Research on Learning and Teaching Ocean and Aquatic Sciences

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To achieve an ocean and aquatic literate society, ocean and aquatic sciences must be valued and integrated into educational practice, research, standards, curricula, textbooks, and assessments. In addition, the ocean and aquatic sciences education community must draw upon research and theory in the learning and teaching of science, and ocean and aquatic sciences in particular. In this article, we summarize two publications that explore these arguments (Payne and Zimmerman, in press; Tran 2009), and situate the findings within the discussion of the Ocean Literacy Scope and Sequence for Grades K-12.

A Dearth of Educational Research: What is Missing and Why it is Important [a]

Earth systems science as a discipline, and ocean and aquatic sciences in particular, are poorly represented in K-12 national and state frameworks and standards (Hoffman and Barstow 2007; McManus et al. 2000), which often drive the curriculum, instruction, and assessment at the local, state, and national levels. Moreover, educational research has paid little attention to teaching and learning of ocean and aquatic science concepts in contrast to other well-studied areas of science such as chemistry, physics, and biology. The effects of this omission and oversight are reflected in a citizenry that has low knowledge and awareness of the concepts and environmental issues pertaining to ocean and aquatic ecosystems (Steel, Smith, Opsommer, Curiel, and Warner-Steel 2005; The Ocean Project 2009).

In a time when we are expected to comprehend and respond to increasingly complex socio-scientific issues (e.g., global climate change, environmental pressures on coastal and ocean resources, and biotechnology potential within the ocean), many people often do so with no more than a sixth grade understanding of how the natural world works and with a non-scientifically accurate understanding of the ocean (The Ocean Project 2009). Despite their limited knowledge, people, especially young people, are willing and interested to take action to protect the health of the ocean and the environment; they just need to know how (The Ocean Project 2009). Indeed, "improving the knowledge base of citizens should be the first step in establishing a nationwide effort to preserve the oceans (Steel, Smith et al. 2005). Furthermore, scientific literacy and technical knowledge are not the only factors influencing the public's decision making on environmental issues. It is important to note that while understanding the science is important for decision making, people also need to have and recognize personal and emotional connections to the phenomena (Steel, Lovrich, Lach, and Fomenko 2005). While 50% of the U.S. population lives within coastal counties, 50% have had little to no exposure to the ocean other than second-hand images (U.S. Commission on Ocean Policy's Report to the President and Congress 2004). Moreover, personal experiences, along with adequate resources and reliable educational research, are important to assist teachers in teaching ocean and aquatic sciences and related environmental stewardship.

There is, however, scant educational research specifically investigating students' understanding of ocean sciences concepts. Brody and Koch (1989-1990) reported that more than 86% of the elementary, middle, and high school students they studied did not know concepts essential to understanding ocean science and ocean resources. The students in this study also held non-normative ideas that would significantly impact their ability to make informed decisions about ocean resources. Ballantyne (2004) found students in South Africa had difficulties understanding ocean concepts, such as sources of salinity, wave propagation, and human impacts. Studies can be found describing particular components of the water cycle and/or climate, but few studies address larger system comprehension, including the interdependence and interactions of the multiple components that comprise the ocean system. However, recent educational research indicates that ocean and aquatic sciences, when integrated into curriculum and instruction, can be used as a model of a large-scale coherent theme to assist in student understanding of complex systems (Fortner, Corney, and Mayer 2005; Lambert 2006). In the absence of additional educational research focused specifically on ocean and aquatic sciences, we look instead to a systems-based approach to teaching and learning.

Learning and Teaching Ocean Sciences: A Complex Systems Approach [b]

Water and Carbon Cycles

While there is limited educational research on learning related to the seven Ocean Literacy Principles specifically, there is a body of literature on students' (Kindergarten to university) understanding of the scientific concepts and ideas underlying the principles that can be used to infer about their ocean literacy. These studies have investigated students' understanding of the water cycle, carbon cycle, density, evolution, and photosynthesis. This review concentrates on the water and carbon cycles in particular, as there is a larger collection of research pertaining to students' understanding of these processes, which allows for a depth rather than breadth of analysis. In addition, these processes are critical to understanding several Ocean Literacy Essential Principles and Fundamental Concepts, most notably Principle 1-c, f, g; Principle 2-a; Principle 3-a, b, c, d, e, f, g; and Principle 6-1.

A review of learning research in chemistry, physics, geology, ecology, environmental education, and systems dynamics provided several major insights. The research showed that having knowledge of conservation of matter and basic particle theory helped students understand the water cycle as the circular movement of water between sources and the atmosphere (Bar and Galili 1994; Johnson 1998; Tytler 2000). Most students, however, did not think of the water cycle as a complex system that occurred over great distances or time (Ben-zvi-Assarf and Orion 2005; Dickerson and Dawkins 2004; Shepardson, Wee, Priddy, Schelleberger, and Harbor 2008). Research on students' understanding of the carbon cycle primarily focused on phenomena—the greenhouse effect, global warming, and climate change. Studies revealed that students did not understand how carbon in the atmosphere affected climate and weather, with most thinking the depletion of the ozone layer led to global warming (Andersson and Wallin 2000; Boyes and Stanisstreet 1993; Groves and Pugh 1999; Lee, Lester, Ma, Lambert, and Jean-Baptiste 2007).

Only a few of these investigations examined students' understanding of the cycles as complex, global systems. These studies reported that when students considered the cycles at a localized place, water and carbon moved from one place to another but did not disappear into oblivion; when thinking about these cycles on a global scale or over time, however, even university students did not understand that water and carbon also should not disappear into oblivion. In other words, students held the concept of conservation of matter when thinking of the cycles locally, but not when considering the cycles as global systems (Ben-zvi-Assarf and Orion 2005; Sterman and Sweeney 2002). Understanding the water and carbon cycles as complex systems may be particularly important to ocean and aquatic science literacy, as the interrelations and interconnections of these processes, over distance and time, are fundamental to the concepts in the seven Ocean Literacy Principles. Emphasis on only individual processes leaves students to make connections between the cycles in a global system on their own, which they may not be able to do. Systems thinking is valued and supported in the National Science Education Standards (National Research Council [NRC] 1996). Studies on systems thinking offer insight to the challenges and strategies for learning and teaching about ocean and aquatic sciences in this way.

Complex Systems: Cognitive Challenge, Pedagogical Support

A complex system is an aggregate of components, all of which are necessary for the system to function (Ben-zvi-Assarf and Orion 2005). Complex systems are hierarchical in nature and have multiple interacting levels (Wilensky and Resnick 1999).

Sylvia Vitazkova and Claudio Vargas use a model of Earth to demonstrate ocean circulation during a Communicating Ocean Sciences Instructors' Workshop in Berkeley, California.

Put differently, the idea and entity of the system at higher levels (e.g., a traffic jam, respiratory system, water cycle) emerge from interactions of objects at lower levels (the cars, cells, water molecules), and is more than an accumulation of the parts. The system maintains stability through self-correcting feedback loops, and even small changes can have significant effects. Systems thinking is the ability to understand and interpret complex systems, and comprises numerous types and levels of thinking skills (Richmond 1993). Thinking in this manner is challenging and students need practice and experiences to become adept at looking at the world as an interconnected system.

The studies in this review reported that students and novices tended to have *a centralized mindset*; that is, they preferred explanations that assumed a single cause or an ultimate controlling factor (Penner 2001; Perkins and Grotzer 2000; Raia 2005; Resnick 1990, 1996; Wilensky and Resnick 1999). Students tended to offer simplified, direct cause-effect explanations for complex events, such as a lead goose causing geese to fly in a "V" formation (Penner 2000), tilt of Earth causing glaciation in the Northern Hemisphere (Raia 2005), and change in temperature can eliminate a species in a food web causing the web to collapse (White 2000). Researchers argued that such a mindset hindered students' ability to consider the effects of the interdependence and interconnection of components in a complex system. Additionally, in this mindset, students neglected emergent properties of complex systems (Penner 2000). Emergent properties are the features, characteristics, or objects of a system that "emerge" from interactions among the lower level properties, such as weather patterns arising from movement of water and air molecules. Students failed to recognize the importance of such factors as time and space when considering causal explanations of complex systems (Feltovich, Spiro, and Coulson 1993; Grotzer 2003), for instance, that it would take years to reduce the amount of carbon in the atmosphere even if anthropogenic input was significantly reduced instantaneously.

Furthermore, comparison studies between experts (scientists) and novices (students) revealed that in noticing the interconnectedness of components in a system, students tended to identify the parts within the system, while experts talked about how the parts worked and their roles in the system as a whole (Hmelo, Holton, and Kolodner 2000; Hmelo-Silver, Marathe, and Liu 2007; Hmelo-Silver and Pfeffer 2004).

Despite these learning challenges, researchers found several teaching methods that facilitated systems thinking skills. First, opportunities for students to use models, and more specifically, to create, manipulate, and revise models helped students think about complex systems. As a critical condition of this first point, students showed improvements when they had the chance to work with models over several iterations so that they could design their model, test out their ideas, rethink, revise, and retest multiple times (Edelson 2002; Hmelo et al. 2000; Kawasaki, Herrenkohl, and Yeary 2004; Penner, Giles, Lehrer, and Schauble 1997). There were also student gains in activities where they used computer-based learning environments (virtual models), such as virtual environments and hypermedia (Barab, Hay, Barnett, and Keating 2000; Evagorou, Korfiatis, Nicolaou, and Constantinou 2008; Kali, Orion, and Eylon 2003). Thus, models—virtual and physical—made the invisible, abstract, and intangible elements of the dynamic processes in complex systems visible, concrete, and tangible for students as they learned. Second, researchers noted that structure and guidance from knowledgeable and skilled classroom teachers was critical for learning. The teachers had systems thinking skills, understood the complex system, and provided support to the students as they struggled in doing the tasks. Third, opportunities for students to have control over their own learning experiences, as well as to talk about and reflect on their ideas with their peers helped students develop systems thinking skills.

The studies in this article provide three major suggestions for the ocean and aquatic sciences education community. First, a systems approach to critical concepts and processes, such as the water and carbon cycles, may support ocean literacy. Systems thinking has great explanatory and predictive power and it is worth the time and effort it takes to help our students achieve this skill. Second, understanding global processes from a systems perspective requires types of thinking skills that are challenging to develop. Strategies that can support systems thinking include: 1) ensuring that teachers have advanced pedagogical knowledge to scaffold student thinking; 2) designing activities that give students control to create and manipulate models (virtual and physical); and 3) providing opportunities for students to talk with peers to reflect on, articulate, and share their thinking. And finally, though not summarized above, informal learning environments (e.g., aquariums, museums, science centers) provide access to objects, organisms, and phenomena that create personal connections for learners. These personal connections have long-lasting effects on individuals' interests and motivations to learn and act (National Research Council [NRC] 2009). While the strategies described here might simply be considered "good teaching" for any science concepts, they may well be especially and disproportionately important, compared to other "good teaching" strategies, for helping students to understand concepts related to the ocean.

CONCLUSION

In sum, the Ocean Literacy Scope and Sequence for Grades K-12 is an instructional tool that shows how concepts in ocean sciences are interconnected, and thus it supports a systems approach for teaching and learning about the ocean. The conceptual flow diagrams for each principle guide users (including educators, curriculum and program developers, administrators) through a potential teaching and learning sequence. The ordering and building of these ideas across grade bands within each Ocean Literacy Principle illustrates how student thinking can be scaffolded from one developmental level to the next. Cross-references between principles within each grade band emphasize the interrelationships of concepts at a particular developmental level. Concepts conveyed by use of the conceptual flow diagrams and engaging learning experiences will allow students to reflect, articulate, and share their thinking; build personal connections that will have a long-lasting effect on their motivations to learn and act; and ultimately to become ocean literate.

AUTHORS' NOTES

[a] This first section is a summary of a chapter (Payne and Zimmerman, in press) in the upcoming monograph *The Inclusion of Environmental Education in Science Teacher Education*, set for publication in 2010 by the Association for Science teacher Education (ASTE).

[b] This second section is a summary of a paper commissioned (Tran 2009) by the National Research Council's Committee to Review NOAA's Education Programs. The paper reviewed the corpus of literature on students' understanding of the water and carbon cycles in order to offer insight on their ocean literacy, as these processes are critical to ocean literacy.

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