Long-term glider observations of temperature, salinity, and dissolved oxygen in the California Current System

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ABSTRACT

Sustained observations of the central and southern California Current System have been made by the California Underwater Glider Network (CUGN) since 2006. Glider observations along three across-shore transects, line 66.7, 80.0, and 90.0, have allowed for calculations of temperature and salinity anomalies since 2006, including interannual variations in ocean temperature and salinity. A high salinity extreme was observed from 2017-2019 while high temperatures were observed from 2014-2019. Subsurface salinity and temperature anomalies are observed to propagate offshore, evidence of subthermocline eddies that are important for the transport of coastal water masses. A new addition to the sustained observing system of CUGN is the regular measurement of dissolved oxygen. Calibrated dissolved oxygen observations since December 2016 have been used to analyze the seasonal cycle. CUGN now has the ability to monitor interannual variations in dissolved oxygen in the California Current System.

Methods

Underwater gliders are buoyancy-driven machines that can collect profile data while also navigating through the ocean on a set path. They can sample for the timescale of months and take profiles with horizontal resolution of a few kilometers and provide information in the depth dimension. Glider propulsion is driven by a pump on board that pushes oil into and out of an external bladder, therefore changing the density or buoyancy of the vehicle. Changes in buoyancy cause vertical movement in the water column and wings allow for horizontal motion.

In the California Current System (CCS), gliders are programmed to profile to 500 m depth, and the saw-tooth or "v" pattern the glider makes through the water sets the horizontal speed of the glider which is 0.25 m s^{-1}. The gliders generate profiles to 500 m depth at 3-km spatial and 3-hour temporal resolution. As the CCS is an eastern boundary current system which has relatively weak mean currents, the gliders there do well to sample along transects. With a network of gliders, transect lines can be monitored continuously. When used to repeatedly sample along one transect, gliders can be used to monitor for ocean changes in the section over time.

Data from 2006-2013 for temperature and salinity were used to make an annual cycle and interannual anomalies of properties (Rudnick et al. 2017). Interannual anomalies were investigated for the period 2006-2019 to understand a salt extreme and subthermocline eddies. An annual cycle from 2017-2021 using calibrated glider dissolved oxygen observations (Ren et al. 2023) was used to study the annual cycle of oxygen including air-sea gas exchange.

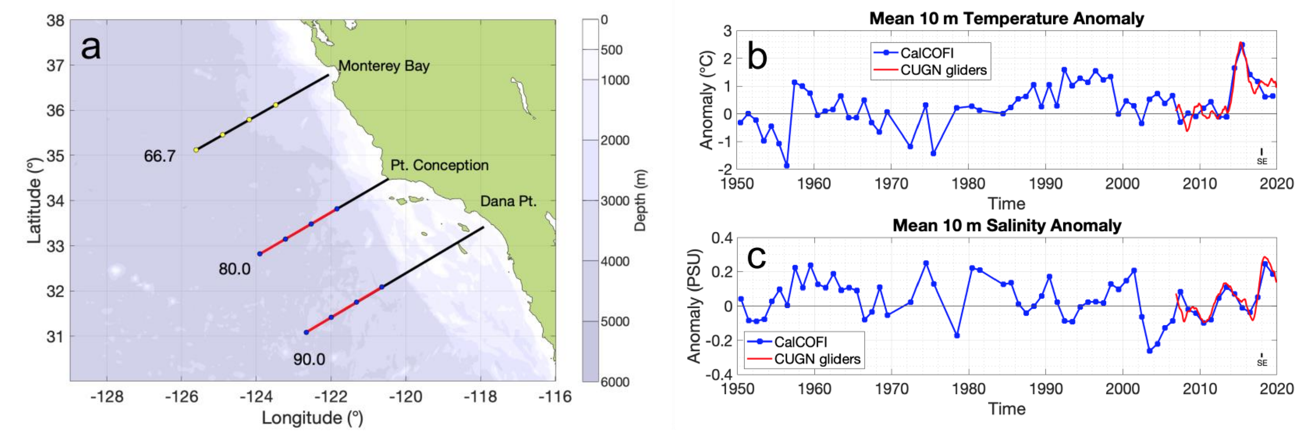
Coastal Observation

The resolution in time and space of observations from a network of gliders like CUGN allows for studying questions from the mesoscale, or the Rossby radius, to the large scale, such as an eastern boundary current like the California Current. In addition, CUGN has approaching 20 years of continuous observation at 3-km and 3-hour resolution, allowing for study of climate variability. Integration of biogeochemical variables like dissolved oxygen will mean that variables related to ecosystem health can be monitored on interannual and long-term timescales.

The California Current System

The CCS is the eastern boundary current system of the north Pacific Ocean. All eastern boundary current systems have upwelling caused by equatorward winds which cause offshore Ekman transport and divergence at the coast. In the CCS, the California Current flows equatorward as a surface intensified current generally offshore of 150 km from the coast while the California Undercurrent flows poleward and is the mean flow within 150 km of the coast (Rudnick et al., 2017). El Nino is a large driver of interannual variability. Recently, marine heat waves in 2014-2016 and 2019-2020 have affected the CCS, with warmer than average temperatures impacting marine life.

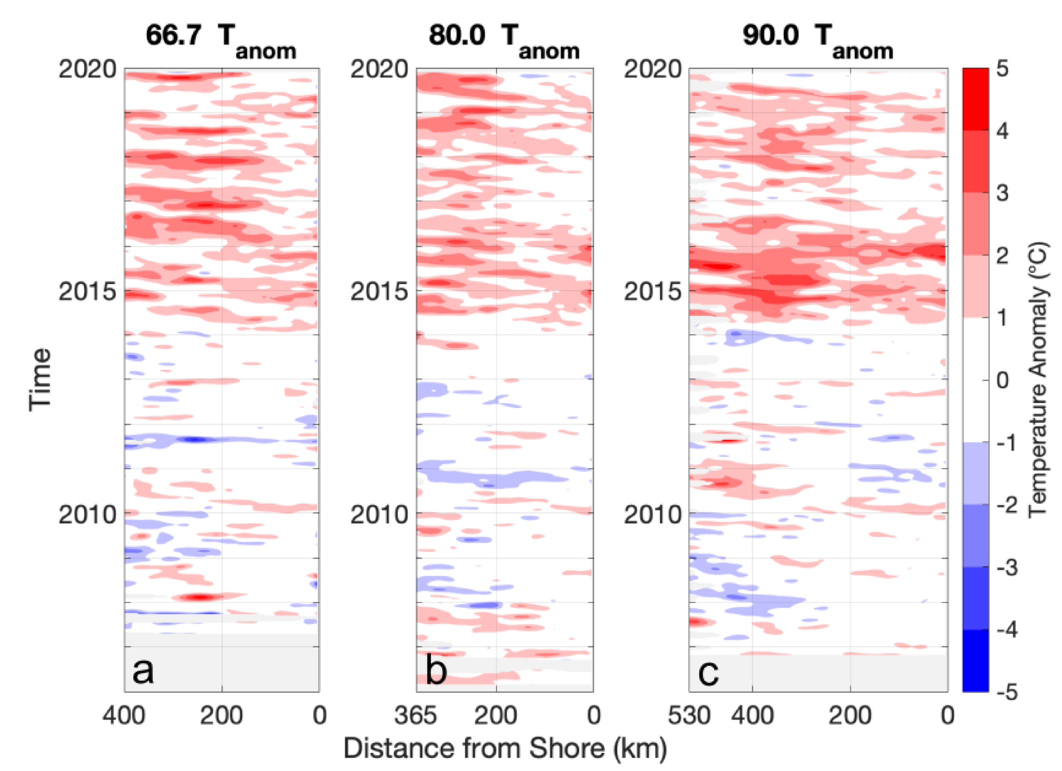
Ren, A. S., Rudnick, D. L., & Twombly, A. (2023). Drift characteristics of Sea-Bird dissolved oxygen optode sensors. *Journal of Atmospheric and Oceanic Technology*, *40*(12), 1645-1656.
Rudnick, D. L., Zaba, K. D., Todd, R. E., & Davis, R. E. (2017). A climatology of the California Current System from a network of underwater gliders. *Progress in Oceanography*, *154*, 64-106.



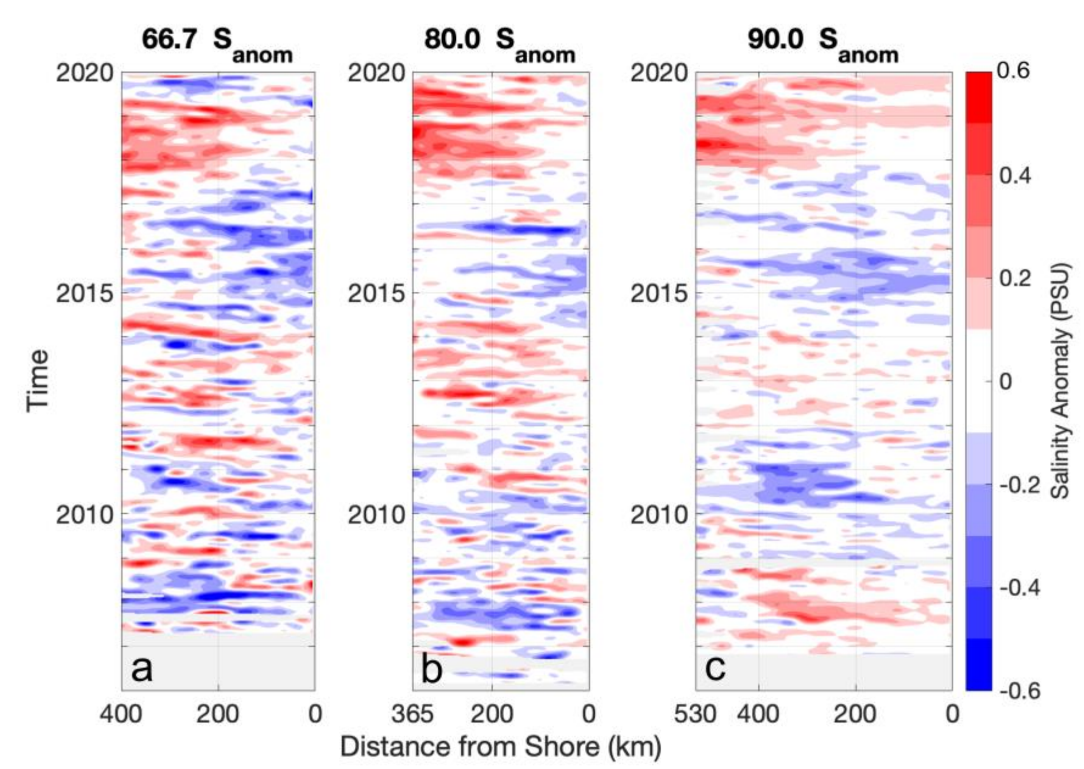
Domain and time-series of temperature and salinity anomalies at 10-m in offshore regions.

Temperature and Salinity Extremes from 2007-2019

Glider observations show warming from 2014-2019 and a high salinity anomaly from 2017-2019.



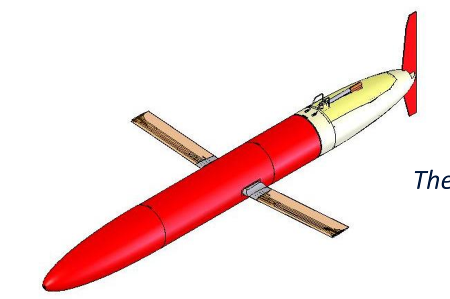
Upper 100-m averaged temperature anomalies along three transect lines, 66.7, 80.0, and 90.0 compared to the mean from 2007-2013.



Upper 100-m averaged salinity anomalies along three transect lines, 66.7, 80.0, and 90.0 compared to the mean from 2007-2013.

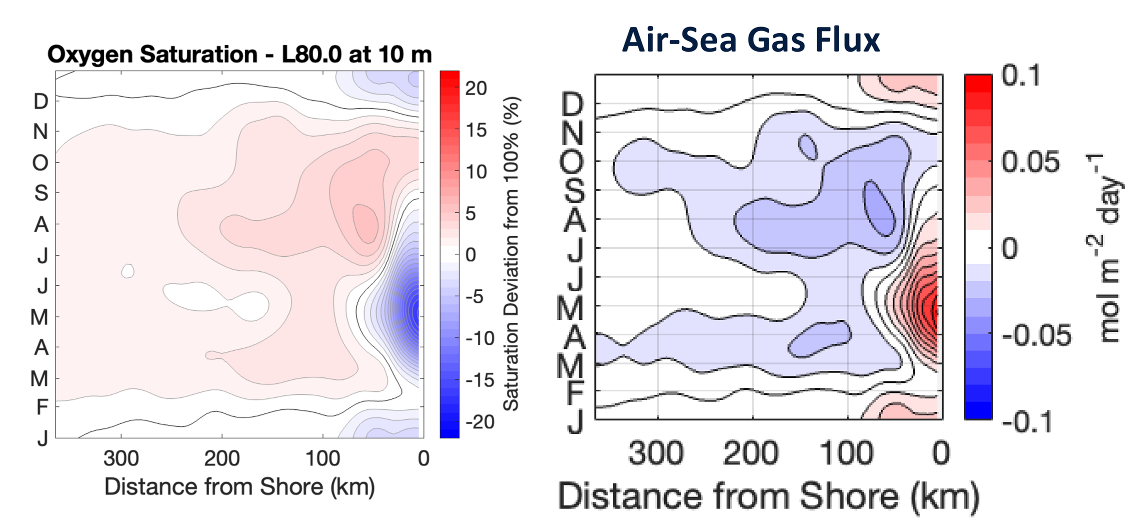
Ren, A. S., & Rudnick, D. L. (2021). Temperature and salinity extremes from 2014-2019 in the California Current System and its source waters. *Communications Earth & Environment*, *2*(1), 1-9.

Annual Cycle of Coastal Dissolved Oxygen

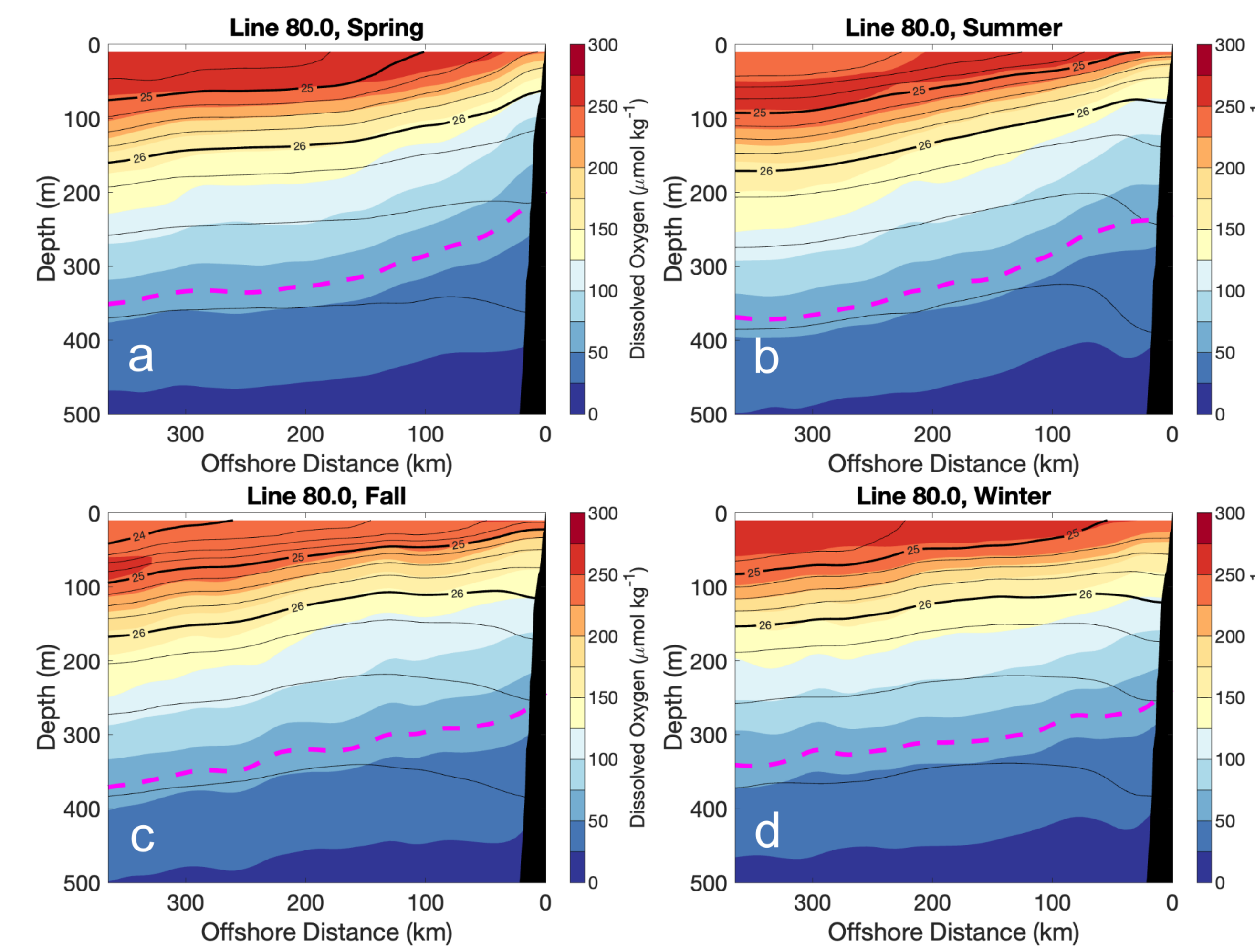


The spray glider

Calibrated dissolved oxygen observations from 2017-2021 are used to study the seasonal dynamics of coastal upwelling. The CCS is prone to hypoxic conditions, defined as an oxygen concentration that has negative effects on marine organisms. Air-sea interactions, biological processes, and ocean dynamics all influence dissolved oxygen in the CCS.

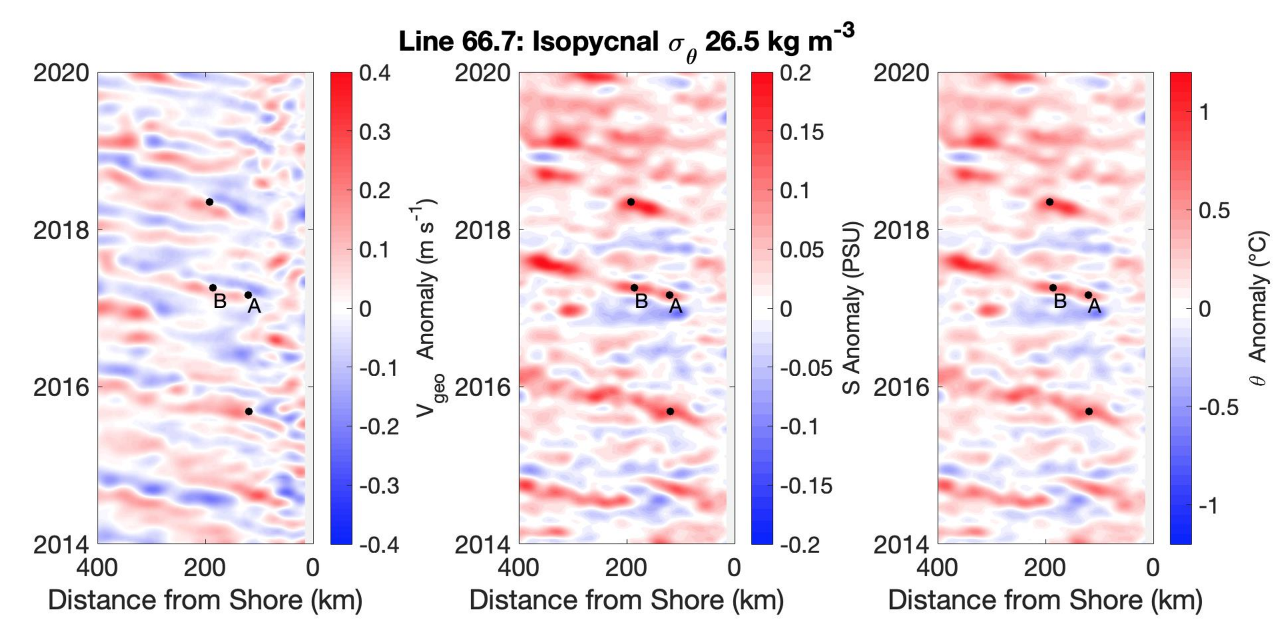


Seasonal 10-m dissolved oxygen saturation deviation from 100% and estimated air-sea gas flux, following the Liang (2013) parameterization including bubble effects. On right, red (blue) denotes oxygen entering (leaving) the ocean surface.



Seasonal plots of dissolved oxygen on Line 80.0. (a) Spring (b) summer (c) fall and (d) winter. The winter season is defined as December through February. Thin black lines denote potential density surfaces. Thick black lines denote σ_θ 24 kg m^{-3}, 25 kg m^{-3}, and 26 kg m^{-3}. A hypoxic boundary of 60 μmol kg^{-1} is plotted in a dashed magenta line.

Liang, J. H., Deutsch, C., McWilliams, J. C., Baschek, B., Sullivan, P. P., & Chiba, D. (2013). Parameterizing bubble-mediated air-sea gas exchange and its effect on ocean ventilation. *Global Biogeochemical Cycles*, *27*(3), 894-905.
Ren, A.S., Rudnick, D.L., and Nicholson, R. "Seasonal Dissolved Oxygen Gas Exchange in the California Current Upwelling System." *Under Review.*



Hovmoller diagrams from the CUGN climatology of a) geostrophic velocity anomaly b) salinity anomaly and c) potential temperature anomaly on potential density surface sq 26.5 kg m-3. Subthermocline eddies identified by inspection of the glider profile data are marked with black dots. The STE found in March and April 2017 is labeled by letters "A" and "B" respectively. Positive potential temperature anomalies and geostrophic velocity anomaly positive-negative pairs are found to propagate offshore with positive salinity anomalies.

Across-shore propagation of subthermocline eddies

Though subthermocline eddies (STEs) have often been observed in the world oceans, characteristics of STEs such as their patterns of generation and propagation are less understood. Here, the across-shore propagation of STEs in the California Current System (CCS) is observed and described using 13 years of sustained coastal glider measurements on three glider transect lines off central and southern California as part of the California Underwater Glider Network (CUGN). The across-shore propagation speed of anticyclonic STEs is estimated as 1.35-1.49 ± 0.33 cm s^{-1} over the three transects, Line 66.7, Line 80.0, and Line 90.0, close to the westward long first baroclinic Rossby wave speed in the region. Anticyclonic STEs are found with high salinity, high temperature, and low dissolved oxygen anomalies in their cores, consistent with transporting California Undercurrent water from the coast to offshore. Comparisons to satellite sea-level anomaly indicate that STEs are only weakly correlated to a sea surface height expression. The observations suggest that STEs are important for the salt balance and mixing of water masses across-shore in the CCS.

Ren, A. S., & Rudnick, D. L. (2022). Across-Shore Propagation of Subthermocline Eddies in the California Current System. *Journal of Physical Oceanography*, *52*(1), 39-51.

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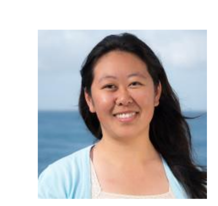

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