Acta Oceanol. Sin., 2019, Vol. 38, No. 7, P. 114–120
https://doi.org/10.1007/s13131-019-1463-3
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Enhancing the observing capacity for the surface ocean by the use of Volunteer Observing Ship

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Received 2 July 2018; accepted 17 October 2018

Abstract
Knowledge of the surface ocean dynamics and the underlying controlling mechanisms is critical to understand the natural variability of the ocean and to predict its future response to climate change. In this paper, we highlight the potential use of Volunteer Observing Ship (VOS), as carrier for automatic underway measuring system and as platform for sample collection, to enhance the observing capacity for the surface ocean. We review the concept, history, present status and future development of the VOS-based *in situ* surface ocean observation. The successes of various VOS projects demonstrate that, along with the rapid advancing sensor techniques, VOS is able to improve the temporal resolution and spatial coverage of the surface ocean observation in a highly cost-effective manner. A sustained and efficient marine monitoring system in the future should integrate the advantages of various observing platforms including VOS.

Key words: volunteer observing ship, ship of opportunity, surface ocean, *in situ* observation, sensor

Citation: Jiang Zong-Pei, Yuan Jiajun, Hartman Susan E., Fan Wei. 2019. Enhancing the observing capacity for the surface ocean by the use of Volunteer Observing Ship. Acta Oceanologica Sinica, 38(7): 114–120, doi: 10.1007/s13131-019-1463-3

1 Introduction

The surface ocean exchanges material and energy directly with the atmosphere, land, and deep ocean. It plays an important role in the marine biogeochemical cycle and is more vulnerable to anthropogenic influences. Understanding surface ocean dynamics and their controls is critical to predict the oceanic response to future environmental changes. However, the interactions of physical and biogeochemical processes result in substantial variability in different environmental settings and on various time scales. It is therefore critical that appropriate observing systems are in place to monitor the surface ocean with sufficient spatial coverage and temporal resolution. However, most ocean measurements are not made on adequate temporal and spatial scales to meet the fast-growing demands for widespread, long-term and sustained *in situ* data. These data gaps are the major hindrances limiting our ability to accurately assess the climate- and human-induced changes in the marine environment (Petersen et al., 2011).

Recent developments in sensor technology and instrumentation offer the possibility to use volunteering observing ship (VOS) or ship of opportunity (SOOP) to collect high quality scientific data in a cost-effective way. In this paper, we highlight the potential of the use of VOS, as carrier of automatic instrument system and platform for sample collection, to enhance our observing capacity for the surface ocean. The concept, history, present status and future development of VOS operation are reviewed, with focus on the achievements of several successful VOS projects. We also summarize the advantages and shortcomings of various observing methods in order to propose a better strategy for future surface ocean observation.

2 VOS concepts and history

The origin of the international VOS scheme dates back to the first international meteorological meeting in Brussels in 1853. At the beginning stage, the VOS program was proposed to recruit volunteer ships (merchant ships, ferries, fishing vessels and sailing yachts) to collect meteorological data for weather warnings and forecasts. During the past few decades, it is realized that long-range weather forecasts on timescales of months to years can be achieved by incorporating oceanographic data. The need for improved knowledge of the atmosphere-ocean link has been further reinforced by the threat of global climate change. Accordingly, the VOS program has been extended to include hydrographic and biogeochemical observation in the surface ocean. In response to the increasing requirements for enhanced observational coverage of the world's oceans, the World Meteorological Organization (WMO, https://www.wmo.int) and the Intergovernmental Oceanographic Commission (IOC, http://ioc-unesco.org/) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), have been working with the maritime community to enhance the effort in VOS observation. Currently, the VOS program is run by the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (https://www.jcomm.info/). The VOS data are transmitted in near real time by satellite and are publicly available for weather and climate forecasting and marine research.

Foundation item: The National Natural Science Foundation of China under contract No. 41506090; the National Key Research and Development Program of China under contract No. 2016YFA0601400; the Key Laboratory of Global Change and Marine-Atmospheric Chemistry under contract No. GCMAC1408.
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3 Comparison of the methods for surface ocean observation

There are various methods to observe the surface ocean, each of which has its advantages and shortcomings (Table 1).

3.1 *Scientific expedition*

Most of the historical observational data in the ocean came from dedicated oceanographic surveys carried out by research vessels. The traditional shipboard survey is capable of sampling the full water column and sediment. It allows extensive range of measurements to be made with high precision and accuracy. The scientific survey is therefore the ideal approach for detailed *in situ* process studies. However, this kind of survey only provides a snapshot of the ocean with very limited temporal and spatial coverage. Also, a research cruise is generally expensive and is difficult to operate with high frequency.

Table 1. Advantages and shortcomings of various methods for surface ocean observation

	Scientific expedition	Fixed point time-series	Satellite	VOS
Number of available platforms	limited	limited	very limited	√ high
Required resources	large	maintenance	huge	√ cost-effective
Temporal resolution	limited	√ high	depends	depends
Spatial coverage	limited	single-point	√ broad	depends
Number of measurable variables	√ high	limited	very limited	limited
Precision and accuracy	√ high	high (discrete sample), depends (*in situ* sensor)	limited	high (discrete sample), depends (*in situ* sensor)
Full water column sampling	√ capable	depends	surface only	surface only

Note: The symbol √ indicates advantage over other methods.

3.2 *Fixed point time series*

Continuous time series records can be obtained at fixed positions either from *in situ* measurement by autonomous sensors on buoys and moorings, or at stations repeatedly visited by cruise surveys. This is the most powerful approach to investigate the temporal evolution in a certain region. Time series stations are often carefully chosen to be representative of oceanic settings in different biogeochemical provinces of the world's ocean. However, the success of continuous *in situ* measurements relies heavily on the application of mature sensor technologies. Meanwhile, bio-fouling problems can significantly affect the reliability and quality of the measurement over long time period. The frequency of maintenance (from every week to every half a year) depends on the water temperature and eutrophic status of the water systems. The operational cost of time series observation could be high because of the cruises required for maintenance.

3.3 *Remote sensing*

Remote sensing from satellite provides large-scale observation of the surface ocean by measuring the characteristics of light or radiance that are emitted or reflected from the ocean. In order to develop reliable satellite algorithms, *in situ* observations are required to find consistent relationships between the radiances and the surface variable and then to test these algorithms in different types of water. However, the resources needed for launching the satellites are huge. Only a few parameters can be derived from space with limited accuracy at present, and the measurement from space is affected by cloud cover and the complex optical environment of coastal waters.

3.4 *VOS*

In comparison to the traditional ocean observing platforms, VOS has many advantages: no ship costs, a wider spatial coverage offered by the network of merchant vessels, large VOS (i.e., ferry, cargo) can operate under a range of weather conditions that may restrict smaller research vessels, maintenance is cheaper and easier, repeated measurement can be obtained on regularly operated routes. Sensors equipped on VOS also have many advantages when compared to those working under *in situ* conditions on other platforms (buoys, moorings, gliders, etc.): (1) The cost and effort for installation is low due to the available infrastructure on the VOS. (2) Sensors inside VOS are not limited by energy consumption and mechanical dimensions. VOS thus provides an ideal environment for the installment of more complicated, power hungry and sophisticated equipment. (3) Sensors will function more reliable under protected and controlled conditions than offshore deployed devices. (4) Many underway systems already provide automated cleaning and antifouling devices, which minimizes the bio-fouling problem.

3.5 *New technologies*

In recent years, there are emerging new technologies available for marine research (remote operated vehicle, autonomous underwater vehicle, glider etc.). This provides more possibility to enhance our ability for ocean observation.

4 VOS achievements

4.1 *Continuous Plankton Recorder (CPR) survey*

Plankton are the foundation of marine food webs supporting the ecosystem in the ocean. It plays an important role in climate change through the biological pump and can rapidly respond to environmental stressors. One of the earliest and most successful VOS application observing the biological variability in the surface ocean is the Continuous Plankton Recorder (CPR) survey operated in the UK (Reid et al., 2003). The CPR (Fig. 1), towed from the stern of VOS, collects plankton samples including phytoplankton, zooplankton, fish larvae, bacteria and viruses. Since the first CPR tow in 1925, the CPR surveys have accumulated 86-year towing records and sampled 5 050 800 nautical miles in total (updated on July 2018, https://www.cprsurvey.org/). In recent years, the towed body of CPR is equipped with a range of sensors to extend its utility for integrated observation on physical and biogeochemical properties of the seawater (Fig. 1). The long-term sampling and observation provide valuable information on biogeography and ecology of the planktonic community in changing environmental conditions (Brander et al., 2003; Reid et al., 2003).

4.2 *FerryBox system for VOS*

The concept of "FerryBox" refers to the automated instrument package that can be installed on VOS to make unattended

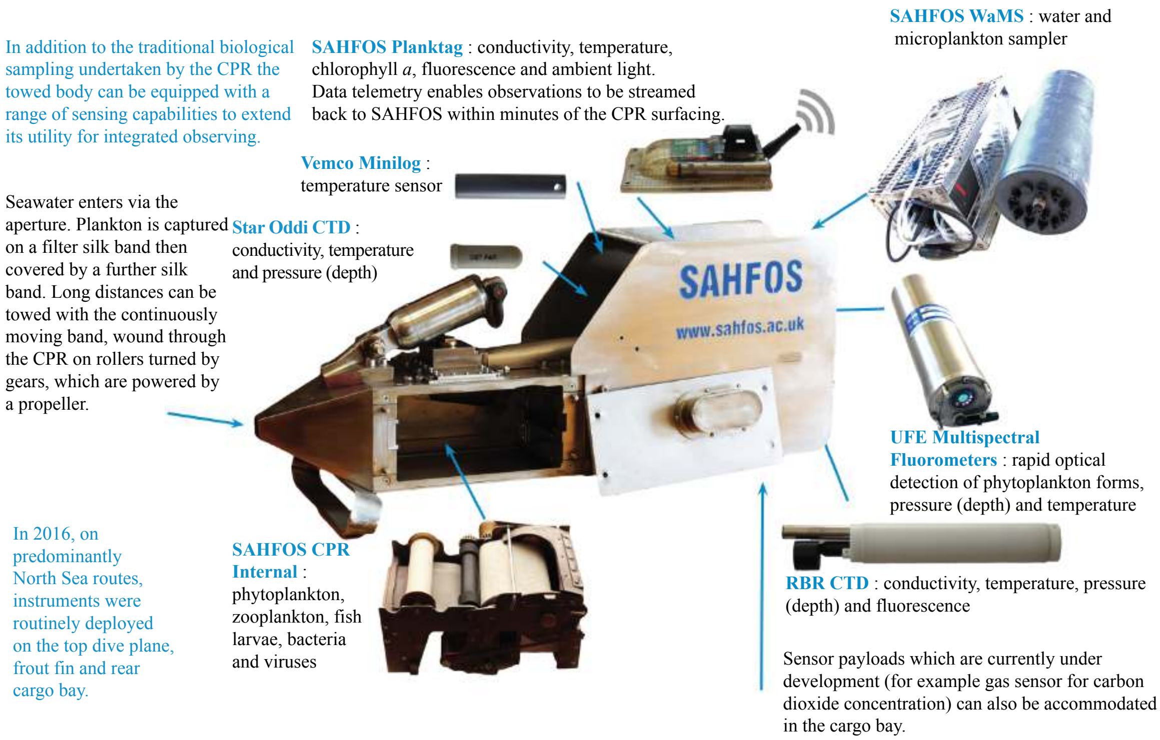

Fig. 1. Schematic of the Continuous Plankton Recorder (CPR) towed by VOS. With sensors equipped on the towed body, the CPR can be used as a platform for integrated ocean observing system. Figure taken from the Sir Alister Hardy Foundation for Ocean Science 2016 Annual Report.

long-term observations (Petersen, 2014). As shown in Fig. 2, the general design of FerryBox consists of a flow-through system equipped with various sensors for physical, chemical and biological parameters. The EU FerryBox project (http://www.ferrybox.com/) successfully established the coordinated use of FerryBox on commercial ships to routinely collect hydrographic and biogeochemical data in European waters. Four core parameters (temperature, salinity, turbidity, and chlorophyll *a* fluorescence) were measured on all EU FerryBox routes, alongside other route-specific measurements on currents, pH, dissolved oxygen, nutrients and algal species. The VOS-mounted FerryBoxs are used globally in Europe, USA, Australia and Japan. The successes of these applications have proved the operability, reliability and long-term stability of FerryBox system.

4.3 *CO_2 observation from VOS*

Carbon dioxide (CO_2) is one of the most important greenhouse gases and it plays a critical role in modulating the climate of the planet. The CO_2 volunteer observing ship program was initiated in 1992 for the assessment of carbon sources and sinks in the global oceans. For instance, CO_2 VOS observation is carried out by the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic and Atmospheric Administration (NOAA) in the US. NOAA researchers equip VOS with thermosalinographs and automated underway CO_2 measuring systems to measure the temperature, salinity and partial pressure of CO_2 (pCO_2) in surface water and air. To date, PMEL maintains three open ocean routes across the Pacific Ocean and three coastal routes along the west US coast: https://www.pmel.noaa.gov/co2/story/Volunteer+Observing+Ships+(VOS).

Another example of the VOS-based pCO_2 observing system is the Swire NOCS Ocean Monitoring System (SNOMS, http://www.snoms.info/) operated by the National Oceanography Centre, Southampton in the UK (Hydes and Campbell, 2007; Hydes et al., 2013). A low-maintenance flow-through tank system (Fig. 3) was assembled to measure seawater properties including pCO_2, temperature, salinity, dissolved oxygen, as well as atmospheric temperature, pressure, humidity and CO_2 concentration. The major practical advantage of the SNOMS is that this ship has a very clear chain of management and responsibility and it is possible to have the ship's crew involved in maintaining the system and collecting calibration samples. Discrete samples were also collected by the trained crew on a daily basis to provide additional information on CO_2-ralated variables and to calibrate the pCO_2 sensor. The measured data could be used to determine the variability of the surface CO_2 as well as the CO_2 exchange flux between the ocean and atmosphere (Dumousseaud et al., 2010; Jiang et al., 2013).

4.4 *Marine instrument deployment*

VOS also aids in the efforts for the deployment of marine observing instruments including expendable bathythermograph (XBT), Argo floats and drifting buoys worldwide. From almost 60 active VOSs, ~20 000 XBTs are launched every year which provides vital observations to estimate the heat content in the upper ocean (Fuda et al., 2000; Korres et al., 2009). Argo is an international program to deploy a global array of temperature and salinity profiling floats. Approximately 3 800 autonomous Argo floats have been deployed over the global oceans (up to July 2018, http://www.argo.ucsd.edu/). Satellite-tracked surface drifting buoys for the observation of sea surface temperature, salinity, currents, atmospheric pressure, and winds were also deployed worldwide (http://www.aoml.noaa.gov/phod/dac/index.php). VOS provides a low-cost way of participating in the deployment

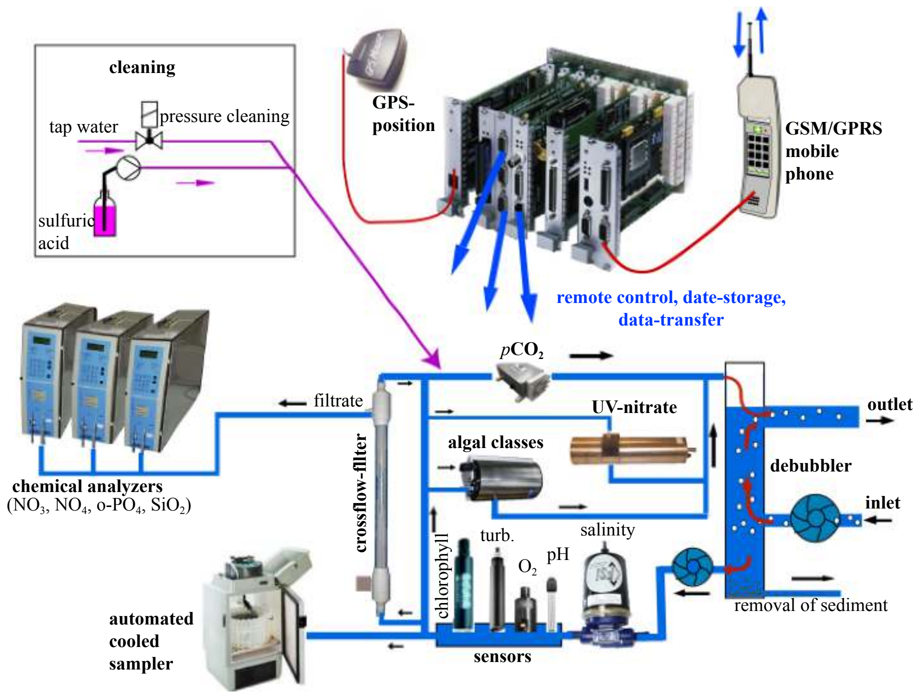

Fig. 2. The general set up of the FerryBox system. Figure taken from the FerryBox website: https://www.ferrybox.org/about/principle/index.php.en.

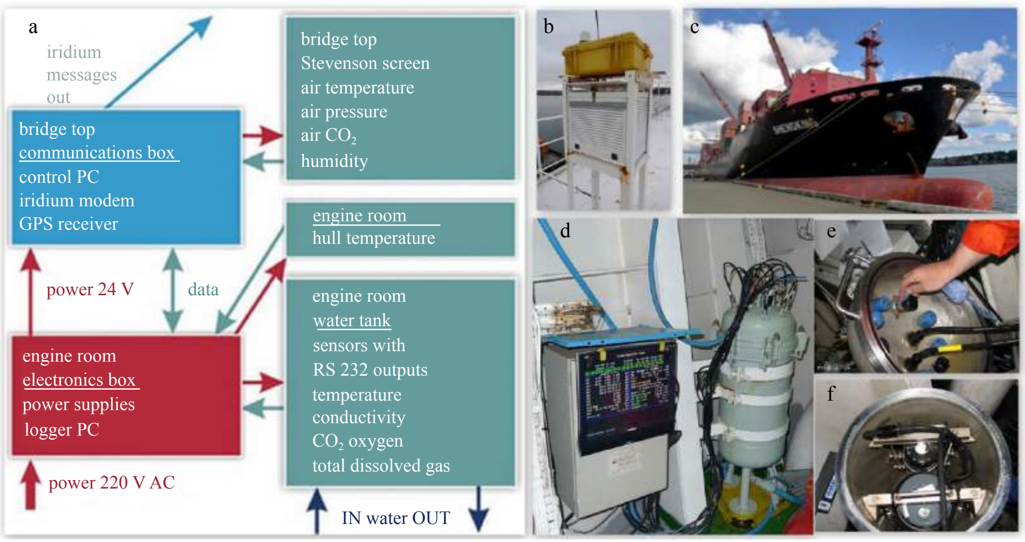

Fig. 3. Schematic and photos of the Swire NOCS Ocean Monitoring System (SNOMS). a. Schematic of the SNOMS, see the text for detail; b. the stevenson screen box (bottom) for atmospheric measurements and the electronic cabinet (top) containing the Iridium satellite modem on the bridge top; c. the *MV Shengking*; d. the instrument package in the engine room including the flow-through pressure tank and controlling computer; e. the triplicate sensors for temperature, conductivity, and dissolved oxygen fitted to the lid of the tank; f. the ProOceanus CO_2-Pro^{TM} and GTD sensor in the tank. Figure taken from Jiang et al. (2014a).

of these ocean monitoring instruments.

5 Present status and future development of VOS

The overall objective of VOS is to use volunteer ships to provide a cost-effective way for surface ocean monitoring and help to solve environmental problems. Current international efforts on VOS operations by the European Union, USA, Japan and Australia significantly improve the spatial coverage of surface ocean observation (Fig. 4). Although there is a large amount of merchant marine vessels travelling in the Chinese Seas, VOS still constitutes an underutilized resource for ocean monitoring in China (Liu, 2009). More efforts from scientific community and the shipping industry are needed for future exploitation of VOS monitoring programs in China.

It has been shown that VOS contributes substantially to marine meteorology in increasing our understanding of the atmosphere-ocean linkages for the development of long-range weather forecasts. VOS also provides valuable information for the fish-

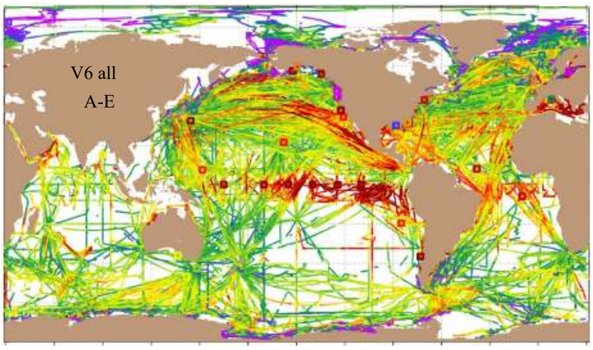

Fig. 4. Map of VOS data (pCO_2 and other variables) collected from 1957 to 2017 for the global oceans and coastal seas. Figure taken from www.socat.info.

ing and aquaculture community. The use of VOS as platform for marine research has also been promoted in recent years (Ainsworth, 2008; Goni et al., 2010; Rossby et al., 1995). VOS provides observations along selected tracks on a regular basis helping to detect short-term phenomena and processes, such as algal blooms (Garcia-Soto and Pingree, 2009; Schneider et al., 2006; Seppälä et al., 2007), upwelling (Kikas and Lips, 2016) and coastal pollution (Andrady, 2011; Hartman et al., 2014b; Kelly-Gerreyn et al., 2007). The long-term time series on repeated VOS track can be used to investigate the seasonal and interannual changes of CO_2 (Bakker et al., 2016; Dumousseaud et al., 2010; Jiang et al., 2013), nutrients (Hartman et al., 2014a), plankton and biological production (Ostle et al., 2015; Petersen et al., 2011; Reid et al., 1998). The VOS traveling around the globe allows a comparative study in different marine environmental settings (Jiang et al., 2014b). Additionally, the VOS observation delivers a large set of ground truth data for remote sensing applications to validate and calibrate satellite data such as suspended matter and chlorophyll. In turn, remote sensing expands the transect view of the VOS observation to a broader area. Moreover, the VOS data strongly benefit the validation and assimilation of numerical models to improve their accuracy and prediction quality (Grayek et al., 2011; Haller et al., 2015).

At present, the VOS operation is already mature in the perspectives of suitable flow through systems, control systems, data logging and transmission. The key factor remains in the development of reliable sensors for automatic long-term operation. Currently, the observations made from VOS have included a range of parameters: upper ocean thermal structure (Beggs et al., 2012; Donlon et al., 2008; Goni et al., 2010), salinity, light, turbidity, current, phytoplankton (Reid et al., 1998; Schneider et al., 2006; Seppälä et al., 2007), anthropogenic pollutants (Andrady, 2011; Kelly-Gerreyn et al., 2007), and biogeochemical parameters such as nutrients, dissolved oxygen, and CO_2-related variables (De La Paz et al., 2010; Hydes et al., 2009; Lüger et al., 2006; Petersen et al., 2011; Schneider et al., 2006). As shown in Table 2, several mature sensors have been made available for VOS observation, and many new emerging technologies are under development with focus on biogeochemical variables. With the development of sensor technology, VOS observation could play a more important role in enhancing our observing capacity for the surface ocean in the future.

6 Recommendations for VOS operation

The following recommendations should be considered when planning the implementation of a VOS observation system:

(1) The installment, operation and maintenance of VOS rely heavily on the collaboration from the owners and operators of the vessels. The collaboration between the scientific community and the shipping industry is therefore vital for the success of VOS operation.

(2) Among the available shipping routes, a careful assessment should be carried out to choose the most appropriate track to meet the monitoring or research objectives (Petersen and Colijn, 2017). A fixed and repeated ship route is preferred. The logistic issues should also be considered in advance, e.g., maintenance work can be conducted in port located nearby to the operating institution.

(3) Exploit shipping routes in spatially and temporally under-

Table 2. Sensors and analyzers that can be equipped on VOS and their current performance

Variables	Instruments suitable for VOS application
Temperature	mature commercial sensor available
Salinity	mature commercial sensor available
Turbidity	mature commercial sensor available
Photosynthetic available radiation	mature commercial sensor available
Dissolved oxygen	mature commercial optode available (Hydes et al., 2009; Tengberg et al., 2006)
Chlorophyll-a fluorescence	mature commercial sensor available
Auto water sampler	commercially available
Current	mature commercial acoustic doppler current profiler available, though its accuracy is affected by the comparatively high speed of the vessel
Nutrients	chemical and optical analyzer commercially available but analyzer for long-term unattended operation is still under development (Frank et al., 2006)
pH	commercial electrode available; spectrophotometric analyzer with higher accuracy under development (Aßmann et al., 2011)
pCO_2	commercial sensor available while its accuracy needs to be improved; automatic analyzer with higher accuracy under development (DeGrandpre et al., 1995; Jiang et al., 2014a; Lu et al., 2008; Rubin and Wu, 2000; Wang et al., 2002, 2003)
Dissolved inorganic carbon	sensor under development (Bandstra et al., 2006; Sayles and Eck, 2009; Wang et al., 2013)
Total alkalinity	sensor under development (Li et al., 2013; Martz et al., 2006)
Phytoplankton biomass and community structure	multi-wavelength fluorometer (Wollschlager et al., 2013), flow cytometer (Thyssen et al., 2015; Zubkov et al., 2000), rRNA biosensor (Diercks-Horn et al., 2011) under development
Algal activity	fast repetition rate fluorometry
Biological production	underway measuring system under development (Cassar et al., 2009)

sampled regions such as the Southern Ocean, the Chinese seas (Liu, 2009).

(4) When constructing a VOS observing system, suitable sensors should be carefully chosen considering their applicability, reliability and accuracy, as well as the meaningfulness of the measured variables to the intended monitoring or scientific tasks.

7 Towards a better strategy for surface ocean observation

In order to build an efficient marine monitoring and management system, the strengths of individual ocean observing platforms should be integrated. Laboratory experiments and field expeditions should be carried out to investigate the mechanisms regulating the physical and biogeochemical dynamics on molecular to regional levels. In addition to research surveys, the time resolution and spatial coverage of *in situ* observation can be further improved by the use of automatic instruments on various platforms such as VOS, Argo floats, moorings and gliders. Furthermore, satellite data should be used to extrapolate and upscale *in situ* observations to larger space scales. Based on the knowledge gained from laboratory studies and observations, sophisticated numerical models can be developed to examine the complex physical and biogeochemical interactions and to predict its potential future changes. Ultimately the combination of complementary full depth process studies, *in situ* and remote observations and modeling efforts will lead to an advanced understanding of the surface ocean dynamics.

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