Oceans and the carbon cycle: What drives air-sea exchange of CO_2?

Exploring large datasets from the Ocean Observing Initiative

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Nadia Pierrehumbert[1] , Randal Reed[2*], Sage Lichtenwalner[3], Catherine Halversen[4], Anna Pfeiffer-Herbert[5], Robert Rhew[6*]

[1] Illinois Mathematics and Science Academy, Aurora, IL. [2] Shasta-Tehama-Trinity Joint Community College District, Redding, CA. [3] Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ. [4] Lawrence Hall of Science, University of California, Berkeley. [5] Stockton University, Galloway, NJ. [6] Dept of Geography, University of California, Berkeley. * Presenters

SUMMARY https://datalab.marine.rutgers.edu/explorations/2019/co2.php

Here we present an online Data Exploration for students to investigate patterns and forcings that elucidate the exchange of CO_2 between the atmosphere and ocean. Central to this Data Exploration is an interactive, web-based tool ('widget') to examine the air-sea gas exchange of carbon dioxide in a large dataset, collected as part of the Ocean Observing Initiative (OOI) *[Smith et al., 2018]*. Students will access Pacific and Atlantic Ocean coastal array data, and they can explore the impact of temperature, surface wind speed, surface salinity, and chlorophyll concentrations on variations in air-sea CO_2 flux. This interactive tool is coupled with lesson plans that follow the learning cycle, from invitation to application, so that this site can be utilized flexibly in a range of educational settings.

LEARNING GOALS

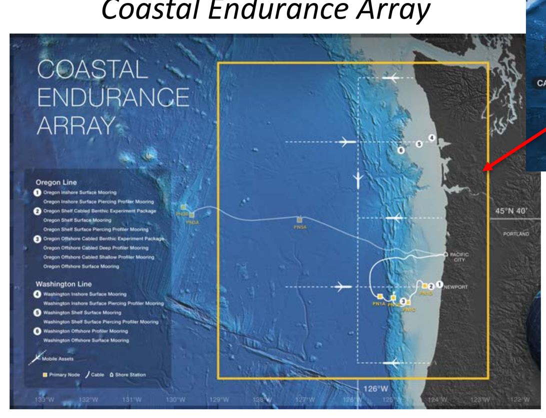
After engaging with the Data Exploration a student will be able to:

- Identify periods of time during which the ocean is a source or a sink of CO_2
- Explore patterns in temperature, salinity, wind speed, and chlorophyll concentration data to identify causes of changing CO_2 concentration and flux
- Temporal: Assign relative flux magnitudes across time within a site (as driven by seasonal temps, winds, primary production as discovered in #2).
- Spatial: Compare relative flux magnitudes between sites (cold west coast currents vs warm east coast waters as discovered in #2).

USING OOI DATA

The abundance of data collection at the array sites offers both opportunity and challenge for educational purposes. The opportunity involves the ability for students to work with massive, free data sets of real oceanographic data to replicate authentic scientific inquiry and discovery. The challenge involves the difficulty in downloading, interpreting, conducting quality control, and developing user interfaces from these data sets so that students can readily engage with the actual processes underlying the data. The first two challenges involved selecting arrays and then choosing the sites within the arrays. We chose two of the 7 OOI arrays: the Coastal Endurance Array in the Pacific Ocean and the Coastal Pioneer Array in the Atlantic Ocean (**Figs. 1 and 2**) *[OOI website]*.

Pacific Ocean: Coastal Endurance Array



Atlantic Ocean: Coastal Pioneer Array

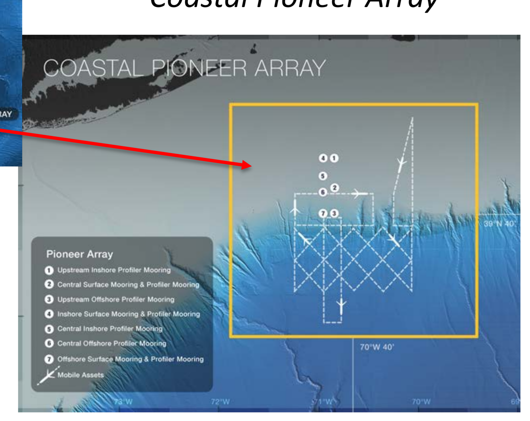
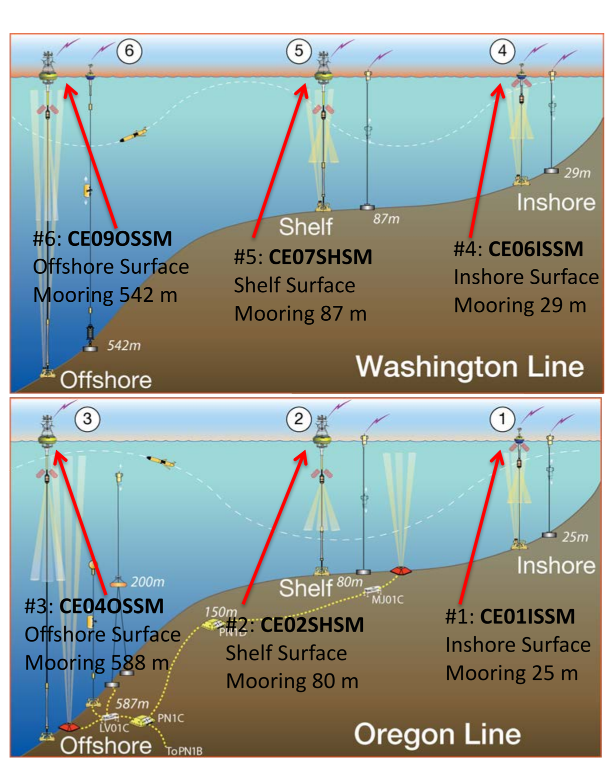


Figure 1. Two of the 7 OOI arrays were chosen for this study to compare and contrast the near coast Pacific (Coastal Endurance Array, left) and Atlantic (Coastal Pioneer Array, right) off of North America. Research array maps from the OOI website: https://oceanobservatories.org/



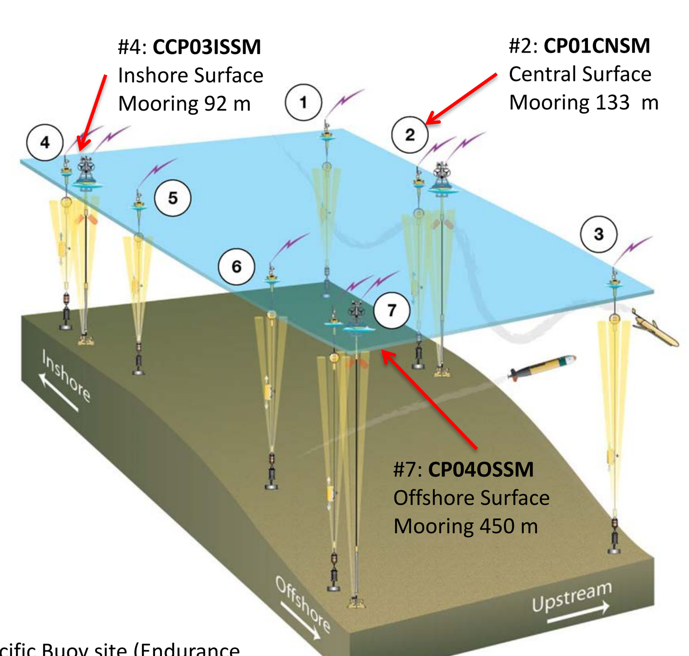


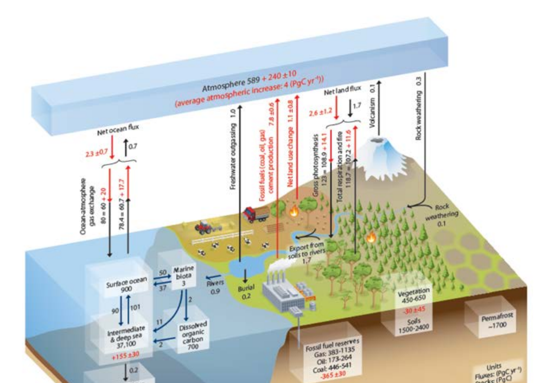
Figure 2. Six Pacific Buoy site (Endurance Array, left) and three Atlantic Buoy sites (Pioneer Array, right) were considered.

#	Code	Depth	Mooring	Data check	2016–2019 (months 1–12 per year)
Pacific Ocean: Coastal Endurance Array					
#1	CE01ISSM	25 m	Inshore (Ore)		*inshore data not considered*
#2	CE02SHSM	80 m	Shelf (Ore)	2 usable yrs	T/S missing; no CO2/wind (u)/T/S
#3	CE04OSSM	588 m	Offshore (Ore)	1 season	
#4	CE06ISSM	29 m	Inshore (Wash)		*inshore data not considered*
#5	CE07SHSM	87 m	Shelf (Wash)	1 usable year	Test Widget
#6	CE09OSSM	542 m	Offshore (Wash)	multi-season	
Atlantic Ocean: Pioneer Array					
#2	CP01CNSM	133 m	Central	multi-season	T/S missing; no CO2/u/TS
#4	CCP03ISSM	92 m	Inshore	multi-season	
#7	CP04OSSM	450 m	Offshore	1 yr, 3 sprng	

Figure 3. Buoy sites were selected based on the quality and availability of CO_2 flux data and relevant parameters. The first test was conducted on Endurance Site 5, but there was only 1 usable year of data (4/18 – 5/19) with a two month break in the middle. Hence 3 other sites were selected (highlighted in blue). The time period Januay 2016 to March 2018 were selected as having the most direct overlap for comparison.

INVITATION

The burning of fossil fuels since the Industrial Revolution has caused global atmospheric CO_2 concentrations to increase from 288 ppm to 411 ppm (as of November 2019, https://www.co2.earth/monthly-co2). This excess of greenhouse gases traps more heat at the earth's surface, leading to warming of the planet's surface. However, concentrations would have increased twice as much if all of the CO_2 emitted by human activities remained in the atmosphere. Where did all the extra CO_2 go? Where is this "missing carbon"? What process removed this extra CO_2 from the atmosphere? Will it continue to do so in the future?



The diagram shows the carbon cycle, with natural (pre-industrial) fluxes indicated by black arrows and human-influenced fluxes (perturbations to the carbon cycle) with red arrows. Modern-day annual CO_2 emissions caused by Fossil Fuel Burning (7.8 Pg/yr) and Land Use Change (1.1 Pg/yr) are shown by red arrows to the atmosphere. What fraction of this accumulates in the atmosphere? Where does the rest of the CO_2 go? (Look for the red arrows going from the atmosphere).

Figure 4. Gobal carbon cycle (IPCC, 2013). Boxes represent reservoirs, numbers indicate reservoir mass in PgC (=10^{15} grams C) and annual fluxes (in Pg yr^{-1}).

Overall the oceans are a large net "sink" for CO_2. But how does the surface ocean take up atmospheric CO_2? Can it emit CO_2 as well (i.e., become a "source")? Look at the following 2 plots of the oceans from two different studies (25 years apart). Where is the ocean a source and where is it a sink? Can you find differences between the locations of sources and sinks between these two studies?

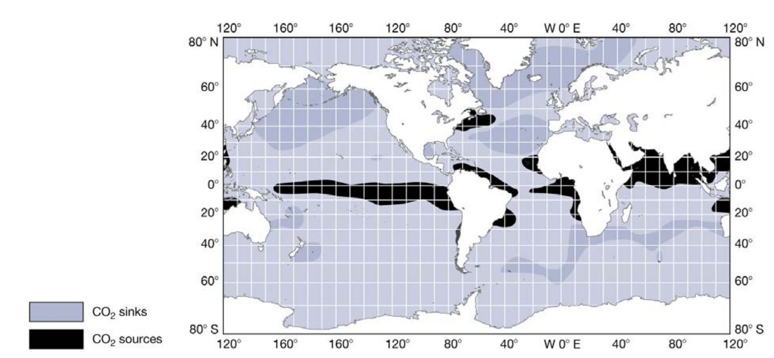


Figure 5. Map of oceanic CO_2 sources (emission from ocean) and sinks (uptake from atmosphere). Figure from Kump *et al.*, The Earth System, 2nd ed, adapted from T. Takahashi, *Oceanus* 32, 1989, p 22-29.

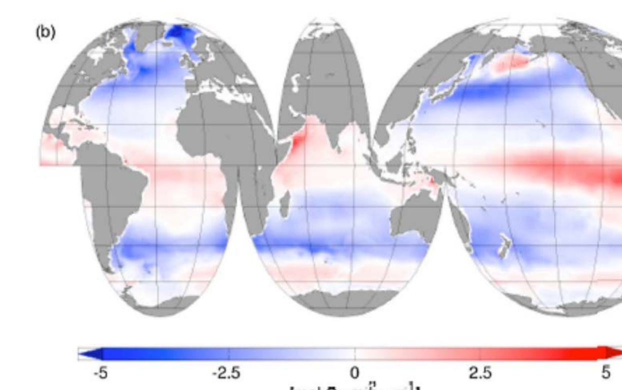


Figure 6. Map of oceanic CO_2 sources (red) and sinks (blue) from 1998 through 2011. Figure from Landschützer *et al.*, 2014.

EXPLORATION #1

(https://datalab.marine.rutgers.edu/explorations/2019/co2.php?level=exploration)

The overall objective is for students to use atmospheric conditions and water properties to identify drivers of CO_2 flux between the atmosphere and ocean. Students will first compare atmospheric and oceanic pCO_2 plots from a Pacific site (Coastal Endurance array) to identify periods of time during which the ocean is a source or a sink of CO_2, or is at equilibrium.

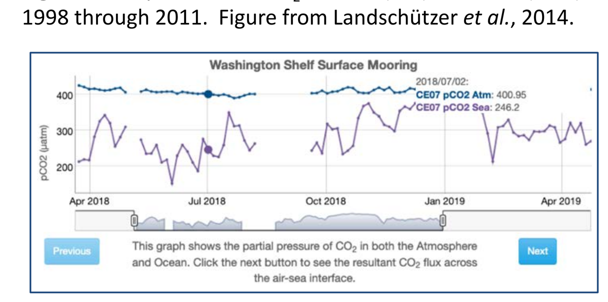


Figure 7. First step shows only atmospheric and oceanic pCO2 concentrations, omitting periods with instrumental issues. This test plot is from buoy #5 (**CE07SHSM)**, final product will be from buoy #2 (**CE02SHSM)**, which has a longer period of usable data.

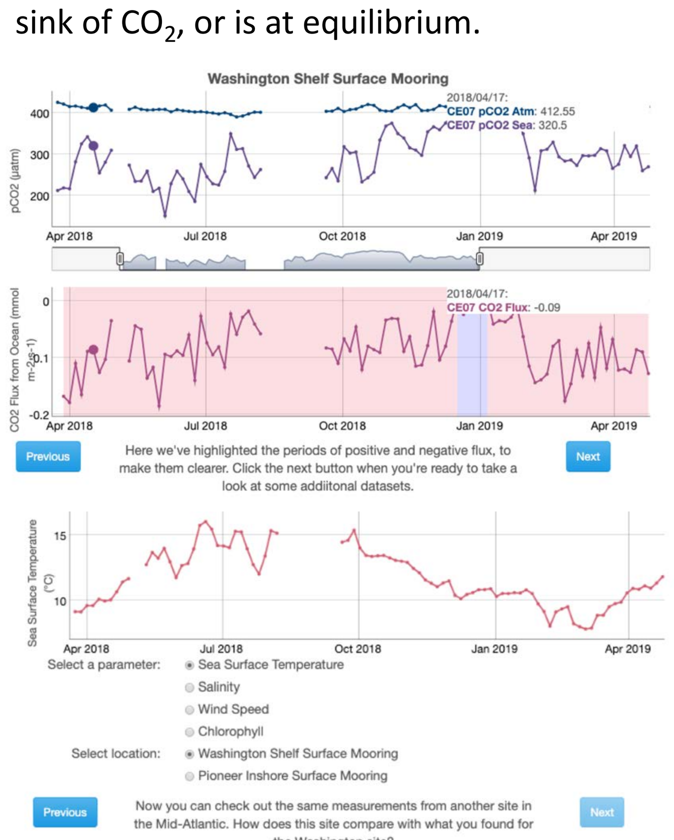


Figure 8. Second and third steps of exploration activity shows consecutive graphs of flux and environmental parameters. This test plot is from Washington line buoy #5 (87m depth, **CE07SHSM).** The final product will be from Oregon line buoy #2 (80m depth, **CE02SHSM).**

→ Clicking the "Next" button shows calculated fluxes using the pCO_2, wind, temperature, and salinity data. Students should share observations of patterns with partners. What evidence are they using to address the following questions:

* What do the y-axes represent in each graph?
* Is the ocean here a source or sink of CO_2 overall?

→ Clicking "Next" highlights positive and negative fluxes within the flux graph. Flux values can be qualitatively described with relative magnitudes using terms like ***minor*** (+/- 0.01 to 0.05), ***moderate*** (+/- 0.05 to 0.15) and ***major*** (+/- 0.15 and greater) flux values.

→ Cllicking "Next" appends a graph capable of plotting four additional variables: sea surface temperature, surface salinity, wind speeds at the air-sea interface, and chlorophyll concentrations. Radio buttons allow the student to toggle between them to see how they vary with the flux and pCO_2 conditions. Students should seek correlations between these variables and flux magnitudes, potentially coupling one or more to any temporal relationships (seasonality) they discovered. Then ask what questions they might be able to answer with these data.

* Do the patterns they identify reveal something about the ocean-atmosphere interactions that their prior knowledge can help explain?
* Having studied the data, is there anything they are wondering about that they might not yet be able to explain? What more information do they want or need?

The exploration phase could be structured as a jigsaw activity. Small groups of students focus on one of the environmental variables and its connection or lack of connection to changes in CO_2 flux. In the second phase of the jigsaw, students would examine all of the environmental variables and evaluate their relative importance in driving the patterns in CO_2 flux. This approach may be especially successful in lower-level classes where students have less prior knowledge about fundamentals of oceanography and require more time to understand the basic meaning of the environmental variables.

CONCEPT INVENTION #1

Once exploration #1 is completed, students should be able to summarize a set of conditions and associated temporal relationships that influence CO_2 flux. This includes using conditions to explain positive and negative fluxes as well as why flux values vary from minor to major.

EXPLORATION #2

In the second part of this activity, students look at an east coast (Atlantic Ocean) site in the same way as in Part #1. The Coastal Pioneer array (New England) site #4 (**CP03ISSM**) is at a nearly identical latitude and water depth, differing a bit in its distance from the shoreline. Geographic comparisons can be made in regards to CO_2 flux. Are flux conditions greater along one coast as compared to the other? What conditions might support such variation?

CONCEPT INVENTION #2

Students should now be able to compare and contrast CO_2 fluxes from the west coast and east coast shelf sites, specifically noting the magnitude of positive and negative flux differences between the two, and relating conditions that drive these differences across the two sites. Given the geographic positions of the two sites, they should also speculate about any influences not presented in the graph variables that might influence the flux differences.

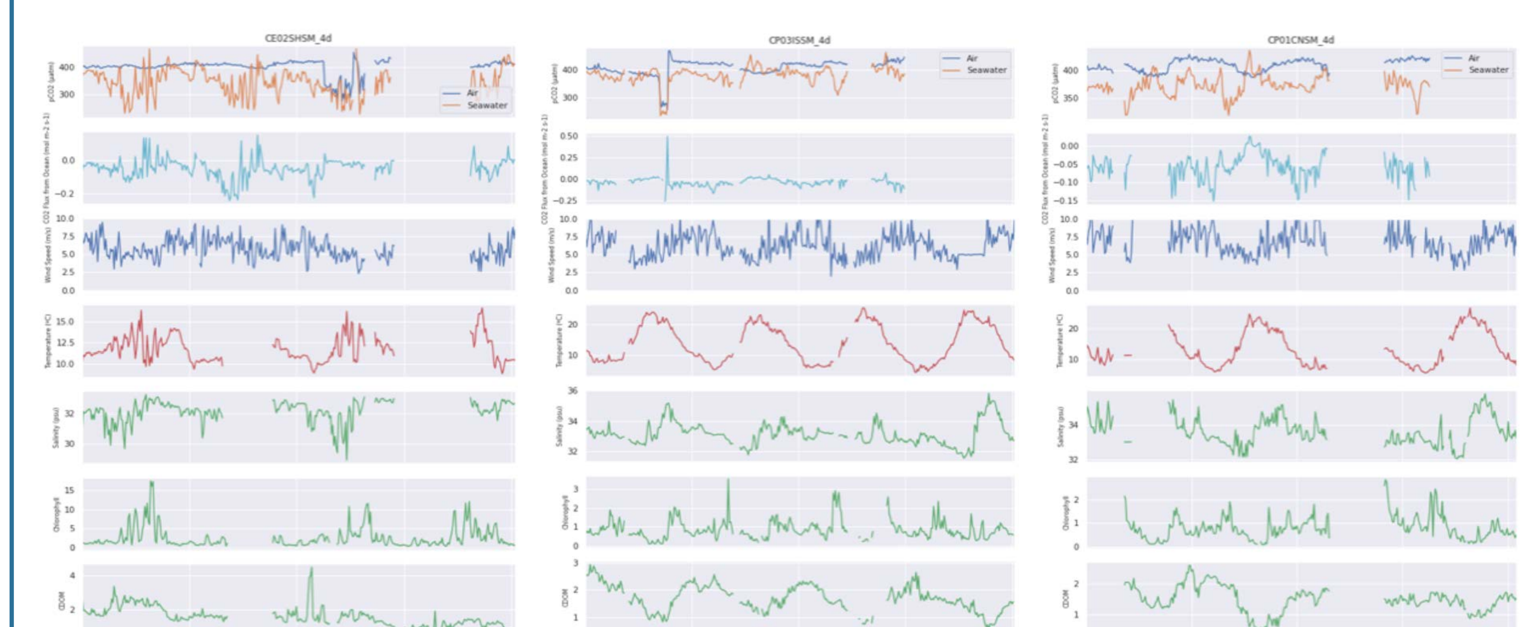
APPLICATION

In the final portion of this Data Lab Exploration, students apply their developed conceptual understanding as they evaluate a third "mystery" site. Just as in Phase #1 and #2, students are presented with the same sets of graphs and variables, except from a "mystery" site at nearly the same latitude and anchored in water of the same depth. Are trends from the "mystery" site more similar to the west coast site (Exploration #1) or the east coast site (Exploration #2)? Does the "mystery" site show the same trends or do some features fall outside of the concepts that they developed across the first two explorations? At this point, it may be worth discussing the periods of missing data. What can happen to create missing data? Can you make reasonable assumptions about what the data would look like? What evidence do you have to support this, and what are the risks in making such assumptions?

REFLECTION

Although we often study separately the different pieces of the ocean system, this case study shows the interaction of the atmosphere, environmental conditions and water properties in relationship to pCO_2. As you tied together all of these pieces you learned something new about the ocean-atmosphere interactions.

* What concepts did you need to learn more about in order to figure out what air-sea interactions may affect pCO_2, and explain how to predict when does the ocean gain CO_2, when does it lose CO_2, and when is it in equilibrium?
* What predictions can you make regarding the future of the oceans to continue taking up CO_2? Are there factors that might cause CO_2 flux to increase or decrease? In what direction?



Left: Exploration #1, Pacific Ocean, Endurance Array, Oregon line, buoy #2 (80 m depth, **CE02SHSM**)

Middle: Exploration #2, Atlantic Ocean, Coastal Pioneer array (New England) site #4 (92m depth, **CP03ISSM**)

Right: Mystery Site (133 m depth, **CP01CNSM)**

Figure 9. OOI data from 3 buoy sites to be used in this Data Exploration. After quality control on the data, these will be converted into 'widgets' for the Exploration #1 (left), Exploration #2 (middle), and Application (right).

Activity Citation:
Pierrehumbert, N., R. Reed, R. Rhew, and C. S. Lichtenwalner (2019). CO_2 Exchange Between Air and Sea. *OOI Data Labs Collection.*

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Kump, L., J. Kasting, R. Crane (2004) The Earth System, 2nd ed., Pearson, New Jersey (Fig 8-13, p.161)
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You can find the full collection of Data Explorations and other resources at:
datalab.marine.rutgers.edu

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