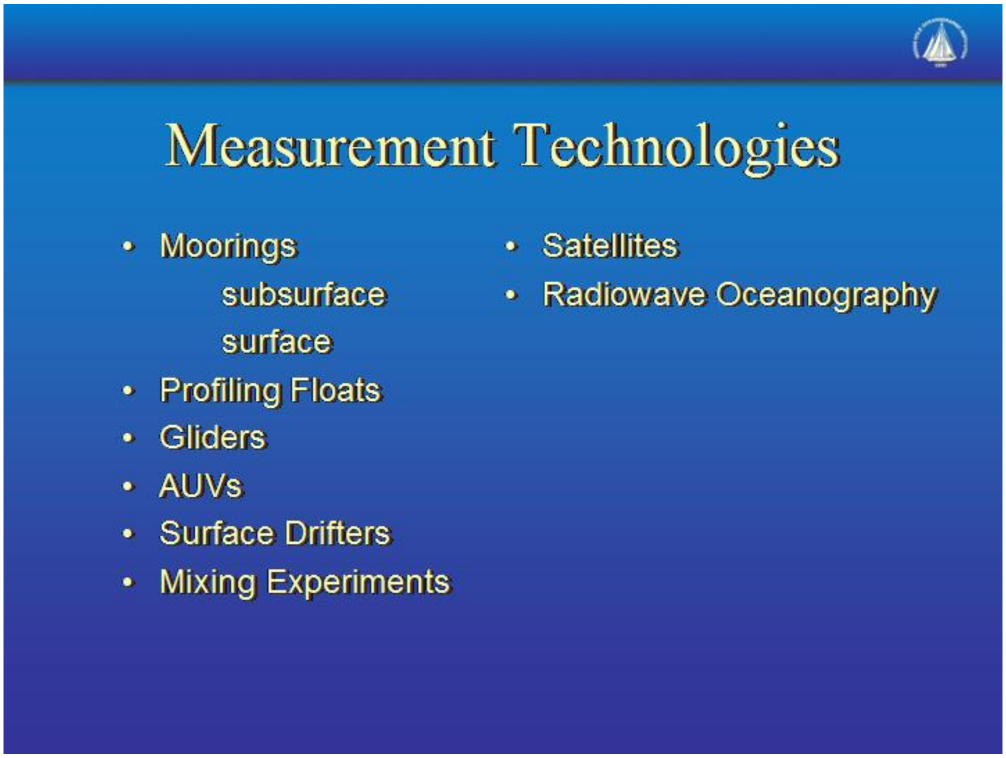

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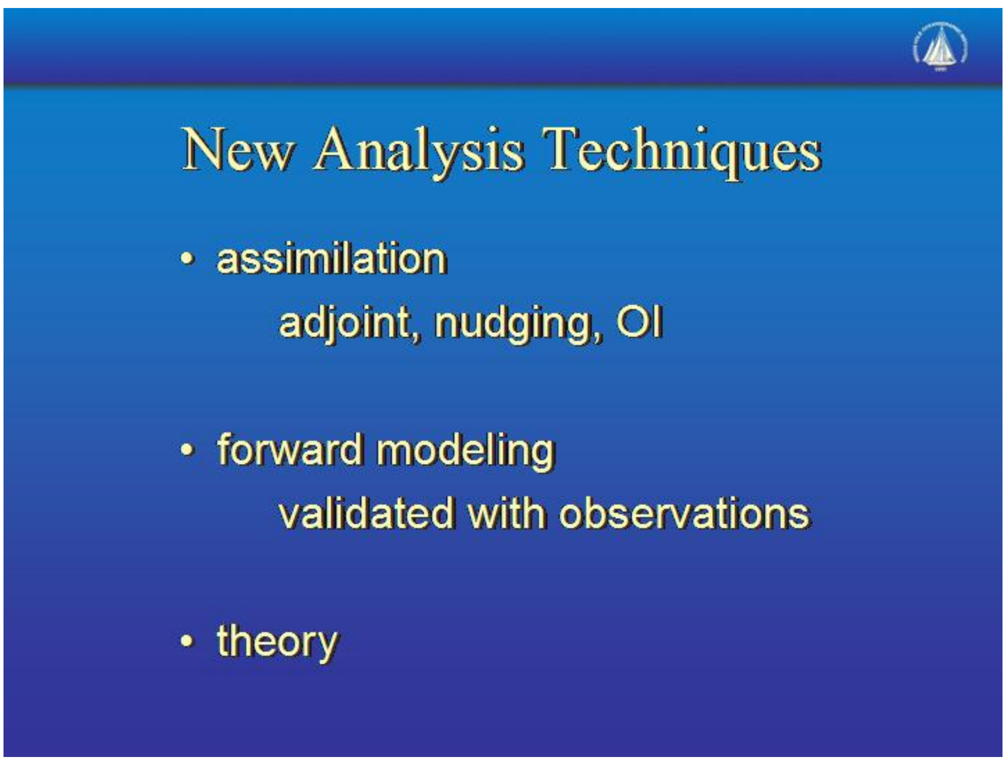

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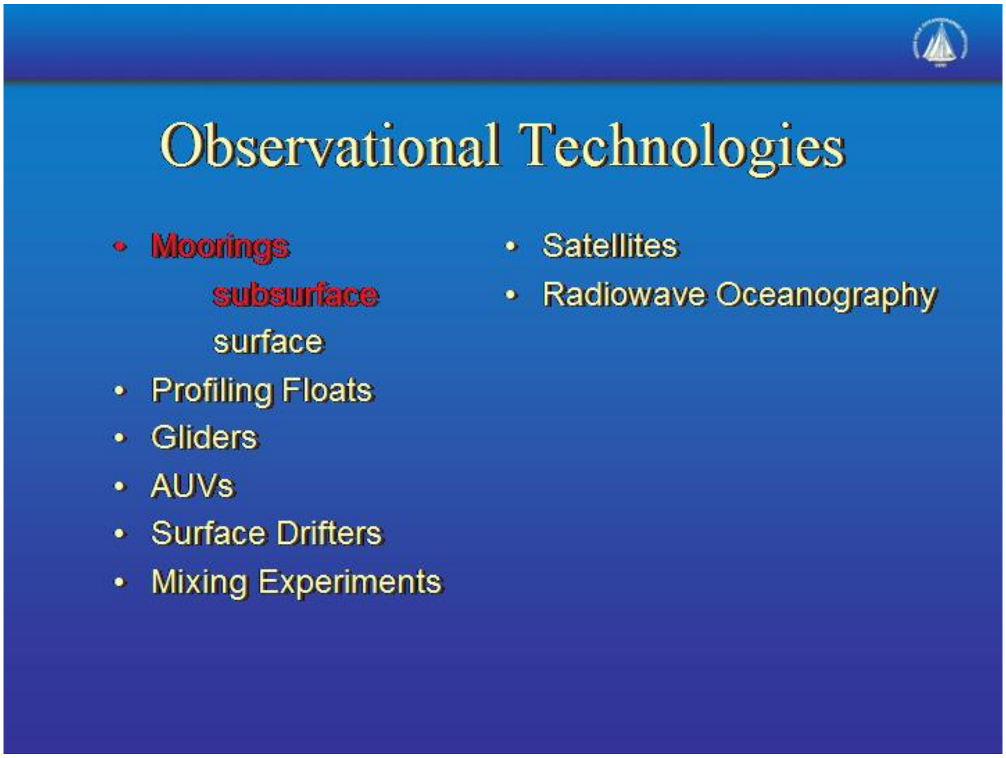

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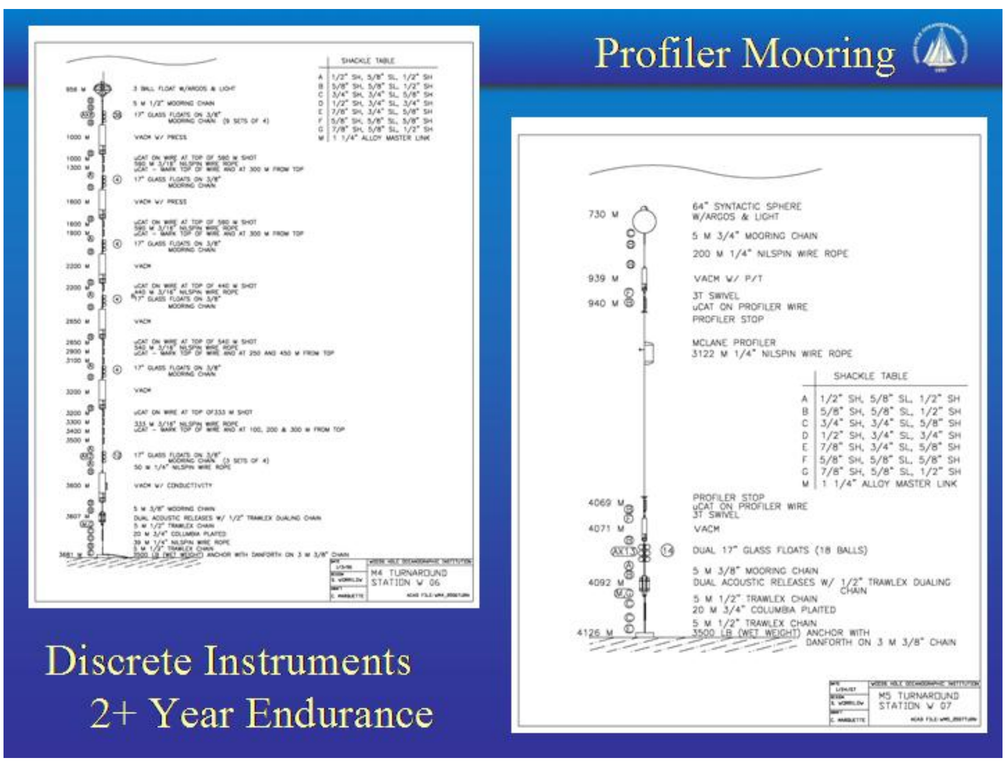

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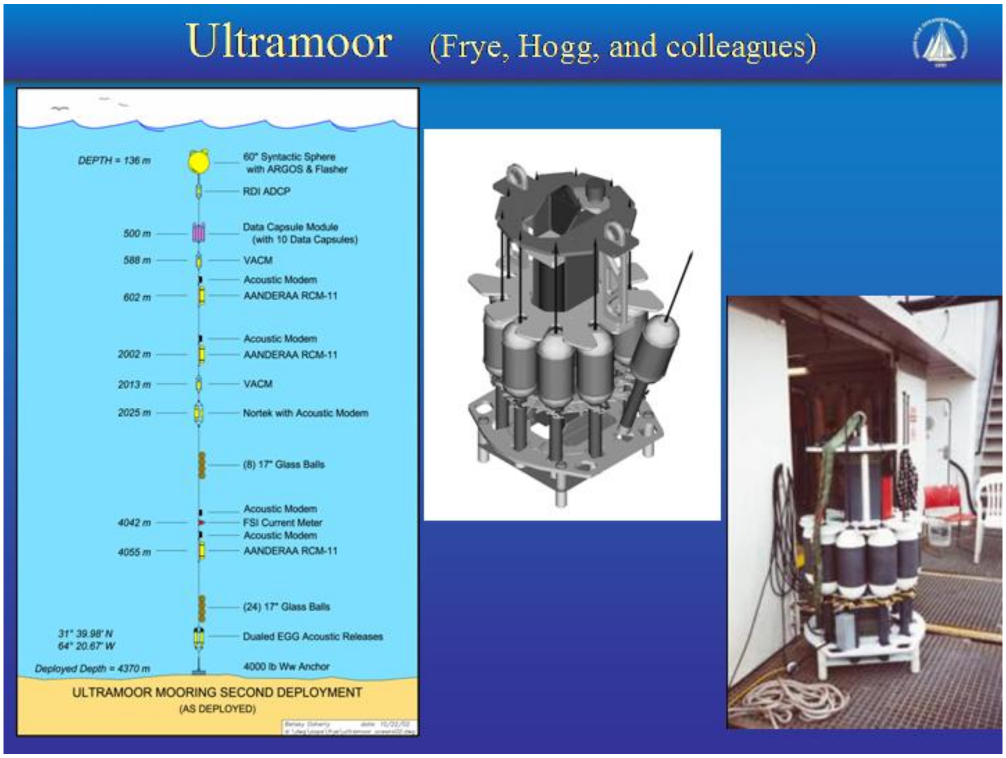

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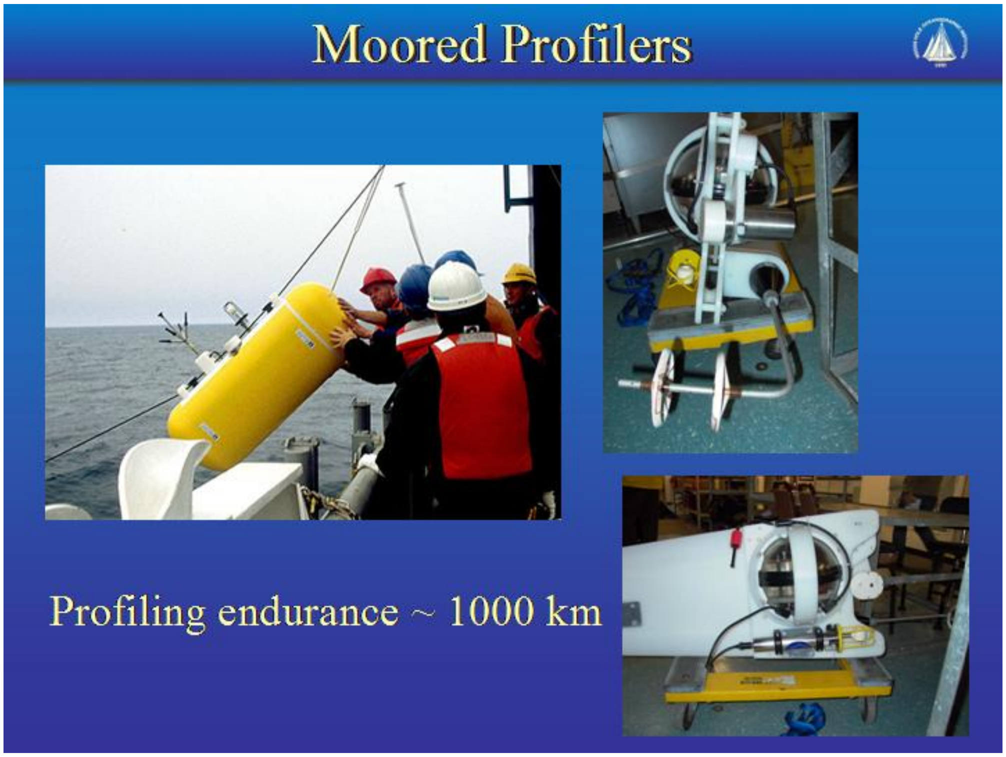

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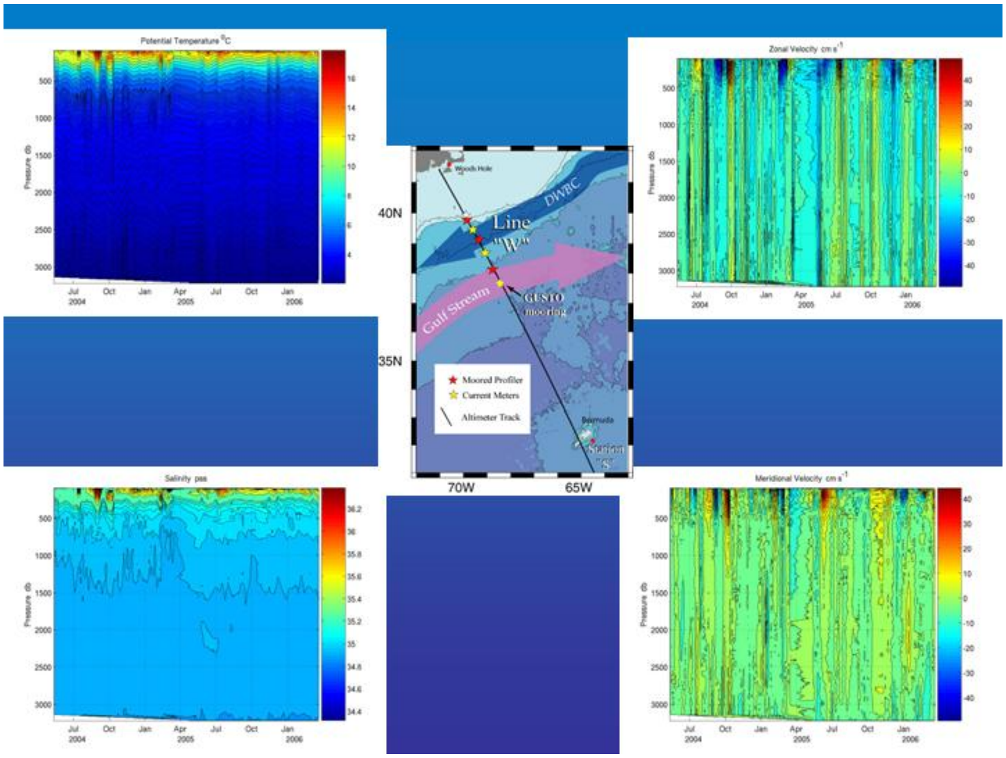

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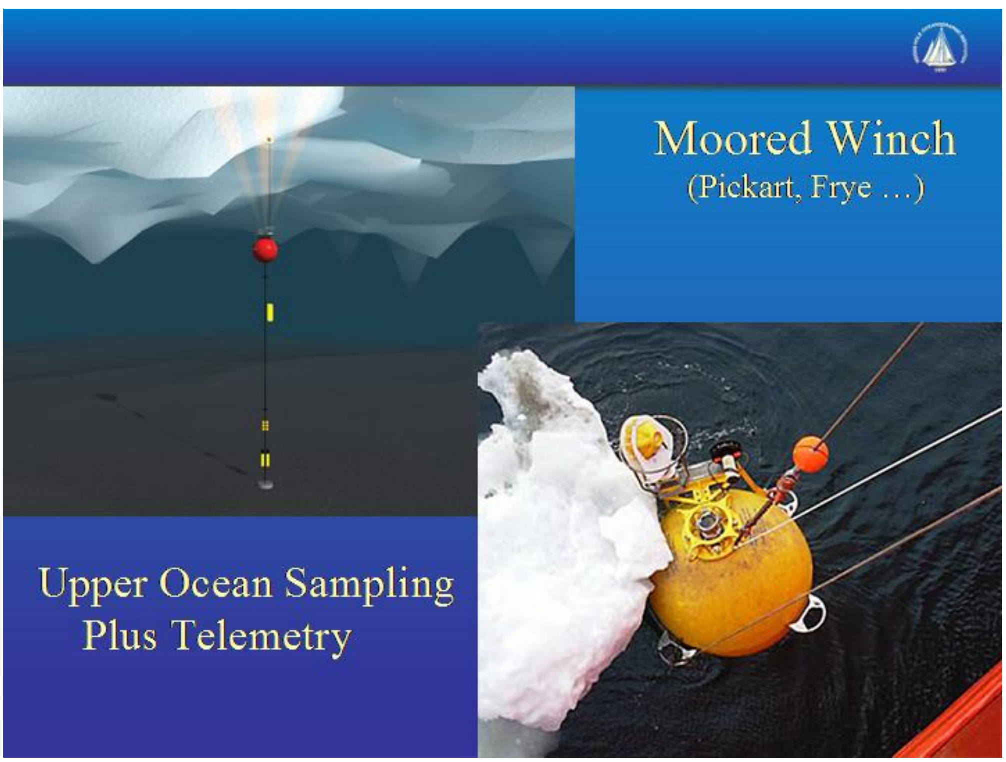
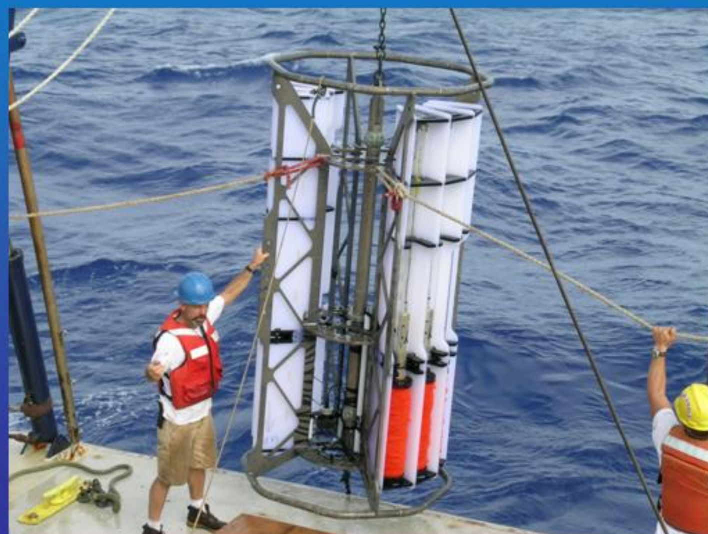


Slide 10

SALP – Submerged, Autonomous Launch Platform

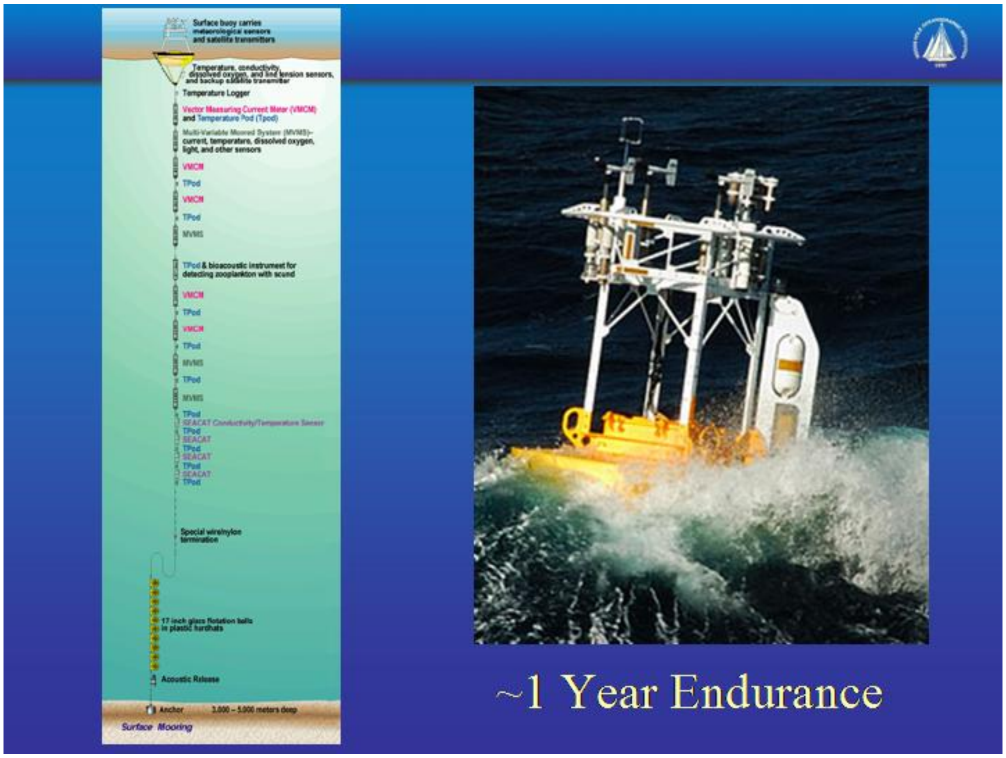


Slide 11

Observational Technologies

- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiments
- Satellites
- Radiowave Oceanography

Slide 12



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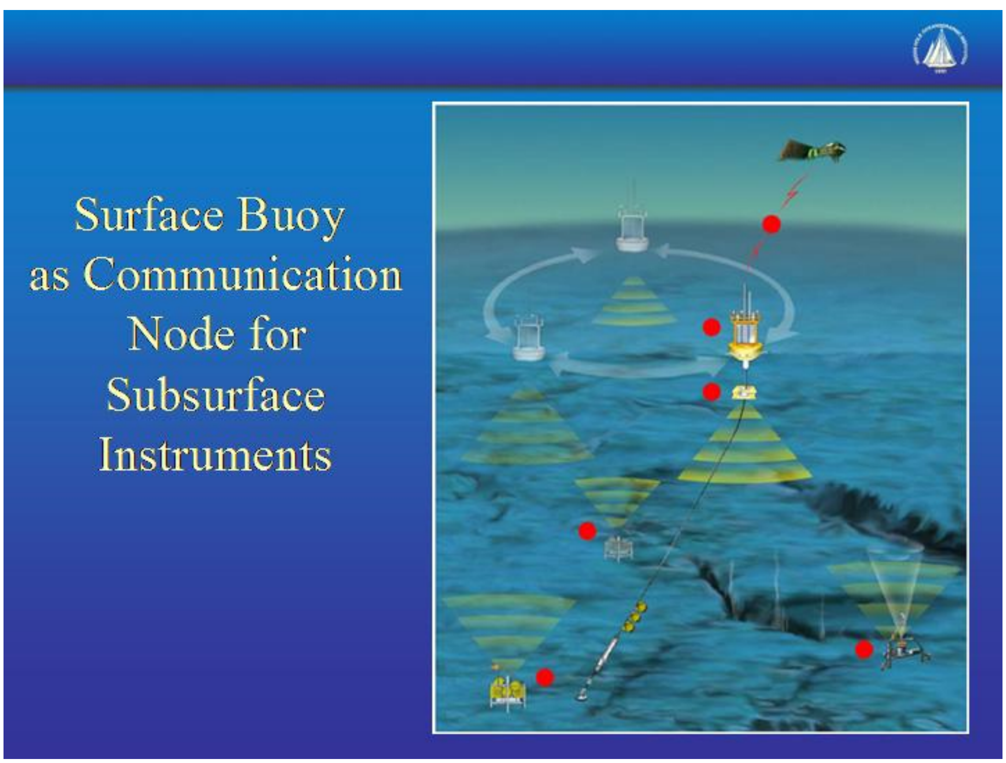


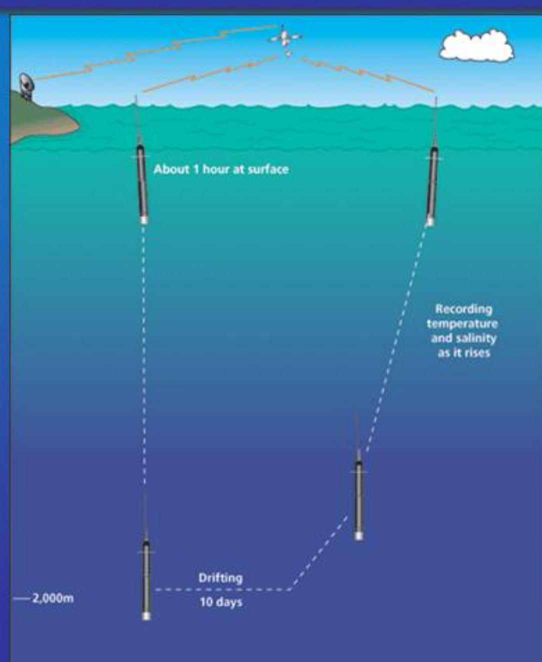
Slide 14

Observational Technologies

- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiments
- Satellites
- Radiowave Oceanography

Slide 15

Argo Float



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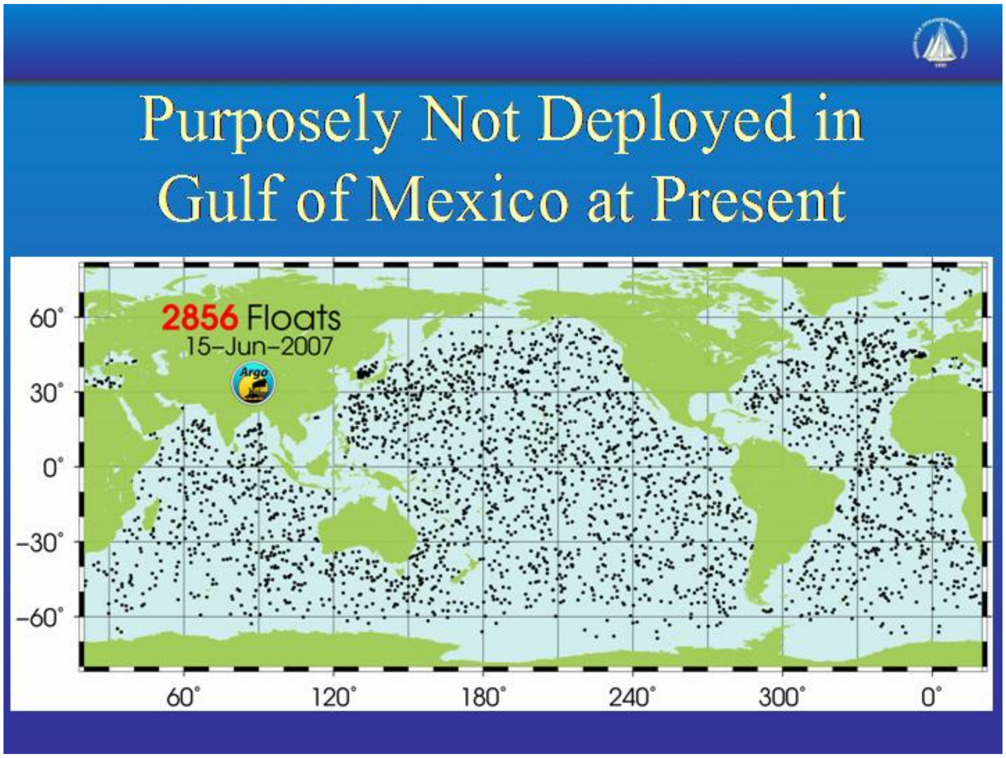

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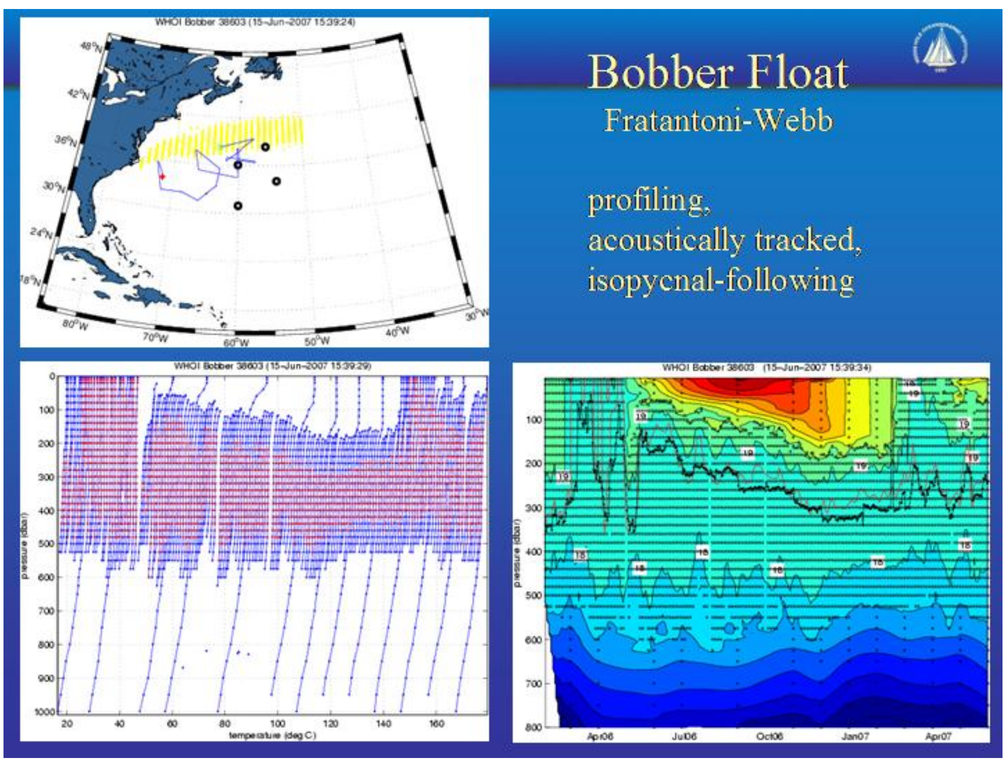


Slide 18

EM-Apex Profiling Float (Sanford-Webb)

Slide 19

Velocity Profiles Based on the Physics of Motional Electromagnetic Induction

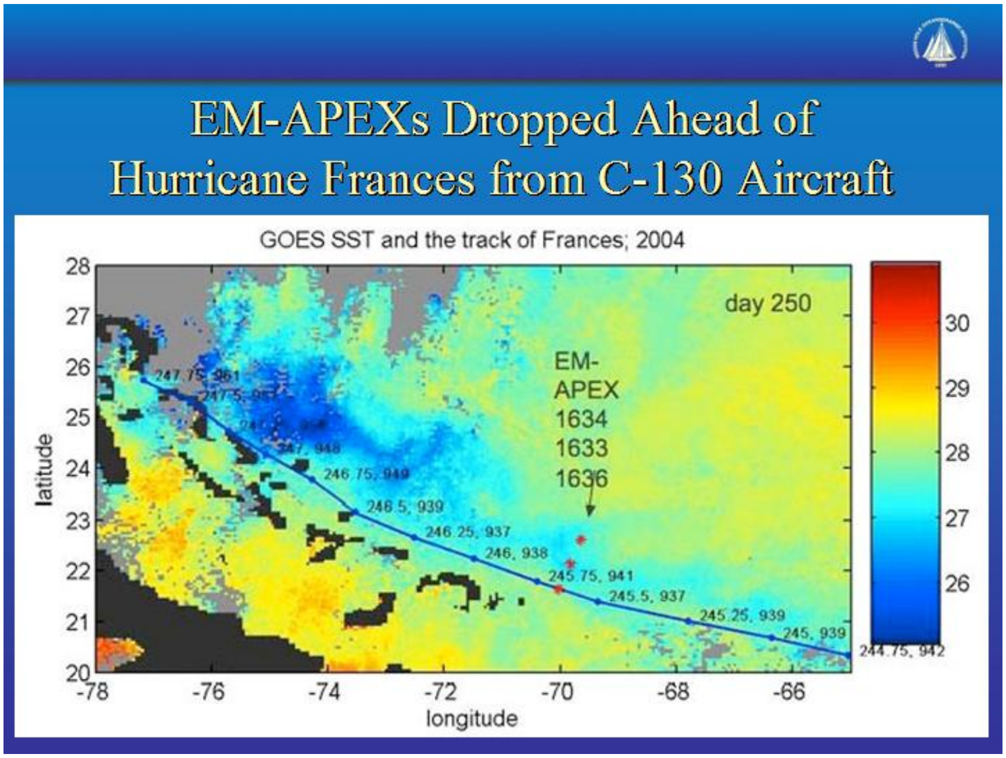
Velocity Is Measured by Motional Induction

The horizontal components of the motionally induced ocean electric field as measured by sensors moving with the horizontal flow are (Sanford 1971):

$$\nabla h\phi a \approx -Fz\,(v(z) - \overline{v^*}) \times k$$

where $\nabla h\phi a$ is the measured (apparent) potential gradient at a sensor moving with velocity v, Fz is the vertical component of the Earth's magnetic field, σ is electrical conductivity, v^* is the vertically-integrated, conductivity-weighted ocean velocity and k is the vertical unit vector. Hence the measured ocean voltage gradient can be converted to a relative velocity profile. It is important to realize that the measured velocity is relative to a depth-independent constant, not to the motion of the profiler.

Slide 20



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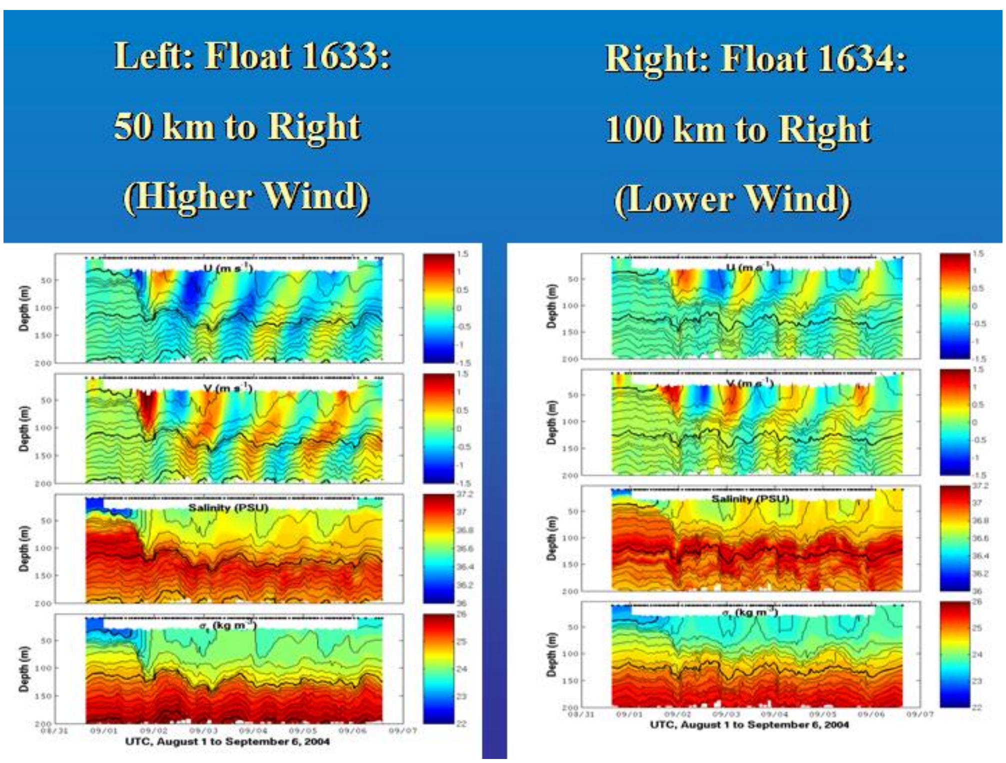

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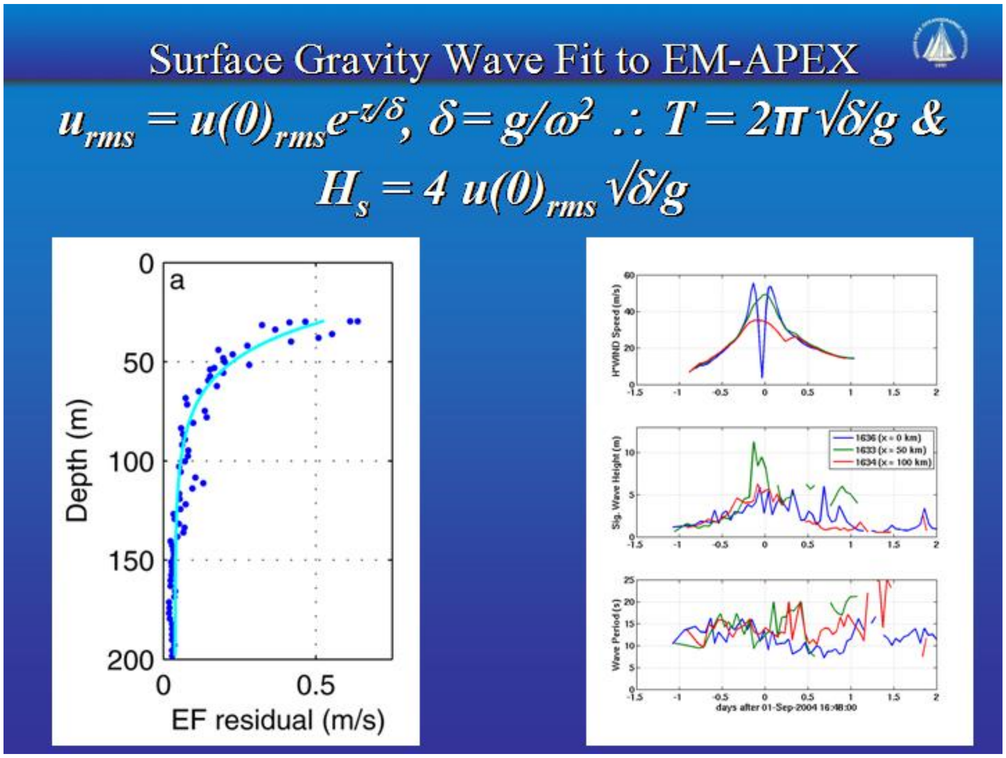

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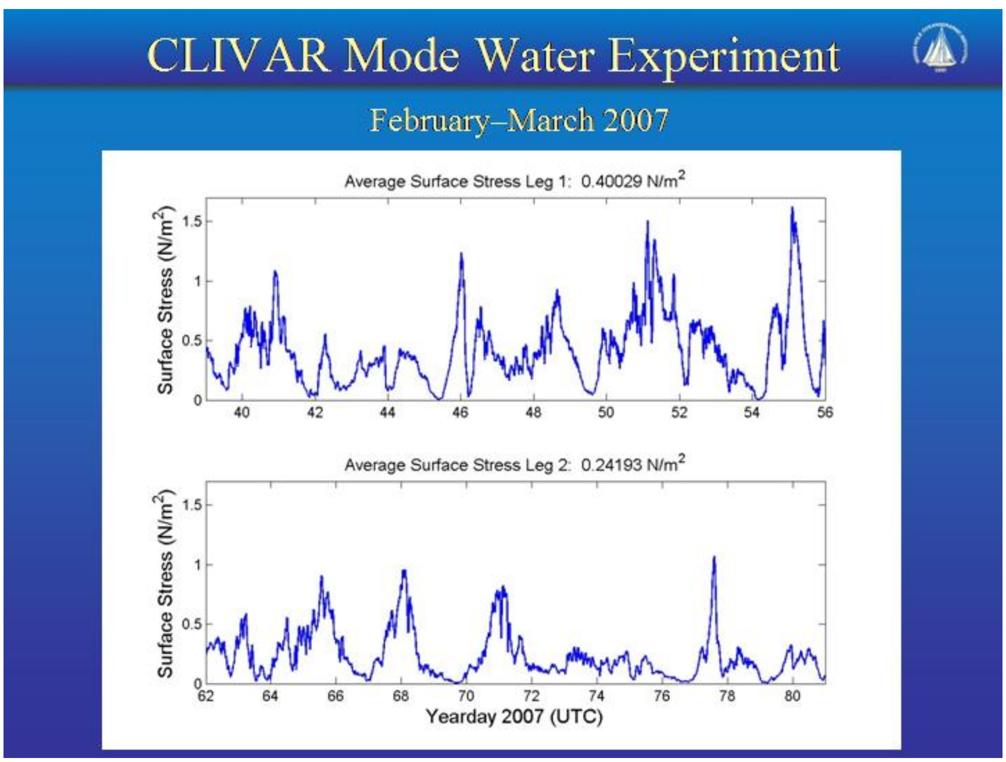

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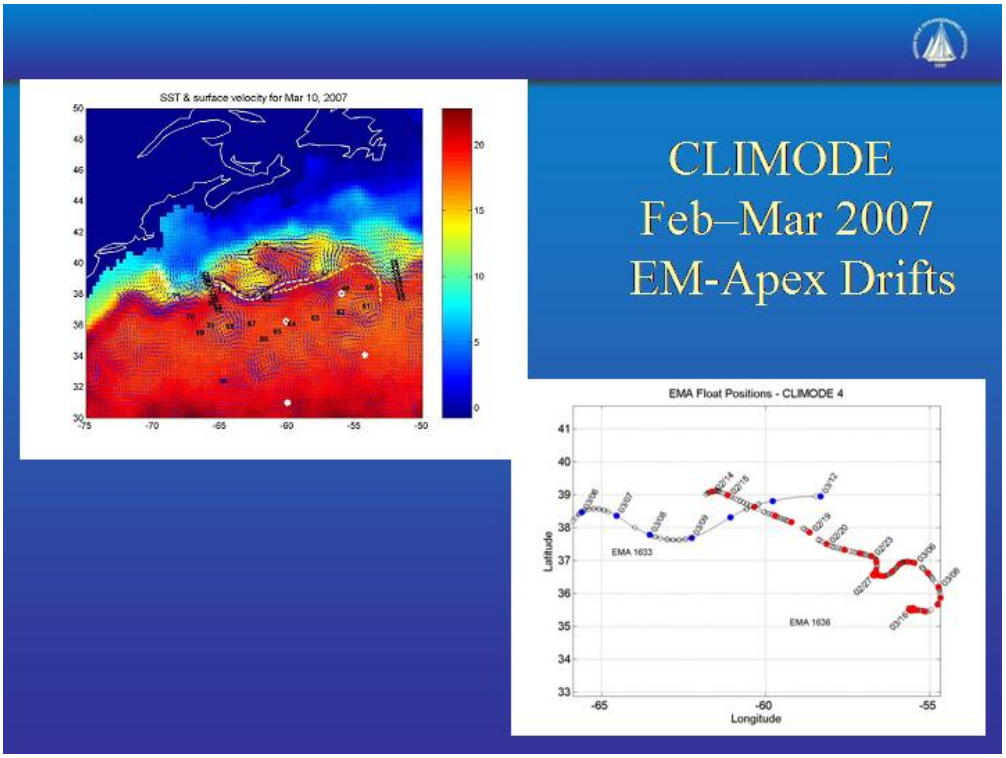

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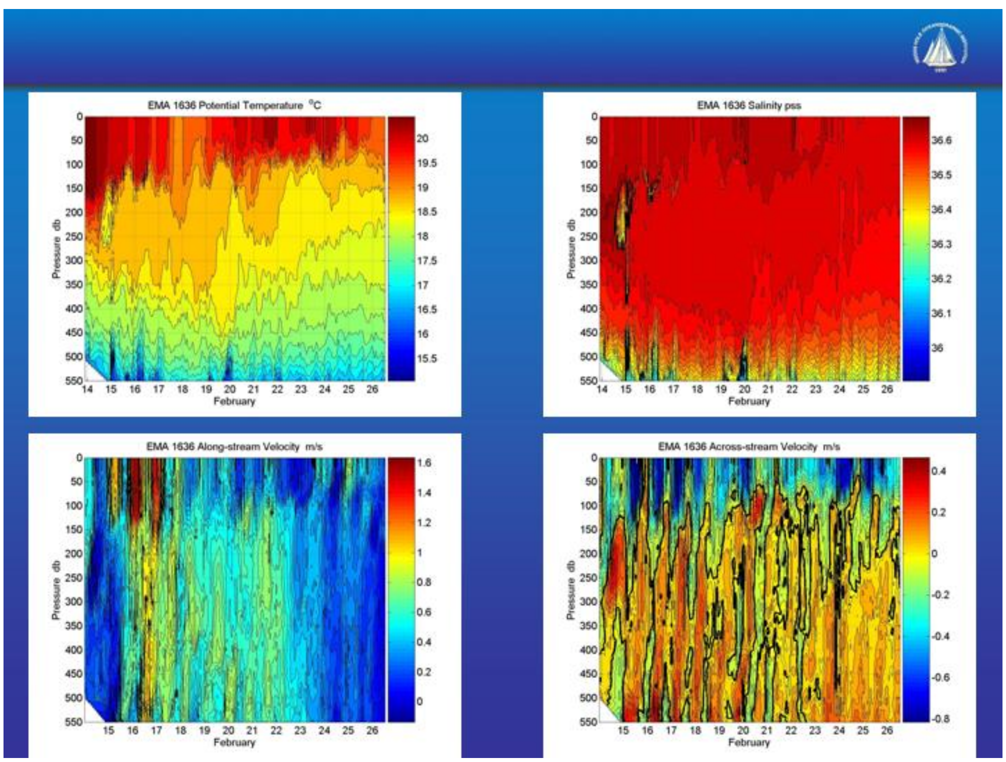

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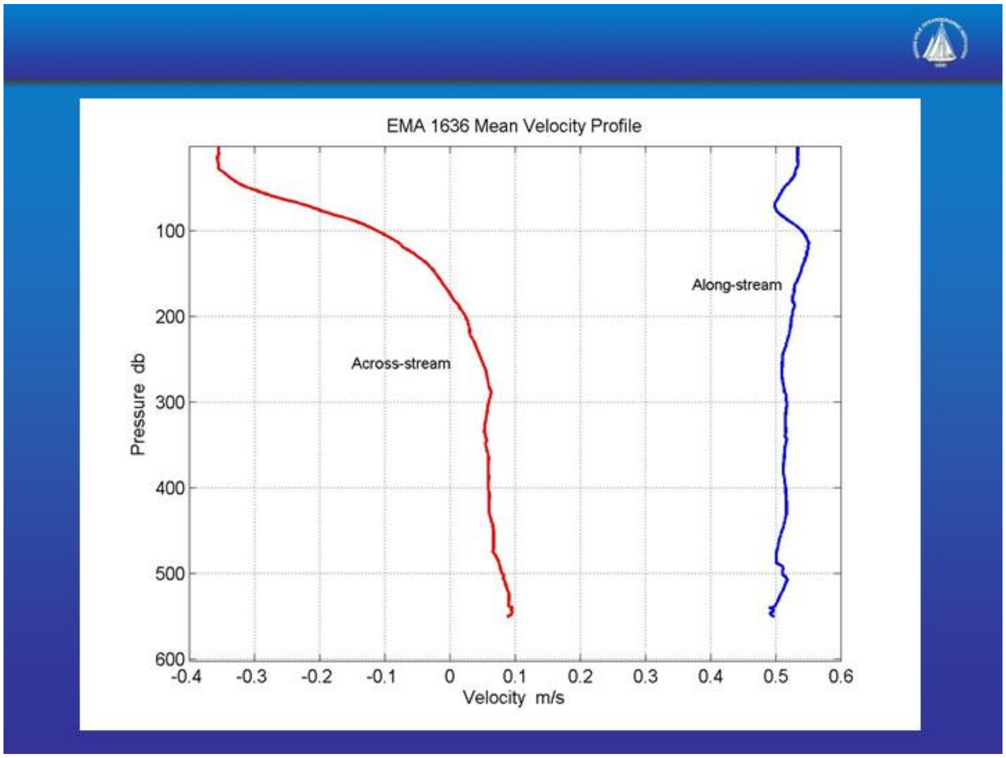


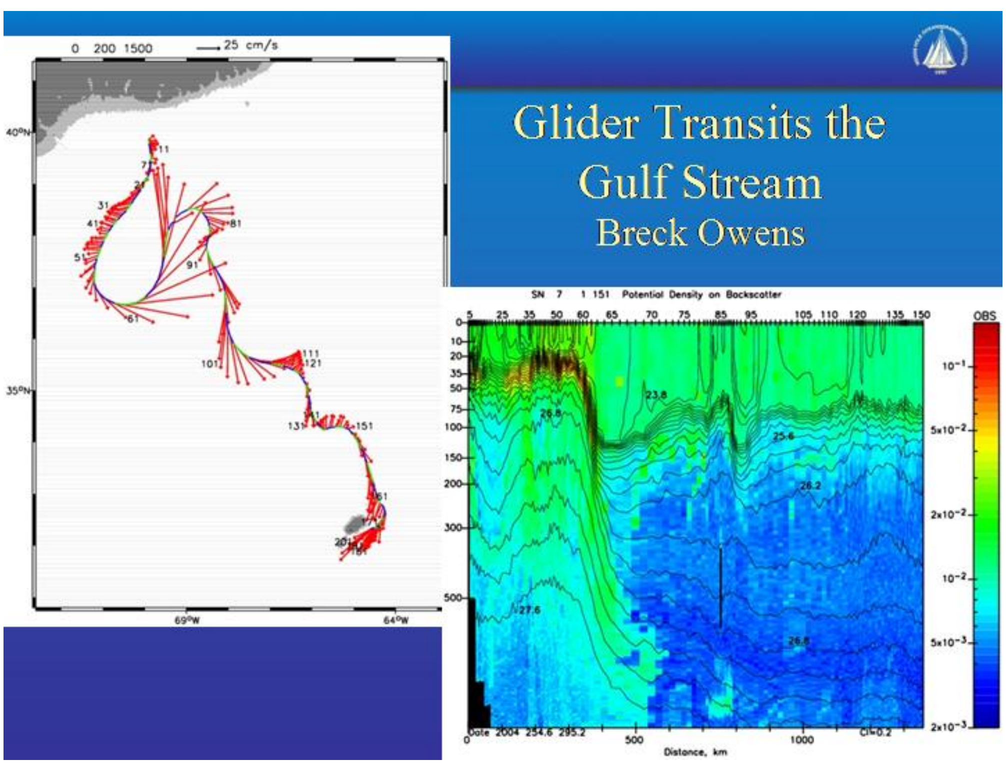
Slide 27

Observational Technologies

- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiment
- Satellites
- Radiowave Oceanography

Slide 28

Slide 29

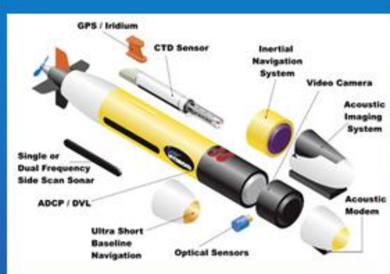


Slide 30

Observational Technologies

- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiments
- Satellites
- Radiowave Oceanography

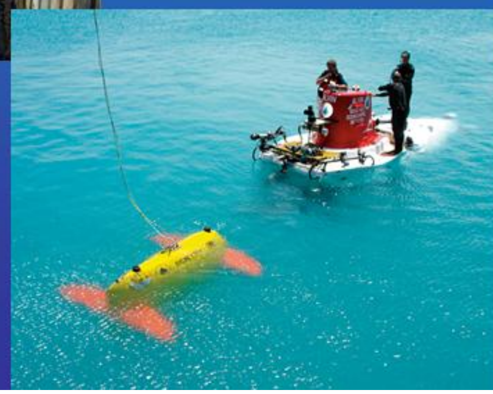
Slide 31



Fast (3–5 knots)
Limited Endurance
(hours-days)

Slide 32

ABE and Sentry



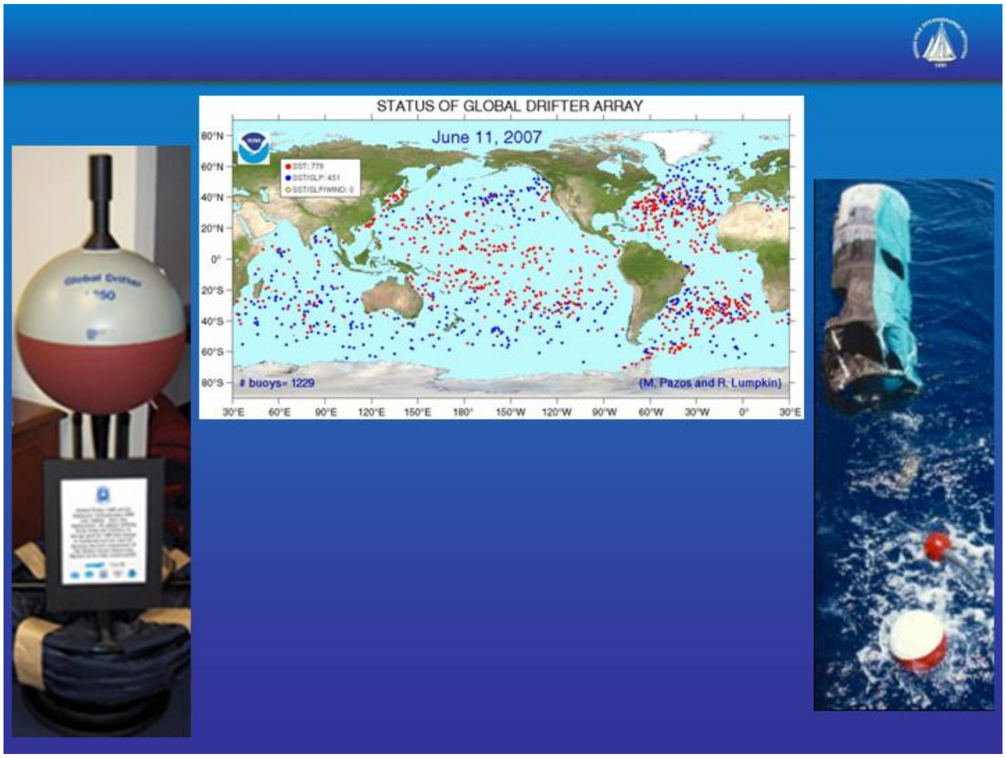
Slow: 0–1.4 Knots
20–40 km Range
Large Payload

Slide 33

Observational Technologies

- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiments
- Satellites
- Radiowave Oceanography

Slide 34



Slide 35

Observational Technologies

- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiments
- Satellites
- Radiowave Oceanography

Slide 36

Turbulence Instruments

- Full-depth profilers (free-fall)
  - Rockland Scientific
  - HRP-II
- Upper-ocean profilers (loose tethered)
  - AMP Gregg (APL/UW)
  - European companies
- Towed systems
  - Marlin (OSU)

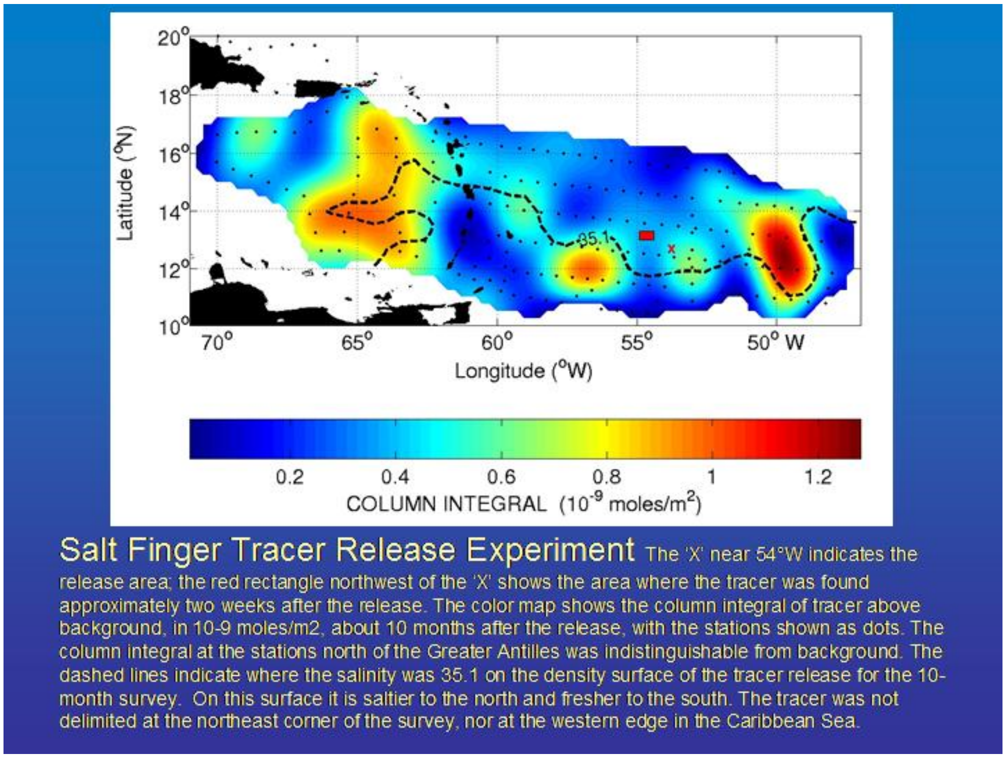
Slide 37

Tracer Release Experiments

Jim Ledwell (WHOI)

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

Slide 38



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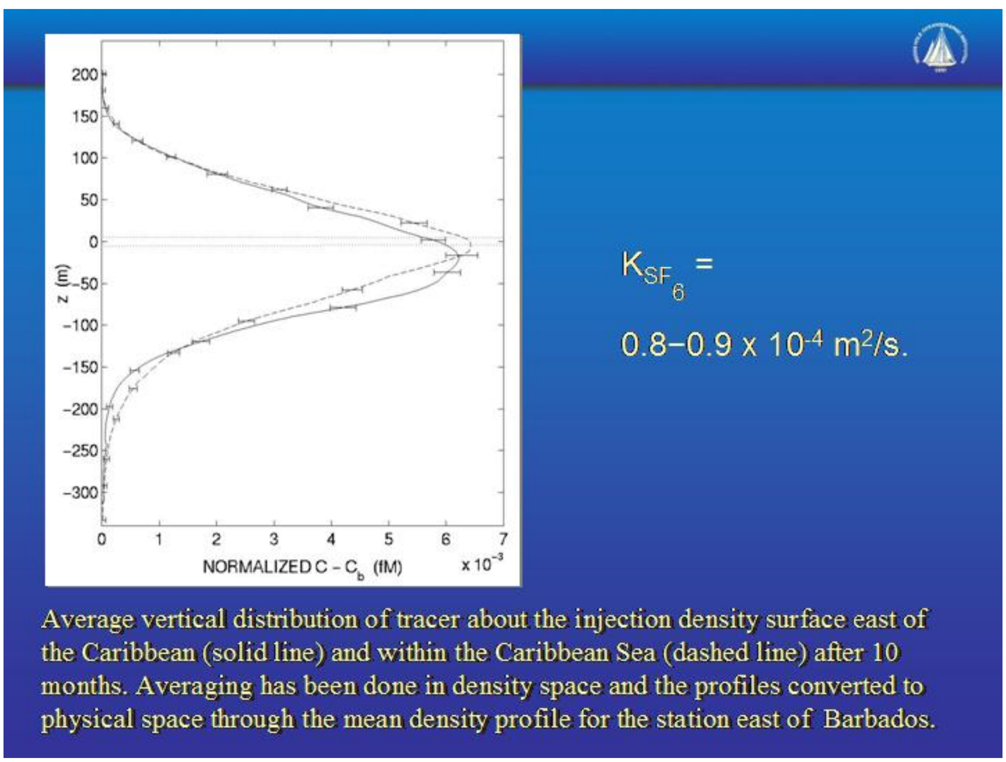
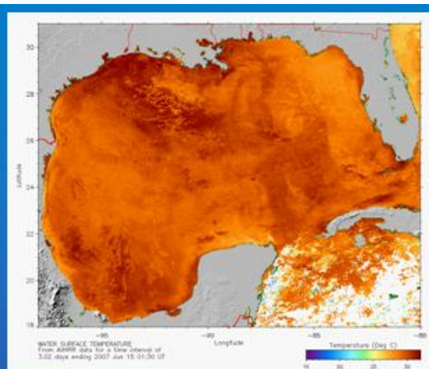


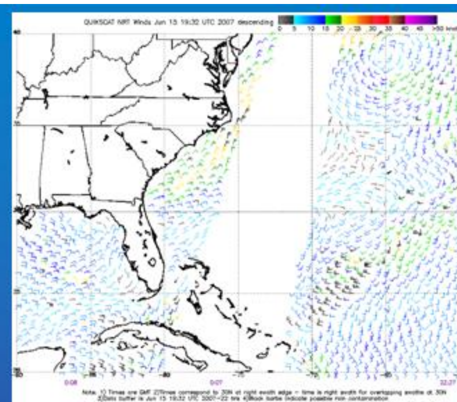
Slide 40

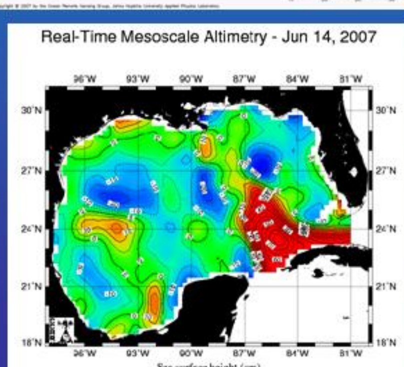
Observational Technologies

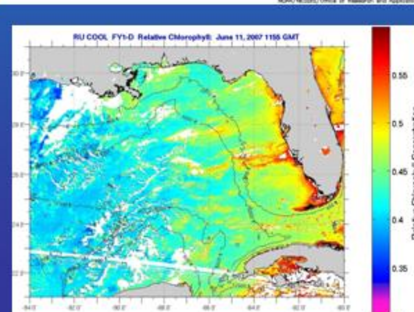
- Moorings
  - subsurface
  - surface
- Profiling Floats
- Gliders
- AUVs
- Surface Drifters
- Mixing Experiments
- Satellites
- Radiowave Oceanography

Slide 41









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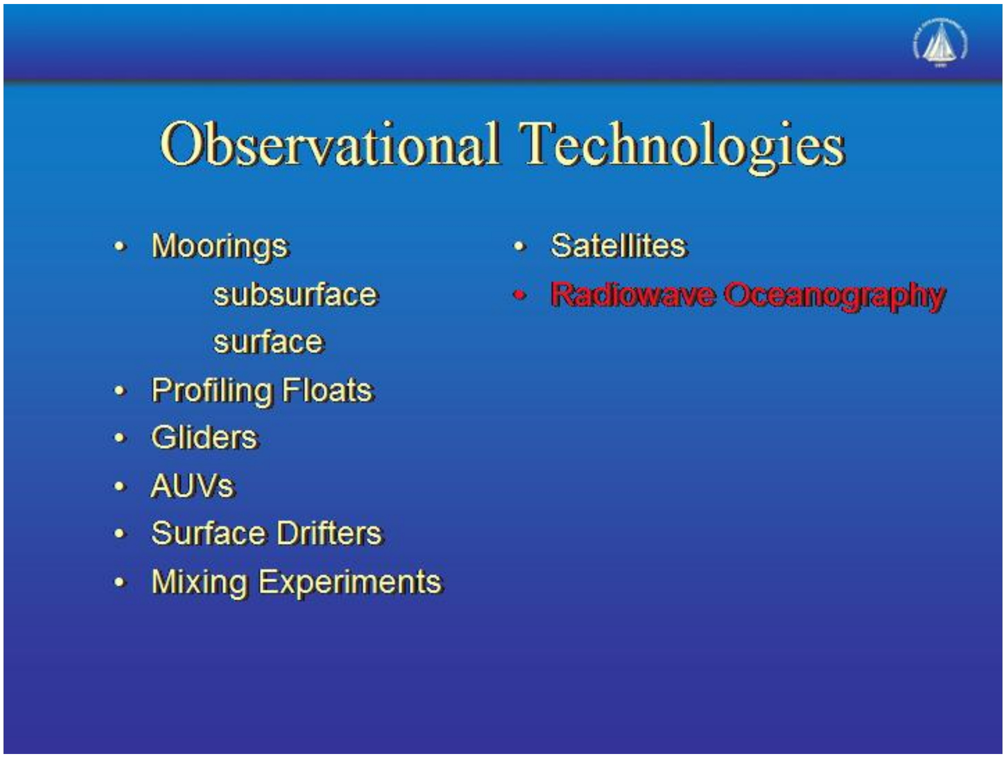

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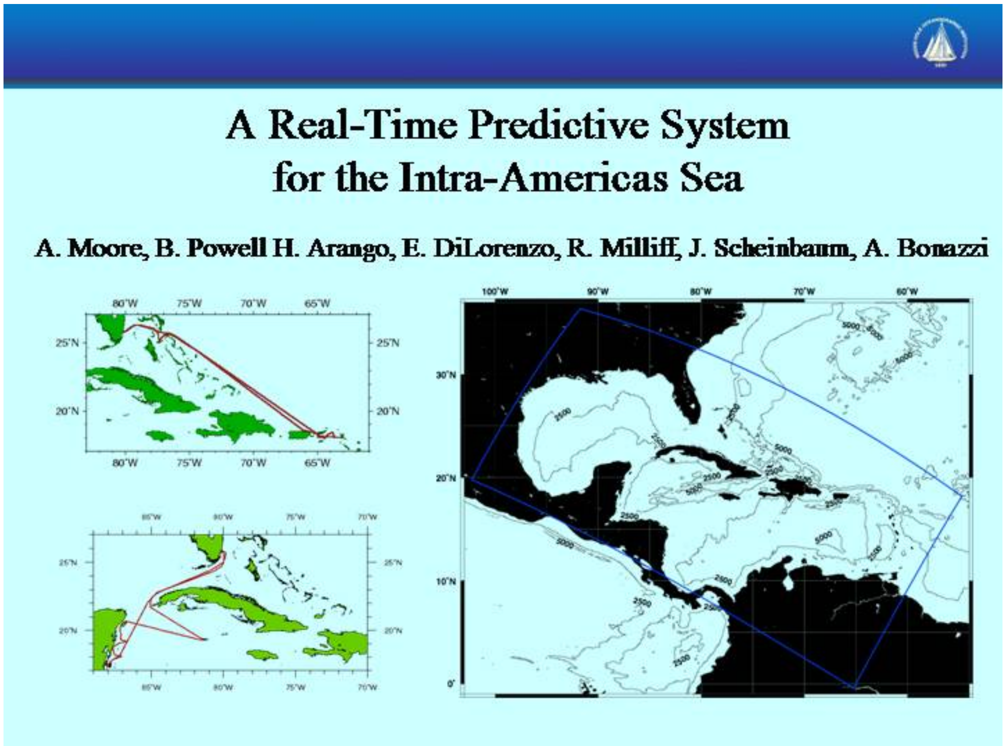

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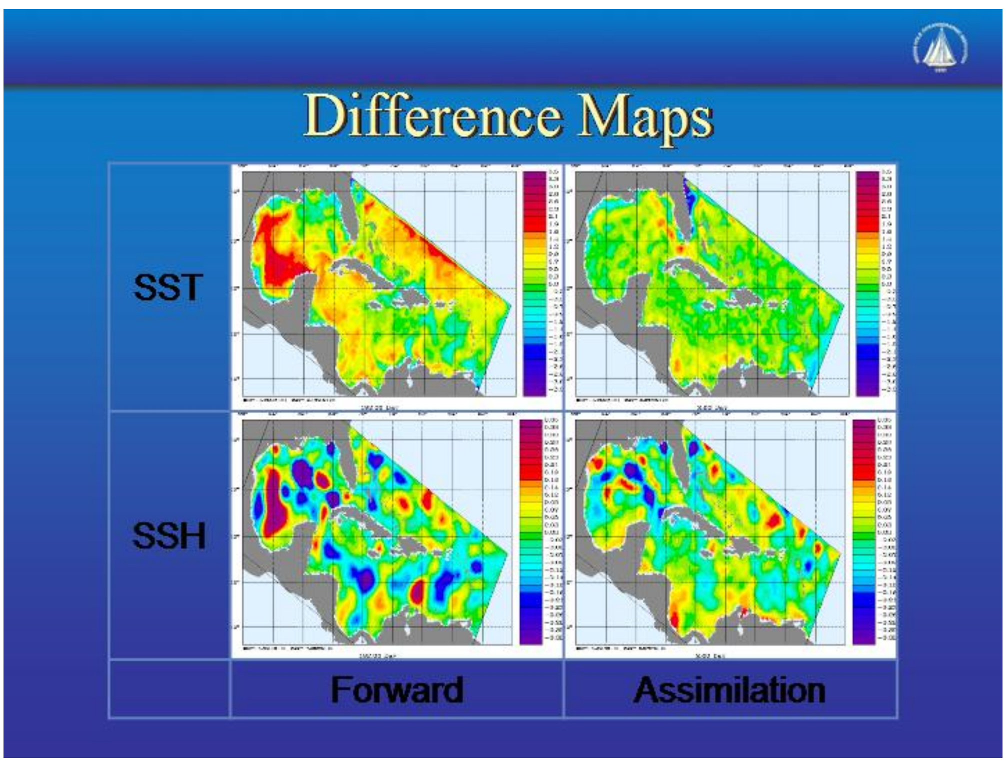

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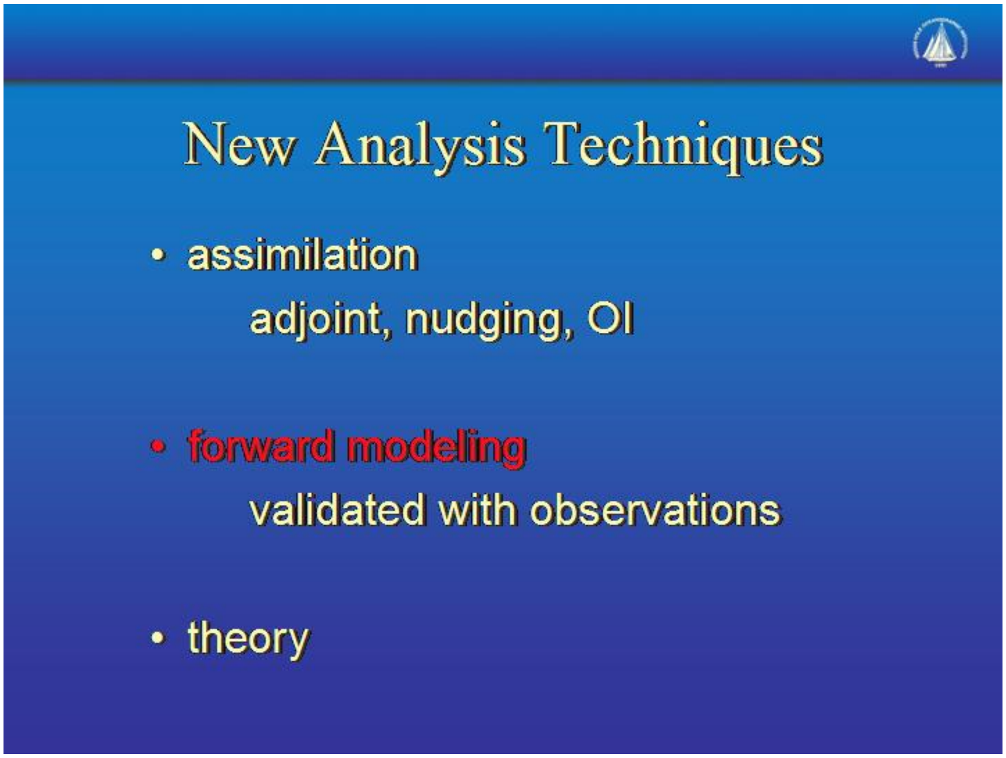

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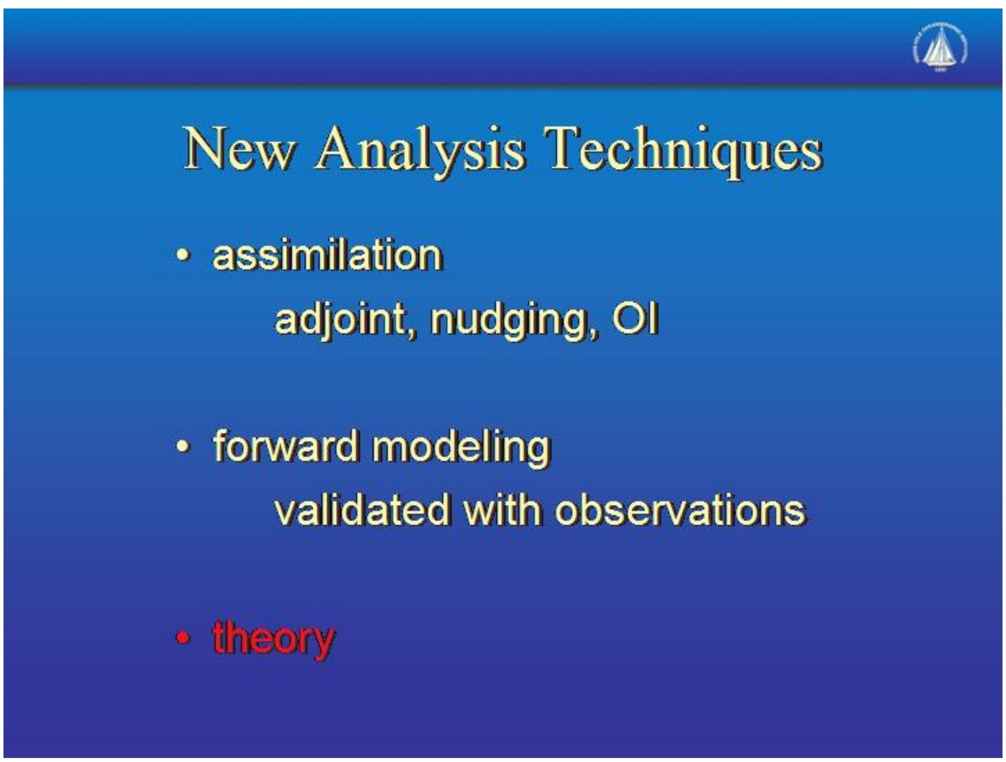

BREAKOUT SESSION SUMMARIES

The purpose of the USA-Mexico Workshop on the Deepwater Physical Oceanography of the Gulf of Mexico was (1) to determine future observational plans and needs for modeling information in USA and Mexican waters, (2) to determine future modeling plans and needs for observational information in USA and Mexican waters, and (3) to initiate intensive USA coordination with Mexico in planning and implementing future physical oceanographic modeling and data acquisition in the Gulf of Mexico. Breakout sessions were conducted to fulfill these purposes.

OBSERVATIONAL PLANS AND NEEDS FOR MODELING INFORMATION IN USA AND MEXICAN WATERS (S-1 & S-3)

Co-Chairs: Dr. Steven DiMarco, TAMU
Dr. Antonio Badan, CICESE
Rapporteur: Dr. Walter Johnson, MMS

Leading Gulf of Mexico processes of concern include the Loop Current (LC) position, transport, and stability; Loop Current Eddy (LCE; anticyclone) shedding and translation; Loop Current frontal eddy (LCFE; cyclone) dynamics; LCFE generation at (and downstream translation from) Campeche Bank; deep water general (mean) and transient (e.g., Topographic Rossby Waves (TRWs) and deep eddies) circulation; and dynamic mechanisms coupling the deep and shallow Gulf currents. While satellite radar altimetry and thermal and color imagery can serve to delineate shallow Gulf general circulation and eddy features, they are ineffective for this purpose in the lower layer of the deep Gulf. There is special interest in the response of the Gulf to extreme wind events; e.g., air-sea interaction in the upper 200 m, near-surface (upper 10 m) processes (e.g., near-inertial motions, frontal convergences, momentum transfers, heat content and fluxes, and mixing), and open ocean upwelling and turbulent entrainment. Reflecting the predominance of steep continental slopes (escarpments) in the Gulf, there is also a special interest in escarpment dynamics, including LC-topography interactions, generation of bedforms and furrow currents, and shelf/slope vertical exchanges of nutrients, biomass, heat, particles, etc. that couple biogeochemical and circulation processes through, for example, wintertime cascading of shelf waters at the shelfbreak of the Northern Gulf. With a sill depth of 1,900 m and the deepest depth reported in the range of 3,750 to 4,380 m, the flushing time and flushing processes of the deep water are open questions. For example, deep ventilation of the water column must play a role on time scales of a year and longer, but little is known about it.

Improvements in transport estimates are needed. A fully consistent set of simultaneous estimates of volume transport through the Yucatan Channel and Straits of Florida (Key West to Havana, Old Bahamas Channel, Northeast Providence Channel, and West Palm Beach to Settlement Point, Bahamas) does not exist. Considering the nature of the variability, several-year time series of de-tided daily values and a careful design of the sampling grid are needed. In particular, CICESE colleagues may be able to help access Cuban waters, which would greatly facilitate these transport balance studies.

Influences on the LC and LCE shedding process from perturbations in the Cayman Basin circulation, or further upstream in the IAS, are of interest.

The impact of strong storms on the open Gulf, including the LC and LCEs, as well as coastal waters, is of great scientific interest and practical consequence to the offshore industry in planning evacuations from its moored platforms. This topic requires attention to the upper ocean heat content and wave field, as well as surface winds and currents and their variation in space and time. The generation and vertical and horizontal propagation of near-inertial motions in the presence of the LC and warm and cool core eddies and their interactions are significant. Storm intensification over warm core eddies can be important. These transient, submesoscale processes present space-time resolution challenges for both observationalists and modelers. These challenges can only be met by a comprehensive approach, including air-deployable sensing systems, airborne remote sensing, moored and drifiting buoys with ADCPs, thermistor strings, etc. NOAA (NWS & OAR), Navy, environmental companies, and academia have much of the required infrastructure; however, better coordination among these groups is needed.

A good example of improved coordination is the spatial array of real-time reporting ADCPs attached to dozens of oil rigs in the Northern Gulf fostered by MMS, with the data management provided by NDBC and cooperation from the offshore industry.

Another example is the present effort to coordinate MMS and PEMEX observational programs across the deep Gulf, including moored current meter and PICES arrays and hydrographic (CTD) transects. There is also hope for collaboration between American and Mexican circulation modelers. And there is hope that the Gulf of Mexico Coastal Ocean Observing System Regional Association (GCOOS-RA) and the Southeast Coastal Ocean Observing Regional Association (SECOORA), both regional coastal ocean components of the USA's Integrated Ocean Observing System (IOOS), will become coordinated and work with Mexican and other adjacent entities in the Caribbean Sea.

PEMEX is conducting studies of Campeche Sound where surface drifters have found cyclones with current speeds of 100 cm/s and other currents up to 100 to 150 cm/s. PEMEX is also conducting studies of Campeche Bank where an ultra-deep cyclone has been found propagating to the west. PEMEX is pursuing exploratory studies on the Western Gulf Shelf with a large number of moorings and needs to coordinate with USA, including for acoustic sources used for tracking floats in deep water. The long-term moorings need to be maintained for 5 to 10 years for stable statistics. Mobile moorings are used for exploratory purposes. USA-Mexican collaboration could include coordination of hydrographic transects and moorings.

An LSU group (*viz*., Inoue, Welsh, and Rouse) is maintaining a long-term current meter mooring under the LC. Their results will help design and interpret future studies in the Northern Gulf.

Coastal HF radars have proven to be useful for estimating synoptic maps of surface currents in the coastal ocean, especially within the IOOS program. There is potential for extending their use to offshore platforms, which would require cooperation with the offshore industry and various agencies.

There is no other observational subsystem more important for estimating the space-time evolving quasi-geostrophic circulation of the LC, LCE, etc. than the satellite radar altimeters. Hence, support of the satellite altimeter constellation should be shown by the ocean community at every opportunity.

The Gulf of Mexico modeling strategy should include utilization of an (atmospheric) mesoscale meteorological model, wind-current interactions in momentum flux estimates, and independent observations for heat and moisture fluxes to validate and verify model estimates of these fluxes.

Physical-biological interactions of significance in the Gulf of Mexico include open ocean and coastal upwelling, the impact of near-bottom currents on benthic communities, and the affinity of whales for cyclonic eddies in the Western Gulf.

Highest priority was given to process studies of (1) eddies and fronts, (2) lower layer circulation, (3) Loop Current, (4) upper layer circulation (including air–sea exchanges and responses to severe weather events), and (5) biogeochemical coupling.

A model-based re-analysis using the observations from 2001 to 2005 would be valuable for diagnostic studies.

The MMS NTL (Notice to Lessees) No. 2009-G02 regarding the Ocean Current Monitoring dataset has potential for further enhancement of sensor suites; e.g., adding air-sea sensors. However, there are stewardship issues to be resolved.

From a numerical modeling perspective, data from the NDBC, TABS, and COMPS buoys are valuable for forcing, verification and validation, and/or data assimilation. However, there is concern for adequate resources to support the manpower needed for analysis.

There is a need for a specific Loop Current study with the following components:

- moored sensor array deployed for mapping purposes
- deep Lagrangian floats
- gliders with CTDs (profiling from the surface to 1 km deep, and deployed for up to six months), including in the Mexican waters of the Southwestern Gulf
- AXCTDs (air-deployed CTDs)
- AXCPs (air-deployed electromagnetic profilers for measuring currents)
- surface drifters, especially for the data void in Mexican waters off the western Yucatan Peninsula

Satellite remote sensing (esp. radar altimetric SSH and SST) is a viable observing system component. Air-deployed sensing systems are invaluable for adaptive sampling of the LC, LCEs, and LCFEs. Coastal HF radars can be useful for making synoptic surface current maps for the deep Gulf, especially in the Northern Gulf with its relatively narrow shelf.

For the MMS transect study, the survey lines should extend across the Gulf with three parallel meridional lines between 88 and 91 W. The lines should be, as much as possible, perpendicular to the bottom topography. And their selection and design should be based upon the space-time-amplitude scales of the prevailing processes. The transects should be sampled with gliders and PIES. The mean and variable flow through the transects would be observed. However, the observations would not be sufficiently coherent for mapping TRWs and eddies. Yet, they could provide information about Mississippi Canyon of use to whale and other ecological studies. It is curious that NOAA's global GOOS surface drifter and ARGO profiing float observing systems aim to estimate meridional transports, yet they are missing from the Gulf.

For long-term monitoring, MMS could consider the NSF OOI concept of "Endurance" (i.e., fixed positions) and "Pioneer" (i.e., movable positions) arrays. MMS should also consider CPIES long-term stations along altimeter paths, which would constitute a sparse array. PIES arrays in the Yucatan Strait and the Straits of Florida might facilitate a transport sensitivity study.

MODELING PLANS AND NEEDS FOR OBSERVATIONAL INFORMATION IN USA AND MEXICAN WATERS (S-2 & S-4)

Co-Chairs: Dr. Robert Weisberg, USF
Dr. Julio Sheinbaum, CICESE
Rapporteur: Dr. Carole Current, MMS

Fundamental Questions

The first task was to identify the physical oceanographic questions that should be addressed to meet the implicit objectives of breakout sessions S-2 and S-4. These objectives were to formulate modeling plans and address and prioritize needs for observational information in USA and Mexican waters.

Although many possible questions were considered, the most necessary questions were determined by identifying and prioritizing crucial information gaps in Gulf of Mexico physical oceanography.

Three major physical oceanographic questions (Table 1) that remain substantially unanswered in the Gulf of Mexico were identified.

Table 1. Major Scientific Questions

- What controls the Loop Current evolution and eddy shedding processes in the Gulf of Mexico?
- What are the energy cascades from the Loop Current and its eddies to other motions: TRWs, vortices, subsurface jets, and other ocean processes, including the fluxes of energy through and the dissipation of energy within the Gulf of Mexico?
- Is there a deep, coherent mean ocean circulation in the Gulf of Mexico?

Processes that control the growth and penetration of the Loop Current in the Gulf of Mexico, as well as those governing eddy shedding frequency and location, remain uncertain at present. The Loop Current and associated Loop Current Eddies are a source of tremendous energy within the Gulf of Mexico, and the processes such as Topographic Rossby Waves (TRWs), vortices, subsurface jets, and other ocean processes by which this energy moves through the Gulf and eventually dissipates need further investigation. Evidence indicates that a deep mean cyclonic (or anticlockwise) flow exists at 2,000 m depth around the perimeter of the Gulf (Sturges et al. 2004).

However, the mean flow is not known throughout the deep Gulf of Mexico at most depths. Future Gulf deep ocean observations should determine whether or not a deep, coherent mean ocean circulation exists.

The modeling program formulated to deal with the questions of Table 1 is discussed in the next section, Modeling Program. Observations needed in support of this modeling program are discussed in the final section, Observations in Support of Models.

Modeling Program

Modeling plans for USA and Mexican waters that are designed to answer the questions presented in Table 1 were discussed and formulated. Elements of the modeling program that emerged are listed in Table 2 and described and discussed in this section.

A modeling program that is *conjoined* with a data acquisition effort in a unified modeling and observational program can be established and operated using the best available observational database relative to a given period of time. **Modeling and observational studies should be done simultaneously and cooperatively to improve modeling results.** Although conjoined modeling and data acquisition efforts are recommended, it is with full knowledge that this interaction is not always easy.

Table 2. Attributes of Modeling Program

- The modeling program should be conjoined with the observational program.
- The modeling component should encourage the exercise of several different model frameworks (models and data assimilation schemes) and modeling groups.
- Models all require diagnostic analysis to define the kinematics, dynamics, and energetics of the eddy shedding processes and the energy dissipation within the Gulf of Mexico; i.e., how do the models themselves work and what do they tell us?
- Model-observation and model-model comparisons should be performed, including the development of appropriate metrics on which to base these comparisons.
- Model-observation comparisons should include process diagnoses as model validations.

About 20 different numerical models are presently available that have been adapted for simulation of circulation within the Gulf of Mexico, although simulations by some, such as the Princeton Ocean Model (POM) (and its derivatives) and the Hybrid Community Ocean Model (HYCOM), often may be more useful than simulations by others. Some models are better adapted to certain applications than others; for example, operational models tend to be relatively simple, robust, and efficient, but may not give the best results for research purposes.

A unified circulation model of the Gulf may be developed in the long-term future, but it may be better at present to encourage three to five of the 20 models. Much is learned from differences between models, though the modelers probably differ more in their approaches than the models *per se*. Hurricane prediction depends on an ensemble of models but at the present stage of development, a solidly funded modeling base must precede any later consideration of ensemble modeling.

Models should focus on triggers of high energy events such as eddy spawning and LC intrusions. Objectives of Gulf of Mexico process modeling should include description of the kinematics and energetics of eddy shedding, as well as relevant dynamical balances. Eddy shedding processes are very relevant to the MMS mission for several reasons, including the effects of LCEs on oil and gas production in the Gulf.

The Gulf circulation may often behave as a two-layer system, and this concept can be helpful for purposes of modeling and data analyses. Modelers should examine the processes that link upper and lower layers of Gulf of Mexico ocean circulation. The interaction of these layers and energy flow between upper and lower layers is of particular interest in deep waters. Frictional dissipation of energy at the seafloor and other interactions of the deep layer with bottom topography are relevant as well.

Prediction of eddy shedding can be a challenging goal for numerical modelers. However, difficulties in determining phasing of instabilities could be addressed with assimilation of additional observational data.

Selection of model resolution is not a simple issue and should be carefully weighed. For some problems, models of eddy-resolving mesoscale resolution are preferable, and, for other problems, Topographic Rossby Wave (TRW) -resolving models, as an example, are used. Model resolution can be selected with the objective of pinpointing the correct physical processes, or it might be selected with the objective of enhancing predictability.

Physical oceanographic modeling is often dependent on the extent of observational data available in the regions to be modeled. Boundary conditions, initial conditions, forcing functions, and data assimilation all benefit from access to and usage of the best possible meteorological and physical oceanographic data available within and around the model domain. Wind speed and direction, river outflow, surface and subsurface temperature and salinity fields, satellite altimetric Sea Surface Height (SSH) and other satellite observations, surface and subsurface current speed and direction from Lagrangian drifters or Eulerian moored data, ocean current transport estimates, and wave field data can all be helpful in setting up and operating a skillful simulation of surface and subsurface ocean currents and circulation processes in the Gulf of Mexico.

A single model ensemble or multi-model ensemble approach is recommended, possibly by the four groups that are running adjoint models in the Gulf. Errors for prediction must be addressed, as well as uncertainties for interpreting observations.

Particular attention of modelers to thorough sensitivity testing is needed during this modeling program. Sensitivity testing is too often neglected or minimized, especially in data assimilation applications.

Model–observation comparisons should be performed for purposes of model validation and verification and model intercomparisons. Model output should be compared with site specific deep mooring data. The statistics ought to compare well. For example, modeled currents are often too weak when compared with field observations, a deficiency which needs to be established and dealt with in each model implementation. Large datasets that will soon be available from three recent MMS studies need to be utilized further in detailed model/data comparisons. These studies are The *Exploratory Study of Deepwater Currents in the Gulf of Mexico* (Donahue et al. 2006), the *Survey of Deepwater Currents in the Northwestern Gulf of Mexico* (Donahue et al. 2008), and the *Survey of Deepwater Currents in the Eastern Gulf of Mexico* (field work is completed and draft report is in preparation).

Metrics of comparison for modelers should guide establishment of initial conditions, boundary conditions, forcing requirements, and error estimates which will include model error estimates, observational error estimates, boundary conditions and errors, surface forcing and uncertainty estimation, and background or "first guess" estimation. The metrics needed by modelers are further discussed below.

Observations in Support of Models

Observational data from USA and Mexican waters that must be acquired in support of the modeling program described in Table 2 were discussed (Table 3).

Table 3. Attributes of Observations Needed in Support of Models

- Rely on the PEMEX and CICESE arrays to obtain a large-scale, basin-wide set of moored observations.
- Concentrate the USA full water column fixed array on the LCE shedding region.
- Plan for the use of gliders, floats, drifters, expendable profilers, etc. in addition to the usual MMS instrumentation suite to maximize 3-D, subsurface data acquisition over a variety of scales.
- Plan an adaptive sampling program to observe cyclonic/anticyclonic vortex evolution and interactions.
- Consider conducting a deep Lagrangian observational and modeling experiment.
- Archive data at the regional data center at TAMU as well as at NODC.
- Encourage agency support for improved atmospheric forcing fields through IAS meso-scale modeling.
- Encourage Mexican support for HF-radar coverage across the Yucatan Strait.
- Encourage Mexican support for the redeployent of a Yucatan Strait array.
- Ensure observations are fully 3-D because subsurface data are necessary for modeling.

Surface data are relatively easily available to modelers, but modelers also need data from throughout the water column. Subsurface data are crucial for adjoint data assimilation efforts. The Navy needs subsurface real-time data (ideally, full water column currents) for their predictive modeling. Instrumentation used in the field observation program should include floats and gliders, as well as Inverted Echo Sounders with Pressure (PIES), and current meter moorings. Data throughout the upper 60 m of the water column are especially needed to model the upper ocean response to hurricanes, cold front passages, and other storms. Technologies suggested for acquiring these storm data include moorings designed to withstand storm conditions, surface drifters, Profiling Autonomous Lagrangian Circulation Explorer (PALACE) floats, expendable current and CTD profilers (e.g., EM-APEX), and High Frequency (HF) radar. For example, HF radar-derived surface currents could be acquired from the Yucatan Peninsula by the Mexicans.

What fraction of Loop Current energy is transferred into TRWs? Overall, the amount of energy may be relatively small. This information will indicate how much of the study should be involved with TRWs.

Satellite datasets are currently used to guide adaptive data acquisition schemes. However, use of additional field observations as well as modeling can be helpful in this regard. An adaptive data acquisition/modeling program using gliders and air-deployable, expendable profilers could resolve features such as cyclones (LCFEs) that form along the frontal edges of the LC. These new technologies should be tried.

The Gulf of Mexico is a large domain for modelers, and obtaining sufficient data within this entire domain is not easy. The LC is historically under-sampled, and more field observations in the LC region are recommended. Measurements of deep cyclones of diameter <100 km are needed to improve modeling of their origins, movements, and dynamics. Field observations of shelf and deep circulation interactions would be useful to modelers. In addition, further field observations covering the deep outflow of the Gulf would be useful. Scarcity of historical data in the Southern Gulf is a problem that should be addressed in upcoming observational programs. Possibly MMS could sponsor a Southwestern Gulf of Mexico data acquisition program, in cooperation with PEMEX.

Modelers and modeling should play a role in planning data acquisition campaigns. Initialization is crucial for process modeling in the deep ocean, and this should be considered in determining the LC array locations. The array recommended by MMS (Figure 12C), if shifted slightly in location, could reveal more about upstream conditions. The array recommended by SAIC (Figure 12A), if more spread out, would allow models to more easily assimilate data indicating the position of the LC. However, modelers also would like a greater concentration of field observations in the two LC areas where deep cyclones are thought to originate. The present location of Mexican moorings (Figure 12B) and future Mexican plans for these moorings should be considered in the array design.

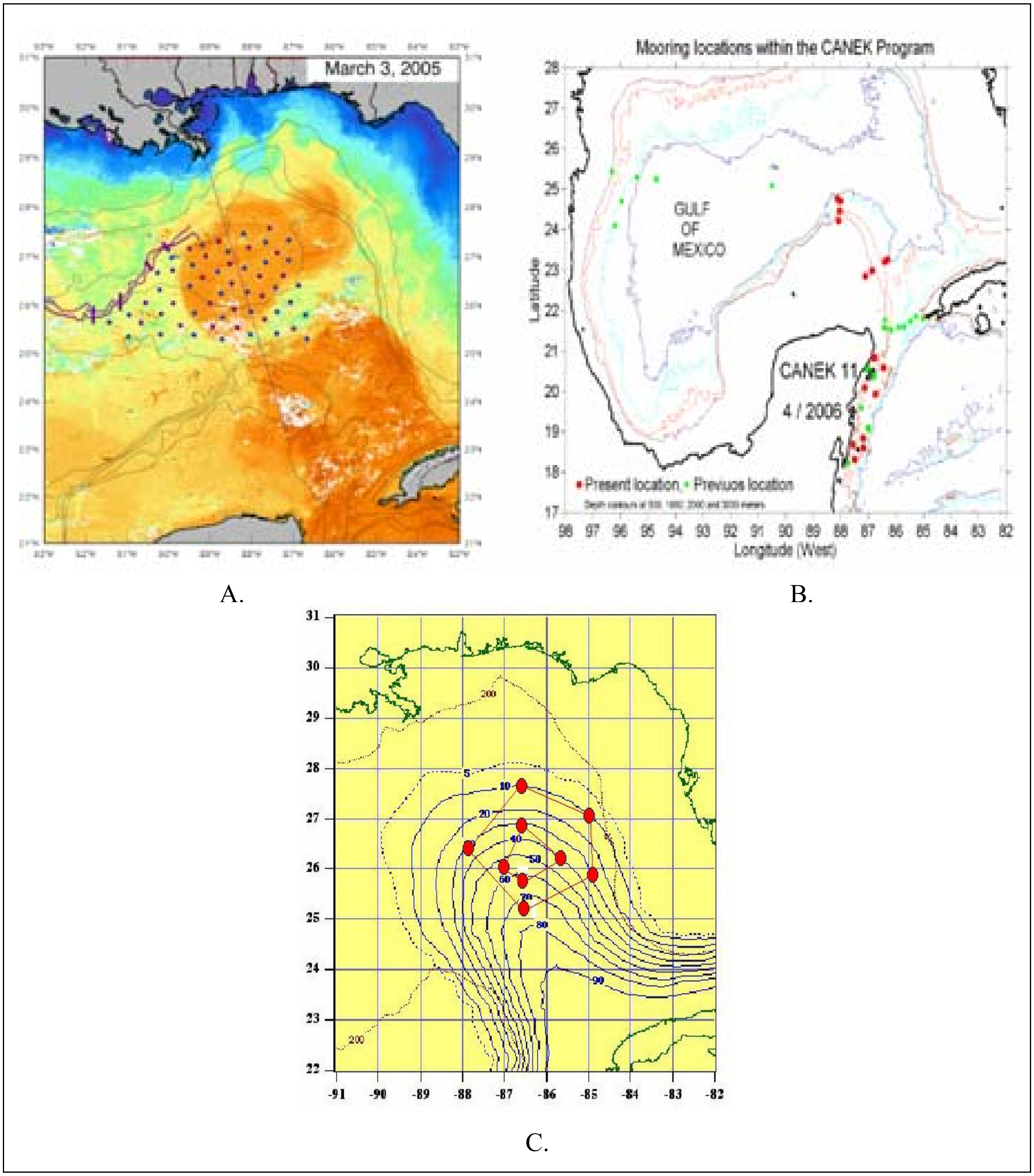

Figure 12. Observational array configurations discussed. A) Hamilton/SAIC suggested array configuration including over two dozen PIES as well as moorings. B) Some of the currently operational (red) and historical (green) locations of Mexican moorings. C) Lugo-Fernández/MMS suggested mooring array configuration.

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RECOMMENDATIONS

In addition to numerous recommendations embedded throughout this report, five salient, over-arching recommendations are articulated below:

- Progress towards fulfilling the long-term goal of establishing a synoptic analysis and retrospective re-analysis system for the Gulf of Mexico depends upon conducting rigorous skill assessments of numerical models on a continuing basis as the modeling subsystems and observing subsystems advance.

- Hence, a suite of phenomenological as well as statistical and operational metrics needs to be developed against which progress can be measured (see Appendices I & II for a start).

- To complement the satellite radar altimeters, the real-time observing subsystem needs to include (1) long-term moorings/stations; (2) CTD, etc. profiling floats and gliders; (3) deep floats; (4) surface drifters; and (5) offshore bottom pressure gauges to complement coastal tide gauges.

- Substantial and enduring progress will depend upon collaboration between USA and Mexico, observationalists and modelers, researchers and operational oceanography personnel, oceanographers and ecologists, and industry and agencies. In particular, in the USA, in addition to MMS leadership, engagement by the Navy, NOAA, NASA, NSF, and possibly EPA and USACOE is essential.

- Provision needs to be made for periodic scientific communication between American and Mexican cohorts concerned with the observing and modeling subsystems of the Gulf of Mexico.

APPENDIX I: IMPORTANT METRICS FOR GULF OF MEXICO MODEL SKILL ASSESSMENTS

General Considerations

- Include both free-running simulations and data assimilative runs.
- Include subsurface metrics, as well as metrics for surface fields.
- Conduct sensitivity studies for every adjustable parameter, including open boundary conditions, surface forcing, horizontal and vertical resolution, and turbulence closures.
- Conduct process validations as the first priority and gridded-field verifications as the second priority.

Major Processes to Be Validated

- LCE (i.e., large anticyclones/rings) statistics; e.g., pdf for eddy shedding intervals, eddy paths, eddy translational velocities, eddy sizes and strengths, and eddy decay rates and zones
- Similar statistics for upper ocean and deep ocean mesoscale cyclones and anticyclones
- General energy levels, spectra, and energy fluxes
- Near-inertial motions and their generation, propagation, dispersion, and dissipation
- Tidal energy on shelves versus deepwater
- TRW generation, propagation, dispersion, and dissipation
- Transports through Yucatan Channel and Straits of Florida, including backflows, tidal fluxes, barotropic and baroclinic components, heat and salt fluxes, water mass fluxes
- Lagrangian as well as Eulerian transports
- Vertical and horizontal structure of the LC
- Benthic mean and variable general circulation patterns

APPENDIX II: KEY OBSERVATIONAL DATA SETS AVAILABLE FOR MODEL SKILL ASSESSMENTS

1 – Current Meter Data under the Loop Current:

Inoue, M., S.E. Welsh, L.J. Rouse, Jr., and E. Weeks. 2008. Deepwater currents in the Eastern Gulf of Mexico: Observations at 25.5°N and 87°W. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2008-001. 95 pp.

2 – Loop Eddy and Loop Current Altimetry Analyses:

Donohue, K., P. Hamilton, K. Leaman, R. Leben, M. Prater, D.R.Watts, and E. Waddell. 2006. Exploratory study of deepwater currents in the Gulf of Mexico. Volume II: Technical report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2006-074. 430 pp.

McKone, K., N. D. Walker, and E. Weeks. 2007. Full-water column currents near the Sigsbee Escarpment (91-92ºW. Longitude) and relationships with the Loop Current and associated warm and cold-core eddies, U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2007-056. 107 pp.

3 – Spatial Arrays of Current Meter Data:

Donohue, K., P. Hamilton, K. Leaman, R. Leben, M. Prater, D.R.Watts, and E. Waddell. 2006. Exploratory study of deepwater currents in the Gulf of Mexico. Volume II: Technical report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2006-074. 430 pp.

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Hamilton, P., J.J. Singer, E. Waddell, and K. Donohue. 2003. Deepwater Observations in the Northern Gulf of Mexico from *In-Situ* Current Meters and PIES. Final Report. Volume II: Technical Report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2003-049. 95 pp.

McKone, K., N. D. Walker, and E. Weeks. 2007. Full-water column currents near the Sigsbee Escarpment (91–92ºW. Longitude) and relationships with the Loop Current and associated warm and cold-core eddies, U.S. Dept. of the Interior, Minerals Management

Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2007-056. 107 pp.

Sheinbaum J., A. Badan, J. Ochoa, J. Candela, D. Rivas, and J.I. González. 2007. Full water column current observations in the central Gulf of Mexico. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2007-022. xiv + 58 pp.

4 – Platform Data:

NDBC Web Site: http://www.ndbc.noaa.gov/maps/ADCP_WestGulf.shtml

5 – Lagrangain Trajectories:

Donohue, K., P. Hamilton, K. Leaman, R. Leben, M. Prater, D.R.Watts, and E. Waddell. 2006. Exploratory study of deepwater currents in the Gulf of Mexico. Volume II: Technical report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2006-074. 430 pp.

6 – Historical Data Analyses:

Nowlin, W. D., Jr., A. E. Jochens, S. F. DiMarco, R. O. Reid, and M. K. Howard. 2001. Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data: Synthesis Report. OCS Study MMS 2001-064, U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. 528 pp.

Further relevant reports can be found at:
http://www.gomr.mms.gov/homepg/regulate/environ/techsumm/rec_pubs.html
In particular, for eddy statistics, see Bob Leben's altimetric SSHA movie, Peter Hamilton's current meter and PIES data, Nan Walker's GOES imagery, and Bob Leben's altimeter data.

ACRONYMS

ADCP	Acoustic Doppler Current Profiler
ARGO	Global array of several thousand profiling floats
AXCP	Air Deployable Expendable Current Profiler
AXCTD	Air Deployable Expendable Temperature and Salinity Profiler
CICESE	Centro de Investigacion Cientifica y de Educacion Superior de Ensenada, BC
COMPS	Coastal Ocean Monitoring and Prediction System
CONACyT	Mexican National Council for Science and Technology
CPIES	PIES with a current meter
CTD	Temperature and Salinity Profiler
CU	University of Colorado
EM–APEX	Electromagnetic–Autonomous Profiling Explorer, an air-deployable, expendable velocity profiler
GCOOS-RA	Gulf of Mexico Coastal Ocean Observing System Regional Association
GOOS	Global Ocean Observing System
Gulf	Gulf of Mexico
HF	high frequency
HYCOM	Hybrid Community Ocean Model
IAS	Intra-Americas Sea (*viz.*, the combined Gulf of Mexico, Caribbean Sea, Straits of Florida, and adjacent Atlantic waters west of 55W)
IASNFS	Intra-Americas Sea Ocean Nowcast/Forecast System
IES	Inverted Echo Sounder
IOOS	USA Integrated Ocean Observing System
LC	Loop Current
LCE	Loop Current Eddy (i.e., large, deep anticyclonic “ring”)
LCFE	Loop Current Frontal Eddy (i.e., small, shallow cyclonic eddy)
LSU	Louisiana State University
MMS	Minerals Management Service
NDBC	National Data Buoy Center/NWS

NESDIS	National Environmental Satellite Data and Information Service/NOAA
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center/NESDIS
NRL	Naval Research Laboratory
NRL ONFS	Naval Research Laboratory Ocean Nowcast/Forecast System
NSF	National Science Foundation
NWS	National Weather Service/NOAA
OAR	Office of Oceanic and Atmospheric Research/NOAA
OOI	Ocean Observing Initiative/NSF
PALACE	Profiling Autonomous Lagrangian Circulation Explorer float
PEMEX	Petroleos Mexicanos (Mexico's state-owned petroleum company)
PIES	IES with bottom pressure sensor
POM	Princeton Ocean Model
PU	Princeton University
RAFOS	SOFAR spelt backwards; acoustically tracked subsurface floats
RSMAS	Rosenstiel School of Marine and Atmospheric Science, University of Miami
SAIC	Science Applications International Company
SECOORA	Southeast Coastal Ocean Observing Regional Association
SSH	Sea surface height
SST	Sea surface temperature
TABS	Texas Autonomous Buoy System
TAMU	Texas A&M University
TRW	Topographic Rossby Wave
URI	University of Rhode Island
USF	University of South Florida
WHOI	Woods Hole Oceanographic Institution

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.