RECENT ADVANCES IN MARINE SCIENCE AND TECHNOLOGY, 92

Edited by

Narendra Saxena
Professor of Civil Engineering
University of Hawaii
Honolulu, Hawaii, U.S.A.

May 1993

Published by
PACON International
P.O. Box 11568
Honolulu, Hawaii 96828
U.S.A.

ISBN 0-9634343-0-6 (this volume)
ISBN 0-9634343 (series)

Printed in the United States of America

THE HAWAII OCEAN TIME-SERIES PROGRAM: RESOLVING VARIABILITY IN THE NORTH PACIFIC

C.D. Winn, R. Lukas, D. Hebel, C. Carrillo, R. Letelier, and D.M. Karl
University of Hawaii
Honolulu, Hawaii, U.S.A.

ABSTRACT

Time-series measurements of biological, chemical and physical parameters in the North Pacific Subtropical Gyre have been made on a regular basis since October 1988. These observations now comprise one of the longest sets of time-series measurements in the central Pacific Ocean, and are the only time-series observations available for a variety of parameters in this ocean basin. The time-series observation program has provided a unique view of the extent of variability in the central Pacific, and has begun to improve our knowledge of the dynamics which take place there. The understanding which is emerging from the time-series dataset will be useful for interpreting the historical oceanographic database within the context of future environmental change.

INTRODUCTION

Time-series datasets are rare in the oceanographic literature. This is unfortunate, since it is well-recognized that time series measurements, particularly those made for a decade or more, are powerful tools for understanding and observing the slow process and irregular events that take place in nature (Franklin, 1988). This is now particularly important because of the need to understand the environmental changes that are taking place as a result of anthropogenic influences on the chemistry of the earth's atmosphere and oceans (Magnuson, 1990). Consequently, time-series measurements in a variety of environments are now especially useful. Time-series datasets are not abundant because long-term observation programs are expensive and are usually difficult to maintain. This is especially true of the ocean sciences where data collection requires costly research vessels and sophisticated sea-going equipment.

The usefulness of time-series observations of the natural world has been amply demonstrated. One of the most prominent examples is the over three decade long record of atmospheric carbon dioxide concentrations compiled by Charles Keeling at Scripps Institution of Oceanography (Keeling, et al., 1982; Moore and Bolin, 1987). This dataset has been invaluable for documenting the anthropogenic increase in atmospheric carbon dioxide concentrations and for developing models of the global carbon budget. Other time-series programs have documented changes in the pH of rainwater in the northern hemisphere (Likens, 1983) and documented other long-term changes in the physical and biological conditions in terrestrial environments (Brock, 1985; Peterson, 1984). Time-series observations in the oceans are more rare. For the most part, time-series datasets in the marine environment have involved measurements at higher trophic levels such as commercial fish and zooplankton (McGowan, 1990). A notable exception includes the long time-series of observations made by the California Cooperative Oceanic Fisheries Investigation (Chelton, et al., 1982). This long-term oceanographic study has included chemical and physical measurements as well as estimates of plankton biomass.

The world's oceans act to modulate global climate and are believed to be the predominant sink for anthropogenic carbon dioxide. However, the magnitude of the oceanic sink in various parts of the world's oceans is uncertain (Tans, et al., 1990; Broecker and Peng, 1992; Sarmiento and Sundquist, 1992). In addition, a detailed understanding of the rates and mechanisms of the cycling of carbon within the interior of the ocean is lacking (Longhurst and Harrison, 1989). In large part, this lack of understanding is due a to paucity of data in both space and time. For this reason time-series measurements of the oceanic carbon system are particularly important for understanding and eventually predicting the magnitude and rates of future climate change.

The need for time-series studies was clearly recognized when in 1987 the International Council of Scientific Unions (ICSU) established the Joint Global Ocean Flux Study (JGOFS) as part of its International Geosphere-Biosphere Program (IGPB) for the study of global change. As a consequence, the JGOFS program called specifically for establishment of oceanic time-series studies at strategic ocean sites which were envisioned as being maintained for at least a decade. As a part of the United States JGOFS study, two time-series were begun in 1988. One of these time-series programs was established at the Bermuda Biological Station where the 35 year time-series established at hydrostation "S" would be continued. A second time-series program was established at a new location in the Central Pacific Ocean near the Hawaiian archipelago (Karl and Winn, 1991).

THE HAWAII OCEAN TIME-SERIES PROGRAM

In November 1988, a long time-series program was begun in the Central Pacific Ocean. This research effort was initiated in an effort to produce a time-series dataset for the central Pacific Ocean. The Pacific time-series was named the Hawaii Ocean Time-Series (HOT) program. The primary purpose of this research effort is to identify annual and interannual variability in the physics, chemistry and biology at a single location in the North Pacific Subtropical Gyre. The Hawaii program is a joint effort between the National Science Foundation's Joint Global Ocean Flux Program (JGOFS) and the World Ocean Circulation Experiment (WOCE). This research effort is coordinated by scientists at the University of Hawaii and was funded initially for a 5 year period beginning in May of 1988. Although the program is presently funded for only a five year period, it is anticipated that the program will continue for at least 10 years.

The time-series permanent station is located 100 km due north of the island of Oahu, Hawaii at 22°45'W and 158°00'N (Figure 1). The location of the time-series station was chosen to minimize the influence of the Hawaiian archipelago (island mass effects) on the biogeochemistry of the water column at the time-series station. The permanent time-series station was therefore located upwind (northeast of the Hawaii Archipelago). Station ALOHA (A Long-Term Oligotrophic Habitat Assessment) is located in 4750 m of water and approximately 50 km (one Rossby wave radius) away from the steep topography associated with the Hawaiian Archipelago. A near-shore equipment test site at Kahe Point is also visited each month.

An extensive suite of measurements are made on each HOT cruise. These measurements include standard hydrographic, and optical measurements using continuous sensors mounted on lowered profiling devices, chemical measurements made at discrete depths collected with standard oceanographic sampling bottles, measurements of the rate of primary production as well as the rate of particle flux, and the measurement of upper ocean currents using an acoustic doppler current profiler (Table 1). The results of these routine measurements are available in tabular form in the

Table 1. Time-series parameters measured at station ALOHA

Parameter	Depth Range(m)	Analytical Procedure
I. CTD Measurements		
temperature	0–4750	Thermistor on Sea-Bird CTD package with frequent calibration
salinity	0–4750	Conductivity Sensor on Sea-Bird CTD package, standardization with AGE Inductive Salinometer against Wormly Water
oxygen	0–4750	Polarographic Sensor on Sea-Bird CTD package with Winkler standardization
fluorescence	0–1000	Sea-Tech Flash Fluorometer on Sea-Bird CTD package
II. Optical Measurements		
solar radiance (PAR)	Surface	Licor Cosine Collector and Biospherical 2 pi Collector
underwater irradiance (PAR)	0–150	Biospherical Profiling Natural Fluorometer 4 pi Collector
III. Water Column Chemical Measurements		
oxygen	0–4750	Winkler Titration
total carbon dioxide	0–4750	Coulometry
dissolved inorganic nitrate plus nitrite	0–4750	Autoanalyzer
dissolved ammonium	0–4750	Autoanalyzer
dissolved inorganic phosphorus	0–4750	Autoanalyzer
dissolved inorganic silica	0–4750	Autoanalyzer
dissolved organic carbon	0–1000	persulfate wet oxidation
dissolved organic nitrogen	0–1000	U.V. oxidation
dissolved organic phosphorus	0–1000	U.V. oxidation
particulate carbon	0–1000	high temperature combustion
particulate nitrogen	0–1000	high temperature combustion
particulate phosphorus	0–1000	high temperature combustion
IV. Water Column Biomass Measurements		
chlorophyll *a* and phaeopigments	0–200	Fluorometric Analysis / High Liquid Chromatography
adenosine 5'-triphosphate	0–1000	Firefly Bioluminescence
picoplankton / nanoplankton number	0–1000	Epifluorescence Microscopy
V. Carbon Assimilation and Particle Flux		
primary production	0–200	"clean" ^{14}C incubations
carbon, nitrogen, phosphorus, and mass flux	150, 300, 500	Free-Floating Particle Interceptor Traps
VI. Currents		
Acoustic Doppler Current Profiler	0–300	hull mounted
Acoustic Doppler Current Profiler	0–1000	lowered

annual data reports published by the HOT program (Chiswell, et al., 1990, Winn, et al., 1991). The entire suite of HOT program measurements are also available via the international internet system as described in the annual program data reports. Detailed information about methodology is available in a manual of methods prepared by JGOFS program scientists (Karl, et al., 1990).

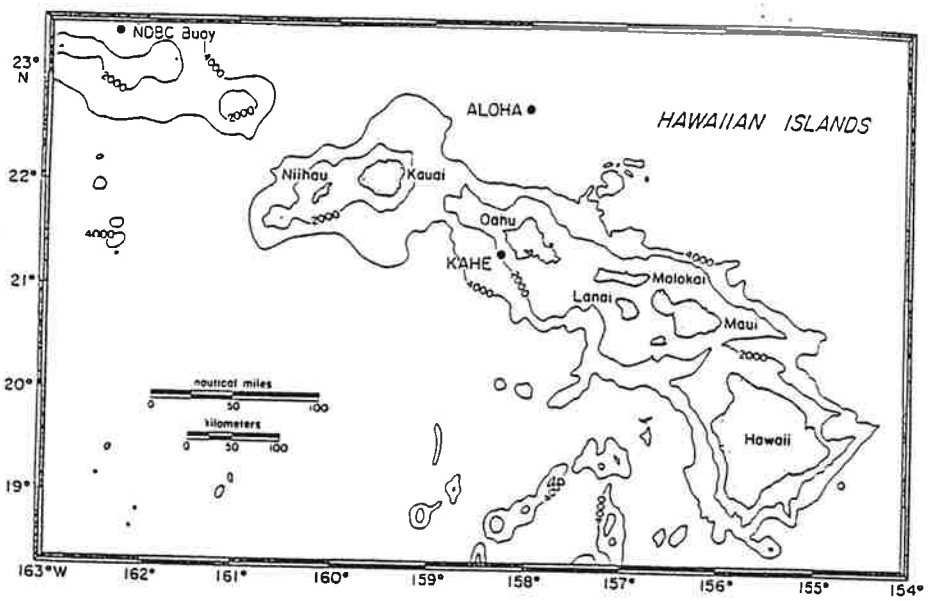


Figure 1. Location of the Hawaiian Ocean Time-series permanent station and the location of the near-shore equipment test site at Kahe Point

SELECTED RESULTS FROM THE HAWAII OCEAN TIME-SERIES PROGRAM

Hydrography

Figures 2 and 3 show contour plots of representative results of hydrographic measurements made over a three-year period at Station ALOHA. Figure 2 shows a contour plot of potential temperature to 1000 decibars. A contour plot of nitrate plus nitrite to 1000 decibars is shown in Figure 3. As one would expect, surface water temperature has varied seasonally from approximately 23 to 26 degrees Celsius at the time-series permanent station. The isotherms below the mixed layer have remained relatively constant with only minor variations. Nitrate plus nitrite has remained low in the surface waters, and there is no evidence of substantial injection of nutrients into the upper ocean as a result of seasonal mixing.

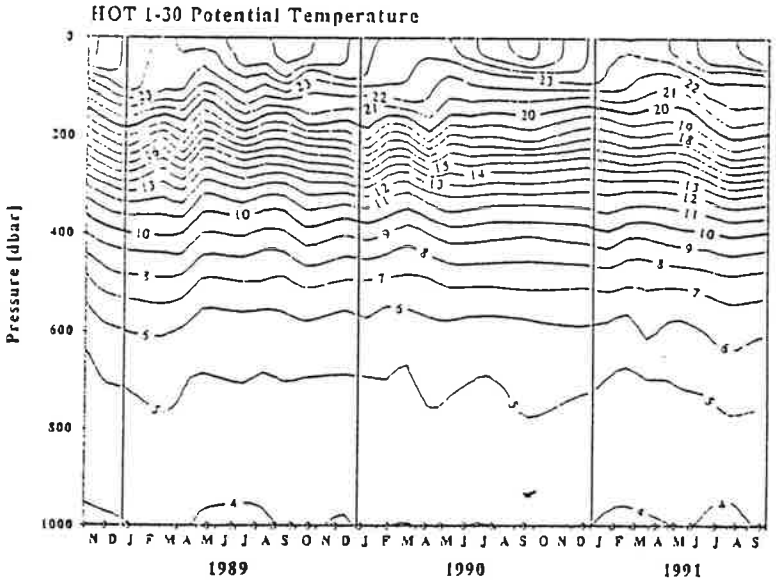


Figure 2. Contour plot of potential temperature (°C) to 1000 decibar versus time at Station ALOHA

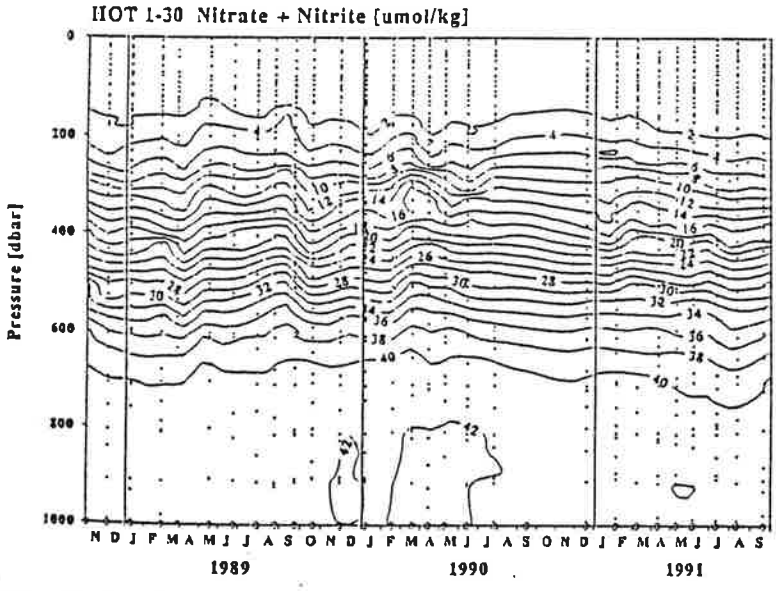


Figure 3. Contour plot of nitrate plus nitrate to 1000 decibar versus time at Station ALOHA

Primary Production and Particle Flux

The results of our time-series measurements of integrated primary production and carbon flux at 150 m are shown in Figure 4. These measurements have been made with carbon-14 using "clean" techniques (Fitzwater, et al., 1982) and 12 hour on-deck and in situ incubations (Karl, et al., 1990; Winn, et al., 1991). These data comprise the longest time-series of primary production and particle flux in the North Pacific Subtropical Gyre. The rate of primary production measured over a three year period ranges from a high of approximately 1100 and low of approximately 250 mg C $m^{-2}d^{-1}$. The highest rate of production was measured on a cruise during August of 1989. A surface accumulation of *Trichodesimum sp.* was observed near Station ALOHA on this cruise (Karl, et al. 1992), and may have been responsible for this anomalously high value. Excluding this value, the rate of primary production measured at the HOT permanent station varies by approximately a factor of 3. The temporal variability observed in the rate of primary production at Station ALOHA appears to be stochastic with little evidence of a seasonal cycle.

The mean rate of primary production is approximately 450 mg C $m^{-2}d^{-1}$. This rate of production is higher than historical data would suggest (Ryther, 1969), but is remarkably consistent with more recent measurements in the North Pacific Subtropical Gyre using newer "clean" C-14 primary production techniques (Martin, et al., 1987).

The rate of carbon flux at 150 m shows substantial annual variability and ranges over a factor of approximately 3 (Figure 4b). In both 1988 and 1989 there is a peak in carbon flux at 150 m in the spring and a second peak in summer. Although a peak in carbon flux in both 1989 and 1990 is observed in both the spring and the summer, only a single peak is observed in early summer in 1991.

In general, the rate of particle flux in marine environments is believed to be controlled primarily by the rate of primary production in the overlying euphotic zone. Although temporal variability in the flux of particulate material has been measured in several marine environments, most of the direct evidence for a link between primary production and particle flux at depth comes from observations in the Sargasso Sea at or near the Bermuda time-series site. Temporal variability in particle flux at 3200 m in the Sargasso Sea has been shown to vary in a pattern consistent with expected changes in surface water primary production (Deuser and Ross, 1980; Deuser, et al., 1981; Deuser, 1986). More recently, Deuser, et al. (1990) have shown a direct relationship between carbon flux at this depth and satellite derived estimates of surface ocean pigment concentration near the Bermuda time-series site. In addition, Asper, et al. (1992) have recently demonstrated a relationship between primary production measured with carbon-14 incubations and the flux of total particulate material throughout much of the water column at this same location. These results are not surprising, since one would expect the flux of particulate material in the central ocean basins away from the direct influence on terrigenous runoff to be dependent upon the production of biogenic particulate material in the euphotic zone.

It is surprising that the first three years of data collected by the HOT program show little evidence of a relationship between carbon flux at 150 m and euphotic zone primary production. Whereas a clear oscillation in the rate of particle flux is easily resolved by our monthly sampling, a similar trend in the rate of primary production is not evident (Figure 3). Although the poor correlation between these measurements has not yet been explained, several hypotheses can be advanced to account for this observation. These explanations fall into two broad categories. First, it is possible that the

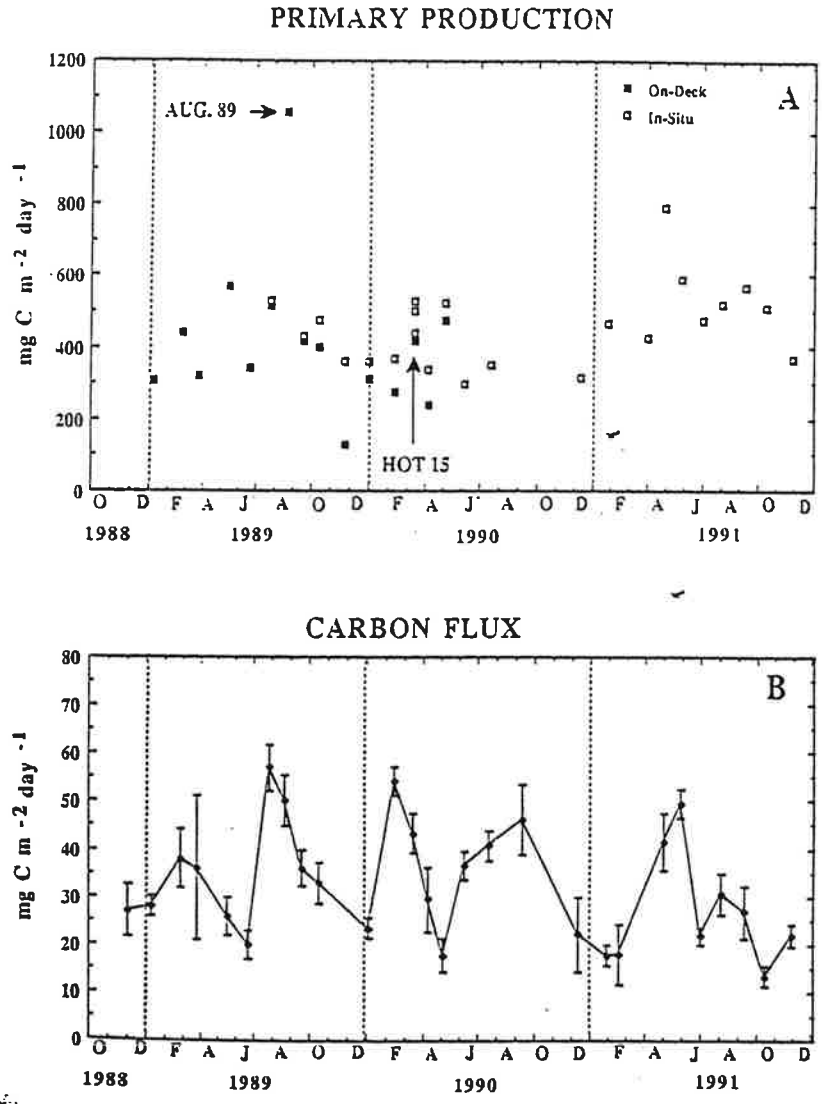


Figure 4. Primary production and particle flux measured over a three-year period at Station ALOHA. Panel A shows primary productivity integrated over the upper 200 m of the water column from eight incubation depths. Panel B shows carbon flux measured at 150 m over a 72-hour period with free-floating sediment traps.

expected relationship between particle flux and primary production exists at Station ALOHA, but our primary production measurements are unable to resolve the annual cycle in primary production that the flux data suggest exists in this process. Second, it is also possible that a tight relationship between primary production and particle flux does not exist at this location, and that the some other process or combination of processes are controlling the measured rate of particle flux.

A correlation between particle flux and primary production may exist at Station ALOHA but, especially in the central Pacific Ocean where temporal variability in the physical and biological conditions are known to be small, our C-14 measurements may not be able to resolve the annual signal in primary production. Support for this scenario can be found in an experiment conducted in March of 1990. On this cruise, primary production was measured in situ on three consecutive days (Figure 3b). The production rates measured over this three day period varied by more than 100 mg C $m^{-2}day^{-1}$. Excluding the one high value measured in August of 1989, this is equivalent to approximately 25% of the range of values measured over the duration of the program. The high degree of variability observed over this 72 hour period could be due to a highly variable rate of production which varies widely from day-to-day. The average rate experienced over the 72 hour trap deployment may therefore not be representative of that measured on a single day. Imprecision in the measurement of primary production may also play a role in this. Since we are calculating the integrated rate of production from a total of only eight incubation depths in the upper 200 m, and since primary production rates measured in incubation bottle maintained at fixed depths are known to be aliased by internal waves, it is possible that a large portion of the variability observed over this 3-day period is also due to "noise" in our primary production measurements.

As an alternative, it is also possible that factors other than primary production may greatly influence particle flux at the time-series site. Variability in the number of grazers and/or vertical migrators, for example, could be responsible for changes in the rate of particle flux independent of a change in the rate of primary production. In addition, atmospheric inputs of dust (Ditullio and Laws, 1991) could also influence the rate of particle flux on time and space scales which are not reflected in rates of primary production.

Whatever the underlying cause in the annual variation in the rate of particle flux at Station ALOHA, it is interesting that the sediment trap particle flux measurements are capable of resolving an annual cycle in an environment that is known for its temporal stability. This observation is especially noteworthy in light of the recent claims that particle traps do not provide accurate measurements of particle flux (Buesseler, 1991). Contrary to Buesseler's finding the results of the time-series program indicate that particle traps do, in fact, provide a excellent record of annual variability in an environment known for its low seasonal variability. Although we cannot yet definitively identify the mechanism which produces the observed annual variability in particle flux it is almost impossible that the regular pattern of variability observed over this three year period is due to random errors in the measured rate of particle flux, and therefore must be indicative of an annual cycle in the physical, chemical or biological conditions in the central Pacific Ocean.

Dissolved Inorganic Carbon

The first time-series measurements of dissolved inorganic carbon and titration alkalinity obtained in the surface waters of the central Pacific Ocean are shown in Figure 5. Specific alkalinity averages approximately 2315 ueq/kg and is very consistent with

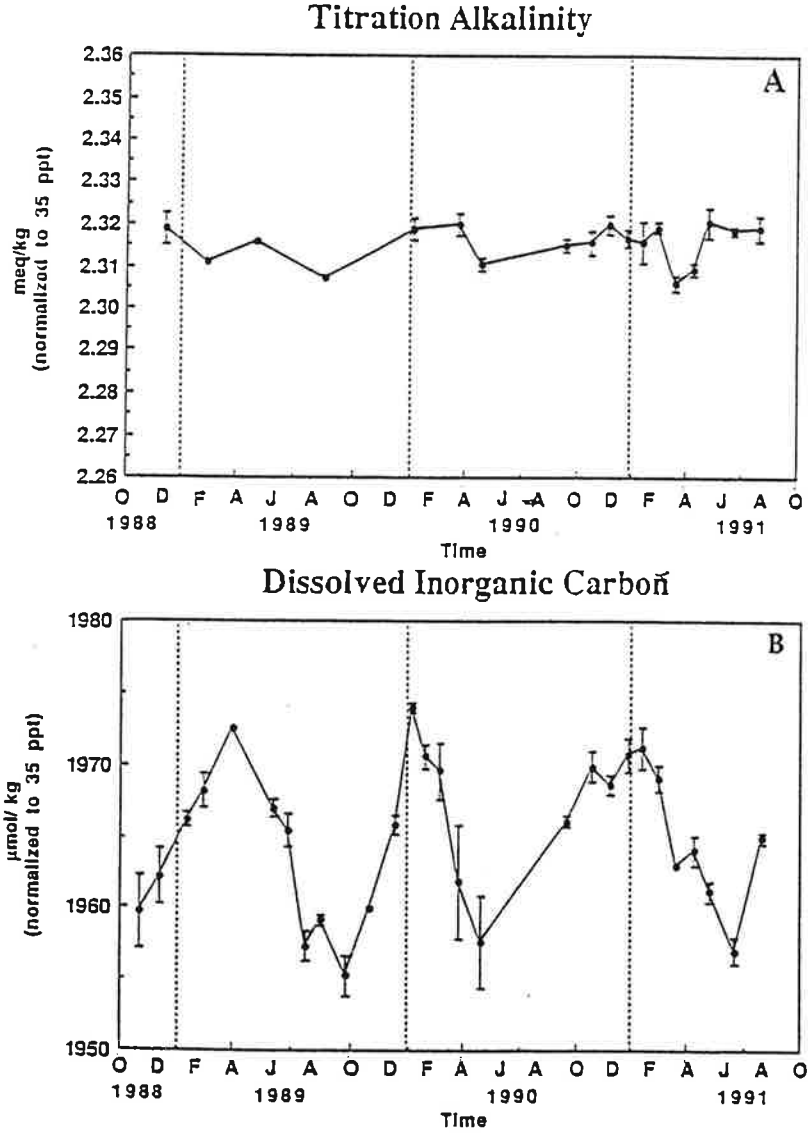


Figure 5. Titration alkalinity and dissolved inorganic carbon measured over a three-year period at station ALOHA. Panel A shows titration alkalinity normalized to 35 ppt salinity. Error bars show the standard deviation of replicate measurements in the upper 50 m. Panel B shows dissolved inorganic carbon normalized to 35 ppt salinity. Error bars represent the standard deviation of replicates in the upper 50 m.

other measurements made in the North Pacific Subtropical Gyre (eg., GEOSECS Program). Although some real variability in the specific alkalinity is evident, variability in titration alkalinity normalized to 35 parts per thousand salinity appears to be stochastic and shows no evidence of a regular annual cycle. In contrast, dissolved inorganic carbon (DIC) averaged over the upper 50 decibars and normalized to 35 parts per thousand salinity, displays a very regular annual cycle with a maximum in surface water in winter and a minimum in summer. Because the partial pressure of carbon dioxide changes by approximately 4% per degree Celcius, this pattern is consistent with a flux of carbon dioxide across the air-sea interface driven by changes in surface water temperature. In winter, when surface water temperature falls, pCO_2 also decreases and the net flux of carbon dioxide is from the atmosphere to the ocean. In summer, when surface water temperature rises, the net flux of carbon dioxide is from the ocean to the atmosphere. Using the time-series dataset and assuming that the mixed layer averages 60 m, the seasonal exchange of carbon dioxide between the ocean and the atmosphere at Station ALOHA is approximately 1 mole of carbon per m^{-2}. Therefore approximately 1 mole of carbon is transported across the air-sea interface from the atmosphere to the ocean during fall and approximately this same quantity of carbon dioxide is transported in the opposite direction during spring. This flux is approximately 20 times the projected rate of anthropogenic carbon dioxide accumulation rate (Tans, et al., 1990, and references therein).

CONCLUSIONS

In contrast to the classical view of the central Pacific as a extremely stable environment, the time-series dateset has shown that considerable variability does exist in this region. Particle flux measurements in the upper ocean show an annual cycle in the rate of carbon flux at the time-series site. In both 1989 and 1990, two peaks in particle flux, one in spring and one in summer are observed. In 1991, only a single statistically significant peak in mid-summer is apparent. A similar pattern in primary production is not obvious in any of the three years of time-series observations. Although the cause of the annual and interannual variability in carbon flux has not yet been identified, one interpretation of these data is that carbon flux, measured by free-floating sediment traps, provides a more accurate estimate of biological activity in the overlying euphotic zone than primary production measured with carbon-14.

The time-series observations of upper ocean dissolved inorganic carbon and alkalinity indicate a substantial flux of carbon dioxide across the air-sea interface at Station ALOHA. These data suggest that approximately one mole of carbon dioxide moves in and out of the surface ocean each year. This flux appears to be driven by the annual oscillation in upper ocean temperature. The magnitude of this annual exchange is approximately 15 to 20 times the projected rate of carbon dioxide increase in the surface ocean due to the rise in the increase in atmospheric carbon dioxide, and indicates that several years of regular measurements will be needed to accurately quantify the upper ocean anthropogenic carbon dioxide accumulation rate.

The data collected by the HOT program, comprise the longest and most extensive set of time-series measurements available for the central Pacific Ocean. These data are the first and only time-series available for a variety of parameters in the North Pacific Subtropical Gyre. These time-series data have already provided a unique view of the extent of variability in this ocean basin, and have begun to improve our understanding of the dynamics which take place there. The understanding which is emerging from the time-series dataset will be useful for interpreting the results of the spatial scale studies planned for the central Pacific, and for interpreting the historical database within the context of future environmental and climate change.

REFERENCES

Asper, V.L., W.G. Deuser, G.A. Knauer, and S.E. Lorenz. 1992. Rapid biogeochemical coupling between surface and deep ocean waters via particles. *Nature*. In press.

Broecker, W.S., and T. Peng. 1992. Interhemispheric transport of carbon dioxide by ocean circulation. *Nature*. 356:587-589.

Brock, T.D. 1985. A Eutrophic Lake: Lake Mendota, Wisconsin. New York: Springer-Verlag.

Buesseler, K.O. 1991. Do upper ocean sediment traps provide an accurate record on particle flux? *Nature*. 353:420-423.

Chiswell, S.E., E. Firing, D. Karl, R. Lukas, and C.D. Winn. 1990. Hawaii ocean time-series data report #1: 1988-1989. SOEST Technical Report #1. University of Hawaii: Honolulu, Hawaii.

Chelton, D.B., P.A. Bernal, and J.A. McGowan. 1982. Large-scale interannual physical and biological interaction in the California Current. *Journal of Marine Research*. 40:1095-1125.

Deuser, W.G., and E.H. Ross. 1980. Seasonal change in the flux of organic carbon to the deep Sargasso Sea. *Nature*. 283:364-365.

Deuser, W.G., E.H. Ross, and R.F. Anderson. 1981. Seasonality in the supply of sediment to the deep Sargasso Sea and implications of the rapid transfer of matter to the deep ocean. *Deep-Sea Research*. 28:495-505.

Deuser, W.G. 1986. Seasonal and interannual variations in deep-sea particle fluxes in the Sargasso Sea and their relation to surface hydrography. *Deep-Sea Research*. 33:225-246.

Deuser, W.G., F.E. Muller-Karger, R.H. Evans, O.B. Brown, W.E. Esaias, and G.C. Feldman. 1990. Surface-ocean color and deep-ocean carbon flux: how close a connection? *Deep-Sea Research*. 37:1331-1343.

Ditullio, G.A., and E.A. Laws. 1991. Impact of an atmospheric-oceanic disturbance on phytoplankton community dynamics in the north pacific central gyre. *Deep-Sea Research*. 38:1305-1329.

Fitzwater, S.E., G.A. Knauer, and J.H. Martin. 1982. Metal contamination and its effect on primary production. *Limnology and Oceanography*. 27:544-551.

Franklin, J.F. 1988. Importance and justification of long-term studies in ecology. In: Long-term Studies in Ecology: Alternatives and Approaches, ed. G.E. Likens, pp. 3-19. Springer-Verlag.

Karl D.M., C.D. Winn, D. Hebel, and R. Letelier. 1990. Hawaii ocean time-series program: field and laboratory protocols. University of Hawaii, Honolulu Hawaii.

Karl, D.M., and C.D. Winn. 1991. A sea of change: monitoring the oceans' carbon cycle. *Environmental Science and Technology*. 25:1976-1981.

Karl, D.M., R. Letelier, D.V. Hebel, D.F. Bird, and C.D. Winn. 1992. Trichodesmium blooms and new nitrogen in the North Pacific Gyre. In: Marine Pelagic Cyanobacteria: Trichodesmium and other Diazotrophs, eds. E.J. Carpenter, et al., pp. 219-237. Kluwer Academic Publishers.

Keeling, C.D., R.B. Bacastow, and T.P. Whorf. 1982. Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii. In: Carbon Dioxide Review, ed. C. Clark, pp. 377-385. New York: Oxford University Press.

Likens, G.E. 1983. A priority for ecological research. *Bulletin of the Ecological Society of America*. 64:234-243.

Longhurst, A.R., and W.G. Harrison. 1989. The biological pump: profiles of plankton production and consumption in the upper ocean. *Progress in Oceanography*. 22:47-123.

Martin, J.H., G.A. Knauer, D.M. Karl, and W.W. Broenkow. 1987. VERTEX: carbon cycling in the northeast Pacific. *Deep-Sea Research*. 34:267-285.

Magnuson, J.J. 1990. Long-term ecological research and the invisible present. *Bioscience*. 40:495-501.

McGowan, J.A. 1990. Climate and change in oceanic ecosystems: the value of time-series data. *Trends in Ecology and Evolution*. 5:293-299.

Moore, B., and B. Bolin. 1987. The oceans, carbon dioxide and global climate change. *Oceanus*. 29:9-15.

Peterson, R.O. 1984. Wolves, moose and the allometry of population cycles. *Science*. 224:1350-1352.

Ryther, J.H. 1969. Photosynthesis and fish production in the sea. *Science*. 166:72-76.

Sarmiento, J.L., and E.T. Sundquist. 1992. Revised budget for the oceanic uptake of anthropogenic carbon dioxide. *Nature*. 356:589-593.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational contraints on the global atmospheric CO2 budget. *Science*. 247:1431-1438.

Winn, C.D., R. Lukas, D. Karl, E. Firing, and S.E. Chiswell. 1991. Hawaii ocean time-series data report #2: 1989-1990. SOEST Technical Report #, pp. 175. University of Hawaii: Honolulu, Hawaii.