Bio-Optical Response and Coupling with Physical Processes in the Lombok Strait Region

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LONG-TERM GOALS

Our overarching long term goal is to understand the coupling of bio-optical processes and properties with physical processes in ocean regions of strong physical forcing. Strong physical forcing can include several processes such as wind forcing, tidal forcing, and in the case of this project, flow through archipelagos.

In addition, we desire to understand the relationship between optical signatures and the components of the water column (e.g. sediments, phytoplankton and dissolved organic material) that create these signatures. Biological, chemical, geochemical, and geological processes contribute to these signatures.

We desire to couple these in-the-water signatures with remotely sensed ocean color such that the remotely sensed observations can be used to interpret the processes occurring in a dynamic region where in situ observations are not always possible.

OBJECTIVES

The primary goals of this study are to understand:

1. The three-dimensional distribution of inherent optical properties in the Philippine archipelago, a relatively unexplored region of the world ocean for which relatively little optical data exist.
2. The coupling of bio-optical properties with the physical processes that contribute to and result from the dynamics of flow through straits and steep topography.

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3. Relationship between the surface expression of three-dimensional ocean processes and the interior processes.
4. The contribution of dissolved and particulate matter to in-water optical properties and their effect on ocean color remote sensing.

APPROACH

Our field approach to achieving the above objectives consistent of four observational components:

1. Three-dimensional physical/bio-optical mapping is carried out in regions of the archipelago where strong physical dynamics are expected. Optical sensors are mounted on the UW-APL towed undulating Triaxus vehicle for mapping 3-dimensional distributions of inherent optical properties that should respond to the physical processes of the straits. We equipped the Triaxus with a Wetlabs ACS hyperspectral absorption/attenuation meter, a Wetlabs BB3 3-wavelength backscatter sensor, and chlorophyll and colored dissolved organic matter (CDOM) fluorometers.

2. Continuous nearsurface underway measurements of inherent optical properties are obtained from the ship's underway seawater flow system. These measurements include unfiltered and filtered absorption/attenuation measurements using either Wetlabs AC9 or ACS instruments, spectral backscatter, and particle size spectra with the LISST-100. Both this set of measurements and the underway remote sensing reflectance measurement (item 3 below) are important for interpreting remotely sensed ocean color observations.
3. Continuous ship-based measurements of "on the water" hyperspectral remote sensing reflectance was obtained with a Satlantic HyperSAS system. The HyperSAS provides high spatial and spectral resolution of remotely sensed remote sensing reflectance without atmospheric interference, which is key to linking in water optical properties distributions with remotely sensed optical signals.
4. Station based high resolution vertical profiles of physical, inherent optical, and radeiometric optical properties were obtained with a bio-optical profiler. These measurements are made in conjunction with CTD-rosette casts to provide verification and interpretation of the in situ towed observations and the remotely sensed apparent optical properties.
5. We also provided optical sensors for continuous near-surface underway measurements for the regional characterization cruise (Arnold Gordon, chief scientist) that followed the process cruise.

WORK COMPLETED

The second intensive observational period (IOP) process study of the Philippine Straits Dynamic Experiment (PHILEX) was carried out from February 6 to 22, 2009. The goal of the cruise was to observe processes that develop in response to the northeast monsoonal winds in February and build on the obsevations that we obtained in 2008. The cruise emphasized two regions (Figure 1): 1) the "triple junction"/"mixing bowl" region that we studied in 2008. This region is bounded by Mindoro, Panay and the island cluster to the west that includes Carnasa, Macaranao, and Pan de Azucar Islands. ; 2) the San Bernardino Strait that is one of two major openings to the Pacific Ocean on the eastern side of the archipelago.

Preliminary data processing has been completed, but data merging of the combined sensors from the tow vehicle needs to be completed. The data processing for the underway data has been completed. The LISST particle size analyzer had an electronic failure and did not produce data for the February 2009 cruise. Simlarly, we have limited data from the Satlantic HyperSAS underway remote sensing system. It relies on having clear skies for the downwelling irradiance and sky radiance, but frequent cloud cover hampered our ability to obtain high quality measurements.

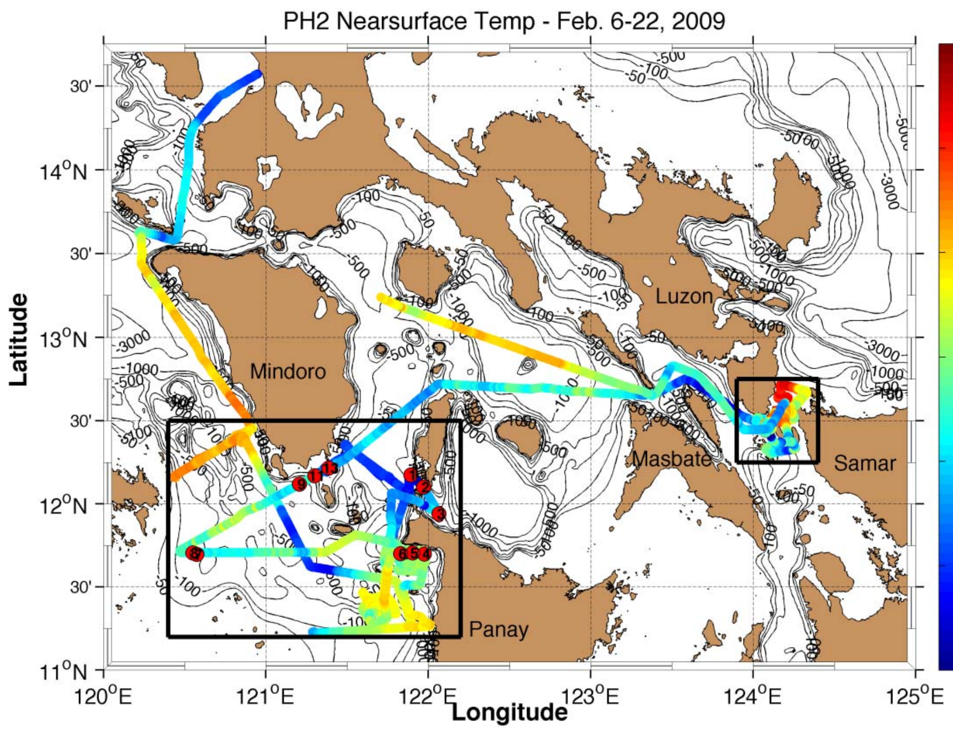

Figure 1. Map of the study region for the second intensive observational period, February 6-22, 2009. The continuous colored line is the cruise track with sea surface temperature (°C) indicated by the line color (see color scale on right). The black boxes outline the two regions of intensive Triaxus tows – the left box around the "mixing bowl"/"triple junction" area, and the right hand box around San Bernardino Strait. The red dots indicate the location of full bio-optical profiles and numbers inside the red dots indicate the station number for these profiles.

RESULTS

The Mixing Bowl / Triple Junction Region – Between Mindoro and Panay

Optical signatures are generated in regions where there is flow around the corners of islands, flows are converging, and/or there is significant coastal topography that interacts with the flow. These types of features have been observed in remotely sensed ocean color. To explore this feature from the 3-dimensional perspective, the region between Mindoro and Panay was studied with the Triaxus tow vehicle.

During February 2009 the region near the southern end of Mindoro (Figure 2) is very similar to the 2008 observations (not shown). Similar to 2008, enhanced mixing in the region is indicated by the increased salinity in the nearsurface region near the southern end of Midnoro Island. The transect that passes south of Mindoro, between Mindoro and Jintotolo Islands, where the water shallows to 39 meters, shows high concentrations of suspended particles in the surface layer of the passage extending westward and coming off the westward slope of the feature between 100 and 150 meters depth. These high suspended particle concentrations are not associated with correspondingly high chlorophyll concentrations. However, surface chlorophyll is elevated to the west and south of this region, as it was in 2008. It appears that flow through this narrow shallow feature results in significant vertical mixing of the water column that contributes to the higher chlorophyll to the west and south, and to significant resuspension of suspended particles over the shallow, narrow sill. However, these resuspended particles are not transported more than a few kilometers west of the feature.

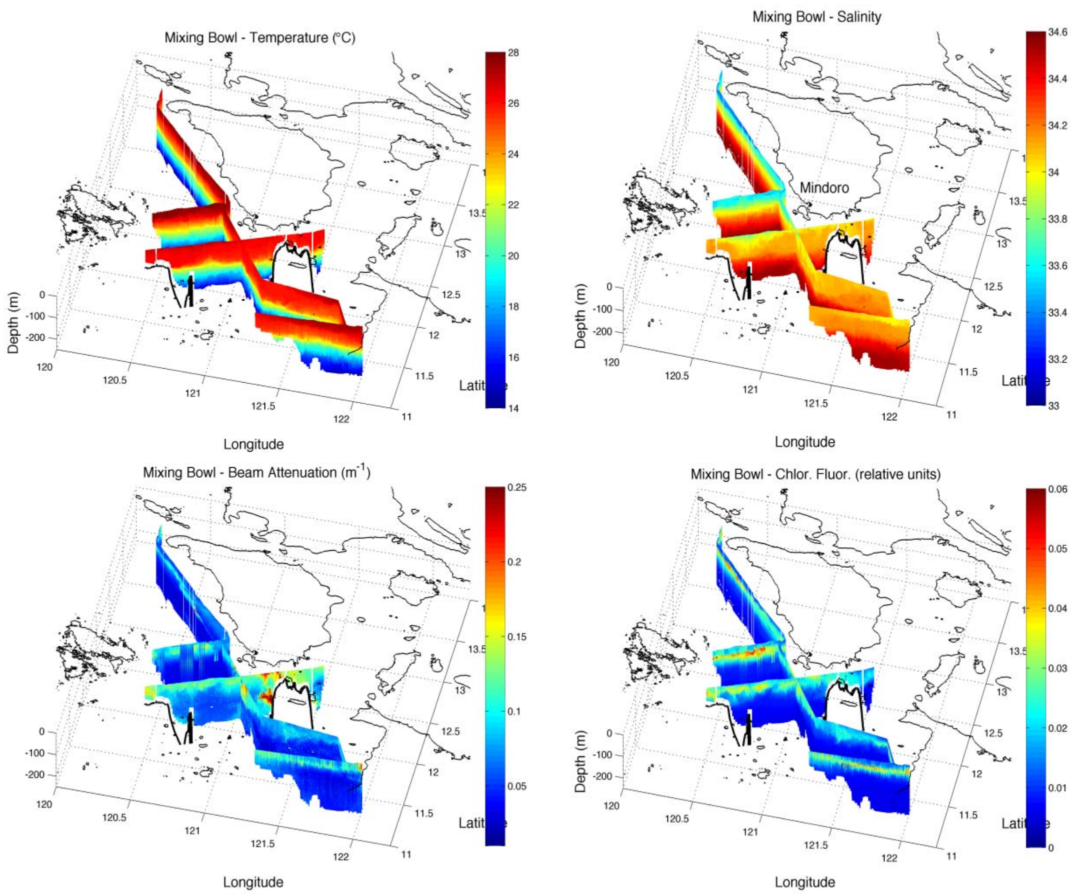

Figure 2. Curtain plots of Triaxus sections in the central mixing bowl and along the Mindoro Strait for the period of February 6-16, 2009. The panels show temperature (upper left), salinity (upper right), beam attenuation [c660] (lower left), and chlorophyll fluoresence (lower right). The lighter black lines show the coastline of the islands. The heavier black line show the bottom topography for the one transect south of Mindoro.

The San Bernardino Strait – Strong Tidal Forcing

The San Bernardino Strait region was studied over a 5-day period (February 17-21, 2009) to examine the effects of strong tidal flows through a narrow strait. Peak flows through the strait was up to 3-3.5

$m \cdot s^{-1}$. Three of the regions were mapped continuously for a 24 hour period (Figure 3). A repeated thalweg section along the axis of the strait was performed after completion of the four other regions.

As shown in Figure 4, both physical (salinity) and bio-optical variables varied considerably with tidal phase. The western part of this region consistently contains high chlorophyll as shown in the figure and also in ocean color imagery (not shown). During the ebb tide, the strong currents transport a portion of this high biomass water into the San Bernardino Strait and toward the Pacific Ocean. The strong flow result in horizontal stretching and stirring, and vertical mixing of the biology of the upper layer. Thus in order to sustain the phytoplankton (and optical signature), a supply of nutrients is required. This study has not yet resolved whether the nutrient supply is from vertical mixing of nutrient-rich deep water or runoff from land, but lack of significant CDOM in the surface layer, suggest that the source nutrient supply was from vertical mixing or transport from outside the strait rather than from runoff.

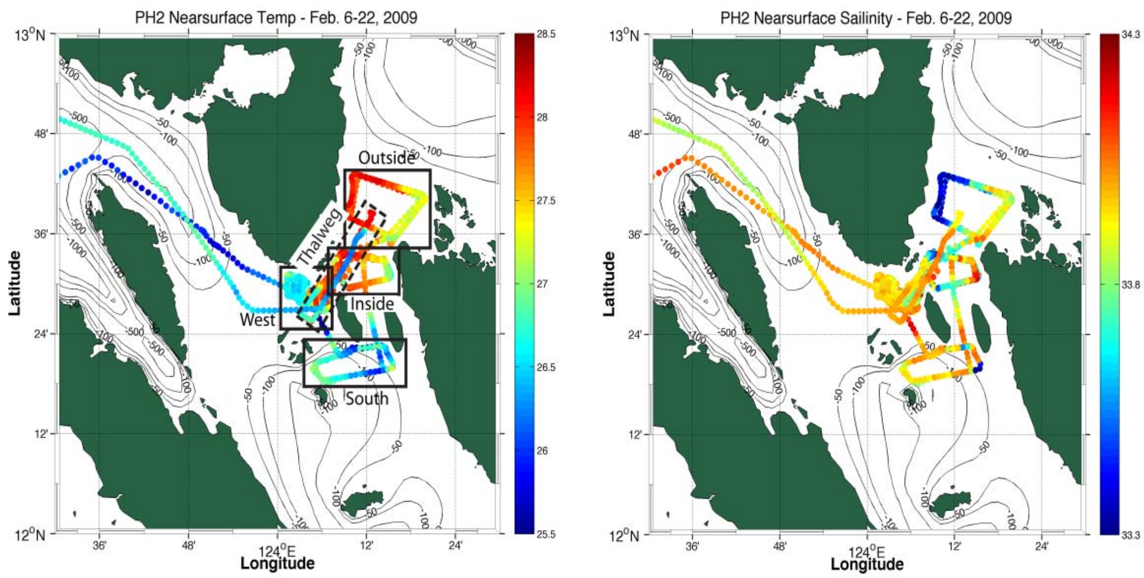

Figure 3. Cruise track in the San Bernardino Strait region. Colors along the track indicate temperature (°C – left) and salinity (right). The four black boxes in the temperature plot indicate the regions focal regions where tidally resolving studies were performed. The dashed box indicates the thalweg section that was performed along the axis of the strait.

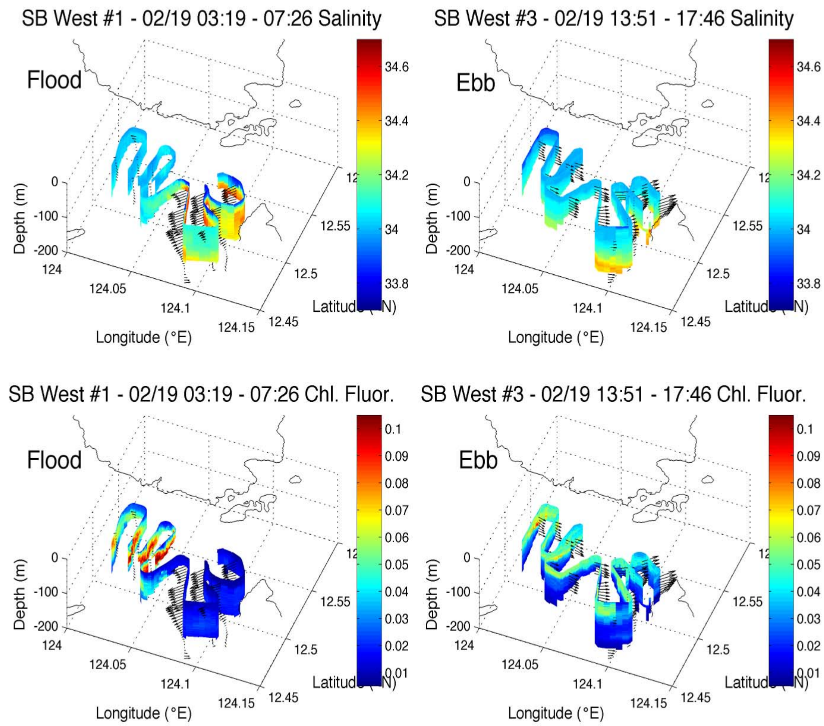

Figure 4. Salinity and chlorophyll curtain plots for the San Bernadino Strait WEST region during flood tide (left panels) and ebbing tide (right panels). The vectors are the current velocity vectors for from the ship's acoustic Doppler current profiler.

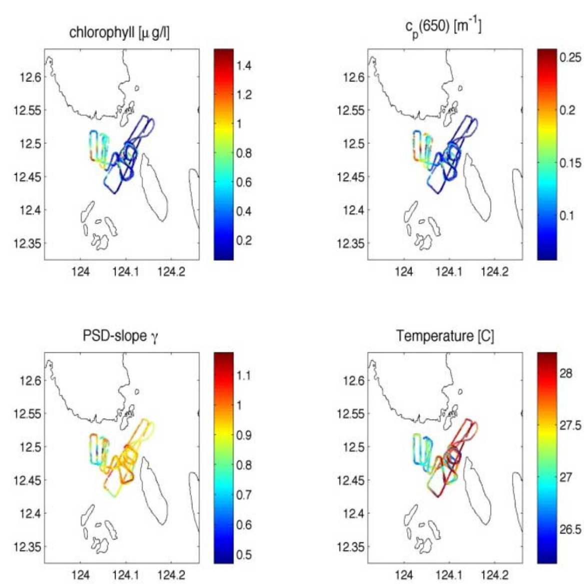

Figure 5. Surface underway measurements of optical properties and temperature for the San Berardino West and Thalweg region. The chlorophyll and beam attenuation at 650 nm ($c_p(650)$) indicate a correlation between chlorophyll and particle abundance, and the the particle size distribution (PSD-slope γ) indicates that the high particle, high chlorophyll region is composed of larger particles (smaller γ).

Analysis of the underway optical data from the San Bernardino Strait region shows the high upper layer chlorophyll concentration and the particle concentration are well correlated indicating that for this region the primary particle source near surface is the phytoplankton population (Figure 5). These phytoplankton particles are larger than the particles found northward into the strait.

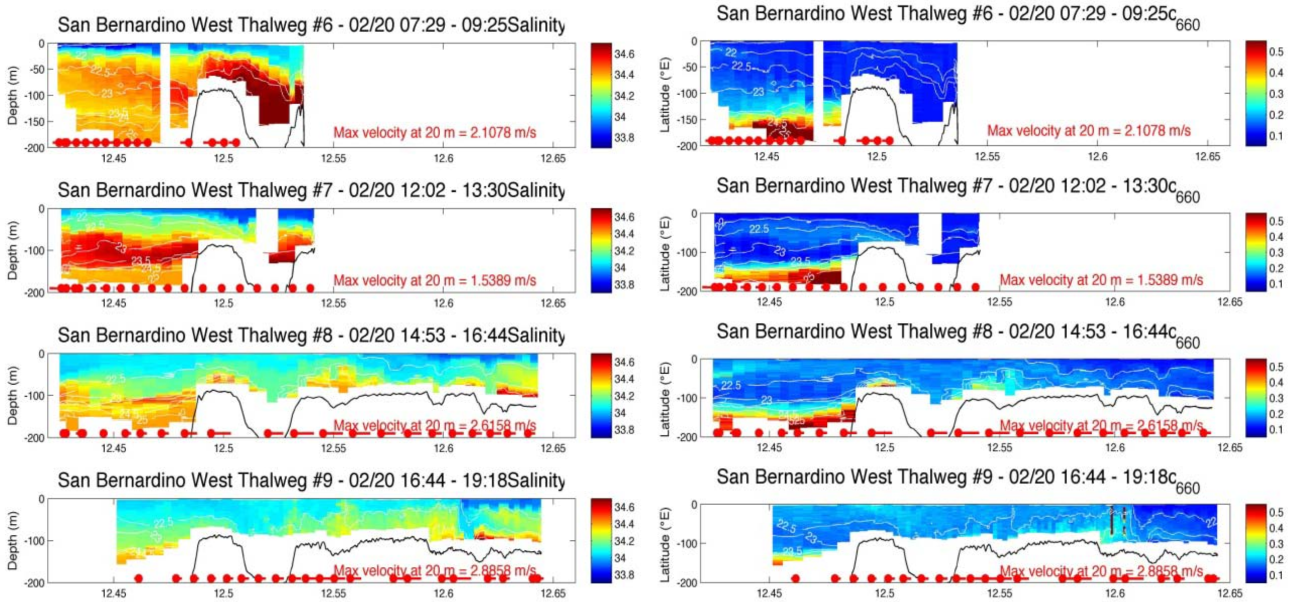

Figure 6. Thalweg sections of salinity (left) and beam attenuation (c660; right) along the axis of the San Bernardino Strait during flood (upper two panels for each variable) and ebb stages (lower two panels of each variable). The red dots with a line extending from them indicate the relative current speed and direction for the currents at 20 meters depth. The direction of the line from the dot indicates the direction of the flow. The maximum speed for each plot is indicated). The x-axis of the plot is latitude.

The thalweg study of the strait consisted of running a repeated transect through the strait for as much of the tidal cycle as possible (Figure 6). During this study, maximum tidal velocities were on the order of 3 m/s (~6 knots). During the flood portion of the study, low surface salinity, low beam attenuation (suspended particles), and low chlorophyll characterized the upper layer. On the ebbing tide, elevated chlorophyll consistent with transport of higher chlorophyll water from the West study area advected seaward and mixed uniformly throughout the upper layer. Simultaneously, deeper high salinity water and higher in suspended particles (higher beam attenuation) was advected over the sills of the channel rising to depths as shallow as 50 meters, and possibly entrained into the upper layer. During strong ebb flow (20 meter speed ~2.6 m/s) the isopleths of physical and optical variables paralleled the bottom topography, suggesting significant hydraulic control of the flow by the bottom topography.

Major conclusions from the 2009 process cruise:

1. In the Triple Junction / Mixing Bowl region between Mindoro and Panay there is a recurrent region where vertical mixing of the upper layer is enhanced and is accompanied by increased phytoplankton biomass. This region appears to receive contributions from flow through the narrow,

shallow strait south of Mindoro and from convergence of the flows from the Mindoro, Tablas, and Panay Strait regions.

2. Significant resuspension of particles occurs in the narrow passage below Mindoro. Resuspension was observed both in the shallow part of the passage and on the westward side of the feature. Resuspended particles are present all the way to the surface over the passage but sink rapidly from the upper layer westward into deeper water.
3. The rapid tidal flow through the San Bernardino Strait causes significant vertical mixing that contributes to a "steady" production of phytoplankton inside of the strait. This produces a clear remote sensing signal that is then entrained in the flow through the strait into the coastal waters beyond the strait.
4. Aspiration of deeper water occurs during the strong tidal flows through the strait where there are shallow sills in the channel. This aspiration brings deeper saltier, low oxygen, high particle water over the sill and into the upper water column.
5. During strong flow, the vertical distribution of isopycnals appears to be directly coupled with the bottom topography apparently through hydraulic control of the flow. Mixing of the surface water to the bottom of the channel was observed at the frontal boundaries.

IMPACT/APPLICATIONS

The observations from this effort will facilitate interpretation of physical processes and structure from remotely sensed ocean color in the region of the Philippine archipelago. The results will also be useful for assimilation and verification of numerical modeling efforts that include inherent optical properties, particle dynamics and transformations that occur in and around island archipelagos. The optical signatures provide insight into the stirring and mixing processes occurring within the strait regions.

This project provide a significant dataset of optical properties of the Philippine archipelago, a region with very little available data to date.

RELATED PROJECTS

We have collaborations related to this program with the following ONR principal investigators:

Mr. Robert Arnone	NRL-SSC http://www7333.nrlssc.navy.mil/
Dr. Pierre Flament	University of Hawaii http://www.satlab.hawaii.edu/users/pflament/
Dr. Arnold Gordon	Columbia University – Lamont Dougherty Earth Observatory http://www.ldeo.columbia.edu/~agordon/
Dr. Michael Gregg	University of Washington http://opd.apl.washington.edu/scistaff/bios/gregg/gregghome.html
Dr. Craig Lee	University of Washington http://iop.apl.washington.edu/
Dr. Carter Ohlman	University of California, Santa Barbara
Dr. Larry Pratt	Woods Hole Oceanographic Institution
Dr. Pierre Lermisaux	Massachusetts Institute of Technology