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Time series of the northeast Pacific

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Abstract

In July 2006, the North Pacific Marine Science Organization (PICES) and Fisheries & Oceans Canada sponsored the symposium "Time Series of the Northeast Pacific: A symposium to mark the 50th anniversary of Line P". The symposium, which celebrated 50 years of oceanography along Line P and at Ocean Station Papa (OSP), explored the scientific value of the Line P and other long oceanographic time series of the northeast Pacific (NEP). Overviews of the principal NEP time-series were presented, which facilitated regional comparisons and promoted interaction and exchange of information among investigators working in the NEP. More than 80 scientists from 8 countries attended the symposium. This introductory essay is a brief overview of the symposium and the 10 papers that were selected for this special issue of Progress in Oceanography.

1. Introduction

There is a long history of oceanographic research in the northeast Pacific (NEP) Ocean, which has enabled the study of ocean variability on time scales of days to decades. Among the longest oceanographic time series in the NEP are the Line P program (http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/linepdata/default_e.htm), the Gulf of Alaska (GAK) line (http://www.ims.uaf.edu/gak1/), the Newport Hydrographic (NH) Line (http://ltop.oce.orst.edu), the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program (http://calcofi.org/newhome/), and the Hawaii Ocean Time-Series (HOT; http://hahana.soest.hawaii.edu/hot) (Fig. 1). In July 2006, the North Pacific Marine Science Organization (PICES) and Fisheries & Oceans Canada sponsored the symposium "Time Series of the N.E. Pacific: A symposium to mark the 50th anniversary of Line P", convened by Howard Freeland and Angelica Peña. The symposium consisted of plenary talks by invited speakers and contributed posters. Presenters reviewed: (i) results from each of the principal oceanographic time series of the northeast Pacific; (ii) main findings from the Line P program, including presentations of the physical variability, plankton and biogeochemical cycles, and ecosystem modelling; and (iii) overviews of recent process studies in the NEP, including discussion of the factors influ-

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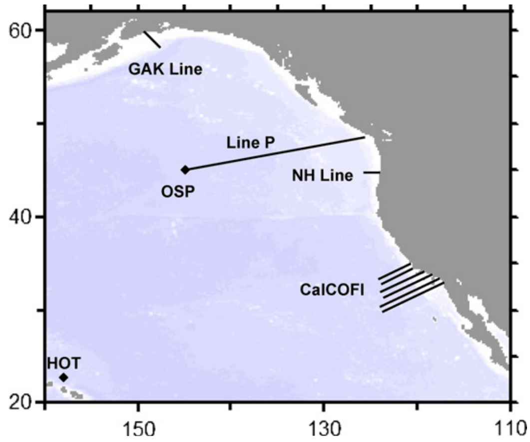

Fig. 1. Map of the northeast Pacific showing locations of principal long-term oceanographic time series.

encing gas exchange, the large-scale iron fertilization experiment (Subarctic Ecosystem Response to Iron Enrichment Study – SERIES), and the influence of eddies and mesoscale variability in the region.

Coastal waters of the northeast Pacific are highly productive, supporting numerous commercially valuable fisheries. This is reflected in the original motivation and design of long-term coastal time series programs such as CalCOFI and the GAK line. The CalCOFI program began sampling the physics, chemistry, and biology of the California Current System in 1949, following the collapse of the West Coast sardine fishery (Hewitt, 1988; Bograd et al., 2003). Sampling has continued with few interruptions to the present day, with current sampling focused on six hydrographic lines extending offshore several hundred km between San Diego and Pt. Conception, California (Fig. 1). With a 57-year time series (and counting), CalCOFI data are being used to resolve processes of physical-biological coupling on scales ranging from seasonal to decadal. CalCOFI is one of the few programs in the global ocean with sufficient data to begin to resolve the effects of climate change on ecosystem structure (Checkley, personal communication).

The GAK line has been sampled intermittently for 35 years with more intensive sampling during the Global Ocean Ecosystems Dynamics (GLOBEC) Coastal Gulf of Alaska (CGOA) program (1997–2004) (Batchelder et al., 2005). The marine ecosystem in the northern Gulf of Alaska is strongly influenced by the seasonally varying Aleutian Low, which induces large annual cycles in heat fluxes, freshwater runoff, and winds, and by a complex bathymetry and coastal orography (Weingartner et al., 2002). Cross-shelf variabililty in phytoplankton and zooplankton appear linked to freshwater dispersal processes and along- and cross-shelf transports.

The Newport Hydrographic (NH) Line extends along 44.65°N from the central Oregon coast to 160 km offshore. Sampling along the NH Line started in 1961 and was designed to resolve spatial variation in the coastal ocean (Huyer, 1977). Regular seasonal sampling occurred during two periods: 1961–1971 and 1997–2003, with occasional sampling during the intervening period. The NH Line time series is largely in the coastal domain, and thus especially subject to strong seasonal forcing by local winds and to remote forcing from the Equatorial Pacific through the coastal wave guide (Smith et al., 2001).

Line P is a 1425 km-long transect between the coast of British Columbia and Ocean Station Papa (OSP; 50°N and 145°W) in the subarctic Pacific. Observations were initiated in 1956 at stations along the line. Since then, surveys have been undertaken many times each year. OSP, the offshore end station of Line P, is one of the longest-running ocean time series in the world, providing a unique dataset that has greatly improved our understanding of ocean processes. Meteorological and surface ocean sampling from a weather ship at OSP began in 1949. Early work at OSP was critical to our present understanding of HNLC (high-nutrient, low-chlorophyll) regions and to the formulation of the iron limitation hypothesis, whereby the availability of iron was proposed to be the main control on primary production and nitrogen uptake. Results from a large scale iron fertilization experiment (Subarctic Ecosystem Response to Iron Enrichment Study – SERIES), conducted in the Northeast Pacific in July 2002 as part of the Canadian Surface Ocean Lower Atmosphere Study

(SOLAS) program, showed an important increase in phytoplankton biomass, a moderate increase in carbon sequestration, and a decrease in dimethylsulfide (DMS) concentrations, leading to conditions that would not mitigate greenhouse warming (Harrison et al., 2006). Modelling studies at OSP have been integral to the major cooperative ecological programs. In the last decade, studies at the air–sea interface have been carried out at OSP, including multi-year moorings and sampling of the sea-surface microlayer. These studies have found differences in the thickness of the microlayer between OSP and coastal waters, and that increasing gas transfer rates are coincident with increasing winds and deepening bubble penetration depth (Zhang et al., 2006). Studies along Line P have greatly improved out understanding of the interactions among trace metals, microbes and ocean biogeochemical cycles. A brief history of Line P program is given by Howard Freeland in this issue.

Open-ocean time-series sites are valuable for monitoring biogeochemical cycles, ecosystem variability, and climate change. For example, in the North Pacific Subtropical Gyre, the HOT long-term records of water-soluble reactive phosphorus (SRP) concentration indicate that during warm phases of the Pacific Decadal Oscillation (PDO), microbial assemblages are able to deplete SRP well below the concentrations observed during cold PDO phases (Corno et al., 2007). These observations, when combined with other physical and biological time-series data, suggest an increase in nitrogen fixation and the relative contribution of prokaryotic photoautotrophs to this ecosystem during warm PDO phases. In addition to HOT, the subarctic and mid-latitude North Pacific and its marginal seas include several of the world's longest and richest marine zooplankton time series, displaying large amplitude interannual to decadal changes in total zooplankton biomass, community composition, and body size and life cycle timing within individual species (Mackas, 2006).

The following 10 manuscripts in this volume make use of the vast quantities of data provided by these long time series to provide a multi-disciplinary, multi-year perspective of the temporal and spatial variability in the northeast Pacific.

2. Papers in the volume

Results from sampling of the Newport Hydrographic (NH) Line are summarized by Huyer at al. Observations show that the seasonal cycle is very strong with rapid transitions in spring and fall. Both the seasonal chlorophyll cycle and the seasonal cycle in alongshore currents appear to be important to copepod biomass, which peaks in summer when nutrients are plentiful, and diversity, which peaks in winter when warmer waters and subtropical species are advected northward. Comparison of summer regimes between two epochs (1961–1971 through the TENOC 'Next Ten Years of Oceanography' program and 1997–2003 through the GLOBEC Northeast Pacific Long Term Observations Program (LTOP)) shows the near-surface layer at most locations is significantly warmer and fresher, with a significant rise in steric height over the continental slope during the recent period.

Hydrographic casts, net tows and other measurements began in 1956 along Line P between the coast of British Columbia and OSP. Several contributions in this issue use this long record of observations to examine ocean variability. Crawford et al. use the 50 years of temperature and salinity measurements to compute anomaly time series of these properties. They show that the upper layer of Line P increased in temperature by 0.9° from 1958 to 2005, that much of the variance in temperature is in the upper 50 m, and that temperature changes tend to be uniform along Line P except for waters on the continental margin. They find that many of the temperature and salinity changes in the upper 50 m are largely driven by changes in wind patterns and speed. Whitney et al. document the decline in oxygen levels in the interior waters of the eastern subarctic Pacific. They show that between 1956 and 2006, waters below the ocean mixed layer to a depth of at least 1000 m have been warming and losing oxygen. During this time, the hypoxic boundary (defined as 60 μmol O_2 kg^{-1}) has shoaled from ~400 to 300 m. Peña and Varela describe the spatial and temporal variability in mixed-layer phytoplankton biomass, macronutrient concentration, and nitrogen uptake rates along Line P. They show a marked interannual variability in macronutrient concentrations during the last 36 years, which was correlated with westerly winds and PDO since 1981 but not correlated with either climate index between 1973 and 1981. Mackas et al. examine the consequences for pelagic communities of warming trends in the subarctic NEP by analysing copepod abundance and phenology time series from net tow and Continuous Plankton Recorder surveys. They show latitudinal shifts in centers of abundance of many species, and changes in the life cycle timing of *Neocalanus plumchrus* in both oceanic and coastal regions.

The variability of the North Pacific Current and its subtropical and subpolar branches is discussed by Cummins and Freeland using sea surface height data from altimetry, dynamic heights from Argo and multi-decadal simulations with a wind-driven numerical model. Indices of the strength of the subpolar and subtropical components of the North Pacific Current show periods of both correlated and anti-correlated variability in the transport of these gyres. A decomposition of these time series indicates that the dominant mode of variability is a 'breathing' mode in which the subpolar and subtropical gyres co-vary in response to fluctuations in the strength of the North Pacific Current. Combes and Di Lorenzo explore the response of the Gulf of Alaska circulation to large-scale North Pacific climate variability using three regional ocean model ensembles over the period 1950–2004. They show that on interannual and decadal timescales the mean circulation is strongly modulated by changes in the large scale climate forcing associated with PDO and ENSO. Along the eastern side of the Gulf of Alaska basin, interannual changes in the surface winds also modulate the seasonal development of mesoscale anticyclonic eddies. Crawford et al. use SeaWiFS satellite colour time series and satellite-based measurement of sea surface height to show that more than half of all surface chlorophyll within pelagic waters of the northern Gulf of Alaska was inside anticyclonic mesoscale eddies, yet these eddies enclosed only 10% of the total surface area of pelagic waters in the gulf. They outline several physical processes that allow these eddies to carry coastal chlorophyll and macro- and micro-nutrients several hundreds of kilometres into near-surface, mid-gulf waters.

Lipsen et al. report on the spatial and temporal variability in coccolithophore abundance and production of particulate organic and inorganic carbon along Line P during the 1998 El Niño, the 1999 La Niña, and 2000. They found that the abundance of coccolithophores was much higher in June during the 1998 El Niño than in the 1999 La Niña. Production rates of particulate inorganic carbon did not consistently correlate with areas of high coccolithophore abundance. Wong et al. examine how nutrient, carbon and other hydrographic parameters are affected by regime shifts in the subarctic NEP. They show that long term changes in oceanographic and chemical parameters were influenced by climate regime shifts with a "step change" of anomalies for nutrients and carbon during the 1976/77 and 1988/89 regime shifts.

3. Conclusions

Some of the most important knowledge of the ocean has come from long term measurements at particular sites or from repeated measurements along sections. Sustained observations of the oceans are necessary to improve our understanding and prediction of ecosystem/climate connections and for management of marine and coastal ecosystems and resources. Moreover, knowing accurately the time variability in even a few locations around the world is important, as very long records are needed to determine the difference between multi-decadal cycles and climate trends. Trends over a few years or even a couple of decades can be quite misleading because of sampling and aliasing limitations. Continued observations will be important in documenting changes and verifying climate model forecasts.

The Line P program is highly regarded by the scientific community and has itself benefited from numerous collaborations and partnerships with national and international research communities. Since its initiation, it has been a multi-disciplinary program including oceanic and atmospheric processes, physical, chemical and biological studies of the upper mixed layer. The long time series of oceanographic measurements collected during the Line P program has provided an invaluable background both for special intensive physical and ecological projects and for the development of ecosystem models. In recent years, the Argo Program (http://wo.jcommops.org) has been seeding the oceans with profiling drifters, providing invaluable spatial coverage that aids in the interpolation of data between fixed time series locations.

Despite the past successes of the northeast Pacific time-series programs, several challenges were identified during the symposium including continuity, innovation, funding, and the need to provide results useful for management and policy. How to sustain observing efforts? Present funding paradigms do not yet incorporate the critical need for multi-decade high resolution observing. Time series are a critical part of the observing system. International efforts to coordinate sustained observations of the ocean, such as the Global Ocean Observing System (http://www.ioc-goos.org) and OceanSITES (http://www.oceansites.org), can result in improved data access, better products, and enhanced public information on ocean change.

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