The Scientific and Societal Uses of Global Measurements of Subsurface Velocity

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The Scientific and Societal Uses of Global Measurements of Subsurface Velocity

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Ocean velocity defines ocean circulation, yet the available observations of subsurface velocity are under-utilized by society. The first step to address these concerns is to improve visibility of and access to existing measurements, which include acoustic sampling from ships, subsurface float drifts, and measurements from autonomous vehicles. While multiple programs provide data publicly, the present difficulty in finding, understanding, and using these data hinder broader use by managers, the public, and other scientists. Creating links from centralized national archives to project specific websites is an easy but important way to improve data discoverability and access. A further step is to archive data in centralized databases, which increases usage by providing a common framework for disparate measurements. This requires consistent data standards and processing protocols for all types of velocity measurements. Central dissemination will also simplify the creation of derived products tailored to end user goals. Eventually, this common framework will aid managers and scientists in identifying regions that need more sampling and in identifying methods to fulfill those demands. Existing technologies are capable of improving spatial and temporal sampling, such as using ships of opportunity or from autonomous platforms like gliders, profiling floats, or Lagrangian floats. Future technological advances are needed to fill sampling gaps and increase data coverage.

Keywords: velocity, ocean measurements, subsurface, database, sampling network, ADCP, autonomous vehicle, floats

INTRODUCTION

Ocean circulation plays a critical role in the Earth's climate and biosphere through transport of heat, freshwater, momentum, nutrients, and biota. Ocean circulation, in turn, arises from ocean velocity that is driven by processes on a wide range of temporal and spatial scales. Although most of our knowledge of ocean circulation derives from indirect measurements...
MEASURING SUBSURFACE OCEAN VELOCITY

Ocean velocity is measured by a variety of techniques with differing temporospatial response. An overview of common sensors or techniques is needed to understand how to create common frameworks from disparate measurements. Selected examples (Figure 1) convey the insight provided by velocity sampling.

Sensor Techniques

Acoustic Doppler

Acoustic Doppler current measurements rely on the frequency shift of an acoustic signal when it reflects off of a moving body. Acoustic Doppler current profilers (ADCPs) transmit acoustic pulses and fit Doppler shifts to gated time bins, thus providing a profile of along-beam velocity. Acoustic beams oriented in multiple directions resolve currents in 2 or 3 dimensions. Typically, ensembles of single-ping estimates are averaged over a few minutes to improve signal-to-noise ratios. Modern systems installed on ships can typically reach 900–1200 m at 38 kHz or 50–80 m at 300 kHz, and sometimes deeper under ideal conditions. Five-beam systems with a central beam pointing upwards are available to measure vertical velocity (e.g., Guerra and Thomson, 2017).

Acoustic Doppler current profilers can be installed on fixed moorings or on moving platforms. Any platform motion present needs to be removed during processing. Moving platforms include surface ships (shipboard ADCP, sADCP, see Figure 1a), CTD rosettes (lowered ADCP; Fischer and Visbeck, 1993), or increasingly on small autonomous platforms such as subsurface gliders (Todd et al., 2017) or surface autonomous vehicles (Thomson and Girton, 2017). The depth of ADCP sampling is only constrained by its platform.

Lagrangian Tracking

Acoustic tracking of subsurface floats provides estimates of averaged Lagrangian velocity between positions fixes (see Rossby and Özgökmen, 2007). Long range acoustic tracking is possible because of a sound guide at 700–1000 m throughout much of the global ocean. This fact permits successful tracking down to 4000 m with a few moored sound sources transmitting a few times per day. When applied to tracking 10–100 floats that follow a constant pressure or seawater density surface (RAFOS floats; Levine et al., 1986; Rossby et al., 1986; Richardson, 2018), this method traces advective-diffusive pathways of water parcels over years. For example, a recent study in the deep subpolar North Atlantic (Figure 1b; Bower et al., 2009) found that the Deep Western Boundary Current is remarkably leaky to the interior basin despite being topographically trapped. This tracking method is also useful in Polar Regions where ice hinders surface tracking (Chamberlain et al., 2018). Multicycle profiling floats can also estimate their subsurface drift velocity from surface GPS fixes (Lebedev et al., 2007), typically over a 10-day interval, while frequent surface fixes track surface drifters (Lumpkin et al., 2016a).
Szuts et al. Coordinated Use of Subsurface Velocity Observations

** FIGURE 1 |** Examples of velocity data. (a) Variance ellipses from repeated Shipboard ADCP transects across the Gulf Stream (e.g., Rossby et al., 2010). Long time-series are needed to show that variability on the flanks is directed toward the center of the Gulf Stream. (b) Map of subsurface pathways from Lagrangian drifters (Bower, pers. comm.). Color shows the normalized temperature anomaly relative to the float’s initial temperature. These 2-year trajectories of RAFOS floats in the subpolar North Atlantic show how they almost exclusively leave the deep boundary-intensified southward current, and instead recirculate in the interior basin. (c) Velocity at 200 dbar (red) and 1500 dbar (blue) from electric field profiling floats in a topographically-induced meander of the Antarctic Circumpolar Current, with branches of the Antarctic Circumpolar Current from concurrent satellite altimetry shown as dashed lines (Phillips, pers. comm.). Note how vertical shear varies consistently for cyclonic (marked “C”) and anticyclonic (marked “A”) curvature, and how surface fronts are often crossed by deep trajectories.

**Point Sensors**

Point sensors are typically installed on moorings that sample regional circulation. Mooring designs have great variety depending on the research focus, and are even possible on moving sea-ice (Cole et al., 2015). When many moorings are collected into databases (Figure 2B), they provide high temporal resolution velocity that are suitable for additional purposes, from scientific (e.g., Wunsch, 1997) to societal (tracking deep oil spills in the Gulf of Mexico, e.g., Hamilton et al., 2011).

**Motional Induction**

Horizontal water velocity is obtainable by measuring oceanic electric fields caused by salt ions moving through the Earth’s magnetic field (Sanford, 1971). The relation between velocity and electric field is simple and provides a near instantaneous response anywhere in the water column. Electric field measurements are possible from multiple platforms (see review by Szuts, 2012): fixed sensors give time-series of depth-averaged velocity (Meinen et al., 2002) or transport (Larsen and Sanford, 1985; Szuts and Meinen, 2013), while implementation on expendable (Sanford et al., 1982) or multicycle profiling floats (Sanford et al., 2007; Kilbourne and Girton, 2015) provides vertical profiles of horizontal velocity. Example data in the Southern Ocean (Figure 1c; Phillips and Bindoff, 2014), shows how vertical shear in the Antarctic Circumpolar Current varies with meander curvature, and how surface streamlines identified by fronts are often crossed by deep trajectories.

**Existing Sustained Programs That Measure Ocean Velocity**

There are three categories of platforms onto which velocity sensors can be mounted: fixed in space (Eulerian), drifting with currents (Lagrangian), or self propelling. There are a few existing velocity sampling networks that are formed by a distributed array of similar platforms.

**Shipboard ADCP Records**

Oceanographic vessels are outfitted with sADCPs as standard instrumentation, and many countries archive measurements made from their research vessels. For the United States UNOLS
cargo vessels in the North Atlantic and Nordic Seas (Rossby and Flagg, 2012). Instrumenting additional commercial vessels with sADCPs would expand repeat sampling of upper ocean velocity. Additional insight can be added to such systems by expendable temperature probes (Goni et al., 2014), especially if deployed adaptively based on sADCP measurements (Rossby et al., 2011), or by adding colocated meteorological, surface ocean, and biological measurements (OceanScope, 2012).

Mooring Database
Collecting many mooring records together enables new consideration of measurements that are often collected for a specific regional purpose. One database is provided by Oregon State University1, while some long-duration programs serve data on their own sites (e.g., the 26°N RAPID Overturning Array2) or on national servers. Included in this category are mooring programs that maintain arrays intended for measuring ocean transport through a combination of velocity and density measurements (e.g., RAPID, OSNAP3, Agulhas System Climate Array4), or other techniques (Florida Current transport from cable voltages5). A sustained global array of equatorial moorings (TAO/TRITON, PIRATA, RAMA), supported by multi-national collaborations and publicly available6, is especially important to understand non-geostrophic equatorial currents and for model validation (e.g., Kessler et al., 2003).

Argo Network of Drifting Profiling Floats
Although primarily a system for measuring temperature and salinity profiles (Riser et al., 2016), the profiling floats used by Argo measure Lagrangian displacement at 1000 m over 10 days. Argo drift velocities are available from the YoMaHa07 database (Lebedev et al., 2007), which is now regularly updated and publicly available7. It is based on Argo data from the Global Data Assembly Center (GDAC)8. Detailed quality control and gridding of drift velocities are available from multiple sources (G-YoMaHa, Katsumata and Yoshinari, 2010; ANDRO, Ollitrault and Rannou, 2013; GADV, Gray and Riser, 2014).

Subsurface Float Drifts
Lagrangian tracks of RAFO-style float trajectories from many regional studies are now archived and publicly available (Ramsey et al., 2018). Originally compiled by the WOCE Subsurface Float Data Assembly Center in Woods Hole, this comprehensive database is now maintained by NOAA/AOML9. Float positions are typically at a temporal resolution of 12 h. As of the latest update (December 2017), the database had trajectories from 2,193 unique floats, half above 1000 dbar and spanning 1972–2015.

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1http://kepler.orec.orst.edu/
2http://www.rsmas.miami.edu/users/mocha
3https://www.o-snap.org
4http://beal-agulhas.rsmas.miami.edu/research/projects/asca/index.html
5http://www.aoml.noaa.gov/phod/floridacurrent/index.php
6https://www.pmel.noaa.gov/gtmba/
7http://apdrc.soest.hawaii.edu/projects/Argo/data/trjctry
8http://www.coriolis.eu.org or http://www.usgodae.org/argo
9http://www.aoml.noaa.gov/phod/float_traj
Another data repository for subsurface floats can be found at the PANGAEA data repository\textsuperscript{10}.

**RECOMMENDATIONS FOR INCREASED SOCIETAL USE OF OCEAN CURRENTS**

Direct measurements of ocean velocity provide insight into the ocean that can aid societal decisions in many domains to respond to and manage the ocean environment. There is a strong need for improving communication pathways and building dissemination infrastructure to bring together researchers and end users.

**Potential End User Applications**

Although ocean circulation is fundamental to many societal users of the marine environment, ease of use and applicability are critical for end users to be able to use velocity measurements. Developing derived products for specific applications will require joint discussion between communities.

Similar to other types of observations, velocity observations have clear uses with numerical models. The simplest use is for model validation, to quantify and improve how well models represent the real ocean. Validation can extend beyond mean velocity to include velocity variability, for example to test whether a known subsurface maximum of eddy kinetic energy is reproduced. This is similar to diagnosing Gulf Stream separation latitude based on surface maps of eddy kinetic energy. More formalized use, such as through assimilation into models (Taillandier et al., 2006), will need large advances in understanding velocity structures in space and time, or increased sampling density. One example of model improvement comes from tropical cyclone studies, where measuring the ocean response to winds with electromagnetic velocity profilers (expendable and multi-cycle) enabled an improved parameterization of wind input of momentum that has increased the skill of coupled model forecasts (Shay and Jacob, 2006; Sanford et al., 2011). The Global Drifter Program (GDP, Lumpkin et al., 2016a,b) found that derived products like monthly-averaged maps are often preferred by modelers. Once data are accessible from a single source, then derived products with more uniform spatial or temporal information will be easier to create.

Another use of ocean velocity sampling is to relate remote sensing measurements to subsurface structure (e.g., Chiswell, 2016). This is necessary now for coastal high frequency radar that measures surface currents (Paduan et al., 2004) and for satellite measurements of sea surface height, temperature, or salinity. Though global surface maps have a wide range of applications, fully understanding the subsurface ocean requires measurements in the water column. Tying subsurface velocity to surface conditions will be especially important for upcoming and proposed satellite missions that will sample the ocean at submesoscales (SWOT, US NASA/French CNES) and will potentially provide direct measurements of surface velocities (SKIM from the European Space Agency, Ardhuin et al., 2018; or WaCM from NASA in the United States of America, Chelton et al., 2018).

**Data Access**

The first step for broader use of velocity observations is better visibility and accessibility. Improving data processing and data management should receive dedicated and systematic support from funding agencies and institutions. The infrastructure for disseminating ocean velocity should be developed now, so that new and emerging capabilities to measure subsurface velocity can be fully utilized as soon as they become available.

Much progress has been made toward this goal through two newly released databases that deserve wider awareness in our community. The United States NOAA National Centers for Environmental Information (NCEI) released a Global Ocean Current Database (GOCD)\textsuperscript{11} on 21 July 2015 (Sun, 2018). The database includes measurements from shipboard ADCPs and current meter moorings, and has developed archiving formats and quality control procedures (Sun, 2015). Screen shots of coverage maps for two instrument categories (Figures 2A,B) show higher density near coasts and in the northern hemisphere. The GOCD has also created archive-ready velocity file formats suitable for many platforms and sensors. A second database, also released in the past year, archives subsurface float tracks (Ramsey et al., 2018; see description in section “Data Access”). Although studies with acoustically tracked floats have predominantly been done in the Atlantic Basin (Figure 2C) to study regional circulation, the compilation of these data now permits additional studies, from comparative analyses to basin-wide model validation studies. Additional work is needed, however, to cover more velocity sampling programs, create archiving standards for all types of velocity measurements, and, ideally, provide a common access point.

In addition to the two active subsurface velocity databases above, our suggestions are informed by the experience of two databases for surface velocity, the NOAA Global Drifter Program\textsuperscript{12} that uses low-cost GPS-tracked surface drifters (Lumpkin et al., 2016b), and a network of coastal radars for surface velocity as part of the U.S. Integrated Ocean Observing System\textsuperscript{13}. Though these two programs only sample the surface, their data dissemination strategies and user groups provide positive examples.

**Limitations of Present-Day Velocity Sampling**

Without an easy way to summarize all present sampling, it is hard to evaluate coverage of existing programs and fill potential holes in global sampling. The coverage maps (Figure 2) highlight

\textsuperscript{10}https://www.pangaea.de
\textsuperscript{11}https://www.nodc.noaa.gov/gocd/index.html
\textsuperscript{12}http://www.aoml.noaa.gov/phod/gdp/index.php
\textsuperscript{13}https://hfradar.ioos.us
the limited sampling outside of the northern hemisphere and Atlantic basin. Temporal coverage is also necessary to resolve seasonal patterns or high frequency variability that impact net fluxes or transports. The community should use existing technologies and platforms to fill these gaps in the short term, coordinated through existing or new sampling programs. Possibilities include collecting ADCP measurements from autonomous vehicles, expanding partnerships with the merchant marine community, deploying velocity profiling floats globally for long duration missions, or sampling subsurface connectivity with tracked Lagrangian floats. In the long term, we must identify new technologies, cost savings, or implementations that increase data return.

**SUMMARY OF RECOMMENDATIONS**

This article aims to increase use of subsurface ocean velocity measurements beyond their originating community to meet societal needs. The recommendations above fall into three broad categories:

**Provide Centralized Access**
- Improve visibility and accessibility of existing programs through a common access point
- Contribute, archive and disseminate data from centralized database (e.g., NCEI GOCD)
- Develop data repository standards and format converters for common methods of measuring velocity

**Identify and Meet Users Needs**
- Define end-user requirements for data formats
- Identify derived products through discussion with potential users. Examples uses include assimilation for numerical models, combining multiple data sets for model validation, interpreting surface satellite observations, or using profiler measurements to improve coupled models that forecast storm events.

**Support Data Management and Improve Sampling**
- Provide funding and institutional support for data management
- With collaborating agencies, develop data servers, data formats, format converters, and meta-data standards
- Fill observational gaps and improve spatial coverage of velocity sampling
- Apply existing technologies to fill gaps in global coverage in the short term
- Develop technology to increase velocity sampling rates, through cheaper platforms, cheaper sampling networks, or increased data return resulting from more sensor power and/or longer platform lifetimes
- Increase the amount of velocity sampling, for instance by reducing costs (of platforms, networks), improving sensors, or extending vehicle lifetimes.

We encourage scientists, research institutions, and funding agencies to support the actions above in a systematic way to improve our understanding and stewardship of the marine environment.

**AUTHOR CONTRIBUTIONS**

ZBS conceived and organized the study. ZBS, ASB, KAD, JBG, JMH, KK, RL, PBO, HEP, HTR, LKS, CS, and RET contributed to their area of expertise and to the writing and organization of the article as a whole.

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