Monterey Bay Aquarium Research Institute

Using gliders to study air-sea CO_2 flux in an upwelling region

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Summer 2020

Keywords: biogeochemistry, glider, carbon, flux, California Current Ecosystem, upwelling

ABSTRACT

An algorithm commonly used to predict open ocean biogeochemical parameters from more commonly observed variables was applied to observations from an underwater glider located off Monterey, CA in the California Current Ecosystem. Pre-industrial and future anthropogenic dissolved inorganic carbon (DIC) estimates were applied to one glider transect, and the Revelle Factor and partial pressure of carbon dioxide gas (pCO_2) were analyzed under preindustrial, modern, and future ocean conditions. Results show a larger pCO_2 increase at depth due to the waters' higher Revelle Factor at depth. Air-sea CO_2 flux was also calculated for the transect. With increasing anthropogenic carbon, fluxes will likely become larger in magnitude and more variable due to an increasing relative sensitivity of pCO_2 changes to DIC changes, corresponding to an increasing Revelle Factor. Results are preliminary but may be improved with pH sensors on gliders and with more accurate regional projections of anthropogenic carbon in the California Current System.

INTRODUCTION

Seasonal upwelling in the California Current System brings offshore, deep waters naturally high in carbon and nutrients onto the continental shelf and supports the productive ecosystem. Anthropogenic carbon has been shown to intensify the low pH conditions during these upwelling events (Feely et al., 2008).

The ocean is the largest sink for anthropogenic carbon (Sabine et al., 2004). Carbon dioxide enters the ocean through air-sea flux, which is a function of the difference in CO_2 partial pressure between the air and ocean, wind speed, and sea surface temperature and salinity. During upwelling events in the California Current System, nearshore regions can be an acute source of pCO_2 to the atmosphere, while offshore waters tend to be a pCO2 sink due to biological productivity fueled by the upwelled nutrients (Hales et al., 2005).

The Revelle Factor (RF) is defined as the relative change in pCO_2 for a given change in DIC. A larger RF corresponds to a lower buffer capacity, or a decreased efficiency of the ocean to uptake atmospheric CO_2. Waters at depth in the North Pacific naturally have a high RF because the waters are old and have experienced a lot of respiration. The RF is expected to increase with increasing anthropogenic carbon (Egleston et al., 2010).

METHODS

Data was obtained from a spray glider maintained and supported by CenCOOS, MBARI, and Scripps Institute of Oceanography, with funding from NOAA and the State of California (Rudnick et al., 2017). The glider completes transects along CalCOFI line 66.7 off of Monterey Bay. DIC, total alkalinity, silicate, and phosphate concentrations were calculated from glider temperature, salinity and oxygen observations using the CANYON-B algorithm (Bittig et al., 2018). See the paper by 2020 intern Ally Morris for an evaluation of the validity of these algorithms in the California Current System. The Revelle Factor and pCO_2 were calculated using CO2SYSv1.1 with inorganic carbon system inputs of total alkalinity and DIC, the k_1k_2 constants of Leuker et al 2000, the KSO_4 constants of Dickson, and the boron-to-salinity ratio from Uppström 1979.

Anthropogenic dissolved inorganic carbon estimates were found using the potential density-anthropogenic carbon developed by 2020 MBARI intern Anna Hughes

(see her intern paper for more information). This estimate was developed using observations from the same Monterey glider line between May and July 2019 and February 2020 from a glider equipped with a pH sensor. The relationship was applied below the mixed layer depth, while above the mixed layer, anthropogenic carbon was estimated by Hughes to be ~67 µmol/kg on average. The mixed layer was defined as the top layer with a potential density difference less than 0.035. The anthropogenic carbon estimates were subtracted from glider carbon estimates derived using CANYON-B.

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Future sea surface anthropogenic carbon values in the study region were roughly estimated using the NOAA GFDL ESM2M model under a "business-as-usual" scenario (Dunne et al., 2012 and Dunne et al., 2013). To determine the amount of anthropogenic carbon added between 2017 and 2100 near the glider transect, the average July 2017 glider DIC value in the top 8m of water was subtracted from the average model 2090s surface DIC value from the same region. This value is then added to the near surface glider DIC values to estimate the 2100 conditions across the full glider transect. While this approach provides only a very rough estimate of future conditions, it makes it possible to use the model atmospheric pCO2 values to quantify potential future flux conditions.

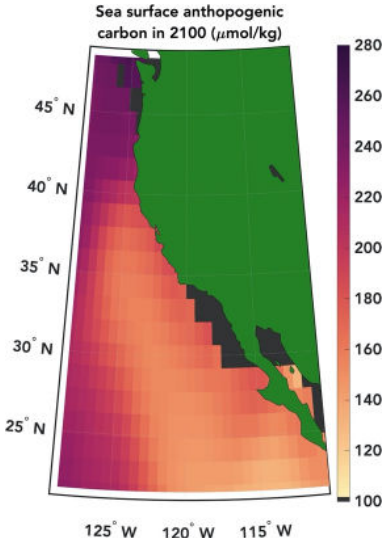

Figure 1: Difference in sea surface DIC values between the 2090s and preindustrial period from the NOAA GFDL ESM2M model under a "business-as-usual" scenario. We use this as a very coarse estimate of the anthropogenic carbon content in the region by the end of the century.

Air-sea CO_2 flux was calculated using the bulk wind speed formulation of Wanninkhof 2014, which uses inputs of the air-sea pCO_2 difference (ΔpCO_2), wind speed, and sea surface temperature and salinity. A pre-industrial atmospheric pCO_2 value of 280 µatm was used. The ESM2M model provided an atmospheric pCO_2 value of 914 µatm in 2100. 2017 monthly-averaged wind speeds were obtained from ECMWF's ERA-interim reanalysis product. MODIS satellite sea surface temperature measurements were used to provide a more accurate temperature at the surface than the glider, which 'surfaced' at an average depth of 1m (NASA Goddard Space Flight Center). pCO_2 was adjusted from the glider conditions to the surface temperature and pressure.

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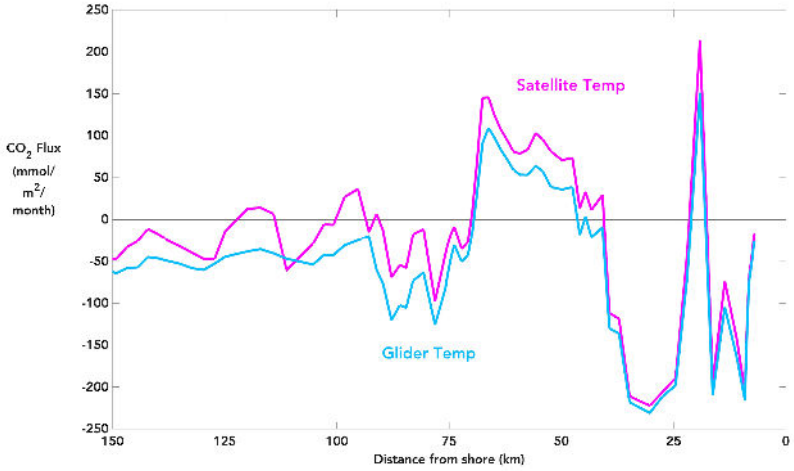

Figure 2: Air-sea CO_2 flux for the July 2017 Monterey glider transect calculated using the glider "sea surface" temperature, and the satellite sea surface temperature. Flux is higher when using the satellite temperature because the temperature is higher and the pressure is lower, increasing the pCO_2.

The glider was limited to performing operations at distances >8 km from the shore. In order to extend the range of flux calculations all the way to shore where upwelling waters often breach the sea surface, an estimate of the surface pCO_2 was made

using a relationship between seawater pCO_2 and temperature. The nearshore sea surface temperature measured by satellite is then used to determine the associated pCO_2 value from this relationship.

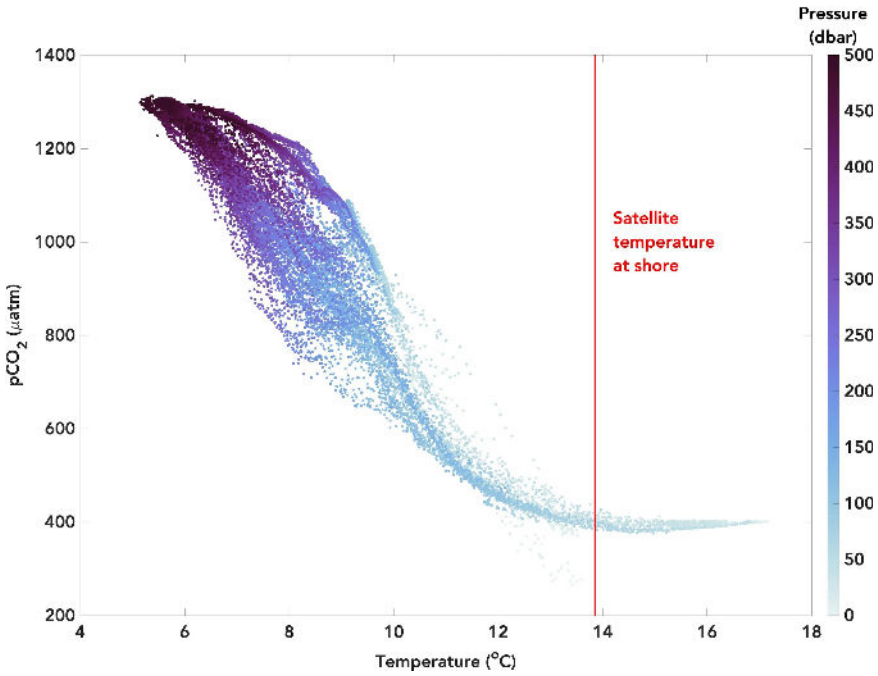

Figure 3: Temperature versus pCO_2 for the July 2017 glider transect. Pressure is shown with a color bar. pCO_2 varies the most at mid temperatures and pressures and is more predictable at depth and at the surface. The nearshore temperature measured by satellite is shown with the red line. The average of pCO_2 values at this temperature was used for the flux calculations.

RESULTS

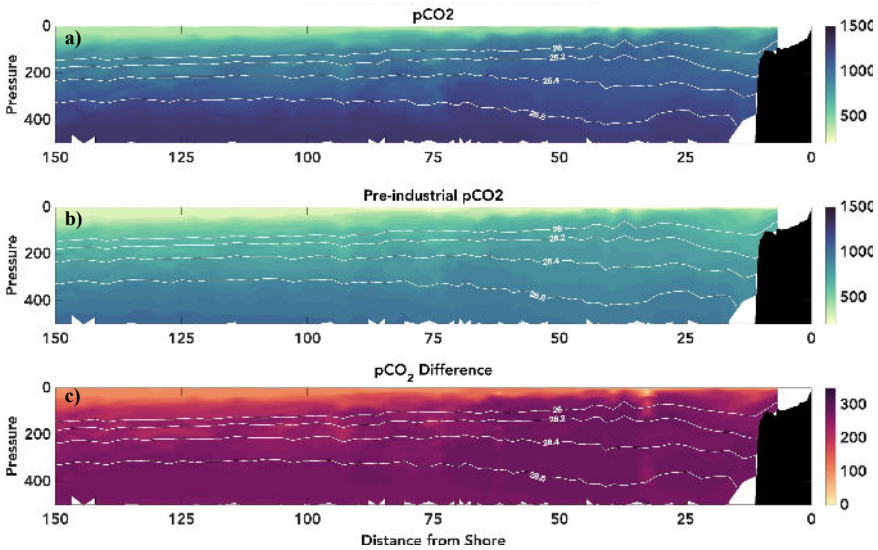

Figure 4: a) pCO_2 from a July 2017 Monterey glider transect with potential density contours in white. b) pCO_2 after anthropogenic carbon estimates are removed. c) The difference in pCO_2 between a) and b). Generally, pCO_2 has increased, and the greatest change in pCO_2 is subsurface.

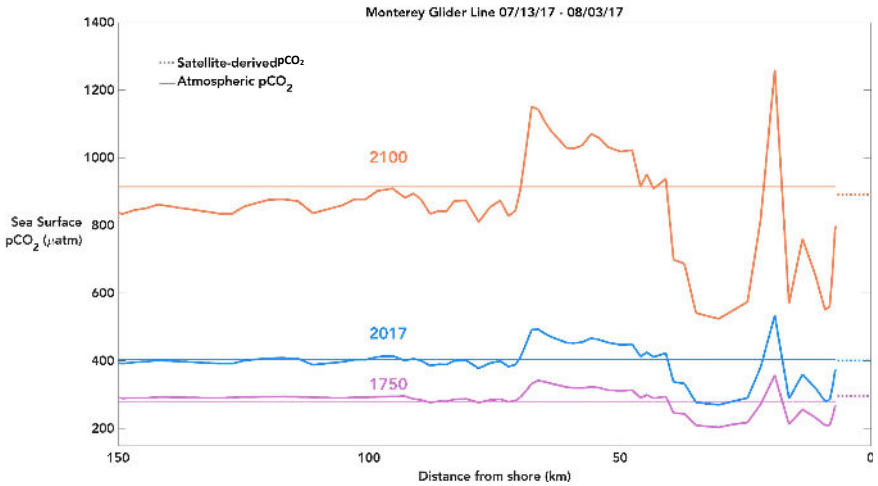

Figure 5: Sea surface pCO_2 in 1750, 2017 and 2100. Thin line shows atmospheric pCO_2 and dashed line shows the satellite-derived sea surface pCO_2.

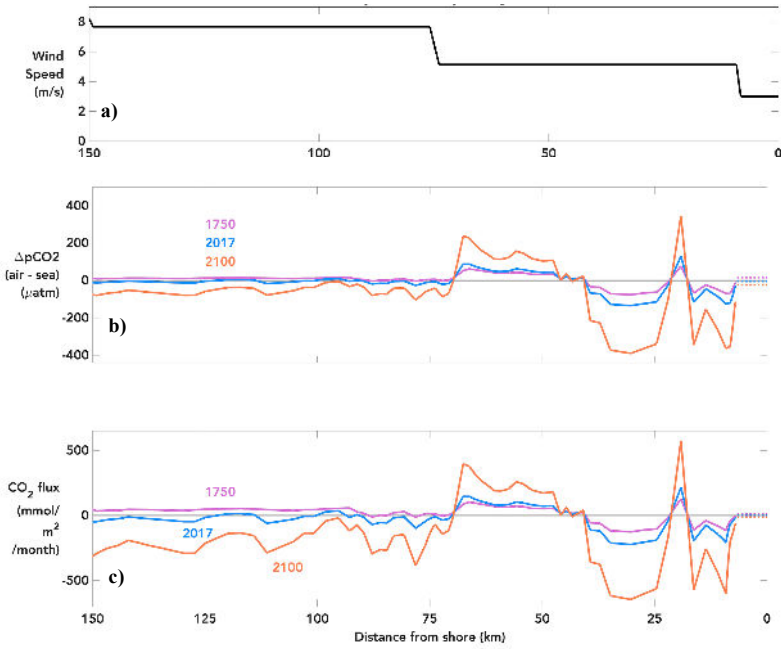

Figure 6: a) Monthly averaged wind speeds for July 2017 collected from ECMWF ERA-interim reanalysis product (Dee et al., 2011). Wind increases from onshore to offshore. b) The difference in pCO_2 between the atmosphere and sea surface for the glider transect calculated for 1750, 2017 and 2100. c) Air-sea CO2 flux. A negative flux represents a sink into the sea, and a positive flux represents a source to the atmosphere.

When comparing pCO_2 from a July 2017 transect and the corresponding pre-industrial pCO_2, there is a greater increase at depth, as opposed to at the surface where anthropogenic carbon is being added. This is an unusual result and is explained by a higher Revelle Factor at depth. The high RF at depth is a natural feature of the North Pacific. Onshore drivers of variability are upwelling and subsequent biological productivity, whereas offshore CO_2 values remain relatively close to the atmospheric value. Fluxes are amplified with increasing anthropogenic carbon. This is explained by an increasing RF, or decreased buffering of pCO_2 to changes in DIC.

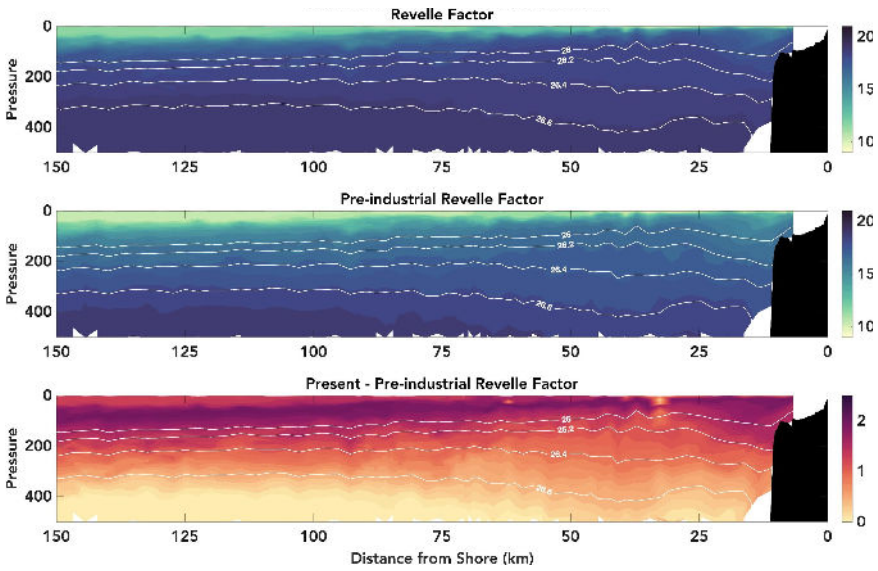

Figure 7: a) The Revelle Factor for a July 2017 glider transect with potential density contours in white. There is a uniformly high RF subsurface. b) The RF after anthropogenic carbon estimates are removed. c) The difference in RF between a) and b). RF increases overall, with the greatest change being slightly subsurface.

DISCUSSION

These results could be improved by using a sea surface anthropogenic carbon model that is more specific to the California Current System. Due to inconsistencies between the glider DIC values and the predicted anthropogenic DIC values, the direction of the fluxes is uncertain, and conclusions cannot be made about the California Current System increasingly becoming a sink, which the figure seems to indicate. However, the increased magnitude of fluxes with increasing anthropogenic carbon is a trustworthy result and is verified because the Revelle Factor is expected to increase with increasing anthropogenic carbon.

The results could further be improved by using wind and satellite temperature data that is higher resolution spatially and temporally, so that the measurements could correspond more closely with the time and place of the data collected.

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CANYON-B was found to give adequately accurate results in the California Current Ecosystem, however, at the surface, DIC values fall within a wide confidence interval of about ±12 μmol/kg. More accurate glider-based carbon measurements can be obtained by applying pH sensors to gliders, which is being tested by MBARI scientist Dr. Yui Takeshita.

The satellite temperature-derived pCO_2 estimate is very rough, but provides more information than would otherwise be known, and fills an observing gap near shore where upwelled waters often breach the surface, bringing the highest pCO_2 water near shore. The estimate will not work as well with increased upwelling, as pCO_2 is more variable at lower temperatures, though density may be an alternative proxy. Additionally, the estimation method assumes that the water's pCO_2 is entirely predicted by temperature and does not change as it is transported.

CONCLUSIONS

These results are preliminary and carry uncertainty, however gliders are promising tools for calculating air-sea CO_2 flux. Under increasing anthropogenic carbon, flux variability will likely become larger and more variable in the California Current System. This work shows that satellite measurements may be used to roughly extend the range of flux calculations, since gliders often do not cover the important region closest to shore. Future work will improve the accuracy of these flux estimates by incorporating data from a new forward projection from a high-resolution biogeochemistry model in the California Current System.

ACKNOWLEDGEMENTS

I would like to thank Andrea Fassbender for allowing me to work with her this summer, and for supporting my learning and the progress of this project. I am grateful to Yui Takeshita for providing weekly lectures on biogeochemical oceanography topics, and to Magdalena Carranza and Jacki Long for providing weekly help with MATLAB. I would like to thank intern Ally Morris for the collaboration and support, and intern Anna Hughes for sharing the anthropogenic carbon-potential density relationship that she

developed. George Matsumoto, Megan Bassett, and Tatjana Ellis provided amazing guidance and a well-organized intern program. I would like to acknowledge Scripps Institute of Oceanography and MBARI for maintaining the spray glider line, NOAA and the State of California for funding the glider line, and CenCOOS for providing the data. Finally, thank you to the Dean and Helen Witter Family Fund, the Rentschler Family Fund, the David and Lucille Packard Foundation, and MBARI for making this internship experience possible.

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