The Hawaii Ocean Mixing Experiment (HOME): Is the Abyssal Stratification Maintained by Tidalgenic Mixing?

D.S. Luther and the HOME PIs*

School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii

Abstract. Physical processes accounting for the flow of energy from the external tide to small scale turbulence will be studied during this multi-institutional experiment funded by the National Science Foundation. The topography of the Hawaiian Ridge is expected to catalyze these processes. Observations and numerical models will be employed to elucidate the physics and spatial variability of the energy pathways. Direct and indirect techniques will be employed to quantify energy fluxes.

Introduction

HOME is predicated on the assumption that the vertical structure of the abyssal[1] thermal field is maintained primarily by a balance between the downward diffusion of heat by mechanical mixing and the upward advection of cold water. Munk's (1966) global budget for this balance has been updated by Munk and Wunsch (1998; hereafter, MW98) in an article that is sobering for its enumerations of the large uncertainties in our knowledge of how the abyssal stratification is maintained.

The global vertical advection-diffusion balance requires a diapycnal diffusivity of $K_\rho \sim 10^{-4}$ m^2/s and a power throughput of ~ 2 TeraWatts (TW). Yet in situ mechanical energy sources (mainly internal waves) can generate diapycnal diffusivities of only ~ 10^{-5} m^2/s (e.g., Gregg, 1989; Ledwell et al., 1993; Toole et al., 1994). How then is the stratification maintained? Without sufficiently strong downward mixing of heat in the tropics and sub-tropics, the deep ocean should have a weaker vertical temperature gradient, with probably weaker and shallower thermohaline convection cells. Clinging to the in situ mechanical mixing[2] model, eschewing the possibility of even partial direct ventilation of the abyss (which displaces the required mixing of the abyssal waters from the deep ocean to the surface at high latitudes), higher levels of mixing observed in proximity to constrained, acute and rough topographic features (e.g., Hogg et al., 1982; Kunze and Toole, 1997; Lueck and Mudge, 1997; Polzin et al., 1997) provide one exit from this quandary as postulated by Munk (1966), although quantitatively not an obvious one (e.g., Kunze and Toole, 1997). The products of the near-boundary mixing, but not the turbulence itself, are assumed to be advected isopycnally into the ocean's interior (MW98).

Several sources of mechanical energy are available for mixing near sub-thermocline topography, including mean flows in constricted regions (e.g., sills and fracture zones; Hogg et al., 1982), mesoscale currents (e.g., Armi, 1978), external[3] and internal tides, and high frequency internal waves (e.g., Eriksen, 1985). HOME is focused on the tidal energy sources for several reasons: (i) tidal currents are often the most energetic currents in the deep sea; (ii) recent observations show relatively large internal tides well away from continental boundaries yet close to mid-ocean acute topography (e.g., near Hawaii; Dushaw et al., 1995; Ray and Mitchum, 1996); and, (iii) the global application of simple 2-D internal tide generation models (Sjöberg and Stigebrandt, 1992; Morozov, 1995) and global numerical models (e.g., Egbert, 1997) suggest that much more external tide energy is dissipated via the internal tides than the longheld estimate of 10% (which is ~.4 TW; e.g., Wunsch, 1975). From a practical point of view, the determinism of the tides should set up temporal (e.g., the spring-neap cycle) and spatial patterns of variability (mixing) that are observationally distinct.

This paper will briefly describe the goals and strategy of HOME. More complete details of the experiment motivation, design and analysis techniques can be found in the full text of the HOME proposal on the website www.soest.hawaii.edu/~dluther/HOME/proposal.htm. A list of HOME participants, and their involvement in the various HOME programs, is provided in Table 1.

General Goals

HOME investigators have chosen to look for tidally driven (tidalgenic) mixing at a mid-ocean topographic feature, the Hawaiian Ridge, because mid-ocean features are often (and Hawaii in particular is) oriented perpendicular to the principal axes of the external tide currents, which logically should result in the formation of more baroclinic phenomena than at continental borders[4] where the currents tend to oscillate parallel to the boundary. Therefore, the principal HOME goal is to

[1] "abyssal" is used here to refer to the ocean below the main thermocline that is still well above the bottom.

[2] "mixing" hereafter refers to diapycnal mixing.

* The HOME PIs are listed in Table 1.

[3] "external" refers to the surface (barotropic) tide.

[4] Whether the corrugations of the continental boundaries are significant sources of barotropic to baroclinic tide energy conversion is an unresolved issue.

Table 1. HOME Principal Investigators

	HOME Programs*				
	HDA	MOD	SUR	FF	NF
NASA					
Richard Ray		X			
NOAA/NMFS					
Rusty Brainard	X				
Oregon State Univ.					
Timothy Boyd			X		X
Douglas Caldwell			X		X
Gary Egbert		X			
Murray Levine			X		X
James Moum ‡			X		X
Scripps Inst. of Ocean.					
Bruce Cornuelle				X	
Jean Filloux				X	
Walter Munk				X	X
Robert Pinkel # ‡			X	X	X †
Daniel Rudnick ‡			X †		X
Jeffrey Sherman			X		X
Peter Worcester ‡				X †	
Univ. of Hawaii					
Eric Firing	X				
Pierre Flament					X
Douglas Luther ‡	X †			X	X
Mark Merrifield ‡		X †			X
Univ. of New South Wales					
Peter Holloway		X			
Univ. of Washington					
Brian Dushaw				X	
Michael Gregg			X		X
Bruce Howe				X	
Eric Kunze ‡			X		X
Craig Lee			X		X
Jack Miller			X		X
Thomas Sanford			X		X
Woods Hole Ocean. Inst.					
Alan Chave				X	

Overall HOME Project Coordinator
† Program Leaders
‡ HOME Steering Committee
* HOME Programs:
HDA - Historical Data Analysis
MOD - Modeling
SUR - Survey
FF - Farfield
NF - Nearfield

determine whether mid-ocean topographic features such as the Hawaiian Ridge are significant sites of topographically catalyzed, tidalgenic mixing.

There are a number of paths along which energy can travel from the external tides to mechanical mixing, such as direct generation of boundary layer turbulence by external currents rubbing along the boundaries of channels, or generation of internal tides at sills or critical slopes which propagate away from the source region before losing part of their energy to mixing via instability mechanisms. To obtain a bound on all the possible sinks for tidal energy around the Hawaiian Ridge, a second goal of HOME is to create a simple, quantitative energy budget for Hawaiian tides. Elements of the budget will include the energy lost from the external tide in the vicinity of the Hawaiian Ridge, the energy radiated away from the Hawaiian Ridge in low-mode internal tides, and the observed energy dissipation in tidalgenic mixing in the vicinity of the Hawaiian Ridge.

In order to have a hope that the HOME program produces information that can be usefully extrapolated to other topographic environments and that can be employed in improving estimates of the amount of tidal energy available for maintaining the abyssal stratification, the specific mechanisms of energy transfer from the external tide down to the small-scale mixing must be observed. This constitutes the third goal of HOME: to observe the principal mechanisms which transfer energy from the large scale tides to turbulent motions. How do these mechanisms depend on the structure of the topography? Do they work differently in the deep sea versus the upper ocean? How do the depth and lateral dependencies of K_ρ depend on the characteristics of the topography and the tides?

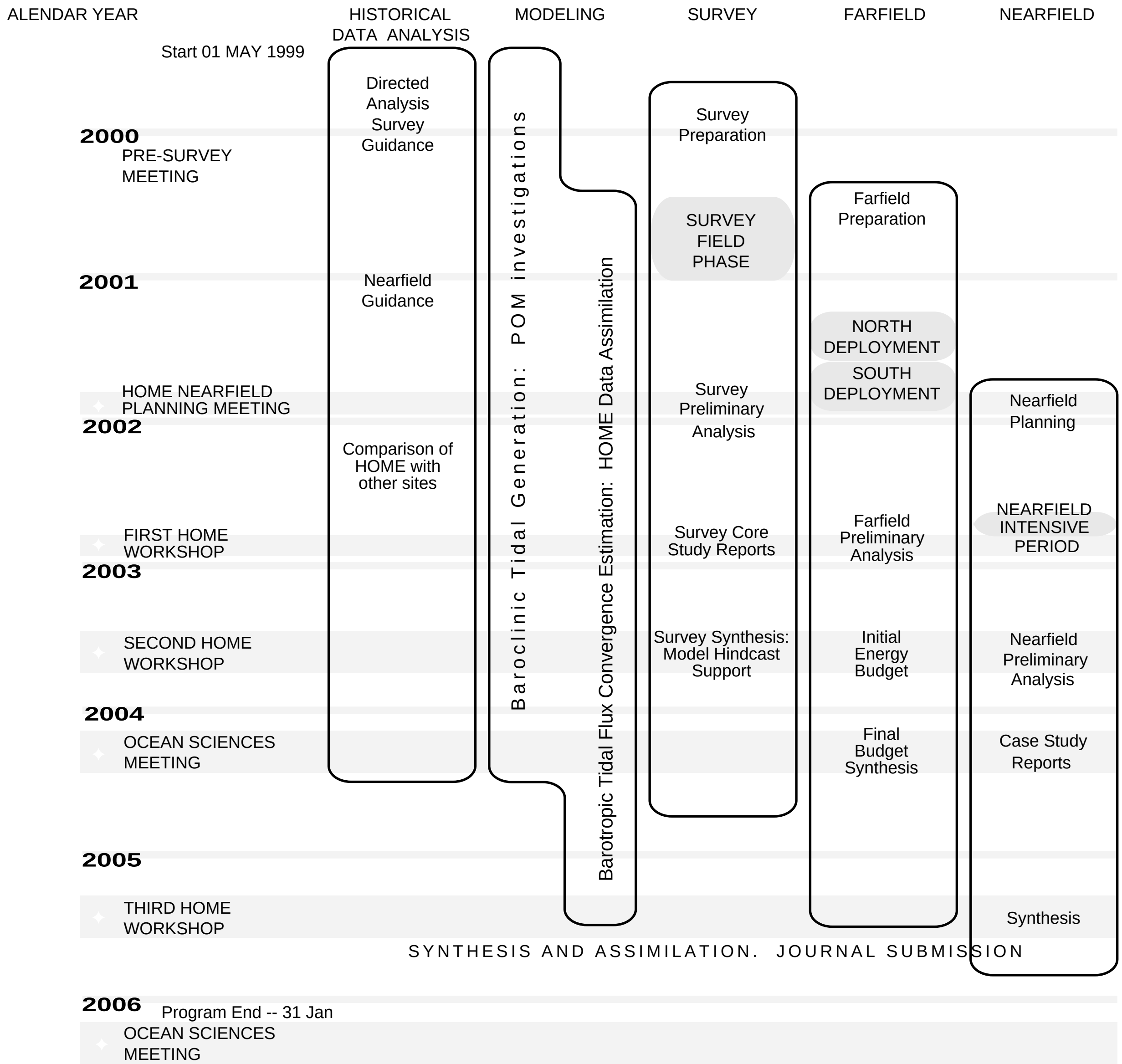
Ultimately, global generalization of the HOME results will depend on how well we understand the energy transfer mechanisms, how well we have quantified them, and how well we can model them either directly or parametrically. Thus, the final goal of HOME is to validate numerical models of external tide propagation and dissipation, and models of internal tide generation, propagation and dissipation, all in the presence of acute and irregular topography.

In the best of all possible outcomes, HOME will advance understanding of topographically-catalyzed mixing, and will contribute significantly to the classical problems of tidal dissipation, global diapycnal mixing, and the maintenance of the abyssal stratification. HOME will contribute to the advancement of tidal models through improved parameterizations of energy dissipation processes. And, HOME will contribute to the advancement of ocean and climate modeling through improved parameterizations of abyssal mixing processes.

Strategy

The HOME goals will be achieved through a judicious integration of modeling and observational enterprises. The timeline for HOME activities is presented in Table 2.

Table 2. HOME Time-line [5]



HOME begins with a year of analysis of historical data[6] to provide preliminary information on the locations and strengths of enhanced mixing in relation to topography. Coincident modeling will suggest whether these sites are related to the generation of internal tides. This information will be employed in the design of the first field program, the Survey.

In the Summer and Fall of 2000, a Survey of the Ridge from 150° W to 165° W will employ both shallow and deep instruments (towed, dropped, and moored) to gather information on the principal phenomena involved in mixing, their geographic distribution and, to a lesser degree, their temporal variability. A schematic of the Survey field work is presented in Figure 1. Table 3 summarizes the tools and participants to be used in the Survey. Descriptions of the instrumentation can be found in the HOME proposal on the web page previously cited.

Based on the information obtained from the Historical Data Analysis, Modeling and Survey efforts, a specific site will be selected for an intensive Nearfield experiment. This site will encompass topography ranging from 500m

[5] Table prepared by R. Pinkel.

[6] Historical data includes the following: near-surface currents from shipboard ADCP transits to/from the Hawaii Ocean Time-series (HOT) stations (see the web site http://www.soest.hawaii.edu/HOT_WOCE/), and to/from Hawaiian ports by various oceanographic vessels, including the R/V Cromwell that makes 10 transits a year along the Hawaiian Archipelago (see the ADCP archive http://ilikai.soest.hawaii.edu /sadcp/); repeated CTD's from several sites occupied during HOT and Hawaii-to-Tahiti Shuttle cruises; CTD's from oceanographic cruises in the vicinity of the Hawaiian Islands; a variety of nearshore moored current meter data; and more.

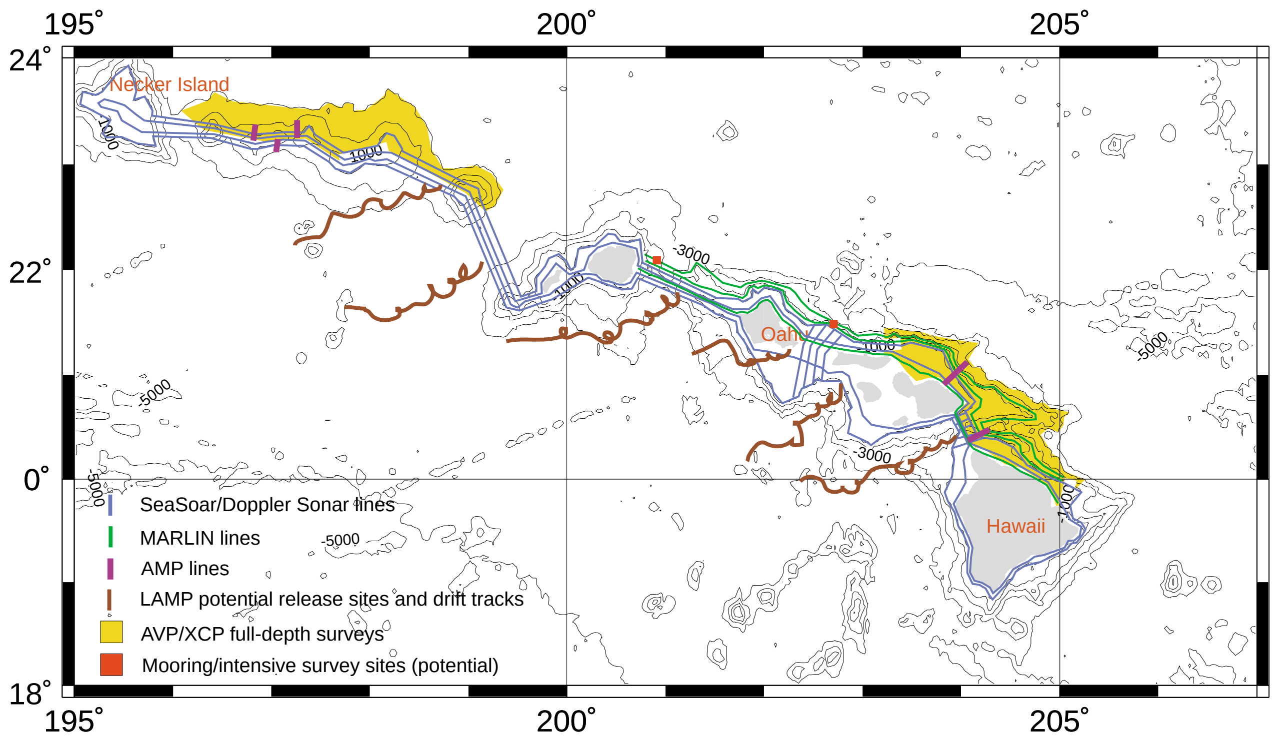


Figure 1. Schematic display of the geographic extent of the Survey program sampling. This plan will evolve as information is obtained from the Historical Data Analysis and Modeling programs, and from the real-time analysis of the Survey data. SeaSoar Doppler Sonar and MARLIN lines represent towed sampling, while AMP and AVP/XCP regions mark areas for sampling by dropped profilers. LAMP drifter tracks are represented by wiggly lines. Moorings, represented by red squares, will be deployed for 3 months. See Table 3 for a list of instrumentation, variables to be measured, and sampling characteristics. (Figure prepared by D. Rudnick.)

to over 3000m in depth, over which significant tidalgenic mixing will have been observed. The Nearfield program will study the spatial and temporal structures of mixing processes in detail in order to understand the mechanisms involved, quantify mixing rates, determine the explicit connections between the mixing and the deep sea environment, and develop parameterizations of the dominant processes.

As part of the Nearfield program, moorings and a high frequency radar system (e.g., Paduan and Rosenfeld, 1996) will be deployed for a full year to establish the long-term surface and sub-surface environmental characteristics of the site. During the Fall, 2002, a six-week intensive observation period will be undertaken using much of the same instrumentation as employed during the Survey (Table 3), but concentrated in the smaller Nearfield site to achieve greater spatial and temporal definition..

A Farfield component of HOME will be deployed in 2001, between the Survey and Nearfield experiments (Table 2). The Farfield experiment will obtain measurements of the external tidal energy flux via a combination of bottom pressure (Pb) measurements with measurements of the external tide currents using both tomographic (e.g., Dushaw et al., 1995) and horizontal electric field (HEM) techniques (e.g., Filloux et al., 1991). Figure 2 displays the Farfield array of instruments. Energy flux convergence at the Ridge will be estimated directly, but raw fluxes will also be used to tune an external tide model for a potentially more accurate flux divergence calculation.

The outward flux of low mode internal tide energy will also be measured during the Farfield experiment, principally by tomography (e.g., Dushaw et al., 1995, Dushaw and Worcester, 1998). The specific vertical modal structure of the internal tides within the Farfield array will be determined by high resolution current and stratification profiling from the R/P FLIP.

Throughout the duration of HOME numerical modeling efforts will be focused on elucidating the generation mechanisms and structures of the internal tides around Hawaii. HOME experimental results (data and analysis products) will be assimilated into regional barotropic and baroclinic tide models in order to rationally extend the HOME tidal energy flux convergence estimates to the whole length of the Ridge (and eventually globally), and to study further the structure and decay characteristics of the internal tides as a function of distance from the source regions.

Table 3. Survey Participants and Tools

P.I.	Instrument	Variables	Vertical Rseolution, Range	Horizontal Resolution, Range	Temporal Res., Tow Speed, Profile Time
Rudnick	SeaSoar CTD Transmissometer	T, S, Optical Transmissivity	Sawtooth: 1 m res. 400 m range	Sawtooth 3 km res. Level: 4 m res.	8 knots (86 km in 6 h)
Pinkel	Doppler Sonar	u, v	3 m res. to 400 m 10 m res. to 1 km	3 km res.	8 knots
Sherman	LAMP	T, S, χ_T	400 m range	Determined by current	3 h
Gregg, Miller	AMP	T, S, ε, χ_T	1500 m range	1 km	15 min to 300 m
Gregg, Miller	BioSonics echo sounder	Acoustic backscatter	200 m range	8 m	8 knots
Kunze, Sanford, and Lee	AVP	u, v, w, T, S, ε, Optical Transmissivity	1-2 m res. 10 m from bottom	15 km	4 h to 4500 m
Kunze, Sanford, and Lee	XCP	u, v, T	O(m) res. 1600 m range	15 km	6 profiles per 12 h night
Moum, Caldwell	MARLIN	u, v, T, S, ε, χ_T, χ_S, TKE, Optical Transmissivity	u, v: O(m) res. 200 m range from body to 2500 m	T, S, ε, χ: O(m)	2 knots (22 km in 6 h)
Levine, Boyd	Moorings (2) ADCP Temperature Conductivity	u, v, T, S	u, v: 8 m res. bottom 400 m range T: 9/mooring S: 4/mooring	N/A	10 min

Relevance of HOME

Under the principal assumption motivating HOME, that the structure of the abyssal stratification is fundamentally determined by abyssal mechanical mixing rather than ventilation at high latitudes, the required mixing must occur via phenomena engendered at the water-earth boundary. The existence of such "boundary" mixing, being certainly unevenly distributed in space, could have a fundamental impact on the qualitative character of the ocean circulation, on the strength of the meridional overturning circulation (MOC), and on the role of the ocean in fixing the present climate state as well as past climate states. For example, if boundary mixing provides diapycnal fluxes, the depth-dependence of the large-scale diffusivity canot be considered to be known; plausible variations in the depth-dependence lead to different signs for the direction of the mean meridional flows in the ocean interior (Gargett, 1984). And, horizontal localization of mixing can produce significant qualitative changes in the expected ocean circulation (e.g., Marotzke, 1997; Samelson, 1998)

The potential importance of abyssal mechanical mixing is firmly advanced by Munk and Wunsch (1998): "the strength of the MOC and associated [poleward] heat flux may well be primarily determined not by the high-latitude buoyancy forcing, but by the power available to return the fluid to the surface layers", and "the equator-to-pole heat flux of 2000 TW associated with the meridional overturning circulation would not exist without the comparatively minute [~2 TW] mechanical mixing sources. Coupled with the finding that mixing occurs at a few dominant sites, there is a host of questions concerning the maintenance of the present climate state, but also that of paleoclimates and their relation to detailed continental configurations [and bathymetry], the history of the earth-moon system, and a possible great sensitivity to details of the wind system." (Bracketed text inserted by us.)

In simplest terms, if there is no mechanical energy available to mix heat downward from the surface, within a few thousand years the oceans would consist of a very cold nearly isothermal layer beneath a relatively thin, warm surface layer with a stratification that is principally determined by ventilation and which has only a very weak convective circulation. Without a strong MOC, poleward heat flux would be dramatically reduced. In the geologic past, tidal dissipation was weaker because the tides were less resonant, and mixing in the deep ocean may have been much less energtic than today leading to a signifcantly different MOC than at present and much

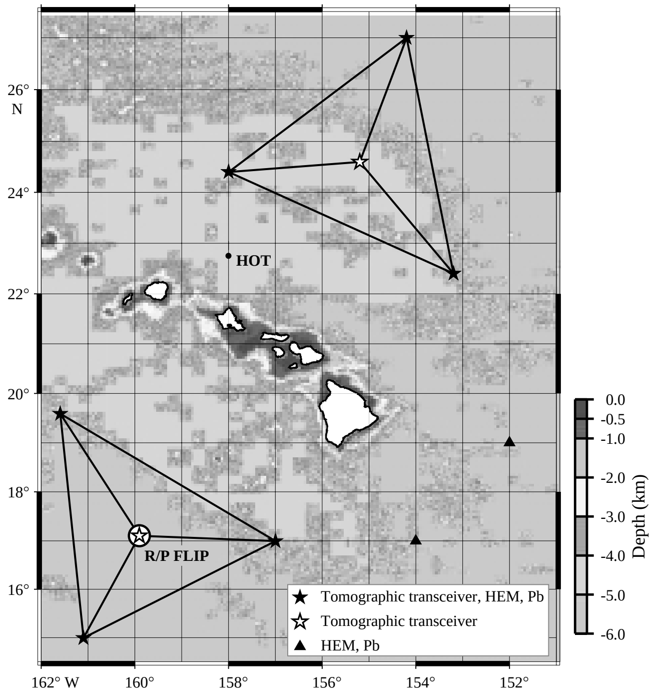


Figure 2. Map of the Hawaiian Is. and vicinity, displaying the probable locations of the tomographic transceivers co-located with the HEM/Pb pairs (solid stars), the tomographic transceivers alone (open stars), the HEM/Pb pairs alone (triangles) and the location where R/P Flip will be moored for a duration of one month (open circle). The shaded topography is taken from the Smith and Sandwell (1997) bathymetric dataset. (Figure prepared by P. Worcester.)

different abyssal circulation patterns.

But after stating all this, and after expending all the effort to design HOME and secure its funding, it must be acknowledged that the processes maintaining the abyssal stratification are very poorly understood. How important is direct ventilation? Is it strong enough to obviate the need for more abyssal mechanical mixing than is provided by the internal wave field? On the other hand, if bottom water formation is much greater than the 30 Sv assumed by MW98, both ventilation and significant mechanical mixing at the boundaries may be required to maintain the abyssal stratification. That the maxima in boundary mixing have not yet been observed is certainly likely. What processes lie waiting to be discovered?

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