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Impact of ocean acidification on marine ecosystems: educational challenges and innovations

G. Fauville · R. Säljö · S. Dupont

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Abstract Population growth and social/technological developments have resulted in the buildup of carbon dioxide (CO_2) in the atmosphere and oceans to the extent that we now see changes in the earth's climate and ocean chemistry. Ocean acidification is one consequence of these changes, and it is known with certainty that it will continue to increase as we emit more CO_2 into the atmosphere. Ocean acidification is a global issue likely to impact marine organisms, food webs and ecosystems and to be most severely experienced by the people who depend on the goods and services the ocean provides at regional and local levels. However, research is in its infancy and the available data on biological impacts are complex (e.g., species-specific response). Educating future generations on the certainties and uncertainties of the emerging science of ocean acidification and its complex consequences for marine species and ecosystems can provide insights that will help assessing the need to mitigate and/or adapt to future global change. This article aims to present different educational approaches, the different material available and highlight the future challenges of ocean acidification education for both educators and marine biologists.

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G. Fauville (✉) · S. Dupont
The Department of Biological and Environmental Sciences, University of Gothenburg, The Sven Lovén Centre for Marine Sciences, Kristineberg, 451 78 Fiskebäckskil, Sweden
e-mail: geraldine.fauville@loven.gu.se

R. Säljö
Department of Education, Communication and Learning, University of Gothenburg, 405 30 Gothenburg, Sweden

Introduction

Ocean acidification (OA) is now recognized as "the other CO_2 problem" in addition to global warming (Turley and Blackford 2005). Population growth and social/technological development have resulted in the buildup of carbon dioxide (CO_2) in the atmosphere and oceans to the extent that we now see changes in the earth's climate and ocean chemistry. If the atmospheric partial pressure of CO_2 continues to increase at current rates as we emit more CO_2 into the atmosphere (through the burning of fossil fuels, cement manufacturing and land use change), global oceanic pH will fall substantially. Simulations highlight the importance for quick mitigation. Without any mitigation, the global mean surface pH can decrease from 8.15 to 7.67 by 2100. Only strong and urgent mitigation, emissions peaking in 2016 and reducing by 5 % per year, are shown to limit this minimum to 8.02 (Bernie et al. 2010). Rising atmospheric CO_2 levels attributable to human activity have already reduced ocean pH by approximately 0.1 units. Recent estimations suggest that a global reduction of up to 0.4 pH units (corresponding to a doubling in acidity) over the coming 100 years is possible in an uncontrolled emission scenario (Caldeira and Wickett 2003). These global changes will have different consequences at the local scale depending on local natural and anthropogenic status. For example, CO_2-driven acidification will be exacerbated by the deposition of acidic sulfur and nitrogen oxides (SO_x and NO_x) in heavily trafficked shipping lanes (Hunter et al. 2011) or by the eutrophication in coastal zones (Borges and Gypens 2010).

A growing body of evidence demonstrates that OA alone, or in synergy with other stressors, can have direct and indirect impacts on marine species and ecosystems, including potential extinction of keystone species (e.g.,

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Dupont et al. 2008). These marine ecosystems provide goods and services to humankind, including serving as a food source that many nations and billions of people depend upon as their main protein source. However, despite growing research efforts, OA research is still in its infancy and many gaps in knowledge (e.g., the extent of species-specific impacts, long-term effects, evolutionary perspectives, ecological interactions) make any local or global prediction of OA impacts on marine ecosystems and their goods and services difficult (e.g., Hilmi et al., this issue). Despite this complexity, both at chemical and at biological levels, and the related uncertainties, OA is a fact and is expected to have significant impacts on marine ecosystems with subsequent consequences for humankind. A failure to deal efficiently with these problems risks causing a decrease in protein supply and a reduction in other valuable goods and services provided by oceans.

OA, like climate change, is a global issue and it is not possible to alleviate CO_2-driven acidification at a local scale only by reducing local/regional emissions. This requires reduced global CO_2 emissions and consequent CO_2 concentrations in the atmosphere. Reducing acidification due to other sources (e.g., SO_x and NO_x) may, however, be possible by cutting these emissions at local/regional scale. Other actions should also be implemented, for example, reduction in other environmental stressors (e.g., overfishing) and the development of marine protected areas that maintain and restore function and increase the resilience of marine ecosystems (Hugues et al. 2010).

Society's handling of environmental problems typically boils down to policy; either by politicians handing over responsibility and action to the market through the use of market-based policy instruments (e.g., taxes, subsidies, trade instruments) or via legal and other regulations that steer or encourage society's actors to take on more pro-environmental behaviors (Sterner 2003). One of the most popular policy instruments—among both policy makers and most of society's actors—is information. However, research typically demonstrates that information is a weak policy instrument but can play an important role in regard to environmental politics by raising the public's (environmental) problem awareness (Sterner 2003). This awareness is assumed to increase public acceptance of other policy instruments that are more efficient such as environmental taxes or legal regulations. However, informing citizens does not lead so easily to the adoption of environmentally friendly behavior. First of all, the more complex the environmental problem, and thus more difficult to communicate, the less likely information about the problem at hand will affect individuals' behavior. Secondly, citizens' attitude and belief are resistant to change since the public tends to engage in motivated reasoning where they dismiss evidences challenging their prior belief and favor supportive evidence (Taber and Lodge 2006). Finally, corrective information seems to fail to reduce misperceptions (or even strengthen misperceptions) if they threaten one's ideology as suggested by Nyhan and Reifler (2010). As a consequence, using information as an attempt to increase public awareness of OA, to change individual behavior (e.g., reduce individual direct and indirect CO_2 emissions) and to increase political engagement and acceptance of the needed policy instruments is not enough. A solid understanding of science (science literacy), marine ecosystem and complex environmental changes, including OA, is needed to allow citizens to make well-informed choices and then be able to contribute to both their everyday life and the public debate in a participatory democracy. Moreover, there are different ways to present environmental facts to trigger behavior change among citizens, and recent studies indicate that focusing on the social values might be a more efficient trigger for a long-term success rather than focusing on personal wealth (Crompton 2011).

The main institution responsible for communicating science literacy to citizen is the school. However, in recent decades, new institutions such as science centers, museums and aquaria have come to play an increasing role. This article will present the different instructional strategies that have been used so far to promote OA knowledge in the classroom (formal education) and in science centers, aquaria, natural history museums (informal education) and discusses the importance of the evaluation process. Of course, OA cannot be taught properly unless there is an already reasonable science education foundation to build upon. Thus, science education is a key prerequisite to provide the knowledge citizens need to take informed decisions.

Science, environmental and marine education

Today, citizens encounter a number of science-related issues that are part of the public debate; for example, the advantages and risks of gene-modified organisms in food production or the impact of various energy sources on the environment. As a consequence, scientific insight is needed to participate in political decision making and a limited understanding can have direct negative consequences on society. For example, the fraudulent publishing about a possible link between measles, mumps and rubella (MMR) vaccine and autism (Wakefield et al. 1998; Deer 2011) received considerable media attention and led to public suspicion and a decreasing percentage of MMR vaccine uptake followed by a measles outbreak in the United Kingdom (Jansen et al. 2003). Issues related to climate change and OA may also be victim to similar risks of simplified and partially incorrect arguments spreading in the public debate. Moreover, for many years, groups of deniers (often affiliated to fossil fuel or free market think thanks) have aimed at inserting climate controversy in media trying to respect the norm of balanced reporting by covering both sides of any debate. Despite the consensus among climate change scientists, this journalistic norm biased the coverage of climate change information causing the spread of misinformation (Boykoff and Boykoff 2004; Antilla 2005). Fortunately, this "balanced" issue, mainly reported within the US newspapers, has declined since 2005 in favor of reports more closely reflecting the consensus among scientists (Boykoff 2007). Nevertheless, nowadays, the content and frequency of climate change information provided by different media varies greatly holding consequences in how the public understands and considers climate change (Feldman et al. 2011). In that respect, citizens need to maintain a critical attitude toward climate change information provided by media.

Citizens need to develop adequate science literacy with relevant knowledge and skills required to function in a society that is both increasingly complex and "science and technology dependent" (Linder et al. 2011; Roth and Désautels 2004). The interest in science generally develops before the age of 14 (Osborne and Dillon 2008) and it is therefore important to provide stimulating learning environments in which children and young people discover the excitement of studying science. However, many studies have documented a decline in students' interest in science and mathematics (Rocard et al. 2007). Recent work indicates that over the last decade, the proportion of students studying science in many parts of Europe has decreased, while more than eighty percent of European citizens consider that "young people's interest in science is essential to our future prosperity" (European Commission 2005). The Eurobarometer pointed out that Europeans consider themselves poorly informed on issues concerning science and technology. Moreover, there is an obvious link between a weak interest and a lack of information (European Commission 2005). The public perception of scientists is also somewhat ambiguous; on the one hand, citizens see the positive role of scientists in our society, and on the other hand, they are concerned about the obscurity surrounding scientific results and the way information and research results are communicated to the public.

Across the globe, there is an intense effort aimed at developing science teaching and learning for the future (Osborne and Dillon 2008; Rocard et al. 2007). The main recommendation emerging from such activities is the promotion of student-active forms of learning, which allow for hands-on experimentation and exploratory activities in a manner that makes the topics studied relevant and exciting to pupils. Teaching should focus mainly on learning about scientific concepts and reasoning, methods and ways of doing research, rather than on retaining information, which is the current focus in many parts of the world. An obvious dilemma for school systems is that the production of information and knowledge is so enormous that schools cannot keep up. One solution to this rapid development of science is to try to engage children in research activities that allow them to see how important problems are formulated, investigated and how one finds answers that are relevant and trustworthy. It is important that current curricula (set of courses, and their content, offered at a school or university) are redesigned to reflect prominent issues in modern science and to highlight the role of scientific knowledge in society (Rocard et al. 2007).

The interest in environmental teaching and learning methods has increased dramatically in the past decade. However, these issues are complex and multidisciplinary in character, involving knowledge from many fields (natural and social sciences, humanities, law, etc.), while most curricula in European school systems are still designed on the basis of traditional disciplines. Thus, teachers and schools need support to take on the challenges of teaching and learning about climate change (including OA), and teaching has to be innovative and engage young people in exploring these issues in novel ways.

Some educational resources start to be dedicated to OA. The next section will highlight the weakness and strengths of the available resources as well as point to the importance of future collaboration between marine scientists and educators. It will demonstrate how environmental education and marine biology need to be interconnected to foster fruitful ocean and OA literacy among citizens who will then have the tools to preserve the marine environment through action and decision.

While learning science can occur in a large number of settings and from different sources, there are two main contexts: formal and informal education. Formal education takes place in schools, upper secondary schools and universities and is guided by a curriculum. Participation at mandatory and voluntary levels of education is increasing rapidly in the world. However, learning is not limited to formal education. Much informal learning takes place through media (newspapers, radio and television), and the Internet serving as an increasingly important channel for both the provision and discussion of information. In addition, in many societies, we have seen institutions such as museums, sciences centers, zoos and botanical gardens assume an increasingly important role for learning. In such settings, temporary and permanent exhibitions often deal with issues related to ecology, climate change and threats to the environment. The next sections aim to introduce different learning opportunities in formal and informal education and describe how those opportunities have or have not yet been used to promote OA literacy (see Table 1 for a review of OA educational resources).

Table 1 Educational resources available on OA

Category	Name	Institutions	URL	Evaluation	Language
OA background information	FAQ	OCB, EPOCA, UKOARP	http://www.whoi.edu/OCB-OA/FAQs/	Not evaluated	English, French, Chinese, German
	Factsheet	EPOCA, CarboSchools	http://www.carboeurope.org/education/epoca-july2009_single_pages.pdf	Not evaluated	English, French
	Factsheet	EUR-OCEANS	http://www.ocean-acidification.net/OAdocs/FS7_oceanacidification.pdf	Not evaluated	English
	Factsheet	The Pew Charitable Trusts NOAA	http://www.pmel.noaa.gov/pubs/PDF/feel2899/feel2899.pdf	Not evaluated	English
	Factsheet	Digital explorer	http://oceans.digitalexplorer.com/resources/fact-sheets/	Not evaluated	English
	Factsheet	NOAA	http://www.pmel.noaa.gov/co2/files/noaa_oa_factsheet.pdf	Not evaluated	English
Teacher training	ScienceBridge	UC San Diego	http://sciencebridge.ucsd.edu/programs/sciencebridge-labs/content-areas/ocean-acidification	Not evaluated	English
		Digital explorer	http://oceans.digitalexplorer.com/training/	In progress	English
	Geosciences Information For Teachers (GIFT)	European Geoscience Union	http://www.egu.eu/fileadmin/files/GIFT/gift_brochure_penang_2011.pdf	Increase in teachers OA awareness and will to dissemination OA information (Laj, personal communication)	English
Hands-on experiment	OCB OA laboratory kit	OCB	http://www.nrdc.org/oceans/acidification/files/labkit.pdf	Not evaluated	English
	ScienceBridge	UC San Diego	http://sciencebridge.ucsd.edu/programs/sciencebridge-labs/content-areas/ocean-acidification	Not evaluated	English
	C-MORE Science Kit to loan	C-MORE	http://cmore.soest.hawaii.edu/education/teachers/science_kits/ocean_acid_kit.htm	In progress	English
	COSEENOW	COSEE	http://coseenow.net/files/2010/12/Ocean-Acidification.pdf	Not evaluated	English
	Experiment ideas	Digital explorer	http://oceans.digitalexplorer.com/resources/experiment-ideas/	In progress	English
	Climate Change & Coral Activities	NOAA Coral Reef Conservation Program	http://coralreef.noaa.gov/education/oa/resources/climate_change_corals_activities.pdf	In progress	English
Virtual hands-on experiment	Acid Ocean virtual lab	Inquiry-to-Insight (University of Gothenburg and Stanford University)	http://i2i.loven.gu.se/AcidOcean.htm	Positive effect on learning outcome (Fauville et al. 2011; Petersson et al. 2011)	English, French, German, partly Mandarin, Portuguese in progress
	e-CO_2 School Lab	University of Trieste and University of Gothenburg	http://dsvs1.units.it/eco2/	In progress	English, Italian

Table 1 continued

Category	Name	Institutions	URL	Evaluation	Language
Students as knowledge creators and as community educators	The Other CO_2 Problem	Ridgeway School and PML	http://www.youtube.com/watch?v=55D8TGRsl4k (English) http://www.youtube.com/watch?v=KqtxGZKItS8 (French) http://www.youtube.com/watch?v=ywOcLrISzCE&feature=youtube (Spanish) http://www.youtube.com/watch?v=55D8TGRsl4k (Italian)	Not evaluated	English, French, Spanish, Italian, Catalan (in progress)
Scientists-students interaction	Ask a scientist	EPOCA, CarboSchools	http://www.epoca-project.eu/index.php/what-is-ocean-acidification/ask.html	Not evaluated	English
	EPOCA blog	EPOCA	http://epocaarctic2010.wordpress.com/	Not evaluated	English, German, Norwegian, French
	Interactive online presentation	Inquiry-to-Insight (University of Gothenburg and Stanford University)	http://voicethread.com/share/1978581/	Planned in 2012	English
Multimodal learning experiences	SOAP	Crystal Cove Alliance	http://soapglp.org/	Not evaluated	English
Analyze of scientific data in the classroom	NODE	Data in the classroom	http://www.dataintheclassroom.org/content/oa/	In progress	English
Films	Acid Test	Natural Resources Defense Council	http://www.nrdc.org/oceans/acidification/aboutthefilm.asp	Not evaluated	English
	Tipping Point	EPOCA	http://www.youtube.com/watch?v=J8XqYvgxmCo&feature=youtu.be	Not evaluated	English, French
	Acidification de l'océan	EUR-OCEANS	http://www.eur-oceans.info/Resources/PlayerVideo.php?film=acidification_english.flv (English) http://www.eur-oceans.info/Resources/PlayerVideo.php?film=acidification.flv (French) http://www.eur-oceans.info/Resources/films.php (German and Spanish subtitles available)	Not evaluated	English, French, German, Spanish
	A sea change	Niijii Films	http://www.aseachange.net	Not evaluated	English
	Ocean acidification: Connecting science, industry, policy and public	PML and UKOARP	http://www.youtube.com/watch?v=_BPS8ctVW2s	Not evaluated	English, French subtitles
	Ocean acidification—Hermie the hermit	GBRMPA	http://youtu.be/RnqJMInH5yM	Not evaluated	English
	Ocean Acidification in a nutshell	Greenpeace	http://www.youtube.com/watch?v=d0kacyyLVB4	Not evaluated	English
	NOAA OA demonstration	NOAA	http://www.youtube.com/watch?v=xuttOKcTPQs	Not evaluated	English
	Rob Dunbar: The threat of ocean acidification	TED	http://www.youtube.com/watch?v=evfgbVjb688	Not evaluated	English

Table 1 continued

Category	Name	Institutions	URL	Evaluation	Language
Podcast	Adapting to OA	NERC, PlanetEarth Online	http://planetearth.nerc.ac.uk/multimedia/story.aspx?id=15	Not evaluated	English
	Rockpools and ocean acidification	NERC, PlanetEarth online	http://planetearth.nerc.ac.uk/multimedia/story.aspx?id=789	Not evaluated	English
	Confronting Ocean Acidification	ScienceNow	http://news.sciencemag.org/sciencenow/2010/02/podcast-confronting-ocean-acidif.html	Not evaluated	English
		Ask Science Dude	http://asksciencedude.info/podcast-episode-21-ocean-acidification	Not evaluated	English

OA in formal education

To introduce OA in a curriculum (course content), a teacher needs to find relevant background information and/or teaching methods. The lack of science professional development programs is mentioned by many teachers as a major limitation. Journals targeting educators (e.g., Bioscience Explained or Current) are a valuable but limited source of information since it is dependent on subscription, editorial choices and scientist personal involvement. The Internet is the most accessible source of information, but the quality of the information offered is extremely variable. The most reliable source of information is the peer-reviewed research publications but they may not be available at school districts for budget reasons, and when available, the content might be too narrow, specific or difficult to understand. The available options for teachers are websites from well-established institutions providing documentation specifically designed for broader audiences. For example, factsheets, frequently asked questions (FAQ) and leaflets published by OA consortia or by marine research centers are good source of reliable information for teachers. The FAQ produced in collaboration between OCB (Ocean Carbon and Biogeochemistry), EPOCA (European Project on OCean Acidification) and UKOARP (UK Ocean Acidification Research Programme) provides peer-reviewed answers to the most common questions related to OA in an accessible language. In total, 27 scientists from five countries contributed to the whole process of organizing the site and the FAQ is now available in four languages (English, French, Chinese and German). Such initiatives play a critical role in providing reliable information on OA. Unfortunately, no evaluation or quantitative information is available on how this information was used by teachers or students and what the impact of this education initiative is.

Apart from collecting valid information on OA, teachers need to find a way to implement the OA topic in the curriculum. In that respect, teacher training is central in the attempts to increase attention about OA. Teacher training is organized very differently around the world. In some countries, teacher training is part of universities, and here there should be possibilities to introduce teaching and learning about OA as part of teacher programs through collaboration between scholars with relevant backgrounds. In other countries, teacher education is organized outside the regular university system, which may make it difficult for lecturers and students to establish contacts with research on climate change and OA. Another very important issue is to reach teachers who are already active through in-service training targeting OA. This is quite a demanding task since the number of teachers is so large and considerable resources are necessary for reaching large proportions of practicing teachers. One interesting initiative in this field is ScienceBridge at UC San Diego (UCSD). This outreach initiative engages scientists in education and provides science teachers and their students with opportunities to learn about current scientific research. ScienceBridge offers training on different topics including OA. The teachers and two or three of their students (the latter will become "student leaders" when back in the classroom) come to UCSD and are introduced to OA by a climate change scientist and then separated into two rooms. The teachers get a more in-depth presentation on the science of OA (chemistry, biology, etc.) and learn two experiments to run in their classroom. Meanwhile, the students discuss their roles as leaders in the classroom and engage in an activity about how the ocean and its inhabitants are affected by increased CO_2. Teachers and students are then reunited and teachers guide the students through the laboratory experiments learned early. Later on, the students learn about calcifying organisms and about their life cycle, feeding habits and different types of shells. In 2 years (September 2009–November 2011), 82 teachers have been trained, 63 teachers have implemented the activity and approximately 6,360 students have participated in the laboratory activity. Additionally, the curriculum available online has been downloaded from the website 2,363 times.

Instructional activities are regulated by curricular restrictions and regulations of time. A concrete problem for teachers is how to make space in the schedule for activities that will allow students to learn about OA. For such themes to enter schools, there must be teaching materials and outlines of instruction that teachers can adopt for their own purposes and the time available. Topics of teaching have to be suggested, and indications of how teaching and learning could be organized to provide insights into OA should be prepared. In the following, we will briefly describe examples of such innovative resources that may be introduced into classrooms for teaching about OA and related areas.

Hands-on experiment

To understand science and scientific reasoning, students have to be introduced into the nature of scientific work. It is not enough to learn about the products of science, one must also find out how scientists work and analyze what they study. Many argue that instruction in science should be based more on experimentation that allows students to follow the scientific process of formulating problems, testing hypotheses, analyzing data and finding answers. As already John Dewey (1938) argued, in order to learn, we should have a question or something that we want to find out as a background for our activities. This is the principle of learning through "inquiry," and experimentation is a manner of learning how to find answers.

Several laboratory kits on OA are available online (Table 1). Teachers can either borrow a laboratory kit coming with different devices or buy the items required to run the experiment. For example, the OA laboratory kit created by the Ocean Carbon and Biochemistry Program based at Woods Hole Oceanographic Institution gathers a series of hands-on experiments that are low-cost and targets students aged 11–18. Most of the materials required can be found at grocery and pet stores. In the laboratory setup notes, hints and ideas are provided in order to adapt these exercises to match teachers' time and resources. By themselves, these laboratories will not fully explain OA to students, but they will complement teachers' classroom presentations of the issue. On the other hand, the C-MORE OA Science kit includes all lesson materials needed to integrate OA lessons in the classroom. On the website, one can download key introductory materials such as PowerPoint presentations, answers to verify students' answers and optional readings. Teachers can send a request to borrow a kit containing material to perform two lessons in the classroom.

First, students compare the effect of adding vinegar to basalt and carbonate sand. In lesson 2, students generate carbon dioxide (CO_2) with yeast and sugar. The CO_2 generated in is bubbled into water where students measure the pH change. The results of the experiment are graphed by the students and compared to oceanographic data collected by the Hawaii Ocean Time-series. The kit contains all equipment requested to perform the two lessons with five groups of students (e.g., data recorders, CO_2 probes, water heater, scissors). Also included are a teacher guide, teacher answer keys, pre-/post-surveys, PowerPoint presentation, script, student worksheets and articles.

Little information is available on the impact of such initiatives. However, C-MORE was used by 7,000 students and a formal assessment with pre- and post-test in order to test knowledge gain is in progress (Foley personal communication).

Virtual hands-on experiment

Digital tools offer new possibilities for organizing learning activities in many areas. During the past decades, digital learning environments have become more flexible and allow for interactivity. Many of these resources are web-based and can be accessed from the classroom. In this development, the possibilities of performing virtual experiments have increased in many areas such as physics, chemistry and the life sciences (e.g., Shim et al. 2003). Virtual experimentation implies that students can study phenomena that are difficult, even impossible, to experiment with in the traditional school context. In the virtual setting, scenarios that mimic complex changes in nature that extend over long periods of time can be designed. This is particularly promising in the field of climate change and OA, where the effects of various projected changes in CO_2 levels may be observed. To date, only two virtual laboratories have been developed on OA (Acid Ocean Virtual laboratory and e-CO_2 School Lab, Table 1), where students virtually reproduce complex experiments testing the impact of OA on sea urchin larvae and coralline. The Acid Ocean Virtual laboratory starts with general background on acidification and its possible biological impacts on calcifying organisms. Then, students enter the virtual laboratory, where they investigate the impact of OA on sea urchin larvae development. They run an acidification experiment, measure larvae size, calculate means and analyze and interpret their data. All the data used are provided by scientists working on ocean acidification. In the process, students not only recreate an experiment, but they also learn important general scientific issues related to sample size, replicates and statistical validity. Preliminary evaluation results indicate that this activity significantly increases students' knowledge on OA (Fauville et al. 2011) and improve their scientific way of thinking (Petersson et al. 2011). The French version was funded by EPOCA, while the German one was funded by POLMAR.

Field experiment

Outdoor field visits and experimentation offer important opportunities for learning. Pupils can go to nearby points of interest and make observations relevant to learning about OA. Through such activities, one may learn how to observe and document information relevant for investigating phenomena in nature. The SOAP project (Table 1) has been organizing OA field trips for about 1,200 students in the past 3 years in the Crystal Cove State Park, California. During the field trip, students collect water samples from different locations and measure parameters such as temperature and pH along with tide level, weather. The data feed a database common for all the students participating.

Students as knowledge creators and as community educators

Learning is not only acquiring knowledge as an individual. Opportunities for learning and understanding scientific issues will increase when knowledge is acquired and integrated into social activities; for instance, engaging students in community projects where the target of their activities is to contribute to making important local and global issues accessible to other citizens. An illustration of this is the short animation created by fifteen students from Ridgeway School in Plymouth, UK. They were involved in an OA project and created an 8-min clay animation called "The Other CO_2 Problem" aiming to educate and inform all citizens, including other children (Table 1). The students used a low-tech approach of clay modeling to create the stars of the film, and then followed up with sophisticated computer-based animation techniques. They researched the topic, planned the story board and wrote and performed the stars' voice-overs. While students gave positive feedback, the learning impact of this project on student participating was not formally evaluated. This animated movie is also a great dissemination resource. In order to reach more students across Europe, the movie was translated in French by EPOCA and the Institut océanographique, Fondation Prince Albert 1er, Prince de Monaco. The Spanish, Catalan and Italian version were funded by MedSeA (Mediterranean Sea acidification in changing climate).

Scientists–students interaction

Another mode of engaging young people in science is to organize activities where students have the opportunity to interact with researchers. Direct contact with scientists (e.g., visits at research facilities or scientists in the classroom) can be critical to instilling a life-long interest in science. But such arrangements are also quite difficult to organize on a large scale owing to practical limitations. The OA scientific community has made some attempts to use virtual solutions to foster discussion with students but with relatively low success. In June 2010, EPOCA created a webpage, where the public could send questions concerning OA to scientist. But after one and an half year, not a single question had been sent online. A team from the University of Gothenburg and Stanford University (Inquiry-to-Insight, Table 1) created an online multimedia conference using an online resource (Voicethread.com) allowing students to leave questions on the scientist presentation. The scientist can answer the questions creating an ongoing student–scientist discussion. Each classroom receives its own link to a private version of the interactive presentation. This allows a "private" discussion between the classroom and the scientist. This method of interaction will be evaluated in 2012, but informal evaluations highlighted students' enthusiasm.

Multimodal learning experiences

The recent advancements in digital technologies open for organizing learning environments that make use of multiple instructional methods and approaches. Virtual experimentation is one example, and such learning resources may be combined with traditional instruction, visits to museums and science centers, field trips where natural events are documented and analyzed.

The SOAP introduces OA to students through multidisciplinary lessons. During the first lesson, students collect seawater samples from the shoreline and record physical parameters such as temperature and pH. Using laboratory equipment, the students investigate how carbon dioxide in the atmosphere can increase acidity in the oceans. Later, students answer the question of which local shelled animals could be most affected by OA by measuring the loss of mass in different shell samples. Finally, they measure the average length of sea urchins larvae arms grown in normal and acidic ocean conditions in the Acid Ocean virtual laboratory (described above). Following data collection, the students create graphs to analyze their results and post it to the SOAP website to share with the other groups around the world.

Analysis of scientific data in the classroom

There is a growing interest in trying to close the gap between research, researchers and schools by establishing collaborations that give teachers and students a role in local research projects. This implies that specific parts of the documentary and analytical work that are carried out in projects (making observations, organizing data etc.) take place in classrooms, where teachers and students work with original data.

The NOAA Ocean Data Education (NODE) Project developed a resource for high-school students designed to help teachers and students to use real scientific data to explore OA and understand the impact on a regional or global scale. In order to help teachers implement the OA module in their classroom, NOAA organized day-long workshops during the summer 2011 attended by eighty teachers. During the workshops, educators learned to use real data from NOAA to teach ocean acidification and how it affects coral reefs and other marine calcifiers. The workshop was evaluated in terms of knowledge gains, effectiveness and materials with pre- and post-tests. The evaluations show that the materials are appropriate and helpful to teachers and that the workshop prepares them to use the materials in their classrooms and increases their knowledge of ocean acidification. Moreover, some teachers will be followed closely as they use the NODE module in their classroom. The learning outcomes for the students participating will be evaluated as well (Davis and Maurin 2011).

OA in informal education

In recent decades, there has been a worldwide development for trying to provide alternative contexts of learning, for instance, in terms of science centers and exhibitions at museums. These developments testify to the increased emphasis on offering informal opportunities for learning for children as well as adults in a world where knowledge is developing rapidly.

Science centers

Most aquaria, science centers and other science museums are very keen on covering the climate change issue through exhibitions, workshops and hands-on activities. Since OA is a relatively new topic, the coverage in informal education is still quite limited, although rising. For example, within the ACCENT project (aiming to strengthen the efforts of science centers and museums in nine European countries), the Universeum (Gothenburg, Sweden) raises public awareness about how emissions of carbon dioxide in the atmosphere are affecting the life into the sea through a combination of exhibition, hands-on, discussions and debates. The Lagos Live Science Centre (Portugal) has a permanent workshop called “Ecological Footprint” for students where the issue of OA is addressed. At the Oceanographic museum of Monaco, different actions are organized to educate the public to OA including movies, conferences and a temporary exposition.

Movies

Many movies and television programs have been made about environmental issues. These programs attract considerable audiences and contribute to sustaining an interest in environmental issues. Several movies have been produced on OA (Table 1), for example the 90-min film “A sea change”. This film includes many interviews of international leading researchers in OA. In 2010 “A Sea Change” won six awards in different film festivals across the world as well as the NOAA Environmental Hero Award.

Podcasts

Podcasts are episodic series of audio or video files that could be downloaded from the web to desktop or mobile devices such as mp3 players, smartphones and tablets. Podcasts have been increasingly used in higher education and have caught the researchers’ attention (Copley 2007;

Table 2 Costs and benefits of a range of educational resources./, free; +, low, ++, average, +++, high

	Cost for institution creating the resources		Cost for the school using the resources (school)		Potential of dissemination
	In time	In money	In time	In money	
Hands-on experiment	+ → ++	+ → ++	+ → ++	/ → +	+ → ++ (depending if material requested or not)
Virtual hands-on experiment	++ → +++	++ →+++	+	/	+++
Field experiment	+ →++	+ → ++	++ → +++	+ →++	+
Scientists–students interaction	++ → +++	+ → +++	+ → ++	/	+ → +++
Podcasts	+ → ++	+ → ++	+	/	+++

Bolliger et al. 2010). Podcasts present different educational advantages. The voice communication is more personal and brings information to life in a digital environment mainly dominated by images and text. Thanks to podcast, learners are more in control of their learning deciding where and when to use them (Donnelly and Berge 2006). For example, The Natural Environmental Research Council created two podcasts on adaptation to OA and the impact on rock pools.

TED talks

TED (Technology Entertainment and Design; http://www.ted.com/) is a global set of conferences created by Sapling Foundation, aiming to disseminate "ideas worth spreading". From 1990, TED became an annually event from 1990 hold in Monterey with a focus on technology and design. Nowadays, the TED events are held in Europe, USA and Asia and address a wide range of topics within the research and practice of science and culture. The TED speakers have maximum 18 min to share his topic in the most engaging and innovative way to the audience at the event and online. About a thousand talks are freely available online, and in June 2011, there has been more than 500 million viewing. One can regret that so far no talk have been dedicated to OA, but this issue has been mentioned in a few talks such as in Rob Dunbar talk "Discovering ancient climates in oceans and ice" where OA is highlighted as the most worrying issue related to climate change.

Discussion

In this paper, we described different teaching methods and illustrated what has been done in OA so far. All these methods have different limitations and teaching potentials summarized in Table 2. The decision to invest into the creation of any education material is then based on trade-offs between costs (time/money) and benefits. For example, a hands-on experiment can be created at relatively low-cost and does not imply additional costs for the schools but its dissemination potential is limited by the material requested. The more advanced experiments require specific material that the creating institution would need to make available to the schools. The number of kits available will limit the dissemination, and the management of such kits will increase the costs for the managing institution. A more basic experiment could be performed with material that the school can buy in general stores, but this increases the cost (in time and budget) for this activity. On the other hand, this material issue can be overcome by creating virtual hands-on experiments, but this comes with a high cost for the creating institution, while the school will be able to use it for a very low or no cost at all. The potential of dissemination is also very high, since it only requires an Internet connection.

Field experiments come with a variable cost for creating institutions and schools. The cost for the creating institution is minimal, if they only create a lesson plan describing how to organize a field experiment, but can be very costly for the school in charge of gathering the material needed and taking care of the traveling. Also, inevitably, security issues and other problems may arise. On the other hand, field experimentation can also be very time and money demanding for the creating institution if they decide to take care of the organization of the whole process. The potential for dissemination is limited, because there will always be high costs (for the school and/or creating institution) and such arrangements can only involve a limited number of schools.

Direct interactions between scientists and students are time-consuming for the scientist involved. However, the cost for the organizing institution and the scientist can be reduced if the interaction takes place on a digital platform rather than as a physical meeting. This method does not affect the school's budget, and the time allocation is relatively low. Finally, the dissemination potential varies highly depending on the method of communication used; scientists visiting schools will be very difficult to use on large scale but an online solution can reach a larger population.

In summary, among all the educational tools available, the virtual resources are one of the more expensive to develop but have the highest potential for long-term and large-scale dissemination. Moreover, these tools can easily be translated into different language without major additional costs.

Another key parameter to consider while choosing an educational tool is its efficiency. Table 1 illustrates the diversity of OA educational resources and highlights the lack of thorough evaluations. It is impossible to know which tools are the most effective or appropriate in different learning situations. This situation is partly due to the fact that these resources were mainly created by natural scientists lacking expertise in education science research and theories of learning. The learning potential of educational resources should be tested by an independent institution to avoid any conflict of interest. Moreover, most natural scientists are not trained in social science and have little experience in evaluation methods involving qualitative data acquisition and analyses. For example, evaluation may require to methods rarely used in biology such as videotaping of the students interacting with the educational resource in the classroom, interviews of students and teachers and/or using pre- and post-tests and questionnaires to compare knowledge gains and attitude changes (Repstad 2007). An early collaboration between marine biologists and education scientists is then suggested as a model of work. Secondly, it is relatively difficult to access to those resources created by different institutions around the world. Teachers interested in implementing OA in their curriculum will have to spend extra time for searching and trying to locate those resources. An institution eager to create an OA education resource will encounter the same problem and will either have to spend time investigating the OA tools already available or will stay unaware of what other colleagues have already created. In order to work toward a more integrated creation of OA resources, a more integrative approach is needed; for example through a website gathering and indexing the OA teaching resources. This repertoire could serve as meeting point for creators who could share best practices and be aware of potential pitfalls. The NOAA coral reef conservation program recently launched a webpage gathering some educational resources on OA created by US institutions. This is a step in the right direction, although a more international effort on OA education is still needed.

It is also important to remember that any educational resource is only a tool that is only be as good as the context in which it is used. At the end of the day, it is the activities of teachers and students that matter and that decide if a teaching resource is going to be productive. In that respect, it would be wise for institutions to suggest ways to integrate different resources (requesting collaboration between different institutions) in order to have an in-depth, multidisciplinary and relevant picture of this issue.

Conclusion

OA is a relatively new research area. However, there is an obvious and encouraging will from research institutions to communicate this marine environmental issue through formal and informal education. Despite this enthusiasm for education, the resources created are often developed without deep considerations of educational and dissemination issues, and they generally lack implementation and evaluation plans that would make it possible to assess their potentials. A more coordinated strategy is needed including collaboration between different institutions creating resources but also with specialists in education such as educators, teachers, social and education scientists. This would allow developing and implementing efficient resources that will not only integrate the scientific dimension but also the pedagogical one.

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