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A climatology of the California Current System from a network of underwater gliders

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ABSTRACT

Autonomous underwater gliders offer the possibility of sustained observation of the coastal ocean. Since 2006 Spray underwater gliders in the California Underwater Glider Network (CUGN) have surveyed along California Cooperative Oceanic Fisheries Investigations (CalCOFI) lines 66.7, 80.0, and 90.0, constituting the world's longest sustained glider network, to our knowledge. In this network, gliders dive between the surface and 500 m, completing a cycle in 3 h and covering 3 km in that time. Sections extend 350–500 km offshore and take 2–3 weeks to occupy. Measured variables include pressure, temperature, salinity, and depth-average velocity. The CUGN has amassed over 10,000 glider-days, covering over 210,000 km with over 95,000 dives. These data are used to produce a climatology whose products are for each variable a mean field, an annual cycle, and the anomaly from the annual cycle. The analysis includes a weighted least-squares fit to derive the mean and annual cycle, and an objective map to produce the anomaly. The final results are variables on rectangular grids in depth, distance offshore, and time. The mean fields are finely resolved sections across the main flows in the California Current System, including the poleward California Undercurrent and the equatorward California Current. The annual cycle shows a phase change from the surface to the thermocline, reflecting the effects of air/sea fluxes at the surface and upwelling in the thermocline. The interannual anomalies are examined with an emphasis on climate events of the last ten years including the 2009–2010 El Niño, the 2010–2011 La Niña, the warm anomaly of 2014–2015, and the 2015–2016 El Niño.

1. Introduction

Eastern boundary current systems show profound effects of climate variability. An example is the California Current System (CCS), which has substantial variability on interannual to decadal time scales. This variability affects the physical environment and ultimately the biota in this very productive region. Fluctuations in fisheries off California were the motivation for the California Cooperative Oceanic Fisheries Investigations (CalCOFI), one of the longest running boundary current observational programs in the world. The need for sustained observation in boundary currents is met here through repeated deployments of underwater gliders.

Underwater gliders (Davis et al., 2003; Rudnick et al., 2004; Rudnick, 2016) are well suited for the task of observing the coastal ocean, and of bridging the coast and open ocean. The California Underwater Glider Network (CUGN) uses Spray underwater gliders (Sherman et al., 2001) performing missions of roughly 100 days, covering over 2000 km during that time while traveling at speeds of about 0.25 m s^{-1}. The gliders profile between the ocean surface and either 500 m or the bottom, whichever is shallower, with a complete dive cycle taking 3 h and covering 3 km in the horizontal. The gliders have sensors to measure pressure, temperature, salinity, chlorophyll fluorescence, acoustic backscatter, and velocity. Deployed on three of the traditional CalCOFI lines (Fig. 1.1), line 90.0 off Dana Point, line 80.0 off Point Conception, and line 66.7 off Monterey Bay, the gliders produce roughly 20–30 profiles per day. During the nearly 9 years of continuous operation, the CUGN has amassed over 10,000 glider-days, covering over 210,000 km with over 95,000 dives.

Just as underwater gliders are a successor technology to profiling floats, the regional climatology presented here is inspired by the global climatologies made possible by Argo (e.g., Roemmich and Gilson, 2009; Schmidtko et al., 2013). These climatologies are uniformly gridded products that provide convenient access to the Argo data set. By making the data easier to access, these climatologies enable the community to address scientific problems

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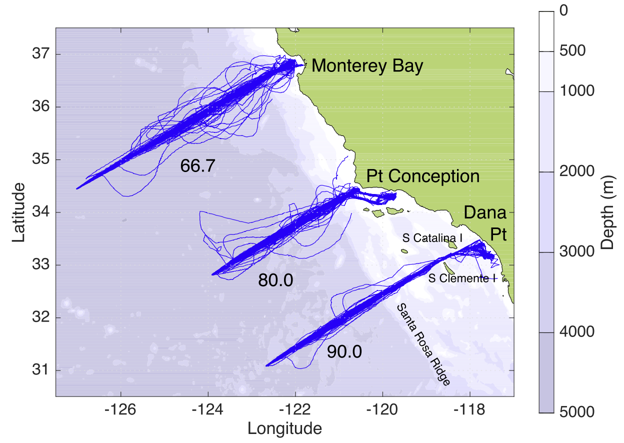

Fig. 1.1. Trajectories of underwater gliders in the California Underwater Glider Network. From north to south are lines with CalCOFI designations 66.7, 80.0, and 90.0. Geographic features mentioned in the text are labeled.

without the need to download Argo's over one million individual profiles. By the same token, the goal of our glider climatology is to enable scientific analyses of the CCS, with a particular emphasis on the mean, the annual cycle, and the interannual variability. The climatology on each of the three lines is produced as a function of depth, along-line distance, and time. This first effort at a climatology focuses on the physical variables of temperature, salinity, and velocity.

The CalCOFI program is in many ways the gold standard for sustained observation of a coastal region (McClatchie, 2014). The CalCOFI program has its roots in surveys dating back to the 1930s by H.U. Sverdrup and colleagues at Scripps Institution of Oceanography as reported in the seminal volume "The Oceans" (Sverdrup et al., 1942). Regular sampling on a standard fixed grid began in 1951, constituting the start of the CalCOFI time series. The current survey has 75 stations sampled quarterly on 6 lines oriented approximately normal to the coastline. The lines are 40 nautical miles apart, and station spacing along the lines is 40 nautical miles offshore, and progressively finer towards shore. Perhaps the most impressive aspect of CalCOFI observations is the sheer number of variables measured, including quantities relevant to the physics and chemistry, and all trophic levels from phytoplankton to zooplankton, fish, marine birds and mammals. The duration and richness of the CalCOFI program provides an excellent background for the evaluation of underwater gliders as a measurement technology.

The data contributing to the climatology have been reported in several scientific publications. The first comprehensive publication, within two years of the start of sustained deployments of our Spray gliders, focused on the mesoscale structures in the CCS (Davis et al., 2008). The gliders' absolute depth-average velocity, estimated by dead reckoning between GPS fixes at the beginning and end of dives, provide a reference for both geostrophic and Doppler measurements of velocity. In this way, Davis et al. (2008) discovered a deep poleward flow in the Southern California Bight. The poleward flows were revisited by Todd et al. (2011b), with the benefit of over three years of continuous observations and using the results of a regional model that assimilated the glider data, who showed that a dominant source of variability was annually occurring westward propagating Rossby waves. The combination of glider data and a regional model were used to examine persistent layers of thermohaline variability (Todd et al., 2012), demonstrating a particular strength of gliders for sustained observations of fine horizontal scales. The 2009–2010 El Niño was the first observed by gliders (Todd et al., 2011a), which also was the first objective analysis of these data as in the climatology presented here. The anomalous warming of 2014–2015 was described (Zaba and Rudnick, 2016) using a recent version of the climatology. These data contributed to a comparative study of climate variability using an assimilating model (Jacox et al., 2016). The past year (2015–2016) has seen the strongest El Niño since 1997–1998 (Lynn and Bograd, 2002), and the effects on the CCS are reported here.

The paper is organized as follows. The essentials of Spray gliders and the data they produce are presented in Section 2. The methods used to analyze these data are the topic of Section 3. The bulk of the paper, Section 4, is the presentation of the results in a form similar to an atlas organized first by time scale (mean, annual cycle, interannual anomaly) and then by glider line. A discussion of the results with reference especially to the recent (2014–2016) anomalies is in Section 5. Some brief concluding remarks are in Section 6.

2. Gliders and data

Relevant aspects of Spray underwater gliders (Sherman et al., 2001) and the data produced by them are summarized to aid in understanding what gliders can deliver. Underwater gliders (Davis et al., 2003; Rudnick et al., 2004; Rudnick, 2016) are essentially profile generating machines, much like profiling floats, except the horizontal position of the profiles is controllable within the limitations imposed by glider speed and ocean currents. The ocean current that matters is what the glider experiences over the course of the dive, which, given the glider's usually symmetric dive trajectory, is essentially a depth-average. In the relatively weak flows of an eastern boundary current, as in the CCS, the gliders are able to travel reliably along defined lines (Fig. 1.1). A glider's trajectory through the water is a saw tooth (Rudnick and Cole, 2011), with the angle to the horizontal of about 20°. Moving at a horizontal speed of about 0.25 m s^{-1}, the gliders are typically able to complete a section in about 2–3 weeks.

The gliders carry a conductivity-temperature-depth sensor (CTD), for which the data collection and processing are described below. The CTD is a Sea-Bird 41CP pumped at about 10 cm^3 s^{-1}. The CTD is sampled every 8 s, yielding vertical resolution of about 0.8 at the vertical profiling speed of approximately 0.1 m s^{-1}. The inlet to the CTD is mounted on top of the glider, so it receives clean flow during ascent. All sensors are run only on ascent because the CTD data are superior, and to save power. While running the sensors on both ascent and descent would double horizontal resolution at the midpoint of the profile, there is no improvement in resolution at the top and bottom. Tributyltin inserts at the inlet and outlet of the plumbed stream help to control biofouling. The CTD is turned off at 2 m on ascent to avoid the ingestion of floating material. CTD data sent back by satellite during a mission are averaged over 3–4 samples to limit the amount of communication, both to manage costs and to minimize time at the surface. The data set therefore includes finer vertical resolution for completed missions than it does for active missions.

Quality control involves both automatic and manual components. Navigational data (time, latitude, longitude) from the GPS are subjected to automatic quality control based on measures like how far the glider could reasonably move during a dive. The navigational data are then flagged and corrected. Upon recovery, this automatic quality control is checked manually. Quality control on CTD data is performed after recovery, consisting of an automatic highlighting of possibly bad data, and manual flagging of individual data points profile by profile. CTD data from actively deployed gliders are included in the climatology, although these have not yet been subjected to manual quality control. Thus the climatology is