Using Authentic Data from NSF's Ocean Observatories Initiative in Undergraduate Teaching: An Invitation

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Abstract

There are many benefits to using real data in undergraduate science education, including building analytical and problem-solving skills and visualizing concepts through real world examples. The Ocean Observatories Initiative (OOI) provides a unique source of continuous, long-term oceanographic data from multiple locations in the world's ocean. Each array hosts a suite of co-located instruments measuring physical, chemical, geological, and biological properties. In this paper, we present existing educational resources derived from OOI data that can be leveraged for undergraduate teaching activities in and beyond the classroom, as well as highlight opportunities for new resources to be developed by the community. Additionally, we provide example applications of the use of OOI resources in lesson plans and research experiences for undergraduates. Our goal is to help guide educators in determining appropriate OOI datasets and applications for their own needs and invite them to develop and share their own materials.

Introduction

The National Science Foundation's (NSF) Ocean Observatories Initiative (OOI) is a new source of open access, continuous, long-term digital oceanographic data streaming from a suite of co-located instruments measuring physical, chemical, geological, and biological properties at multiple locations in the world's ocean (Smith et al., 2018; Trowbridge et al., 2019). These data, made publicly-available in real time, provide a valuable resource that undergraduate educators can use to teach a range of oceanographic principles and make the scientific process tangible through engagement with authentic data. Using real data, like those collected and served through OOI, in undergraduate science education offers significant benefits for developing students' analytical and problem-solving skills (e.g., Gougis et al., 2017; O'Reilly et al., 2017; McDonnell et al., 2015).

In this paper, we present existing educational resources derived from OOI data that can be leveraged for undergraduate teaching activities and give example applications of these resources in lesson plans and research experiences for undergraduates. Additionally, we suggest opportunities for new resources that can be developed by the community. Our goal is to help guide educators in determining appropriate OOI datasets and applications for their own needs and invite them to develop and share their own materials to help grow the OOI as a community resource in support of data-focused activities to benefit educators and students at any institution. Though this paper focuses on undergraduate geoscience education, the resources and example applications introduced could be expanded to include other levels such as K-12 education and graduate student research opportunities.

Background

Engaging students in active learning by modeling the scientific process using real-world data is a high-impact educational practice (Deslauriers et al., 2019; O'Reilly et al., 2017; Rubin and Abrams, 2015; Soule et. al., 2018). Data explorations allow students to engage in academically complex and challenging activities that require conceptual thought through the validation of physical models (Resnick et al., 2018) and the procedural knowledge needed to produce an analytical result (Kastens et al., 2015). Working with real data allows students to conduct inquiries that model the actual process of science, facilitating knowledge retention and development of more sophisticated cognitive skills (Bybee et al., 2006; Krathwohl, 2002), such as the higher skill levels of Bloom's taxonomy (Bloom et al., 1956; Krathwohl, 2002). When students analyze data, create figures, and explain their interpretation of the data, they must apply broader scientific principles to their observations, thereby engaging at a higher level on Bloom's pyramid (Gougis et al., 2017; Massimelli et al., 2019).

Though students may initially be challenged by the "messiness" of real data (Ellwein et al., 2014), as students gain confidence with the mechanics of data analysis, they can use authentic, open access datasets to independently solve complex, unstructured questions (Carey et al., 2015; Kastens et al., 2015), improving their understanding of the nature of science and the limitations of any dataset (Lederman, 1992). Data-driven activities can also encourage peer learning through small group work (Brame and Biel 2015; Grosser et al., 2008; Springer et al., 1999; Thomas and Brown, 2011; Toven-Lindsey et al., 2015) and cultivate data skills needed for future careers in academic and workplace environments (Carey and Gougis, 2017; Langen et al., 2014; Rubin and Abrams, 2015). Even the use of a single data-driven activity can result in students being more comfortable dealing with large datasets and becoming more quantitatively literate (Klug et al., 2017) and more competent manipulating data in a spreadsheet (O'Reilly et al., 2017).

Despite the well-documented link between data-focused lessons and development of higher-level cognitive skills, data-focused activities are often lacking in undergraduate curricula (Brewer and Gross, 2003; Carey et al., 2015; Michener and Jones, 2012; Rubin and Abrams, 2015). Some models for teaching effectively with authentic data in the undergraduate classroom do exist within the geoscience education community and have been found to increase knowledge retention and self-efficacy (e.g., Teasdale et al., 2015). A number of activities and resources are available through the Science Education Resource Center's (SERC) Teaching with Data portal (https://serc.carleton.edu/sp/library/twd/index.html). The InTeGrate (Interdisciplinary Teaching about Earth for a Sustainable Future: https://serc.carleton.edu/integrate/index.html) program uses data and systems thinking to engage students in interdisciplinary problem solving. Project EDDIE (Environmental Data-Driven Inquiry and Exploration: https://serc.carleton.edu/eddie/index.html) consists of a suite of flexible classroom teaching modules using large, publicly available Science, Technology, Engineering, and Math (STEM) datasets to engage students in quantitative reasoning. Examples also exist within the field of oceanography, including K-12 (e.g., *NOAA Data in the Classroom*, https://dataintheclassroom.noaa.gov/) and undergraduate level (e.g., *MARGINS Data in the Classroom* https://serc.carleton.edu/margins/index.html, and *Ocean Tracks* http://oceantracks.org/curriculum/undergraduate) resources. However, there is a need for further development of activities involving authentic data that cross the subdisciplines of oceanography, and OOI's unique infrastructure of co-located instruments provides such a resource.

The Ocean Observatories Initiative

The OOI is an NSF large research facility designed as an open resource for ocean scientists, with the goal of providing long-term observational data from several contrasting oceanic regimes (Smith et al., 2018). One of the key elements of the OOI is that its data are freely available online (Smith et al., 2018). As such, the OOI provides an open opportunity to examine continuous, long-term, high-resolution datasets through its Data Portal and other websites (Table 1, Vardaro and McDonnell, 2018). Data collected by the OOI have been publicly available since the project was commissioned in late 2015 (https://oceanobservatories.org/2016/01/ooi-status-update-january-08-2016/).

The OOI infrastructure (https://oceanobservatories.org) consists of seven instrumented arrays located in the coastal and open oceans of the North and South Atlantic and Pacific (Figure 1). Arrays consist of instrumented moorings, autonomous underwater vehicles, and seafloor observatories that measure physical, chemical, geological, and biological properties and processes from the seafloor to the air-sea interface. Moorings contain instruments deployed on a variety of platforms, including surface buoys and wire-following profilers, as well as fixed instruments deployed at discrete depths along the mooring cable and on the seafloor (Smith et al., 2018). These instruments capture a range of ocean properties (e.g., salinity, temperature, density, dissolved oxygen, fluorescence, nitrate, optical backscatter, pH, pCO_2) on a variety of temporal and spatial scales. Sensors are distributed throughout the water column and cover a range of geographic areas contrasting coastal with open ocean and polar with temperate ocean environments. Cabled seafloor observatories include deep and shallow profiler moorings, highdefinition video cameras, hydrophones, benthic heat, fluid and methane flux instruments, seismometers, tiltmeters, and a host of other bottom mounted instruments that provide real-time data designed to capture activities near methane seeps, hydrothermal vents, and a seafloor volcano.

Observations from the OOI can be used to explore a myriad of Earth system processes (Trowbridge et al., 2019), such as undersea volcanic eruptions (Wilcock et al., 2018), methane hydrates (Philip et al., 2016), earthquakes (Tréhu et al., 2018), coastal hypoxia (Barth et al., 2018), heat budgets (Chen et al., 2018), warm core rings (Gawarkiewicz et al., 2018), global ocean-atmosphere exchange processes (Ogle et al., 2018), and the oceanic biological pump (Palevsky and Nicholson, 2018). The OOI's real-time data streams not only provide an effective resource for improving ocean literacy (Adams and Matsumoto, 2007, 2009) and bring to life many important concepts taught in ocean and Earth science classes (Table 2), but also represent an opportunity for the oceanographic community to expand the reach of its science into classrooms.

From the outset, supporting undergraduate educational efforts was part of the OOI's design (OOI Final Network Design, https://oceanobservatories.org/planning-history/final-network-design/). During construction of the OOI, a small team within the project was dedicated to developing educational resources and tools to complement the scientific and engineering aspects of the program to provide a gateway for educators to use OOI data (McDonnell et al., 2018). A later effort, Data Explorations, curated and condensed several key datasets from the OOI database into easily accessible interactive data widgets – or interactive data visualizations (e.g., Figure 2a) – to support data-based learning activities for undergraduate students in oceanography (Table 3, Table 4). These widgets were reviewed and successfully implemented by 20 educators in introductory oceanography courses at the undergraduate level (Hunter-Thomson et al., 2017). The OOI Data Labs project (https://datalab.marine.rutgers.edu/) is the contemporary extension of the Data Explorations project that has expanded the initial set of explorations to over 30 curated online interactive data activities and is actively seeking to engage the education community (https://datalab.marine.rutgers.edu/join-our-community/).

Challenges and Opportunities of Using OOI Data and Resources in the Classroom

Because of the size and diversity of its data, the OOI has the potential to provide a rich resource for educators to bring the ocean into the classroom. There are several challenges associated with using OOI data, however, that extend beyond the general challenges of using data in the classroom. First, the OOI arrays have been deliberately located in complex oceanographic settings with high spatial and temporal variation (Trowbridge et al., 2019). Therefore, the data often do not replicate simplified textbook examples. While this is a challenge, it is also an opportunity for educators to use the data to communicate to students the dynamic nature of the ocean and the complex interplay of various processes. Second, as scientists, we understand that gaps in observational data are unavoidable, but students may struggle with how to interpret missing data or how to reconcile and analyze an incomplete time series. This again can provide an opportunity to discuss the challenges of ocean observation, such as instruments withstanding intense winter conditions at high latitudes or biofouling, that may have caused these gaps. Lastly, perhaps the biggest barrier to educational use of OOI data is that the current system is designed to deliver data in near-real time, which means minimal processing and quality control are done on the data prior to posting online (Table 1). As such, using data from the current OOI data archive in an introductory undergraduate classroom requires an initial time investment to select appropriate and available instruments, download data, verify its quality, and manipulate it into usable formats.

Though instructors and students with more advanced experience can make meaningful use of the data directly accessed from OOI data portals (Table 1), the initial effort required to learn the system and manipulate the data can provide a barrier of entry for many instructors. Fortunately, along with the Data Labs project, there is a growing online community of educators who have created and shared their curated OOI datasets, tools, and lesson plans for others to use (Table 3). These curated datasets and online interactive widgets allow even introductory students to engage with these datasets in meaningful ways. As the OOI community continues to grow, we anticipate more datasets and activities will become available.

Example Applications

To demonstrate the value of curated OOI datasets for education, we highlight example applications for introductory oceanography courses and for student research projects that have been pilot-tested by several authors of this paper.

Classroom Activities

The example classroom activities make use of existing interactive online Data Explorations (Table 4) and associated lesson plans and student worksheets that are available online (https://datalab.marine.rutgers.edu/tos-lesson-plans/). The activities are designed to take information introduced through lectures or textbook readings that engage students at the foundational levels of *remember* and *understand* and facilitate student engagement with the more sophisticated *apply*, *analyze* and *evaluate* cognitive skill levels of Bloom's taxonomy (Bloom et al., 1956; Krathwohl, 2002). Each set of activities and tools can be applied in a variety of class sizes and learning environments (Soule et al., 2018) to achieve a range of content and skill-development objectives. Adaptations can be made as well to use these activities in remote (homework or online) settings that do not have real-time instructor interactions. If access to a computer lab is not available, widgets can be implemented using personal laptops, tablets, or even smartphones. Ideally, students work in small groups with the graphs on a shared screen to optimize interactivity, but the graphs can also be displayed on a projection screen or printed in hard copy if necessary. Although the lessons presented here have specific classroom settings, the curricular materials utilized are flexible and can be adapted to meet diverse course needs.

1) Controls on Primary Productivity

Primary production in the ocean links ocean biology to atmospheric composition, ocean circulation, continental run-off, the global carbon cycle, and the geological record. Chlorophyll concentration, though a measure of phytoplankton biomass rather than a direct measure of the rate of production, is often used to study primary production. Examining changes in chlorophyll concentration in different geographic settings on various temporal scales (daily, seasonally, inter-annually) and analyzing how production limiting factors are related to these concentrations provides key insights into primary production dynamics in the ocean. OOI arrays are located in areas where primary productivity is controlled by a range of limiting factors often discussed in textbooks (e.g., Figure 2b). The Irminger Sea array, for example, shows a strong signal of seasonal light limitation, while the Endurance Array on the Washington Shelf showcases the effect of upwelling. Other oceanic regions that can be compared are Pacific versus Atlantic, inshore versus offshore, Northern versus Southern hemisphere, and polar versus temperate biomes.

In the example primary productivity lesson, students used chlorophyll time series from several OOI arrays to investigate variability in primary production. Students completed a guided data analysis exercise to explore and answer questions about chlorophyll data – such as identifying phytoplankton biomass maxima, minima, time periods, and seasonal variations – collected from surface moorings in different geographic settings, including the subpolar North Atlantic (Irminger Sea Array), eastern subarctic North Pacific (Station Papa Array), Washington shelf upwelling (Endurance Array), and eastern Pacific sector of the Southern Ocean (Southern Ocean Array). They were asked to identify patterns in realistic chlorophyll data that relate to primary production cycles, describe geographic and seasonal variation in phytoplankton biomass and primary production rates, and apply prior knowledge of limiting factors (nutrients, light, stratification) to develop hypotheses about primary production in different ocean regions. The classroom activities were conducted based on several interactive data widgets in the OOI Data Labs *Primary Production* collection (Table 4, Figure 2a). Versions of this activity were conducted in both 100- and 200-level Introduction to Oceanography courses across three institutions – a small liberal arts college, a regional public university, and a research-focused university. The class sizes ranged from fewer than 20 to more than 100 students and included both science and non-science majors. Lesson plans and materials for each application (https://datalab.marine.rutgers.edu/tos-lesson-plans/) provide further details regarding the variation in use across these educational contexts.

Goals for student learning for the primary productivity activity span several cognitive skill levels:

1. Identify, describe, and explain the dynamics of and controls on primary production in different ocean regions throughout the year; reinforcing and reviewing concepts previously covered in lecture and/or homework assignments *(Bloom's cognitive process: understand)*.
2. Analyze and interpret "messy" real data rather than a highly conceptualized textbook figure *(Bloom's cognitive process: apply).*
3. Identify and interpret figure axes and relationships among different parameters and formulate and test hypotheses *(Bloom's cognitive processes: apply and analyze).*
4. Identify limiting factors and formulate hypotheses about primary production in different regions of the ocean *(Bloom's cognitive processes: evaluate and create).*

Instructors may build on this example activity for use in more advanced classes. For example, additional auxiliary measurements can be used to provide additional physical and biogeochemical context, including salinity, temperature, nitrate, oxygen, optical backscatter and colored dissolved organic matter. Extension activities incorporating advanced concepts were included in different versions of this activity across the three institutions, including: (1) examination of covariance between chlorophyll and nitrate (Table 4, Figure 2c,d); (2) exploration of physical and biogeochemical factors influencing bloom dynamics across three high-latitude ocean regions; and (3) a jigsaw activity using static graphs of data from the Irminger Sea Array (Palevsky and Nicholson, 2018) to compare trends in temperature, chlorophyll, and dissolved oxygen over the seasonal cycle. Instructors can also expand beyond these developed materials by adding a discussion of ocean engineering and challenges of obtaining sustained time-series data across the range of locations, leveraging examples of missing data as a learning opportunity.

2) Submarine Volcanism - the Axial Seamount

Plate tectonic processes are commonly taught in introductory ocean and Earth science classes but can be an abstract concept for students. The OOI Regional Cabled Array Axial Seamount site, located on a divergent plate boundary, is home to the most magmatically active volcano on the Juan de Fuca ridge (Chadwick et al., 2016). Seafloor eruptions were directly observed at Axial Seamount in 1998 and 2011, with an eruption recorded in real-time by OOI instruments in 2015. All three eruptions occurred at a predictable level of seafloor inflation and, based on current inflation rates, we expect another eruption at Axial before 2022 (Wilcock et al., 2018). This creates a unique opportunity to study the relationship between different geophysical parameters over the course of an eruption.

A classroom activity using interactive graphs in the OOI Data Labs *Exploring Tectonics & Seamounts* collection (Table 4) was conducted in an Introduction to Oceanography lecture class of 35 students at a regional public university (https://datalab.marine.rutgers.edu/tos-lesson-plans/) to help students better understand the complex geophysical dynamics of volcanic eruptions. After a brief introduction to the tectonic setting and eruption patterns of the volcano, students were directed to investigate geological features of the seamount by viewing graphs of seafloor depth and x- and y-axis tilts at three locations before and after an April 2015 eruption. In order to help them navigate the three-dimensional spatial reasoning required to interpret these graphs, students were directed to kinesthetically represent the change in tilt of the seafloor by tilting a flat surface, such as a textbook. Students then applied their knowledge of eruption patterns to the record of caldera inflation and, using an eruption threshold, made a prediction of the timing of the next eruption.

Goals for student learning for the submarine volcanism activity span several cognitive skill levels:

1. Describe the connection between divergent plate boundaries and volcanic seamounts *(Bloom's cognitive process: understand)*.
2. Interpret graphs and kinesthetically visualize three-dimensional changes in the seafloor (inflation and tilt) from time-series graphs *(Bloom's cognitive processes: apply and analyze)*.
3. Formulate a prediction for the next eruption based on seafloor inflation trends *(Bloom's cognitive process: evaluate)*.

This activity can be extended to serve the needs of an upper level class by including data science, time series skills, statistical skills, or upper level geophysical content. Depending on the students' level of computational skills, students can be asked to plot the bottom pressure and tilt time series instead of using a pre-constructed graph or be tasked with downsampling the data to remove the tidal signature. Advanced students can use regression analysis to calculate inflation rates between eruptions to identify changes in slope. The time series can also be compared to pre-processed seismic data available online by William Wilcock (http://axial.ocean.washington.edu/) to calculate earthquakes per day, allowing students to visually identify the relationship between changes in inflation rate and changes in the amount of daily seismicity (Natalie et al., 2018).

3) Salinity and Stratification

Salinity and temperature determine density and affect stratification and mixing in the ocean, as well as drive thermohaline circulation. OOI data provides the opportunity to examine real-world salinity in different coastal and open ocean regions over a range of timescales and throughout the water column with data from hundreds of CTDs (Conductivity, Temperature, and Depth sensors) deployed across the arrays. An activity using the OOI Data Labs salinity related widgets (Table 4) was embedded into an Introductory Oceanography lab to explore the effects of temperature and salinity on density and stratification in the ocean.

After initial hands-on activities and demonstrations of the relationship between temperature, salinity, density, and stratification, students were asked to investigate processes that affect salinity (e.g., seasonal variations, changes with depth, geographic location) using the salinity data exploration widgets (Table 4). Explorations included (1) comparing time series of air temperature, surface salinity, precipitation, evaporation, and rain rate at a coastal site in the Northern Pacific Ocean (Coastal Endurance Array) to explore changes, patterns and trends; and (2) comparing seasonal variations in surface salinity data across coastal and open ocean regions and with depth. Students were asked to provide explanations of their observations by discussing the processes that appeared to affect salinity, as well as how and why salinity changed over time in different regions of the ocean. The activity was implemented on two campuses of a public university: a small (n=22) lab class at a small teaching-focused campus and a large (n=150), multi-section lab class at a large research-focused campus. Lesson plans and worksheets can be found online (https://datalab.marine.rutgers.edu/tos-lesson-plans/).

Goals for student learning for the salinity and stratification activity span several cognitive skill levels:

1. Explain the relationship between temperature, salinity, density, and stratification *(Bloom's cognitive process: understand)*.
2. Interpret time series and profile data visualizations and explain the changes in salinity and stratification *(Bloom's cognitive processes: understand and apply)*.
3. Compare and contrast salinity across geography, season, and depth *(Bloom's cognitive processes: analyze and evaluate)*.

This activity can be extended for upper level classes by having students directly access real-time salinity data, for example through the OOI Regional Cabled Array Data Portal (Table 1) in addition to using the online widget. For more advanced classes, students can download temperature, salinity and density profile data to (1) plot vertical profiles at various locations for different seasons to compare stratification; (2) make contoured sections of these water properties over time; and/or (3) conduct water mass analyses using T-S plots.

Beyond the Classroom: Using OOI Data in Undergraduate Research Projects

The wealth of publicly-available OOI data also provides opportunities for students to engage beyond the classroom by using these data in undergraduate research projects. There is abundant evidence that early undergraduate research (Thiry et al., 2012), supplemental instruction (Villarejo et al., 2008), and faculty partnerships (Nagda et al., 1998) can be transformative for undergraduate students, especially those from underrepresented populations (Nagda et al., 1998; Russell et al., 2007). These experiences foster enhanced scientific thinking, increased confidence conducting research, increased enthusiasm for science, and real-world experiences advantageous for graduate school or private sector job applications (Hunter et al., 2007). Additionally, projects engaging students in independent research enable them to work at the top levels of Bloom's taxonomy (*cognitive processes: evaluate and create*), synthesizing prior learning to evaluate hypotheses and create new knowledge (Krathwohl, 2002).

Utilizing free online datasets like the OOI opens opportunities for cutting-edge, authentic oceanographic research experiences without requiring access to the resources of a large research institution. Students and faculty advisors can access the data from anywhere through the data portal to be processed on a personal computer. If a project requires high processing power to deal with large data there are cloud computing resources (e. g. Google Colab, Pangeo) that are now free to anyone online. The wide range of available data from the OOI allows a faculty mentor to tailor projects according to a student's skills, interests, and time availability. All that is required is data science skills, an idea that can be addressed within the scope of the available data streams, and a willingness to engage.

Since OOI data first became publicly available in 2015, undergraduate students have conducted OOI-based research in a wide range of institutional settings. Some of these are traditional oceanographic institutions, e.g., Woods Hole Oceanographic Institution, the University of Washington (UW), and Scripps Institution of Oceanography (Zhang and Partida, 2018; Philip et al., 2016; Ogle et al., 2018). Others are from less traditional oceanographic settings, such as Millersville University, a landlocked public university in central Pennsylvania (Alexander et al., 2018), Wellesley College, an undergraduate-only women's liberal arts college (Wanzer and Palevsky, 2018), and Queens College, an urban, minority-serving institution (Rahman et al., 2017; Pesar et al., 2018; Tesin et al., 2019; Sacker et al., 2019). Many student and early career projects have been highlighted through a feature series on the OOI website (https://oceanobservatories.org/tag/early-career-highlight/). These student projects have addressed a wide range of research questions, from air-sea heat exchange to seafloor hydrothermal processes to biologically-driven carbon cycling, and in all cases engaged students in analyzing large datasets from a diverse range of oceanographic sensors.

As with classroom applications, one of the challenges in using OOI data for undergraduate student research is that the data are delivered in raw or minimally processed formats and thus require scientific programming and data analysis skills in order to use. To overcome these challenges, it is critical that faculty mentors scaffold their students' data science skill development through means such as guided online tutorials and pair programming exercises to learn Unix, Python, R, and MATLAB coding. The challenges, however, are also opportunities for undergraduate researchers to develop sought after programming skills valuable for their future careers.

In addition to creating opportunities for research through its online data, the OOI has created opportunities for diverse groups of undergraduate students to gain hands-on research experience at sea, providing additional depth to data analysis-focused student research experiences. Seagoing experiences can be transformative for undergraduate researchers (Finley and McNair, 2013; Olson and Riordan, 2012), both for the opportunity to actively participate in field work and for the chance to develop relationships with the scientists and engineers onboard. One example is the UW-NSF funded VISIONS cruises (https://interactiveoceans.washington.edu/expeditions/) conducted by the University of Washington to provide annual maintenance to the OOI Regional Cabled Array. Since 2013, approximately 150 students from multiple academic institutions have been selected through an annual application process to go out on the cruise, producing a myriad of creative contributions (http://ooica.net/student-projects/) and resulting in several senior theses and presentations at national meetings from students who used sensor data from the Regional Cabled Array in their projects (e.g., Rahman et al., 2017; Pesar et al., 2018; Tesin et al., 2019).

Other OOI maintenance cruises have offered to host external researchers, including students, by posting opportunities through the UNOLS Cruise Opportunity Program (https://www.unols.org/unols-cruise-opportunity-program). Though these opportunities are primarily targeted to graduate students, it is conceivable that undergraduate students could participate if accompanied by their faculty advisor, providing another means for undergraduate research students to combine fieldwork with analysis of publicly-available OOI data. For example, a total of four undergraduate students participated in the annual OOI Irminger Sea

Array cruises in 2018 and 2019 with supplemental support from a NSF Chemical Oceanography-funded project, providing each student with their first seagoing research experience (https://irmingersea.blogspot.com). More information on ways to engage with the OOI can be found in Ulses et al. (2018).

Discussion & Future Directions

The OOI was designed for researchers to explore a set of complex oceanographic questions and to serve as an oceanographic educational resource (Smith et al., 2018). Although much of the focus of the OOI program to date has been on cutting-edge scientific research, there are components of the OOI system that lend themselves to teaching students both oceanographic concepts and data analysis skills. The goal of this paper is to raise educator awareness about the opportunities and challenges of integrating OOI data into undergraduate geoscience curricula. Specifically, we highlight materials available for teaching with OOI data, such as online datasets, curricular resources, publications, and online tools (Tables 2,3,4) and provide example applications of their use in diverse learning environments, as well as in undergraduate student research projects.

The examples presented in this paper showcase how incorporating OOI data provides opportunities for students to develop complex cognitive skills at higher levels within Bloom's taxonomy (Figure 3). Each classroom example has objectives for student learning that include both content – *understand* and *remember* (e.g., explaining the factors that lead to a spring phytoplankton bloom) – and skills – *apply* and *analyze* (e.g., determining when the spring bloom has begun by comparing multiple time series). Undergraduate research examples highlighted integrated application of skills and synthesis of content across objectives – *evaluate* and *create* (e.g., conducting a novel analysis of multiple years of sensor data to determine the influence of the spring bloom on the ocean carbon cycle).

We are in the early stages of educational application and community development as the OOI ramps up its research program. As such, many gaps remain where there is potential to develop future educational applications (Figure 3). For example, there remains an opportunity to create and further develop existing educational tools and resources for upper level undergraduate courses to support learning objectives at the higher cognitive skill levels (*evaluate* and *create*) focusing on open-ended data exploration. There is also an opportunity to develop transferable materials to assist faculty in scaffolding the development of data science skills needed to conduct undergraduate research projects with OOI data.

As the examples presented in this paper are pilot applications of using OOI in the classroom, only preliminary assessment of their use in the classroom has been done. We believe, and other studies have shown (Bader et al., 2016; O'Reilly et al., 2018), that integrating real world data into undergraduate geoscience curricula will (1) enhance students' understanding of concepts and make the material more accessible and (2) build students' aptitude and facility with graphing, analyzing, and interpreting data. In order to know if the approach of the data-intensive classroom activities presented achieves these goals, it is critical to assess their effectiveness. A preliminary assessment of the Salinity and Stratification activity yielded no discernable difference in content knowledge between students who did this activity as compared to the previously existing hands-on lab on the same topic (Greengrove et al., 2019). Data analysis skill improvement, however, was not assessed. Additional assessment studies need to be done in order to determine the efficacy of these online widgets, as well as to develop a set of best practices using OOI data in Introductory Oceanography and other Geoscience courses.

Our main purpose in writing this paper was two-fold: 1) to provide the community with an overview of current OOI educational resources and opportunities; and 2) to provide a guide for entry points, avenues, and pathways for educators to get involved and join the community to develop, implement, and assess data-based educational resources. We encourage the community to create new and share existing curated datasets and adaptations as accessible alternatives to processing the raw data. This is an invitation for the community to dive in, build partnerships, and help plumb the depths of the OOI dataset to find new and relevant ways to engage students with the data that can be shared as new activities to benefit educators and students at all institutions.

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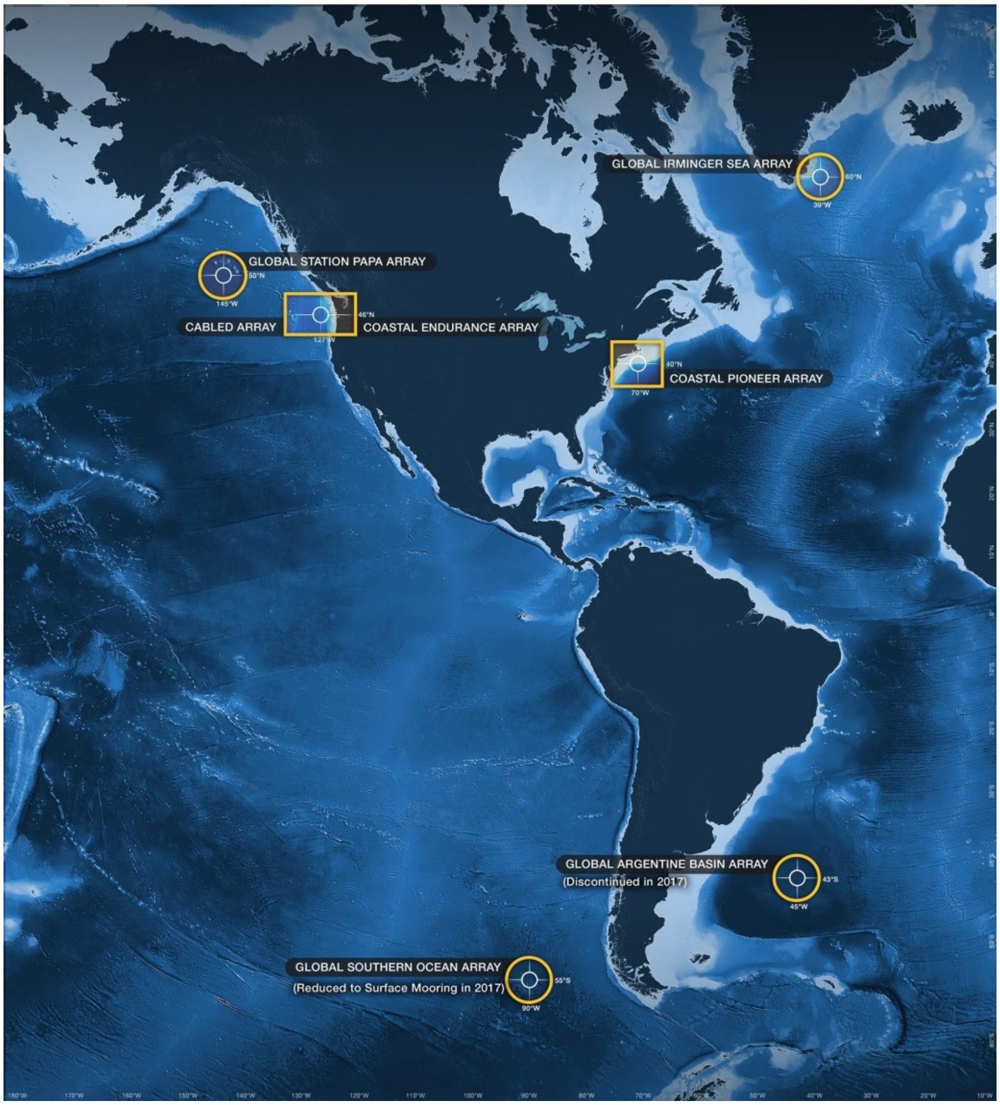

Figure 1. Map of the OOI Array locations. Credit: OOI Cabled Array program & the Center for Environmental Visualization, University of Washington

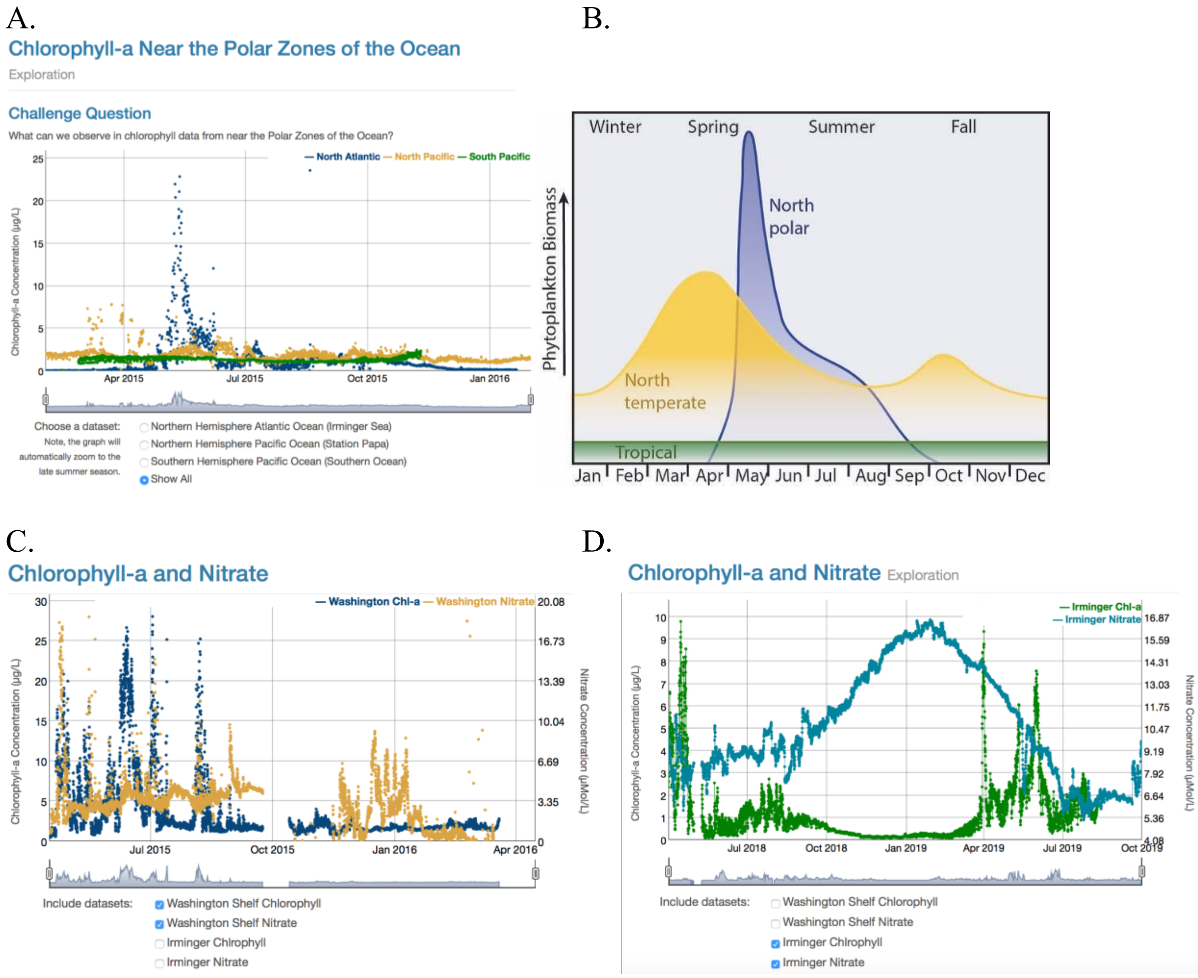

Figure 2: a) Screenshot of the basic chlorophyll data exploration widget (datalab.marine.rutgers.edu/explorations) for three different polar ocean regions. b) Classic textbook figure of phytoplankton biomass variation with latitude. c&d) Screenshots for a similar exercise with increasing complexity, comparing chlorophyll and nitrate data from polar and temperate oceans.

	Introductory →	Upper level →	Undergraduate research
Oceanography concepts: Bloom's understand/remember	Primary Productivity Submarine Volcanism Salinity/Stratification	Primary Productivity	Opportunity
Data skills: Bloom's apply/analyze	Primary Productivity Submarine Volcanism Salinity/Stratification	Primary Productivity	Opportunity
Integrated applications: Bloom's evaluate/create	Opportunity	Opportunity	Opportunity

Well Developed Teaching Activities	Some Teaching Materials Developed	Opportunity to Develop Teaching Activities, Resources & Best Practices

Figure 3. Matrix of OOI data-driven teaching activities mapped onto undergraduate course level (columns) and level of Bloom's taxonomy (rows). Classroom examples used in this paper emphasize lower and middle Bloom's levels in introductory course work with some material applicable to upper level courses. Undergraduate research projects, which incorporate higher order data and application skills, were also presented, but there remains an opportunity to develop shared best practices for engaging students in research using OOI data. There also remains a need for developing lessons geared toward upper level courses and integrated applications at all levels.

Table 1. Examples of portals for accessing OOI Data.

OOI Managed Websites		
Data Access Point	**Description**	**URL**
OOI Data Portal	The primary source for most data available from the OOI, including an overview of all OOI Research Arrays and their instrumentation.	https://ooinet.oceanobservatories.org/
Raw Data Archive	Static repository of raw instrument files (for those who prefer those formats) as well as images, movies, and hydrophone data	https://oceanobservatories.org/data/raw-data/
OOI Alfresco Explorer	Documentation files, including asset information, deployment/recovery cruise reports, and data from cruise-collected validation samples and cruise data, for all arrays	https://alfresco.oceanobservatories.org/
Cabled Array Core Instrument Analytical Data	Processed analytical data and metadata for a subset of Cabled Array instruments that collect fluid or particulate samples that are brought back to shore and analyzed in a laboratory	http://oceanobservatories.org/core-instrument-analytical-results
Interactive Oceans	Real-time data access and plotting portal specifically for the Regional Cabled Array	https://interactiveoceans.washington.edu/
Third Party Websites		
NANOOS Visualization System	Includes data and visualizations from OOI instruments in the NE Pacific (Endurance Array, Station Papa)	http://nvs.nanoos.org/
IOOS Glider DAC	OOI glider measurements are also made available here in a common format.	https://gliders.ioos.us/map/
IRIS	Real-time Seismology and hydrophone data from the Regional Cabled Array	https://www.iris.edu/hq/ http://www.fdsn.org/networks/detail/OO/
GitHub OOICloud Repository	Repository of tools for working with OOI data from across arrays in the cloud using Pangeo	https://www.ooicloud.org

Table 2. Concepts commonly covered in oceanography classes that could be addressed with data available through the OOI. The goal of the table is to identify concepts where OOI data are applicable and resources to illustrate these concepts already exist in the form of classroom-ready interactive data exploration tools and published papers. Many of the classroom-ready activities are aimed at the introductory level, but in many cases these concepts can also apply to upper level and graduate courses when explored in greater detail and complexity. The table also highlights several opportunities for future educational resource development that could further leverage the potential of OOI data in undergraduate classrooms.

Oceanographic Concept	**Ocean Region (OOI site) Showcasing the Concept**	**OOI Infrastructure**	**Educational Resources and Literature Examples**
Geology & Plate Tectonics			
Sea floor spreading (divergent boundary & mid-ocean ridge)	Axial Seamount, Juan de Fuca Ridge, North Pacific	Seismometer data	Tectonics and Seamounts Data Exploration Collection (see Axial case study) *(https://datalab.marine.rutgers.edu/explorations/geology/)* Figure 3 in Trowbridge *et al.* (2019)
Hydrothermal vent communities	Axial Seamount, Juan de Fuca Ridge, North Pacific	Videos, fluid temperature sensors	Time Lapse Videos *(https://ooi-website.whoi.edu/2017/09/new-computer-vision-routine-developed-for-camhd-time-lapse/)* Vent Video Frames Data Exploration *(https://datalab.marine.rutgers.edu/explorations/geology/activity5.php)* OOI Cabled Array Biology Catalog *(https://interactiveoceans.washington.edu/story/Biology_at_OOI_Cabled_Array/)*
Chemistry & Seawater Properties			
Temperature, salinity, density relationships and resulting stratification	Any site. High latitude polar sites (Station Papa & Southern Ocean) can be contrasted with coastal temperate sites (Endurance in the Pacific and Pioneer in the Atlantic). Or pick one site and follow the change over a whole season.	CTD data throughout the water column at discrete depths and on wire-following profilers	Properties of Seawater Data Exploration Collection *(https://datalab.marine.rutgers.edu/explorations/chemistry/)* Greengrove et al. (2019)
Clines: Thermocline, halocline, pycnocline,	Any site. Existing data explorations are from the	Vertical profiles of various properties	Properties of Seawater Data Exploration Collection

nutricline, oxycline, pH-cline	coastal North Atlantic (Pioneer) and North Pacific (Station Papa).	- CTD, nutrients, oxygen, pH	*(https://datalab.marine.rutgers.edu/explorations/chemistry/)* See the following Data Explorations: Halocline; Changes in Salinity with Depth Changes in pH with Depth (note that there are some data quality issues with pH data included here)
Physics & Water Movement			
Seasonal variations in temperature & salinity	Coastal ocean that receives seasonal runoff (Endurance) Offshore station with strong seasonal gradient (Station Papa). Differences in Northern vs. Southern Hemispheres (Irminger Sea vs. Southern Ocean)	Surface CTDs CTD data throughout the water column at discrete depths	Properties of Seawater Data Exploration Collection *(https://datalab.marine.rutgers.edu/explorations/chemistry/)* See the following Data Explorations: Seasonal Variation of Surface Salinity; Processes that Change Salinity
Ocean-Atmosphere interactions	Strong seasonal cycles/winter storm events: Southern Ocean and subpolar North Atlantic (Irminger Sea) Hurricane and extra-tropical storm signatures: coastal new England (Pioneer)	Surface buoy instrumentation in the air and at the sea surface	de Jong and de Steur (2016); Ogle *et al.* (2018); Josey *et al.* (2019) Figures of curated data showing the signature of extra-tropical storm Hermine captured by the Pioneer Array in 2016 *(https://datareview.marine.rutgers.edu/nuggets/view/11/)*
Upwelling	Coastal Pacific Washington shelf (Endurance); comparison with coastal Atlantic that does not experience upwelling (Pioneer)	Temperature and chlorophyll from surface moorings CTD data throughout the water column at discrete depths and on profilers	Chlorophyll-a Inshore vs. Offshore Data Exploration *(https://datalab.marine.rutgers.edu/explorations/productivity/activity6.php)*
Deep water formation	North Atlantic (Irminger Sea)	CTDs on the wire-following profiler	de Jong and de Steur (2016); de Jong *et al.* (2018)
Water mass identification with temperature-salinity diagrams	Offshore sites with multiple distinct water masses (Argentine Basin is a good example from South Atlantic)	CTD data throughout the water column at discrete depths and on profilers	Opportunity for new educational resource development
Biology			

Primary Production (Seasonal and Latitudinal Variation)	Comparison of temperate and polar sites (Endurance and Irminger Sea)	Chlorophyll, nitrate from surface moorings	Primary Productivity Data Exploration Collection (see Primary Productivity example) *(https://datalab.marine.rutgers.edu/explorations/productivity/)*
Relationship between photosynthesis and dissolved gases	Strong productivity cycles in subpolar North Atlantic (Irminger Sea). New resources could be developed to add coastal arrays (Endurance and Pioneer).	Oxygen and chlorophyll vertical profiles and time series data from surface moorings	Worksheet D in the Primary Productivity Data Exploration Collection (see Primary Productivity example) *(https://datalab.marine.rutgers.edu/tos-lesson-plans/)*
Zooplankton & predator/prey relationship	Example of diurnal variation and influence of solar eclipse (captured at Endurance)	Acoustic backscatter, light sensors	Figure 6 in Barth *et al*. (2018)
Euphotic Zone Depth	Compare coastal with an open ocean site (e.g., North Pacific Coastal Endurance, Ocean Station Papa)	Light sensors, chlorophyll	Opportunity for new educational resource development
Integrative			
Hypoxia	Oxygen Minimum Zone, Washington Shelf (Coastal Endurance)	Oxygen sensors, nitrate	Figure 4 in Barth *et al.* (2018) Anoxia Data Lab (*https://datalab.marine.rutgers.edu/explorations/2019/anoxia.php*)
Coastal Ocean Acidification (relationship with upwelling, low O_2)	Compare coastal ocean pH with open ocean site, North Pacific (Coastal Endurance, Ocean Station Papa)	pH, sea surface temperature, oxygen from surface moorings	Opportunity for new educational resource development (updated pH data to come online soon)

Table 3. Examples of Existing and Emerging Resources for using OOI Data in Education

Resource Description	Example OOI Data Used	URL
OOI – Data Explorations		
The OOI Ocean Data Labs project is developing, testing, refining, and disseminating easy to use, interactive data widgets from both the Data Explorations and Data Labs projects that will allow undergraduates to use authentic data in accessible ways, while being easy for instructors to integrate into their teaching.	● Exploring Primary Production with OOI Data ● Exploring Properties of Seawater with OOI Data ● Exploring Tectonics & Seamounts with OOI Data	https://datalab.marine.rutgers.edu
OOI Educational Data 'Nuggets'		
Through the OOI Synthesis and Education Project, data are being thoroughly reviewed for quality and educational possibilities. A collection of data "nuggets" are being identified for possible use in the development of future activities. Each nugget consists of one or more instruments, an identified timeframe, and an interesting story or process, which students could investigate by delving into the data. The collection provides a go-to source for faculty interested in useful datasets to engage students in the OOI dataset.	● Global Irminger seasonal seawater temperature cycle ● Global Station Papa mixed layer depth ● Endurance- Biofouling for Dissolved Oxygen Sensor ● Endurance - Covariation of Salinity and Density ● Global Argentine BasinSeasonal phytoplankton cycle ● Pioneer - Signature of storm Hermine in upper ocean ● Pioneer - An eddy ring entrains shelf water	https://datareview.marine.rutgers.edu/nuggets
Project EDDIE		
Project EDDIE (Environmental Data-Driven Inquiry and Exploration) is a suite of educational projects that includes flexible classroom teaching modules using large, publicly available, sensor-based data sets.	Project EDDIE is newly funded to develop 40 data centered teaching modules and actively seeking collaborators to develop OOI-focused modules.	https://serc.carleton.edu/eddie/index.html

Table 4. Widgets used in Example Applications available through the OOI Data Exploration portal (https://datalab.marine.rutgers.edu/explorations)

Widget	URL
Primary Production	https://datalab.marine.rutgers.edu/explorations/productivity/
Chlorophyll in Temperate Zones	https://datalab.marine.rutgers.edu/explorations/productivity/activity4.php
Chlorophyll near Polar Zones	https://datalab.marine.rutgers.edu/explorations/productivity/activity5.php
Chlorophyll Across the Year	https://datalab.marine.rutgers.edu/explorations/productivity/activity2.php
Chlorophyll Inshore vs. Offshore	https://datalab.marine.rutgers.edu/explorations/productivity/activity6.php
Chlorophyll Across the Globe	https://datalab.marine.rutgers.edu/explorations/productivity/activity3.php
Chlorophyll and Nitrate	https://datalab.marine.rutgers.edu/explorations/2019/chl_nitrate.php
Exploring Tectonics & Seamounts	https://datalab.marine.rutgers.edu/explorations/geology/
Geologic Features of a Seamount	https://datalab.marine.rutgers.edu/explorations/geology/activity2.php
Seamount Diking-Eruption Event	https://datalab.marine.rutgers.edu/explorations/geology/activity3.php
Salinity	https://datalab.marine.rutgers.edu/explorations/chemistry/index.php
Processes that Change Salinity	https://datalab.marine.rutgers.edu/explorations/chemistry/activity2.php
Surface Salinity Seasonal Variation	https://datalab.marine.rutgers.edu/explorations/chemistry/activity1.php
Halocline	https://datalab.marine.rutgers.edu/explorations/chemistry/activity6.php