Sediment trap flux measurements for the Hawaii Ocean Time-Series (HOT) project from December 1988 to November 2021 at Station ALOHA

Website: https://www.bco-dmo.org/dataset/737393
Data Type: Cruise Results
Version: 2
Version Date: 2023-08-08

Project
» [Current] Hawaii Ocean Time-series (HOT): 2023-2028; [Previous] Hawaii Ocean Time-series (HOT): Sustaining ocean ecosystem and climate observations in the North Pacific Subtropical Gyre (HOT)

Programs
» Ocean Time-series Sites (Ocean Time-series)
» Ocean Carbon and Biogeochemistry (OCB)
» U.S. Joint Global Ocean Flux Study (U.S. JGOFS)

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Abstract
Particle flux measurements from the Hawaii Ocean Time-Series (HOT). Particle flux was measured at a standard reference depth of 150 meters using multiple cylindrical particle interceptor traps deployed on a free-floating array for approximately 60 hours during each cruise. Sediment trap design and collection methods are described in Winn et al. (1991). Samples were analyzed for particulate carbon, nitrogen, phosphorus, and silica. Typically six traps are analyzed for particulate carbon and particulate nitrogen, three for particulate phosphorus, and another three traps for particulate silica.

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Coverage

Spatial Extent: **Lat**:22.75 **Lon**:-158
Temporal Extent: 1988-12-01 - 2021-11-01

Dataset Description

Monthly measurements of particle flux were collected at Station ALOHA as part of the HOT program. Passively

sinking particulate matter is intercepted using a free-floating sediment trap array. After screening the collected materials to remove zooplankton and micronekton carcasses, portions of the remaining sample are analyzed for C, N, P and biogenic-Si flux.

Methods & Sampling

Particle flux was measured at a standard reference depth of 150 meters using multiple cylindrical particle interceptor traps deployed on a free-floating array for approximately 60 hours during each cruise. Sediment trap design and collection methods are described in Winn et al. (1991). Passively sinking particulate matter is collected, prescreened (335 µm) to remove zooplankton and micronekton carcasses, then the sample materials are analyzed for C, N, P and mass flux (mg m-2 d-1). Samples were analyzed for particulate carbon (PC), nitrogen (PN), phosphorus (PP), and silica (PSi). Typically six traps are analyzed for PC and PN, three for PP, and another three traps for PSi.

A summary of methodology is listed below. Full details can be found at the HOT Field & Laboratory Protocols page. (http://hahana.soest.hawaii.edu/hot/protocols/protocols.html#) or below in Related Publications section (Karl et al., and HOT Program Sediment Trap Protocols: Chapter 18)

1. Principle
Although most of the particulate matter both on the seafloor and in suspension in seawater is very fine, evidence suggests that most of the material deposited on the benthos arrives via relatively rare, rapidly sinking large particles (McCave, 1975). Therefore, in order to describe adequately the ambient particle field and to understand the rates and mechanisms of biogeochemical cycling in the marine environment, it is imperative to employ sampling methods that enable the investigator to distinguish between the suspended and sinking pools of particulate matter. This universal requirement for a careful and comprehensive analysis of sedimenting particles has resulted in the development, evaluation and calibration of a variety of *in situ* particle collectors or sediment traps. The results, after nearly a decade of intensive field experiments, have contributed significantly to our general understanding of: (1) the relationship between the rate of primary production and downward flux of particulate organic matter, (2) mesopelagic zone oxygen consumption and nutrient regeneration, (3) biological control of the removal of abiogenic particles from the surface ocean and (4) seasonal and interannual variations in particle flux to the deep-sea. Future sediment trap studies will, most likely, continue to provide novel and useful data on the rates and mechanisms of important biogeochemical processes.

At Station ALOHA, we presently deploy a free-drifting sediment trap array with 12 individual collectors positioned at 150, 300 and 500 m. The deployment period is generally 72 hours. The passively sinking particles are subsequently analyzed for a variety of chemical properties, including: total mass, C, N and P.

2. Precautions
Because particle fluxes in oligotrophic habitats are expected to be low, special attention must be paid to the preparation of individual sediment trap collector tubes so that they are clean and free of dust and other potentially contaminating particles. Traps should be capped immediately after filling and immediately after retrieval. Attention should be paid to airborne and/or shipboard particulate contamination sources. In addition, the time interval between trap retrieval and subsample filtration should be minimized in order to limit the inclusion of extraneous abiotic particles and the post-collection solubilization of particles.

3. Field Operations
Hardware
The HOT program free-floating sediment trap array is patterned after the MULTITRAP system pioneered by Knauer et al. (1979) and used extensively in the decade-long VERTEX program. Twelve individual sediment trap collectors (0.0039 m2) are typically deployed at three depths (150, 300 and 500 m). The traps are affixed to a PVC cross attached to 1/2" Spectra (polyethylene) line. The traps are tracked using XEOS and Argos satellite transmitters, VHF radio, and strobelights. Since HOT-71 cruise (insert date here), both the trap array configuration and the deployment period (formerly 72 hours) were altered to conserve ship time.

Trap solutions
Prior to deployment, each trap is cleaned with 1 M HCl, rinsed thoroughly with deionized water then filled with a high-density solution to prevent advective-diffusive loss of extractants and preservatives during the deployment period and to eliminate flushing of the traps during recovery (Knauer et al., 1979). The trap solution is prepared by adding 50 g of NaCl to each liter of surface seawater. This brine solution is gravity filtered through a 0.2 µm filter cartridge after the addition of 10 ml per liter 100% formalin solution. Individual traps are filled and at least 10 liters of the trap solution is saved for analysis of solution blanks.

Post-recovery processing
Upon recovery, individual traps are capped and transported to the shipboard portable laboratory for analysis. Care is taken not to mix the higher density trap solutions with the overlying seawater. Trap samples are processed from deep to shallow in order to minimize potential contamination. The depth of the interface between the high density solution and overlying seawater is marked on each trap and a second mark is made 5 cm above the interface. The overlying seawater is then aspirated with a plastic tube attached to a vacuum system to the upper mark in order to avoid disturbing the high density solution below. Because some sinking particulate material collects near the interface between the high density solution and the overlying seawater, the overlying seawater is removed only to a depth that is 5 cm above the previously identified interface.

After the overlying seawater has been removed from all the traps at a given depth, the contents of each trap is gently mixed to disrupt large amorphous particles and then passed through an acid rinsed 335 µm NitexR screen to remove contaminating zooplankton and micronekton which entered the traps in a living state and are not truly part of the passive flux. The traps are rinsed with a portion of the <335 µm sample in order to recover all particulate matter, and the 335 µm NitexR screen is examined to determine whether residual material, in addition to the so-called "swimmers", is present. If so, the screens are rinsed again with a portion of the 335 µm filtrate. After all traps from the same depth have been processed, the 335 µm screen is removed and placed into a vial containing 20 ml of formalin-seawater solution, and stored at 4°C for subsequent microscopic examination and organism identification and enumeration.

4. Determination of C, N, P and biogenic-Si Flux
The quantities of particulate C, N, P and biogenic silica in the screened trap solutions are determined using methods described in the chapters for Particulate Carbon and Nitrogen, Particulate Phosphorus, and Particulate Biogenic Silica in the HOT protocols document (*see Related Publications section below*). Six replicate traps are used for C/N determinations and three additional traps for P. Typically, 1.5 to 2 liters are used for a single C/N or P measurement, and a subsample of 250 mL for Si. An equivalent volume of the time-zero sediment trap solution, filtered through the appropriate filters is used as a C, N or P blank

Addendum - PPO4 protocol (April 7, 2015)
The method used for the analysis of particulate phosphate (PPO4) has been modified and applied to samples analyzed from November 2011 (HOT 236) to the present. The previous protocol was in use over at least the previous 10-year period. The modified procedure included vortexing of the sample prior to a longer leaching time (1 hour versus 30 min) of the GFF filter in 0.15 N HCl at room temperature.

Both the previous and modified procedures were tested in paired analyses on samples collected over one year (12 cruises). The modified procedure resulted in higher yields by approximately 50% for water column samples (integrated 0-100 m: old method 1.00±0.27 mmol P m-2, versus 1.56±0.14 mmol P m-2) and approximately 30% for P-flux estimated from sediment trap samples (old method: 0.31±0.07 mg P m-2 d-1 versus 0.40±0.09 mg P m-2 d-1).

Key to Treatment indicator:

- C = Solutions from individual traps combined and replicate subsamples drawn from this solution;
- I = Individual traps sampled as replicates;
- W = Swimmers picked out before analysis;
- O = Some other treatment.

Data Processing Description

Calculations

C, N, P and biogenic-Si flux is calculated as follows:

$$\text{mg C (or N, P) m-2 d-1} = \frac{[(Cs-Cb)] * Vt}{Vf * 0.0039 * t}$$

where:

- Cs = carbon (mg) in sample
- Cb = carbon (mg) in blank
- Vt = volume of trap (liters)
- Vf = volume filtered (liters)
- 0.0039 = cross-sectional area of trap (m2)
- t = deployment period (d)

BCO-DMO Processing Description

- Transferred data from the University of Hawaii ftp site to the BCO-DMO servers.
- Concatenated the data files and ordered by cruise
- Added column for original datafile name
- Added columns for latitude and longitude of Station ALOHA.
- Combined separate Date and Time columns into single ISO8601 datetime format

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Data Files

File
737393_v2_particle_flux.csv (Comma Separated Values (.csv), 72.90 KB) MD5:816963a0efadf4fee3b631d4dc423423 Primary data file for dataset 737393 version 2

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Related Publications

Fujieki, L., F. Santiago-Mandujano, C. Fumar, R. Lukas and M. Church. (2015) Hawaii Ocean Time-series Program Data Report 24: 2012.
Results
,
Methods

Hawai'i Ocean Time-Series (HOT) Program Field and Laboratory Protocols. Chapter 18: Sediment Trap Protocols Free-Floating Array. https://hahana.soest.hawaii.edu/hot/protocols/protocols.html?Chapter=18#
Methods

Karl, D., Winn, C., Hebel, D., and Letelier, R. Hawai'i Ocean Time-Series Program Field and Laboratory Protocols. https://hahana.soest.hawaii.edu/hot/protocols/protocols.html#
Methods

Knauer, G. A., Martin, J. H., & Bruland, K. W. (1979). Fluxes of particulate carbon, nitrogen, and phosphorus in the upper water column of the northeast Pacific. Deep Sea Research Part A. Oceanographic Research Papers, 26(1), 97–108. doi:10.1016/0198-0149(79)90089-x https://doi.org/10.1016/0198-0149(79)90089-X
Methods

McCave, I. N. (1975). Vertical flux of particles in the ocean. Deep Sea Research and Oceanographic Abstracts, 22(7), 491–502. doi:10.1016/0011-7471(75)90022-4
Methods

Nielsen, E. S. (1952). The Use of Radio-active Carbon (C14) for Measuring Organic Production in the Sea. ICES Journal of Marine Science, 18(2), 117–140. doi:10.1093/icesjms/18.2.117
Methods

Scharek, R., Tupas, L., & Karl, D. (1999). Diatom fluxes to the deep sea in the oligotrophic North Pacific gyre at Station ALOHA. Marine Ecology Progress Series, 182, 55–67. https://doi.org/10.3354/meps182055
Methods

Winn, C., C. Sabine, D. Hebel, F. Mackenzie and D. M. Karl. (1991) Inorganic carbon system dynamics in the central Pacific Ocean: Results of the Hawaii Ocean Time-series program. EOS, Transactions of the American Geophysical Union 72, 70.
Results

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Parameters

Parameter	Description	Units
Cruise	Cruise number	unitless
Latitude	Latitude	decimal degrees
Longitude	Longitude	decimal degrees
Start_ISO_DateTime_UTC	Start datetime in ISO 8601 format	unitless
End_ISO_DateTime_UTC	End datetime in ISO 8601 format	unitless
Depth	Depth	meters
Treatment	Treatment of the sample (C=Solutions from individual traps combined and replicate subsamples drawn from this solution; I=Individual traps sampled as replicates; W=Swimmers picked out before analysis; O=Some other treatment)	unitless
Carbon_flux	Carbon flux	milligrams per square meter per day (mg/m^2/d)
Carbon_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	milligrams per square meter per day (mg/m^2/d)
Carbon_numreps	Number of replicate carbon samples collected for replicate analysis	unitless
Nitrogen_flux	Nitrogen flux	milligrams per square meter per day (mg/m^2/d)
Nitrogen_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	milligrams per square meter per day (mg/m^2/d)
Nitrogen_numreps	Number of replicate nitrogen samples collected for replicate analysis	unitless
Phosphorus_flux	Phosphorus flux	milligrams per square meter per day (mg/m^2/d)
Phosphorus_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	milligrams per square meter per day (mg/m^2/d)
Phosphorus_numreps	Number of replicate phosphorus samples collected for replicate analysis	unitless

Mass_flux	Mass flux	milligrams per square meter per day (mg/m^2/d)
Mass_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	milligrams per square meter per day (mg/m^2/d)
Mass_numreps	Number of replicate mass samples collected for replicate analysis	unitless
Silica_flux	Silica flux	milligrams per square meter per day (mg/m^2/d)
Silica_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	milligrams per square meter per day (mg/m^2/d)
Silica_numreps	Number of replicate silica samples collected for replicate analysis	unitless
Delta_15N	Delta-15N of particulate nitrogen (permil vs air-N2)	permil vs. air-N2
Delta_15N_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	permil vs. air-N2
Delta_15N_numreps	Number of replicate nitrogen isotope samples for replicate analysis	unitless
Delta_13C	Delta-13C of particulate carbon (permil vs. VPDB)	permil vs. VPDB
Delta_13C_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	permil vs. VPDB
Delta_13C_numreps	Number of replicate carbon isotope samples for replicate analysis	unitless
PIC_flux	Particulate Inorganic Carbon flux	milligrams per square meter per day (mg/m^2/d)
PIC_sd_diff	Either standard deviation or difference. If num replicates >= 3, then std dev. If num reps = 2, then difference	milligrams per square meter per day (mg/m^2/d)
PIC_numreps	Number of replicate PIC samples collected for replicate analysis	unitless
Filename	Original filename of particle flux data from HOT	unitless

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Instruments

Dataset-specific Instrument Name	PE-2400 Carbon/Nitrogen analyzer with integrator
Generic Instrument Name	Particulate Organic Carbon/Nitrogen Analyzer
Dataset-specific Description	PE-2400 Carbon/Nitrogen analyzer with integrator
Generic Instrument Description	A unit that accurately determines the carbon and nitrogen concentrations of organic compounds typically by detecting and measuring their combustion products (CO2 and NO).

Dataset-specific Instrument Name	Cahn electronic microbalance
Generic Instrument Name	scale
Dataset-specific Description	Cahn electronic microbalance
Generic Instrument Description	An instrument used to measure weight or mass.

Dataset-specific Instrument Name	sediment trap array
Generic Instrument Name	Sediment Trap
Dataset-specific Description	sediment trap array (spar buoy, radiotransmitter, strobe light, floats, trap supports, collector tubes)
Generic Instrument Description	Sediment traps are specially designed containers deployed in the water column for periods of time to collect particles from the water column falling toward the sea floor. In general a sediment trap has a jar at the bottom to collect the sample and a broad funnel-shaped opening at the top with baffles to keep out very large objects and help prevent the funnel from clogging. This designation is used when the specific type of sediment trap was not specified by the contributing investigator.

Dataset-specific Instrument Name	spectrophotometer and 1-cm cuvette
Generic Instrument Name	Spectrophotometer
Dataset-specific Description	spectrophotometer (Perkin-Elmer Lambda 3B) and 1-cm cuvette
Generic Instrument Description	An instrument used to measure the relative absorption of electromagnetic radiation of different wavelengths in the near infra-red, visible and ultraviolet wavebands by samples.

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Deployments

HOT_cruises

Website	https://www.bco-dmo.org/deployment/58879
Platform	Unknown Platform
Report	http://hahana.soest.hawaii.edu/hot/
Start Date	1988-10-31
Description	Since October 1988, the Hawaii Ocean Time-series (HOT) program has investigated temporal dynamics in biology, physics, and chemistry at Stn. ALOHA (22°45' N, 158°W), a deep ocean field site in the oligotrophic North Pacific Subtropical Gyre (NPSG). HOT conducts near monthly ship-based sampling and makes continuous observations from moored instruments to document and study NPSG climate and ecosystem variability over semi-diurnal to decadal time scales.

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Project Information

[Current] Hawaii Ocean Time-series (HOT): 2023-2028; [Previous] Hawaii Ocean Time-series (HOT): Sustaining ocean ecosystem and climate observations in the North Pacific Subtropical Gyre (HOT)

Website: https://hahana.soest.hawaii.edu/hot/

Coverage: North Pacific Subtropical Gyre; 22 deg 45 min N, 158 deg W

NSF Award Abstract:

Long-term observations of ocean physics, biology, and chemistry across decades provide a powerful lens for understanding the response of the oceans to environmental change. This award will continue the Hawaii Ocean Time-series (HOT) research program, which began in 1988, for an additional five years. Continuity of these observations will improve the value of the dataset for deciphering how natural and human-influenced climate signals affect ecosystem structure in the Pacific Ocean. All HOT program data are publicly available and are frequently used by researchers and policy makers around the world. HOT also serves as (1) a testbed for the development of new sensors and methodologies, (2) a calibration/validation site, (3) an invaluable training ground that attracts students and researchers from around the globe, and (4) a forum for international collaboration and capacity building.

The proposed research will rely on shipboard observations and experiments conducted on ten separate five-day expeditions per year along with near-continuous moored platform measurements of air-sea interactions, ocean mixing, and physical characteristics of the deep sea. Observations include biogeochemical and physical measurements required for continued assessment of dynamics in ocean carbon and nutrient pools and fluxes, plankton community structure, ecosystem productivity, and inherent optical properties of the water column. The major program goals and objectives over the next 5 years remain as in prior years and include: (1) sustain high quality, time-resolved oceanographic measurements on the interactions between ocean-climate and ecosystem variability in the North Pacific Subtropical Gyre (NPSG), (2) quantify time-varying (seasonal to decadal) changes in reservoirs and fluxes of carbon and associated bioelements (nitrogen, phosphorus, and silicon), (3) constrain processes controlling air-sea carbon exchange, rates of carbon transformation through the planktonic food web, and fluxes of carbon into the ocean?s interior, (4) extend to 40 years a climatology of hydrographic and biogeochemical dynamics from which to gauge anomalous or extreme changes to the NPSG habitat, forming a multi-decadal baseline from which to decipher natural and anthropogenic influences on the NPSG ecosystem, (5) continue to provide scientific and logistical support to ancillary programs that benefit from the temporal context, interdisciplinary science, and regular access to the open sea afforded by HOT program occupation of Station ALOHA, including projects implementing, testing, and validating new methodologies and transformative ocean sampling technologies, and (6) provide unique training and educational opportunities for the next generation of ocean scientists.

Hawai'i Ocean Time-Series Project Summary

Systematic, long-term observations are essential for evaluating natural variability of Earth’s climate and ecosystems and their responses to anthropogenic disturbances. Since October 1988, the Hawaii Ocean Time-series (HOT) program has investigated temporal dynamics in biology, physics, and chemistry at Stn. ALOHA (22°45' N, 158°W), a deep ocean field site in the oligotrophic North Pacific Subtropical Gyre (NPSG). HOT conducts near monthly ship-based sampling and makes continuous observations from moored instruments to document and study NPSG climate and ecosystem variability over semi-diurnal to decadal time scales. HOT was founded to understand the processes controlling the time-varying fluxes of carbon and associated biogenic

elements in the ocean and to document changes in the physical structure of the water column. To achieve these broad objectives, the program has several specific goals:

1. Quantify time-varying (seasonal to decadal) changes in reservoirs and fluxes of carbon (C) and associated bioelements (nitrogen, oxygen, phosphorus, and silicon).
2. Identify processes controlling air-sea C exchange, rates of C transformation through the planktonic food web, and fluxes of C into the ocean's interior.
3. Develop a climatology of hydrographic and biogeochemical dynamics from which to form a multi-decadal baseline from which to decipher natural and anthropogenic influences on the NPSG ecosystem.
4. Provide scientific and logistical support to ancillary programs that benefit from the temporal context, interdisciplinary science, and regular access to the open sea afforded by HOT program occupation of Sta. ALOHA, including projects implementing, testing, and validating new methodologies, models, and transformative ocean sampling technologies.

Over the past 24+ years, time-series research at Station ALOHA has provided an unprecedented view of temporal variability in NPSG climate and ecosystem processes. Foremost among HOT accomplishments are an increased understanding of the sensitivity of bioelemental cycling to large scale ocean-climate interactions, improved quantification of reservoirs and time varying fluxes of carbon, identification of the importance of the hydrological cycle and its influence on upper ocean biogeochemistry, and the creation of long-term data sets from which the oceanic response to anthropogenic perturbation of elemental cycles may be gauged.

A defining characteristic of the NPSG is the perennially oligotrophic nature of the upper ocean waters. This biogeochemically reactive layer of the ocean is where air-sea exchange of climate reactive gases occurs, solar radiation fuels rapid biological transformation of nutrient elements, and diverse assemblages of planktonic organisms comprise the majority of living biomass and sustain productivity. The prevailing Ekman convergence and weak seasonality in surface light flux, combined with relatively mild subtropical weather and persistent stratification, result in a nutrient depleted upper ocean habitat. The resulting dearth of bioessential nutrients limits plankton standing stocks and maintains a deep (175 m) euphotic zone. Despite the oligotrophic state of the NPSG, estimates of net organic matter production at Sta. ALOHA are estimated to range ~1.4 and 4.2 mol C m^2 yr^1. Such respectable rates of productivity have highlighted the need to identify processes supplying growth limiting nutrients to the upper ocean. Over the lifetime of HOT numerous ancillary science projects have leveraged HOT science and infrastructure to examine possible sources of nutrients supporting plankton productivity. Both physical (mixing, upwelling) and biotic (N2 fixation, vertical migration) processes supply nutrients to the upper ocean in this region, and HOT has been instrumental in demonstrating that these processes are sensitive to variability in ocean climate.

Station ALOHA - site selection and infrastructure
Station ALOHA is a deep water (~4800 m) location approximately 100 km north of the Hawaiian Island of Oahu. Thus, the region is far enough from land to be free of coastal ocean dynamics and terrestrial inputs, but close enough to a major port (Honolulu) to make relatively short duration (<5 d) near-monthly cruises logistically and financially feasible. Sampling at this site occurs within a 10 km radius around the center of the station. On each HOT cruise, we begin each cruise with a stop at a coastal station south of the island of Oahu, approximately 10 km off Kahe Point (21' 20.6'N, 158' 16.4'W) in 1500 m of water. Station Kahe (termed Station 1 in our database) is used to test equipment and train new personnel before departing for Station ALOHA. Since August 2004, Station ALOHA has also been home to a surface mooring outfitted for meteorological and upper ocean measurements; this mooring, named WHOTS (also termed Station 50), is a collaborative project between Woods Hole Oceanographic Institution and HOT. WHOTS provides long-term, high-quality air-sea fluxes as a coordinated part of HOT, contributing to the program's goals of observing heat, fresh water and chemical fluxes. In 2011, the ALOHA Cabled Observatory (ACO) became operational. This instrumented fiber optic cabled observatory provides power and communications to the seabed (4728 m). The ACO currently configured with an array of thermistors, current meters, conductivity sensors, 2 hydrophones, and a video camera.

HOT Sampling Strategy
HOT relies on the UNOLS research vessel Kilo Moana operated by the University of Hawaii for most of our near-monthly sampling expeditions. The exact timing of HOT cruises is dictated by the vessel schedule, but to date, our sampling record is not heavily aliased by month, season, or year. When at Station ALOHA, HOT relies on a variety of sampling strategies to capture the dynamic range of time-variable physical and biogeochemical dynamics inherent to the NPSG ecosystem, including high resolution conductivity-temperature-depth (CTD) profiles; biogeochemical analyses of discrete water samples; in situ vertically profiling bio-optical instrumentation; surface tethered, free-drifting arrays for determinations of primary production and particle fluxes; bottom-moored, deep ocean (2800 m, 4000 m) sediment traps; and oblique plankton net tows. The suite of core measurements conducted by HOT has remained largely unchanged over the program's lifetime.

On each HOT cruise, samples are collected from the surface ocean to near the sea bed (~4800 m), with the most intensive sampling occurring in the upper 1000 m (typically 13-15 CTD hydrocasts to 1000 m and 2 casts to ~4800 m). HOT utilizes a "burst" vertical profiling strategy where physical and biogeochemical properties are measured at 3-h intervals over a 36-h period, covering 3 semidiurnal tidal cycles and 1 inertial period (~31 h). This approach captures energetic high-frequency variability in ocean dynamics due to internal tides around Sta. ALOHA.

Scientific Background and Findings

Central to the mission of the HOT program is continued quantification of ocean carbon inventories and fluxes, with a focus on describing changes in the sizes of these pools and fluxes over time. HOT routinely quantifies the vertical distributions of the major components of the ocean carbon cycle: dissolved inorganic carbon (DIC), pH, total alkalinity, dissolved organic carbon (DOC), and particulate carbon (PC). The HOT dataset constitutes one the longest running records from which to gauge the oceanic response to continued anthropogenic changes to the global carbon cycle. The 24+ year record of ocean carbon measurements at Station ALOHA document that the partial pressure of CO2 (pCO2) in the mixed layer is increasing at a rate (1.92 ± 0.13 microatm yr-1), slightly greater than the trend observed in the atmosphere (1.71 ± 0.03 microatm yr^{1}). Moreover, mixed layer concentrations of salinity-normalized DIC are increasing at 1.03 ± 0.07 micromol kg^{1} yr^{1} (Winn et al., 1998; Dore et al., 2009). These long-term changes in upper ocean carbon inventories have been accompanied by progressive decreases in seawater pH (-0.0018 ± 0.0001 yr^{1}) and declines in aragonite and calcite saturation states (Dore et al., 2009). Although the penetration of anthropogenic CO2 is evidenced by long-term decreases in seawater pH throughout the upper 600 m, the rate of acidification at Sta. ALOHA varies with depth. For example, in the upper mesopelagic waters (~160-310 m) pH is decreasing at nearly twice the rate observed in the surface waters (Dore et al., 2009). Such depth-dependent differences in acidification derive from a combination of regional differences in the time-varying climate signatures imprinted on the ventilation history of the waters, mixing, and changes in biological activity associated with different water masses.

Superimposed on these progressive long-term trends in the seawater carbonate system are seasonal- to decadal-scale variations in climate and biogeochemical dynamics that ultimately influence CO2 inventories, fluxes, and trends. Changes in temperature, evaporation-precipitation, and mixing all impart complex, time-varying signatures on the ocean carbon cycle. For example, interactions among low-frequency climate oscillations such as those linked to the El-Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Pacific Gyre Oscillation (NPGO) influence the frequency, intensity, and tracks of winter storms in the NPSG (Lukas, 2001), which in turn modifies physical forcing (wind and air-sea heat/water fluxes) and upper ocean response (stratification, currents and mixing). Such dynamics have important, often non-linear, influences on ocean carbon uptake and biogeochemistry.

Time-series measurements at HOT have also highlighted complex relationships between ecosystem dynamics and climate-driven physical forcing. Historically, the abundances and distributions of the resident plankton community of the NPSG were thought to be relatively stable in both space and time. However, HOT program measurements have identified remarkable temporal (and spatial) heterogeneity in biogeochemical processes and planktonic community structure over seasonal to interannual time scales. In many cases, climate-forced fluctuations in plankton population dynamics resonate from the base of the picoplankton food web to higher trophic levels (Karl, 1999; Karl et al., 2001; Sheridan and Landry, 2004; Corno et al., 2007; Bidigare et al., 2009). However, we currently lack a complete mechanistic understanding of the processes underlying variability in NPSG biogeochemistry.

With continued lengthening of the time series record, HOT measurements have become increasingly useful for identifying low-frequency, interannual- to decadal-scale signals in ocean climate and biogeochemistry. Upper ocean physical dynamics, nutrient availability, plankton productivity, biomass and community structure, and material export at Sta. ALOHA have all been shown to be sensitive to regional- to basin- scale climate oscillations of the Pacific (Karl et al., 1995; Karl, 1999; Dore et al., 2002; Corno et al., 2007; Bidigare et al., 2009). One of the most notable examples coincided with major phase shifts in the ENSO, PDO, and NPGO indices in 1997-1998. Fluctuations in mixing and hydrological forcing accompanying these transitions had important consequences for ocean biogeochemistry and plankton ecology, including changing upper ocean nutrients, concentrations of DIC, and ultimately influencing organic matter export (Dore et al., 2003; Corno et al., 2007; Bidigare et al., 2009). Moreover, these dynamics preceded a shift in plankton community composition, as reflected through nearly 40% increases in concentrations of 19-butanoyoxyfucoxanthin (19-but), 19-hexoyloxyfucoxanthin (19-hex), and fucoxanthin pigment biomarkers used as proxies for pelagophytes, prymnesiophytes, and diatoms, respectively (Bidigare et al., 2009). Similarly, mesozooplankton biomass increased nearly 50% during this period, suggesting sensitivity of trophodynamic coupling to interannual to subdecadal scale variations in ocean climate.

HOT also provides some of the only decadal-scale measurements of in situ primary production necessary for

assessing seasonal to secular scale change. Since 1988, depth integrated (0-125 m) inventories of both chlorophyll a and 14C-based estimates of primary production at Sta. ALOHA and BATS have increased significantly (Corno et al., 2007; Saba et al., 2010). However, these long-term trends are punctuated by considerable interannual variability, much of which occurs in the mid- to lower regions of the euphotic zone (>45 m depth), below depths of detection by Earth-orbiting satellites. The emerging data emphasize the value of in situ measurements for validating remote and autonomous detection of plankton biomass and productivity and demonstrate that detection of potential secular-scale changes in productivity against the backdrop of significant interannual and decadal fluctuations demands a sustained sampling effort.

Careful long-term measurements at Stn. ALOHA also highlight a well-resolved, though relatively weak, seasonal climatology in upper ocean primary productivity. Measurements of 14C-primary production document a ~3-fold increase during the summer months (Karl et al., 2012) that coincides with increases in plankton biomass (Landry et al., 2001; Sheridan and Landry, 2004). Moreover, phytoplankton blooms, often large enough to be detected by ocean color satellites, are a recurrent summertime feature of these waters (White et al., 2007; Dore et al., 2008; Fong et al., 2008). Analyses of ~13-years (1992-2004) of particulate C, N, P, and biogenic Si fluxes collected from bottom-moored deep-ocean (2800 m and 4000 m) sediment traps provide clues to processes underlying these seasonal changes. Unlike the gradual summertime increase in sinking particle flux observed in the upper ocean (150 m) traps, the deep sea particle flux record depicts a sharply defined summer maximum that accounts for ~20% of the annual POC flux to the deep sea, and appears driven by rapidly sinking diatom biomass (Karl et al., 2012). Analyses of the 15N isotopic signatures associated with sinking particles at Sta. ALOHA, together with genetic analyses of N2 fixing microorganisms, implicates upper ocean N2 fixation as a major control on the magnitude and efficiency of the biological carbon pump in this ecosystem (Dore et al., 2002; Church et al., 2009; Karl et al., 2012).

Motivating Questions
Science results from HOT continue to raise new, important questions about linkages between ocean climate and biogeochemistry that remain at the core of contemporary oceanography. Answers have begun to emerge from the existing suite of core program measurements; however, sustained sampling is needed to improve our understanding of contemporary ecosystem behavior and our ability to make informed projections of future changes to this ecosystem. HOT continues to focus on providing answers to some of the questions below:

1. How sensitive are rates of primary production and organic matter export to short- and long-term climate variability?
2. What processes regulate nutrient supply to the upper ocean and how sensitive are these processes to climate forcing?
3. What processes control the magnitude of air-sea carbon exchange and over what time scales do these processes vary?
4. Is the strength of the NPSG CO2 sink changing in time?
5. To what extent does advection (including eddies) contribute to the mixed layer salinity budget over annual to decadal time scales and what are the implications for upper ocean biogeochemistry?
6. How do variations in plankton community structure influence productivity and material export?
7. What processes trigger the formation and demise of phytoplankton blooms in a persistently stratified ocean ecosystem?

References

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Program Information

Ocean Time-series Sites (Ocean Time-series)

Coverage: Bermuda, Cariaco Basin, Hawaii

Program description text taken from Chapter 1: Introduction from the **Global Intercomparability in a Changing Ocean: An International Time-Series Methods Workshop** report published following the workshop held November 28-30, 2012 at the Bermuda Institute of Ocean Sciences. The full report is available

from the workshop Web site hosted by US OCB: http://www.whoi.edu/website/TS-workshop/home

Decades of research have demonstrated that the ocean varies across a range of time scales, with anthropogenic forcing contributing an added layer of complexity. In a growing effort to distinguish between natural and human-induced earth system variability, sustained ocean time-series measurements have taken on a renewed importance. Shipboard biogeochemical time-series represent one of the most valuable tools scientists have to characterize and quantify ocean carbon fluxes and biogeochemical processes and their links to changing climate (Karl, 2010; Chavez et al., 2011; Church et al., 2013). They provide the oceanographic community with the long, temporally resolved datasets needed to characterize ocean climate, biogeochemistry, and ecosystem change.

The temporal scale of shifts in marine ecosystem variations in response to climate change are on the order of several decades. The long-term, consistent and comprehensive monitoring programs conducted by time-series sites are essential to understand large-scale atmosphere-ocean interactions that occur on interannual to decadal time scales. Ocean time-series represent one of the most valuable tools scientists have to characterize and quantify ocean carbon fluxes and biogeochemical processes and their links to changing climate.

Launched in the late 1980s, the US JGOFS (Joint Global Ocean Flux Study; http://usjgofs.whoi.edu) research program initiated two time-series measurement programs at Hawaii and Bermuda (HOT and BATS, respectively) to measure key oceanographic measurements in oligotrophic waters. Begun in 1995 as part of the US JGOFS Synthesis and Modeling Project, the CARIACO Ocean Time-Series (formerly known as the CArbon Retention In A Colored Ocean) Program has studied the relationship between surface primary production, physical forcing variables like the wind, and the settling flux of particulate carbon in the Cariaco Basin.

The objective of these time-series effort is to provide well-sampled seasonal resolution of biogeochemical variability at a limited number of ocean observatories, provide support and background measurements for process-oriented research, as well as test and validate observations for biogeochemical models. Since their creation, the BATS, CARIACO and HOT time-series site data have been available for use by a large community of researchers.

Data from those three US funded, ship-based, time-series sites can be accessed at each site directly or by selecting the site name from the Projects section below.

Ocean Carbon and Biogeochemistry (OCB)

Website: http://us-ocb.org/

Coverage: Global

The Ocean Carbon and Biogeochemistry (OCB) program focuses on the ocean's role as a component of the global Earth system, bringing together research in geochemistry, ocean physics, and ecology that inform on and advance our understanding of ocean biogeochemistry. The overall program goals are to promote, plan, and coordinate collaborative, multidisciplinary research opportunities within the U.S. research community and with international partners. Important OCB-related activities currently include: the Ocean Carbon and Climate Change (OCCC) and the North American Carbon Program (NACP); U.S. contributions to IMBER, SOLAS, CARBOOCEAN; and numerous U.S. single-investigator and medium-size research projects funded by U.S. federal agencies including NASA, NOAA, and NSF.

The scientific mission of OCB is to study the evolving role of the ocean in the global carbon cycle, in the face of environmental variability and change through studies of marine biogeochemical cycles and associated ecosystems.

The overarching OCB science themes include improved understanding and prediction of: 1) oceanic uptake and release of atmospheric CO2 and other greenhouse gases and 2) environmental sensitivities of biogeochemical cycles, marine ecosystems, and interactions between the two.

The OCB Research Priorities (updated January 2012) include: ocean acidification; terrestrial/coastal carbon

fluxes and exchanges; climate sensitivities of and change in ecosystem structure and associated impacts on biogeochemical cycles; mesopelagic ecological and biogeochemical interactions; benthic-pelagic feedbacks on biogeochemical cycles; ocean carbon uptake and storage; and expanding low-oxygen conditions in the coastal and open oceans.

U.S. Joint Global Ocean Flux Study (U.S. JGOFS)

Website: http://usjgofs.whoi.edu/

Coverage: Global

The United States Joint Global Ocean Flux Study was a national component of international JGOFS and an integral part of global climate change research.

The U.S. launched the Joint Global Ocean Flux Study (JGOFS) in the late 1980s to study the ocean carbon cycle. An ambitious goal was set to understand the controls on the concentrations and fluxes of carbon and associated nutrients in the ocean. A new field of ocean biogeochemistry emerged with an emphasis on quality measurements of carbon system parameters and interdisciplinary field studies of the biological, chemical and physical process which control the ocean carbon cycle. As we studied ocean biogeochemistry, we learned that our simple views of carbon uptake and transport were severely limited, and a new "wave" of ocean science was born. U.S. JGOFS has been supported primarily by the U.S. National Science Foundation in collaboration with the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Energy and the Office of Naval Research. U.S. JGOFS, ended in 2005 with the conclusion of the Synthesis and Modeling Project (SMP).

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