Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis

D.V. Holliday
Graduate School of Oceanography
University of Rhode Island
5034 Roscrea Avenue
San Diego, CA 92117
phone: (858) 279-5369 fax: (401) 874-6240 e-mail: van.holliday@gso.uri.edu

C.F. Greenlaw
302 Tailwind Drive
Seguin, TX 78155
phone: (830) 372-3239 fax: (401) 874-6240 e-mail: cfgreenlaw@alumni.utexas.net

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LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

OBJECTIVES

We are working with our collegues in the ONR-sponsored research program on Layered Organization in the Coastal Ocean (LOCO) to jointly analyze data collected in Monterey Bay, CA during FY2002, 2005 and 2006. Our work this year has involved data analysis, presentation of our results at several scientific meetings, and the preparation of publications.

APPROACH

During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, and water column physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in northeastern Monterey Bay. Other team members examined larger scale horizontal distributions and temporal thin layer patterns in deeper water nearby, while still others collected plankton and made measurements of turbulence, nutrients and various optical properties of the water column. Our part of this research involved the deployment of several acoustic and ancillary sensors on the seabed. The acoustic sensors were used to describe the distributions of small zooplankton, micronekton and small gas bubbles. Other LOCO principal investigators also used a variety of sensors to examine thin layers and the conditions and processes that led to their formation and destruction during each of the field periods in Monterey Bay. We have been analyzing and sharing our data, comparing it to measurements made by our colleagues, making presentations at technical meetings, and submitting papers for publication.

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WORK COMPLETED

We have analyzed acoustical and environmental data collected in Monterey Bay during each of the LOCO field periods. Specific data sets, especially several that were of special interest to both us and our colleagues who are concerned with the optical signatures of thin layers were analyzed in detail to support the preparation of invited presentations and papers for publication. We also met with most of the LOCO principal investigators in Orlando, FL before the 2008 Ocean Sciences Meeting, where we compared data sets. Selected results from our research have been presented via invited papers at a special session on thin layers at the ASLO/TOS/AGU meeting in Orlando, FL and as an introduction to a session on ecosystem monitoring at the ICES Symposium on the Ecosystem Approach with Fisheries Acoustics and Complementary Technologies (SEAFACTS) in Bergen, Norway in June 2008.

RESULTS

Since the LOCO research program is in the data synthesis phase, the following discussion is a short summary of results for some of the data analyses carried out cooperatively by Van Holliday, Charles Greenlaw, Percy Donaghay, Jim Sullivan, and Jan Rines. Some elements of the discussion below are the subject of a paper now in review for a special issue of the ICES Journal of Marine Science during the summer of 2009 (Holliday *et al*. [submitted, 2009]).

Although temperature and salinity fine-structure has long been known to exist in the sea, the processes that lead to the formation of thin acoustic scattering layers are less well known. Closely spaced vertical profiles collected either by high frequency echo sounders during a transect, or by a bottom-mounted, up-looking sounder as water moves over the sensor, often reveal acoustic scattering layers with thicknesses of tens of centimeters to a few meters. Sometimes these layers are coincident with a particular isopycnal, isotherm or salinity surface. At other times they do not appear to be tightly associated with any parameter that we have measured. Volume scattering strengths are displayed in Figure 1 at two minute intervals for a 24-hour interval between beginning at noon August 26, 2005 in Monterey Bay, CA. This volume scattering strength (Sv) record is from the 700 kHz channel of a TAPS-6 deployed in a bottom-mounted, up-looking mode. The TAPS-6 is a multi-frequency acoustic sensor specifically designed to study zooplankton and micronekton. Sampling was done with a vertical resolution of 12.5 cm at intervals of 2 min. Temperature contours are overlaid as measured by a thermistor chain, located nearby. Those samples were also collected at 2 min intervals.

Scatterers located near the surface during daylight hours were observed to migrate to the depths of two specific isotherms (14.2 and 13.0 °C). The migration started slowly at sunset (19:45 Pacific Daylight Time) and for the next hour was only visible in the top 2 m. At 20:45 PDT (30 min after nautical twilight), the downward migration began in earnest. The first cohort of migrators reached the 14.2 °C isotherm at 21:10 and remained very near that isotherm in a 30 cm thick scattering layer until 23:00 PDT, after which the layer began to thicken and then disperse upward. Acoustic inverse methods were used to determine the size-abundance spectrum for scatterers in the water column (Holliday 1977; Costello, Pieper and Holliday 1989). For the shallower of the two layers, at the 14.2 °C isotherm, we determimed that the scattering was likely caused by two kinds of migrating organisms. The most abundant were 1 mm long copepods with a biovolume of 35,000 mm^3 m^{-3}. One millimeter long *Acartia tonsa* were collected within a meter of the sea surface during the daytime, before the evening migration. Additionally, elongate scatterers with a length of 3.6 mm were detected with an estimated biovolume of 14,000 mm^3 m^{-3}.

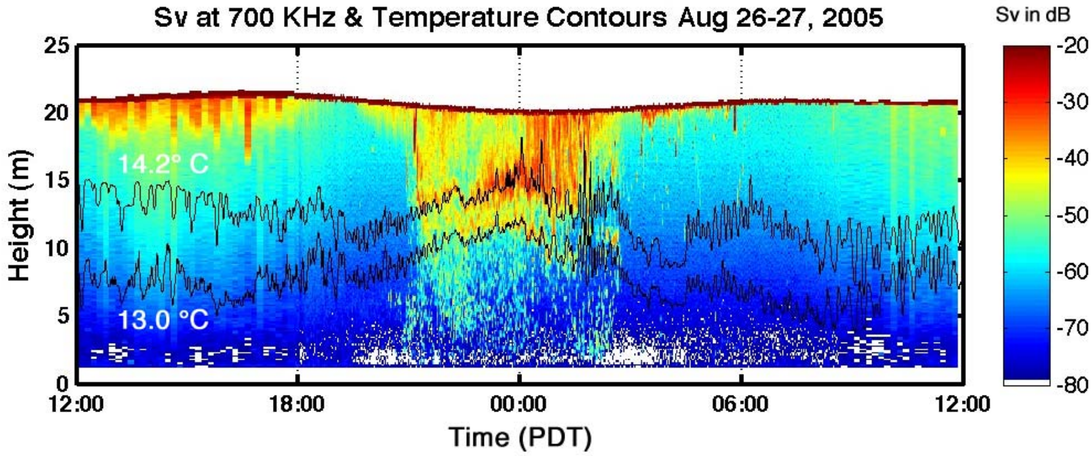

Figure 1: . Volume scattering strengths, measured at 2 minute intervals are displayed for a 24-hr period between noon, Aug. 26 and noon, Aug. 27, 2005. A downward vertical migration from above 50 cm below the sea's surface started at dusk on the 26th. As a result, a thin acoustic scattering layer quickly formed on the 14.2 °C isotherm and a second layer formed about an hour later on the 13.0 °C isotherm. These two layers closely tracked these isotherms until scatterers gradually began returning to the surface. All scatterers were back at the surface by 03:00 PDT, well before sunrise at 06:34 PDT.

The second cohort of scatterers may have left the surface at a slightly later time than the first group. In any case, they swam downward at a slower rate and passed through the 14.2 °C isotherm, settling on the 13.0 °C isotherm at *ca*. 23:20 PDT. They remained on that isotherm until *ca*. 01:40 PDT and then quickly returned to the surface. This deeper of the two scattering layers also contained considerably less biomass. Only 750 mm^3 m^{-3} of the 1 mm long copepods and 300 mm^3 m^{-3} of the 3.6 mm elongate scatterers were necessary to explain the volume scattering strengths measured in that layer. The scatterers in the deeper of these two layers (at the 13.0 °C isotherm) left for the surface at *ca*. 02:40 PDT. Within *ca*. 20 min, all scatterers that had migrated into the water column at, and just after dusk, had arrived at the sea surface. A few migrators had bypassed both isotherms and dispersed in the lower half of the water column. Those scatterers also returned to the surface before 03:00 PDT. This was well before sunrise at 06:34 PDT.

Hourly ORCAS profiles were also collected at this site by Percy Donaghay's research team (Figure 2, contour overlay). Estimates of the Chl-a profiles were derived from ac-9 measurements of absorption at 650 and 676 nm using the method documented by Sullivan *et al*. 2005. Those hourly profiles were contoured and are overlaid on the TAPS-6 700 kHz Sv data for the same period. Although contours between measurements are interpolated and could vary from the true values between samples, contours have been constrained to pass through measured data points collected on the hour. Examination of the estimates of Chl-a indicate minimal correlation with the volume scattering profiles collected during the same interval of time. An ORCAS profile collected at midnight, just after the second thin acoustic scattering layer had arrived at the 13.0 °C isotherm, revealed that there was a strong Chl-a peak (> 20 µg/l) at the base of the seasonal thermocline, *between* the 14.2 and 13.0 °C isotherms (Figure 2, *ca*. 12 m above the seabed, at 00:00 hrs.).

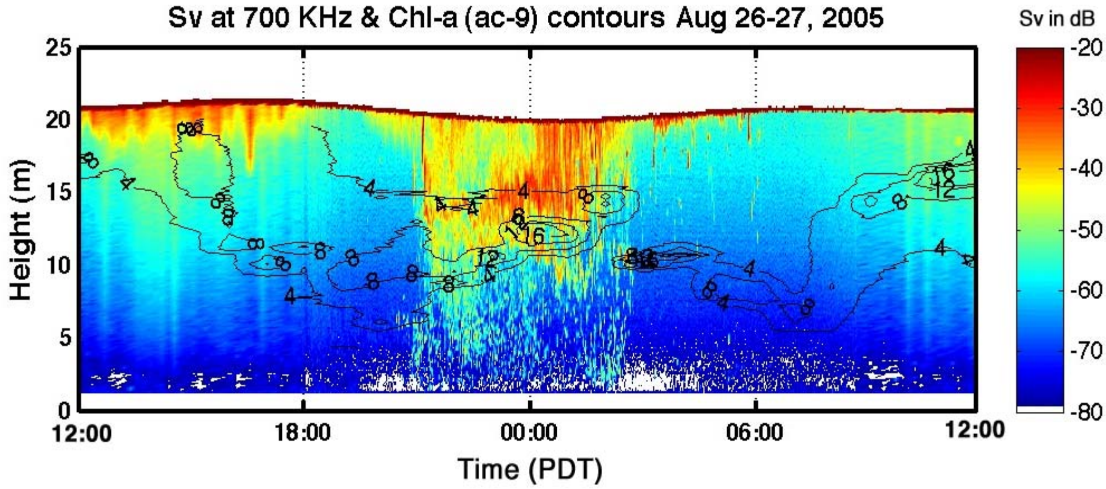

Figure 2: The volume scattering strength profiles of Figure 1 are overlaid with estimates of Chl-a derived from an ac-9 aboard an ORCAS profiler deployed near the TAPS-6. Chl-a levels are not well correlated with Sv measurements. The peak Chl-a level during the time when acoustic scattering layers were present in mid-water occurred just after midnight at a height above the bottom of ca. 12.5 m. This location was between the two zooplankton layers. Chl-a data provided by Percy Donaghay and Jim Sullivan.

Estimates of the slope of the optical attenuation coefficient derived from the ORCAS profiler data for this layer suggests the presence of larger particles in the layer than are present in the water just above or below the layer. A time record of hourly data from the ORCAS sensor package, along with samples collected at the surface during the day, revealed that the thin Chl-a layer was associated with the dinoflagellate *Akashiwo sanguinea*. During our occupation of the Monterey Bay study site, this organism migrated to successively deeper depths each night in order to reach the nutricline and returned shallower depths, presumably for better access to sunlight during the day. The size of this organism, *ca*. 70 microns, is consistent with the optical estimates of length for the Chl-a layer detected with the ac-9. The smaller particles above and below this layer included a diverse collection of small diatoms of different species.

Although one can often associate the presence of a thin acoustic scattering layer with vertical structure in the physics or chemistry of the water column, or with the presence of potential prey, it is also not unusual for thin acoustic scattering layers to be located at depths not obviously associated with such fine-structure. This suggests that zooplankton and micronektion may be responding to as yet undiscovered stimuli or combinations of environmental conditions that they perceive to be optimal. Alternatively they might be avoiding conditions or organisms they view as threatening. In any case, our observations suggest that zooplankton behavior should not be ignored when considering processes leading to the formation of thin acoustic scattering layers. In fact, it is not at all unusual to observe multiple layers forming at the same location with different processes appearing to be active at different depths. On July 18-19, 2006 a thin layer of warm water appeared in the top 2 m of the water column at one of our TAPS deployment sites in Monterey Bay. There was also a deeper pycnocline in mid-water (Figure 3).

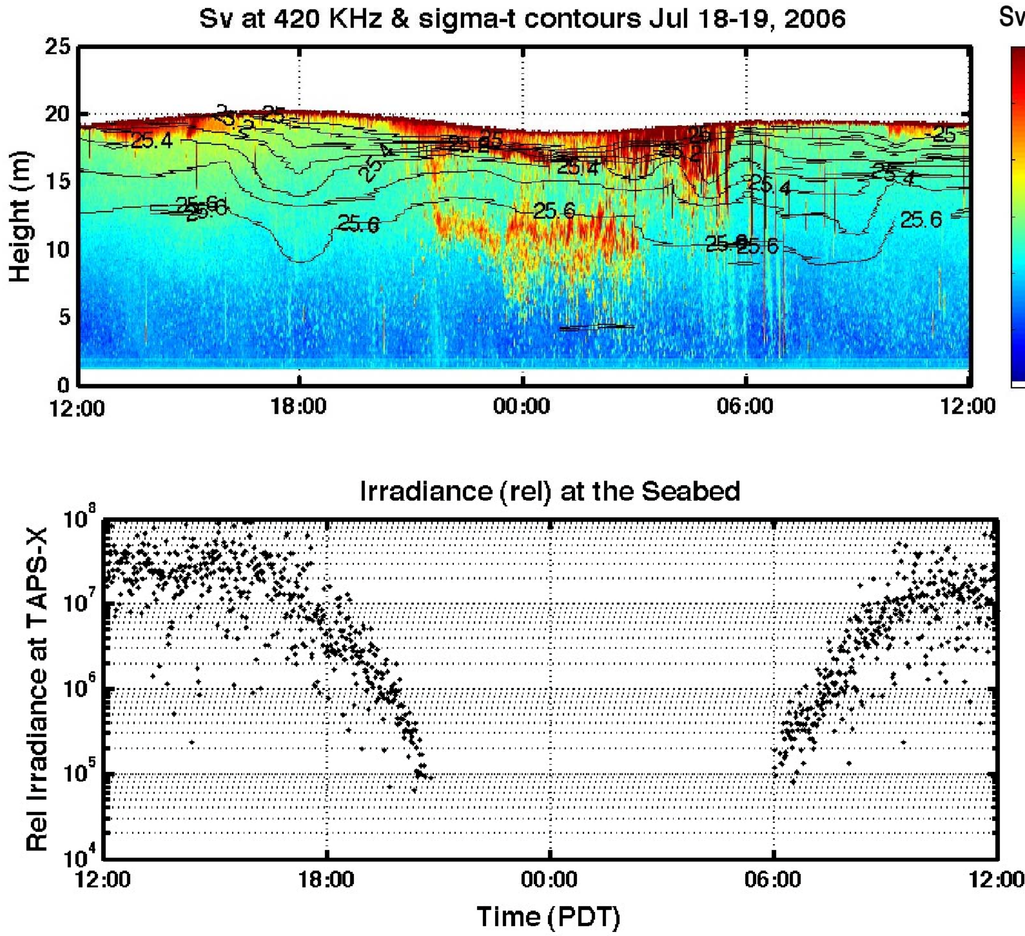

Figure 3: Volume scattering strength profiles (Sv) at 420 kHz are displayed at 2 min intervals from noon July 18 through noon July 19, 2006 versus height above an up-looking multiple frequency TAPS sensor mounted on the seabed (top panel). Sigma-t contours are overlaid (ORCAS data courtesy of Percy Donaghay and Jim Sullivan). Relative irradiance at the seabed is illustrated in the bottom panel. Two acoustic scattering layers appeared at sunset, one of which remained above ca. 2 m depth. The other rapidly descended into the water column, where it was visible between 10 to 14 m above the seabed until about 03:00 PDT.

A warm, light shallow layer was observed near the surface at sunset and it disappeared about dawn. Its presence may have been associated with the tidal flow, wind driven advection, or both. A thin, strong acoustic scattering layer formed on the steep density gradient at the base of this lens of warm water. The main pycnocline was located on a sigma-t surface of *ca*. 25.6 in midwater. Although the pycnocline was not always sharply defined, the deeper acoustic scattering layer did not appear to be tightly coupled to this density surface. Thus, in data from the same day, two different migratory patterns for the zooplankters were observed. In one case, a layer formed on, and closely tracked a shallow temperature and density gradient. In the other, the acoustic scattering layer migrated through the strong thermocline, forming a thin scattering layer several meters deeper in the water column. The upward migrations for both layers, but especially from the one in midwater began and were completed before sunrise.

The relative irradiance (bottom panel, Figure 3) illustrates that while downward migrations at the shelf location in Monterey Bay in the summer were consistently triggered by the arrival of dusk, the main migration was often delayed beyond that time. On the day shown, the shallow scattering layer dispersed at sunrise, but the deep layer had already dispersed hours earlier. In many cases, however, when multiple layers were present, both dispersed, often via with a rapid migration to the surface, long before dawn.

At first glance, the observed patterns of zooplankton and phytoplankton migration in Monterey Bay during 2005 and 2006 seem very complex, however, some features appear to be quite consistent from day-to-day. We continue to examine measured patterns in acoustic scattering, dynamic diel changes in zooplankton distributions derived from the TAPS data, patterns in fluorescence and optical scattering and attenuation, the physical structure of the water column as measured with Donaghay's ORCAS profilers, and samples of the phytoplankton, in an attempt to understand what is driving the most common, repeated features in the patterns of vertical migration.

Although our analyses of the LOCO data are ongoing, we can draw several conclusions from our observations in Monterey Bay and other coastal locations.

Phytoplankton and zooplankton in open coastal systems can and do form decimeter (and smaller) scale layers. Since these layers may contain as much as 80% of the water column biomass for each trophic level, it is likely that they affect the the biological dynamics of these ecosystems.

LOCO investigators have found that phytoplankton, protists, microzooplankton, zooplankton, micronekton and fish larvae sometimes aggregate on physical or water mass boundaries forming thin layers. Often they are found at other locations in the water column as well. Not all thin layers are co-located with physical structure in the water column. Some thin layers appear to form as the result of organism behavior.

Finally, if predator and prey are to interact, they must spend time together. At our study site, an energy transfer model that assumed that zooplankton nighttime foraging began at sunset, lasted until sunrise, and was proportional to the total Chl-a in the water column would have been very questionable. At this site at least, unless one looked with sufficiently high temporal and spatial resolution at how vertical profiles of phytoplankton and secondary producers changed and interacted, it is likely that attempts to model the transfer of energy between the two trophic levels in a simple way would have led to serious errors in estimates of grazing. Trophic models that do not take vertical fine-structure and zooplankton behavior into account may sometimes be attractive, elegant, and simple, but in Monterey Bay during the time we were making observations they would also have led to incorrect conclusions. Most of the time, secondary producers tended to ignore the organisms associated with the highest Chl-a distributions, preferring to co-locate and presumably forage on a collection of diatoms exhibiting lower levels of Chl-a. Additionally, the depth history of migrating zooplankton and micronekton was complex, depending on not only diel changes in light levels and the vertical distribution of phytoplankton, but also on the horizontal advection of fine-scale vertical structure in temperature and salinity. Our preliminary analyses also suggest the possibility that the vertical migration history for zooplankton can be influenced by the vertical distribution of phytoplankton that can be toxic (e.g., *Alexandrium catenella*).

IMPACT/APPLICATIONS

Our results strongly suggest that fine-scale vertical structures in marine plankton are ecologically important features in the upper part of the water column. When thin plankton layers are present, food densities appear to rival or even exceed those in the traditional chlorophyll maximum (Cassie 1963; Lasker 1975; Mullin and Brooks, 1976) and in zooplankton patches (Steele 1976). As such they are a mechanism for creating concentrations of food at scales necessary for the survival of individual fish larvae (Jones 1973). For a population of some species of fish, the widespread occurrence and persistence of thin layers at the time of first feeding could mean a good year class, or a very poor one. Although their occurence is seasonally dependent on local physical oceanography (e.g., upwelling and relaxation) in some coastal locations, thin layers appear to be widespread and frequently present in coastal zones. Although further study is needed to conclusively support their frequent occurrence offshore, our prior experiences with the use of high frequency sensors such as MAPS (the Multifrequency Acoustic Profiling System) suggests that thin layers may well occur in deep offshore water as well as on the continental shelf. Mechanisms for their formation, maintenance, and destruction will likely vary according to an area's physical and biological environments.

Our acoustical data, especially when viewed alongside synoptic optical data, strongly suggest that plankton behavior, especially diel vertical migration, can strongly contribute to the formation of thin plankton layers. However, the same acoustical and optical data also reveal that the interactions between phytoplankton, zooplankton, fish, and physio-chemical ocean fine structure is extremely complex. The sensors used in the LOCO research program have provided us with detail regarding fine-scale structure in the marine ecosystem and dynamic interactions that has never previously been available for critical examination.

As aggregating mechanisms, thin layers clearly impact food availability for several trophic levels and they are critical for larval organisms before they are able to swim and forage effectively. Even after horizontal swimming is possible, when such layers are present there is an advantage for local foragers since simple vertical migration will bring about an encounter with a layer. We suggest that horizontal migration to find patches is more challenging and less likely to be productive than is vertical migration for fish larvae and even for juveniles.

TRANSITIONS

Much of the multi-frequency technology that we developed under sponsorship of ONR has been transitioned to the measurement of zooplankton size and abundance from moorings deployed in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). Multiple frequency echo sounders and sonars have also found widespread use for fisheries assessment purposes. We were recently recognized for having played a significant role in introducing multifrequency acoustics to the fisheries management community (see Honors/Awards/ Prizes/, below). This transition would not have been possible without ONR's support in developing multifrequency acoustical technology.

RELATED PROJECTS

We continue to support NOAA's Alaska Fisheries Science Center and NOAA's Pacific Marine Environmental Laboratory personnel by processing the TAPS-8 data being telemetered from the Bering Sea. A significant part of the development of the TAPS sensor technology was funded by ONR.

The effort is funded by NOAA's Coastal Ocean Program. Our co-PIs at NOAA have now collected three years of data from the Coastal Gulf of Alaska (CGOA) and three years of data from the M2 mooring on the Bering Sea shelf, north of the Aleutian Islands. We will be assisting NOAA in the processing and publication of papers related to the collection of those data, which are now transmitted to shore hourly via the Iridium satellite network. We have prepared a manuscript based on the CGOA data set and are organizing at least one additional publication that will deal with the Bering Sea data.

One of the PIs (Holliday) has served for the last three years on the scientific organizing committee for the International Symposium on the Ecosystems Approach with Fisheries Acoustics and Complementary Technologies (SEAFACTS) in Bergen, Norway, 16-20 June 2008. He was invited to open the SEAFACTS session on Ecosystems and Fisheries Monitoring Session with a presentation designed to focus on the role of technology in support of an ecosystems approach to fisheries management. That presentation featured some of the LOCO data from Monterey Bay, CA. Data from the ONR sponsored LOCO DRI were used to illustrate ways in which acoustical estimates of zooplankton biomass profiles, and optical estimates of biomass profiles of phytoplankton could be used to advance ecosystem-based fisheries management. Several LOCO participants, i.e., Holliday, Donaghay, Greenlaw and Sullivan, have, along with Jeff Napp, prepared a paper on this subject. It has been submitted for peer review and possible inclusion in a special issue of the ICES Journal of Marine Science.

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HONORS/AWARDS/PRIZES

The International Council for the Exploration of the Sea (ICES) presented its first Prix d'Excellence Award to Van Holliday in Halifax, NS, Canada during its Annual Science Conference in September 2008. The description of this award is as follows. The award recognizes the highest level of contribution to the ICES vision of "An international scientific community that is relevant, responsive, sound, and credible, concerning marine ecosystems and their relation to humanity". Recipients of this award need not be associated with ICES, although their work must be relevant to the mission of ICES. They will have contributed through their research, scientific leadership, and/or leadership in the objective application of science to policy for sustained use and conservation of marine ecosystems. Innovation, teamwork, mentoring, and objective communication with the public must exemplify the career of the recipient. The ICES Prix d'Excellence Award will generally be made no more often than every third year, and then only if there is an appropriate candidate.