Primary productivity measurements from the Hawaii Ocean Time-Series (HOT) project from 1988-2021 at Station ALOHA

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

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Abstract
Primary productivity measurements from the Hawaii Ocean Time-Series (HOT) from 1988 to 2021. The 14C-radiotracer method was used to measure the assimilation of dissolved inorganic carbon (DIC) by phytoplankton as an estimate of the rate of photosynthetic production of organic matter in the euphotic zone. All incubations from 1990 through mid-2000 were conducted in situ at eight depths (5, 25, 45, 75, 100, 125, 150 and 175m) over one daylight period using a free-drifting array as described by Winn et al. (1991). Starting October 2000 (HOT-119), samples were collected from only the upper six depths while the lower two depths were modeled based on the monthly climatology. During 2015, all incubations were conducted in situ on a free floating, surface tethered array. Integrated carbon assimilation rates were calculated using the trapezoid rule with the shallowest value extended to 0 meters and the deepest extrapolated to a value of zero at 200 meters.

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Coverage

Spatial Extent: **Lat**:22.75 **Lon**:-158
Temporal Extent: 1988-10-31 - 2021-10-29

Dataset Description

Monthly measurements of primary production were collected at station ALOHA as part of the HOT program.

Methods & Sampling

Photosynthetic production of organic matter was measured by the ^{14}C tracer method. All incubations from 1990 through mid-2000 were conducted in situ at eight depths (5, 25, 45, 75, 100, 125, 150 and 175m) over one daylight period using a free-drifting array as described by Winn et al. (1991). Starting October 2000 (HOT-119), samples were collected from only the upper six depths while the lower two depths were modeled based on the monthly climatology. During 2015, all incubations were conducted in situ on a free floating, surface tethered array. Integrated carbon assimilation rates were calculated using the trapezoid rule with the shallowest value extended to 0 meters and the deepest extrapolated to a value of zero at 200 meters.

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.)

1. Principle
The ^{14}C method, originally proposed by Steeman-Nielsen (1952), is used to estimate the uptake of dissolved inorganic carbon (DIC) by planktonic algae in the water column. The method is based on the fact that the biological uptake of ^{14}C-labeled DIC is proportional to the biological uptake of ^{12}C-DIC. If one knows the initial concentration of DIC in a water sample, the amount of ^{14}C-DIC added, the ^{14}C retained in particulate organic matter (^{14}C-POC) at the end of the incubation and the metabolic discrimination between the two isotopes of carbon (i.e., 5% discrimination against the heavier ^{14}C isotope), then it is possible to estimate the total uptake of carbon from the following relationship:

$$\text{C uptake} = \frac{\text{DIC} * {}^{14}\text{C-POC} * 1.05}{{}^{14}\text{C-DIC added}}$$

2. Cleaning
Due to the potentially toxic effects of trace metals on phytoplankton metabolism in oligotrophic waters, the following procedure is used to minimize the contact between water samples and possible sources of contamination. HCl (Baker Instra-Analyzed) solution (1M) is prepared with high purity hydrochloric acid and freshly-prepared glass distilled deionized water (DDW). 500 ml polycarbonate bottles are rinsed twice with 1M HCl (Baker Instra-Analyzed) and left overnight filled with the same acid solution. The acid is removed by rinsing the bottles three times with DDW before air drying. Go-Flo bottles, fitted with teflon-coated springs, are rinsed three times with 1M HCl and DDW before use. Pipette tips used in the preparation of the isotope stock and in the inoculation of samples are rinsed three times with concentrated HCl (Baker Instra-Analyzed), three times with DDW and once with the sodium carbonate solution (Chapter 14, section 3.2) and stored in a clean polyethylene glove until used.

3. Isotope Stock
The preparation of the isotope stock is performed wearing polyethylene gloves. A 25 ml acid-washed teflon bottle and a 50 ml acid-washed polypropylene centifuge tube are rinsed three times with DDW. 0.032 g of anhydrous Na_2CO_3 (ALDRICH 20,442-0, 99.999% purity) are dissolved in 50 ml DDW in the centrifuge tube to provide a solution of 6 mmol Na_2CO_3 per liter. 3.5 ml of NaH-$^{14}CO_3$ (53 mCi mmol-1; Research Products Inc.) are mixed with 16.5 ml of the above prepared Na_2CO_3 solution in the teflon bottle. The new stock activity is checked by counting triplicate 10 µl samples with 1 ml β-phenethylamine in 10 ml Aquasol-II. Triplicate 10 µl stock samples are also acidified with 1 ml of 2 M HCl, mixed intermittently for 1-2 hours and counted in 10 ml Aquasol-II to confirm that there is no ^{14}C-organic carbon contamination. The acidification is done under the hood. The acidified dpm should be <0.001% of the total dpm of the ^{14}C preparation.

4. Incubation Systems
Typically primary production is measured using in situ incubation techniques. A free-floating array equipped with VHF radio and strobe light is used for the in situ incubations. Incubation bottles are attached to a horizontal polycarbonate spreader bar which is then attached to the 200 m, 1/2" polypropylene in situ line at the depths corresponding to the sample collections. Generally eight incubation depths are selected (5-175 m, approximately).

5. Sampling

Approximately 3 hours before local sunrise, seawater samples are collected with acid-washed, 12-liter Go-Flo bottles using Kevlar line, metal-free sheave, Teflon messengers and a stainless steel bottom weight. A dedicated hydrowinch is used for the primary productivity sampling procedures in a further effort to reduce/eliminate all sources of trace metal contamination. Under low light conditions, water samples are transferred to the incubation bottles (500 ml polycarbonate bottles) and stored in the dark. Polyethylene gloves are worn during sample collection and inoculation procedures. No drawing tubes are used.

6. Isotope Addition and Sample Incubation
Three light bottles, three dark bottles and 1 time-zero control (see HOT Protocols Chapter 14, section 8) are collected at each depth for in situ incubation. In situ dark bottles are deployed in specially- designed, double-layered cloth bags with Velcro closures. After all water samples have been drawn from the appropriate Go-Flo bottles, 250 µl of the 14C-sodium carbonate stock solution is added to each sample using a specially-cleaned pipette tip. The samples are deployed before dawn on a free-floating, drifter buoy array. At local sunset, the free-floating array is recovered and all in situ bottles are immediately placed in the dark and processed as soon as possible. The time of recovery is recorded.

7. Filtration
Filtration of the samples is done under low light conditions and begins as soon as the incubation bottles are recovered from the in situ array. 200 µl are removed and placed into a second LSC vial containing 0.5 ml of β-phenethylamine. This sample is used for the determination of total radioactivity in each sample.The remainder is filtered through a 25 mm diameter GF/F filters. The filters are placed into prelabelled, clean glass liquid scintillation counting vials (LSC vials) and stored at -20 °C.

8. ^{14}C Sample Processing
One ml of 2 M HCl is added to each sample vial (under the hood). Vials are covered with their respective caps and shaken in a vortex mixer for at least 1 hour with venting at 20 minute intervals. To vent, the vials are removed from the shaker, and the cap opened (under the hood). After shaking is completed, the vials are left open to vent under the hood for an additional 24 hours. Ten milliliters of Aquasol-II are added per vial (including vials for total ^{14}C radioactivity) and the samples are counted in a liquid scintillation counter. Samples are counted again after 2 and 4 weeks, before discarding. Counts have shown a consistent increase during the first two weeks and become stable between the second and the fourth week. This is probably the result of sample hydrolysis or diffusion of radioactivity from the GF/F filter matrix, thereby reducing the extent of self-absorption. Therefore, only the 4-week count is used for ^{14}C calculations. Counts per min (CPM) are converted to disintegration per min (DPM) using the channels ratio program supplied by the manufacturer (Packard Instrument Co.)

Analysis History for HOT program

- HOT-1 to HOT-7, on deck incubations only
- HOT-8 to HOT-17, on deck and *in situ* incubations
- HOT-18 to present, *in situ* incubations only
- HOT 97 to present samples from CTD rosette mounted PVC bottles only (previously using Go-Flo bottles, Kevlar line, Teflon messengers)
- HOT 119 to present, six incubation depths (5-125 m), light bottles only. Previously eight depths (5-175 m) and light and dark incubations
- HOT 178 switch from Aquasol II to Ultima Gold LLT scintillation cocktail

Data Processing Description

From the data derived we can estimate several properties of the phytoplankton populations at Station ALOHA:

1. Total daylight organic carbon production is calculated from the 12-hour uptake data (after corrections for 12-hour dark activities).
2. Net daily organic carbon production is calculated from the 24-hour light/dark samples (corrected for the time-zero blank activities).
3. Phytoplankton population respiration is taken as the difference between the 12-hour light and the 24-hour light/dark incubations.
4. Net primary production is used as the estimate of phytoplankton carbon production for the purposes of comparison to other ecosystem-level processes (e.g., standing stock assessments, vertical C-flux, etc.).

Quality Flags
Quality Flags were assigned for the bottle, chlorophyll, pheopigments, light incubation, dark incubation, salinity & bacteria values respectively.
1: not quality controlled
2: good data
3: suspect (questionable) data
4: bad data
5: missing value
9: variable not measured during this cast

BCO-DMO Processing Description

Concatenated new data from 2020 and 2021 to previous 30 years of primary production data

- Minor modification within Excel prior to running through BCO-DMO pipeline processing tool to accommodate filetype formatting
- Adjusted parameter/column names to conform with BCO-DMO naming conventions.
- Combined separate date and time columns into a single ISO8601 formatted date
- Added columns for latitude and longitude of station ALOHA
- Added columns for individual parameter flags
- Added column for data source filename (e.g. hot326-334.pp)
- Checked for missing cruises

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Data Files

File	
737163_v2_HOT_prim_prod_1988_2021.csv	(Comma Separated Values (.csv), 446.56 KB) MD5:5229aa13a65708aed2687e9e502fee03
Primary data file for dataset 737163 version 2. HOT TimeSeries Primary Production 1988-2021	

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Related Publications

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

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

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 (West is negative)	decimal degrees
ISO_StartTime_UTC	Start date and time in ISO 8601 format	unitless
ISO_EndTime_UTC	End date and time in ISO 8601 format	unitless
Depth	Depth	meters (m)
Incubation	Incubation type. O = GO-FLO sampled on deck incubation, I = GO-FLO sampled in-situ incubation, R = Rosette sampled in-situ incubation, N = External closing Niskin sampled in-situ incubation	unitless
Time_duration	Incubation time	hours
Chl_a_mean	Chlorophyll a mean value	miligrams per cubic meter (mg/m3)
Chl_a_sd	Chlorophyll a standard deviation	miligrams per cubic meter (mg/m3)
Pheo_mean	Pheopigments mean	miligrams per cubic meter (mg/m3)
Pheo_sd	Pheopigments standard deviation	miligrams per cubic meter (mg/m3)
Light_rep1	Light replicate #1	miligrams Carbon per cubic meter (mg C/m3)
Light_rep2	Light replicate #2	miligrams Carbon per cubic meter (mg C/m3)
Light_rep3	Light replicate #3	miligrams Carbon per cubic meter (mg C/m3)
Dark_rep1	Dark replicate #1	miligrams Carbon per cubic meter (mg C/m3)
Dark_rep2	Dark replicate #2	miligrams Carbon per cubic meter (mg C/m3)
Dark_rep3	Dark replicate #3	miligrams Carbon per cubic meter (mg C/m3)
Salt	Salinity (PSS-78)	unitless

Prochl	Prochlorococcus	count per milliliter
Hetero	Heterotrophic bacteria	count per milliliter
Synecho	Synechococcus	count per milliliter
Euk	Eukaryotes	count per milliliter
Flag	Quality Flags for the bottle, chlorophyll, pheopigments, light incubation, dark incubation, salinity & bacteria values respectively. 1: not quality controlled, 2: good data, 3: suspect (questionable) data, 4: bad data, 5: missing value, 9: variable not measured during this cast	unitless
Flag_Bottle	Quality flag for Bottle sample	unitless
Flag_Chla	Quality flag for Chlorophyll a measurement	unitless
Flag_Pheo	Quality flag for Pheopigment measurement	unitless
Flag_Light	Quality flag for Light incubation bottles	unitless
Flag_Dark	Quality flag for Dark incubation bottles	unitless
Flag_Salt	Quality flag for Salinity	unitless
Flag_Prochl	Quality flag for Prochlorococcus	unitless
Flag_Hetero	Quality flag for Heterotropic Bacteria	unitless
Flag_Synecho	Quality flag for Synechococcus	unitless
Flag_Euk	Quality flag for Eukaryotes	unitless
PrimProd_filename	Original filename of the primary production data from HOT	unitless

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Instruments

Dataset-specific Instrument Name	Go-Flo bottles
Generic Instrument Name	GO-FLO Bottle
Dataset-specific Description	Go-Flo bottles
Generic Instrument Description	GO-FLO bottle cast used to collect water samples for pigment, nutrient, plankton, etc. The GO-FLO sampling bottle is specially designed to avoid sample contamination at the surface, internal spring contamination, loss of sample on deck (internal seals), and exchange of water from different depths.

Dataset-specific Instrument Name	liquid scintillation counter
Generic Instrument Name	Liquid Scintillation Counter
Dataset-specific Description	liquid scintillation counter (Packard model 4640; United Technologies Inc.)
Generic Instrument Description	Liquid scintillation counting is an analytical technique which is defined by the incorporation of the radiolabeled analyte into uniform distribution with a liquid chemical medium capable of converting the kinetic energy of nuclear emissions into light energy. Although the liquid scintillation counter is a sophisticated laboratory counting system used the quantify the activity of particulate emitting (ß and a) radioactive samples, it can also detect the auger electrons emitted from 51Cr and 125I samples.

Dataset-specific Instrument Name	External closing niskin
Generic Instrument Name	Niskin bottle
Dataset-specific Description	External closing niskin sampled in-situ Incubation.
Generic Instrument Description	A Niskin bottle (a next generation water sampler based on the Nansen bottle) is a cylindrical, non-metallic water collection device with stoppers at both ends. The bottles can be attached individually on a hydrowire or deployed in 12, 24, or 36 bottle Rosette systems mounted on a frame and combined with a CTD. Niskin bottles are used to collect discrete water samples for a range of measurements including pigments, nutrients, plankton, etc.

Dataset-specific Instrument Name	NORDA/USM incubation system
Generic Instrument Name	Shipboard Incubator
Dataset-specific Description	temperature- and light-controlled deck incubation system (NORDA/USM incubation system)
Generic Instrument Description	A device mounted on a ship that holds water samples under conditions of controlled temperature or controlled temperature and illumination.

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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?

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Program Information

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).

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.

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Funding

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NSF Division of Ocean Sciences (NSF OCE)	OCE-0926766
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