Children and adults' understanding of ocean and climate sciences

FINAL PAPER

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INTRODUCTION

The purpose of this paper is to inform the National Research Council's Committee to Review the NOAA Education Program on what is known about what people (children and adults) know and understand about ocean and climate sciences as identified and organized in the Ocean Literacy Principles and Climate Literacy Principles documents. This paper is organized into four sections to respond to the committee's requests. First, there is a brief discussion on terms used in this paper and referenced in the literature, such as misconception, alternative conception, and children's thinking. This section serves as a framework to consider the "evidence" used to determine knowing and understanding in subsequent sections.

The second section reports on what research says about what people know and think about the ocean and climate. Whilst there is a dearth of learning research in these domains specifically, there is a corpus of literature on people's understanding of the scientific concepts and ideas underlying the 14 Literacy Principles from which to extrapolate insight on people's ocean and climate literacy. These investigations include people's understanding of the water cycle, density, evolution, and photosynthesis. These concepts are important for ocean and climate literacy, though this section concentrates on the water and carbon cycles in particular, as these processes are critical to knowing about the ocean, climate, and their relationship. Moreover, there is a large body of research pertaining to people's understanding of these processes, which allow for a depth rather than breadth of analysis.

Section three examines the thinking skills that are essential for ocean and climate science literacy, and the teaching methods that support them. Indeed, understanding science requires an extensive skill set. The survey of the literature in this section concentrates on skills for understanding complex systems, since this perspective emerges in section two to be necessary and missing from people's knowledge of the water and carbon cycles. The final section examines the contributions of informal learning environments on ocean and climate literacy; as such environments gain prominence in contributing to science learning and are relevant to the NOAA's educational programs.

1. KNOWING & EVIDENCE

There is agreement in the education field that learners are active builders of their knowledge; they are not *tabulae rasae*—blank slates waiting for information to be transferred to them (Driver, Asoko, Leach, Mortimer, & Scott, 1994). Instead, educators are encouraged to inquire of their learners, "what is their prior knowledge? What knowledge are they activating when they encounter activities, content, and concepts?" And then, teach them accordingly (Ausubel, 1963). Alexander articulated the role of learners' prior knowledge in learning as: "one's knowledge base is a scaffold that supports the construction of all future learning" (1996, p. 89). Furthermore, within a constructivist view of learning, it is important to connect new knowledge to be acquired with existing knowledge that learners have, in order to promote meaningful learning (Limón, 2001). Thus, in valuing what learners already know, terminology such as alternative frameworks or conceptions, misconceptions, naïve theories or conceptions, preconceptions, students' or learners' ideas are plentiful (see Driver, 1995 for an extended review of the terminology). While there is not consensus on what term is best, and their differences are sometimes nuanced, it is clear that teaching begins with what the learner already knows. In this paper, we refer to learners' thinking as just that, learners' thinking, and also learners' ideas, conceptions, and understanding. Learners reveal their thinking—how they conceptualize the scientific concepts and ideas under study—through their comments, explanations, and responses in interviews, surveys, written work, class observations, and illustrations. Researchers compare learners' thinking with canonical explanations of these ideas to determine whether the learners understand and the extent to which they understand. In some cases, the researchers devise models of learners' conceptions in order to organize and explicate different ways of thinking, as well as evolution of ideas. The volume of studies, diversity of research methods, and age span of learners available in the literature that is reviewed here reveals how the range of thinking may be related to age, connected to instruction, associated with maturation and life experiences, divulged in conversations, and concomitant with understanding other concepts and ideas.

2. UNDERSTANDING OCEAN AND CLIMATE SCIENCES

A Survey of Surveys

National surveys of public knowledge, attitudes, behaviors, and perceptions of the ocean and climate are modest, though they offer an overview of what Americans know and think about the ocean and climate. The view is not pretty, but it is hopeful. The Ocean Project and AAAS independently commissioned national opinion polls of 1,500 and 2,400 American adults in 1999 and 2003, respectively (AAAS, 2004; The Ocean Project, 1999). Both reported that most Americans recognized human activities might have negative impacts on the ocean, though few believed that there was urgency to act or that their personal actions affected the health of the ocean and coastal regions. That said, many people remarked that they were willing to take personal actions and sacrifices for helping the ocean, such as eat less of certain kinds of fish and supporting government regulations. The Ocean Project's poll also found that the public possessed superficial understanding of the ocean, its functions, and its connections to humans and our activities. These findings were further supported by separate national and regional surveys conducted by academic researchers in Oregon (Steel, Lovrich, Lach, & Fomenko, 2005; Steel, Smith, Opsommer, Curiel, & Warner-Steel, 2005). In a large scale survey of ocean knowledge among American adults in the Pacific Northwest (N=3,204), researchers reported correlation between knowledge of ocean science content and public policy (Steel, Lovrich et al., 2005). That is, people who were more knowledgeable of ocean science concepts were also more likely to be knowledgeable and supportive of the policy and regulations to protect the ocean. These surveys and opinion polls suggested that while Americans were willing to help the ocean, they had very basic knowledge of the ocean. The disconnect between action and knowledge had implications on people's perceptions of urgency to act, their support of public policy, and their personal contributions; this disconnect emerged in national surveys on climate change as well.

National public opinion polls and academic surveys (Leiserowitz, 2005, 2007) reported that most Americans showed high awareness of global climate change, had a strong belief that it was real, and demonstrated significant concern about the issue. However, the majority of the American public did not consider climate change an imminent or high priority danger, believing that the impacts would be moderate and most likely affect geographically and temporally distant people, places, or nonhuman nature. Americans were willing to accept that human activities contributed to global warming, but many were not yet convinced that human activities were the primary cause (Leiserowitz, 2007). Damage to the ozone layer was consistently identified as the primary cause for global warming, though nuclear power plants, toxic waste, and aerosol cans were also mentioned (Bord, O'Connor, & Fisher, 2000; Bostrom, Morgan, Fischoff, & Read, 1994; Dunlap, 1998; Leiserowitz, 2006; Read, Bostrom, Morgan, Fischoff, & Smuts, 1994). Consistent conflation of ozone depletion and climate change could be attributed to inaccuracy of people's mental model of global climate change, even among highly educated people (Bostrom et al., 1994; Read et al., 1994). These national surveys also reported that the American public was willing to avoid buying gas-guzzling cars, install more insulation in their homes, and replace inefficient appliances, but were unwilling to volunteer to drive less or use less air conditioning and heating. Finally, people's affects, emotions, values, and worldviews strongly influenced the way Americans currently thought about the risks and public policy options to mitigate global climate change (Leiserowitz, 2006). Thus, similar to the ocean science surveys, these climate science surveys revealed that Americans might be willing to act to mitigate global climate change, but their actions and urgency to act could be affected by other factors.

These national surveys suggest that most Americans have limited understanding of, and affective connections to, the ocean and climate. That is, they do not comprehend the science and believe that these are the problems of people far away. These findings emphasize the important relationship between public knowledge and public policy (Bord et al., 2000; Steel, Smith et al., 2005). Indeed, "improving the knowledge base of citizens should be the first step in establishing a nation-wide effort to preserve the oceans [and mitigate global climate change] (Steel, Smith et al., 2005, p. 99). That said, scientific literacy and technical knowledge are not the only factors influencing the public's decision making in regards to climate change (Leiserowitz, 2006). It is important to note that ocean and climate science and the policies to regulate them do not occur in a sociopolitical vacuum. While understanding the science is important for decision-making, people also need to have and recognize personal and emotional connections to the phenomena. The remainder of this section offers a closer examination of people's understanding of the water and carbon cycles, as they are extremely important concepts to understanding the Ocean and

Climate Literacy Principles. The affective and emotional connections are explored further in the last section of this paper.

Water and Carbon

The water and carbon cycles are conceptual models to explain the cyclical movement of water and carbon, respectively, around Earth as processes in global systems like watersheds and climate. The water cycle offers an explanation of how water on Earth moves across sources (watersheds, ocean basins) and from sources of water (ocean, reservoirs, plants) into the atmosphere (evaporation, transpiration, water vapor), and then across and down to Earth (condensation, cloud formation) and back to the sources of water (precipitation, weather). Similarly, the carbon cycle explicates the circular movement of carbon from the atmosphere (CO_2) to plants and animals (photosynthesis, food web) or into the ocean (gas exchange), then down to the ground (decay, sedimentation), and finally returns to the atmosphere (burning fossil fuel). The cyclic movement of water and carbon has implications for life, geologic features, weather, and climate on Earth, as they move between the biosphere, atmosphere, lithosphere, and hydrosphere. There is an abundance of research that explores learners' understanding of the water cycle that delves into educational research in chemistry, physics, geology, ecology, and environmental education; investigations on what people know about the carbon cycle is not as plentiful and diverse. Nonetheless, the literature can be organized into several themes for discussion. One theme of study examines learners' understanding of the physics and chemistry underlying the water cycle—evaporation, condensation. A second theme connects the water cycle and the ocean from a systems perspective, as water moves through watersheds and weather. Finally, the carbon cycle is examined through studies on the greenhouse effect and global warming, which serve as potential seeds for future exploration of people's understanding of the climate.

WATER CYCLE

Physics and Chemistry of the Water Cycle

Learners can be formally introduced to ideas of the water cycle as early as grades K-4 (National Research Council, 1996), though they first encounter these ideas well before schooling when they experience rain and snow, watch clouds in the sky, and notice what happens to a puddle of water. Researchers argue that understanding how the water cycle works requires knowledge of phases of matter and phase change, which rely on learners' conceptions of the conservation of matter and particulate theory of matter (Bar & Galili, 1994; Johnson, 1998c; Tytler, 2000). Phase change of water, in evaporation and condensation, explains the transformation of water from its sources into the atmosphere and the return of water from the atmosphere back onto Earth. For learners to understand these phenomena they need to have a conversation of matter; that is, they need to recognize that matter can neither be created nor destroyed (Piaget, 1929). In addition, particulate theory of matter possibly facilitates the understanding of phases of matter and phase change as it offers learners a plausible explanation of how matter can be conserved while at the same time change from one state to another (Harrison & Treagust, 2002; Papageorgiou & Johnson, 2005). Researchers have investigated learners' understanding of the water cycle in the light of these ideas and phenomena, and findings reveal several models to describe progressions of understanding from young children to adults.

Conservation of matter

Early studies concluded that conservation of matter is critical to understanding evaporation and condensation (Osborne & Cosgrove, 1983; Piaget, 1929), otherwise, learners may believe water can disappear into oblivion when it evaporates or arise out of nowhere to condense into clouds. The subsequent research that reported children's conceptions on conservation of water spanned ages 5 to 18. One contentious issue pertained to young children's ability to conserve matter. Using evidence from multiple choice tests and clinical interviews about evaporation and condensation, Bar (1989; 1994) reported that young children in Israel (ages 5-7) did not conserve matter, which was consistent with findings from previous studies that were designed similarly (Osborne & Cosgrove, 1983; Piaget, 1929; Russell, Wynn, & Watt, 1989). Children offered that God created rain and clouds, clouds opened and rain fell out, and water in puddles "disappeared". Conversely, interview studies in Sweden and Australia with children as young as five suggested that they did not believe water ceased to exist when it 'dried up' or 'disappeared' (BouJaoude, 1991; Löfgren & Helldén, 2008; Tytler, 2000; Tytler & Peterson, 2000). In all these cases, the researchers reported that when children were probed further about what happened to the water when it 'disappeared', children's responses and reactions revealed that they meant water was no longer visible, not that it ceased to exist.

Tytler (2000; Tytler & Peterson, 2000) suggested that the inconsistency in findings could be attributed to language; that is, the appropriation of language as a cultural tool, and the meaning adults held for words compared to children. So when children said water 'disappeared', to the adult researcher, these children did not have conserve matter, but to the children, they might have used the word to mean many ideas they were not yet able to articulate. Tytler offered that, in these cases, children were still negotiating their mastery of the language associated with evaporation and condensation, and thus cautioned against conclusions on children's thinking without further exploration of language development (Vygotsky, 1986). Indeed, earlier studies overlooked the role of language on concept formation. Furthermore, in his study (Tytler, 2000), children were given the opportunity to discuss the phenomena with their peers before formulating their explanations, compared to previous studies that took place in isolated interview settings. Tytler reported "children gave individual and considered opinions on these phenomena after the discussion" (p. 462); and argued that talking with their peers gave children a chance "to try out ideas and collect their thoughts, and a better indicator of their potential response to ideas presented in a classroom sequence" (p. 462).

Children who had a conservation of matter offered ideas of displacement to explain what happened to the water (Bar, 1989; Bar & Galili, 1994; Johnson, 1998a; Russell et al., 1989; Tytler, 2000). In other words, water did not disappear, but was displaced; it moved downward into the ground (ages 6-9) or upward into the ceiling or sky (ages 7-10). In both cases, there was no phase change; the water as liquid changed its location, down or up. In Greece, Hatzinikita and Koulais (1997) reported children up to age 13 offered displacement or absorption ideas to explain evaporation, while those older than 13 said water transformed from liquid to gas. Tytler (2000) argued that the fundamental difficulty for children was not that water 'disappeared' or was 'displaced' downward or upward, but the idea that "water could be present in non-perceptible form in the air, or atmosphere.…Children do not have a working mental model of the atmosphere and air, or the form in which water might exist in the air" (p. 352). This difficulty in thinking is supported by studies showing the challenge of understanding what is a 'gas' (Stavy, 1988a, 1988b), including research reporting that condensation is more difficult to understand than evaporation (Johnson, 1998b; Tytler, 2000). It is not easy or intuitive to conceptualize gas as it is not visible, and that gas is as much a substance as tangible and visible objects like a nail or tree.

To explain the movement of water when they did not have a clear conception of the process, children drew on a range of associations to support their thinking, and in challenging situations, these associations became the explanations themselves (Tytler, 2000). They commented that 'the sun goes into the sea and heats the water' or that 'the sun boiled sea water' to create water vapor (Bar, 1989, p. 490), associating the sun evaporating seawater with a kettle boiling water, an obvious heat source needed to be near the water to boil it in order for the water to move from the source into the air. The idea that evaporation required heat in order to occur persisted among Turkish upper secondary and university students (Canpolat, 2006; Coştu & Ayas, 2005). Students also linked condensation with coldness using comments like 'hot and cold reacting to make fog', 'moisture is associated with cold', and 'dampness moves through a can to appear as moisture' (Tytler, 2000, p. 454). Gopal, Kleinsmidt, Case, and Musonage (2004) and Chang (1999) reported that some university students also made this association, which they ascribed to language and diagrams in textbooks, as well as the classic activity for condensation involving a dry vessel containing ice or cold liquid. Tytler and Peterson (2000) explained that associative thinking lies at the core of our understandings, as they are evidence of learners making connections between ideas and experiences. Early connections occur as perceptual and anecdotal associations, and evolve towards conceptual associations. Tytler (2000) found that older children drew on a greater store of experiences to make associations to develop their thinking. While younger children also had access to personal experiences, albeit over fewer years than older children, they were less able to make the connections between them and the activities in the study. Again, the challenge in characterizing associative explanation is the ambiguity of language. There might be subtle differences in how children use terms like 'air', 'atmosphere', 'moisture', or 'vapor', or whether those terms were used interchangeably.

Particle theory

Interestingly, children as early as age 10 recognized the plausibility that water, as smaller particles, moved upwards (basic particle theory), suggesting a phase change from liquid to gas, and that this water became a part of the air (Bar & Galili, 1994). However, it was believed that children did not offer ideas of particle theory without formal instruction (Bar & Galili, 1994; Johnson, 1998c). In fact, without instruction on, or a developed understanding of, particle theory, (secondary to university) students proposed that evaporation was a chemical change where water broke down into hydrogen and oxygen (Bar & Galili, 1994; Chang, 1999; Coştu & Ayas, 2005; Hatzinikita & Koulaidis, 1997; Johnson, 1998c; Tytler, 2000). Johnson demonstrated that secondary students (ages 11-14) were able to use particle theory to explain change of matter from liquid to gas during boiling (1998a), as well as describe condensation and evaporation at room temperature (1998b). He asserted that there was a distinction between evaporation and condensation with an obvious energy source like fire for boiling water and making steam, and evaporation at room temperature and condensation of existing, atmospheric water vapor. His position was further supported by reports that some (secondary and undergraduate) students believed evaporation only occurred when the temperature of the environment was higher than that of the liquid, that there was a temperature gradient between the liquid and the environment, and that boiling was required for evaporation to occur (Canpolat, 2006; Chang, 1999; Coştu & Ayas, 2005; Gopal et al., 2004).

It is argued here that both phenomena are significant for students to understand the basic mechanisms of the water cycle. The former pertains to students' understanding of what 'gas' might be, that water can exist as a gas in the atmosphere. The latter is pertinent to understanding that water does not need to boil in order to move from sources into the atmosphere, and that clouds and precipitation come from water that exists in the atmosphere.

In his longitudinal investigation of children's (ages 11-14, Year 7-9) understanding of particle theory in the UK, Johnson (1998a) reported that children, on their own, "had no conception of a liquid turning to 'a body of gas' as something that can happen" (Johnson, 1998a, p. 576). Before instruction on basic particle theory (Year 7), most students' responses in interviews about boiling suggested that there was "no link between the interior of the bubbles and the loss of water – 'air' did not seem to mean 'water as an 'air''" (Johnson, 1998a, p. 573). Students used the terms 'air', 'oxygen', and 'gas' synonymously. They envisaged the link between air and decreasing water level as a mechanical association; that is, the hot, air-filled bubbles in boiling water carried water out of the beaker as they burst at the top. This conception was also reported in other studies (Tytler, 2000). Interviews with students two years later (Year 9), following instruction on basic particle theory, showed that students used particle ideas to explain the composition of the bubbles, and those with a "developed understanding" of the basic particle theory recognized that water as a liquid could turn into a gas. Johnson emphasized that while students acknowledged that substances could be in three states of matter—solid, liquid, and gas, the notion that the same substance changed from a liquid into a gas was challenging without understanding basic particle theory.

In that same study, Johnson also explored children's understanding of evaporation and condensation at room temperature (1998b). He reported that without any concept of water existing in the air as vapor, students struggled to explain condensation and evaporation below boiling point, or even to recognize the relationship between condensation and evaporation. Under conditions of boiling, students observed bubbles and steam to account for evaporation and condensation taking place; at room temperature, students struggled to imagine liquid water move into the atmosphere to become water vapor, or invisible water vapor already present in the air to form water droplets. Similar challenges have been reported among adults (ages 15-27) enrolled in reading and writing classes in night school (Dibar Ure & Colinvaux, 1989) as well as non-science majors in university (Chang, 1999). As students develop particle ideas, they began to recognize that water existed in the air as vapor and that there was a reversible change between liquid water and vapor. Surprisingly, in some cases, students struggled with condensation even though they had a particulate understanding of evaporation. Tytler (2000) found similar struggles among Year 1 and Year 6 students. "It is one thing to be able to explain the disappearance of water by particles dispersing into the air, it is another to conceive of those particles as ***already existing*** in the air and so being a potential source of water" (Johnson, 1998b, p. 705, italics in original).

From this 3-year study of secondary students (ages 11-14), Johnson proposed four distinct mental models (Model X, A, B, and C) that students held and progressed through about particles (1998c), which continued along two dimensions—continuous-particulate and macroscopic-collective. He was reluctant to claim age-relations for each model, but instead connected students' progression to instruction. In Model X, substance was continuous, "particle ideas [had] no meaning. Nothing that resemble[d] having particles of any description [were] drawn" (p. 399). Next, Model A, particles were in the continuous substance, "particles [were] drawn, but the substance [was] said to be between the particles. The particles [were] additional to the substance" (p. 399). In Model B, particles were the substance, "particles [were] drawn and [were] said to be the substance. There [was] nothing between the particles" (p. 399). Additionally, particles had macroscopic character; individual particles were seen as being of the same quality as the macroscopic sample—particles were literally small bits of the substance itself. And finally, in Model C—the developed understanding of particle theory, particles were the substance, "particles [were] drawn and [were] said to be the substance" (p. 399). In this case, the properties of the state of a matter were seen as collective properties of the particles.

Johnson (1998c) reported that students' progression from Model X to Model C was incremental over the three years of his study, and occurred along different dimensions for different students. In general, students applied the models to samples of substances in each of the three states, though there were occasions where students mixed models and applied different models for substances in different states. For example, moving to a Model B understanding of sugar, but maintaining a Model A explanation for water. He pointed out that students' notions of particle ideas were introduced by instruction because prior to the teaching unit, students on their own did not suggest these ideas, which was consistent with Bar's conclusion (1994). For instance, while students' understanding progressed along one dimension at a time with nearly all students moving along the continuous-particulate dimension first, the instructional units addressed the continuous-particulate dimension before macroscopic-collective. He acknowledged that as a result of a significant occurrence of Model A after an early unit in the study, teaching materials for subsequent units were re-worded to avoid phrases such as 'the particles in a solid'. Johnson contended that for some students Model A was a necessary stage in the development of their understanding, but for others, who held Model B in early units of the study, instruction (in his units as well as textbook illustrations and teachers' phrases) may have unnecessarily led them into Model A.

Water Cycle as a System

The physics and chemistry ideas discussed above only explains one aspect of the water cycle, the transformation of water from its sources into the atmosphere and the return of this water. To recognize how and why the water cycle is important, especially for ocean and climate literacy, we must also understand that this water moves across temporal and geographic scales where there are implications for geology, living organisms, weather, and climate (American Geophysical Union (AGU), 1995). The water cycle is a complex system. There is, however, a modest body of literature that explores students' ideas of the water cycle from a systems perspective. These investigations report on students' conceptions of components of the water cycle such as groundwater and watersheds, cyclic thinking, and the interactions between humans and the water cycle. Findings offer sharp criticism for the emphasis on evaporation and condensation in research and school curriculum, as well as the way the water cycle is represented in instructional and educational materials.

Studies reveal that adults and children had limited knowledge of watersheds, which had implications for the public's understanding of the water cycle as a global system and human contributions to water pollution. National surveys by the National Environmental Education and Training Foundation reported that three out of five American adults did not know what is a watershed (NEETF, 1998), and only 22% knew stormwater runoff was a major cause of stream pollution (NEETF, 1999). Studies of children's understanding of watersheds and the water cycle showed that children's ideas (grades 4 to 12) about watersheds were limited to mountainous terrains, rivers and streams, and predominantly restricted to precipitation, evaporation, and condensation (Shepardson, Harbor, & Wee, 2005; Shepardson, Wee, Priddy, Schelleberger, & Harbor, 2008; Shepardson, Wee, Priddy, Schellenberger, & Harbor, 2007).

Shepardson and his colleagues examined drawings and written explanations from about 1,300 students in the Midwest. While a higher percentage of middle school and high school students than elementary students had a more developed and dynamic conception of the water cycle, most students across all grade levels conceptualized the water cycle as evaporation, condensation, and precipitation. Put differently, when asked to describe the water cycle, students focused on water storage and transformation, with little emphasis on the transportation of water across land and in streams and rivers (Shepardson et al., 2008). Students tended to portray a watershed as an area of land with high relief and elevation where water is cycled, stored, or transported (Shepardson et al., 2007). Interestingly, a greater percentage of elementary and middle school students than high school students conceptualized a watershed as a dynamic process incorporating a developed view of the water cycle. Furthermore, more high school students than middle and elementary used the words "water" and "shed" to describe a watershed. That is, these students used everyday language in the meaning-making process, using sheds and towers to represent watersheds. However, in a smaller, earlier study Shepardson (2005) reported that student representation of watersheds literally as sheds that held water occurred among sixth graders, and reduced from seventh to ninth grade, and that, the water cycle as a component of a watershed increased by grade level. Regardless, in all three studies, Shepardson et al. reported that few students incorporated runoff or groundwater, and no students included the impact of human activities on the water cycle or biological entities (trees, plants) as a part of watersheds and water cycles. Instead, the water cycle was portrayed in mountainous and coastal environments (even for Midwest students), and not as a part of the watershed or climate system. Shepardson and his colleagues suggested that students' characterizations of watersheds and water cycle could be attributed to diagrams in textbooks, websites, and other educational materials. Watersheds and the water cycle were often depicted in mountainous or coastal regions, and without inclusion of human activity or the role of biological factors.

Dickerson and his colleagues wrote that groundwater was not an educational priority, that despite students' incomplete understanding of groundwater (Dickerson & Callahan, 2006; Dickerson, Callahan, Van Sickle, & Hay, 2005; Dickerson & Dawkins, 2004; Dickerson, Penick, Dawkins, & Van Sickle, 2007). Dickerson and Dawkins (2004) reported that middle school children in the US thought of groundwater as pools, lakes, and pipes of water underground. Interestingly, they also revealed that children's conceptions might be masked by their use of scientific vocabulary and vernacular. For example, some students used words and phrases such as 'underground pools and streams' to describe groundwater, but upon further probing during interviews, students did not necessarily think of groundwater as a solid body of water. Conversely, many students used the terms 'porosity' and 'permeability' in diagrams and discourse during the study, but were not able to explain appropriately what the terms meant. Students offered the idea that rocks 'soak up water like a sponge', but could not speak further about what types of rock and under what conditions the sponge-like effect would take place.

Moreover, Dickerson et al. (2005) reported that, in terms of (secondary and post-secondary) students' mental models, scale might be more important than vernacular. For instance, students' ideas about groundwater as underground pools and lakes that were microscopic or eraser sized might not adversely affect their understanding if those terms were used to represent pore space. Alternatively, some students might use scientifically appropriate terms like pore space, but think a pore was half a kilometer in diameter. In this case, "when they combine that inappropriately scaled conception with their other conceptions of permeability, aquifer, etc, the result is likely to be an inappropriately constructed mental model" (Dickerson et al., 2005, p. 379). Dickerson et al. (2007) argued that students' spatial reasoning abilities and schoolteachers' limited knowledge of groundwater might have contributed to their incomplete conceptions.

Ben-zvi-Assarf and Orion (2005a) offered additional information, from Israel, to shed light on middle school students' understanding of groundwater and the water cycle as a system. Student drawings of the water cycle typically presented only the atmospheric component (evaporation, condensation, and rain). Similar to Shepardson et al's findings (2008; 2007), most students (70% of 177) did not identify groundwater as a part of the water cycle, and even fewer (<10%) included components of the biosphere (plants, animals, humans) or interactions between humans and the water cycle (water consumption, pollution, sewage). More than half of the students who did include groundwater described it as a static sub-surface lake, or as a disconnected system that had no relationship with the surrounding rock. Further probing in interviews revealed that some students thought rain that penetrated rocks might move horizontally under the ground toward the ocean. Most students claimed that underground water could only be found in rainy areas.

Additionally, Ben-zvi-Assarf and Orion (2005a) reported that students lacked an understanding of the cyclic process for matter. Most students, during interviews, claimed that 'there must be a beginning point…the end point, I don't know' or "the end point could be either the sea or the groundwater" (p. 370). The authors raised doubt on the extent to which students maintained the conservation of matter when applied to a cyclic process. For instance, while students recognized that evaporation transferred water from the ocean to the atmosphere, students commonly thought, "true, water evaporates from the ocean, but the total amount of water that evaporates is too small" (p. 370). Furthermore, only 44.2% of students disagreed with the statement "the amount of water in the ocean is growing from day to day because rivers are flowing continuously into the ocean" (p. 370). Interestingly, there was a significant positive correlation between students who included groundwater in their drawings and those who demonstrated cyclic thinking in questionnaire responses. Thus, groundwater may be a critical mechanism for students to understand cycling of water in the water cycle.

CARBON CYCLE

Global Weather & Climate

Research on people's understanding of the carbon cycle and how it relates to weather and climate, however, is not as plentiful and thorough as that for the water cycle. Most of the research on the carbon cycle pertains to people's understanding of the greenhouse effect, global warming, and climate change. These studies are found in literature from science education, public understanding of science, and risk management.

Compounds in the Atmosphere

One critical question to understanding the carbon cycle in the climate system is how do students conceptualize the role of compounds in the atmosphere. The volume of international research on students' understanding of global warming and the greenhouse effect provide insight into students' understanding of the compounds in the atmosphere, radiation entering and exiting Earth, and the ozone layer.

First, students recognized gases in the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbon (CFC), were connected to the greenhouse effect, though they were not always certain on the sources of these gases or how these gases were part (or not part) of the greenhouse effect (Andersson & Wallin, 2000; Koulaidis & Christidou, 1999; Lee, Lester, Ma, Lambert, & Jean-Baptiste, 2007; Rye, Rubba, & Wiesenmayer, 1997). In some cases, students believed that CO_2 and CH_4 came from natural and anthropogenic sources, though many students thought CO_2, CH_4, and CFC were strictly human-made. They also thought CO_2 and CFC, in particular, were responsible for depleting the ozone layer, which was the cause for global warming.

Second, some students acknowledged the greenhouse effect referred to an invisible "barrier of gases" that kept radiation from escaping out to space, and thus warmed Earth (Andersson & Wallin, 2000; Dove, 1996; Groves & Pugh, 1999; Koulaidis & Christidou, 1999; Lee et al., 2007). Most students confused what comprised this "barrier" and how this "barrier" worked. For some English language learners, they thought of the greenhouse effect as greenhouses, literally (Lee et al., 2007). Few students identified CO_2 and CH_4 as the greenhouse gases that made the "barrier" to trap the heat; most students considered the ozone layer to be the "barrier" (Boyes & Stanisstreet, 1993; Dove, 1996). Only in a few instances did students mention radiation reflecting off Earth as long-wave radiation to be the heat that was trapped by the "barrier" (Dove, 1996; Koulaidis & Christidou, 1999).

Finally, students conflated ozone depletion and global warming (Andersson & Wallin, 2000; Boyes & Stanisstreet, 1993; Dove, 1996; Koulaidis & Christidou, 1999; Lester, Ma, Lee, & Lambert, 2006; Papadimitriou, 2004; Rye et al., 1997), which was consistent with reports in national academic surveys and public opinion polls of adults (Bostrom et al., 1994; Leiserowitz, 2007; Read et al., 1994). Related to the previous point, students thought that an intensified greenhouse effect was caused by increased amounts of solar radiation reaching Earth and that this increase was due to holes in the ozone layer. In other words, the hole in the ozone layer allowed more solar radiation through to reach Earth, leading to global warming. Additionally, students connected CFC and skin cancer to global warming. The former because they learned from media that CFC was responsible for creating the hole in the ozone layer, and the latter because more solar radiation was reaching Earth through the hole in the ozone layer. Disturbingly, the direct causal relationship between ozone depletion and global warming was reported in varying levels of frequency in all studies referenced here. For these students, they considered the amount of solar radiation reaching Earth as the cause for warming, not entrapment of outgoing radiation. Rye et al. (1997) reported that despite instruction deliberately intended to decouple global warming and the ozone layer, for the American middle school students in their study, that causal connection persisted. However, in a study in Italy, Mason and Santi (1998) reported changes in children's thinking about global warming and ozone layers when given the opportunity to share, argue, and defend their ideas in small group discussions.

Sterman and Sweeney (2002; 2007) explored people's systems thinking abilities relating to the balance and effects of the chemical compounds in the atmosphere. They argued that if people did not "understand the fundamental mass balance principle that stabilizing GHG [greenhouse gas] concentrations requires emissions equal net removal, providing them with better information on future removal will do little to alter the belief that stabilizing emissions would quickly stabilize the climate" (2007, p. 222). Researchers sought to understand whether highly educated adults— graduate programs at MIT, Harvard, and the University of Chicago, two-thirds of whom studied engineering or science as undergraduates—understood and could describe an emissions path consistent with CO_2 stabilization given their estimated removal path. Students were given descriptions of climate systems and charts of global mean temperature and CO_2 concentration and emissions levels, and were asked to respond to two hypothetical conditions: human CO_2 emissions fall instantly to zero and human CO_2 emission pattern required to reach specific concentration targets. Researchers reported that students did poorly and regularly violated basic laws of physics, specifically conservation of matter. Students consistently underestimated the delay in response of temperature to changes in CO_2

concentration, drawing trajectories in which CO_2 and temperature followed the same pattern. They relied on a pattern heuristic, matching the shape of the output of the system to the shape of the input, rather than drawing on the relationship between the net flow into a stock and the rate of change of the stock. Most believed that atmospheric greenhouse gas concentrations could be stabilized even as emissions into the atmosphere continuously exceeded rate of removal, thus favoring a "wait and see" stance on policies. That is, let's "wait and see" what type of effects the changed conditions really have on the environment, and before we do something about it.

Consequences and Actions

The literature on what people thought about the consequences and actions to take pertaining to carbon input into the atmosphere was interesting and disconcerting. Similar to the national surveys described earlier (Bord et al., 2000; Leiserowitz, 2005, 2007), there was awareness of the issues, but consistent lack of understanding and willingness to act. Boyes and Stanisstreet (1993) reported some students in the UK (mostly older students, 15/16) realized that a warmer Earth could change weather patterns, which would result in desertification due to warmer temperatures and flooding due to melting polar ice caps. Interestingly, some students (mostly younger students, 11/12) believed drinking water would be poisoned due to global warming, and most students (11-16) thought more people would get skin cancer as a result of global warming. This latter connection was reported in other studies (Dove, 1996; Groves & Pugh, 1999; Lee et al., 2007) and was attributed to the common conflation between the global warming and ozone depletion. People believed that all environmentally harmful acts contributed to climate change (Gowda, Fox, & Magelky, 1997), which was supported by people's ideas on actions they could take to mitigate global warming.

Many students felt reducing car usage, planting trees, and using alternative energy sources helped reduce global warming (Boyes & Stanisstreet, 1993; Dove, 1996; Papadimitriou, 2004); though American adults did not recognize driving less as a primary solution (Leiserowitz, 2007). Students, however, offered an even longer list of acts of environmental stewardship that were not related to global warming directly. These included recycling, using environmental friendly products, raising awareness, cleaning up litter at the beach, protecting endangered species, eliminating aerosol spray cans, reducing insecticides, and eliminating nuclear usage (arsenal and energy). These proposed actions questioned the extent to which people understood the causes of global warming; though they also revealed that people believed they had personal responsibility and control to do something about it. Lester, Ma, Lee, and Lambert (2006) reported a positive correlation between fifth grade students' expressions of activism and their scientific knowledge. That is, students with adequate science knowledge expressed activism more frequently, and these expressions increased as they gained better science understanding after instruction.

Ungar (2000) sought to explain how the ozone depletion issue has succeeded to engender public understanding and concern, while climate change has failed or is consistently coupled with ozone depletion. One reason he identified was mass media, both due to the volume of attention offered and the quality of complete information presented. Ungar argued that science is "an encoded form of knowledge that needs to be decoded to be accessible to the public" (p. 302). Mass media is positioned as the decoder of science, where national and local news media are the most relied upon source of environmental news for the American public (Steel, Lovrich et al., 2005). Ungar borrowed Kempton et al.'s argument that Americans assimilated the greenhouse effect to a model of ozone depletion. Ozone depletion was introduced to the public earlier, and the concept was simpler with fewer causes and consequences. With the barrage of media, political, and economic attention paid to climate change, and in the light of the complexity and emerging research, the public made climate change a subset of ozone depletion. That said, mass media could also contribute positively to science literacy in general (NRC, 2009), and ocean literacy more specifically (Steel, Lovrich et al., 2005; Steel, Smith et al., 2005).

Thus textbooks, teaching methods, and mass media attributed to affecting adults' and children's conceptions and conflations of the greenhouse effect, global warming, and ozone depletion. Dove (1996) argued that textbooks on global warming and the greenhouse effect were often out of date because the scientific research was still emerging and changing. Dove (1996) and Rye et al. (1997) criticized mass media for reporting but not informing the public about the ozone hole, acid raid, and global warming. Ungar (2000) pointed out that only a few mass media provided sufficiently accurate, detailed, sophisticated, or concerted coverage to take someone beyond simple awareness. The onus was on the individual to pursue and "decode" the science.

However, more studies are needed to explore the effects of mass media on climate (and ocean) literacy, as increasingly, it is through the media that most people learn about climate science (Wilson, 2000). These studies that criticize the contributions of mass media on people's (erroneous) conceptions of climate change are more than 10 years old. In that time, research on climate change has progressed significantly, while portrayal of climate change in American popular culture has evolved. There is rigorous and scientifically grounded programming for the general public, such as Al Gore's "Inconvenient Truth," as well as a strong presence in advertisements and speeches during the 2008 presidential election.

Papadimitriou (2004) indicated that teachers were challenged with finding innovative and creative techniques, as the issues of climate change were complex. Österlind (2005) contended that environmental issues required domain-specific knowledge and students needed to understand better certain fundamental concepts (e.g. photosynthesis, radiation). Andersson and Wallin (2000) proposed a thematic approach to teaching about climate change. They found that students taught by a thematic approach, rather than in separate subjects gained a better grasp of complex environmental problems. Teaching in the traditional way did not provide students with functional science concepts that they could apply to new situations. They recommended introducing topics, such as the greenhouse effect, and allowing students to work in small groups to discuss the causes of the greenhouse effect, share their ideas, and challenge each other's models—a position that was supported by Mason and Santi's work (1998).

Summary

The research reviewed in this section sheds light on what we know about adults and children's understanding of the water and carbon cycles. Specifically, the review focuses on people's understanding of the mechanisms of water transformation through the water cycle, the cyclic movement of water through natural systems, and the effects of compounds in the atmosphere. Several critical points can be made from the synthesis of these investigations.

First, claims that a learner understood evaporation by this age and condensation by this age should be taken lightly, as studies showed that both children and adults might have similar conceptions about evaporation and condensation that were contrary to scientific explanations. For example, children as young as five and seven had a conservation of matter when talking about water evaporating (BouJaoude, 1991; Löfgren & Helldén, 2008; Tytler, 2000; Tytler & Peterson, 2000), but they might not apply that conservation of matter as water cycles through a watershed system (Ben-zvi-Assarf & Orion, 2005a). In fact, even highly educated adults struggled with conservation of matter in the context of complex systems (Sterman & Sweeney, 2002, 2007). It might be more sensible, as Russell (1989) suggested, "to locate that learner on a qualitative scale of understanding in relation to various manifestations of the concept" (p. 575). In other words, rather than adopting an all or nothing stance or imposing age indicators, it might be more appropriate to consider the understanding of evaporation and condensation along a progression, and then placing learners along that scale.

Second, researchers repeatedly called attention to the ways in which instruction and instructional materials contributed to learners' conceptualizations of the water cycle, and the role of mass media in climate issues. In particular, they cautioned that diagrams and other graphical representations in textbooks, websites, and other materials could attribute to learners' incomplete conceptualization of the water cycle and watershed system. For instance, several studies reported that students tended to omit human activities and biological organisms from their illustrations of the water cycling through a watershed system (Ben-zvi-Assarf & Orion, 2005a; Shepardson et al., 2005; Shepardson et al., 2007), both of which were typically missing from many instructional diagrams. These students' erroneous conceptions could also be attributed to demonstration activities that teachers conducted in class (Chang, 1999; Gopal et al., 2004; Tytler, 2000). Indeed, activities were used in all studies, and were crucial for offering learners the chance to see, touch, and experience the phenomena under study. However, these same experiences might also be the sources of students' erroneous understanding, such as (adult and children) students associating coldness and condensation due to the "cold can" demonstration.

Third, researchers emphasized the importance of language use and conversations to developing students' thinking. They pointed out that students' use of words – both scientifically acceptable as well as every day language – did not necessarily represent their understanding (Dickerson & Dawkins, 2004; Johnson, 1998a; Tytler, 2000; Tytler & Peterson, 2000), and thus researchers and educators needed to encourage, and give opportunities for, students to explain, state, and clarify their thinking before drawing conclusions. Students who were given the opportunity to talk, argue, and defend their ideas in small groups showed positive change in their understanding of difficult and complex concepts, like evaporation (Tytler, 2000) and climate change (Mason & Santi, 1998). Attention from mass media was recognized as a powerful source of scientific information (NRC, 2009; Wilson, 2000), though care must be given to the media's ability to sensationalize and popularize but not inform and educate (Ungar, 2000).

Fourth, students' knowledge of the water cycle was compartmentalized, and research on students' understanding of the relationship between the ocean and atmosphere, specifically, was explored only peripherally. This relationship was critical for ideas on weather and climate. At best, students understood that water evaporates from the ocean, the ocean is a major source of water, and weather is alluded to with mention of cloud formation and rain. For most students, however, condensation was a more difficult concept to grasp than evaporation, especially condensation of invisible water vapor already in the atmosphere (Johnson, 1998b; Tytler, 2000), which was critical for understanding weather and climate. Research on watershed systems revealed that most students did not have a complete systems and cyclic conceptualization of the movement of water. Many students might recognize the movement of water across land and into the ocean, but they did not understand movement of water under the ground (Dickerson & Dawkins, 2004), the conservation of water in this system (Ben-zvi-Assarf & Orion, 2005a), and the role and affects of the biosphere and human activities (Ben-zvi-Assarf & Orion, 2005a; Shepardson et al., 2005; Shepardson et al., 2007).

Fifth, adults and children were able to conceptualize the presence of invisible gases in the atmosphere, and that these gases played an important role in Earth's temperature and weather patterns. However, this thinking might not assist them in understanding ideas in weather and climate. For instance, research reported that people had difficulty contemplating how water vapor already existing in the atmosphere could condense into clouds (Johnson, 1998b; Tytler, 2000). Additionally, they typically confused the greenhouse effect and ozone layer, and attribute the latter for causing global warming (Boyes & Stanisstreet, 1993; Dove, 1996; Groves & Pugh, 1999; Koulaidis & Christidou, 1999). Finally, in the context of a complex system, people did not hold a conservation matter (Ben-zvi-Assarf & Orion, 2005a; Sterman & Sweeney, 2002).

Finally, research on people's understanding of the carbon cycle and climate focused on the greenhouse effect, global warming, and ozone layer almost exclusively. Indeed it was important to know how people conceptualized these ideas; though these studies all reported the same thinking—most people think global warming is caused by holes in the ozone layer. What we do not know is whether students think about global warming and greenhouse effect as phenomena within the larger system of the carbon cycle. This cyclic model uses the movement of carbon to explain the relationship of the phenomena rather than discussing them as individual events, thus could possibly offer a conceptual model to decouple the ozone layer and global warming.

3. THINKING SKILLS, TEACHING APPROACHES

The water and carbon cycles are complex systems. Review of the literature in the previous section suggests that understanding them as such is challenging. Learners are taught and recognize the individual components of the cycles, but are not cognizant of the interactions and interdependence of these components to make up the systems. Some researchers argue that the water and carbon cycles need to be taught from a systems perspective (Mayer, 1995; Orion, 2002), and that understanding them in this way requires learners to have dynamic, systems, and cyclic perceptions of their world (Kali, Orion, & Eylon, 2003). However, there are numerous cognitive challenges associated with developing system thinking skills and hence, understanding complex systems (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006). This next section reviews the major barriers for understanding complex systems, as they have implications on learning, and also explores some teaching approaches that may support them.

In brief, complex systems are hierarchical in nature and have multiple interacting levels (Wilensky & Resnick, 1999). In other words, 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. A complex system is an aggregate of components, all of which are necessary for the system to function (Ben-zvi-Assarf & Orion, 2005b). The system maintains stability through self-correcting feedback loops (Hmelo-Silver, Marathe, & Liu, 2007), and even small changes can have big effects. However, thinking in these ways is difficult. System thinking is the ability to understand and interpret complex systems, and comprises numerous thinking skills: dynamic thinking, closed loop thinking, generic thinking, structural thinking, operational thinking, continuum thinking, and scientific thinking (Richmond, 1993).

Challenges for Understanding Complex Systems

Centralized Mindsets

Students and novices tended to have *centralized* or *deterministic mindsets*; that is, they preferred explanations that assumed a single cause or an ultimate controlling factor (Penner, 2001; Perkins

& Grotzer, 2000; Raia, 2005; Resnick, 1990, 1996; Wilensky & Resnick, 1999). These studies showed that students favored simple and linear causality, causal control, and predictability across several domains of science knowledge, and these researchers argued that such a mindset hindered students' ability to consider the effects of the interdependence and interconnection of components in a complex system. Moreover, in this mindset, students neglected emergent properties of complex systems (Penner, 2000), such as weather patterns resulting from movement of water molecules; students failed to recognize temporal and spatial distance in causal explanations of complex systems (Feltovich, Spiro, & Coulson, 1993; Grotzer, 2003), for instance, that it would take years for carbon in the atmosphere to reduce even if anthropogenic input was significantly reduced instantaneously. Instead macro-level patterns were attributed to the actions of leaders or the effects of preexisting heterogeneity of the system, and temporal and spatial continuity were preferred for cause and effect relationships.

Jacobson (2001) found that there was noticeable distinction between the ways novices and experts reasoned about systems. Experts solved problems in a nonreductive manner, described order as an emergent property of decentralized interactions in a system, and considered nonlinearity and random factors; in contrast, novices' solutions to the problems were opposite that of the experts in almost every way. Jacobson argued that while it might be convenient to attribute this difference to experts' depth of knowledge on concepts such as evolution and equilibration processes, it was not entirely appropriate. He pointed out that while students in his study might not understand the concepts at the depth of experts, they also did not make reference to the ideas or phenomena. He suggested that people's ontological and epistemological beliefs might contribute to their "centralized mindsets"; novices believed order was imposed by central control, while experts believed order emerged from decentralized interactions. Moreover, Grotzer (2003) asserted there might be confusion over objects at different levels. In the water cycle, for instance, at the microlevel (physics and chemistry) individual water molecules were the objects, whereas at the macrolevel (watersheds) the objects were the bodies of water and the geographic locations across which water moved. She provided evidence in reasoning about ecosystems to support this claim: students had difficulty in reasoning about ecosystems interactions at the level of population, such as balance and flux, and instead preferred to apply the interactions to individuals.

Through their extensive studies of medical students in North America, Feltovich et al.

(1993) found that students' erroneous understanding of conceptions were primarily due to their propensity to simplify the underlying concepts in the first place. They argued that this mindset among medical students was perhaps attributable to the tendency towards oversimplification and use of static models to represent systems in early grades. Thus the prior knowledge and experiences with complex systems provided in K-16 education possibly impeded understanding and using complex systems in professional education.

Structure Only

Further to students' (novices') inclinations for single causes and simple explanations, Hmelo-Silver and her colleagues offered more details about students' single-mindedness from another perspective—an approach to systems from artificial intelligence, Structure, Behavior, & Function (SBF) Theory (Goel & Chandrasekaran, 1989; Hmelo, Holton, & Kolodner, 2000). They argued that the "SBF representation allows one to reason effectively about the functional and causal roles executed by the structures in a system because this representation accounts for a system's parts, their purpose in the system, and the mechanisms that enable their functions" (Hmelo-Silver et al., 2007, p. 309). They conducted comparison studies between the ways that novices (students) and experts (professionals and scientists) thought about and explained effects on a system (an ecosystem in a terrarium, human respiratory system) (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004). In both studies, they found that novices typically focused on structures. That is, when asked to describe a system, such as the ecosystem of a terrarium, students identified the parts in the terrarium.

In contrast, experts concentrated on the function and behavior of the parts. Experts identified the structures in the terrarium only to use them to talk further about the functions of the structures in the terrarium ecosystem, how their presence contributed to the ecosystem (the behavior), and speculated what would happen if they were not there to serve their functions. Hmelo-Silver et al. (2007; 2004) concluded that structures of a system were most cognitively available to novices, and typically emphasized in science lessons. Moreover, students might not identify structures of subsystems, as that presupposed comprehension of the relationships that connected the parts of a subsystem (Evagorou, Korfiatis, Nicolaou, & Constantinou, 2008) and was considered a higher-order thinking skill (Ben-zvi-Assarf & Orion, 2005b). Experts organized their knowledge of systems according to behaviors and functions, what Hmelo and her colleagues (2007; 2004) described as "deep principles". The behaviors and functions of a system represented a more elaborate network of the concepts, principles, and their interrelationships; behavioral mechanisms, in particular, might be dynamic and invisible processes, and thus might be difficult to represent.

Mental Models, Working Memory

People manipulate mental models in order to consider the challenges and complexities of systems (Doyle & Ford, 1998). A mental model is an internal conceptual system representing the external physical system that is being reasoned, manipulated, or examined (Doyle & Ford, 1998; Nersessian, 2008). Working memory is the capacity to simultaneously store and process information (Daneman & Carpenter, 1980, 1983). Studies in cognitive psychology report high correlations between the capacity of students' working memory and their reasoning skills and ability to create mental models (Barrouillet & Lecas, 1999; Conway & Engle, 1996; Kyllonen & Cristal, 1990). As we discussed above, students have difficulty thinking about complex systems, where manipulating mental models requires a lot of working memory (Narayanan & Hegarty, 1998). Grotzer (2003) proposes that, for students and novices, there may be cognitive overload in holding in one's mind all the individual parts and imagining the various effects, changes, interactions and outcomes of a complex system simultaneously. She acknowledges the value of computer-based learning environments, like StarLogo, in facilitating learners' reasoning and mental modeling, as it enables them to view manipulations and changes to the system.

Summary

In sum, understanding complex systems is difficult. Due to the ways students typically think about and organize ideas, they tend to miss the interconnectedness and complex causal relationships within and among systems. Consequently, they do not think about ripple effects and feedback loops, and do not recognize properties of systems that emerge from the interactions and interrelatedness of the components in the systems. For instance, novices do not recognize that one event might lead to another event to another event that might actually cause an effect that appears completely unrelated, e.g. a traffic jam that emerges from cars on a crowded highway actually moves backwards while individual cars move forward (Wilensky & Resnick, 1999). Thus students (novices) typically do not think about systems as many moving parts, where all the parts have important functions and behaviors in the system, and altering one part affects the whole system. Nonetheless, there is evidence to suggest that students (learners, novices) can develop the thinking skills to overcome these barriers.

Supporting Understanding of Complex Systems

Design Activities

Design activities may facilitate understanding of complex systems (Edelson, 2002; Hmelo et al., 2000; Penner, Giles, Lehrer, & Schauble, 1997). Design activities involve learners creating a model of the complex system, and then use their model to reason about and understand that system. Design activities are iterative and "require the designer to identify ways of accomplishing desired functions and fit them together to create a system or artifact" (Hmelo et al., 2000, p. 251). In this process, therefore, learners apply, argue, and evaluate the models they construct, and as a result, they are constructing knowledge rather than receiving it (Hmelo et al., 2000; Penner et al., 1997).

In designing their own three-dimensional models, elementary through college students developed a better understanding of the content, changed their conceptual understanding, and gained and applied scientific knowledge to solve the problem (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kawasaki, Herrenkohl, & Yeary, 2004; Penner, Lehrer, & Schauble, 1998). The design activity also facilitated some students as young as grades 1-2 to detach the perceptual relationship between a model and the real thing (Penner et al., 1997) that had been argued to be a hindrance on students' ability to use models to test and construct ideas (Grosslight, Unger, Jay, & Smith, 1991). For complex systems, Hemlo et al. (2000) reported that students who participated in a design activity to make an artificial lung were better able to talk about the functions of the respiratory system, as compared to their schoolmates in the control group. They asserted that this gain was significant for understanding complex systems, as the design activity encouraged students to think beyond just the structures of a system. Students talked about the functions of the parts and their behavioral effects on the system, which was more in line with how experts organized and explained systems (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004).

Computer-based Learning Environments

Computer-based learning environments (CBLEs), including hypermedia, virtual reality environments, interactive simulations, and programming, have been used to facilitate learning and thinking about systems (Azevedo, 2005; Barab, Hay, Barnett, & Keating, 2000; Evagorou et al., 2008; Grotzer, 2003; Resnick, 1990). Hypermedia and hypertext refer to material (the Internet) that uses links to connect nodes of digitally encoded symbols (text, pictures, animations, and videos). They are argued to allow once disparate technologies to be amalgamated as a learning resource, as nodes of digital information are linked in a flexible, nonlinear manner (Jacobson & Archodidou, 2000).

In some studies, the CBLEs were programs out-of-context; that is, students were invited to use the program several different times independent of school lessons, and researchers observed, tested, and interviewed the students for effects of the "treatment" (Jacobson & Archodidou, 2000; Resnick, 1990; Wilensky & Resnick, 1999). In other investigations, the CBLEs were fully integrated into an instructional curriculum, and students took part in the intervention as a part of their regular schooling (Barab et al., 2000; Evagorou et al., 2008; Kali et al., 2003). Regardless, researchers reported conceptual gains and conceptual change among the student participants, across several domains of science (astronomy, ecosystem, evolution, geoscience). Students also showed gains in some system thinking skills (Evagorou et al., 2008; Kali et al., 2003; Resnick, 1990), such as skill transfer, temporal and spatial distance in causal explanations. Cyclic and feedback thinking skills remained particularly challenging to develop (with or without CBLEs)—the idea that one change can produce a short-term effect that can equilibrate over time or that can then feedback to influence the change that produced it (Evagorou et al., 2008; Grotzer & Basca, 2003; Hogan, 2000; Kali et al., 2003).

Furthermore, the versatility and flexibility of hypermedia could facilitate students' understanding of complex system, though they required high levels of self-regulated learning (Azevedo, 2002, 2005; Azevedo, Guthrie, & Siebert, 2004). Self-regulated learning is a perspective that learners set their own learning goals, and then attempt to plan, monitor, regulate, and control their cognition, motivation, behavior, and context (Azevedo, 2002). As a result, self-regulated learning has been argued to be consistent within a constructivist perspective on learning (Boekaerts, 1997). Nonetheless, students also required scaffolding in the content of the domain and processes of self-regulated learning from educators and tutors in order to understand complex systems (Azevedo, 2005).

Teacher Knowledge, Student Control & Conversations

Teacher knowledge and student conversations were two contributors to understanding complex systems that were not studied explicitly, but were integral to the research design. The studies on design activities and computer-based learning environments pointed out that given the resources, activities and instruction, students could develop the thinking skills needed to understand complex systems. The researchers further emphasized the need for teachers to be educated on the domain knowledge, have system thinking skills and causal reasoning, and understand complex systems in order to use educational resources and design their curriculum to support student learning. Most of the intervention studies that showed conceptual gains and changes in students understanding of complex systems involved significant levels of structure, scaffolding, and instruction from the teacher (e.g., Barab et al., 2000; Evagorou et al., 2008; Hmelo et al., 2000; Kali et al., 2003; Penner et al., 1997). Indeed the literature on pedagogical content knowledge offered evidence to support the significance of teacher knowledge of content and pedagogy for student learning (Clermont, Borko, & Krajcik, 1994; Shulman, 1987; Van Driel, Verloop, & de Vos, 1998).

In addition to the design and computer-based activities and intellectual support from teachers, the tasks in these studies required and encouraged students to talk and share ideas with one another and with their teachers as they created and manipulated their (physical and virtual) models. In one study, researchers used a participatory pedagogical model that included activities on the individual, local, and public levels (Barab et al., 2000). That is, the tasks involved individual reflections of the ideas, negotiating those ideas with classmates in their group, and sharing collective group ideas with peers on the Internet. Consistent across all of these studies, students worked in collaborative peer groups to engage in shared activities where they were given control over what and how to make changes in order to accomplish the assigned task (e.g., Barab et al., 2000; Evagorou et al., 2008; Hmelo et al., 2000; Kali et al., 2003; Penner et al., 1997). As a part of the intervention for these research studies, participatory learning environments were created. Barab et al. (2000) described such environments as establishing "rich contexts that encourage explanation and discovery … and to support students working collaboratively on the construction of personally meaningful and conceptually functional representations" (p. 721). Thus, critical characteristics of these learning environments for the students were having control over their learning and the opportunity to talk with their peers.

Summary

The studies reviewed in this section acknowledged the difficulty in understanding complex systems, but also recognized that students, if given the necessary support, could learn to understand them and develop the skills necessary to do so. The tools, resources, and interventions proposed to facilitate understanding of complex systems allowed students to manipulate (physical and virtual) models that made the system framework explicit and gave them extended experiences with, and exposure to, the complex system. Many studies also emphasize the value on learning when students are allowed to talk and collaborate with one another. The tasks in all the studies reviewed make the invisible, abstract, or intangible elements of a complex system visible, concrete, and tangible. The experiences are operational, interactive, and iterative, and in some cases, cooperative and discursive as well. While more time is preferred, some studies report some improvement in as few as three sessions. Finally, a knowledgeable facilitator is critical; someone needs to be available to offer students' intellectual support and guidance, as they need it.

Models are simplified representations of ideas, concepts, objects, events, systems, and processes. For scientists, they play key roles in the explanations of science, as they facilitate the formulation, plausibility, and generalizability of these explanations and theories. For students, models can be used to encourage them to reflect on their ideas while creating mental models of their thinking, and then test and retest their theories and understanding. Models and model-based reasoning has been found to support conceptual change as well (Nersessian, 2008). Models could be viewed as relieving strain on working memory, as students worked to understand the complexity of the systems (Grotzer, 2003; Narayanan & Hegarty, 1998). In the studies reviewed above, both virtual and physical models facilitate student learning of complex systems. Studies specifically comparing the effect of virtual versus physical materials on student learning reveal that, all other variables and conditions remaining equal, there is no difference in (elementary to undergraduate) students' gains (Klahr, Triona, & Siler, 2008; Klahr, Triona, & Williams, 2007;

Zacharia & Constantinou, 2008). In other words, with teacher support and instruction being consistent, “hands on” activities with physical manipulatives yielded similar gains as those with virtual, computer-based manipulatives. However, there are certain domains where one type of object may be more advantageous than the other. For instance, physical objects may be advantageous in domains requiring physical manipulation and tactile senses when mixing chemicals, or learning life sciences where the real thing can make an affective connection (Eberbach & Crowley, 2005; Leinhardt & Crowley, 2002). Alternatively, and perhaps for the water and carbon cycles as complex systems, virtual materials may offer a dynamic way to depict the phenomena and concepts, such as the temporal and geographical dimensions of water and carbon moving across the ocean and atmosphere.

It is important to note the dearth in studies exploring understanding of complex systems as it pertains to the ocean and climate science concepts explored in this review, water and carbon cycle. Only one study (in Israel) specifically targets students’ understanding of the water cycle as a complex system (Ben-zvi-Assarf & Orion, 2005a). However, there are studies on ecosystems (Evagorou et al., 2008; Grotzer & Basca, 2003; Hogan, 2000) and the rock cycle (Kali et al., 2003) from a system perspective that are relevant to ocean and climate sciences.

4. INFORMAL LEARNING ENVIRONMENTS

National surveys reviewed in section two note that affective, emotional, and personal connections to the ocean and climate have significant influences on American adults’ knowledge, attitudes, behavior, perceptions of risk, and policy preferences (Bord et al., 2000; Leiserowitz, 2006; Steel, Lovrich et al., 2005; Steel, Smith et al., 2005). Individuals’ values and worldviews are also influential (Leiserowitz, 2006). In brief, survey respondents with more direct connections with coastal areas through personal visits or business interests had more knowledge of coastal and ocean resource issues (Steel, Lovrich et al., 2005). On climate change, without directly obvious experiences, Americans believe it is something that happens in distant places to people far away (Leiserowitz, 2006). The need for personal experiences is not surprising, as they have long been argued to be quintessential to learning (Dewey, 1938). In this section, research in informal environments is surveyed, in brief, to propose how these learning environments offer personal experiences and connections that contribute to ocean and climate literacy among the American public.

Designed settings

"Informal environments that are intentionally designed for learning about science and the physical and natural world" (NRC, 2009, pp. 5-1) may promote science literacy. These settings include zoos, aquariums, nature centers, museums, and science centers. The recent comprehensive review by the National Research Council synthesizes the growing volume of evidence that indicates the ways in which such settings promote scientific literacy among the public. These informal environments designed for science learning: develop interest in science among their visitors by encouraging excitement, interest, and comfort; promote understanding of scientific concepts, arguments, explanations, models, and facts; engage learners in scientific reasoning and practices through interactivity, conversations, and explanations; encourage reflections on the cultural and political influences of science, as well as individuals' learning of science; and even identifying with scientific enterprises and committing to actions for conservation and stewardship. Thus, for science literacy in general, the NRC review is encouraging; despite early criticisms (Shortland, 1987), people do learn science when they appear to just "mess around." For ocean and climate sciences literacy, specifically, there remains a dearth of research available in this body of literature.

For ocean sciences, there is some research that takes place in aquariums, which indicate that children and adults can make cognitive and affective gains as a result of visits to aquariums. There may be an increase in, and retention of, factual knowledge, but not necessarily improved higher order thinking (Briseño-Garzón, Anderson, & Anderson, 2007; Falk & Adelman, 2003; Falk et al., 2007). Aquariums contribute to visitors' attitudes and understanding of conservation and environmental stewardship, though it is necessary for visitors to be able to connect with the content through their prior experiences, knowledge and interests in order for the gains to be lasting and meaningful (Ballantyne, Packer, Hughes, & Dierking, 2007; Falk et al., 2007). Aquariums, like other designed settings for science learning, offer the public access to objects—in this case marine organisms—that they might not otherwise encounter, and thus make the experiences memorable (Leinhardt & Crowley, 2002).

For climate sciences, there is a weather museum in Houston, TX, though it is more common to have exhibitions and special programs that explore weather phenomena in science centers, such as ***Discover R Weather*** at the Rochester Museum and Science Center[1] and ***Wild Weather and Changing Climate*** at the University of Michigan's Exhibit Museum of Natural History[2]. There are also exhibitions and programs that target climate change specifically; these include ***Climate change: The threat to life and a new energy future*** at the American Museum of Natural History[3], ***Altered state: Climate change in California*** at the California Academy of Sciences[4], ***Weather report: Art and climate change*** at the Boulder Museum of Contemporary Art[5], and ***Feeling the heat: The climate challenge*** at the Birch Aquarium[6]. However, there is no research on how such exhibitions and programs may affect people's understanding of climate sciences.

Outdoor settings

Informal learning environments can also occur in outdoor settings, which offer personal experiences that promote ocean and climate literacy through direct contact with the actual environment that they are trying to understand (and sometimes, to protect). These settings include public places, parks, marine sanctuaries, and marine protected areas, such as beaches, tidepools and the ocean itself. People visit these settings in leisure time or as a part of formal schooling, and they engage freely or take part in organized programming. There is, however, limited research specifically exploring the learning that takes place in these settings as they pertain to ocean and climate literacy. Research in outdoor education, in general, suggests that experiences in the natural environment contribute to people's understanding of, and commitment to, environmental conservation and stewardship (Bogner, 1998; Dillon et al., 2006). More specifically, there are some studies in marine wildlife tourism literature that provides some empirical evidence on how experiences in outdoor settings may contribute to ocean sciences literacy.

In 2001 the International Fund for Animal Welfare reported that whale watching, as a commercial endeavor, was a $1 billion USD industry, which engaged nine million people in over 87 countries in a common experience—watching cetaceans in their natural environments (Hoyt,

[1] http://www.rmsc.org/MuseumAndScienceCenter/exhibits/weather/
[2] http://www.exhibits.lsa.umich.edu/exhibitmuseum/publicprogrms/special_programs/winter_family_science_reading/
[3] http://www.amnh.org/exhibitions/climatechange/?src=e_h
[4] http://www.calacademy.org/academy/exhibits/nat_history/
[5] http://www.bmoca.org/artist.php?id=74
[6] http://aquarium.ucsd.edu/Exhibits/Feeling_the_Heat/

2001). In many places in the US and abroad, whale watching was a valuable, and sometimes crucial, source of income to the community, as it created jobs and businesses. Moreover, the report revealed that whale watching helped to foster an appreciation of marine conservation among tourists, offered local communities a sense of identity and pride, and provided a ready platform for scientists to study cetaceans or the marine environment. A study in Oregon explored the effects on people's educational and conservation values from whale watching trips (Christensen, 2007). Results showed that people's past experiences with whales and the marine environments positively influenced their environmental value orientations (being more biocentric), which positively influenced awareness of consequences of their own actions on whales and marine areas.

A reflective narrative on whale watching in Hawaii by a marine biologist, who studied the natural history, social dynamics, and individual behavior of humpback whales, offered a different type of insight (Forestell, 1993). Forestell noted two interesting patterns in participants' comments after their whale watch excursions. First, they contrasted and compared what they knew or believed prior to the trip (from school, television, magazines) with what they just saw or learned during the trip. Second, they began to incorporate their whale watch experience into a broadened vision of environmental issues (global threats like oil spills, whaling, drift nets, marine debris, over-development); where environmental stewardship did not only pertain to all the whales in the ocean, but the very whales they just observed. Forestell's observations highlighted the powerful affordances of outdoor settings and their access to real organisms in their natural environment, which was echoed in Zeppel's (2008) literature review.

Zeppel (2008) conducted a review of 18 empirical studies on facilitated marine educational programs in outdoor and designed settings in Australia, New Zealand, and the US. In sum, the studies she reviewed reported change in participants' lifestyle, behavior, knowledge, and conservation appreciation as a result of personal contact with marine wildlife complemented with educational programs. She also commented that most of these studies measured intention to act, not actual behavior, and they relied on self-report. Nonetheless, she found that marine wildlife tours with an educational focus affected pro-environmental attitudes, beliefs, and behavior of participants, but pointed out that longitudinal studies were needed to determine the lasting effects of these experiences.

Teacher education

Informal environments can also contribute to teacher education by offering programs and being practicum sites, and in this way, they offer school science teachers personal experiences with the content they teach. There are institutions, such as the Lawrence Hall of Science, Monterey Bay Aquarium Research Institute, and Shedd Aquarium, that offer teacher education programs specific to ocean sciences, while other institutions, such as the American Museum of Natural History and California Academy of Sciences, provide teacher education programs to complement specific exhibitions. However, existing research, even those in aquariums, pertains to science and science pedagogy in general.

Phillips, Finkelstein, and Wever-Frerichs' (2007) survey study reported four categories of support offered to teachers by designed settings: direct-to-student programs, teacher professional development programs, collaborative and national programs, and classroom materials and curricula programs. They found that these programs were generally underutilized; that is, 53% (N=305) of respondents reported that their programs could work with more participants than currently served. The researchers did not offer reasons for this underutilization. Regarding the teacher professional development programs specifically, respondents reported using a combination of features, with emphasis on features that have been found to be effective at changing teachers' practices, such as extended duration (≥25 hours) and activities for teachers to use back in their classrooms. These programs targeted teachers' content knowledge, primarily, and they offered teachers unique experiences, like engaging with the institutions' exhibits or integrating the institutions' resources into their instruction.

Designed settings have been used as sites of practicum for pre-service teachers as a part of their teacher education program. In Canada, Anderson, Lawson, and Mayer-Smith (2006) reported on such a partnership between the Vancouver Aquarium Marine Science Centre and the University of British Columbia; in the US, Saxman and Gupta (2009) described the collaboration between the New York Hall of Science and the City College of City University of New York. In both partnerships, participants were undergraduate pre-service teachers, the practicum in the designed settings were formally adopted by the teacher education program, and pre-service teachers spent several weeks engaging with the public in existing programs at the designed setting. Anderson et al. (2006) found that the experience teaching in the aquarium, with the support of their university professors, was overwhelmingly positive and useful for these pre-service teachers. In particular, the pre-service teachers developed a broader view of education, increased their understanding of constructivism and teachable moments, developed a broader skill set for working with students from K to 12th grade, recognized the power of hands-on experiences, and gained knowledge of leading school trips. Saxman and Gupta (2009) compared teaching practices of teachers who participated in their program and those who went through traditional teacher education program without practicum in the designed setting. They observed noticeable differences between these two populations of teachers, where teachers who had opportunity to practice teaching in the designed setting consistently outperformed the control group in constructivist and inquiry-based teaching practices.

Summary

The studies in this section demonstrate that informal environments, whether designed or undersigned, inside or outside, offer learners (adults and children) firsthand contact with the science concepts, real organisms, and the natural environment that they may not have access otherwise. As a result, these experiences create personal connections in people's memories and experiences that may have implications for cognitive learning later, but also provide a sense of informed conservation that influences decision-making and individual actions. However, longitudinal studies are needed to inquire about the lasting and actual effects of these experiences. Research in designed settings report the affordances of these environments for promoting science literacy in general, while those in outdoor settings focus on marine environmental stewardship. Climate sciences are overlooked in this body of research, though climate change is gaining attention and popularity as a topic and issue to explore in designed settings. As discussed in sections two and three, understanding climate change requires people to have an understanding of the carbon cycle as a complex system, though it is not certain how these ideas are presented in these exhibitions. Finally, informal environments can be valuable places for student teachers to learn and practice constructivist and inquiry-based teaching methods. While these studies do not address ocean or climate literacy specifically, they report on the contribution of these environments for supporting quality teacher learning.

CONCLUSION

This paper has reviewed the research literature for queries posed by the NRC Committee to Review the NOAA Education Program. This review highlights the paucity of research on learning and teaching about ocean and climate sciences directly. There are, however, insights to be drawn from across several domains of literature that can be used to inform Committee's charge.

What is known about people's understanding of ocean and climate sciences?

The committee asked:

- Is there any "baseline" for the current level of ocean or climate literacy among the US public, or in informal environments (i.e. Aquarium and museum visitors)? K-12 students?
- What evidence is there about what people know and don't know (about ocean and climate sciences)?
- What is known about the development of misconceptions among learners of ocean and climate sciences?
- Is different evidence needed for principles that focus on facts vs. concepts vs. nature of science (e.g. observations, experimentation, and modeling)?
- Are there specific concepts that are more difficult to learn?

National opinion polls and academic surveys revealed that the American public's baseline knowledge of the ocean and climate, their functions, and the affects of human activities "superficial" (AAAS, 2004; Leiserowitz, 2005, 2007; Steel, Smith et al., 2005; The Ocean Project, 1999). This limited knowledge had implications on people's perceptions of the urgency to act, their support of public policy, and consequences of their own behaviors. People's personal connections to the ocean were also found to correlate with their knowledge and actions (Leiserowitz, 2006; Steel, Lovrich et al., 2005). While these national surveys were useful in offering a general overview of the literacy levels of Americans, a deeper probing was necessary to determine exactly what and how people understood ocean and climate sciences. Given the numerous concepts underlying the 14 Literacy Principles and the varying quantity and quality of research available on all the concepts, the in depth review focused on the water and carbon cycles, as these are quintessential processes for understanding the ocean and climate.

Science educational research in chemistry, physics, geology, ecology, environmental education, and system dynamics were reviewed; the studies spanned from kindergarten to university students, with the majority in K-8 grades. These investigations showed that having a conservation of matter and knowledge of the basic particle theory helped students understand the water cycle as the circular movement of water between sources and the atmosphere (Bar & Galili, 1994; Johnson, 1998c; Tytler, 2000), but students were not thinking of the water cycle as a complex system with temporal and geographical distances (Ben-zvi-Assarf & Orion, 2005b; Dickerson & Dawkins, 2004; Shepardson et al., 2008). This incompleteness in students' thinking would have consequences for understanding the water cycle as it pertained to ocean and climate sciences, though more studies are necessary to support this claim. In contrast, research on students' understanding of the carbon cycle primarily focused on phenomena—the greenhouse effect, global warming, and climate change. These studies revealed that students did not understand how carbon in the atmosphere affected climate and weather, with most conflating the depletion of ozone layer with global warming (Andersson & Wallin, 2000; Boyes & Stanisstreet, 1993; Groves & Pugh, 1999; Lee et al., 2007). For both cycles, the studies predominantly explored students' understanding of different phenomena of each cycle, and not the cycles as complex systems or as part of the global system. Moreover, students held conservation of matter when thinking of the cycles locally, but even university students did not hold conservation of matter when considering the cycles as global systems (Ben-zvi-Assarf & Orion, 2005b; Sterman & Sweeney, 2002).

Understanding the water and carbon cycles as complex systems may be particularly important to ocean and climate sciences literacy because the interrelations and interconnections of these processes, over geographic and temporal distances, are fundamental to the concepts in the 14 Principles. For instance, more compounds in the atmosphere traps more outgoing radiation, leading to warming of the atmosphere. Warm air can sustain a higher concentration of water vapor than cooler air (University Corporation for Atmospheric Research (UCAR), 2000). Therefore, as air warms, more evaporation may take place, which increases the concentration of water vapor in the atmosphere and warms the atmosphere further. Emphasis on only individual processes leaves students on their own to make connections between the cycles in a global system, which they may not be able to do. More research is necessary to support this claim, as there is hardly any research specifically exploring the water or carbon cycles as complex systems. However, studies on system thinking may offer insight on the challenges and strategies for learning and teaching about ocean and climate sciences in this way.

What are the challenges and strategies for learning and teaching about the ocean and climate?

The committee asked:

- What are the unique challenges and opportunities for learning and/or teaching these essential principles?
- What types of tools (i.e. interactive models, simulations, etc.) support students understanding of these principles?
- Is there evidence to support the perceived importance of hands on learning experiences? If so, is there research that points to best practices in hands on learning activities (e.g., connections to classroom activities, group discussions, or teaching strategies)?
- Is there evidence that particular teaching strategies are effective in supporting individuals understanding of these principles? Do these strategies vary across ages or venues?

Research in science education, learning sciences, cognitive psychology, and system dynamics were examined to determine students' understanding of complex systems. These studies reported that students' tendency towards simple, linear causality impeded their ability to consider the dynamic processes of a complex system, such as emergent properties, feedback loops, and multiple cause-and-effect relationships (Evagorou et al., 2008; Raia, 2005; Resnick, 1990; Wilensky & Resnick, 1999). Moreover, comparison studies between experts (scientists) and novices (students) revealed that in noticing the interconnectedness of components in a system, experts focused on the behavior and functions, whereas novices concentrated on the structures (Hmelo et al., 2000; Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004). That is, 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. It was proposed that thinking about the dynamic processes of complex systems required significant working memory, which could be cognitive overload for students (novices) (Conway & Engle, 1996; Grotzer, 2003; Narayanan & Hegarty, 1998).

Despite these challenges on learning, researchers found several teaching methods that facilitated system thinking skills. First, using models, and more specifically, opportunities for students to create and manipulate models facilitated thinking about complex systems. Students showed gains in their thinking about complex systems in activities that offered them the opportunity to design their own physical model through an iterative process that was further supported by structure and guidance from a knowledgeable facilitator (Edelson, 2002; Hmelo et al., 2000; Kawasaki et al., 2004; Penner et al., 1997). There were also student gains in activities where they used computer-based learning environments (virtual models), such as virtual environments and hypermedia (Barab et al., 2000; Evagorou et al., 2008; Kali et al., 2003). Studies comparing learning gains between physical versus virtual manipulatives did not report a difference on student learning, though these studies did not explore complex systems in particular (Klahr et al., 2008; Klahr et al., 2007; Zacharia & Constantinou, 2008). Models—virtual and physical—could make the invisible, abstract, and intangible elements of the dynamic processes in complex systems visible, concrete, and tangible for students as they learn.

The second and third methods were not studied specifically, but they were part of the intervention and were recognized by the researchers to be important contributors to students' learning gains. Second, scaffolding from knowledgeable and skilled classroom teachers was critical for learning. In these studies, the teachers had system 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 learning experiences, as well as talk about and reflect on their ideas with their peers. Indeed, students were capable of developing processing skills to think about complex systems. Opportunities to engage in the iterative process of designing, manipulating, and redesigning models with their peers could facilitate understanding of complex systems, though only one study (Ben-zvi-Assarf & Orion, 2005b) examined the water cycle as a system.

What are the affordances of informal learning environments for promoting and supporting ocean and climate literacy?

The committee asked:

- Are there different challenges and opportunities across venues (e.g. K-12 classroom, after-school, or museums) or ages?

Psychology, science education, and learning sciences research on learning in informal environments, as well as research in tourism and leisure studies were explored in order to determine the affordances and contributions of environments outside of formal schooling for promoting and supporting ocean and climate literacy. These studies indicated that these environments offered visitors experiences that provided a personal connection between them and the distant environment (Ballantyne et al., 2007; Christensen, 2007; Zeppel, 2008). National surveys revealed that while Americans were willing to take personal action to help the ocean and climate, they also perceived the problems pertained to people, places, and time far away from them (Leiserowitz, 2006; Steel, Lovrich et al., 2005). These surveys also reported correlations between people's knowledge, personal connections, and behaviors and actions. Informal learning environments, whether designed settings or outdoor, natural settings, provided learners with access to objects, organisms, and phenomena so that they could make those personal connections. However, no studies were available that showed the extent to which experiences in these environments led to increased ocean and climate literacy.

In conclusion, the studies in this review provide three major suggestions for the Committee. First, a systems approach to critical concepts and processes, such as the water and carbon cycles, may support ocean and climate literacy. Second, understanding global processes from a system perspective requires thinking skills, which is challenging to develop. There are strategies that can support system thinking, including schoolteachers with the pedagogical content knowledge to scaffold student thinking, design activities that give students control to create and manipulate (virtual and physical) models, and opportunities for students to talk with peers in order to reflect on, articulate and share their thinking. And finally, informal learning environments 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.

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