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Potential for an underwater glider component as part of the Global Ocean Observing System

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Abstract :

The contributions of autonomous underwater gliders as an observing platform in the *in-situ* global ocean observing system (GOOS) are investigated. The assessment is done in two ways: First, the existing *in-situ* observing platforms contributing to GOOS (floats, surface drifters, moorings, research/commercial ships) are characterized in terms of their current capabilities in sampling key physical and bio-geochemical oceanic processes. Next the gliders' capabilities are evaluated in the context of key applications. This includes an evaluation of 140 references presented in the peer-reviewed literature.

It is found that GOOS has adequate coverage of sampling in the open ocean for several physical processes. There is a lack of data in the present GOOS in the transition regions between the open ocean and shelf seas. However, most of the documented scientific glider applications operate in this region, suggesting that a sustained glider component in the GOOS could fill that gap. Glider data are included for routine product generation (e.g. alerts, maps). Other noteworthy process-oriented applications where gliders are important survey tools include local sampling of the (sub)mesoscale, sampling in shallow coastal areas, measurements in hazardous environments, and operational monitoring. In most cases, the glider studies address investigations and monitoring of processes across multiple disciplines, making use of the ease to implement a wide range of sensors to gliders. The maturity of glider operations, the wide range of applications that map onto growing GOOS regional needs, and the maturity of glider data flow all justify the formal implementation of gliders into the GOOS. Remaining challenges include the execution of coordinated multinational missions in a sustained mode as well as considering capacity-building aspects in glider operations as well as glider data use.

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Keywords : Global ocean observing system, GOOS, Underwater glider, Sustained observations

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1. Introduction

Since first prototype testing in the early nineties (Simonetti 1992) underwater gliders have been rapidly taking up an important role in ocean observing and research (see Testor et al. 2010 and Rudnick 2015 for a comprehensive overview). This rapid transition towards a widely used observing platform can first of all be attributed to the fact that glider observations provide critical data for many applications. Historically, gliders have been used most frequently by scientists to observe particular oceanographic processes. Increasing interest of navies from different countries on the operations on coastal waters for naval operations (e.g. Renaud 2003) has contributed to the rapid development of glider technology as well. Underwater gliders use a buoyancy engine to survey the ocean interior along saw-tooth paths. Their operation times are typically of up to several months, depending on battery capacity and sampling configuration. Glider manufacturers and users have implemented a wide range of sensors on the platform and various physical and biogeochemical parameters can be recorded, many of them accessible in near real time.

Testor et al. (2010) gave a review of requirements and challenges of a global coordination for efficient use of underwater gliders. One of the recommendations was the establishment of a global glider system as an extension of the Global Ocean Observing System (GOOS). This idea is further elaborated in the assessment presented here, that benefits from a consolidation of national glider activities, namely the pan-European glider infrastructure design project, Gliders for Research, Ocean Observation and Management (GROOM). One of the main outcomes of GROOM was the identification of the need for a centralized coordinating body that would act as a centre of reference for the nascent European glider network infrastructure, by providing a platform for exchanging expertise, experience, equipment, facilities, and services and develop data sharing protocols and policies. Much of this is happening already on an informal, fragmented basis in Europe, but of course also in other regions such as Australia, in the context of the Integrated Marine Observing System (IMOS) Ocean Gliders facility, and the United States for example in the context of the Ocean Observatories Initiative (OOI) or the Glider Operations Center (GOC) at the Naval Oceanographic Office (NAVOCEANO). Regional US glider observing groups (Rutgers University, University of Washington, Scripps Institution of Oceanography) are also organized in the US IOOS.

The Global Ocean Observing System (GOOS) is a permanent system for coordinating the global ocean observatory efforts including infrastructure, data flow and data processing. Ocean processes operate on time scales from fractions of a second to multiple decades temporally and from millimetres to thousands of kilometres spatially (Ruhl et al. 2011). Monitoring the ocean in four dimensions and across disciplines therefore requires integration of data collected from a multiplatform system (e.g. Summerhayes 2002, table 1). Only a concerted use of individual platform sampling strengths can overcome other platform weaknesses and limitations. Currently GOOS comprises observing efforts carried out by ships, moorings, floats, surface drifters, marine mammals and sea level observatories (for example Fig. 1). Guidance to help identify observing requirements and implementations is provided via disciplinary expert groups (physics and climate, biology and ecosystem, and biogeochemistry) and also by considering specific regional requirements (GOOS regional alliances).

Defining observing needs depends on societal and scientific objectives as well as technological readiness (Lindstrom 2012). Roughly, the requirements fall under three main themes, which are, however, linked with each other: climate, ocean health, and real-time (operational) services.

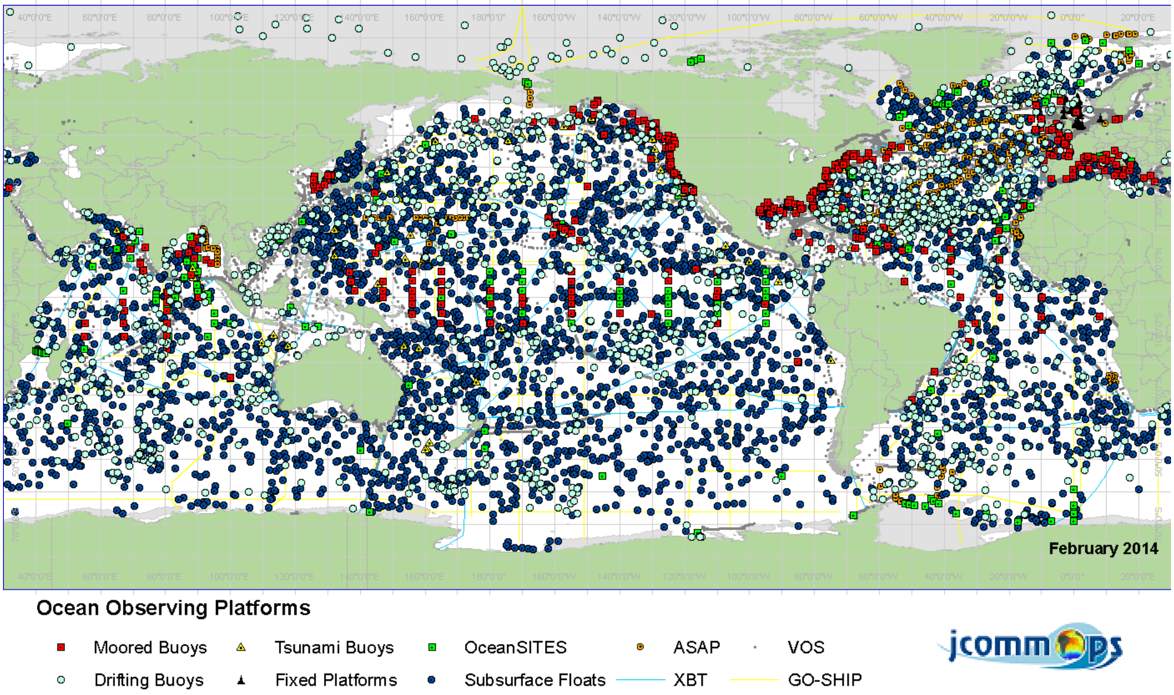

Figure 1. Summary map of all available in situ data as reported by JCOMMOPS in February 2014. Automated Shipboard Aerological Programme (ASAP) and Tsunami buoys are not under investigation in the present study (see http://www.jcommops.org/ for a recent update).

The coordination of the observational effort in GOOS is realized under the auspices of the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) through the Observations Coordination Group (OCG). Currently OCG provides coordination at the international level for oceanographic and marine observations from autonomous data buoys, Argo, OceanSITES moored buoys in the high seas, surface drifters, voluntary observing ships and ships of opportunity, and the global sea-level observing system, with the help of JCOMMOPS (JCOMM *in-situ* observing Platform Support Centre) and considering biogeochemical variables via the International Ocean Carbon Coordination Project (IOCCP).

In the present paper we evaluate the use of underwater gliders as an integral part of GOOS. We focus on the sampling capabilities of gliders and how they fit into the observing needs of GOOS. We first present a short description of sampling characteristics of the in-situ observing platforms currently organized in GOOS as well as ocean underwater gliders. We then assess the past use of gliders in ocean observing on the basis of reviewed publications making use of glider data and discuss the potential contribution of a glider component in GOOS.

2. In-situ observing platforms in GOOS

GOOS *in-situ* observing system consists of several platform types (e.g. Trtanj and Houston 2014; Legler et al. 2015): research vessels, profiling floats, surface drifters, ships of opportunity and voluntary observing ships, moorings, marine mammals and sea level stations. Each platform type has its own characteristics such as spatial and temporal resolution of sampling, coverage, endurance, costs, sustainability, sensor payload, accuracy, calibration issues and data transfer/availability. It is through the coordination of observing platforms in the GOOS that the limitations inherent in each of the platforms will be overcome and an optimized system is created that enables sampling relevant time, space, and parameters domains.

An approach to analyse the potential contribution of each platform to the system is to overlay ocean processes with the spatial and temporal scales resolved by the various platforms in the framework of a “Stommel diagram” (Stommel 1963) (Figs 2 to 6, and Fig. 7 and summarized in Table 1). Temporally the upper limits are defined to be the lengths of time-series of the corresponding platform. Spatially both horizontal and vertical dimensions are taken into account. We limit this approach to an analysis of the capabilities in the frame of a simplified set up and with a primary focus on physical processes. For example the problems for a certain platform to sample in a dynamically active regions (e.g. sampling a fast flowing boundary current) is not adequately represented in the space/time diagram. Moreover, the sampling required to resolve phenomena related to other disciplines (e.g. biogeochemistry, biology) is not explicitly resolved, this is true for the space/time domains but also in relation to the parameter domains.

However, an attempt to consider the sensor/parameter availability of the GOOS observing platforms (Table 1) was done by focussing on parameters that are frequently measured with gliders and that resemble a subset of essential climate variables (Houghton et al. 2012). As such, the list of parameters shown in Table 1 is only a small subset of variables that can be potentially measured with the different *in-situ* observing platforms.

We do not discuss factors like costs, maintenance and endurance of observing platforms, data quality, accuracy of sensors, or logistics. All will play an important role in creating and maintaining a sustained system. The interested reader may find a summary of three years of glider infrastructure set-up, operational and maintenance costs of the case of European operators in GROOM (2014), including the wide range of estimated daily costs for operations and for emergency recoveries.

Argo

The global array of temperature and salinity profiling floats (“A real-time geostrophic array” Argo) is the prime example of a sustained network of observing platforms of global importance (Riser et al. 2016). The array was designed based on a well-defined scientific objective of global relevance, namely monitoring the upper ocean heat content variability with spatial resolution 3 x 3 degrees between latitudes 60°N and 60°S on seasonal and longer time scales. That required an array of 3000 floats sampling every 10 days the upper 2000m (White 1994; Argo Science Team 1998). An Argo float’s sensor sampling rate is up to 1 Hz depending on the transmission mode (Iridium, ARGOS). The full-resolution data or data interpolated to standard depths are transmitted. Trajectory data of Argo floats allow estimating current velocities at parking depth (set around 1000 m in the global basins, less in enclosed seas like the Mediterranean).

In order to establish the array, international coordination efforts considered and properly addressed the following: legal aspects for deployment and drift, data quality control and timely distribution, formation and operation of coordination teams (data, science and implementation). The currently operational array (defined by the floats accessible via the Argo data centre) counts more than 3800 floats (as of March-2016, see http://www.jcommops.org/board?t=Argo for an update). This “oversampling” against the core science objective (upper ocean heat content variability) can be explained by the implementation of data from “non-sustained”, science project based deployments, such as about 250 floats that belong to the “pilot network” of floats that carry biogeochemical sensors (oxygen, chlorophyll-a/fluorescence, Gruber et al. 2010). However, recently Durack et al. (2016) have pointed that number of floats might decrease to 3200 in 2018 due to reduction in Argo deployments. The ease in implementing floats into the sustained array has substantially increased the data return against the defined science goal and allows for an improved use in GOOS.

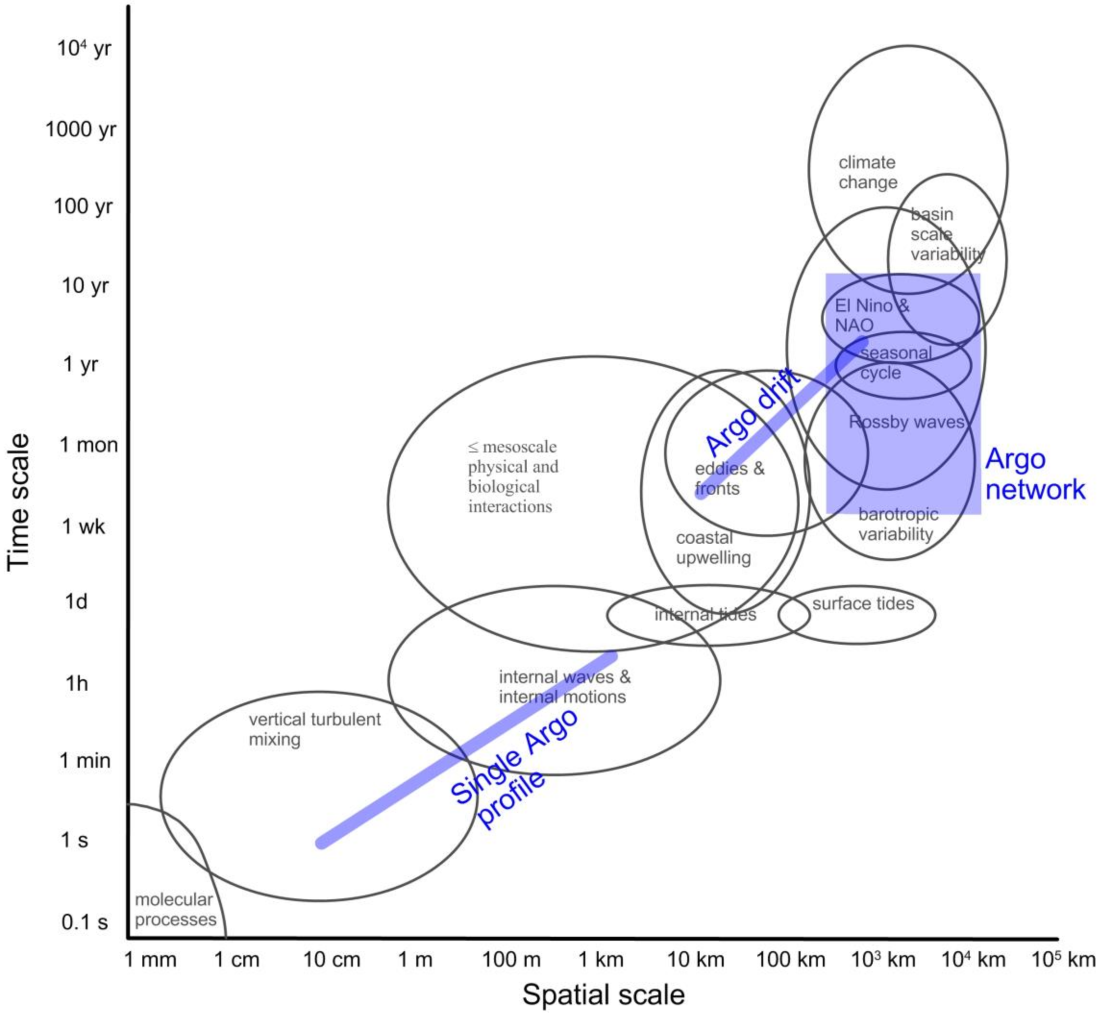

Figure 2. Time-space diagram of ocean and earth processes (after Ruhl et al. 2011) and sampling capabilities of Argo. The sampling capabilities of both a single Argo float and a network of floats (Argo network) are distinguished. Both vertical and horizontal dimensions are considered in spatial scale.

Argo is considered a sustainable part of the polar oceans observing systems (Abrahamsen 2014) because under-ice operations are feasible using acoustic tracking during extended periods of non-surfacing (Klatt et al. 2007). The planned extension of the depth range to 4000 and even 6000m (Roemmich et al. 2014) will extend the theoretically observable ocean volume (currently it is only 48% due to the 2000m depth limit) substantially. However, for deep ocean observing the major limitation is currently the accuracy and stability of temperature and salinity sensors. Other future developments include use of shallow floats that can operate in regional seas (e.g. Baltic Sea; Purokoski et al. 2013; Coral Seas Kessler and

Cravatte 2013) and air-deployable profiling floats to study hurricanes (alamo.whoi.edu). In general the array as a whole cannot resolve processes at the mesoscale (Figure 2).

An important complementary source of CTD (Conductivity, Temperature, Depth) data in polar, ice-covered regions in the Southern Ocean and Arctic stems from marine mammal tagging (e.g. Fedak 2013). The sampling accuracies and resolution are relatively similar to Argo floats, although they typically profile more frequently (normally one profile per day is transmitted). These data sets are often treated similar to Argo float data in respect to automatized real-time and delayed mode quality control procedures but also in way in distributing the data.

Global Drifter Program

The Global Drifter Program (GDP) was introduced at the beginning of the 1980s (see Legler et al. 2015 for a recent review). The primary scientific objective of the GDP is a near-real time observing system for sea surface temperature (Zhang et al. 2010) and large-scale ocean surface circulation and its seasonal variability (Lumpkin et al. 2016). A coverage in 5 x 5 degrees squares was estimated as the minimal array design (Lumpkin et al. 2016; Fig. 3), translating to a need of about 1250 satellite tracked surface drifters to be operational. Individual floats can resolve mesoscale variability along their trajectory. Besides drift estimates, the GDP array provides sea surface temperature data as well as sea level pressure data (Keeley et al. 2008). The latter parameters are provided by about half of the drifters. The typical temporal resolution of drifter measurements after data processing is 6 hours (Lumpkin and King 2008). Single drifters (process studies) can be set to send their data two or three times per hour. As for the Argo array, drifters that have been launched in the framework of projects/process studies, and therefore are not part of the sustained system, have increased data availability for GOOS. At any given time, there are approximately 1440 drifters in operation and these data are freely available in real time either as individual drifter tracks or as gridded products.

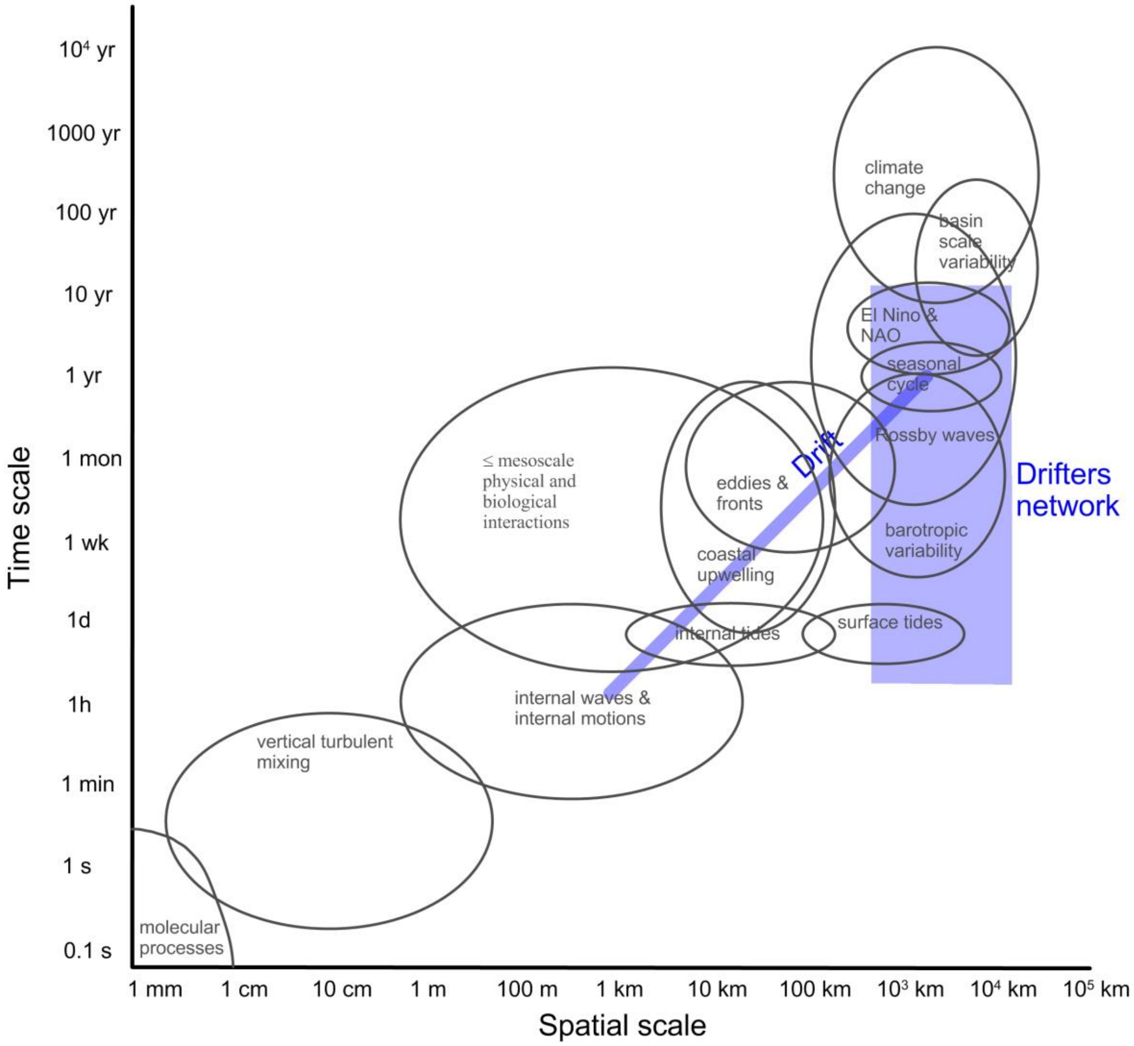

Figure 3. As Fig. 2 but for the global drifter network. Single drifter as well as the drifter network are separated.

Since drifters have great ability to estimate currents in the upper ocean, they can be deployed for local studies such as tracking oil spills (Sharma et al. 2010), and their data can be efficiently used in search and rescue operations in the ocean (Breivik et al. 2013). In coastal areas, drifters have been used in case studies to investigate dispersion or spreading of substances. In ice-covered regions surface drifters become trapped in sea ice, so their typical lifetime is reduced (Thompson et al. 2009) but may allow ice drift estimation instead (e.g. Häkkinen et al. 2008, Leppäranta et al. 2001).

Ships of Opportunity and Voluntary Observing Ships programs

The Ships Observations Team (SOT) comprising the Ships of Opportunity Program (SOOP; Goni et al. 2010), the Voluntary Observing Ships Program (VOS; Kent et al. 2010), and the Automated Shipboard Aerological Program (ASAG), coordinate the collection of underway measurements that are acquired on board merchant-, cruise- and research vessels (Smith et al. 2010, Legler et al. 2015). The VOS program was initiated in the 19th century and it has been an important data source for marine climate (Worley et al. 2005). Of particular importance is the collection of data along repeated transects using merchant ship routes that have been maintained for many years and even decades (e.g. Vranes and Gordon 2005; Rossby and Zhang 2001).

The SOOP include upper ocean observations of temperature profiles using eXpendable BathyThermographs (XBTs) and temperature and salinity time series data collected near the surface with the thermosalinograph (TSG) from the ships' flow-through system. The XBT data bridge the heat content studies from pre-Argo era to the present day and were also used for the design of the Argo array (White 1994).

Dedicated XBT sections of VOS are often sampled with monthly resolution (e.g. the Oleander Project, Rossby and Zhang 2001) while various TSG tracks are repeated with even higher frequencies, depending on the route length. Re-visit can be from a couple of times a day in marginal seas (e.g. Lips et al. 2011) to several times a year in open ocean (e.g. Rossby and Zhang 2001; Feely et al. 2012).

XBT profile data are acquired with a horizontal resolution of typically 150 km along frequently visited transects (Fig. 4) and can be as high as 25 km for high resolution sections. Vertical resolution is 10 m and range down to about 750 m depth. The TSG is typically set to sample every 20 seconds and thus resolves horizontal scales of a few hundreds of metres after processing (Fig. 4). Thus automated underway measurements provide high-resolution data from the upper layer, which are very useful for front determination. TSG data are especially valuable in coastal zones, where global systems (Argo, GDP) might be too sparse. For comparison with satellite retrievals, TSG data have been used as instrumental reference, in particular for the recent satellite salinity missions (SMOS and Aquarius) (Hernandez et al. 2014).

The SOOP also collects current (Acoustic Doppler Current Profiler) data as well as biogeochemical variables such as chlorophyll-a fluorescence, and partial pressure of CO_2 (Surface Ocean CO_2 Atlas- SOCAT; Bakker et al. 2012). Under GOOS pilot project FerryBox, underway systems are commonly used on-board passenger ferries in the North Sea and the Baltic Sea (Hydes et al. 2010). For instance the Alg@Line project has used passenger ferries for over 20 years (Rantajärvi 2003).

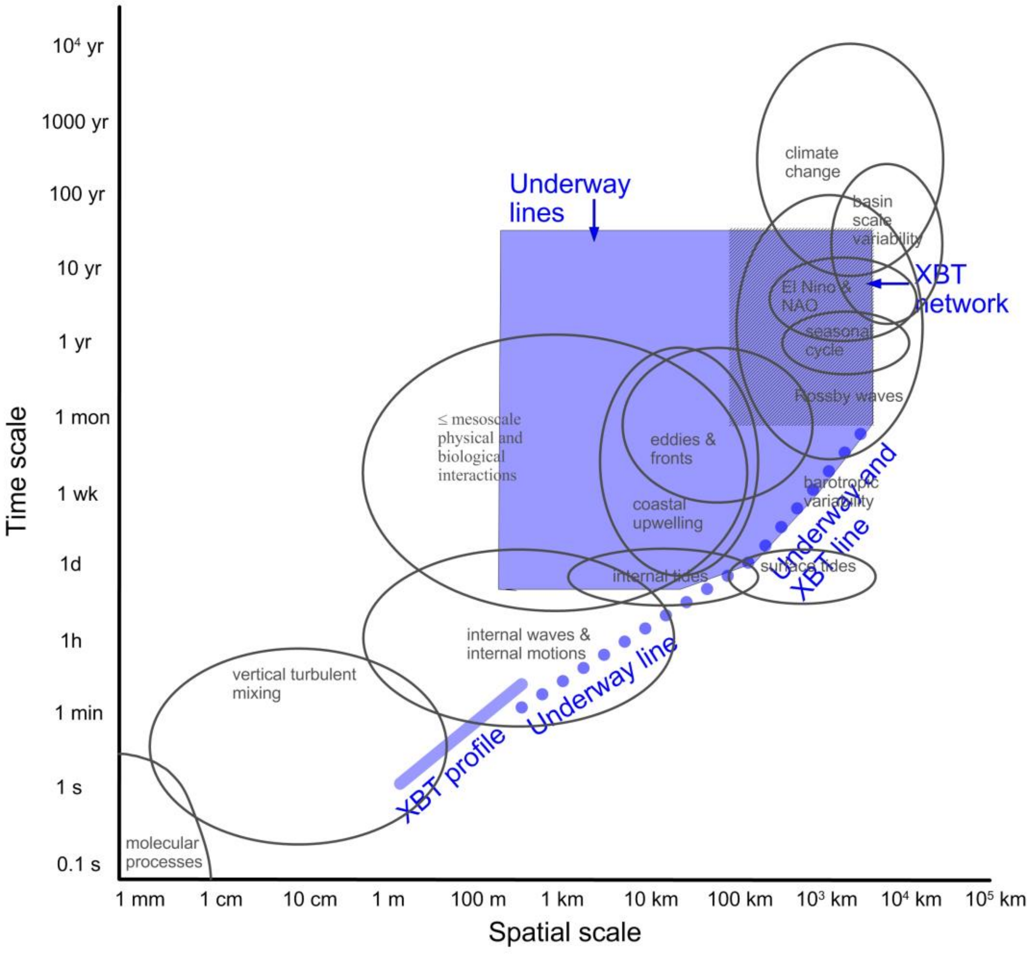

Figure 4. As Fig. 2 but for the XBT network and underway lines.

A special activity in SOOP is the collection of biological data in the context of the Global Alliance of Continuous Plankton Recorder Surveys (GACS). The continuous plankton

recorder is towed behind the ship at a depth of about 10 m where it collects plankton samples, which are later analysed in the laboratory (Reid et al. 2010).
Often the data acquisition from XBT, TSG are (semi) automated and the data are transmitted in real-time through communication satellites (e.g. GOES, METEOSAT, ARGOS, Inmarsat systems) to dedicated data assembly centres as either BATHY or TESAC messages. The observations are compiled into bulletins and distributed globally via the GTS under JCOMM. The data are encoded in the international exchange format MEDSASCII, quality controlled by the operating agencies, and sent at 12-month intervals to the respective Regional National Oceanographic Data Centre (RNODC) for forwarding to the World Data Centres (WDCAs - USA, Russia).

The assembly and incorporation of delayed mode SOOP/VOS data into the Global Temperature-Salinity Profile Program (GTSPP) data stream in a timely manner is an essential activity. Experience has shown that significant amounts of real time data are not being replaced with full resolution data versions, and that large quantities of additional data are only available in delayed mode. While these data are not available for operational use, they are critical for GCOS thus contributing to climate research.

Research vessels and GO-SHIP

Research vessels are important components of the ocean observing system, in particular for specialized and multidisciplinary studies, and studies that require data of high quality (e.g. climate studies). Many parameters cannot be measured by autonomous systems, at least not with the accuracy of those gathered by research vessels.
The open ocean sustained oceanographic measurements on research vessels is coordinated under the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP; Hood et al. 2010). GO-SHIP assembles the high-quality and high-resolution observations of physical, chemical and biological parameters in full ocean depth resolution that originate from dedicated ship surveys. The sections are repeated multi-annually and provide critical data for long term changes of the ocean state. A very important activity within GO-SHIP is in defining standard procedures for sampling in order to assure high data quality and comparability over time and measuring platforms.

Other sustainable sources of ship-gathered data are national monitoring programs, which are often coordinated by intra-governmental bodies; such are e.g. HELCOM (for the Baltic Sea), OSPAR (North-East Atlantic), BSIMAP (for the Black Sea) and AMAP (for the Arctic). Such monitoring programs typically collect data on a monthly or seasonal basis.

Although not compulsory, many vessels are advised to provide collected data in near real time on GTS or as BATHY or TESAC (e.g. data transmission to the Coriolis Data Centre, Integrated Ocean Observing System US-IOOS and Australian Integrated Marine Observing System IMOS ocean portal). The GO-SHIP panel, for instance, recommends the following data-release guidelines: preliminary dataset released within 6 weeks (e.g. all data measured on the ship), 6 months for final physical data and 1 year for final data of all other variables.

Data from research ships have traditionally been assembled by National Oceanographic Data Centres (NODCs), regional centres, like the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES) and to global data centres, which are today part of the World Data System, WDS (http://www.icsu-wds.org/). A Pan-European infrastructure has been developed in the SeaDataNet project (Schaap and Lowry 2010) that provides one access point to the distributed national data centres.

Tropical moored arrays and OceanSITES

Moored systems acquire observations at fixed geographic locations and with instruments mounted at fixed depths (although mooring vertical displacement is inevitable during strong currents). Moorings deliver temporally high-resolution data (Fig. 5) and, as the payload capabilities are large, can host a variety of sensors of different complexity. The observations cover a wide spectrum of physical (incl. geophysical), biological, and biogeochemical parameters. The systems can extend over the whole water column including the air/sea interface. The configuration of the sensors along the mooring line defines the vertical resolution which is typically tens to hundreds of metres. Specific moorings equipped with profiler systems sample at a higher vertical resolution (e.g. Lips et al. 2011, Send et al. 2013, Zhou et al. 2013).

Real-time access to data from surface as well as subsurface instruments is critical when using the data in forecast models, e.g. in the context of seasonal prediction (e.g. TAO array, PIRATA array). The recovery of the sensors allows for post-calibration and high data quality is possible. Surface buoys are used for calibration/validation activities for satellite retrievals or air/sea fluxes (Sun et al. 2003).

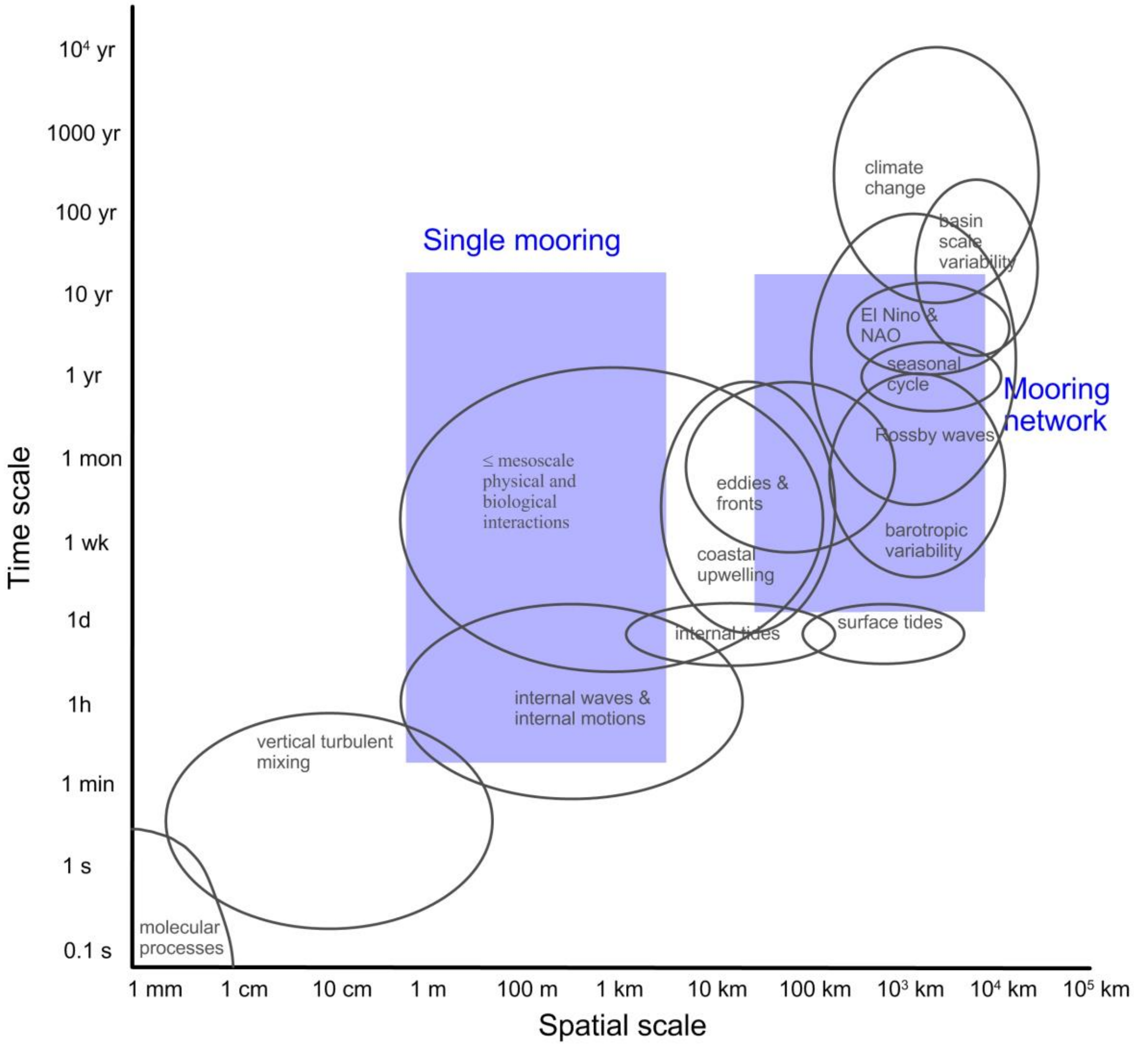

Figure 5. As Fig. 2 but for moorings.

Given different scientific and operational aspects, moorings have been organized in GOOS in two groups: the tropical moored arrays and OceanSITES (Legler et al. 2015). The tropical moored arrays have been designed for a specific scientific objective, to monitor the evolution of the tropical ocean upper flow and temperature field in order to improve the forecast of tropical inter-annual and intra-seasonal variability such as El Nino Southern Oscillation and the Madden Julian Oscillation. The moorings coordinated under OceanSITES (Send, Weller et al. 2010) aim for long (several years) open ocean time series acquisition. As such most of the moorings from the tropical moored arrays are also part of OceanSITES. The OceanSITES objectives include optimized configuration (e.g. sampling depth locations, deep ocean observing efforts) and in particular data management issues.

Global Sea-Level Observing System

The Global Sea-Level Observing System (GLOSS, e.g. Woodworth and Player 2008) is an international programme coordinating a network of sea level monitoring gauges installed along seashores around the world in over 70 countries. The GLOSS is incorporated into tsunami warning systems. Other variables (e.g. near surface temperature) are often measured as well. Because of the importance of sea level extremes in coastal areas, a large fraction of the GLOSS transmit data in near real time (<1h). The GLOSS provide data that is used to assess the link between regional and global sea level rise which is of high socioeconomic importance. The GLOSS has established standards in collecting and processing sea level data. Rather than discourage participation, this enables the network to expand, while still maintaining the quality of the observations (IOC, 1997).

Glider observatories

Most underwater gliders sample the ocean along slanted profiles between the surface and down to 1000 m or even 1500 m depth. Navigational devices on board (compass, pitch/roll sensors) ensure proper navigation during the dive. Comparison with a position estimate through GPS satellites at the surface is used to reset the start coordinates for the next dive and to estimate the dive-average current and the surface drift of the device. The glider moves horizontally about 30 km per day and the maximum endurance is typically a few months in the open ocean, but this depends on many factors such as number of dives per day, the type of sensors in use, the sampling strategy, the stratification, the currents, and diving depth. The U.S. OOI's global array of gliders has endurance of up to 1 year. For a typical diving speed of 0.15 m s^{-1} and sampling at 1 Hz, the vertical resolution is 0.15 m. Horizontal, vertical and temporal variability are all conflated in the observations and this has to be considered when analysing and interpreting the data.

The suite of sensors that have been integrated or mounted on gliders is steadily growing. Variables that can be measured include pressure, temperature, conductivity, chlorophyll-*a* fluorescence, turbidity, chromophoric dissolved organic matter (CDOM) fluorescence, dissolved oxygen, PAR (Photosynthetically Active Radiation), phycobilins, turbulence, currents, wind, nitrate, animal presence and biomass, marine mammal detection (see summary by GROOM 2015). For common physical or biogeochemical parameters, such as temperature, conductivity or chl-*a* fluorescence, the sampling rate is typically 1 Hz, which allows gathering processed data in vertical resolution of the same order as research-vessel collected profiles. The horizontal distance between consecutive dives is in the order of 2-5 km in 1000-1500 m deep dives.

Glider users have been organized, mostly at an opportunistic level, for more than a decade in international groups (e.g. Everyone’s Gliding Observatories (EGO; http://www.ego-network.org)), as well as national consortia (U.S. IOOS), or as part of larger scale, centralized national ocean observing infrastructure (e.g. Australia’s ocean glider facility as part of IMOS). The achieved coordination within the glider user community, in coordination with other groups such as the Argo data expert group, has established a “standardized” data flow and data quality control mechanisms for operational use. As a consequence, glider data are routinely aggregated in DACs such as e.g. Coriolis Data Centre, Integrated Ocean Observing System US-IOOS and Australian IMOS ocean portal. In principle it is possible to make glider data freely available for everyone as it is for Argo and GDP now, and many glider groups already transmit data in near-real-time on the GTS for immediate availability for data assimilation models used by weather forecasting centres and navies.

Currently the world wide largest fleet of autonomous unmanned systems, including ocean gliders, is managed by the GOC at the NAVOCEANO. The glider data (among other data) is used by ocean modelers to estimate current and forecast future environmental ocean conditions. NAVOCEANO then provides these forecasts in near-real time to support strategic, operational, and tactical Navy fleet requirements and activities (Mensi et al. 2014). The GOC glider fleet of >100 devices was build up within a couple of years only and which put the technical maturity of the devices to a different level.

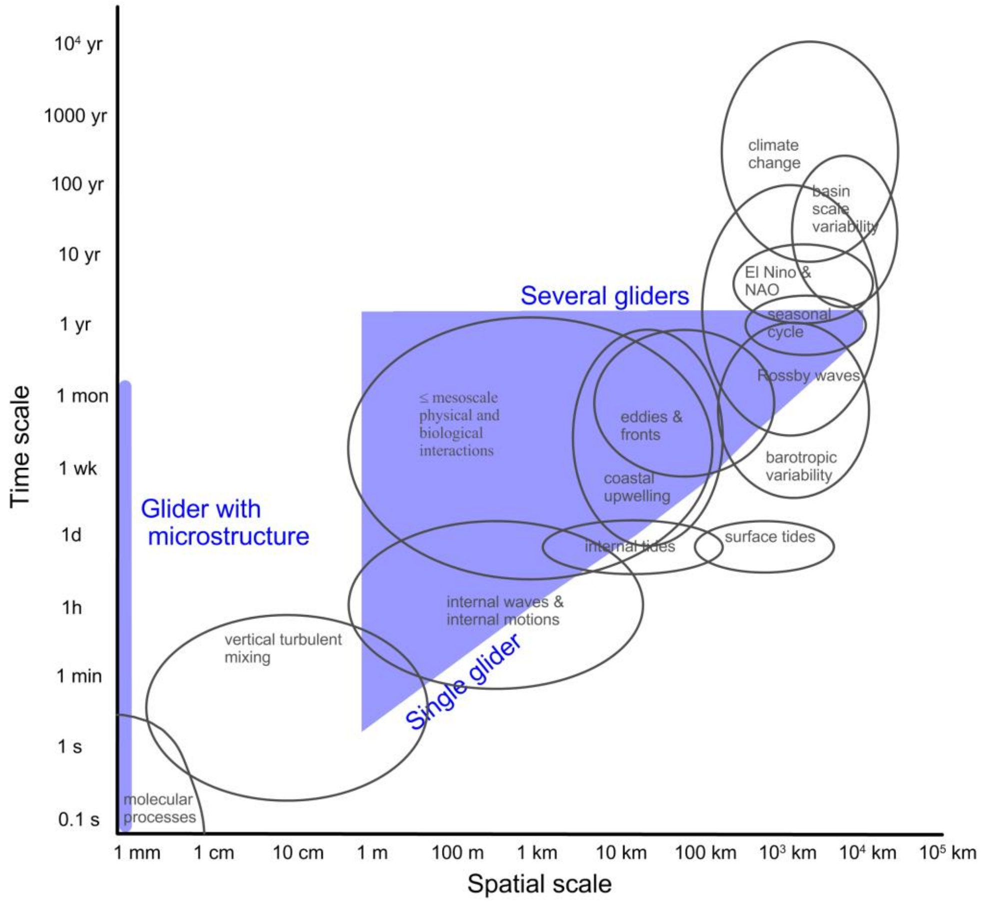

Figure 6. As Fig. 2 but for gliders.

Early design goals for a global glider network envisioned fleets of manoeuvrable autonomous ships (gliders) that would provide a comprehensive view of the interior ocean in space and time (Stommel 1989). Along with the development of glider technology and applications of gliders in ocean research over the last decade, core scientific applications can be identified (see review in appendix 1) and might fall into the following categories: endurance sections in boundary current regions, surveys of the coastal and open ocean transition zone, surveys of the mesoscale and submesoscale variability, surveys in shallow coastal areas and marginal seas, open ocean surveys in connection with existing (often moored) observatories, surveys of remote regions (e.g. high-latitudes) and in extreme environments (e.g. hurricanes), and surveys that are conducted in the context of hazards (e.g. oil spill). Note that glider data such as temperature, salinity, and dive-averaged currents can be used for model data assimilation for all mentioned categories.

Given the high-resolution vertical sampling and the wide range of sensors to be used on the platform, very successful surveys in frontal regions have revealed submesoscale variability in physical and biogeochemical tracer patterns (e.g., Niewiadomska et al. 2008; Pietri et al. 2013). Depending on the time scales of the governing processes, either single gliders or fleets of gliders are required to minimize the effect of aliasing through the quickly evolving distributions. Before the glider era, research vessels were the only platform that allowed for such mapping (e.g. scanfish surveys).

The ease of deploying gliders from coastal areas allowed endurance line applications over several cross-shelf lines and endurance lines at chokepoints in the ocean that have been operational over several years, e.g. in the California Current System (e.g. Ohman et al. 2013), Mid-Atlantic Bight (Castelao et al. 2010), Rockall Trough (Holliday and Cunningham 2013), Oregon coast (Piero et al. 2014), Western Mediterranean (Heslop et al. 2012) and Eastern Mediterrranean (Hayes et al. 2014). Moreover, the boundary regions hosts intense frontal zones where complex biophysical interaction take place and where the various sensors that can be operated on glider show it full potential.

It has been shown that severe weather conditions, such as hurricanes, do not impact the operations of gliders (e.g. Glenn et al. 2008). Moreover, they can also operate in remote locations that are difficult to access by ships. For example gliders were deployed from the edge of the sea ice into the Ross Sea polynya, enabling study of the initialisation of the spring bloom (Queste et al. 2012, Kaufman et al. 2014). Under ice operations are still very limited for gliders, though feasible to some extent (Beszczynska-Möller et al. 2011).

For specific applications a glider can be “switched” to the sampling characteristics of other observing platforms. Programming the glider to drift with currents resembles an Argo float or a drifter. Commanding a glider to continuously return to one waypoint provides data that resembles a virtual mooring/profiler. Such flight configurations are for example used for the gliders operated in the OOI. OOI manages gliders for science as part of their regional and global nodes ocean observing strategy. Given the typical service interval of 1 year for the OOI nodes, glider operations are optimized for long mission with extended drift periods (at depth). It is noteworthy that glider in OOI also operate as data shuttles, retrieving data via acoustic modem communication from moored device. The data is provided in near real-time and accessible via the OOI website (after registration).

Table 1. *Measurement characteristics of various parameters in different platforms: Horizontal resolution (dx), horizontal range (xr), vertical resolution (dz), vertical range (zr), measurement interval of sensor (sensor dt) and measurement repeat time (repeat dt). For the global arrays, such are Argo and drifters, dx implies resolution for both horizontal dimensions while for the XBT and TSG lines horizontal dimension can be determined only for the one dimension (along track). Repeat time is defined as the time interval between two measurements in processed data (surface drifters, moorings, satellites), the time interval between two profiles (Argo, lower limit in research vessels and gliders), the repeat time of section crossings (TSGs, XBTs, research vessels and gliders). Currents are not measured directly by gliders in most cases, but are derived from drift, as in surface drifters and Argo.*

Platform	dx	xr	dz	zr	dt	tr	Standard payload	Additional sensors
Argo	300 km	Global, except high latitudes	5 – 50 m	0 – 2 km	1 s	10 days	P,T,C, mean current	DO, optics
Drifters	500 km	Global, except high latitudes	-	15 m	1-2 minutes	6 hours	T, currents	SLP, C
TSG	150 m - 3 km	Certain routes	-	5 m	1 s – 1 min	12 hours - 3 months	T,C	DO, optics, current profiles, nutrients
XBT	25 - 200 km	Certain routes	10 m	1-750 m	0.1 s	3-12 weeks	T	-
R/Vs	1-100 km	Certain routes (GO-SHIP and national monitoring), otherwise survey specific	1 m	full depth	0.0005 s - 1 s	5 min - 1 decade	All, but depends on survey	All, but depends on survey
Moorings	50 km – 500 km	Selected areas	1 -1000 m	Full depth, except deepest trenches	1 s – 1 min	10 min-1 day	P, T, C, DO, optics, currents	Nutrients, radioactivity
Gliders	100 m-8 km	Survey specific	1 m	0-1500 m	1 - 5 s	5 min-1 year	P, T,C, mean current	DO, optics, current profiles, other acoustics, nutrients, turbulence

3. Potential role of gliders in GOOS

GOOS aims to ensure that critical data are collected to generate the relevant ocean information for science and society. Given the wide range of scales and processes that impact the multiple disciplines with interest in the oceans, only a combination of various observing platforms with individual strengths and limitations can serve the observational needs (Fig. 7).

It can be said that GOOS has for basic physical processes (heat content changes, surface flow) an adequate coverage of large scale sampling in the open ocean and away from boundary currents primarily through the success in establishing Argo and GDP. Many parameters at/close to the ocean surface are well monitored by multiple satellite systems (Le Traon et al. 2015).

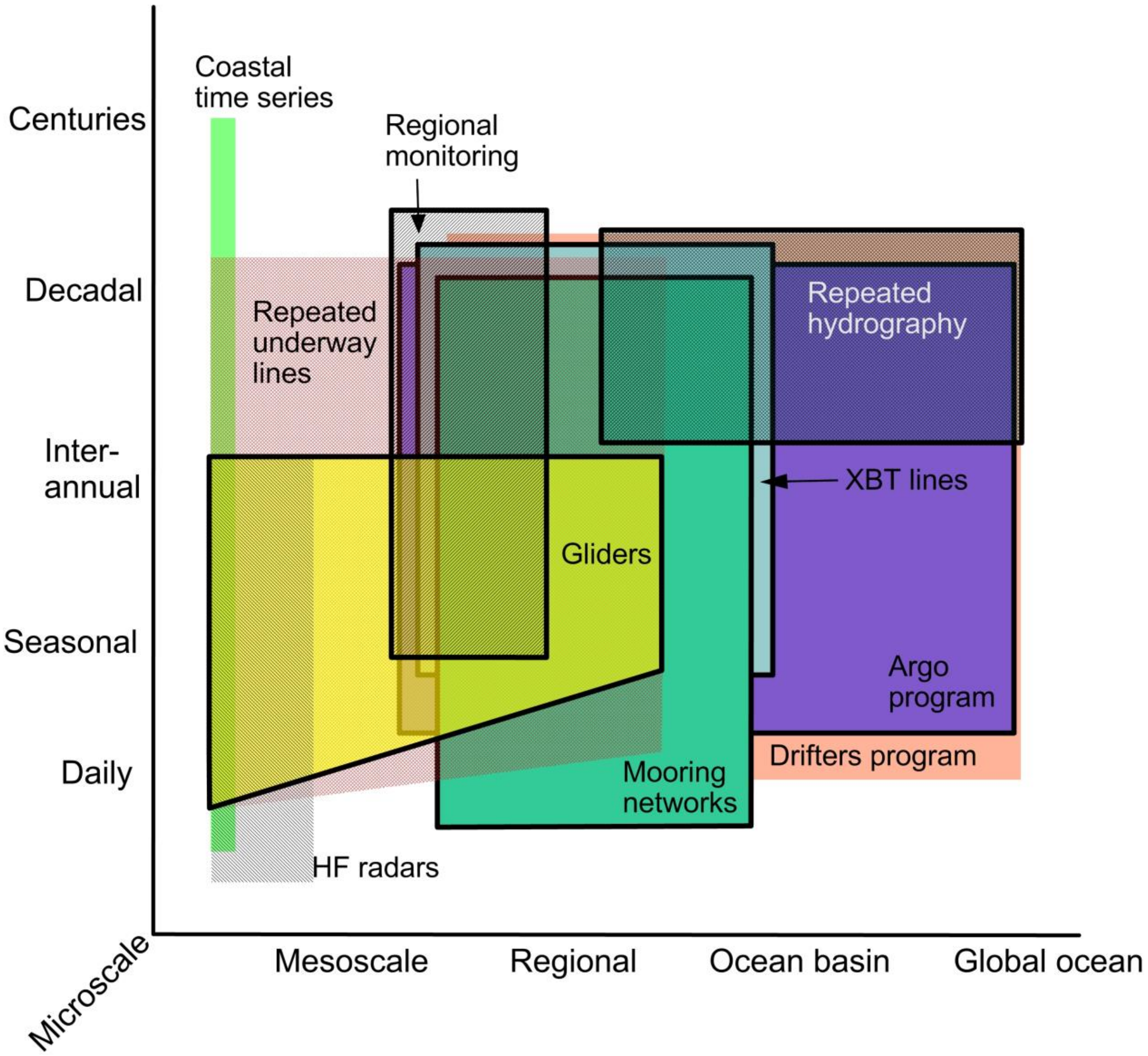

Figure 7. Spatial and temporal coverage of various observatories. Horizontal-spatial scales are represented on x-axis and temporal scales on y-axis. Systems that acquire vertical profiles are surrounded by black bold lines. As in Figures2-6 the upper limits are defined as length of time series of each platform.

Coastal areas are in some cases well monitored by national agencies (especially in the northern hemisphere) and often also in a sustained way. Coastal observations typically include research vessel visits (“regional monitoring” in Fig. 7), time-series in coastal stations, ferries, offering VOOS services (FerryBox), are a well established observing platform in European coastal seas (Hydes et al. 2010).

However, for the coastal/open ocean transition the situation looks different, and observing efforts decrease dramatically. This may related to the fact that it is also a transition between the international patronage of GOOS and national observing priorities in the coastal areas. On the other hand the obvious impact of propagating anomalies from the open ocean into the coastal areas exists (storm surges, tsunami waves, temperature anomalies, nutrient injections/oxygen decrease) and can have substantial impact on societies and economy. The transition zone, which hosts boundary currents, upwelling/ downwelling regions, physical-, biogeochemical- and biological fronts, is very rich in phenomena and consequently requires a high resolution and multidisciplinary mapping. Gliders do resolve the (sub)mesoscale in two spatial dimensions (along track and vertical) and for multiple parameters. As such they are ideal devices to map the coastal/open ocean transition subsurface structures.

Observational data for providing services (e.g. maps, boundary conditions) are expected from the coastal/open ocean transition and daily or even more frequent real-time data access is required (Legler et al. 2015). Drifters, moorings, SOOP/VOS, marine mammals, coastal time series, HF radars and gliders do provide this service. However, if vertical profiles are to be collected at targeted positions over extended periods of time, only moorings and gliders do that autonomously.

Regional expectations for the use of gliders as sustained observing platforms have been outlined by several earlier studies, for example in polar regions (Lee et al. 2010; Rintoul Speer et al. 2010; Abrahamsen 2014) or in boundary current regions (Send et al. 2010). Moreover, sustained use of gliders would enhance the present observatories in respect to monitoring global deep ocean circulation (Garzoli et al. 2010; Rintoul Balmesada et al. 2010), heat content (Palmer et al. 2010), air-sea fluxes (Gulev et al. 2010) and harmful algal blooms (Stumpf et al. 2010).

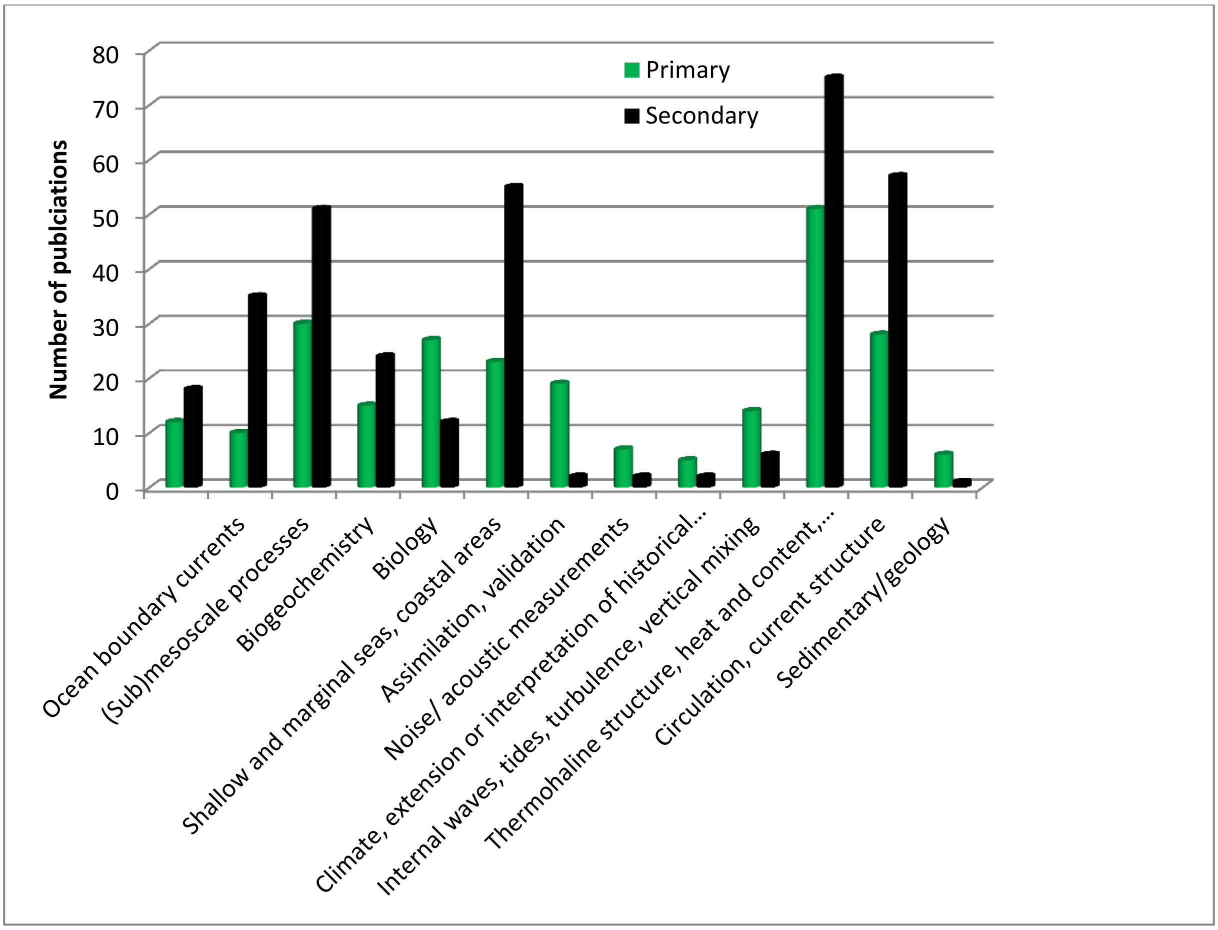

Figure 8. Primary and secondary objectives of 140 arbitrarily selected glider publications. (See further details in Appendix 1)

We performed a review of arbitrarily selected glider publications (Appendix 1) extracted primary and secondary mission objectives (Fig. 8). This review revealed that gliders are commonly applied concurrently with other measurement platforms. The highest synergy appears to be with satellite remote sensing (focussing on subsurface analysis of (sub)mesoscale processes), research vessels and moored platforms. In coastal regions gliders have been used in joint analysis with HF radar surface current. The most frequent use of glider data is in the context of hydrography and current structure analysis. Many studies are related to combining physical with biogeochemical and biological data (Fig. 8).

Thus physical-biogeochemical-biological interaction in meso- and submesoscale is one of the key topics in which gliders will contribute considerably to the GOOS and ocean science in general. Another future niche of gliders could be acoustic measurements in the ocean (e.g. Baumgartner and Fratantoni 2008; Klinck et al. 2012) as well as data shuttle functions.

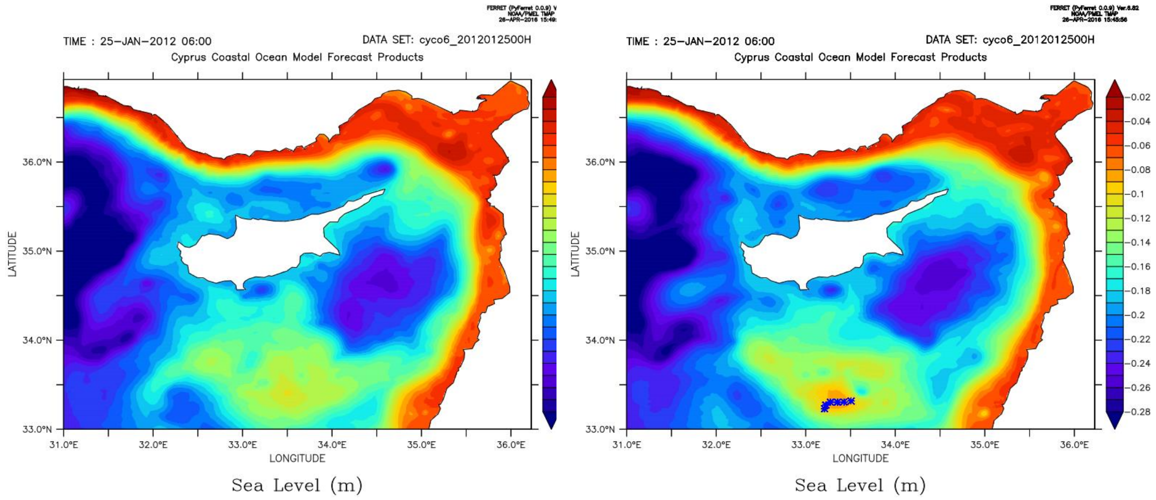

Figure 9. The sea surface height on 2012-01-24 from an experiment using the operational Cyprus Coastal Ocean Model: (right) assimilating glider temperature and salinity profiles daily, and (left) no assimilation. Glider profiles on the respective day are marked as blue points in the area between 33.0-33.5° E and 33.0-33.5° N.

Several studies have shown that assimilation of glider-acquired data enhances simulation performance. Gliders can be an effective operational tool for monitoring different processes (including hazards), either independently or in conjunction with numerical modelling and/or remote sensing. Moreover the transition of ocean forecast models and reanalysis systems towards higher resolution requires high resolution in-situ sampling. Gliders might be the only autonomously operated in-situ platform that can resolve the vertical dimension at the necessary lateral scale.

An example of how gliders can improve mesoscale forecast accuracy is shown in Fig. 9. This shows the effect of operational data assimilation of temperature and salinity profiles from a single glider on the predicted sea surface height compared to a control run. In this experiment, the Cyprus Coastal Ocean Model was run daily with the OceanVar (Dobricic and Pinardi 2008) using 2 day hindcasts, and at the same time a control run was forced with the same open and surface boundary conditions, both initialized from a coarse model in early December 2011 (just before the glider mission began). A higher sea surface height is seen in the region of observations in this case, because a warm sub-surface core in that area was detected (the well-known Cyprus eddy).

Besides delivering data that are used in operational models, alerts can be sent when patrolling areas to detect natural (toxic blooms) or anthropogenic driven (mining, dredging, oil spill) hazards. A good example is the use of gliders (among other platforms) to track the Gulf of Mexico oil spill (Lubchenco et al. 2012).

So far, gliders have been used in operations that contribute to the social benefit areas that have been worked out as part of GOOS strategic mapping (http://lists-ioc-goos.org/strategic-mapping/) and include efficient maritime economy, coastal protection, carbon storage, human health, clean waters, coastal livelihoods, tourism/cultural and food security, climate services, and mitigation of climate change.

The reliability of gliders still needs improvement. For instance the probability of a deep water glider surviving a 90-day mission is approximately 0.5 (Brito et al. 2014). The safe operation of gliders in areas with intensive marine traffic has been questioned in the past. However, glider missions that constantly adjusted their navigation guided by the information from real-time ship traffic monitoring (e.g. via Automatic Identification System, AIS) have successfully been tested and planning software has been developed to minimize this risk (L. Merckelbach, personal communication). Gliders may encounter problems when navigating in regions of strong currents and sophisticated missions planning is required. Specific software that is currently developed, can generate mission plans that take advantage of these currents to visit regions of high uncertainty (D. Hayes, personal communication).

The legal status of glider surveys has been analysed (Bork et al. 2008; Hofmann and Proelss, 2015) including the options for defining the glider vehicle as a hybrid of a surface manoeuvrable and drifting (strong currents) device. Technically, a glider is likely to be classified as SRE (Scientific Research Equipment) carrying out MSR (Marine Scientific Research). In this framework, it is generally “necessary to seek the consent of foreign coastal States for the deployment and use of a glider within the maritime zones under the jurisdiction of these states” (Hofmann and Proelss 2015).

4. Conclusions

Given the ability of gliders to survey a specific segment of the time/space and parameter domain in ocean observing they have become productive and versatile survey platforms in oceanography. This could be evaluated by analysing the primary and secondary mission objectives from a set of 140 arbitrarily selected glider publications. The specific strengths of a sustained glider component in GOOS include:

- the provision of observational data at a resolution that bridge spatial, temporal, and parameter sampling gaps that exist in the present day GOOS in particular for the socially relevant coastal/open ocean transition zone and boundary currents
- the ability of gliders to carry a variety of sensors and to acquire data of relevance for the future challenges of GOOS to include essential biogeochemical, biological and ecosystem variables
- the operational monitoring of natural hazards like toxic blooms, and of anthropogenic activities such as those associated with mining, dredging and oil spills
- the ability to provide in-situ profile data that revolves temporal and spatial scales that are of relevance in assessing or improving the skill of the currently emerging high-resolution ocean forecast models, ultimately improving operational safety of marine activities
- the ability to leverage organizational efforts that have been undertaken over the last decade to establish a globally coordinated network of glider operators who have aimed to develop a platform for training, sharing of best practices, software and hardware, as well as for standardization of operation procedures, and data management.

The close collaboration of glider operators, supported by several projects (e.g. EGO-COST Action ES0904; FP7 GROOM), allowed the creation of a well-connected international network. Out of this network, the basic actions, such as formulating an implementation plan, standardizing data protocols and data transmissions, are under preparation. A full implementation of a sustained glider component in GOOS has been initiated via the World Meteorological Organization (WMO) and UNESCO’s Intergovernmental Oceanographic

Commission (IOC) Joint Technical Commission for Oceanography and Marine Meteorology *in-situ* Observing Platform Support Centre (JCOMMOPS).

We identify two particular challenges for the global glider network: first is capacity building, including glider mission planning and execution as well as training in using glider data. The second is the coordinated planning and execution of multinational missions in a sustained mode. To address the second issue, a coordinated pilot action could be aimed for, e.g. on studies in the coastal/open ocean transition zone and embedded in existing observing projects such as CLIVAR (www.clivar.org). Only overcoming these challenges will ensure a truly global expansion of glider use for the benefit of a variety of societal and scientific areas.

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Appendix 1

Research topics in glider studies and synergy with other platforms

Glider missions have provided a considerable amount of ocean data during the last decade as for example shown from the glider data available via international data centres (Fig. A1). Likewise, the number of scientific studies in which glider data are used has substantially grown. According to Scopus database (scopus.com) 191 papers have been published (abstracts of peer-reviewed articles were searched by term “glider ocean”) during the period of 2009-2015. For earlier years (before 2009) the database gives only 28 entries (as of 25-April-2016).

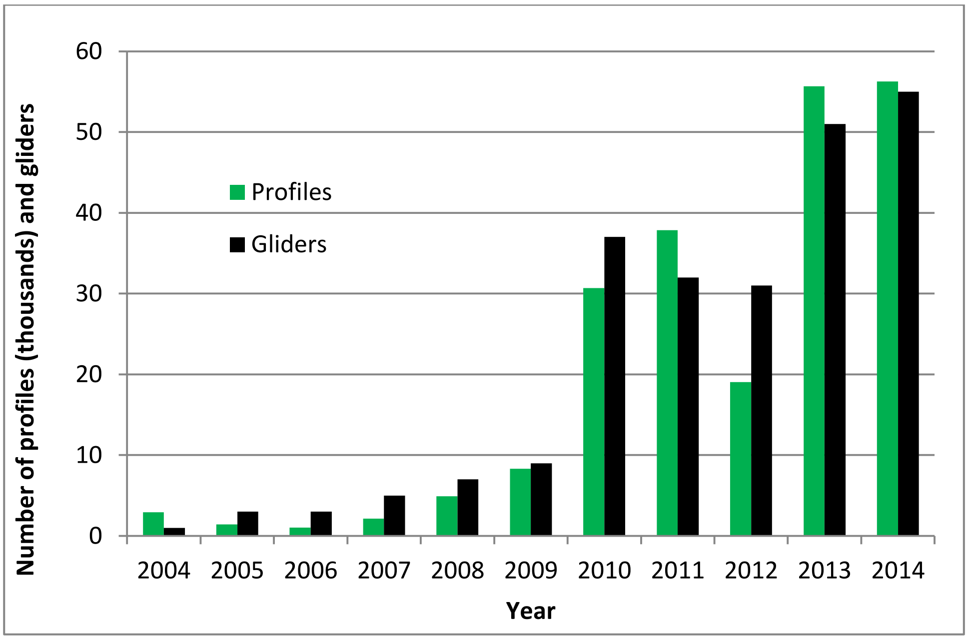

Figure A1. Glider-acquired profiles and number of gliders in Coriolis database (www.coriolis.eu.org).

140 scientific glider papers were randomly selected (from scopus.com) to map topics of glider studies and their synergy with other observing platforms. Studies focused on technical details of gliders were not included. Note that usage of a scientific database might cause slight bias or exclusion of some operational monitoring carried out for environmental or defence

applications. There are only 36 scientific papers where glider data were exclusively used, indicating that in most cases glider data are used in conjunction with other types of measurement platforms.

Overall, a combination of glider data with data from research ships was the most common combination (65 papers). This is possibly because data collected from the research vessels complemented glider data by several means: adding data that are not acquirable with a glider (e.g. currents profiling); collecting high quality data to calibrate glider sensor data; extending temporal (including historical data) and spatial coverage of data.

Glider-gathered data are often (62 papers) combined with remotely-sensed data products. Remote sensing can provide a high-resolution quasi synoptic view of the surface layer, while gliders complement that information by vertical (*in-situ*) structure of the water column (e.g. Bouffard et al. 2010; Alvarez et al. 2013).

In 40 papers gliders were used in combination with data from moorings, including coastal stations. Gliders and moorings supplement each other, as moorings are capable of collecting high-resolution temporal data over longer period while gliders can obtain a spatial picture around mooring location. Often it is difficult to identify if a local (mooring) change is related to propagating anomalies (e.g. fronts, eddies) or to local processes (e.g. vertical mixing).

In coastal regions gliders have been used in synergy with HF radars (15 papers), which can provide comprehensive spatial maps of surface waves- and current patterns, but do not gather vertical structure of the water column (e.g. Weingartner et al. 2013).

Argo (16 papers), surface drifters (5 papers) and XBT lines (6 papers) have been used in combination with glider data. In these cases, the gliders navigational capabilities allow the collection of data in targeted areas, such are boundary currents (Davis et al. 2012) or other variable areas/processes (Frajka-Williams et al. 2009), where present GOOS systems are only available at selected locations or times.

In respect to disciplines, the most popular research area of glider-studies was physical oceanography: 126 papers are directly (primary subject in 51 papers) or indirectly (secondary subject in 75 papers) addressing investigations on hydrography. A popular topic (87 papers) was circulation and current structure. There are several papers in which gliders have contributed to biological (39 papers) and biogeochemical (39 papers) studies. It is notable that

organisms in very different trophic levels (phyto- and zooplankton, fishes, marine mammals) have been investigated using gliders as the observing platform. Fish and marine mammal mapping studies have been carried out using acoustic measurements. There are not many noise/acoustic studies published yet (9 papers), but sound and anthropogenic noise in water and its consequences to the ecosystem, are generally understudied so far in the world ocean. In that respect acoustics in water might be another future niche for gliders (e.g. Klinck et al. 2012; Baumgartner and Fratantoni 2008). The further development of acoustic measurements on-board gliders may lead to increased use of gliders in geological oceanography and sedimentology (7 papers) as well.
Process studies with gliders often address mesoscale or sub-mesoscale processes (81 papers). The ability to acquire information at that scale is an important strength of gliders. Profiles a few kilometres apart can identify for example the processes of cross-frontal exchange and eddy overturning (e.g. Heywood et al. 2014; Thompson et al. 2014).

Motions at different scales like tides, internal waves and turbulence have been studied by using gliders (20 papers). Direct measurements of ocean turbulence (e.g. Beaird et al. 2012, Fer et al. 2014) have shown that a glider offers a low noise platform suitable for ocean microstructure measurements.

There are two main roles of gliders in climatological studies (7 papers): extension or complementing (e.g. Albretsen et al. 2012) of long time-series with glider data and using glider data to interpret historical time-series (e.g. Karstensen et al. 2014).

The exploitation of gliders in marginal seas or coastal areas has become common (78 papers). Some studies use glider data in the context of coastal observing systems to validate/assimilate operational models. Gliders are well established in a number of coastal observatories, such as COSYNA (Stanev et al. 2011), SOCIB (Tintoré et al. 2013), Cyprus (Hayes et al, 2011; 2014), IOOS (Willis 2013), US OOI (Schofield et al. 2010) and IMOS (Hill et al. 2010).

Model performance studies have shown (21 papers) that assimilation of the glider-collected high-resolution data into models improves the ability of simulations. For instance Dobricic et al. (2010) have documented positive impact of glider data assimilation on temperature, salinity and flow fields. They even found that positive impact of glider observation remains several months after the presence of a glider. Moreover the transition of ocean forecast models and reanalysis systems towards higher resolution (e.g. 1/12° degree is used at many centres already) requires matching high resolution in-situ sampling. While satellite and underway systems can provide very high resolution sampling at the sea surface, gliders might be the only autonomously operated in-situ platform that can resolve the vertical dimension at the necessary lateral scale.

30 published papers demonstrate that gliders can operate in high latitudes and even under ice (Beszczynska-Möller et al. 2011) to some extent. Gliders have been used quite often (45 papers) also in ocean boundary current regions (e.g. Todd et al. 2011, Davis et al. 2012, Hoydalsvik et al. 2013).

Table A1: Selected publications, where glider data is included in analysis. Topics were distinguished by importance of given study and marked as primary (P) or secondary (S). If there was another measurement platform used in a study beside glider, it is marked by x".

Publication	High-Latitudes, deep or intermediate water convection	Ocean boundary currents	(Sub)mesoscale processes	Biogeochemistry	Biology	Shallow and marginal seas, coastal areas	Assimilation, validation, data interpolation, network design	Noise/ acoustic measurements	Climate, extension or interpretation of historical data	Internal waves, tides, turbulence, vertical mixing	Thermohaline structure, heat content, freshwater content, stratification	Circulation, current structure	Sedimentary/geology		Moorings and fixed stations	Remote sensing	Research vessel	Argo	HF radars	Surface drifters or other non-profiling floats	(A)XBT
All	30	45	81	39	39	78	21	9	7	20	126	85	7		40	62	65	16	15	5	6
Primary subject	12	10	30	15	27	23	19	7	5	14	51	28	6								
Secondary subject	18	35	51	24	12	55	2	2	2	6	75	57	1								
Ainley et al. 2015	S				P												x				
Albretsen et al. 2012	S	S				P			P		P	S			x		x				
Alford et al. 2012		S	S	S	S					P	S	S			x						
Alvarez & Mourre 2012						S	P				S					x	x				
Alvarez et al. 2013			S			S	S				P	P				x	x				
Asper et al. 2011	P			S	P						S										
Baird & Ridgway 2012		S	P	S					P		S	S			x	x	x	x			
Baird et al. 2011		S	P	P	S						S	S			x	x	x	x			
Baumgartner & Fratantoni 2008					P			P			S						x				
Baumgartner et al. 2008					P			P			S						x				
Beaird et al. 2012	P		S							P	S	S					x				
Beaird et al. 2013	S	S									P	P								x	

Beszczynska-Möller et al. 2011	P	S	S								P	S			x						
Biddle et al. 2015	S			P	P						S					x					
Boettger et al. 2015			S			S				P	S										
Bosse et al. 2015			P			S					P	S				x	x	x			
Bouffard et al. 2010			P			P					S	S				x					
Bouffard et al. 2012			P			P					S	S				x					
Bourrin et al. 2015				S		S					S		P		x	x	x				
Briggs et al. 2011	S			S	P												x				
Brown et al. 2012						S					P					x	x		x		
Castelao et al. 2008			S			P					P										
Castelao et al. 2010			S			P					P										
Chao et al. 2008						P	P				S	S			x	x	x		x		
Cole and Rudnick 2012			P								P	S									
Couvelard et al. 2008		S	S				P				S	P									
Cronin et al. 2015										P	P				x		x	x			
Davis 2010			S			P					S	P									
Davis et al 2012		P									S	P									
Davis et al. 2008		P	S		S	S					P	S									
de Madron 2012			S			P					P	S			x	x	x				
Dobricic et al. 2010			S			P	P				S	S									
Domingues et al. 2015										S	P					x	x				
Evans et al. 2013	P		S	P							S						x				
Evans et al. 2013b	S		S	P		S					S						x				
Fan et al. 2013	P	S	P								S	S			x	x	x	x		x	
Farrar et al. 2015											P	S			x	x		x			
Fer et al. 2014										P	S						x				
Frajka-Williams et al. 2009	S	S	P	S	P						P	S				x					
Frajka-Williams et al. 2011	S											P									

Gangopadhyay et al. 2013			P			S	P				S	S				x			x		
Glenn et al. 2008				S		P				S	S	S	P		x				x		
Gourdeau et al. 2008		P	S								S	P					x	x			
Gower et al. 2013				S	P	P									x	x	x				
Guihen et al. 2014	S				P			P									x				
Haley Jr et al 2009		S	S			S	P				S	S				x	x		x		
Hátún et al. 2007	P	S	P								P	S				x		x			
Heslop et al. 2012			S			S					S	P			x	x	x				
Heywood et al. 2014	P		S	S						S	P	S					x				
Hodges and Fratantoni 2009		S	P		P					S	S	S				x					
Houpert et al. 2015						S			P		P						x	x			x
Hoydalsvik et al. 2013	P	S							S		P	P			x	x	x				
Hristova et al. 2014		S	P								S	S				x					
Jacox et al. 2015				P	P		P									x	x				
Johnston & Rudnick 2015						S				P	S	S									
Johnston et al. 2013		S								P	S	P			x						
Johnston et al. 2015										P	S		S								
Jones et al. 2012		S				P	P				S				x	x					
Juza et al. 2013			S			S					P	P					x	x			x
Kahl et al. 2010	S			S	P	S					S										
Karstensen et al. 2014			P			P		S			S				x	x	x				
Kaufman et al. 2014	S			P	S	S					S					x	x				
Kessler et al. 2013		S	S						S		S	P				x		x			x
Klinck et al. 2012					P	S		P													
Kohut et al. 2013	P			S	S	S					P	P			x		x				
L'Heveder et al. 2013			P					P			S										
Li et al. 2013	S		S			P	P				S	S			x		x		x		
Many et al. 2016				S		P					P		P		x	x	x				
Martin et al. 2009	S		P								S	P				x				x	

Mazzini et al. 2014		P	S			P					P	P			x	x					
Matsumoto et al. 2011								P					P								
McClatchie et al. 2012		S	S		P						S	S				x	x				
Melet et al. 2012		S					P				S	S									
Merckelbach et al. 2010												P									
Miles et al. 2013						P				S	S	S	P		x				x		
Miles et al. 2015						P					S	S	P			x					
Monteiro et al. 2015				P												x	x				
Mourre and Alvarez 2012			S			S	P				S				x	x	x				
Mourre et al. 2014						S	P				P					x					
Ngodock et al. 2014			S			S	P				S				x		x				x
Nicholson et al. 2008			S	P	S						P				x	x					
Nicholson et al. 2015				P	P						S				x						
Niewiadomska et al. 2008			P	P		S					S	S				x	x				
Ohman et al. 2013		S	S	S	S	S					S	S			x	x	x				
Oke et al. 2009		S					P				S	S							x		
Olita et al. 2014			S		P	S					P					x					
Oliver et al. 2013			P	S	P	S					S	S									
Omand et al. 2015			P	P	S						S										
Palmer et al. 2015										P	P										
Pan et al. 2014						S	P								x						
Pascual et al. 2010			P			S					S	S				x	x			x	
Pattiaratchi et al. 2010		S	S		S	S					P	S									
Pattiaratchi et al. 2011		S	S			P					P	S									
Pelland et al. 2013		S	P			S					P	S									
Pelland et al. 2014			S		P	S					S	S				x		x			
Perry et al. 2008			S	S	P	S					P					x					
Pierce et al. 2012		S		P		S			P		S						x				
Pietri et al. 2013		S	P	S		S					P	S				x	x				

Powell & Ohman 2012					P			S									x				
Powell & Ohman 2015			S	S	P	S					S	S									
Qiu et al. 2015										S	P					x					
Queste et al. 2015	S			P	S						S					x	x				
Rainville et al. 2013		S	S			S				P											
Ramp et al. 2009		S	P			S	P				S	P				x	x		x		
Ramp et al. 2011		S	S			S	S				S	P			x	x					
Rayburn et al. 2013			S			S					P						x	x			x
Rudnick and Cole 2011			S							P	P						x				
Rudnick et al. 2013										P	S	S									
Rudnick et al. 2015			P			S					S	S				x					
Ruiz et al. 2009a			P			S					P	S				x	x				
Ruiz et al. 2009b			S			S					P	P				x					
Ruiz et al. 2012			S			S				P	P	S			x						
Schaeffer and Roughan 2015		P	P			S					P										
Schaeffer et al. 2014		P	S	S	S	S					S	P			x	x			x		
Schlundt et al. 2014											P	S			x	x	x	x		x	
Schöneau & Rudnick 2015			S								S	P						x			
Schöneau et al. 2015		P									S	P					x	x			x
Seegers et al. 2015				P	P	P									x	x	x				
Sherwin et al. 2012		S		S					P		P						x				
Sherwin et al. 2015		S	P								S	P				x	x				
Shulman et al. 2009		S				P	P				S	S			x	x					
Shulman et al. 2010		S	P			P					S	P			x		x		x		
Swart et al. 2015	S		S		P						P					x	x				
Zhang et al. 2010						P	P				S	S									
Zhao et al. 2013			S	S	P	S					S	S				x	x				
Thomalla et al. 2015	S		S	S	P						S						x				
Thompson et al. 2014	P		P								P	S									

Thomsen et al. 2016			P	P		S					P	S			x	x	x				
Timmermans & Winsor 2013	S		P			S					P	S							x		
Todd et al. 2009		S	S	S	S	S					P	P			x						
Todd et al. 2011a		S	S			S					P	S									
Todd et al. 2011b		P	S			S					S	P									
Todd et al. 2012		P	S			S					P	S									
Todd et al. 2015		P									S	P									
Ullgren et al. 2014	S		S	S						P	P	S					x				
Wall et al. 2012					P	S		P			S										
Weingartner et al. 2013	P										P	S			x	x	x		x		
Venables and Meredith 2014	P					S					P						x				
Wilkin and Hunter 2013			S			S	P				S	P					x		x		
Xu et al. 2011			S	S	P	S					S	S			x	x			x		

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