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The Hawaii Ocean Time-series (HOT) program: Background, rationale and field implementation

DAVID M. KARL* and ROGER LUKAS*

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Abstract—Long-term ocean observations are needed to gain a comprehensive understanding of natural habitat variability as well as global environmental change that might arise from human activities. In 1988, a multidisciplinary deep-water oceanographic station was established at a site north of Oahu, Hawaii, with the intent of establishing a long-term (> 20 years) data base on oceanic variability. The primary objective of the Hawaii Ocean Time-series (HOT) program is to obtain high-quality time-series measurements of selected oceanographic properties, including: water mass structure, dynamic height, currents, dissolved and particulate chemical constituents, biological processes and particulate matter fluxes. These data will be used, in part, to help achieve the goals of the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) research programs. More importantly, these data sets will be used to improve our description and understanding of ocean circulation and ocean climatology, to elucidate further the processes that govern the fluxes of carbon into and from the oceans, and to generate novel hypotheses. These are necessary prerequisites for developing a predictive capability for global environmental change.

INTRODUCTION

Systematic, long-term time-series studies of selected aquatic and terrestrial habitats have yielded significant contributions to earth and ocean sciences through the characterization of climate trends. Important examples include the recognition of acid rain (Hubbard Brook long-term ecological study, Vermont; Likens *et al.*, 1977), the documentation of increasing carbon dioxide (CO_2) in the earth's atmosphere (Mauna Loa Observatory, Hawaii; Keeling *et al.*, 1976) and the description of large scale ocean–atmosphere climate interactions in the equatorial Pacific Ocean (Southern Oscillation Index; Troup, 1965).

Long time-series observations of climate-relevant variables in the ocean are extremely important, yet they are rare. Repeated oceanographic measurements are imperative for an understanding of natural processes or phenomena that exhibit slow or irregular change, as well as rapid event-driven variations that are impossible to document reliably from a single field expedition. Time-series studies are also ideally suited for the documentation of complex natural phenomena that are under the combined influence of physical, chemical and biological controls. Examination of data derived from the few existing long-term oceanic time-series provides ample incentive and scientific justification to establish additional study sites (Wiebe *et al.*, 1987).

* Department of Oceanography, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822, U.S.A.

The role of the oceans in climate variability is primarily in sequestering and transporting heat and carbon (Barnett, 1978). Both can be introduced into the ocean in one place, only to return to the atmosphere, at a subsequent time, possibly at a far removed location. While both heat and carbon can be exchanged with the atmosphere, only carbon is lost to the seafloor through sedimentation. The oceans are known to play a central role in regulating the global concentration of CO_2 in the atmosphere (Sarmiento and Toggweiler, 1984; Dymond and Lyle, 1985). It is generally believed that the world ocean has removed a significant portion of anthropogenic CO_2 added to the atmosphere, although the precise partitioning between the ocean and terrestrial spheres is not known (Tans *et al.*, 1990; Keeling and Shertz, 1992; Quay *et al.*, 1992).

The cycling of carbon within the ocean is controlled by a set of reversible, reduction–oxidation reactions involving dissolved inorganic carbon (DIC) and organic matter with marine biota serving as the critical catalysts. Detailed information on the rates and mechanisms of removal of DIC from the surface ocean by biological processes, the export of biogenic carbon (both as organic and carbonate particles) to the ocean's interior, and the sites of remineralization and burial are all of considerable importance in the carbon cycle. The continuous downward flux of biogenic materials, termed the "biological pump" (Volk and Hoffert, 1985; Longhurst and Harrison, 1989), is a central component of all contemporary studies of biogeochemical cycling in the ocean and, therefore, of all studies of global environmental change.

During the embryonic phase of ocean exploration more than a century ago (Thomson, 1877), it was realized that a comprehensive understanding of the oceanic habitat and its biota required a multidisciplinary experimental approach and extensive field observations. Progress toward this goal has been limited by natural habitat variability, both in space and time, and by logistical constraints of ship-based sampling. Consequently, our current view of many complex oceanographic processes is likely to be biased (e.g. Dickey, 1991; Wiggert *et al.*, 1994). The synoptic and repeat perspective now available from research satellites is expected to improve our understanding of oceanic variability despite certain limitations.

In 1988, two deep ocean time-series hydrostations were established with support from the U.S. National Science Foundation (NSF): one in the western North Atlantic Ocean near the historical Panulirus Station (Bermuda Atlantic Time-series Study (BATS); Michaels and Knap, 1996) and the other in the subtropical North Pacific Ocean near Hawaii (Hawaii Ocean Time-series (HOT)). These programs were established and are currently operated by scientists at Bermuda Biological Station for Research and the University of Hawaii, respectively.

The primary research objective of the initial 5-year phase of HOT (1988–1993) was to design, establish and maintain a deep-water hydrostation as a North Pacific oligotrophic ocean benchmark for observing and interpreting physical and biogeochemical variability. The design included repeat measurements of a suite of core parameters at approximately monthly intervals, compilation of the data, and rapid distribution to the scientific community. The establishment of the HOT program study site Sta. ALOHA (A Long-term Oligotrophic Habitat Assessment) also provides an opportunity for visiting colleagues to conduct complementary research, a deep-water laboratory for the development and testing of novel methodologies and instrumentation, and a natural laboratory for marine science education and interlaboratory comparison experiments.

This paper provides the history, scientific background and motivation for the development of HOT, from program planning through initial implementation. Detailed scientific results and interpretation of the emergent data sets are presented elsewhere in this volume.

BACKGROUND

North Pacific subtropical gyre: habitat description and physical and biogeochemical dynamics

The subtropical gyres of the world ocean are extensive, coherent regions that occupy approximately 40% of the surface of the earth. The subtropical gyre of the North Pacific Ocean, delimited from approximately 15°N to 35°N longitude and 135°E to 135°W latitude, occupies nearly 2×10^7 km^2 and is the largest circulation feature on our planet (Sverdrup *et al.*, 1946). As characterized by surface dynamic height relative to 1000 db, the center of the N. Pacific subtropical gyre is at 20°N (Fig. 1); relative to 500 db, the center of the gyre is shifted northwards (Wyrtki, 1975). The North Pacific subtropical gyre is a remote habitat that has been undersampled relative to the equatorial and coastal regions of the North Pacific. Once thought to be homogeneous and static habitats, there is increasing evidence that mid-latitude gyres exhibit substantial physical and biological variability on a variety of timescales. The central North Pacific Ocean has an anticyclonic circulation pattern that, although relatively weak, effectively isolates the upper portion of the water column from large volume water exchange with the bordering current systems. Consequently, horizontal gradients in properties such as temperature, salinity and dissolved inorganic nutrients are weak within the gyre (Hayward, 1987). Seasonal changes in the upper water column, including surface mixed-layer depth, are also relatively weak (Bingham and Lukas, 1996). Biogeographical studies show that the central gyre is a distinct faunal province with a unique assemblage of macrozooplankton and nekton (McGowan, 1974; McGowan and Walker, 1979).

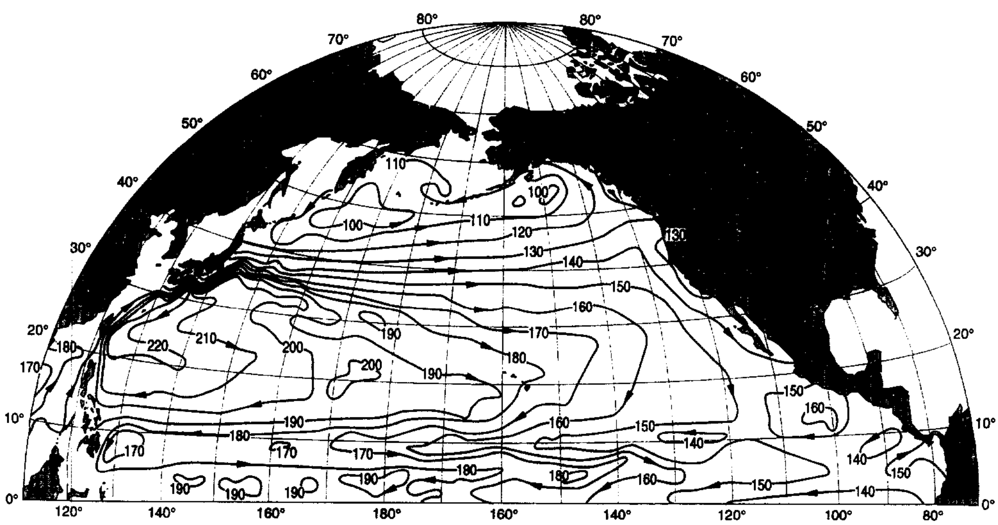

Fig. 1. Dynamic topography of the sea surface relative to 1000 dbar for the North Pacific Ocean based on historical hydrographic observations, from Wyrtki (1975). Arrows show the direction of geostrophic flow.

The thermocline, which separates the warm upper ocean waters of the gyre from the cold deep waters, is found between 150 and 350 m. The gyre "tilts" poleward with increasing depth, so that at the depth of the thermocline, the Hawaiian Islands are south of the "stagnation" region that separates the North Equatorial Current from the North Pacific Current.

The Hawaiian island chain also represents a porous barrier to the ocean circulation, with the distribution of gaps depending on latitude and depth. To the extent that this relatively thin barrier can act as a western boundary, the regional circulation of the North Pacific subtropical gyre will be affected by the presence of the Hawaiian Ridge. Closely spaced hydrographic sections by Roden (1970, 1977) and by Talley and deZoeke (1986) suggest the presence of alternating bands of geostrophic flow with a dominant wavelength of about 200 km that are oriented parallel to the ridge and extend for a distance of several hundred kilometers north of the islands. Maximum calculated geostrophic speeds are about 60 cm s^{-1}.

Each winter, extratropical cyclones track across the North Pacific from west to east, approximately every 5–7 days. The cold fronts associated with these mid-latitude storms sometimes reach the Hawaiian Islands, usually producing several days of very strong northerly and northeasterly winds. The strong winds associated with storms impulsively force the upper ocean, resulting in a deepening of the mixed-layer and a cooling associated with both enhanced evaporation and entrainment of cooler waters from below. This intermittent local forcing is important in determining the annual cycle in the surface waters of the subtropical gyre.

The central gyre of the North Pacific Ocean is characterized by a relatively deep permanent pycnocline (and nutricline), and even during winter-time the long-term climatology indicates fairly shallow mixed-layer depths (Fig. 2). Consequently, the mixed-layer in these mid-latitude regions is chronically nutrient-starved. Furthermore, the near-zero nutrient concentration gradient routinely observed in the upper 100 m of the water column suggests that continuous vertical nutrient flux cannot be the primary source of dissolved inorganic nutrients (e.g. nitrate and phosphate) to the upper euphotic zone (Hayward, 1991).

The observed separation of light in the surface waters from inorganic nutrients beneath the euphotic zone suggests that the surface ocean ecosystem is not only oligotrophic (low standing stocks of nutrients and biomass), but that it also supports a low production rate of organic matter. Ironically, most of the water column primary production occurs in the upper 75 m (Letelier *et al.*, 1996) where inorganic nutrient concentrations are generally below the detection limits of standard techniques. Consequently, total ecosystem productivity must be largely supported by local nutrient regeneration processes or by non-traditional allochthonous inputs of nutrients (Fig. 3).

Because subtropical ocean gyres are dominant habitats of the world ocean, accurate estimation of global ocean production relies upon adequate and reliable measurement of gyre productivity. While most historical (pre-1980) estimates of North Pacific subtropical gyre productivity support the prediction of a virtual biological desert with annual production $\leq$50 g C m^{-2} (Berger, 1989; Table 1), most recent measurements suggest that the production may be higher by at least a factor of two (Table 1). Data from the first 5 years of the HOT program (Table 1) span nearly the entire range of previous measurements, suggesting a substantial variability in primary production.

Based on a systematic analysis of steady-state nutrient flux versus nutrient demand,

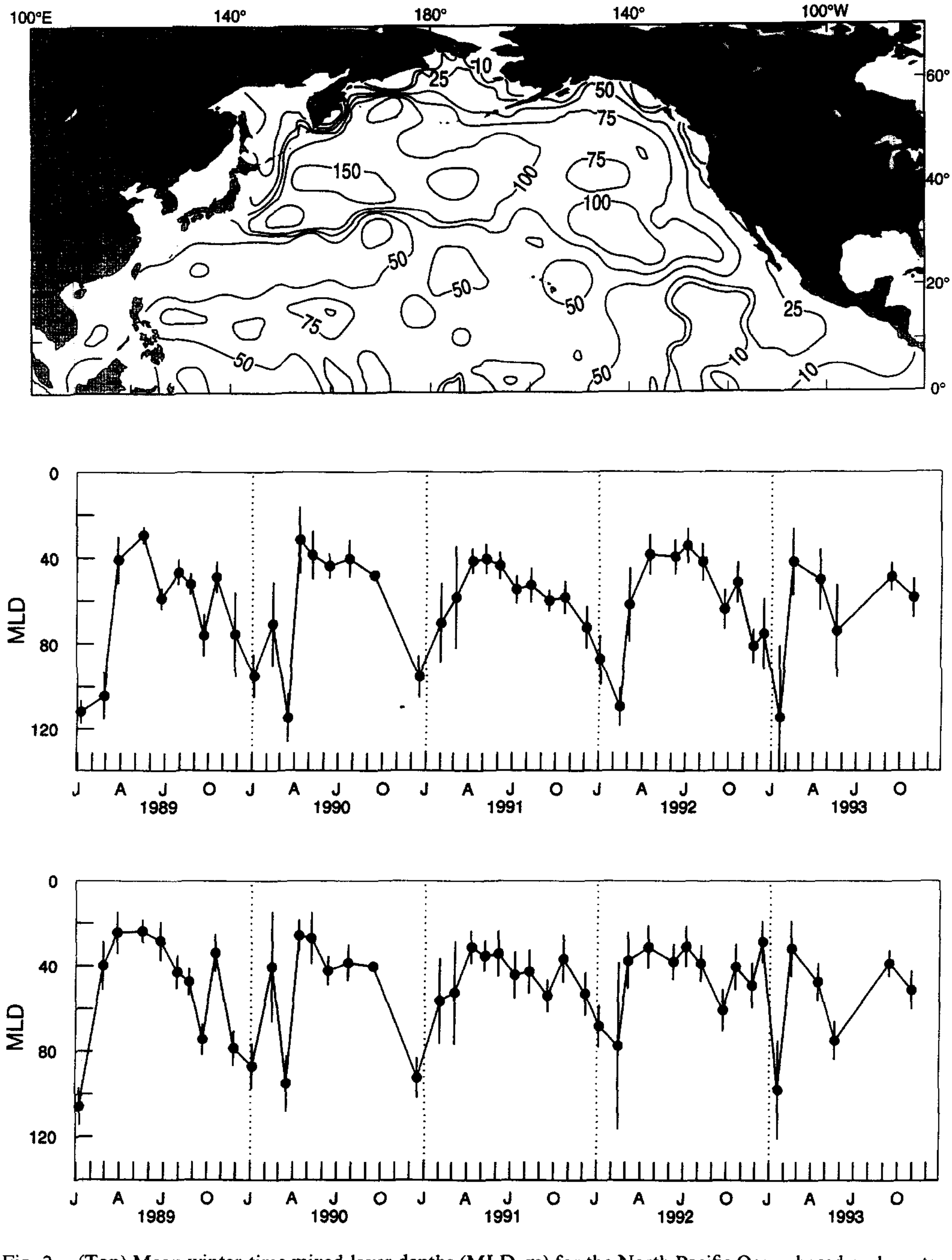

Fig. 2. (Top) Mean winter-time mixed-layer depths (MLD, m) for the North Pacific Ocean based on long-term climatology using a variable potential density criterion (from Glover *et al.*, 1994); (middle) Sta. ALOHA mixed-layer depths (MLD, m) observed during the period 1989–1993 based on a 0.5°C temperature criterion (Levitus, 1982); (bottom) Sta. ALOHA mixed-layer depths (MLD, m) observed during the period 1989–1993 based on a 0.125 unit potential density criterion (Levitus, 1982). For both the middle and bottom panels, the data are presented as mean mixed-layer depth values ± 1 standard deviation of the means as determined from multiple (generally, $n >$ 15) CTD casts on each cruise.

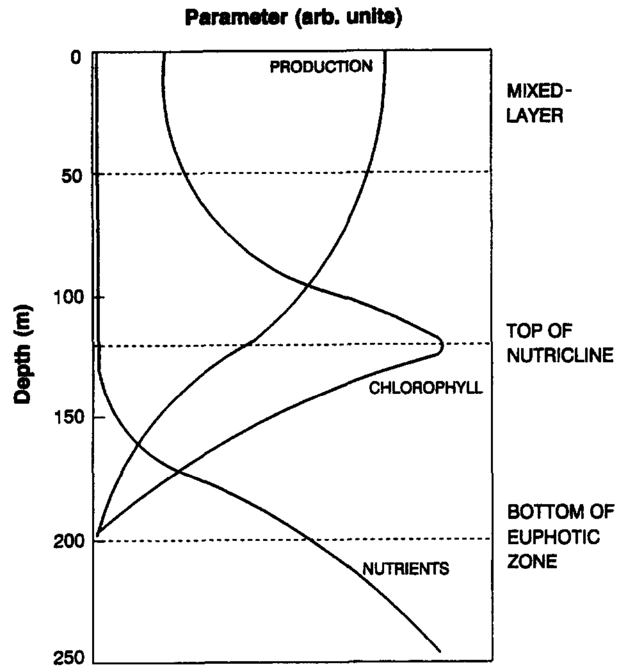

Fig. 3. Schematic representation of the upper water column distributions of light, nutrients, chlorophyll *a* and primary production in the oligotrophic North Pacific subtropical gyre.

Hayward (1987) hypothesized that stochastic habitat variability must occur in the North Pacific gyre. Unfortunately, historical measurements were insufficient for resolving the nutrient budget discrepancies. Several attempts to improve estimates of vertical diffusion rates in the open ocean (Lewis *et al.*, 1986; Ledwell *et al.*, 1993) have failed to lead to budget reconciliation. As discussed by Karl *et al.* (1992), even the lowest measured rates of primary production for the oligotrophic North Pacific ($\approx$0.1 mol N m^{-2} $year^{-1}$, assuming a molar C:N ratio of 6.6 and a mean euphotic-zone *f*-ratio of 0.1) cannot be supported by the steady-state cross isopycnal nitrate diffusion rates estimated for this region (Lewis *et al.*, 1986).

The imbalance between nitrogen uptake and input to the euphotic zone may be caused by non steady-state nutrient injections. Potential mechanisms include episodic deep mixing, atmospheric inputs, nitrogen fixation and active biological migrations. All of these processes may contribute to nutrient transport, resulting in temporal and spatial variability in planktonic production.

It was recently suggested that biological communities of the subtropical North Pacific gyre may exhibit change on decadal timescales in response to ocean–atmosphere interactions. Venrick *et al.* (1987) reported a long-term increasing trend in the chl *a* concentration at the CLIMAX site in the North Pacific Ocean (approximately 28°N, 155°W). Although their time-series record has large data gaps (up to 3 years in duration), they report that summer-time (May–October) concentrations of chl *a* have nearly doubled during the period 1968–1985. Concomitant increases in winter winds and a decrease in sea surface temperature at this site have apparently altered both the habitat and the carrying capacity of the epipelagic ecosystem (Venrick *et al.*, 1987). Analysis of 10,733 Secchi disc records (a measurement of water clarity) for the North Pacific over the period 1900–1981, however, failed to confirm the Venrick *et al.* observations (Falkowski and Wilson, 1992).

Independent climate analyses provide evidence for a substantial change in North Pacific sea level pressure and winds from 1977–1988 (Trenberth and Hurrell, 1994; Polovina *et al.*, 1994). These climatic variations resulted in increased surface mixing and increased frequency of deep mixing events, and ultimately affected productivity of various trophic levels of the marine ecosystem (Polovina *et al.*, 1994). Such low-frequency climate events are undoubtedly important in maintaining the diversity and structure of the oligotrophic marine ecosystem and would not be detected without time-series data sets.

HOT Station ALOHA: roots and branches

A deep-ocean weather station network was established in the post-World War II period as a ship-based observation program designed to improve global weather prediction capabilities. One of the sites, Station November, was located in the eastern sector of the North Pacific Ocean gyre at 30°N, 140°W and was occupied during 121 cruises between July 1966 and May 1974. The intercruise frequency ranged from a few days to a few weeks with a typical cruise duration of 2–3 weeks, including transits. Water samples were collected from approximately 12–14 depths in the range of 0–1500 m using bottles equipped with deep-sea reversing thermometers. Salinity and, on occasion, dissolved oxygen concentrations were measured from the discrete water samples.

During the 1970s, most of the U.S. weather ship stations were phased out of operation and were eventually replaced with more cost-effective, unattended ocean buoys. These buoys measure standard meteorological parameters as well as basic wave characteristics (e.g. significant wave direction, height, period and spectrum) but few, if any, hydrographical variables.

Physical and biogeochemical time-series investigations of the North Pacific subtropical region are sparse (Figs 4 and 5) and consist of a series of unrelated research programs including CLIMAX, Gollum, NORPAX, VERTEX, ADIOS and most recently HOT. CLIMAX I occupied a series of stations near 28°N, 155°W during August–September 1968, and CLIMAX II reoccupied the site during September of the following year. Since that time, scientists from the Scripps Institution of Oceanography have revisited the "CLIMAX region" on 18 cruises between 1971 and 1985 (Fig. 4; Hayward, 1987). It is important to emphasize, however, that the temporal coverage in this time-series is biased with respect to season because approximately 70% of the cruises occurred in summer (June–September) and 35% were in August alone. These observations are also aliased by interannual variations; no cruises were conducted in 1970, 1975, 1978–1979, 1981 or 1984 (Fig. 4). Nevertheless, observations made during this extensive series of cruises, especially the measurements of plankton distributions, nutrient concentrations and rates of primary production, provided an unprecedented view of ecosystem structure and dynamics.

From January 1969 to June 1970, a deep ocean hydrostation (Sta. Gollum; Fig. 5) was established by scientists at the University of Hawaii at a location 47 km north of Oahu (22°10'N, 158°00'W; Gordon, 1970). The water depth was 4760 m, and the location was

Table 1. Chronological list of North Pacific Ocean gyre primary production rates based on the uptake of ^{14}C

Approximate Location	Approximate Distance from Hawaiian Islands (km)	Measurement Date	Rate (mg C m^{-2} day^{-1})	Reference
15°N, 119°W	>1000	1967–1968	$148 \pm 98^{\S}$ (n = 6)	Owen and Zeitzschel (1970)
		cruises on ~3 month intervals		
22°N, 158°W	50	1969–1970	87–737	Cattell and Gordon (unpublished)
		(GOLLUM T–S)	(annual mean = 279)	
31°N, 147°W	800	1971	250–300	Eppley *et al.* (1973)
31°N, 143°W	910		144	
31°N, 136°W	>1000		292	
21°N, 159°W	90	1972	260 (gross)	Gundersen *et al.* (1976)
			82 (net)	
28°N, 155°W	800	1968–1974 (CLIMAX)	60–360*,†	McGowan and Hayward (1978)
28°N, 155°W	800	June 1972 (CATO)	85–220	Eppley *et al.* (1985)
		January 1973 (SOUTHTOW 13)	65–135	
		March 1974 (TASADAY 11)	140–270	
21°N, 158°W	25	1975	289*	Bienfang and Gundersen (1977)
20°N, 164°W	800		72*	
18°N, 170°W	>1000		41*	
12°N, 153°W	960	1982	153	Betzer *et al.* (1984)
20°N, 156°W	20	1978–79 (KEAHOLE T–S)	11–199* (annual mean = 105)	Bienfang and Szyper (1981)
21°N, 158°W	9	1980–81 (KAHE T–S)	36–440* (annual mean = 165)	Bienfang *et al.* (1984)

20°N, 156°W	11	1984	63–208	Hirota *et al.* (1984)
28°N, 155°W	800	1968–82 (CLIMAX)	254† (summer) (range 106–577) 203† (winter) (range 114–275)	Hayward (1987)
28°N, 155°W	800	1984 (VERTEX-5)	401‡	Martin *et al.* (1987)
28°N, 155°W	800	1985 (PRPOOS)	450 ± 37‡,§ (gross) (n = 3) 273 ± 33‡,§ (net) (n = 3)	Laws *et al.* (1987)
28°N, 155°W	800	1985 (PRPOOS)	456‡	Marra and Heinemann (1987)
26°N, 155°W	550	1986 (ADIOS I)	372–605‡	Young *et al.* (1991)
26°N, 155°W	550	1986 (ADIOS I)	493 ± 93‡,§ (n = 6)	DiTullio and Laws (1991)
26°N, 155°W	550	1986 (ADIOS I and II)	484 ± 81‡,§ (n = 8)	Laws *et al.* (1989)
26°N, 155°W	550	1987 (ADIOS III)	777 ± 219‡,§ (n = 6)	Laws *et al.* (1990)
33°N, 139°W	> 1000	1986–88 (VERTEX-TS)	250–550‡,§	Knauer *et al.* (1990)
16°N, 143°W	> 1000	1988	386	Peña *et al.* (1990)
22°45′N, 158°W	100	1988–1993 (HOT)	463 ± 156‡,§ (n = 54) (median = 465) (range 127–1055)	This study

*Estimated by multiplying published hourly rates by 12.

†"Half-day" integrated primary production values were extrapolated to day^{-1} by multiplying the reported values by 2.

‡Trace metal-clean technique employed.

§Mean ± 1 standard deviation, with number of measurements (n) given in parentheses.

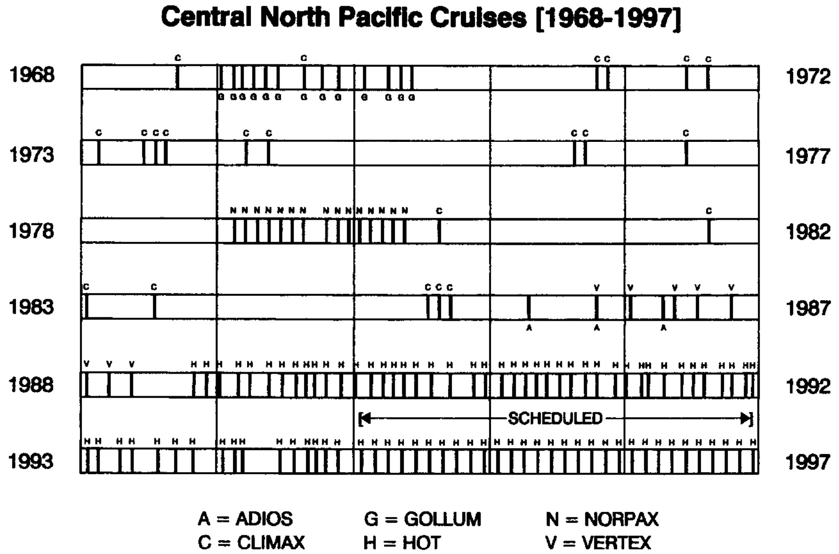

Fig. 4. A three-decade chronology of repeated oceanographic and biogeochemical measurements in the region of the central North Pacific Ocean for the period 1968–1997. The cruises are identified at the bottom of the timeline. CLIMAX (C) refers to a series of irregularly-spaced cruises conducted at a site near 28°N, 155°W conducted over a period of approximately 20 years including the unrelated VERTEX-5 (July 1983) and PRPOOS (Sept. 1985) expeditions. The HOT Program research cruises for 1995–1997 are already funded. We have assumed 10 cruises per year for this period, which is the average for the period 1989–1994. With the exception of the fairly intensive but short-term (1–2 year) temporal coverage during NORPAX and Gollum programs, HOT is the only central North Pacific Ocean data set that is able to resolve adequately both medium frequency (2 months) and lower frequency (~ 1 year) variations in biogeochemical processes.

selected to be beyond the biogeochemical influences of the Hawaiian Ridge (Doty and Oguri, 1956). On approximately monthly intervals, 13 2-day research cruises were conducted to observe and interpret variations in particulate organic matter distributions in the water column and other parameters (Gordon, 1970; Fig. 4).

A major advance in our understanding of biogeochemical processes in the sea was made during the NSF International Decade for Ocean Exploration (IDOE)-sponsored Geochemical Ocean Sections Study (GEOSECS) Pacific Ocean expedition (August 1973–June 1974). Although repeated ocean observations were not made during GEOSECS, the high-precision data, including numerous radioactive and stable isotopic tracers, collected from selected stations in the central North Pacific Ocean can be used as the basis for assessing "change", especially for the concentration and ^{13}C isotopic composition of the total dissolved carbon dioxide pool (Quay *et al.*, 1992). In particular, GEOSECS stations, nos 202 (33°6′N, 139°34′W), 204 (31°22′N, 150°2′W), 212 (30°N, 159°50′W) and 235 (16°45′N, 161°19′W), are the most relevant to our current biogeochemical investigations at Sta. ALOHA (Fig. 5).

In the early 1970s the North Pacific experiment (NORPAX) was initiated as an additional component of the NSF–IDOE. Research was focused on large scale interactions between the ocean and the atmosphere (e.g. El Niño) and the application of this knowledge to long-

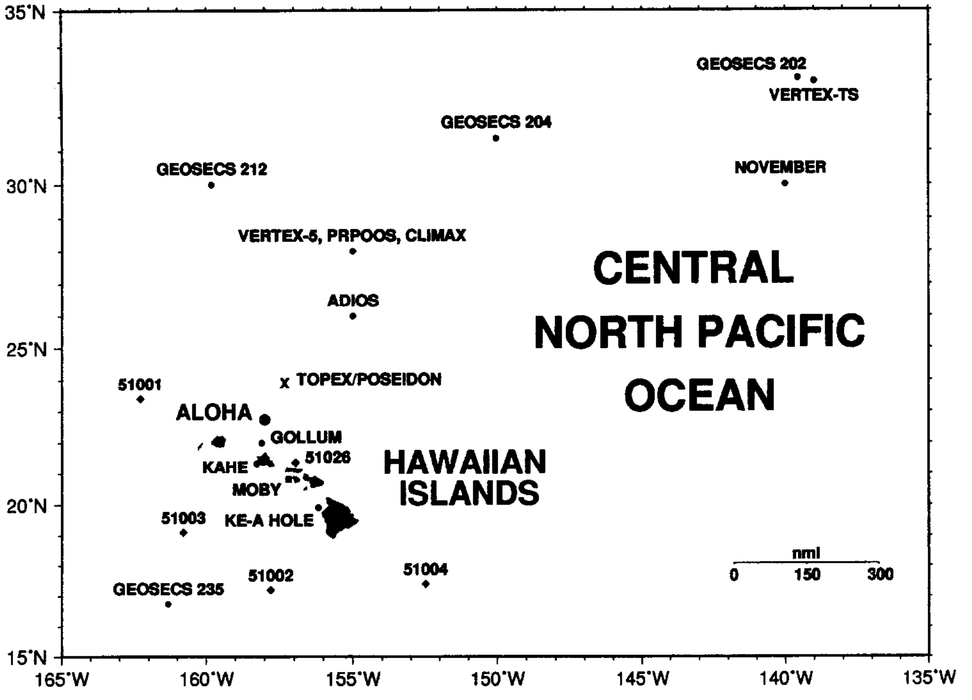

Fig. 5. Map showing the locations of HOT program coastal (Sta. KAHE) and open ocean (Sta. ALOHA) sampling sites in relation to previous oceanographic research programs (•), NOAA–NDBC meteorological buoys (♦) and the MOBY-SeaWIFS calibration buoy (■). The bold X to the northeast of Sta. ALOHA shows the nearest TOPEX/POSEIDON cross-over point.

range climate forecasting. The Anomaly Dynamics Study was one component of NORPAX aimed at understanding interannual variability of the mid-latitude, North Pacific upper ocean thermal structure. Long-term ocean observation programs were fundamental to the success of NORPAX and, accordingly, the Trans-Pac XBT program and the Pacific Sea Level Network were established. Furthermore, the extensive 15 cruise Hawaii-to-Tahiti Shuttle time-series experiment (January 1979–June 1980) was conducted to obtain direct measurements of the temporal variations in thermal structure of the equatorial Pacific region (Fig. 4). These cruises also supported extensive ancillary research programs on chemical and biological oceanography, and provided a rich dataset including measurements of dissolved carbon dioxide and primary productivity (Wyrtki *et al.*, 1981).

With the abandonment of the central North Pacific Ocean weather ship stations and time-series programs such as Sta. Gollum, there remain very few sites where comprehensive serial measurements of the internal variability of the ocean are continuing. The Intergovernmental Oceanographic Commission (IOC) and World Climate Research Program (WCRP) Committee on Climate Change in the Ocean (CCCO) recognized this deficiency, and in 1981 endorsed the initiation of new ocean observation programs. Reactivation of Sta. Gollum was an explicit recommendation (JSC/CCCO, 1981).

In 1986, a biogeochemical time-series station was established in the northeast Pacific Ocean (33°N, 139°W) as one component of the NSF-sponsored Vertical Transport and

Exchange (VERTEX) research program (Fig. 5). A major objective of the VERTEX time-series project was to investigate seasonality in carbon export from the euphotic zone in relation to contemporaneous primary production. During an 18-month period (October 1986–May 1988), the station was occupied for seven 1-week periods on approximately 3-month intervals (Fig. 4). In addition to standard hydrographic surveys, samples also were collected for the measurement of dissolved inorganic and organic nutrients, particulate matter elemental analysis, primary production, nitrogen assimilation rates, microbial biomass and particle flux (Knauer *et al.*, 1990; Harrison *et al.*, 1992). Significant variability was observed in rates of primary production and particle flux, and no clear relationship was found between new production and primary production. Despite the comprehensive scope and intensity of this research project, the sampling frequency was clearly inadequate to resolve much of the natural variability in this oligotrophic oceanic ecosystem.

In response to the growing awareness of the ocean's role in climate and global environmental change, and the need for additional and more comprehensive oceanic time-series measurements, the Board on Ocean Science and Policy of the National Research Council (NRC) sponsored a workshop on "Global Observations and Understanding of the General Circulation of the Oceans" in August 1983. The proceedings of this workshop (National Research Council, 1984a) served as a prospectus for the development of the U.S. component of the World Ocean Circulation Experiment (U.S.-WOCE).

U.S.-WOCE has the following objectives: (i) to understand the general circulation of the global ocean to model with confidence its present state and predict its evolution in relation to long-term changes in the atmosphere, and (ii) to provide the scientific background for designing an observation system for long-term measurement of the large-scale circulation of the ocean. In a parallel effort, a separate major international research program termed Global Ocean Flux Study (GOFS) focused on the ocean's carbon cycle and associated air–sea fluxes of carbon dioxide.

In September 1984, the NRC's Board on Ocean Science and Policy sponsored a workshop on "Global Ocean Flux Study", which served as an eventual blueprint for the JGOFS program (National Research Council, 1984b). In 1986, ICSU established the International Geosphere–Biosphere Programme: A Study of Global Change (IGBP), and the following year JGOFS was designed as a Core Project of IGBP. U.S.-JGOFS research efforts focus on the oceanic carbon cycle, its sensitivity to change and the regulation of the atmosphere–ocean CO_2 balance (Brewer *et al.*, 1986). The broad objectives of U.S.-JGOFS are: (i) to determine and understand on a global scale the time-varying fluxes of carbon and associated biogenic elements in the ocean, and (ii) to evaluate the related exchanges of these elements with the atmosphere, the sea floor and the continental boundaries (SCOR, 1990; JGOFS Rept no. 5). To achieve these goals, four separate program elements were defined: (i) process studies to capture key regular events, (ii) long-term time-series observations at strategic sites, (iii) a global survey of relevant oceanic properties (e.g. CO_2) and (iv) a vigorous data interpretation and modeling effort to disseminate knowledge and generate testable hypotheses. The establishment of the HOT program is expected to contribute, in part, to all of these program elements.

In 1987, two separate proposals were submitted to the U.S.-WOCE and U.S.-JGOFS program committees to establish a multi-disciplinary, deep water hydrostation in Hawaiian waters. In July 1988, these proposals were funded by the National Science Foundation and Sta. ALOHA was officially on the map (Fig. 5). Since that time, there have been numerous noteworthy events in the implementation of this major field program (Table 2).

Table 2. *HOT program chronology and benchmarks*, 1987–1993

Date	Event
May 1987	HOT–WOCE program proposal submitted to NSF Physical Oceanography Program (R. Lukas, E. Firing, S. Smith, co-P.I.s)
Oct 1987	HOT–JGOFS program proposal submitted to NSF Chemical and Biological Oceanography Programs (D. Karl and C. Winn, co-P.I.s)
July 1988	HOT phase I program NSF funding begins (1988–1993); S. Smith resigns from HOT–WOCE program; S. Chiswell added to HOT–WOCE component as co-P.I.
Oct 1988	HOT-1 inaugural cruise aboard R.V. *Moana Wave*; D. Karl and R. Lukas co-Chief scientists
Aug 1989	During HOT-9, a massive accumulation of *Trichodesmium*, a nitrogen-fixing cyanobacterium, was observed in the vicinity of Sta. ALOHA
July 1990	NOAA Climate and Global Change (CGC) program funding augmentation of HOT program for measurement of inorganic carbon system components (C. Winn, F. Mackenzie and D. Karl, co-P.I.s)
Sept 1990	During HOT-20, the hydrowire parted on the first CTD cast at Sta. ALOHA and the CTD-rosette was lost. It was recovered 3 days later using grappling gear and a bit of luck!
Feb 1991	During HOT-23, inverted echo sounder network was established near Sta. ALOHA
Apr 1991	HOT-25 "silver anniversary" cruise aboard R.V. *Alpha Helix*; R. Lukas, chief scientist
July 1991	HOT-28, total solar eclipse (11 July)
Oct 1991	During HOT-31, we expanded the sampling area to include 3 additional stations to the north and south of Sta. ALOHA
June 1992	During HOT-37, a time-series sediment trap mooring site was established near Sta. ALOHA
July 1992	NOAA–CGC funding ends
July 1993	Zooplankton measurement component added to HOT program core (M. Landry, P.I.)
Aug 1993	HOT phase II program NSF funding begins (1993–1998); C. Winn resigns from core HOT–JGOFS program; L. Tupas and D. Hebel added as HOT–JGOFS program co-P.I.s with D. Karl; F. Bingham added as WOCE component co-P.I. with R. Lukas and E. Firing; R. Bidigare (pigments) and C.Winn (inorganic carbon) added as ancillary HOT core program P.I.s
Nov 1993	HOT-50 "golden anniversary" cruise aboard R.V. *Moana Wave*; L. Tupas chief scientist
Nov 1993	HOT Science Symposium: Progress and Prospectus held at East-West Center, Honolulu, HI.

HOT PROGRAM DESIGN AND IMPLEMENTATION

WOCE and JGOFS objectives for HOT

The primary objective of HOT is to obtain a long time-series of physical and biochemical observations in the North Pacific subtropical gyre that will address the goals of the U.S. Global Change Research Program.

The objectives specific to the WOCE program are to:

— document and understand seasonal and interannual variability of water masses;
— relate water mass variations to gyre fluctuations;
— determine the need and methods for monitoring currents at the HOT site;
— develop a climatology of short term physical variability.

In addition to these general primary objectives, the physical oceanographic component of HOT provides CTD/rosette sampling support for the JGOFS time-series sampling program, and supports development of new instrumentation for hydrographic observations. To date, HOT has supported research on lowered acoustic profiler measurements of currents in support of WOCE objectives (Firing and Gordon, 1990), and on dissolved oxygen sensor technology (Atkinson *et al.*, in press).

The objectives of HOT specific to the JGOFS program are to:

— document and understand seasonal and interannual variability in the rates of primary production, new production and particle export from the surface ocean;
— determine the mechanisms and rates of nutrient input and recycling, especially for N and P in the upper 200 m of the water column;
— measure the time-varying concentrations of carbon dioxide in the upper water column and estimate the annual air-to-sea gas flux.

In addition to these general primary objectives, the biogeochemical component of HOT provides logistical support for numerous complementary research programs. To date, HOT has supported studies of oxygen dynamics and biological productivity modeling (Emerson *et al.*, 1993; Schudlich and Emerson, 1996), phytoplankton community structure (Campbell and Vaulot, 1993) as well as trace element, trace gas and radionuclide distributions.

Initial design considerations

There are both scientific and logistical considerations involved with the establishment of any long-term, time-series measurement program. Foremost among these is site selection, choice of variables to be measured, and general sampling design, including sampling frequency. Equally important design considerations are those dealing with the choice of analytical methods for a given candidate variable, especially an assessment of the desired accuracy and precision, and availability of suitable reference materials, the hierarchy of sampling replication and, for data collected at a fixed geographical location, mesoscale horizontal variability.

The HOT program was initially conceived as being a deep-ocean, ship- and mooring-based observation experiment that would have an approximately 20-year lifetime. Consequently, we selected a core suite of environmental variables that might be expected to display detectable change on timescales of several days to one decade. Except for the availability of existing satellite and ocean buoy sea surface data, the initial phase of the HOT program (October 1988–February 1991) was entirely supported by research vessels. In February 1991, an array of five inverted echo sounders (IES) was deployed in an approximately 150 km^2 network around Sta. ALOHA (Chiswell, 1996) and in June 1992, a sequencing sediment trap mooring was deployed a few km north of Sta. ALOHA (Karl, 1994). In 1993, the IES network was replaced with two strategically-positioned instruments: one at Sta. ALOHA and the other at Sta. KAENA (Fig. 5 and Table 3). Except for brief service intervals, both the IES transducers and sediment trap mooring have been collecting data since their respective initial deployments (Table 3).

Sta. ALOHA site selection

We evaluated several major criteria prior to selection of the site for the HOT oligotrophic ocean benchmark hydrostation. First, the station must be located in deep water (>4000 m), upwind (north-northeast) of the main Hawaiian islands and of sufficient distance from land to be free from coastal ocean dynamics and biogeochemical influences. On the other hand, the station should be close enough to the port of Honolulu to make the relatively short duration (<5 days) monthly cruises logistically and financially feasible. A desirable, but less stringent criterion would locate the station at, or near, previously studied regions of the central North Pacific Ocean, in particular Sta. Gollum.

Table 3. Geographical locations of the Hawaii Ocean Time-series (HOT) water column and bottom stations

Station	Coordinates	Approximate Distance from Land (km)	Approximate Bottom Depth (m)	Comments
1 (KAHE)	21°20.6′N158°16.4′W	10	1500	HOT Program coastal time-series station and equipment test site, established Oct 1988
2 (ALOHA)	22°45′N158°00′W	100	4800	HOT Program open ocean time-series station, sampling is confined to a circle with a 6 nmi radius, centered at ALOHA, established Oct 1988
3	23°25′N158°00′W	130	4800	One of three onshore to offshore transect sites, established Oct 1992
4	21°57.8′N158°00′W	20	3800	One of three onshore to offshore transect sites, established Oct 1992
5	21°46.6′N158°00′W	5	400	One of three onshore to offshore transect sites, established Oct 1992
6 (KAENA)	21°50.8′N158°21.8′W	20	2500	Location of long-term IES, established in June 1993
IES-I Network				
N	23°00.7′N157°59.9′W	105	4800	Initial deployment period from Feb 1991 to Feb 1992; second deployment period from June 1992 to April 1993
C	22°44.9′N157°59.9′W	100	4800	
SW	22°37.0′N158°14.7′W	90	4800	
SE	22°30.0′N157°45.2′W	80	4800	
E	22°44.8′N157°54.1′W	100	4800	
Bottom-moored sediment trap				
I	22°57.3′N158°06.2′W	110	4800	1st deployment of bottom-moored sequencing sediment trap, June 1992–Oct 1993
II	23°6.7′N157°55.8′W	110	4800	2nd deployment of bottom-moored sequencing sediment trap, Oct 1993–Oct 1994
NDBC buoys				
No. 51001	23°25′N162°20′W	180	3300	Two NOAA–NDBC meteorological buoys north of the Hawaiian Ridge and used to track conditions at Sta. ALOHA, established in 1981 and 1993, respectively
No. 51026	21°22′N156°58′N	10	2500	

After consideration of these criteria, we established our primary sampling site at 22°45′N, 158°00′W at a location approximately 100 km north of the island of Oahu (Figs 5, 6 and Table 3) and largely restrict our monthly sampling activities to a circle with a 6 nmi radius around this nominal site (Fig. 6). Sta. ALOHA is in deep water (4800 m) and is more than one Rossby radius (50 km) away from steep topography associated with the Hawaiian Ridge. We also established a coastal station west-southwest of the island of Oahu, approximately 10 km off Kahe Point (21°20.6′N, 158°16.4′W) in 1500 m of water. Sta. Kahe serves as a coastal analogue to our deep-water site and the data collected there provide a near-shore time-series for comparison to our primary open ocean site. Sta. Kahe is also used to test our equipment each month before departing for Sta. ALOHA, and to train new personnel at the beginning of each cruise.

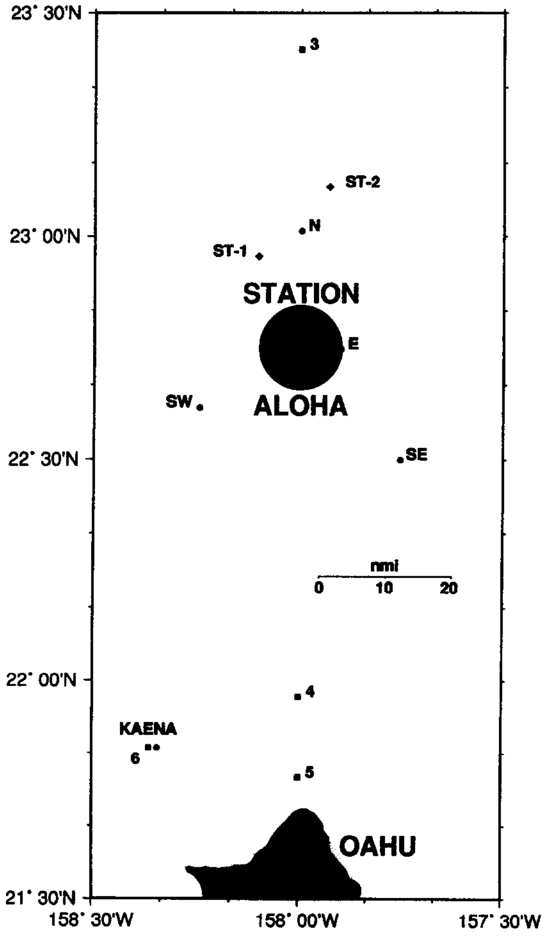

Fig. 6. Map showing the positions of: Sta. ALOHA (shaded circle with 6 nmi radius around reference coordinates 22°45′N, 158°W); Sta. KAENA; transect stations 3, 4 and 5; ALOHA-I and ALOHA-II sediment trap (ST) moorings; IES network and the proposed site of the ALOHA surface mooring.

Field sampling strategy

HOT program cruises, each 5 days in duration, are conducted at approximately monthly intervals (Table 4); the exact timing is dictated by the availability of research vessels. To date, our field observations have not been severely biased by month, season or year (Fig. 4), except perhaps for a slight under-representation of data collected during November and December and slight over-representation in February and September (Fig. 7).

From HOT-1 (October 1988) to HOT-32 (December 1991), underway expendible bathythermograph (XBT; Sippican T-7 probes) surveys were conducted at 7 nmi spacing on the outbound transect from Sta. Kahe to Sta. ALOHA. These surveys were discontinued because the space–time correlation of the energetic, internal semi-diurnal tides made it difficult to interpret these data. Upper water column currents are measured both underway and on station using a hull-mounted acoustic doppler current profiler (ADCP), when available (Firing, 1996). Most of our sampling effort, approximately 72 h per cruise, is spent at Sta. ALOHA.

High vertical resolution environmental data are collected with a Sea-Bird CTD with external temperature, conductivity, dissolved oxygen, fluorescence and light transmission sensors, and an internal pressure sensor. A General Oceanics 24-place pylon and an aluminum rosette containing 24 12-l polyvinyl chloride (PVC) bottles are used to obtain water samples from desired depths. The CTD and rosette are deployed on a 3-conductor cable allowing for real-time display of data and for tripping the bottles at specific depths of interest.

The CTD system takes 24 samples per second, and the raw data are stored both on the computer and, for redundancy, on VHS-format video tapes. We also routinely collect "clean" water samples for biological rate measurements using a system composed of General Oceanics Go-Flo^{R} bottles, Kevlar^{R} cable, metal-free sheave, Teflon^{R} messengers and a stainless steel bottom weight. A dedicated hydrowinch is used for the primary productivity sampling in an effort to reduce further the possibility of contamination. A free-drifting sediment trap array, identical in design to the VERTEX particle interceptor trap (PIT) mooring (Knauer *et al.*, 1979), is deployed at Sta. ALOHA for an approximately 72-h period to collect sinking particles for chemical and microbiological analyses.

Sampling at Sta. ALOHA typically begins with sediment trap deployment followed by a deep (>4700 m) CTD cast and a "burst series" of 12–18 consecutive casts, on 3 h intervals, to 1000 m to span the local inertial period (~ 31 h) and three semidiurnal tidal cycles. The repeated CTD casts enable us to calculate an average density profile from which variability on tidal and near-inertial timescales has been removed. These average density profiles are useful for the comparison of dynamic height and for the comparison of the depth distribution of chemical parameters from different casts and at monthly intervals. For example, by fitting the distribution of inorganic nutrients to this average density structure, the depth of the nutricline can be defined each month, independent of the short timescale changes in the density structure of the upper water column (Dore and Karl, 1996). This sampling strategy is designed to assess variability on timescales of a few hours to a few years. Very high frequency variability (<6 h) and variability on timescales of between 3 days to 2 months are not adequately sampled at the present time. Initial results from the IES network suggest that these frequencies might be important at Sta. ALOHA (Chiswell, 1996). However, no field sampling program, regardless of its intensity, can adequately resolve the entire spectrum of variability that theoretically exists in the ocean (Tabata, 1965).

Table 4. Chronology of HOT program cruises, 1988–1993

Cruise Number	Dates	Vessel	Comments
1	29 Oct–03 Nov 1988	R.V. *Moana Wave*	No KAHE data; no traps
2	30 Nov–04 Dec 1988	R.V. *Moana Wave*	No primary production data
3	06 Jan–10 Jan 1989	R.V. *Moana Wave*	No KAHE data
4	24 Feb–28 Feb 1989	SSP *Kaimalino*	
5	25 Mar–29 Mar 1989	R.V. *Moana Wave*	Limited CTD data at ALOHA
6	16 May–20 May 1989	SSP *Kaimalino*	
7	22 Jun–26 Jun 1989	SSP *Kaimalino*	No deep (> 2000m) samples or CTD data; no fluorescence data
8	27 Jul–31 Jul 1989	SSP *Kaimalino*	No deep (> 1000m) samples or CTD data
9	22 Aug–26 Aug 1989	SSP *Kaimalino*	No deep (> 2500m) samples or CTD data
10	21 Sep–24 Sep 1989	SSP *Kaimalino*	Initial use of 24-place rosette
11	16 Oct–20 Oct 1989	R.V. *Moana Wave*	Initial use of T-C duct on CTD
12	26 Nov–29 Nov 1989	R.V. *Moana Wave*	Limited data; no traps
13	03 Jan–07 Jan 1990	R.V. *Moana Wave*	Lowered ADCP tests
14	13 Feb–17 Feb 1990	SSP *Kaimalino*	
15	17 Mar–21 Mar 1990	SSP *Kaimalino*	
16	11 Apr–15 Apr 1990	R.V. *Wecoma*	
17	07 May–11 May 1990	SSP *Kaimalino*	Flash fluorometer problems
18	11 Jun–15 Jun 1990	R.V. *Wecoma*	
19	23 Jul–27 Jul 1990	SSP *Kaimalino*	
20	13 Sep–17 Sep 1990	R.V. *Moana Wave*	Hydrowire parted, CTD lost and subsequently recovered; limited data
21	17 Nov–20 Nov 1990	R.V. *Na'Ina*	Gale force winds, limited data
22	16 Dec–20 Dec 1990	R.V. *Moana Wave*	
23	01 Feb–06 Feb 1991	R.V. *Moana Wave*	Initial IES deployment
24	05 Mar–09 Mar 1991	R.V. *Alpha Helix*	Rough weather, limited data; no KAHE data
25	08 Apr–12 Apr 1991	R.V. *Alpha Helix*	No traps
26	06 May–10 May 1991	R.V. *Alpha Helix*	
27	03 Jun–06 Jun 1991	R.V. *Alpha Helix*	
28	08 Jul–12 Jul 1991	R.V. *Alpha Helix*	Winch failure 30 h into burst CTD sampling
29	08 Aug–12 Aug 1991	R.V. *Alpha Helix*	
30	16 Sep–20 Sep 1991	R.V. *Moana Wave*	*Trichodesmium* abundant
31	19 Oct–24 Oct 1991	R.V. *Wecoma*	
32	04 Dec–09 Dec 1991	R.V. *Wecoma*	
33	03 Jan–08 Jan 1992	R.V. *Wecoma*	
34	12 Feb–17 Feb 1992	R.V. *Wecoma*	
35	03 Mar–08 Mar 1992	R.V. *Wecoma*	
36	15 Apr–20 Apr 1992	R.V. *Wecoma*	
37	07 Jun–11 Jun 1992	R.V. *Moana Wave*	IES network deployed; sediment trap mooring deployed
38	03 Jul–07 Jul 1992	R.V. *Moana Wave*	
39	03 Aug–08 Aug 1992	R.V. *Moana Wave*	
40	20 Sep–25 Sep 1992	R.V. *Moana Wave*	
41	17 Oct–22 Oct 1992	R.V. *Moana Wave*	
42	23 Nov–25 Nov 1992	R.V. *Kila*	No CTD, primary production or trap data
43	15 Dec–17 Dec 1992	R.V. *Kila*	No CTD, primary production or trap data

Table 4. (*Continued*)

Cruise Number	Dates	Vessel	Comments
44	18 Jan–22 Jan 1993	R.V. *Townsend*	No deep (> 1000 m) samples or CTD data
45	15 Feb–20 Feb 1993	R.V. *Thomas G. Thompson*	
46	12 Apr–17 Apr 1993	R.V. *Wecoma*	
47	18 May–23 May 1993	R.V. *New Horizon*	
48	26 Jul 1993	R.V. *Na'Ina*	Due to inclement weather, no samples or data were collected
49	09 Sep–17 Sep 1993	R.V. *Moana Wave*	Sediment trap mooring recovered and redeployed
50	27 Oct–01 Nov 1993	R.V. *Moana Wave*	

Water samples for a variety of chemical and biological measurements (see *Core measurements, experiments and protocols* section) are routinely collected from the surface to within 50 m of the seafloor (4800 m). To the extent possible, we collected samples for complementary biogeochemical measurements from the same or from contiguous casts to minimize aliasing caused by time-dependent changes in the density field. This is especially important for samples collected in the upper 300 m of the water column. Furthermore, we attempt to sample from common depths and specific density horizons each month to facilitate comparisons between cruises. Water samples for salinity determinations are collected from every water bottle to identify sampling errors. Approximately 20% of the water samples are collected and analyzed in triplicate to assess and track our analytical precision in sample analysis.

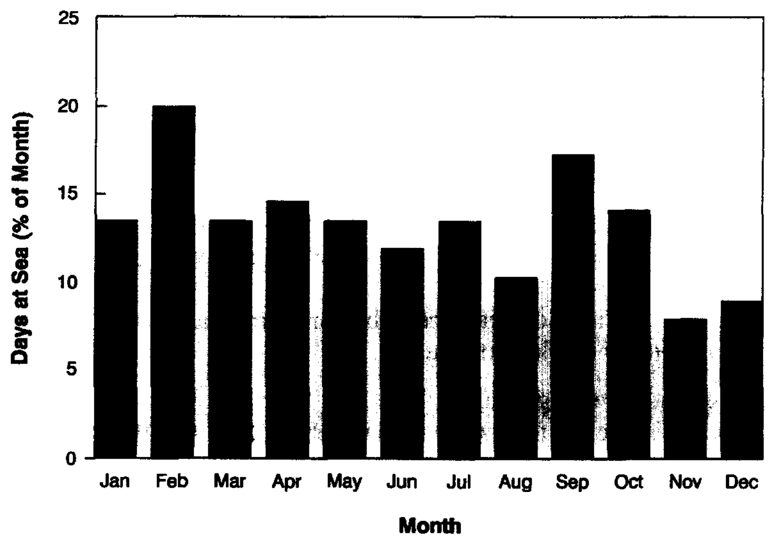

Fig. 7. HOT program field observations for the period October 1988 to November 1993 displayed as a percentage of total month spent aboard research vessels at sea. The overall 5-year mean = 13.6%, median = 13% and range 8% (November) to 20% (February).

Core measurements, experiments and protocols

Our primary study area is characterized by warm (> 23°C) surface waters with low nitrate concentrations (< 15 nM), seasonally variable surface mixed-layers (10–120 m), low standing stocks of living organisms (10–15 $\mu g\ C\ l^{-1}$) and a persistent deep (75–140 m) chl *a* maximum layer. Ideally, the suite of measurement parameters should provide a data base to validate existing biogeochemical models and to develop improved ones. Our list of core measurements has evolved since the inception of the HOT program in 1988, and now includes both continuous and discrete physical, biological and chemical ship-based measurements, *in situ* biological rate experiments, and observations and sample collections from bottom-moored instruments (Table 5). Continuity in the measurement parameters and their quality, rather than the methods employed, are of greatest interest. Detailed analytical methods are expected to change over time through technical improvements. The detailed sampling procedures and analytical protocols are presented, as appropriate, in subsequent chapters of this special volume and also can be obtained via anonymous file transfer protocol (ftp) on the world-wide Internet system (Table 6). In addition to the core data, specialized measurements and process-oriented experiments have been conducted at Sta. ALOHA (Table 7).

HOT PROGRAM ACCOMPLISHMENTS TO DATE

The research conducted at Sta. ALOHA already has provided an invaluable data set on unexpected physical and biogeochemical variability in the subtropical North Pacific Ocean. Some of these results have been published or are described in more detail in this special volume, but most are part of the continuing time-series measurement program. Selected HOT program results include:

I. Physical oceanography:
- relatively shallow depth of the seasonal cycle penetration and shallow surface mixed-layer (Bingham and Lukas, 1996);
- detection of the Hawaiian Ridge Current, and variations thereof (Firing, 1996);
- significant interannual variability in dynamic height, as measured by the IES network (Chiswell, 1996);
- assessment of the influence of Rossby waves, detected by TOPEX altimetry, on oceanographic conditions at Sta. ALOHA (Mitchum, 1996);
- appearance of submesoscale salinity lenses in the mesopelagic zone (Kennan and Lukas, 1996);
- ENSO-related variations of near ocean-bottom temperature (Lukas and Santiago-Mandujano, 1996) and cold water surges.

II. Biological–Chemical Oceanography:
- quantitative assessment of the CO_2 sink which, at Sta. ALOHA, averages 0.7 mol $CO_2\ m^{-2}\ year^{-1}$ (Winn *et al.*, 1994);
- numerical dominance of photosynthetic (oxygenic) bacteria of the genera *Prochlorococcus* and *Synechococcus* at Sta. ALOHA (Letelier *et al.*, 1993; Campbell and Vaulot, 1993);
- ENSO-related changes in subtropical North Pacific community structure and biogeochemical cycling rates (Karl *et al.*, 1995);

Table 5. *HOT program core measurements and protocols*

Parameter	Depth or Depth Range (m)	Sensor or Analytical Procedure
Continuous Profiles		
Depth (pressure)	0–4800	Pressure transducer on SeaBird CTD–rosette package
Temperature (*in situ*)	0–4800	Thermistor on SeaBird CTD–rosette package
Temperature (potential)	0–4800	Derived parameter
Salinity (conductivity)	0–4800	Conductivity sensor on SeaBird CTD–rosette package
Density	0–4800	Derived parameter
Dynamic height	0/1000	Derived parameter
Dissolved oxygen	0–4800	YSI polarographic sensor on SeaBird CTD–rosette package
Fluorescence	0–1000	Sea-Tech fluorometer on SeaBird CTD–rosette package
Photosynthetically-available radiance (PAR)	0–150	Biospherical Instruments, PNF-300
Natural fluorescence	0–150	Biospherical Instruments, PNF-300
Currents	0–300	ADCP-hull mounted
	0–4800	ADCP-lowered
Discrete Water Bottle Samples		
Dissolved oxygen	0–4800	Automated Winkler titration
Dissolved inorganic carbon	0–4800	Coulometry
pH	0–4800	Spectrophotometric pH-sensitive dye measurements
Alkalinity	0–4800	Automated Gran titration
Carbon dioxide partial pressure	0–4800	Derived parameter
Dissolved nitrate and nitrite	0–200	Chemiluminescence (low level)
Dissolved nitrate and nitrite	0–4800	Autoanalyzer (standard)
Dissolved phosphorus (low level)	0–200	Magnesium-induced coprecipitation, spectrophotometry
Dissolved phosphorus (standard)	0–4800	Autoanalyzer
Dissolved silica (low level)	0–200	Magnesium-induced coprecipitation, spectrophotometry
Dissolved silica (standard)	0–4800	Autoanalyzer
Dissolved organic carbon	0–1000	High-temperature oxidation, infrared detection
Dissolved organic nitrogen	0–1000	UV digestion, autoanalyzer
Particulate carbon and nitrogen	0–1000	High-temperature combustion, gas chromatography
Particulate phosphorus	0–1000	High-temperature ashing, spectrophotometer
Pigments, chlorophyll *a*	0–200	High-pressure liquid chromatography and fluorometry
Primary production	0–200	"Clean" ^{14}C *in situ* incubations
Adenosine triphosphate	0–1000	Boiling buffer extraction, firefly bioluminescence
Bacteria and cyanobacteria	0–1000	Epifluorescence microscopy, flow cytometry
Lipopolysaccharide	0–1000	*Limulus* amoebocyte lysate assay
Free-drifting Sediment Traps		
Total mass	150, 300, 500	Filtration and gravimetric analysis
Particulate carbon and nitrogen	150, 300, 500	High-temperature combustion, gas chromatography
Particulate phosphorus	150, 300, 500	High-temperature ashing, spectrophotometry
Identification	150, 300, 500	Brightfield and epifluorescence microscopy
Calcium carbonate	150, 300, 500	Weight loss on acidification of total mass
Biogenic silica	150, 300, 500	Alkaline digestion, spectrophotometry

continued

Table 5. (Continued)

Parameter	Depth or Depth Range (m)	Sensor or Analytical Procedure
Bottom-Moored Sequencing Sediment Traps		
Total mass	800, 1500, 2800, 4000	Filtration and gravimetric analysis
Particulate carbon and nitrogen	800, 1500, 2800, 4000	High-temperature combustion, gas chromatography
Particulate phosphorus	800, 1500, 2800, 4000	High-temperature ashing, spectrophotometry
Identification	800, 1500, 2800, 4000	Brightfield and epifluorescence microscopy
Calcium carbonate	800, 1500, 2800, 4000	Weight loss on acidification of total mass
Biogenic silica	800, 1500, 2800, 4000	Alkaline digestion, spectrophotometry
Inverted Echo Sounder Network		
Acoustic travel time	0–bottom	Acoustic transducer, CTD calibration
NOAA–NDBC Meteorological Buoys		
Air temperature	—	Thermistor
Sea surface temperature	—	Thermistor
Wind speed	—	Vane-directed impeller
Wind direction	—	Vane and fluxgate compass
Wind gust	—	Vane-directed impeller
Barometric pressure	—	Variable capacitance

— potential role of *Trichodesmium* and N_2 fixation in the nitrogen budget (Karl *et al.*, 1992; Karl *et al.*, 1995; Letelier and Karl, in press);

— confirmation of general validity of historical estimates of dissolved organic nitrogen and phosphorus concentrations (5–8 μM DON and 0.3–0.4 μM DOP; Karl *et al.*, 1993), and presentation of revised estimates for dissolved organic carbon concentration (80–110 μM DOC; Tupas *et al.*, 1994) in surface waters;

— discovery of relatively high, but variable, annual rates of primary production ($\sim$14 mol C m^{-2} $year^{-1}$; Karl *et al.*, 1996), compared to historical estimates (e.g. Berger, 1989);

— convergence of new (export) production estimation by three independent techniques (oxygen mass balance modeling, Emerson *et al.*, 1995; mixed-layer dissolved inorganic carbon and $^{13}C/^{12}C$ balance modeling, Quay and Anderson, 1996; direct measurement of particulate matter export, Karl *et al.*, 1996) on a value of $\sim$1 mol C m^{-2} $year^{-1}$;

Table 6. Internet access to the HOT time-series data base and other information on program implementation and scientific progress. The workstation's Internet address is: mana.soest.hawaii.edu or 128.171.154.9. *To access the workstation use the anonymous file transfer protocol (ftp)*

Address or File	Data or Information Available
cd/pub/hot	To access HOT data and information base once connected to *hokulea*
Readme.first	Provides general information about the data base
/pub/hot/protocols	HOT Program Field and Laboratory Protocols Manual, updated periodically
/pub/hot/publication-list	HOT program publication list, updated quarterly

Table 7. List of ancillary investigators supported by the HOT program (1988–1993)

Lead Investigator(s)	Research Topic	Funding Source*
A. Anbar (Cal. Tech.)	Trace metals	NSF
M. Atkinson (Univ. Hawaii)	Oxygen sensor development	NSF
R. Bidigare (Univ. Hawaii)	Pigments	NSF
D. Bird (UQAM)	Distribution of virus particles	Other
K. Bjorkman (Univ. Stockholm)	P-cycle dynamics	GS
L. Campbell (Univ. Hawaii)	Picoplankton	NSF
R. Chen (Univ. Calif.)	DOM fluorescence	NSF
S. Chiswell (Univ. Hawaii)	Dynamic height	NSF
J. Christian (Univ. Hawaii)	Bacterial ectoenzymes	GS (NASA)
D. Collins (NASA–JPL)	Ocean optics	NASA
J. Cowen (Univ. Hawaii)	Marine snow and particle analysis	NSF
J. Dore (Univ. Hawaii)	N-cycle/nitrification	GS (NSF)
S. Emerson (Univ. Washington)	Oxygen dynamics	NSF
E. Firing and R. Gordon (Univ. Hawaii and RDI)	Lowered ADCP development	NSF
J. Hedges and R. Benner (Univ. Washington/Univ. Texas)	DOC/DON studies	NSF
S. Honjo and S. Manganini (WHOI)	Particle flux measurements	NSF
C. Keeling (Univ. California)	Carbon dioxide	NSF
M. Keller (Bigelow Marine Labs)	Phytoplankton taxonomy	NSF
S. Kennan (Univ. Hawaii)	Hydrography of intermediate waters	GS (NSF)
M. Landry (Univ. Hawaii)	Macrozooplankton	NSF
R. Letelier (Univ. Hawaii)	*Trichodesmium* distribution	GS (NSF)
H. Liu (Univ. Hawaii)	Microplankton grazing rates	GS (NSF)
G. Luther (Univ. Delaware)	Iodine cycling	NSF
C. Measures (Univ. Hawaii)	Trace metals	ONR
C. Moyer (Univ. Hawaii)	Picoeukaryote phylogeny	GS (NOAA)
B. Popp and D. Karl (Univ. Hawaii)	Dissolved organic carbon isotopes	NSF
P. Quay (Univ. Washington)	Dissolved inorganic carbon isotopes	NOAA
C. Sabine (Univ. Hawaii)	Dissolved inorganic carbon	GS (NSF)
D. Sadler (Univ. Hawaii)	High-precision pH measurements	GS (NSF)
L. Sautter (College of Charleston)	Foraminifera	NSF
R. Scharek and D. Karl (Univ. Hawaii)	Biogenic-Si/diatoms	NSF
T. Schmidt and E. DeLong (Indiana Univ.)	Bacterial phylogeny	NSF
R. Schudlich (Univ. Washington)	Upper ocean modeling	NSF
J. Sharp (Univ. Delaware)	DOC studies	NSF
C. Smith (Univ. Hawaii)	Deep sea benthic ecology	NSF
H. Thierstein (Swiss Fed. Tech. Inst.)	Coccolithophore distributions	Other
P. Troy (Univ. Hawaii)	Calcite dissolution experiments	GS (NSF)
M. Vernet (Univ. Calif.)	Pigments	NSF
C. Voss and W. Wood (USGS)	Natural ^{14}C abundance measurements	USGS
C. Winn (Univ. Hawaii)	Dissolved inorganic carbon	NOAA
C. Winn and M. Landry (Univ. Hawaii)	Various (REU Site Program)	UGS (NSF)
K. Yanagi (Univ. Hawaii)	Dissolved organic phosphorus	Sabbatical visitor
J. Yuan (Univ. Hawaii)	Dissolved iron measurements	GS (ONR)

*NSF—National Science Foundation, ONR—Office of Naval Research, NOAA—National Oceanic and Atmospheric Administration, NASA—National Aeronautics and Space Administration, GS—graduate student, UGS—undergraduate student.

— observation of a temporal decoupling in organic matter production, export and decomposition (Karl *et al.*, 1996);

DATA AVAILABILITY AND DISTRIBUTION

A major scientific objective of the HOT program is to provide members of the scientific community with a high quality time-series data set of relevant physical and biogeochemical variables for model validation and other purposes. Each year we publish a HOT Program Data Report that summarizes data collected from the previous calendar year. The Data Reports provide summaries of the temperature, potential temperature, salinity, oxygen and potential density at standard National Oceanographic Data Center (NODC) pressures in ASCII files on an IBM-PC compatible 3.5" high-density floppy diskette. Water column chemistry, primary productivities and particle flux data are presented as Lotus 1-2-3™ files. These data are all quality controlled before publication, and a readme.txt file provides a complete description of data formats and quality flags. Single copies of the annual HOT program data reports are available through the U.S.-JGOFS Planning Office (Woods Hole, MA 02543, U.S.A.; attn: H. Livingston) or by contacting the HOT Program office (SOEST, University of Hawaii, Honolulu, HI 96822, U.S.A.; attn: L. Fujieki (lfujieki@soest.hawaii.edu)).

A more complete data set, containing all of the HOT data collected since October 1988, including the 2 dbar averaged CTD data, are available from two sources. The first is through NODC (Washington, D.C., 20235). The second source is via the world-wide Internet system using the anonymous ftp (Table 6). In order to maximize ease of access, the data are in ASCII files with names selected so they can be copied to DOS-based computers without ambiguity. More information about the data base structure and content is provided in several Readme.* files (we suggest that you try Readme.first, first!). Recently, a World Wide Web site has also been established at http://hahana.soest. hawaii.edu/.

PROSPECTUS

Long-term time series programs present special problems for research scientists in general (Strayer *et al.*, 1986) and for oceanographers in particular (Tabata, 1965; Wolfe *et al.*, 1987). Foremost among the major concerns are the procurement of sufficient funding to maintain these costly programs, maintenance of a high-quality data base, retention of dedicated and skilled personnel, and logistical problems inherent in extensive field programs. Furthermore, there has been a negative attitude, and therefore misconception, among certain academic scientists and funding agencies about the value of "environmental monitoring" (Karl and Winn, 1991).

The HOT program is expected to be in operation for a period of at least 20 years. The emergent physical and biogeochemical data sets are already available to the scientific community through a fast, convenient computer network with inexpensive, global access. During the initial phase of HOT we established a sampling and measurement strategy that was designed to satisfy WOCE and JGOFS program objectives and to generate new hypotheses. As novel technologies emerge (e.g. *in situ* chemical and bio-optical sensors) we look forward to assisting with the critical field tests and calibrations and to an eventual improvement of our capabilities to observe and interpret oceanic variability on all timescales.

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