What are Marine Ecological Time Series telling us about the ocean? A status report

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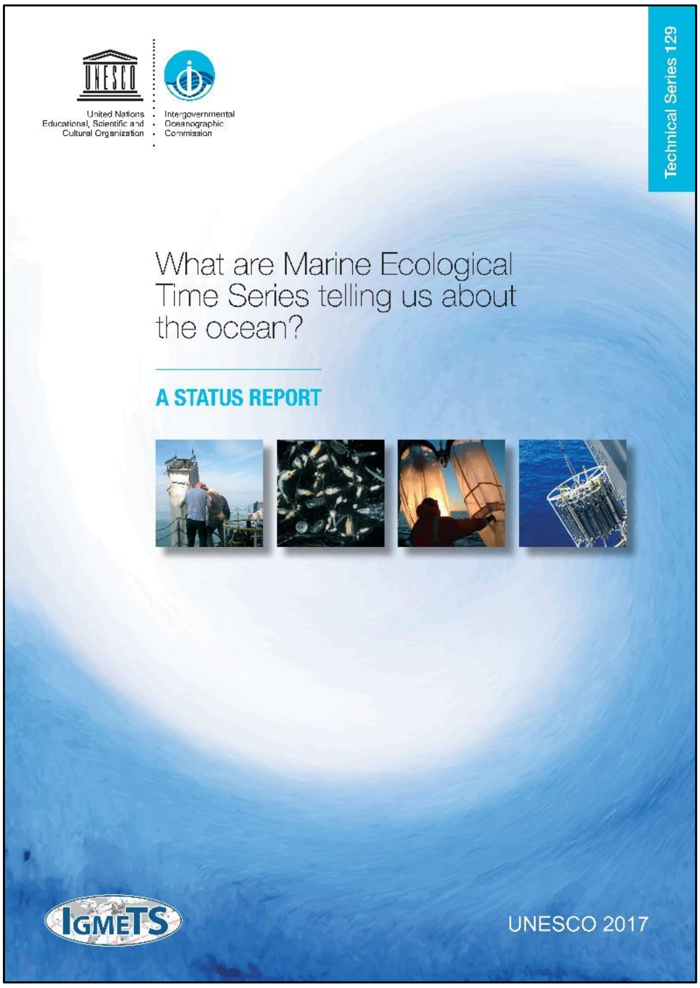

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1 New light for ship-based time series (Introduction)

Luis Valdés and Michael W. Lomas

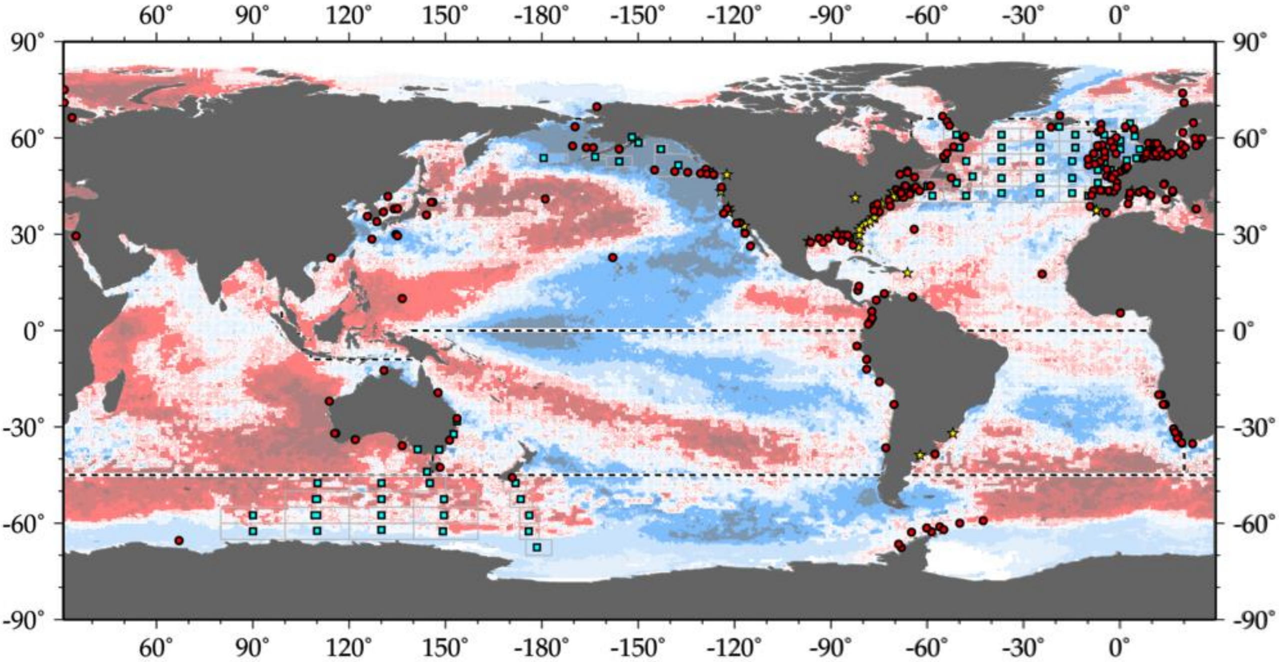

Figure 1.1. Map of IGMETS-participating time series on a background of 10-year (2003–2012) sea surface temperature trends. This map shows 344 time series (coloured symbols of any type), of which 71 were from Continuous Plankton Recorder subareas (blue boxes) and 46 were from estuarine areas (yellow stars). The dashed lines indicate boundaries between IGMETS regions, which are further examined in the chapters of this report. Additional information on the sites in this study is also presented in the Annex.

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1.1 Global importance of time series

The observation of nature and the understanding that there are underlying regularities (cause-and-effect relationships) dates back to the very origin of human culture. In fact, this knowledge allowed for the management of natural resources and for the establishment of the earliest human settlements, e.g. the very first agricultural societies. The prediction of Nile flooding was critical not only for food security, but it was also a matter of political power.

There are many examples of records of long-term systematic observations of natural events and conditions from crop yields, planet movements, sun spots, river discharges, and freezing records dating from ancient times (Bell and Walker, 2013). Many of the most beautiful scientific discoveries were possible thanks to data obtained by regular observations – time series – carried out with the purpose of discovering facts about certain phenomena and to formulate laws and principles based on these facts. [1]

The biogeochemistry of the ocean (Figure 1.1) varies naturally across a range of temporal and spatial scales (Figure 1.2), which is often further conflated with anthropogenic forcing (warming, acidification, pollution, etc.). In a growing effort to distinguish between natural and human-induced earth system variability, sustained ocean time-series measurements have taken on a renewed importance as they represent one of the most valuable tools that scientists have to characterize and quantify ocean ecosystem cycles and fluxes and their associated links to changing climate.

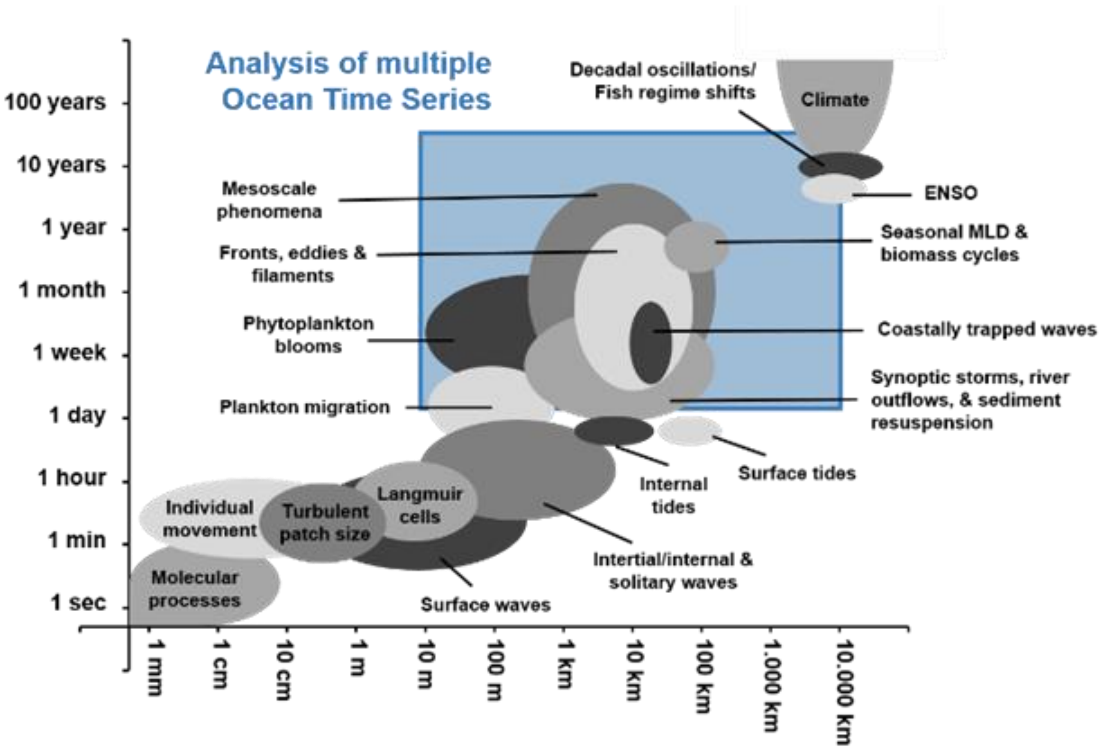

Figure 1.2. Temporal and spatial scales of a range of ocean processes. The blue square highlights the range of space- and time-scales that can be addressed by ship-based, time-series measurements (Adapted from Dickey, 2002).

[1] To state that a particular phenomenon always occurs if certain conditions are present is a principle of conservation laws of physics, which reflects the homogeneity of a process in space and time. The search for patterns and symmetries is one of the main goals of science, and reducing uncertainties in a given phenomenon makes us feel comfortable as if we were able to reduce the entropy and minimize the occurrence, or the impacts, of unexpected events.

Ocean time series, particularly ship-based repeated measurements, consist of one type of observation programmes which are crucial to answering scientific questions and improving decision-making in ocean and coastal management (Edwards *et al*., 2010). They provide the oceanographic community with the long, temporally resolved datasets and high-quality data needed to characterize ocean physics, climate, biogeochemistry, and ecosystem variability and to change what can be used to examine, test, and refine many paradigms and hypotheses about the functioning of the ocean (Henson, 2014). They also help to disentangle natural and human-induced changes in marine ecosystems (Reid and Valdés, 2011).

1.2 Levels of understanding and need for continued sampling

Time-series data help resolve both short- and long-term scales of variability, depending on sampling frequency, and provide context for traditional process-oriented studies.

Depending on motivation, sampling frequency, and length, time series can be used for different purposes (Figure 1.3) and are of critical importance to enable or facilitate: (i) the acquisition of ecosystem baselines and rate and scale of environmental change, including climate change and biodiversity loss, (ii) the understanding of ocean, earth, and climate system processes, (iii) to monitor ecosystem dynamics and its variability, (iv) the detection of hazards and environmental disturbances and the estimation of recovery times, (v) to forecast and anticipate ecosystem changes, and (vi) effective policy-making and sustainable management of the seas and oceans.

Significant advances in our understanding of ocean processes in some well-studied systems have shown that not all ocean regions are changing at the same rate or following the same pattern. This is, in part, because the ocean is characterized by interacting processes, which operate over nearly 10 orders of magnitude in time and space (Dickey, 2001, 2002). Indeed, some regions are more sensitive to environmental change than others. Exploring this temporal and spatial variability of ocean change, at a basin-scale or greater, is largely the realm of earth ecosystem models at present. Indeed, it is only through models that we can learn about the spatial representativeness of existing time series (i.e. the footprint of a time series) and, therefore, inform decisions about where to site new time series (Henson *et al*., 2016).

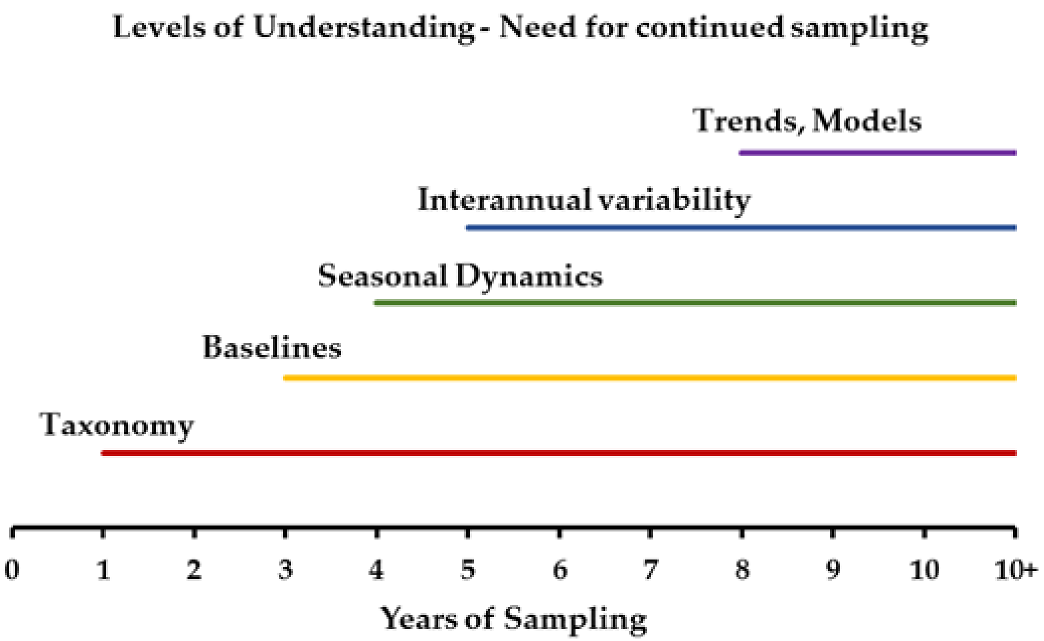

Figure 1.3. Representative sampling time-scales needed to establish a minimum level of understanding across levels of complexity within an ecosystem.

While our understanding of first-order ocean biogeochemical concepts in these models and their coupling to atmospheric forcing is reasonably well developed (Keller *et al*., 2014), these models are still limited by lack of mechanistic and observational knowledge in time and space of how the ocean is changing physically, chemically, and biologically and, worse yet, the interactions between these levels of variability (Heinze *et al*., 2015). This is further exacerbated by the fact that observational time series generally have to be several-fold longer than the time-scale they are trying to resolve, while models can produce multidecadal output with relative ease. For example, published model output suggests that at least three decades would be needed to resolve climate-change response in the North Atlantic in certain variables (e.g. primary production), but less in others (e.g. sea surface temperature) (Henson *et al*., 2010, 2016).

Obviously, the "pay check" you receive from consistent long-term, ship-based marine time series is not regular, but many times it is surprising, as demonstrated by recent discoveries, e.g. proof of ocean acidification, ecosystem regime shifts, and exploration of the deep sea, which illustrate that sustained multidecadal observations are ecological and economical important research investments for future generations.

In a time of increasing pressures on the marine environment, time series are central to understanding past, current, and future alterations in ocean biology and to monitoring future responses to climate change (Valdés *et al*., 2010; Karl, 2014). With many time series now having accumulated sufficient data to quantify variability and trends (see Figures 2.2 and 2.3 in the "Methods and visualization" chapter), it would be foolish to allow reductions or long gaps in sampling to occur, and replacing the ship-based, long-term series with autonomous platforms should not be the ultimate path to follow.

While these tools provide high-quality and high-frequency data for certain, generally physical and geochemical, parameters, ship-based time series are unique in their multidisciplinarity: physical, chemical, and biological parameters can be measured simultaneously. Many ecosystem processes and functions (e.g. primary production, phytoplankton composition, utilization of specific nutrients) cannot be directly obtained from these autonomous sensors, and only some can be derived through proxy measurements. Furthermore, regular and consistent calibration of independent sensors, moorings, and remote-sensing techniques can only be assured with standardized *in-situ* measurements.

1.3 New light for time series: international collaboration in ship-based ecosystem monitoring

The history of long-term ocean time series started more than 100 years ago. In the Western English Channel and around the British Isles, records go back to the late 19th century. A broad suite of marine time-series sites was established in the middle of the 20th century in the Northern Hemisphere, e.g. Station M in the Norwegian Sea (1948), NOAA Ocean Station P Sea in the North Pacific (1947), Henry Stommel's 'Hydrostation S' in the Sargasso Sea (1954), and Boknis Eck Time Series Station where monthly sampling began in April 1957 (Owens, 2014).

Many other coastal and oceanic time series were established across different oceans and managed by different countries since the 1980s and 1990s following recommendations from international programmes such as JGOFS (1990) and GLOBEC (1997).

The value of these measurements has not been fully appreciated, and several sampling sites face severe funding difficulties. Some could not sustain measurements with the same sampling frequency in time, resulting in temporal gaps of observations, and financial resources even ceased, and no alternatives could be obtained (Frost *et al*., 2006). However, many others survived and gained international prestige (e.g. HOT, BATS, CARIACO, ESTOC, Plymouth L4, Helgoland Roads, RADIALES) particularly for providing the reference baselines for different variables at local–regional scales and in different ocean biogeographical provinces.

Difficulties in harmonizing the data, digitalizing results to enhance broad accessibility, and evaluating methods hampered the utilization of these historical datasets. As a contribution to GLOBEC, ICES encouraged the international comparison and analysis of time series, which was adopted by the ICES Working Group on Zooplankton Ecology (Valdés *et al*., 2005; O'Brien *et al*., 2012; Wiebe *et al*., 2016) and then continued by SCOR WG125 and WG137 (WG125: *Global Comparisons of Zooplankton Time Series* and WG137: *Patterns of Phytoplankton Dynamics in Coastal Ecosystems: Comparative Analysis of Time Series Observation*). Now, the International Group for Marine Ecological Time Series (IGMETS; Figure 1.4), under the auspices of the IOC-UNESCO, is taking on the mantle of improving access to time series. All of these groups stressed the need to broaden the scientific utilization of existing time-series datasets and to link current and past studies.

Figure 1.4. Previous and ongoing activities within the scientific community leading up to the IGMETS effort.

The goals of IGMETS are to look at holistic changes in different ocean regions, explore plausible reasons and explanations at regional and global scales, and highlight locations of especially large change that might be of particular importance for model projections or ongoing management policies. In the process, IGMETS intends to aggregate existing time-series sampling sites, establish global baselines, assess spatial variability and response to climate at the basin-scale and greater, and provide the basis for projection and forecasting.

1.4 The ocean time series heritage

A time-series workshop in November 2012 was organized by OCB, IOCCP, and IOC-UNESCO. One of the key outcomes of this workshop was the development of a global time-series network compiling more than 140 ship-based time series and to improve evaluation and coordination of methods and communication among marine biogeochemical time series. The compilation of metadata of time series continued under the IGMETS umbrella; more than 340 open ocean and coastal datasets (Figure 1.1), ranging in length from 5 to >50 years and having a similar set of minimal observations, have so far been identified. Their locations are now displayed in a world map (inner cover of this volume) and in the metadata search on the http://IGMETS.net website. These time-series sampling sites represent a phenomenal heritage legacy, and intergovernmental bodies such as ICES, European Marine Board, or IOC-UNESCO strongly recommend continuing the systematic sampling of the existing sites and establishing new time series based on the knowledge gained.

Given that individual time series are distributed across different oceans and managed by different countries, open collaboration with national institutions managing the time series is essential. Sustaining a ship-based time series requires careful planning, periodic evaluation of approach and methods (including implementation of new methods and measurements as appropriate), and a good data-dissemination policy (Karl, 2010).

IGMETS advocates:

1) **Observations which are not made today are lost forever!**
2) **Existing observations are lost if they are not made accessible.**
3) **The collective value of datasets is far greater than their dispersed value.**
4) **No substitute exists for adequate observations.**
5) **The value of time-series observations is positively correlated with the duration of continuous measurements. Measurements encompassing a time-span of several decades allows identification of seasonal, interannual, and decadal patterns.**
6) **The analysis of multiple datasets from different time-series stations allows the separation of stressors and the evaluation of connected ecosystem responses.**
7) **During previous decades, science and technology evolved along with time-series observations. Anticipated development of new techniques will allow streamlining the measurements and improving their geographical coverage.**
8) **Advanced analysis, including global assessments and improved computation, using existing data, creates new science.**
9) **Models will evolve and improve, but, without data, will be untestable – projections and forecasting require considerable diversification of *in situ* data.**
10) **Today’s climate models will likely prove of little interest in 100 years. But, adequately sampled, carefully quality controlled, and archived data for key elements of the climate system will be useful indefinitely.**

1.5 Overview of this report

There are an extraordinary number of unexploited datasets obtained by long-term ocean time series. Large spatial-scale analyses using many different time series allow us to augment our capacity to detect and interpret links between climate variability and ocean biogeochemistry, ultimately improving our understanding of marine ecosystem change. However, in order to bring together datasets from different time series, it is important that the sampling and analytical protocols used at each site are homogenous, consistent, and intercomparable.

For the purposes of analyses presented in this report, we define a time series as a location that is sampled at least once per season (such that strong seasonal patterns can be removed to study lower-frequency variability). We also only examined near-surface observations. This is, in part, due to taking a global view for this analysis and thus avail ourselves of satellite observations to fill in spatial gaps between *in situ* observations, but also because there are far fewer ecological time series that sample in the vertical domain. Within the time-series compilation records, 214 contain information on zooplankton, 142 on phytoplankton, and 145 on nutrients. Data obtained after 2012 were not included in the analysis, which allows the data owner to be the first to publish new findings in the peer-reviewed literature.

The result presented herein provide a brief overview of the information provided from the long-term time-series sites and describe general hydrographic, climatic, and biological characteristics and trends, explaining the change over time. This analysis allows for comparisons of changes occurring in distant locations and helps to detect changes occurring at broad scales and to distinguish them from local imbalances or fluctuations. Additional analyses integrate relationships to major climatic indices for the different ocean basins.

Analyzing the datasets obtained at multiple ocean time-series sites has high scientific value, but sharing data has also important economic and social benefits. The demand from different stakeholders and decision-makers for answers to the challenges posed by changes in the marine environment is growing rapidly. Sharing and accessing time-series data would reduce uncertainties in the management of marine resources and ecosystem services.

This document reviews the dynamics and climate trends that have been reported from different ocean basins and discusses potential future changes to the ecological processes of marine systems. Forecasting the dynamics of ocean processes requires the use of mathematical models, which are often limited by data availability. Challenges are highlighted in this publication in the hope that continuing research efforts will fill knowledge gaps and thus improve our ability to predict future trends and facilitate the successful management and conservation of marine species, habitats, living marine resources, and ecosystem services.

In summary, this IGMETS report aims to deliver new insights into existing biogeochemical and ecological ship-based times-series and to reduce scientific uncertainty regarding environmental change. The report also features an overview of the gaps and needs for better sampling coverage in the different ocean basins and seas.

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