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# Climate Variability Research Aided by Moored Current Profiles

**By Jerry Mullison**
*RD Instruments*
*San Diego, California*
**Dr. Humfrey Melling**
*Fisheries and Oceans Canada*
*Sidney, Canada*
**H. Paul Freitag**
*Pacific Marine Environmental*
*Laboratory (PMEL)*
*National Oceanic and Atmospheric*
*Administration*
*Seattle, Washington*
and
**Dr. William Johns**
*Rosenstiel School of Marine and*
*Atmospheric Sciences*
*University of Miami*
*Miami, Florida*

# Climate Variability Research Aided by Moored Current Profiles

## *Oceanographic Moorings Around the World Gather Long Time Series of Heat and Freshwater Transport*

**By Jerry Mullison**
*RD Instruments*
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*Pacific Marine Environmental Laboratory (PMEL)*
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*Seattle, Washington*
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**Dr. William Johns**
*Rosenstiel School of Marine and Atmospheric Sciences*
*University of Miami*
*Miami, Florida*

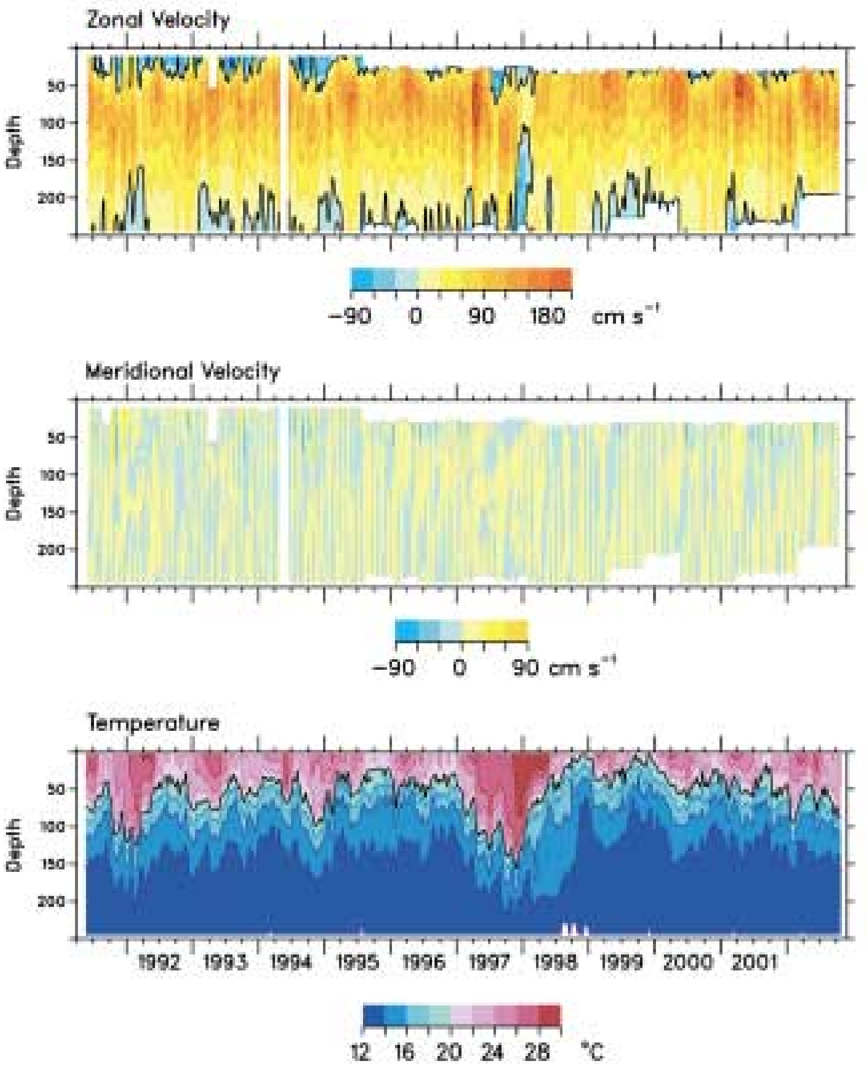
Climate variability research includes questions ranging from "Will this winter be unusually dry or wet?" to "Are recent warming trends due to man's influence?" Their investigation requires the continuous measurement of many parameters over long periods of time, because the relevant forcing mechanisms occur over months to decades.

This article focuses on one of those parameters, ocean currents, because of their role in distributing heat and freshwater in the world ocean. Acoustic Doppler current profilers (ADCPs) are now commonly used to measure ocean currents, and a brief discussion of their history and unique applicability is presented before a detailed discussion of three "prototypical" current regimes: the equatorial Pacific, western boundary currents and the Arctic.

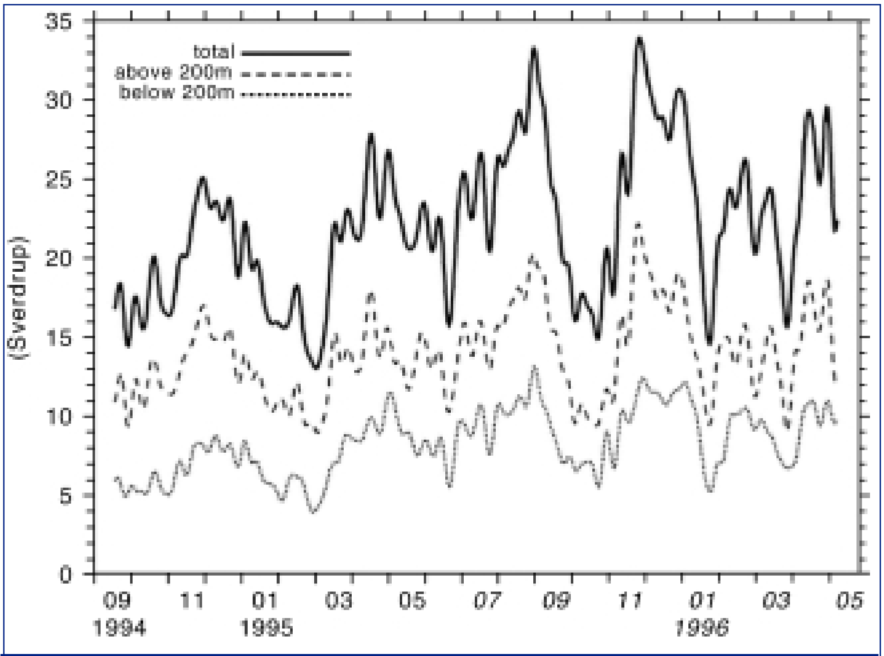
For each regime, the importance of current measurements to climate variability research is presented, and the particular difficulties associated with deploying oceanographic moorings within them are explored.

### A Brief History

Prior to the advent of ADCPs, the vertical current structure was directly measured with a series of current




*Ten-year time series of velocity and temperature from a series of TAO moorings at 0° 110° W. Data have been smoothed with a 21-day Hanning filter.*




*Time series of the volume transport of the Kuroshio passing through the PCM-1 array, and its contributions in depth ranges above and below 200 meters. Units are in Sverdrups (megatons per second).*

meters deployed on a mooring line, each measuring the velocity at one depth. This placed significant cost limitations on the vertical resolution of the measurements. In addition, there are many areas of the world ocean where the traditional current meter mooring is not optimal due to strong flows or the presence of ice. ADCPs overcome many of these difficulties because they remotely measure highly resolved profiles of velocity over significant ranges. In addition, combining these current profiles with temperature and salinity measurements allows the calculation of time series of heat and freshwater transport, which are of critical importance to climate variability research.

When self-contained ADCPs first appeared, they were almost immediately deployed on moorings in the Florida Straits,[1] the Gulf Stream,[2] the Strait of Gibraltar[3] and in the Somali Current[4]. These pioneering deployments were all in areas of such strong flows that they would cause excessive layover of a traditional current meter mooring. Because ADCPs profile remotely, they can measure these large currents from a buoy moored safely beneath the main flow. ADCPs have since been deployed throughout the world ocean, from the Southern Ocean to the North Pole.

The velocity measurements from ADCPs have gained routine acceptance over the last 20 years, and are now so widely used that the number of viable commercial vendors has quadrupled since those pioneering days. Improved signal processing techniques have made ADCPs more sophisticated and efficient, resulting in significant weight reductions, requiring less flotation and reduced power consumption, allowing for a longer time between services. Also, advances in solid state memory devices are such that data storage is now rarely, if ever, a limiting factor. These improvements combine to have an enormous impact on the logistics of configuring, deploying, maintaining and recovering a deepocean mooring.

## The Equatorial Pacific

The El Niño-Southern Oscillation (ENSO) is the most prominent year-to-year climate fluctuation affecting the globe. It originates through coupled ocean-atmosphere interactions in the tropical Pacific, and influences climatic conditions worldwide through oceanic and atmospheric teleconnections. Warm phases (El Niño) and cold phases (La Niña) occur at roughly three to seven-year intervals. The ENSO Observing System[5] is comprised of complementary satellite and *in-situ* measurements, the latter of which include moored and drifting buoys, profiling floats, ship-of-opportunity measurements, and island and coastal sea level stations. The Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) array is comprised of more than 70 surface and subsurface moorings spanning the tropical Pacific. TAO/TRITON is maintained by the National Oceanic and Atmospheric Administration's (NOAA) Pacific Ma-rine Environmental Laboratory (PMEL) and the Japan Marine Science and Technology Center (JAMSTEC).

Sea surface temperature variability on seasonal-to-interannual time scales in the equatorial Pacific is predominately controlled by 3D circulation changes associated with equatorial upwelling and the Equatorial Undercurrent (EUC)-South Equatorial Current (SEC) system. Vertical velocities associated with upwelling, though dynamically significant, are too small to measure directly. However, variations in the horizontal circulation are readily detectable and important to measure directly near the equator where geostrophy breaks down.

Direct measurements of the EUC and SEC, made from PMEL moorings dating back to 1979, were made with single-level mechanical current meters (MCM) such as EG&G Vector Averaging Current Meters and Vector Measuring Current Meters. MCM measurements were primarily made at a few equatorial locations within the array (156º E, 165º E, 140 ºW and 110º E), and continued until 1999. Single level measurements are still made today using point-Doppler acoustic current meters at 165º E, 170º W, 140º W and 110º W to complement and backup ADCP measurements at the same locations.

Weisberg made the first equatorial ADCP measurements from subsurface moorings in 1988 at 170º W.[6] This was followed in 1991 by a mooring at 147º E maintained by JAMSTEC. Between 1990 and 1995, downward-looking narrowband 150-kilohertz ADCPs were mounted from surface TAO moorings at the MCM sites. Current velocity data from these moorings were, at times, biased low due to the presence of pelagic fish, which are known to school around surface moorings. The problem often occurred some months after mooring deployment, suggesting that some time may be required for fish to congregate near the moorings. A fish-rejection algorithm was added to the ADCP firmware, but there remained a residual bias[7,9] that has been corrected using coincident MCM data[8,9]. Since 1996, PMEL has maintained upward-looking narrowband 150-kilohertz ADCPs on subsurface moorings at 165º E, 170º W, 140º W and 110º E. Data from these subsurface moorings are carefully processed to account for variations in mooring depth and sound velocity.[10] All TAO/TRITON ADCP data are available on the Internet at www.pmel. noaa.gov/tao.

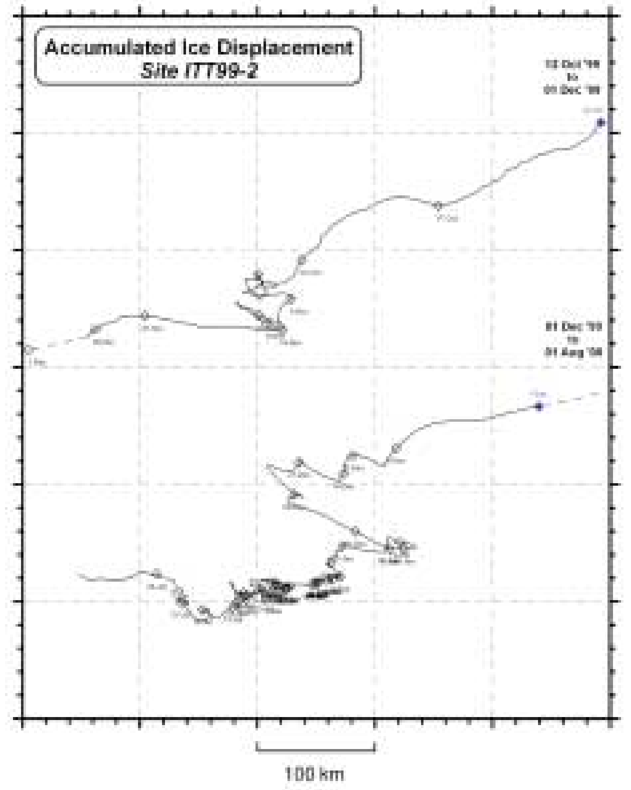
The more than decade-long ADCP record at 110º W provides valuable characterizations of the time and space scales of equatorial currents. The annual intensification of the EUC in boreal spring is a dominant feature of the record. Moreover, the decrease or reversal of the EUC in El Niño years (e.g., 1992 and 1998) is a feature that has been systematically documented by moored current measurements.[11,12,13] Also evident in this long ADCP record are intraseasonal (60 to 90 day) equatorial Kelvin waves. These waves, generated by zonal wind variability in the western Pacific, propagate eastward into the central and eastern Pacific to affect its current and temperature variability.[14] Tropical instability waves with periods of 20 to 30 days are also prominent in time series of meridional velocity. Instability waves are generated by strong lateral shears in the equatorial zonal currents; they transport significant amounts of heat equatorward to warm the equatorial cold tongue, and they also represent a significant frictional drag on the SEC and EUC.

The lack of velocity measurements above 30 meters is due to the corruption of subsurface ADCP data by side-lobe interference from the sea surface, a limitation common to all near-surface ADCP measurements. This loss of data is a primary reason for the continuation of near-surface, single-point measurements from TAO surface moorings. In an attempt to provide velocity profile data near the surface, PMEL is investigating the possibility of using downward-looking high-frequency (600 kilohertz) broadband ADCPs mounted in the surface buoy. If tests prove successful, these higher frequency profilers would complement the point Doppler current meters near the surface.

## Western Boundary Currents

Western boundary currents (WBCs) are a vital component of the Earth's climate system because they transport warm waters from low to high latitudes, thus moderating the high-latitude climate. The most well-known and widely studied of these currents are the Gulf Stream and the Kuroshio, that flow northward on the western sides of the Atlantic and Pacific oceans. The northward flow of these currents, combined with a return flow of cooler waters at depth or in the interior of the oceans, is responsible for about half of the total northward heat transport on the globe. Major WBCs occur in all of the midlatitude ocean basins, among them being the Agulhas Current in the South Indian Ocean, the Brazil Current in the South Atlantic and the East Australian Current in the South Pacific. WBCs are also present in the subpolar and tropical oceans. In addition to their role in global climate, these currents are responsible for much of the intense eddy variability that is found in the oceans, which is generated through instability processes acting on these currents.

Systematic studies of WBCs with current measuring devices date back to Pillsbury's 1890 work in the Gulf Stream off Florida.[15] In the 1970s, studies of WBCs with precursors of today's modern taut-wire subsurface current meter mooring began in earnest.[16] Much of the early work on WBCs with current meters was limited to depths far below the strong surface cores of these currents, due to constraints imposed on mooring design by the strong currents, particularly in the eastward mid-ocean extensions of these currents where they flow out into very deep water. In such cases, it is generally difficult to place conventional current meters within several hundred meters of the surface, and even if this is accomplished, the data retrieved are often seriously contaminated by mooring motion.




***Pseudo-trajectory of ice drift derived by ADCP operating in bottom-track mode. Observations are from the southern Beaufort Sea over 10 months during 1999 through 2000 (trajectory split December 1).***

The use of ADCPs mounted in the upward-looking mode on subsurface moorings provided a breakthrough development in the study of WBCs. The ADCP is mounted in a large syntactic foam sphere, which forms a primary buoyancy element on the mooring and serves to keep the ADCP pointed nearly vertically, even in strong currents. Conventional current meters, or other ADCPs, are added at deeper levels on the mooring line.

The use of such moorings placed in arrays across the axis of a WBC can provide continuous observations of the current structure and volume transport from the ocean floor to very near the surface. Even a single ADCP mooring placed within a meandering current can provide a wealth of information on the vertical and horizontal flow structure, as the current sweeps back and forth over the ADCP location.[17]

With the advent of large ocean circulation and climate programs such as the World Ocean Circulation Experi-ment (WOCE) and Climate Variability and Predictability (CLIVAR), moored ADCPs have become an important tool for studying the climate impacts of WBCs. For example, the WOCE PCM-1 experiment was conducted in 1994 through 1996 to determine the volume and heat transport of the Kuroshio at 24º N at the entrance to the East China Sea.[18] Arrays of ADCP moorings, combined with conventional

*Torsionally rigid moorings carrying 75-kilohertz ADCPs arranged on the USCGC* **Healy** *in the Kennedy Channel. These eight instruments were deployed at the seabed, safe from icebergs, to measure current throughout the 40-kilometer-wide and 350-meter-deep section at 80° N. (Photo courtesy of Gerhard Behrens and Bob McCarthy.)*

current meter moorings and temperature/salinity recorders, provided a continuous 20-month record of the current structure and transport of the Kuroshio and showed that its transport varied considerably on several month time scales about a mean value of 22 Sv (1 Sv = $10^6$ $m^3$ $s^{-1}$). These observations were combined with hydrographic data in the ocean interior and wind stress estimates derived from merchant ships and satellites to produce a new estimate of the transbasin meridional heat flux across the North Pacific.[19]

Similar programs will soon be underway to monitor the meridional overturning circulation and northward heat flux in the Atlantic that will include arrays of moored ADCPs near the western boundary.

## The Arctic

There have been dramatic changes in the pack ice, circulation and hydrography of the Arctic Ocean and its peripheral seas during the last 15 years—a shrinking and thinning of sea ice, an expansion of the influence of North Atlantic cyclones and a redistribution of heat and salt. There is not yet consensus on the cause of these changes. However, their potential impact on northern ecosystems, on traditional living, and on the economies and geopolitics of northern countries is stimulating an acceleration of research to understand the Arctic climate system.

The principal oceanic elements in Arctic climate are the pack ice, the warm inflows from the Atlantic and Pacific, and the storage and transport of salt. The latter is often discussed in terms of fictitious volumes of freshwater diluting standard seawater.[20] The storage of freshwater creates steric anomalies that drive oceanic flows through the Arctic, and its vertical distribution dominates the density stratification that inhibits deep mixing.

Much of the freshwater outflow from the Arctic is ice. The strong influence of freshwater on oceanic stratification motivates interest in the role of Arctic outflows on the global thermohaline circulation. Measurement of the fluxes of ice, freshwater and heat in the ocean are critical to understanding.

A practical technology for measuring oceanic fluxes in the Arctic must address several unique requirements. It should operate from below 45 meters depth to be outside the zone of risk from moving sea ice or, if icebergs are common, from below 200 meters. It should measure current close to the surface, where freshwater flux is concentrated, and the drift of pack ice. It should provide the direction of current within the wide area of the Arctic, where the horizontal geomagnetic field is too weak and variable to be a reference. It should be reliable over long (one to three-year) deployments beneath heavy sea ice, where the difficulty and cost of field logistics precludes more frequent servicing. It should be adaptable to light-weight, compact moorings of simple design that can be conveniently deployed and recovered through rough drifting ice.

ADCPs have been used on moorings in ice-covered waters since the late 1980s because they provide a good match to these requirements.[21] In theory, an ADCP can be deployed at a safe depth beneath pack ice (e.g., 100 meters) and measure current to within 10 to 15 meters of the surface. In practice, this surface zone of side-lobe interference is significantly thicker under pack ice, where one or more of the sonar's beams may be blocked by ridge keels at greater depth. We have been successful in reducing the bias of such occurrences through "smart" signal processing, using an algorithm originally developed for fish-rejection.

A strong seasonal cycle in sound backscatter in the Arctic was not anticipated by early users of Doppler sonar. Echoes during the polar night may decrease by as much as 30 decibels from values during the summertime productivity bloom, causing a substantial reduction in the profiling range of the ADCP. Since range increases with signal-noise ratio, the range in winter can be increased by reducing the noise bandwidth of the ADCP, at a cost in increased energy use. Long deployments in the Arctic typically require supplementary battery packs, particularly when narrow-bandwidth and ice-tracking options are activated.

The capability of Doppler sonar to measure the slow drift of pack ice was demonstrated during trials in the Gulf of St. Lawrence in 1988[22] and in the Beaufort Sea in 1989[21]. The accuracy of ice-velocity measurement is greatly improved by a bottom-detection and tracking algorithm, which adjusts to the extreme roughness of pack ice on scales comparable to the beam spread. The accuracy of ice-tracking is degraded for smooth targets (some types of level ice and calm water) and for targets that are a mix of small floes and open water in the ensemble average (typical in summer), chiefly because of poor signal-noise ratio.[21] Velocity variance associated with swell may obscure smaller ice-drift velocity in the marginal ice zone. In all circumstances, data quality can be improved by stringent quality control on each ping before averaging. ADCPs have been used to measure ice drift as part of ice-thickness monitoring in the Beaufort Sea since 1990.

The horizontal component of the geomagnetic field is smaller than 5,000 nanoTeslas over a wide region centered on the north geomagnetic pole (near 80° N 110° W), which ex-tends from continental Canada to the edge of the Barents Sea. Normal instrument compasses are unreliable within this area.[23,24] Time varying geomagnetic data, available in some areas, may be used to correct compass readings from ADCPs on conventional moorings.[25] However, since the ADCP is a remote sensing instrument, it may be better to deploy it on a torsionally rigid mooring with fixed heading at the seabed.

The actual heading can be determined using a retrievable gyro-compass at the time of deployment, or from the orientation of tidal ellipses in the record when data are analyzed. The latter method has been used successfully within the Canadian Arctic Archipelago since 1998. In August 2003, as part of the international Arctic Sub-Arctic Ocean Fluxes (ASOF) initiative, an array of eight 75-kilohertz ADCPs on torsionally rigid moorings was deployed between northern Greenland and Canada to monitor the freshwater flow to the Atlantic.

In winter, and in close pack in summer, moorings cannot be streamed across the sea surface for anchor-last deployment, but must be assembled tediously, anchor-first. The anchor-first deployment of long moorings with instruments and floatation at many levels is challenging and time consuming. On recovery, long moorings may be draped across floes and ridge keels, increasing the chances for entanglement and loss.[26,27]

Since ADCPs can measure current over a range of depths from a single position, short moorings for Arctic use are quite practical, particularly for studies over the continental shelf. This is a strong incentive for use of ADCPs. On long deployments, the ADCP has the advantage of no moving parts susceptible to wear and fouling. Biologi-cal growth on the face of acoustic transducers has not impeded effective operation of the ADCP, even during three-year deployments, presumably because marine productivity is typically low in ice-covered waters.

## The Future

New developments in ADCP technology promise substantially larger ranges than have been available in most of the above applications. Ranges of over 1,000 meters are now obtained routinely from lower frequency phased array ADCPs mounted to look downward from vessels. Adapting these systems for self-contained operation will, in many cases, allow profiling of most of the water column with a single upward-looking ADCP.

There is now a substantial movement toward cabled ocean observatories, where instruments will be deployed for very long times, but with direct communication to shore. These observatories will allow adaptive sampling strategies (e.g., switching from hourly current profiles to much higher temporal resolution current measurements during storms). In addition, the data will become available to researchers in near-real-time.

## Conclusions

The world's attention is increasingly focusing on complicated questions of climate variability, and researchers have been putting forth an enormous effort to gather the long time series of data that will allow reasoned understanding.

This article has investigated three prototypical regimes of crucial importance to this research, with each presenting unique current measurement challenges. For a host of reasons detailed above, the ability of ADCPs to remotely measure these currents over substantial ranges for long periods of time is proving invaluable to gaining understanding of these vital questions.

## References

For a full list of references, please contact author Jerry Mullison at jmullison@rdinstruments.com. */st/*

*Jerry Mullison is a research specialist with RD Instruments. He received an M.S. in oceanography from Scripps Institution of Oceanography in 1996. Mullison's interests are in acoustical instrumentation for currents and vehicle navigation.*

*Dr. Humfrey Melling is a scientist with Fisheries and Oceans Canada. His re-search focus is the physical coupling between pack ice and the ocean in polar regions. Melling pioneered techniques for aircraft-based oceanography in ice-covered seas and developed the ice-profiling sonar and other specialized instruments for the study of Arctic seas.*

*H. Paul Freitag has been at PMEL since 1975, working with moored instruments in investigations of coastal and equatorial upwelling, ocean dynamics, air-sea interaction, deep-ocean mining, and climate processes and variability. He received an M.S. in oceanography from the University of Washington in 1979.*

*Dr. William Johns is a professor of physical oceanography at the Rosenstiel School of Marine and Atmospheric Science, University of Miami. He received his Ph.D. in oceanography from the University of Rhode Island. Johns' research interests include the study of large-scale ocean circulation, boundary current and mesoscale processes, and marginal seas and straits.*