Underwater Glider Observations in the Oxygen Minimum Zone off Central Chile

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Worldwide, the use of autonomous underwater gliders has spread rapidly, and they have become an important tool in ocean observing systems. Most gliders are equipped with sensors that can measure the physical and biogeochemical properties of the seawater in the first kilometer of the ocean. Small changes in buoyancy allow underwater gliders to move horizontally and vertically by controlling the dive and climb angles and the horizontal direction (Sherman et al. 2001; Davis et al. 2003; Rudnick et al. 2004). Gliders can cover relatively large distances with very low power consumption. The standard scientific equipment carried onboard many ocean gliders includes conductivity, temperature, and depth (CTD) and optical biogeochemical sensors for reading dissolved oxygen, fluorescence, and turbidity levels. Recently, new instruments and sensors such as probes for turbulent microstructure measurements (e.g., Wolk et al. 2009; Palmer et al. 2015) and small current profilers that use acoustic Doppler (e.g., Todd et al. 2011; Siegel and Rusello 2013) have been developed to be used in gliders. Similarly, other new sensors are rapidly being adapted or developed to be mounted on underwater gliders. Presently, many gliders are equipped with oxygen sensors, and they are being used to explore and monitor different oxygen minimum zones (OMZs) around the world.

OMZs are oceanic regions in which waters at upper intermediate depths (~100 to ~800 m) present dissolved oxygen (DO) concentrations persistently lower than ~0.5 mL L⁻¹ (20 µmol kg⁻¹; Kamykowski and Zentara 1990). OMZs result from a combination of ventilation, organic matter respiration, and water-mass age. Their main ventilation occurs remotely in places where the characteristic water mass is formed (i.e., where it is last in direct contact with the atmosphere). Oxygen consumption, on the other hand, results mainly from the microbial aerobic oxidation of organic matter that takes place continuously within a water mass as it travels through the global ocean at depth. Consequently, for a given respiration rate, older water masses should have lower DO values (Karstensen et al. 2008).

Major modern oceanic OMZs are located in the Arabian Sea and in the eastern boundary of the Pacific Ocean (Kamykowski and Zentara 1990). They have become relevant in the context of global change, since models predict a significant reduction of DO in the ocean’s interior and, consequently, their intensification and expansion (Metear and Hirst 2003; Schmittner et al. 2008). Such changes should impact marine ecosystems (Grantham et al. 2004) as well as global biogeochemical cycles (Codispoti 2010). Analyses of historical data appear to support the predictions of reductions in the DO content in the tropical open ocean (Stramma et al. 2008) and in coastal ecosystems (Grantham et al. 2004). However, current ocean
models, which include the main anaerobic processes, are limited in their ability to reproduce DO variability—that is, the distribution and intensity of the OMZ (Najjar et al. 2007; Keeling et al. 2010). Moreover, anaerobic processes alone cannot account for the nitrogen cycling that takes place within the oxygen-depleted waters (Lipschultz et al. 1990; Lam et al. 2009). One of the limitations to understanding the dynamics of OMZ has been the inability to carry out observations with enough temporal and spatial resolution to evaluate the persistence of oxygen-depleted waters, seasonal and higher frequency changes, and the importance of energetic oceanographic processes like mesoscale eddies that contribute to mixing and the ventilation of the OMZ.

Underwater gliders offer a unique opportunity to sample the OMZ with relatively high resolution without using costly oceanographic platforms. Observations made with gliders have been carried out in different regions off Chile since 2009, including the OMZ. Herein, we show observations carried out by the underwater glider group at the University of Concepcion in the southern tip of the OMZ off central Chile and describe new observational initiatives using underwater gliders in the eastern South Pacific for the coming years.

**MEASUREMENTS OF THE OXYGEN MINIMUM ZONE OFF CENTRAL CHILE.**

In the eastern subtropical South Pacific, the OMZ is a permanent feature that extends along the western coast off South America between ~50-m and 800-m depth. Its intensity and vertical and horizontal extension vary along the coast (Fuenzalida et al. 2009; Llanillo et al. 2012), but this layer can be tracked as far south as ~48°S (Silva and Neshyba 1979), with a core centered between 200- and 300-m depth. Off central Chile, the OMZ is located on top of the relatively well-ventilated Antarctic Intermediate Water. The OMZ is more intense near the coast than farther offshore and, on average, it extends several km offshore off central Chile (Fuenzalida et al. 2009). During the upwelling season, its upper boundary is shallow (25-50-m depth), and oxygen-depleted waters may cover a large fraction of the continental shelf (e.g., Paulmier et al. 2006; Sobarzo et al. 2007; Paulmier and Ruiz-Pino 2009). The high productivity observed near the coast may generate local minima of DO when the degradation of organic matter induces intense oxygen consumption (Paulmier et al. 2006).

A nominal transect of about 150–180 km in length has been repeated on several occasions off Concepción (36°30’S) since 2009 (Fig. 1) using Teledyne Webb research Electric Slocum gliders (rated for 1,000-m depth). The horizontal speed of the deep Slocum glider, relative to the water, is nominally ~40 cm s⁻¹ (using a dive angle of 26°; the maximum change in volume of these gliders is 500 cc and their total volume is 56 L). Our own estimates, based on different glider missions, show similar velocities when the glider is far enough from the surface (or from the maximum diving depth), despite the fact that speed depends on the net buoyancy of the glider, set by the ballasting. As the underwater glider can reach ~1,000-m depth, we have been able to sample the entire vertical structure of the OMZ off central Chile.

Gliders were equipped with optical oxygen sensors (Aanderaa Data Instrument oxygen optode model 3830), which are regularly checked in our laboratory using a two-point calibration curve by using one solution of 0% oxygen and one that was 100% saturated with air. Details of the sensor and the physical principles involved in the measurements are described in Körtzinger et al. (2005) and Uchida...
et al. (2008). For the calculation of DO, a fourth-order polynomial in P is used, where the polynomial coefficient C depends on temperature. The time constant of the temperature sensor from the optode is large (~15 s), even for the slow vertical velocity of the glider (~0.2 m s$^{-1}$). In regions with large vertical temperature gradients (e.g., the thermocline), it may be better to use the much faster, more precise temperature sensor from the CTD to calculate DO in the glider. Unfortunately, we did not record the phase P data from the optode sensor for the measurements taken prior to January 2014. Thus, oxygen data were calculated from the optode temperature sensor. Salinity and pressure corrections were estimated based on the polynomial given by Aanderaa.

The new glider data enable us to estimate the offshore extent of the OMZ off Concepción and to visualize its large spatial variability (Fig. 2). Some of this variability seems to be related to mesoscale eddy activity that transports coastal waters from the OMZ offshore (e.g., Hormazabal et al. 2013). Note the close relationship between the minimum oxygen and maximum salinity values (Fig. 2). As salinity acts like a passive tracer, much of the water observed offshore in the core of the OMZ is related to high-salinity Equatorial Subsurface Water (ESSW), which dominates the subsurface waters over the continental shelf and upper slope.

The new dataset also allows us to describe the seasonal change in DO off Concepción (Fig. 3). Large changes in DO occur over the continental shelf and offshore. The total volume, per unit of width, of water with very low DO (< 1 mL L$^{-1}$) observed in March 2011 was about twice that of the volume observed in June and September 2010. These changes are related to changes in the poleward Peru-Chile Undercurrent, which modulates the transport of ESSW (a water mass characterized by very low DO) along with the intense mesoscale variability observed in this zone.

During the austral summer of 2010–11, La Niña conditions prevailed in the tropical Pacific. Off central Chile, interannual winds showed positive (upwelling favorable) anomalies during all of 2010. Interannual coastal sea level anomalies were consistently negative. Nevertheless, during 2011, interannual alongshore wind anomalies decreased and small negative
(downwelling favorable) anomalies prevailed during the second half of 2011. On the other hand, sea level anomalies in Concepción were rather small, but still negative, during 2011. Interannual sea level anomalies off central Chile are inversely related to changes in the poleward subsurface flow (negative sea level anomalies are followed by a weakening of the subsurface poleward flow; Pizarro et al. 2001). As this flow transports low oxygen water southward off Chile, it also can modulate the intensity and offshore extension of the OMZ off Concepción.

Although the sea level suggested that the poleward flow was anomalously weak, direct current observations from the shelf break at 36°33’S (Fig. 4) showed that the glider transect of March 2011, which showed very low values of oxygen with a much longer extension offshore (Fig. 3), took place just after an intense event of subsurface poleward flow (see stick diagrams of the current below 80-m depth in Fig. 4). This event lasted from the last week of January to the middle of March. The poleward current shows intraseasonal variability probably related to coastal trapped waves. These intraseasonal waves largely modulate the variability of the Peru-Chile Undercurrent over the continental shelf and slope off Peru (Huyer et al. 1991) and Chile (Shaff er et al. 1997; Pizarro et al. 2002), and may also contribute to the modulation of the OMZ variability off central Chile. Additional current and oxygen measurements based on moored sensors (not shown here) over the continental shelf off Concepción support this idea.

Near the coast, the distributions of oxygen, salinity, and temperature show the effects of seasonal variability in upwelling (Fig. 2). In summer, the oxycline rises over the continental shelf and hypoxic water, unsuitable for fish and other species, occupies most of the water column. Figure 2 (left panels) shows a front near the surface over the shelf break. This front seems to be related to the cold water upwelled off Punta Lavapie, which is then transported northward by a coastal jet that flows along the shelf break (Fig. 1a; see also Letelier et al. 2009 and Aguirre et al. 2012). Note that the upwelled
waters near the coast have relatively higher salinities than the offshore waters, consistent with the idea that ESSW is one of the main water sources for upwelling off Concepción.

In the frontal region and over the outer shelf, surface waters are slightly saltier than the waters located immediately shoreward, over the midshelf, consistent with the presence of a coastal jet that transports upwelling waters northward from Punta Lavapie, as suggested by the cooler tongue visible in the satellite SST image (Fig. 1, left). These are some of the specific features observed in the ocean off Concepción. A detailed analysis and discussion of these features is beyond the scope of the present note. However, further studies detailing the different topics delineated above are presently in development.

**OBSERVING THE OCEAN OFF CENTRAL CHILE WITH GLIDERS: FUTURE PLANS.**

Since late 2002, a monthly, ship-based, oceanographic time series has been maintained on the continental shelf off Concepción (36.5°S), a well-known zone of intense coastal upwelling. This time series includes a core suite of physical, biological, and biogeochemical parameters and has been the basis for a number of oceanographic studies (e.g., Escribano and Morales 2012). This program has also provided the opportunity for graduate and undergraduate students to conduct thesis research and in situ experiments.

Nevertheless, vast oceanic regions of the eastern South Pacific off Chile remain very poorly sampled. As part of the activities of the recently created Millennium Institute of Oceanography (IMO), a new center for oceanographic research about the southeastern Pacific Ocean, we plan to carry out repeated glider sections twice a year (Fig. 5), extending from Robinson Crusoe Island (~33°40’S, 78°40’W in the Juan Fernandez archipelago) to Concepción Bay at the continent coast (~36°30’S). The transect extends for approximately 600 km and will take about 1 month to complete.

These glider-based time series will make it possible to address a variety of new research problems. Interannual changes occur in the transport of the different flows conforming the Peru-Chile Current System, as do changes in water mass composition, including Antarctic Intermediate Water and the southern tip of the OMZ. Important interannual changes are expected to occur associated with the El Niño-La Niña cycles. Mesoscale eddies transport coastal waters westward (Hormazabal et al. 2013) with very low DO and relatively high salinity (Fig. 2, right panels). This eddy-induced transport may play an important role in shaping the OMZ off Chile. The time series of glider transects will make it possible to address a variety of new research problems. Interannual changes occur in the transport of the different flows conforming the Peru-Chile Current System, as do changes in water mass composition, including Antarctic Intermediate Water and the southern tip of the OMZ. Important interannual changes are expected to occur associated with the El Niño-La Niña cycles. Mesoscale eddies transport coastal waters westward (Hormazabal et al. 2013) with very low DO and relatively high salinity (Fig. 2, right panels). This eddy-induced transport may play an important role in shaping the OMZ off Chile.

The glider transects are initially planned to be occupied twice a year. They are mainly intended to analyze the spatial structure of mesoscale eddies and seasonal and interannual changes in transport, temperature, salinity, and dissolved oxygen in the upper kilometer of the ocean. Seasonal and interannual ocean variability off south central Chile remains poorly explored. Our concept of the oceanic circulation and water mass variability in this region rests in a few sparse oceanographic observations, and its estimates are very uncertain. We think this glider observing program will contribute to reducing these uncertainties. The glider observations will also complement the monthly time series oriented to study the coastal upwelling cell over the continental shelf near 36°30’S (i.e., at the coastal extreme of the glider transect). Furthermore, an oceanic mooring near Robinson Crusoe Island, at the other extreme of the glider transect, has been recently (October 2015) deployed by IMO. Another deep ocean mooring, at 75°W close to the glider path, will be deployed during 2017. These moorings (equipped with current, temperature, conductivity, and oxygen sensors) are planned to be maintained for several years, making it possible to analyze temporal variability associated with...
with mesoscale eddies and the seasonal cycle of the flows (along with other high-frequency processes). These time series will greatly complement the high spatial resolution observations from the ocean gliders.

The new oceanographic data collected by the gliders will be available to the entire scientific community, helping to validate regional model simulations. We also expect to motivate young researchers and graduate students to analyze regional oceanographic problems, and we would also like to contribute to the global oceanic observing systems.

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For Further Reading


Llanillo, P. J., J. L. Pelegrí, C. M. Duarte, M. Eme- lianov, M. Gasser, J. Gourrion, and A. Rodriguez-Santana, 2012: Cambios latitudinales y zonales en...


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