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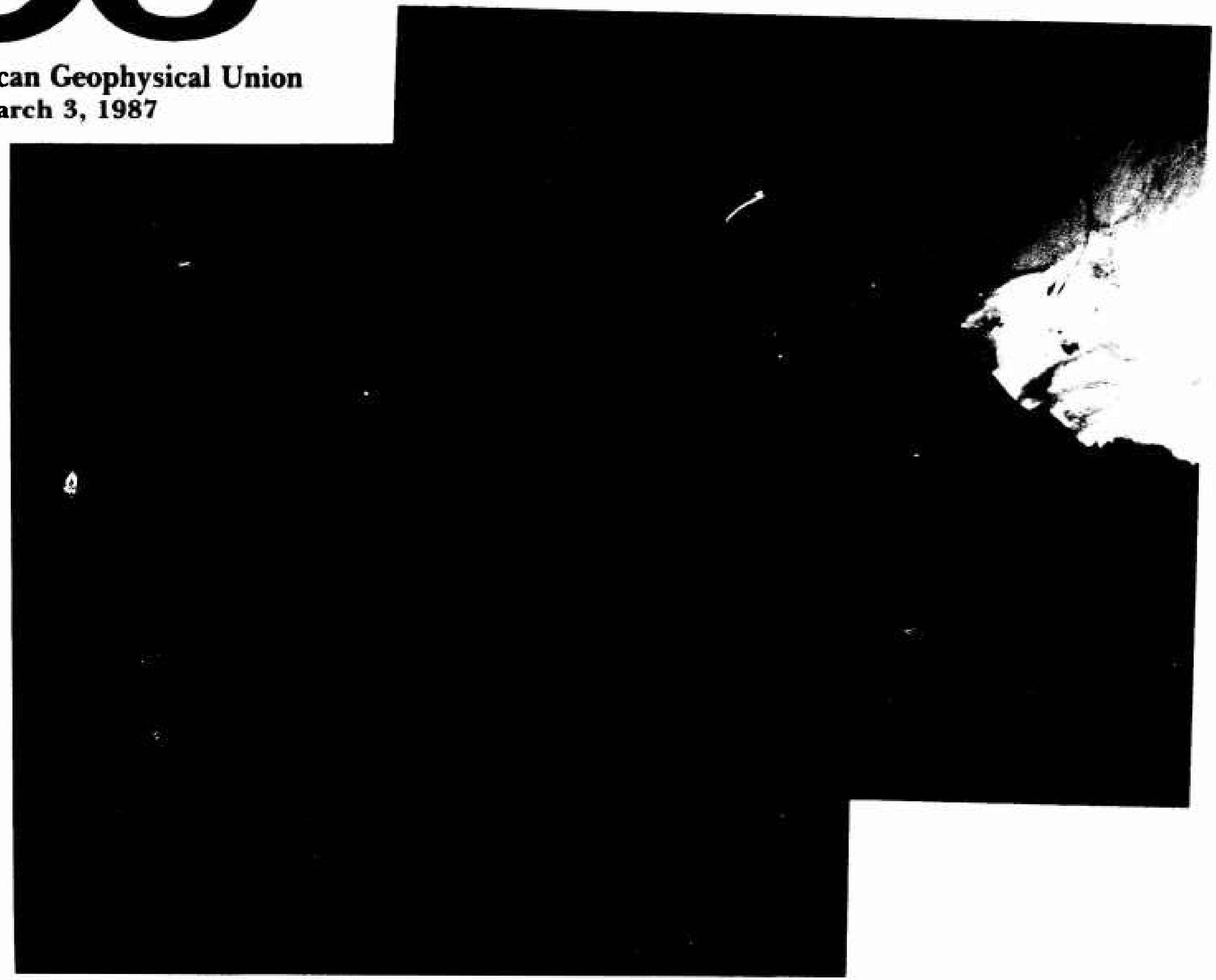

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An Oceanographer in Space: The Next Step

Paul E. La Violette
Naval Ocean Research and Development Activity,
NSTL, Bay St. Louis, Miss.

Charles S. Yentsch
Bigelow Laboratory for Ocean Sciences,
West Boothbay Harbor, Maine

John R. Apel
The Johns Hopkins University,
Laurel, Md.

The *Challenger* tragedy has temporarily halted the U.S. space shuttle program. When the program resumes in early 1988, the opportunity to use the shuttle for ocean research will be renewed. In the U.S. Navy, we are using this hiatus to develop a long-range program for an oceanographer in space. This program will become part of a fully integrated Office of the Chief of Naval Research (OCNR) science and technology plan to guide future programs in space oceanography.

The following is based on the report of the OCNR-sponsored Ad Hoc Oceanographic Committee on the Use of Shuttles in Oceanography and on discussions of a recent meeting of the Office of Naval Research/Office of Naval Technology (ONR/ONT) Man-in-Space Working Group. These activities serve two purposes, with the first ~~(we hope)~~ leading to the second: to show the current ideas on shuttle-based oceanography and to elicit comments from the scientific community that might improve those thoughts.

In the 2 decades that unmanned satellites have been providing ocean data, our concept of the ocean has greatly changed. Satellite data now give us instantaneous information on vast ocean regions that previously took days and even weeks to explore by using ships. The assimilation of this information into our knowledge of the oceans has not been easy. Because of the limitations (as well as the novelty) of the data, oceanographers were slow in accepting the information that the data provided. Although the oceanographic importance of the data is now generally accepted, oceanographers have learned that the satellite data alone are not a panacea but are best combined with in situ data to derive their greatest potential.

In many respects, we are going through similar stages in using ocean data from manned spacecraft. The flight of a dedicated ocean observer, Paul Scully-Power (shuttle mission STS-41-G, October 1982), has once again provided us with both the wonder (and beauty) of the oceans and a practical method of collecting data previously unavailable. The mission demonstrated the researcher-in-space concept to the best advantage: a knowledgeable person in space, controlling the data collection instrument and working with a team of experts on the ocean below. Under the direction of the on-board oceanographer, shuttle photographs taken of the oceans generated questions on exactly what the photographs show and also provided a number of unexpected answers.

Nowhere is the latter more true than in the photographs of the Mediterranean Sea. At the western approaches to the Strait of Gibraltar, the photographs defined lines of rough water delineating a standing internal wave sitting on the sill of the strait, as well as progressive internal waves generated at the sill and moving eastward through the strait to more than 100 km into the Mediterranean Sea (see cover). They indicated the periodicity of these waves and, in combination with surface data, indicated that the periodicity is in tune with the tide.

Farther east in the Mediterranean, in the region of the prime meridian, the photographs showed evidence of the current shear of an ocean front (Figure 1). The front is unusual in that, while it had been previously noted in satellite infrared imagery, it had not been detected in oceanographic analyses of ocean data or included in the modeling of the region.

Most of the questions concern the photographic depiction of spiral eddies, not only in the Mediterranean Sea but in the Atlantic region north of the Gulf Stream (Figure 2). How these features fit into the dissipation of energy in the ocean has to be resolved.

All this information has come from photographs of the sun's reflection off the surface roughness of the ocean. Few of the basic data are quantitative, yet they have provided a great deal of qualitative information. Much of this information was derived when the shuttle photographs were coupled with near-simultaneous data collected by surface platforms and other spaceborne sensors.

Future shuttle missions must evolve from the sole use of photography to equipping future shuttle crews with other remote sensing instruments that can provide quantitative ocean data. In addition, the program must continue to take advantage of trained ocean observers who work interactively with data collection instruments and scientists positioned on the ocean's surface. The questions then become What are these instruments? How should they be used? This issue will be the main thrust of the remainder of this paper. Three unique paths of ocean research appear to be possible aboard future shuttle flights. These topics are presented in order of decreasing sophistication.

Process-Oriented Studies Made in Collaboration With Surface Experiments

These stand-alone experiment results would be expanded greatly by the input of shuttle observations. However, dedicated surface/shuttle experiments could be conducted to study some special ocean process that is not definable except by such an effort. In addition, the shuttle could be used to test new remote sensing instrumentation.

Repeated Surveys of Known Ocean Processes or Events

Many ocean processes could benefit from such surveillance, e.g., internal waves, phytoplankton blooms, bioluminescence, and river outflows.

The Search for Previously Unrecognized Ocean Phenomena

These phenomena could include submesoscale cyclonic eddies, open ocean plankton blooms, and extensive surfactants.

Cover. The Strait of Gibraltar as seen from an altitude of 198 km by the crew of shuttle mission STS-41-G on October 12, 1984. The figure is a montage of two photographs taken less than a minute apart. The photographs show the noon sun reflecting off variations in roughness of the ocean surface (very little of the two photographs contains clouds). Since the surface of the ocean is not smooth, the sun does not appear on the surface as a disc but as a distorted, vaguely edged image whose distortion is determined by the amount of roughness of the surface and the solar incident angle. In simple terms, the ocean's roughness varies according to the pressure of the wind, air/sea-surface temperature differences, and water movement. Because of this, the patterns created by the ocean roughness can delineate the ocean events involving these parameters. The effect is similar to the displays of imaging radars, such as the Synthetic Aperture Radar (SAR), only the solar reflectance in the photographs does not involve coherent energy.

In the right photograph, the most prominent roughness features are those seen bowing eastward into the Mediterranean Sea. These features are the surface manifestations of a packet of 10 or more progressive internal waves whose origin is the bathymetric sill located in the western approaches to the strait. In the left photograph, the sun's reflection defines a standing internal wave situated over the bathymetric sill at −1 h before high tide. Note the packet of progressive internal waves emerging from the southern portion of the standing wave. Other photographs taken seconds later show that the earlier waves had traveled at least 100 km eastward into the Mediterranean. Another set of approximately four progressive waves can be faintly seen in the strait where the two photographs join. It should be emphasized that the internal waves have very small surface amplitude and that the brighter reflections come from disturbed (and thus more reflective) water that constitutes the rip area (NASA photographs 40–049 and 40–050). For more information about future use of the space shuttle as an oceanographic instrument, see the article "An Oceanographer in Space: The Next Step" by Paul E. La Violette et al., p. 121

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It is worth noting that manned and unmanned satellite observations appear to complement rather than compete with one another. For example, unmanned satellites operate in fixed configurations, gather data continuously, use proven technology, and have site revisit capabililty. The shuttle data-gathering capabilities are characterized by considerably more flexibility, and judgments are often conditioned by space crews and/or ground scientists, as well as the opportunity to retrieve, modify, and refly instrumentation. Perhaps most importantly, much of the shuttle data interpretation can be conditioned later by the on-board experience of the oceanographer/astronaut.

The price paid for the flexibility of doing oceanography from the shuttle is in the short flights of the spacecraft and the difficulty in scheduling. A final important limitation is imposed by each mission's orbit angle north or south of the equator. In other words, will the mission's orbit go far enough north (or south) to reach a given area of study? In the period before *Challenger*, only one mission in six went closer to the poles than 28° north or south.

Scientific Program

What can be done by way of "hard" ocean science from the shuttle? The answers, conditioned by short flights and the difficulty of coordinating spacecraft and ship schedules utilize a part or all of the three research paths mentioned.

Origins and Dynamics of Submesoscale Baroclinic Eddies

The recognition of the ubiquitousness and cyclonic nature of the surface submesoscale eddy field, such as shown in Figure 2, is clearly one of the major results from shuttle flight STS-41-G. Whether the eddies are truly oceanic is moot (i.e., do they have a significant subsurface extension, or are they atmospherically induced surface effects?). A set of experiments needs to be conducted, probably in the Mediterranean, in which observations of the ocean density field on a fine grid are made concurrently with shuttle camera recordings and, if possible, Synthetic Aperture Radar (SAR) observations.

The objectives of such a set of experiments would be to test the hypotheses that the eddies are oceanic and that they are shed from the "cyclonic side" of larger-scale geostrophically balanced currents. Repeated observations of the same eddy with accurate camera pointing and geographical location are essential to this type of experiment. In a survey mode, the temporal and geographic distribution of the eddies in the world's oceans would be highly informative.

Oceanic Phytoplankton

Many areas of the ocean are not accessible by ship for studies of phytoplankton activity. Thus knowledge of this phenomenon is virtually nil. Shuttle surveys of such remote regions by colorimetry would add to our understanding of biological activity in the sea. In addition, provocative images and photographs of greenish hues in open ocean areas suggest productivity in regions that conventional wisdom says are relatively sterile. Even coarse measurements of pigment concentrations would, in these cases, be valuable.

Generation and Propagation of Internal Solitons

Packets of internal waves, or solitons, such as shown in the composite photograph on the cover, have been observed from both manned and unmanned spacecraft at a number of sites around the world. While recent oceanic experiments have delineated many of the dynamical characteristics of these waves, much work remains to be done on their generation and dissipation. A surface/shuttle experiment would include thermistor chain and/or conductivity-temperature-depth (CTD) and expendable bathythermograph (XBT) work to measure the subsurface properties at a given position, and repeated camera and SAR images of the area from a shuttle would reveal much of the horizontal extent. Candidate sites are the straits of Messina and Gibraltar, the New York Bight, the Gulf of California, and the Sulu, Andaman, and Celebes seas.

A survey of the distribution, rate of occurrence, and time behavior of internal waves would aid in a deeper understanding of the factors that control their generation, propagation, and dissipation. Certain regions, such as continental shelf edges and island arcs, are especially attractive candidates, but much of the work could take place on a target of opportunity basis, given a moderately well-trained and perceptive shuttle crew.

Oceanic Bioluminescence

Occurrences of natural bioluminescence would be visible from shuttle altitudes. Its nature and distribution in the ocean is complicated. In general, bioluminescence patterns follow the overall patterns of primary productivity in the oceans. However, since many of the photosynthetic organisms are nonbioluminescent, it is difficult to equate the abundance of bioluminescence directly with productivity.

Global measurements could identify regions of active bioluminescence, which could supply predictive information. Since most bioluminescence is caused by stimulation, experiments can be carried out by using a ship to stimulate the luminescence and observing the emission with aircraft and the shuttle. Any experimentation will be difficult because of the problems of identifying the phenomenon and (because of spurious light sources) in making measurements. A camera that intensifies images at low light levels and moonless nights are necessary. Possible sites for such an experiment include Jamaica Bay, the Arabian Sea, and the Gulf of Bengal.

River Outflow/Ocean Interactions

Material-laden river outflows have been repeatedly photographed from space. These images have provided information on the nature of delta formation and on the trajectory of regional longshore flow. Such repeat photographs utilize the river plumes as Lagrangian tracers to define the near-shore oceanic circulation. For example, the Amazon outflow can be used to trace the formation of the equatorial undercurrent by the flow reversal that occurs when the Guiana Current impinges on water masses north of the outflow. The slow salinity and discoloration that occur can be seen as far west as the Barbados Islands. The use of ocean color scanners can yield measurements of the near-surface diffuse attenuation and chlorophyll concentrations, while photographs of the river plume can serve as high-resolution flow tracers that permit small-scale frontal mixing studies. Candidate rivers for the repeated seasonal observations are the Amazon, Orinoco, Mississippi, Nile, Indus, Ganges, and Yangtze.

Surface Effects

The origin of organic films, scums, and oily layers is an intriguing question: Biogenic materials are suspected of being the source of much of the material. Such oils damp the short-length gravity and capillary waves and thus modify the surface optical reflectivity, perhaps including the radar backscatter coefficient. This mechanism would possibly allow camera and SAR imaging of such features as the submesoscale eddies and internal waves. However, there are questions as to whether the camera imagery and the SAR imagery represent the same phenomenon, since the camera images optical wavelengths in forward scatter and specular reflection, while the SAR uses backscattered radiation at centimeter and decimeter lengths. The determination of the variability, extent of coverage, and temporal aspects of these sea surface reflectance patterns is of considerable interest.

Instrument Requirements

A variety of instruments has been considered for use in the proposed programs. The following remarks will discuss these instruments in order of increasing sophistication.

Hand-Held Cameras

Although quantitative radiometric analyses are difficult to do with film imagery, their easy acquisition is an argument for the continued use of film cameras in the shuttle cabin. A battery of two 70-mm cameras with lens turrets, filters, and polarizers has been strongly recommended for use aboard the shuttle.

Automatic recording of the time, pointing angles, exposure parameters, polarization, film type, and lens type would significantly increase the ability to do semiquantitative analyses of shuttle photography. However, the geometric and radiometric distortions of the windows presently in the shuttle cabin prevent the highest resolution spatial or spectral data that are inherent in quality cameras. In addition to optical-quality windows, some method of cleaning the outside of the windows is required. We hope that the shuttle that will replace the *Challenger* will have such improved windows.

Multicamera Battery in the Shuttle Bay

Barring improved data recording and the installation of optical windows, high-resolution optical imaging systems mounted in the shuttle bay would be useful. These systems, open to space, would be used for imaging scenes where resolution, rather than spectral information, is of prime interest (e.g., ship wakes and waves).

The unit, consisting of a multicamera battery that would utilize a variety of film and multispectral or polarizer filter combinations, would be controlled from inside the cabin or on the ground. A charge-coupled device (CCD) video system using two video cameras would be used. One video unit would be directable to allow the astronaut or ground ob-

Fig. 2. Submesoscale spiral eddies caught in the sun glint of the shelf waters off the northeastern seaboard of the United States. This photograph was taken from the shuttle on October 9, 1984, at 1722 UT from an altitude of approximately 200 km. The line of demarcation in the lower right corner of the photograph marks the north wall of the Gulf Stream. The warm waters of the Sargasso Sea lie to the right of the line. To the left of the line and prior to the spiral eddies lies an area of apparent shear related to the countermovement of the northeastward moving Gulf Stream and the southwestward moving shelf water current (NASA photograph 41-046Z).

server to preview upcoming scenes. The second would be bore-sighted with the multicamera battery to allow accurate firing of the film devices. If the system could be fired from the ground, it would be a facility instrument to be carried on many other flights in addition to those with oceanographers on board.

Low-Light Level Camera

Bioluminescence studies can be made from the shuttle by using a low-light level camera in the cabin in controlled experiments. Although strong natural bioluminescence can be seen from shuttle altitudes, several technical difficulties are present, including the need to block out light from the firing of the hydrazene stabilization jets, reduction of interior cabin lights to very low levels, and the need to operate on nights when the moon is not visible. However, space-qualified systems currently exist that appear to meet the requirements.

Multispectral Scanner

The measurement of ocean color with medium-resolution imaging spectral radiometers would be of major oceanographic importance. The success of the Nimbus Coastal Zone Color Scanner (CZCS) in the quantitative determination of chlorophyll concentrations and diffuse attenuation coefficients suggests that flying similar instruments on the shuttle would be useful (especially since the CZCS is no longer functioning and no unmanned satellite sensor replacement is to be made).

In the shuttle, synoptic camera observations and human interpretation would supplement color scanner measurements. Such a system may have to be mounted in the shuttle bay and used in a fashion similar to (and perhaps in conjunction with) the multicamera battery already discussed.

Optical Spectrometer/Fluorometer

A simple, perhaps hand-held, optical spectrometerlescope that records spectra either graphically or on film can be used to make qualitative, rapid observations of the spectral content of optical signals form the ocean surface. Optical fluorescence from the sea would also be useful, since it is currently thought that such signals are strong enough to be seen from spacecraft altitudes. Again, such an instrument could be used in the cabin or placed in the bay and bore-sighted with a multicamera battery.

Synthetic Aperture Radar (SAR)

The shuttle flights that will carry SAR (Shuttle Imaging Radar (SIR) C and D) are exceedingly important opportunities for the oceanographer-in-space program. A wide variety of signatures are apparent in radar images of the ocean surface, some of which are understood quantitatively (and some not at all). Every effort will be made to place an oceanographer on each of the SAR missions. A coordinated surface shuttle program of radar imaging, optical imaging, and visual observations will be planned for these flights. Such phenomena as surface slicks, ship waves, internal waves, and similar processes that modulate the small-scale surface roughness of the ocean are, in principle, observable with all these sensors. (Note that SAR missions are normally planned for higher latitude orbits than other shuttle flights, even as high as the polar regions).

The Next Step

Until now, the shuttle ocean research program has been one of using a platform of opportunity to conduct ocean surveillance. The previous remarks show how the ocean research that is to be conducted on future flights can be expanded to include instrumentation that will qualify active and passive spectral signals of ocean features. To maximize the utility of such instrumentation, the shuttle flights carrying these devices should be coordinated with ongoing ocean experiments utilizing sea observations from ships, platforms, and/or buoys. This effort can be facilitated by coordination between agencies that support ocean research. These programs should be carefully coordinated programmatically, i.e., there should be a close working relationship between OCNR, the National Science Foundation, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and other interested ocean institutions and laboratories.

A critical aspect of this article is the solicitation of the thoughts of readers regarding the conduct of oceanographic research involving a researcher in space. Please consider the remarks that we have presented here and send us any ideas that you might have on scientist-in-space ocean research. Also, if you will be conducting an at-sea experiment during 1988 and believe that shuttle data would expand your results, tell us how you think this might be done. Given the constraints of the program, we will try to join you in a cooperative experiment. Send your ideas and comments to Space Oceanography Working Group, Ocean Science and Technology Directorate, Office of the Chief of Naval Research, 800 North Quincy Street, Arlington, VA 22217–5000. Your participation would be highly appreciated and would significantly help the newly formed ONR/ONT Space Oceanography Working Group to develop the most thorough and meaningful long-range space oceanography science and technology plan.

Appendix A. Some Oceanographic Results That Have Come From Studies of the Shuttle Photographs

- The existence of submesoscale cyclonic eddies in numerous regions of the world, including both the northern and southern hemispheres.
- Ship wakes visible for 200 km.
- Internal solitary waves propagating out of the Strait of Gibraltar into the Mediterranean Sea.
- Submesoscale eddies in the area north of the Gulf Stream.
- Correlations between surface filamentary structures seen in the sun glint with larger-scale thermal flow patterns seen in NOAA Advanced Very High Resolution Radiometer (AVHRR) infrared imagery.
- Island wakes.

- The extent of offshore river outflows.
- The presence of phytoplankton blooms.

Appendix B. Shuttle-Related Research Opportunities

- **Submesoscale Eddies.** Characteristics (temporal and spatial), dynamics, vorticity, origin, and their possible relationship to internal wave field.
- **Ocean Fronts.** Characteristics, dynamics, relationships of apparent shear zone, and current and temperature field.
- **Air-Sea Interaction.** Characteristics, distribution (spatial and temporal), generation, and propagation.
- **River/Ocean Interaction.** Plume distribution, water mass mixing relationships.
- **Sediment Fluxes.** Coastal/ocean sediment distribution.
- **Bioluminescence.** Visibility, distribution of phytoplankton species, relationship to physical environment (if any).
- **Optical Properties.** Diffuse attenuation coefficient; temporal, spatial, and depth distribution; coupling with photosynthetic pigments; and ocean color.
- **Shallow Water Bathymetry.** Optimum spectral wavelength, bottom type, and mapping and charting.
- **Estuarine Oceanography.** Physical and biological characteristics, flow patterns and dynamics.
- **Marine Microlayer.** Surfactant films, distribution, dynamics, origin, polarization, wind effects, and optical and radar scattering
- **Micrometeorology.** Von Karman vorticities, evaporation fluxes, water mass, clouds, and sea/land breeze distributions.
- **Ship Wakes.** Kelvin, nested Kelvin, and turbulent.
- **Surface Gravity Waves.** Spectrum and refracted effects.
- **Island Wakes.** Wind stress/current relationships, stability.
- **Changes in Optical Properties Under El Niño.** Short-term climatic change.
- **Upwelling.** color/roughness/temperature correlations, spatial and temporal distributions.
- **Zero Gravity Hydrodynamics.** (Experiments within the shuttle).