1. Introduction

Bishop Berkeley is reputed to have asked, “If a tree falls in the forest and there is no one around to hear it, did it make a sound?” However, if a fallen tree is encountered in the forest, one can be confident that once it stood upright and even surmise from where it fell. Photographs of a forest taken from the same vantage point at different times, apart allow growth, death and other forms of change in the forest to be evaluated, even without observations of each tree fall.

Observing and understanding change in the ocean present greater challenges. How is it known if a species declines or increases? Sub-surface ecological observations remain difficult and costly and therefore relatively scarce. Isolated observations or “snapshots” of local conditions, unlike photographs of the forest, often prove to be of little value in assessing change, because the ocean is a dynamic environment. The abundance of its ever-shifting, patchily-distributed populations may vary daily, seasonally, inter-annually, and from decade to decade in relation to naturally varying conditions, as well as in response to human influences. Isolated observations may therefore be aliased and of little value in evaluating change. The consistent systematic time series of observations that are required to evaluate change across this range of time scales and to distinguish natural variability from secular climate change must be maintained for a very long time, well beyond the time scale of any single government’s tenure in office or scientist’s career: a very long time, indeed, on the human scale. It is no wonder that such time series are scarce.

Despite the inherent difficulties of achieving long-term ocean time series, they are nonetheless essential, given that the oceans are not at equilibrium, as once believed, but rather continuously varying in response to a poorly-understood array of natural and anthropogenic pressures. Multi-decadal ocean time series are a sine qua non to distinguish natural variability from secular trends induced by climate change and other anthropogenic stressors. Ocean time series are therefore also fundamental to effective ocean management, since without these, the need for management may be missed and the effectiveness of management measures, such as instituting marine protected areas (MPAs), cannot be evaluated.

The United Nations (UN) is conducting its first World Ocean Assessment (WOA) to be completed in 2014, a process intended to parallel the periodic reporting of the UN Intergovernmental Panel on Climate Change. The need for a periodic WOA is clear, given the United Nations’ Intergovernmental Panel on Climate Change. The need for a periodic WOA is clear, given the large number of anthropogenic stressors to which the ocean environment is subjected: overfishing, the impacts of marine industries from fishing and mariculture to mining and energy development, eutrophication due to nutrient runoff, pollution, invasive species, coastal development, warming, acidification, and deoxygenation. The impacts of these stressors are generally poorly understood in isolation from each other, much less in concert with the potential for synergistic interactions. Without time series, it is impossible even to know that there is change in marine ecosystems. And because there are a number of more or
less distinct biogeographic provinces or large marine ecosystems (LMEs) within the global ocean [41,30], a system of representative, consistently sampled ocean observation programs is required to achieve an effective global ocean assessment.

Recent decades have seen dramatic advances in observation systems for the physics and chemistry of the global ocean, with further improvements on the horizon, based on advances in sensor technology. Satellites now provide global coverage of sea surface temperature, altimetry, and chlorophyll $a$ (chl), which is commonly used as an index for phytoplankton abundance. The Argo float program, operational since the early 2000s, today has approximately 3600 floats deployed to sample ocean temperature and salinity to 2000 m depth (Fig. 1). Dissolved oxygen measurements are currently being obtained from a limited number of floats, with plans to add sensors to measure chl, nutrients, and pH. The Argo program monitors the open ocean, and the physical state of the coastal ocean is monitored by the Global Ocean Observing System (GOOS) coastal program.

However, observing the physical state of the ocean is the low-hanging fruit. Measurements of temperature and salinity (and chl) are well-standardized and can be readily and consistently measured to a high level of precision. On the other hand, as a former GOOS director once observed, the critical lack of ecological ocean time series remains an “embarrassing gap” more than 25 years after GOOS was formed [2]. The only possible exception to this gloomy overview is fishery time series. Fishery statistics based on catch and effort have been maintained in parts of the world for on the order of 100 years. However, fishery statistics are generally limited to commercially-exploited species and are influenced by changes in market conditions, technological change, and the effects of over-exploitation itself; fishery-independent time series are generally more limited in duration as well as in the number of species and regions covered.

Several recent issues highlight the need for improved ecological time series for the ocean. These involve ecological groups – gelatinous zooplankton and midwater fishes – that are immensely important in pelagic ecosystems but that have been poorly monitored to date. As a result, potential changes in these groups remain controversial and uncertain, although these groups may be responding to anthropogenic influences and changes in these groups could have profound implications for global marine ecosystems.

The first issue is the uncertainty whether jellies are increasing globally in response to overfishing, eutrophication, and deoxygenation, particularly in degraded coastal ecosystems. Blooms of gelatinous plankton (jellyfishes and salps) have been widely observed in recent years, with implications for marine industries, including fisheries and power plants, and potentially signaling a regime shift in the structure of marine food webs (reviewed in Refs. [34,35,8,19]). However, lack of adequate time series has led a number of leading experts to conclude that it is not possible at present to distinguish natural cycles from a secular increase in their abundance [11]. Indeed, there are no existing quantitative time series in the Pacific Ocean for gelatinous zooplankton [11].

A second issue is the potential impact of deoxygenation on mesopelagic fishes in regions with oxygen minimum zones. Koslow et al. (2011) [25] reported a 63% decline in a broad assemblage of mesopelagic fishes in the California Current (CC), apparently linked to declining oxygen concentrations at midwater depths (200–400 m). Declining oxygen is now reported over much of the global ocean [20] apparently a consequence of global climate change, and global climate models predict continued deoxygenation of the deep ocean as increased warming and stratification of the upper mixed layer leads to decreased ventilation of the deep ocean [39,40]. Mesopelagic fishes are dominant zooplankton consumers in the global oceans; as such, they are key vectors for the transfer of energy to higher trophic levels and for the sequestration of carbon into the deep ocean [13,22]. A significant decline in their abundance could have profound consequences for global marine food webs and biogeochemistry. However, at this time there do not appear to be time series to examine changes in the midwater micronekton in other regions with well-developed oxygen minimum zones [24].

This study examines the availability of ecological time series for pelagic ecosystems in the Pacific Ocean based on a meta-analysis of ocean observation programs. The study concludes with a modest proposal to enhance ecological time series for the global ocean.

2. Methods

This study comprises a meta-analysis of sustained Pacific Ocean observation programs leading to ocean time series based on parameters measured consistently over time in the same geographic region. Short-term projects, surveys, cruises, and expeditions were therefore not considered. The analysis is also restricted to non-proprietary programs and data sets, so military or industrial data sets to which there is no public access were not considered, along with geological data sets (for example, seafloor mapping) that are not, properly speaking, time series observations. For each program, we noted the start and end dates of the program, geographic location (latitude and longitude) of routine data collection, sampling frequency, sampling months and the physical, chemical and biological variables measured, although the focus of the study is on biological observations and time series. Information was obtained from web sites and the scientific literature.

For each variable, sampling methodology and depth range of sampling were noted. Methodology included the oceanographic instrument used for collection at sea (including the net types and mesh sizes) and the method of analysis. For programs with biological time series, the taxonomic resolution or grouping was noted. For zooplankton samples in particular, there is a variety of methods for sample analysis: bulk biomass measurement (displacement volume, settled volume, or wet or dry mass), analysis to functional groups, or species-level enumeration. For surveys of fishes, sampling methods range from sampling with a variety of nets, ichthyoplankton sampling (sampling the fishes during the planktonic phase in their early life history), and acoustic-trawl surveys. The availability of long (> 20 years) and short (< 20 years) time series for zooplankton (both bulk biomass and species-level resolution) and micronekton were mapped using online mapping software, HamsterMap (http://www.hamstermap.com).

3. Results

Pacific Ocean biological observation programs were found in Australia, Canada, Chile, Japan, Korea, Russia, Mexico, Panama, Peru,
Taiwan, and the United States (Fig. 2). However, ocean observation programs exhibit a wide range of capabilities from well-integrated, multi-disciplinary programs to programs whose biological observations remain mostly aspirational. For example, within the USA, there are a number of monitoring programs, including five so-called Integrated Ocean Observing Systems (IOOS): AOOS (Alaska Ocean Observing System), CeNCOOS (Central and Northern California Ocean Observing System), NANOOS (Northwest Association of Networked Ocean Observing Systems), PaCIOOS (Paciﬁc Islands Ocean Observing System), and SCCOOS (Southern California Coastal Ocean Observing System). However, the IOOS programs, with limited funding, have focused on shore-based observations and issues related to water quality, marine operations, coastal hazards, and marine spatial planning. The IOOS programs provide infrastructure and the potential for a representative biological observation program focused on the large marine ecosystems in US waters, but at this time virtually no biological observations are collected, other than data related to harmful algal blooms. Further ecological data are obtained from ongoing state and federal programs and offered on IOOS web-sites but are not consistent across IOOS programs. The IOOS programs were therefore not included in Fig. 2.

The waters around Asia appear to be largely deﬁcient in systematic biological ocean observation programs, with the exception of the waters around Japan, South Korea, and Taiwan. The lack of ecological monitoring in Chinese waters (e.g. the Yellow Sea, East China Sea, and South China Sea) is particularly notable, since these coastal ecosystems appear to be among the most severely impacted by overfishing, pollution, and eutrophication, with increasing deoxygenation and massive algal and jellyﬁsh blooms (reviewed in Ref. [45]). Although a Yellow Sea LME adaptive management project has been approved, which is to include monitoring activities by both China and South Korea [42], no information on ecological monitoring activities was available for Chinese waters, and it was not clear that these are yet operational. The Indonesian GOOS program was also not included because it does not yet appear to be operational [17]. Although the Russian pelagic trawl survey program was included, it is designed primarily to survey salmon in the northwest Paciﬁc and is not systematic. Lack of systematic survey design has also limited the time series that can be obtained from US waters in the Bering Sea, Gulf of Alaska and off Washington and Oregon, despite the considerable research effort expended in those regions.

Although this study focuses on water-column observations, three predominantly benthic observation programs were included in Fig. 2: the reef observation program in Panama, the PISCO project in central California, which focuses on the kelp bed environment, and the Station M deep-sea observations in the CCE [43]. Zooplankton is sampled relatively frequently around the Paciﬁc (Fig. 3). However, methods of sample analysis vary considerably, which greatly limits the usefulness of some time series and their comparability. Several programs limit sample analysis to some form of bulk biomass measurement (e.g. displacement or settling volume, wet or dry weight) or to functional groups, which are of limited utility in detecting and interpreting ecological change. Regime shifts in the ocean often involves shifts in water masses and species composition but not in functional groups [5,33,26]. Zooplankton bulk biomass measurements are extremely coarse, and changes in these measures related to changes in functional groups.
(e.g. between crustacean and gelatinous zooplankton) may be misinterpreted as changes due to productivity (cf [36,28]). It is a positive development that several observation programs that once restricted zooplankton sample analysis to bulk biomass, such as CalCOFI and the A-line off Japan, now carry out species-level analyses. Although zooplankton coverage for the Pacific now appears reasonably good, there are only five long-term (> 20 year) zooplankton time series with species-level resolution (Fig. 3). There are nine more recent (< 20 years duration) Pacific zooplankton time series with species-level resolution, including several Continuous Plankton Recorder transects that cover significant sectors of the open North Pacific and the waters around Australia.

Sampling of the micronekton and fishes (other than those that are commercially exploited) is far more limited (Fig. 4). Only CalCOFI in the CCE has maintained long-term systematic observations of the region’s fishes to species level based on ichthyoplankton surveys, which are used to obtain indices of species’ spawning stock biomass. Russian trawl surveys for salmon in the upper 50 m of the northwest Pacific and Bering Sea have been carried out since about 1980, providing data about micronekton that vertically migrate into near surface water [27]. Ichthyoplankton surveys carried out since the 1970s in the Gulf of Alaska and Bering Sea also provide time series on the micronekton, but the sampling design is not consistent from year to year and is generally limited to the spring spawning period of the Alaska pollock [15]. The Taiwan Cooperative Oceanic Fisheries Investigations (TaiCOFI) program carried out around Taiwan for approximately 10 years may provide a further species-resolution ichthyoplankton time series, but sample analyses to date are limited to isolated cruises [29]. Since about 2000, there have been trans-Tasman ship of opportunity (SOOP) lines between Australia and New Zealand based on acoustics and limited trawling, which provides limited species resolution [18].

Another issue that emerges when comparing ecological time series is that not all observation programs sample ecological variables with comparable oceanographic instrumentation and sampling frequency. There are many zooplankton and midwater net types, with various mouth openings, mesh sizes, and tow characteristics, all of which influence the community that is sampled and the portion that avoids or escapes the sampler (Table 1). Tow depth and tow volume also vary substantially. As a result the sample universe may vary dramatically from one sampling program to another. In addition, the seasonality and frequency of biological sampling may also dramatically influence sample composition, depending upon the various species’ seasonality and other life-history factors influencing distribution and abundance. For example, the ichthyoplankton surveys carried out by the Alaska Fisheries Science Center in the Gulf of Alaska and Bering Sea concentrate on the spawning period of the Alaska pollock and thus the time series only reflect the abundance of fishes that spawn in the same period.

4. Discussion

Major advances in ocean observing have been achieved through remote sensing and the Argo profiling-float program. Satellites designed to observe the ocean now provide global coverage of sea-surface temperature, sea-surface height, and ocean color, from which sea-surface chlorophyll concentrations can be inferred; Argo floats now routinely profile temperature and salinity in the upper 2000 m of
the ocean, with the possibility that chlorophyll, oxygen, and nutrient sensors may be added in future. These time series have proven enormously useful, contributing to our understanding of global primary production [6] and the production systems underlying biogeography [30]. They are also critical to understanding processes of global climate change, such as ocean warming dynamics [9].

Approximately 25 years ago, recognition of the need to monitor a potentially changing ocean biogeochemistry led to development of the Hawaii Ocean Time-series (HOT) and the Bermuda Atlantic Time-series Study (BATS) in the North Pacific and North Atlantic subtropical gyres, respectively. These programs focused on characterizing the physical and biogeochemical pelagic environment based on monthly sampling [23,44]. Consistent with these objectives, the highest trophic level resolved was the zooplankton, whose overall biomass and size structure were examined, but without resolution to species level. However, species-level taxonomic resolution has generally proven necessary to assess changes in phenology, diversity, and community structure, the most sensitive indicators of the ecological impacts of climate variability and change in marine systems [5,4,33,16].

The growing number of zooplankton time series that provide species-level resolution is encouraging. However, our optimism is tempered by recognition that many of these time series are based on CPR sampling, which is inadequate to monitor the gelatinous plankton, because they are too large, and the ichthyoplankton, which are not sufficiently abundant: two groups which are in particular need of adequate time series. We also note that new time series (and old ones as well) are typically founded and maintained based on the hope, hard work, and commitment of a handful of scientists but lack the long-term funding and institutional backing required to maintain these in the long term. A notable example is the Newport (Oregon) line: recent funding cuts threaten its continuation despite its record of scientific excellence and relevance to the fishing industry and management [37,38].

There is growing evidence of significant change in the ocean’s ecology, potentially related to anthropogenic forcing. Prominent
examples include the impacts of global warming eutrophication, overfishing, and acidification on coral reefs, which are iconic, highly visible, and reasonably well-monitored [21], and the impacts of deepwater trawling on deepwater reefs, which are largely out of sight and poorly monitored [10].

However, other issues, potentially of global significance, remain uncertain due to lack of sufficient evidence. Is a combination of overfishing, eutrophication and deoxygenation leading to increased blooms of gelatinous zooplankton ([35,12])? Is deoxygenation leading to a significant decline in mesopelagic fishes ([25])? Is the massive decline of nearshore and oceanic fishes reported in the southern California Current, apparently related to climate change, occurring more widely ([31], Koslow, Miller and McGowan, unpublished results)? There are also pervasive but less well-defined concerns about the state of the oceans, particularly in coastal regions where burgeoning human populations put ocean ecosystems under ever-increasing pressures from recreational and commercial uses, runoff, power plants and waste recycling, habitat modification, and so on.

The oceans contain remarkably complex and poorly-understood ecosystems with diverse functional groups ranging from viruses to whales. Not all groups are monitored adequately, and some not at all. Unfortunately, there is evidence that some groups critical to the ecology and biogeochemistry of the oceans are undergoing change that we are only able to examine now as through a glass darkly.

There can be no responsible ocean stewardship without adequate ocean observations. An adequate global ocean observation system should monitor a consistent set of ocean variables essential to defining the health of ocean ecosystems at sites representative of the ocean’s ~50 major biogeographic provinces [30]. As we have seen in our survey, much of the Pacific Ocean is already covered by biological observation programs that cover one set of variables or another, and most of the ocean’s biogeographic provinces already have one or more active fishery and other ocean observation programs (e.g. GOOS). However, they are generally too narrowly focused, e.g. fisheries programs that do not monitor the oceanography or GOOS programs that do not encompass ecologically relevant parameters. In addition, biological observation programs are often not carried out consistently or fail to be adequately integrated within or between biogeographic provinces. Critically, almost none adequately observes the range of ecological variables essential to define the status of key ecological communities. However, there is often observational infrastructure in place; what is required is to upgrade these systems to include key ecological variables, in addition to fisheries or water quality variables.

Today, CalCOFI appears virtually unique in routinely observing the physical, chemical, biogeochemical, and ecological state of the ocean, with species-level resolution of the fish community (through the ichthyoplankton), seabirds, marine mammals, and spring zooplankton. This has enabled studies of phenological shifts and of community shifts in the California Current ecosystem associated with the ENSO cycle, regime shifts (the Pacific Decadal Oscillation [7] and North Pacific Gyre Oscillation [14]), and climate change [25,26,3]. Although the program today carries out a broad range of observations, it has a simple, proven and inexpensive technology at its core to develop time series with species-level resolution of the zooplankton and fish communities: plankton nets towed obliquely through the upper 200 m of the water column.

Ichthyoplankton surveys are carried out in many parts of the world to assess the stock size of commercial fish species, such as anchovy, sardine, mackerel and others. Although many have an underlying survey design similar to CalCOFI’s, few examine the abundance of fish eggs and larvae of non-commercial species. Because the larval fish are mostly sampled at a very early developmental stage, their abundance is proportional to adult spawning stock biomass. With adequate technical training, ichthyoplankton identification can be carried out routinely today in most parts of the world, so with a modest increment of additional effort the broad community of fishes with a pelagic larval phase may be surveyed, not just the handful of species of commercial interest. (In the CalCOFI ichthyoplankton data set, only 3% of the fish taxa are of commercial interest [1]). The development of community-level time series provides altogether new opportunities for research, assessment, and management at the ecosystem level.

We note that in regions where stock assessment is not an objective and ichthyoplankton surveys are not carried out, there is no need for the extensive sampling programs entailed in CalCOFI and other stock assessment surveys: sampling the ichthyoplankton at a relatively few stations can serve to define shelf and offshore fish communities [32]. Resampling the CalCOFI data set indicates that the abundance of key species and multivariate community abundance patterns tend to be well correlated between the full and reasonably reduced data sets (Koslow and Wright unpublished results).

Who is to pay for expanded ocean observations? Clearly, costs should be met by those utilizing and placing pressure on the marine environment: coastal communities reliant on the oceans for recreation and waste disposal, offshore energy industries, fisheries and aquaculture, shipping, and others. In many instances water quality and HAB surveys are already undertaken; only a modest expansion of these activities is required. It should be noted that the offshore oil and gas industry, worth more than $1 trillion annually and often the cause of spectacular marine environmental disasters, is generally not required to pay for ongoing monitoring of the ocean environment.

There is a global effort underway to develop sustainable management practices in the LMEs of ~110 developing nations in Africa, Asia, Latin America and eastern Europe, funded with $3.1 billion in assistance from the Global Environmental Facility (GEF) and the World Bank [42]. The approach of these programs to ocean observations is still to be defined but this initiative offers perhaps the greatest hope to date for widespread adoption of systematic observations of ocean ecology. The development of comprehensive ocean observation programs can also serve to underpin viable marine science and management infrastructure.

The development of ocean science to underlie ecosystem-based management of the oceans depends on a three-legged stool: observations, experimentation, and modeling. Observations have long been the poor neglected relation in this partnership, but the oceans cannot be managed without improved ecological time series. Models of ocean biogeochemistry and ecosystems are empty if they cannot be developed with data from the field and tested with relevant biogeochemical and ecological time series. Such time series are similarly required to evaluate marine management measures. Time series are the bricks and mortar with which World Ocean Assessments must be built; without these, potentially profound issues of biogeochemical and ecological concern in the global ocean – whether jellies are overwhelming the coastal ocean or mesopelagic fishes are declining in the face of declining oxygen levels – will remain speculative and the potential for action mired in uncertainty. If we fail to develop adequate time series, we fail as responsible ocean stewards and condemn ourselves to continuing to stumble along, deaf and blind to its state.

5. Conclusions

A meta-analysis of ocean observation programs in the Pacific Ocean indicates that the ocean’s chemistry and physics are reasonably well monitored, but ecological monitoring remains largely ad hoc, patchy, unsystematic, and inconsistent. Only a single program, CalCOFI, provides consistent zooplankton and micronekton time
series of greater than 20 years duration and with species-level resolution. Recent studies based on the CalCOFI and other time series indicate profound changes to the fish communities of the southern CC, including nearshore, mesopelagic and other habitats related to declining oxygen concentrations at mesopelagic depths and other aspects of climate change. It is unlikely such changes are isolated to the CC but lack of adequate time series largely precludes their assessment elsewhere. Firm commitment from the global community to sustained, representative, quantitative marine observations at the species level is required to adequately assess the ecological status of the oceans.

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References