CLARIFYING CLIMATE CONFUSION: ADDRESSING SYSTEMIC HOLES, COGNITIVE GAPS, AND MISCONCEPTIONS THROUGH CLIMATE LITERACY

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Abstract: The challenge of significantly increasing the public's climate literacy is a daunting one. While polling research indicates that most American adults believe climate change is happening, the data also show there is widespread confusion about the causes of the change and the degree of scientific consensus around the human impacts on the climate system. Consumers and corporations, who may lack an understanding of the important role of carbon in the climate system, are encouraged to reduce carbon emissions, purchase carbon offsets, and consider carbon labels that show the amount of embedded greenhouse gases in products and services. Utility companies promoting the use of smart meters find that many consumers do not understand how their electricity is generated or the role played by fossil fuels, which are in effect concentrated forms of buried solar energy linking energy use today to past and future climates. While aggressive media, corporate, and political forces are often regarded as the primary cause of the public's climate confusion, a review of five decades of science education relating to climate in general and climate change in particular reveals that basic climate science has not been well addressed in national and state education standards or science education curricula. Moreover, key misconceptions and misinformation about basic climate science are strongly held by students, teachers, and public audiences. We review research on these misconceptions and call upon educators and communicators to address systemic holes and pedagogical gaps with high-quality resources and professional development. The recently developed *Essential Principles of Climate Literacy* provides an authoritative, comprehensive framework for educators and communicators to frame climate science. However, to be effectively used as a tool for increasing broad climate literacy, effective mental models to address misconceptions will need to be integral to the high-quality resources and professional development programs required to significantly increase climate literacy throughout society. [Key words: climate literacy, science education, misconceptions, standards, benchmarks.]

COUNTERING CLIMATE CONFUSION

The basics of the climate system, including the influence of orbital dynamics such as the eccentricity of the Earth's orbit (Milankovitch, 1930), the concept of the greenhouse effect (Tyndall, 1863), and the potential for increased atmospheric warming due to the release of heat-trapping gases from industrial activities (Arrhenius, 1896), have been well understood by climatologists for many decades (Weart, 2004). Anthropogenic forcing of the climate system has also been incorporated in science education, albeit inconsistently, for many years. For example, during the International Geophysical Year in 1958, the U.S. National Academy of

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Sciences described in the pioneering science education publication *Planet Earth: Mystery with 100,000 Clues* (NAS, 1958, p. 24) that the natural greenhouse effect was being altered because "our industrial civilization has been pouring carbon dioxide into the atmosphere at a great rate" and that if it remained "it would have a marked warming effect on the earth's climate" and could "cause significant melting of the great icecaps and raise sea levels in time."

Following the launch of Sputnik and other satellites during the International Geophysical Year (IGY) of 1957–1958, and with the establishment of NASA and the escalation of the Cold War, significant funding flowed into math and science education in the United States through the National Defense Education Act, with IGY education materials playing an important role in science education during the 1960s. Science education in the United States and elsewhere has been dominated by the traditional disciplines of biology, chemistry, and physics, with a secondary role assigned to Earth sciences and geography. The NASA lunar missions and Cold War dynamics invested heavily in math and science education through the 1960s and into the 1970s. Meanwhile, the global network to monitor CO_2 begun during IGY (Weart, 2004), coupled with an increased understanding of carbon isotope ratios that allowed researchers to better isolate human contributions to increased CO_2 levels.

But by the 1980s, science education, which emphasized the three-pronged disciplines of biology, chemistry, and physics had not fostered a science-literate society, and in the decades after IGY, the basics of the climate system and the connections between energy, whether from the sun or fossil fuels, and climate were not an integral part of the curriculum. In the mid-1980s, the Harvard-Smithsonian "Private Universe" study (Schneps and Sadler, 1985) demonstrated that Harvard graduates could navigate 16 years through the world's finest educational systems without learning basic scientific concepts relating to the Earth's climate—specifically that (1) the axial tilt is the reason for the seasons and (2) that plants derive their mass from carbon dioxide in the atmosphere.

By the 1980s, the lack of robust science literacy in the United States inspired the American Association for the Advancement of Science to establish Project 2061 (the date when Halley's Comet will next travel near Earth) and to publish *Science for All Americans* (AAAS, 1989). Throughout most the 1990s and until recently, the topic of climate change and science, including natural variability and human-induced change, was treated, if at all, as a subset of weather in many K–12 classrooms. The influential National Science Education Standards (NSES) content standards developed by the National Research Council (1996), which, like the AAAS Science Literacy benchmarks aimed at reforming science education, did not explicitly highlight content relating to climate except as very foundational concepts. Climate is mentioned nine times in the NSES Science Content Standards, but a human impact on climate is not mentioned once. Books, such as Al Gore's 1992 *Earth in the Balance*, attempted to raise awareness of human-induced climate change above that of the plethora of other environmental concerns. College textbooks on environmental science often brought up the causes and effects of climate variability and change on the Earth's environment almost in passing. Botkin and Keller's textbook *Environmental Science* (1995) had one chapter out of thirty on the atmosphere and

climate change, while the more recent *Environmental Science: A Global Concern* (Cunningham et al., 2003) devotes a total of 10 pages out of more than 600 to climate. Miller's *Living in the Environment: Principles, Connections, and Solutions* (2004) combines climate change and ozone depletion in one out of 26 chapters.

In recent years, there has been some progress. The AAAS Science Literacy Atlas 2 (2007) includes a section on Weather and Climate that features a conceptual "strand map" linked to K–12 science literacy benchmarks on the topic of weather and climate, including anthropogenic forcing. This and related work have helped inform the development of the Essential Principles of Climate Literacy discussed below. However, climate in general and climate change in particular continue to fall through disciplinary cracks and are often missing from state science education standards, which to a large extent drive what teachers must focus on in K–12 classrooms. Kastens and Turrin (2008) note that of 49 states with state education standards, only 30 mention any aspect of anthropogenic climate change, with only 7 mentioning or implying that burning fossil fuels contributes to climate change; 5 mentioning land use changes such as deforestation relating to changes in climate or atmosphere; and only 8 discussing how effects of climate change can be prevented or mitigated. However well intended, state education standards, which often lag behind the science and are infrequently updated, and high-stakes testing to meet No Child Left Behind requirements, make it difficult to integrate inherently interdisciplinary climate science and related topics into the curriculum.

Even in higher education, where many colleges and universities have joined the American Colleges and University Presidents' Climate Commitment, which requires participating schools "to make climate neutrality and sustainability a part of the curriculum and other educational experience for all students," (http://www.presidentsclimatecommitment.org/html/commitment.php) there can be reluctance on the part of faculty to support required courses that ensure all students learn the basics of climate science.

Given the uneven and disconnected state of environmental science education, it is little wonder that few science teachers have been afforded the background, training, or tools to convey the basics of climate or the complexities of climate change to their students, the future citizens and decision-makers of their communities.

Recent research on current public attitudes, misconceptions, and general confusion relating to climate (Krosnick, 2006; ABC/Stanford, 2008; Leiserowitz et al., 2008) suggest that while most American adults believe that climate change is happening, there is widespread illiteracy about the basics of the climate system, the role of human activities and reliance on fossil fuels on the climate system, and the consensus among the climate research community about the issues. These findings are consistent with other studies on science literacy, such as the National Science Foundation's (2008) "Survey of Public Attitudes Toward and Understanding of Science and Technology," which found that while interest in science is strong, 45% of adults surveyed in 2006 were confused about how long it takes the Earth to orbit the sun (one year), and only 43% agreed that "Human beings, as we know them today, developed from earlier species of animals," which is down from 53% in 2001.

Consistently, these studies also show that people consider themselves to be more scientifically literate than they actually are. Media, especially television, is often

singled out as being a primary source of the public's confusion about climate (Boykoff and Boykoff, 2007). Climate science (including the role of carbon in the system and the dynamics of the greenhouse effect) is complex, often nonintuitive, and challenging to convey via television soundbites. It should be a priority throughout science education, not an afterthought that may not fit in with the existing curriculum. In their analysis of the Earth Science Education Standards throughout the United States, Hoffman and Barstow (2007, p. 9) lament the "less-than-rosy status of Earth system science education across the U.S.," noting "the fact that every person in every school district is directly affected on a daily basis by weather and climate should elevate deep understanding of weather and climate to a priority in Earth science education" (Hoffman and Barstow, 2007).

A COHERENT THEORETICAL FRAMEWORK: THE ESSENTIAL PRINCIPLES OF CLIMATE LITERACY

A key factor that has contributed to the dearth of comprehensive climate science education in K–20 education in the United States is the lack of a coherent climate science framework for educators and communicators. Beginning in 2006, an effort to engage a broad community of researchers, educators, and colleagues from multiple disciplines began to develop a research-based framework for climate literacy through an iterative peer-review process. The Climate Literacy effort built on prior literacy efforts, specifically the Ocean Literacy effort led by National Geographic Society and others (2005) that resulted in a brochure entitled *Ocean Literacy: The Essential Principles of Ocean Science*, among other outcomes.

In April 2007, a NOAA-funded workshop entitled "A Framework for Weather and Climate Literacy" was held in Washington, DC, co-hosted by NOAA and the AAAS Project 2061 (Lynds, 2007). The workshop was attended by over 20 participants, including educators and scientists, many of whom were unfamiliar with Project 2061 and the Benchmarks for Science Literacy. During the first portion of the workshop, participants reviewed the prior Ocean Literacy framework, and read a publication produced by AAAS Project 2061 entitled *Communicating and Learning About Global Climate Change* (AAAS, 2007). In addition, they familiarized themselves with the *Atlas for Science Literacy*, including the recently released Volume 2 (AAAS and NSTA, 2007), with specific science literacy benchmarks and the strand map on weather and climate. Initial discussion focused on the vigorous research that had gone into developing the conceptual strand maps, which are organized by grade level and scaffolded to build on prior knowledge. The strand maps, which link to other maps, are built on learning goals as well as research on cognitive development, and an online version of the Weather and Climate strand map is available at: http://strandmaps.nsdl.org/?id=SMS-MAP-1698.

The workshop had several primary outcomes: a draft framework of essential principles and fundamental concepts; a call to establish a climate literacy coalition outside of the federal agencies (which has resulted in the Climate Literacy Network—http://www.climateliteracynow.org); and an iterative process of incorporating feedback solicited online and through a related workshop. After thorough community vetting, the Essential Principles of Climate Literacy framework was released in

Spring 2008 at the National Science Teachers Association meeting, and is available online through the Climate Literacy Network and the NOAA Climate Office (http://www.climate.noaa.gov/education/). The seven essential principles and fundamental concepts nested below them explore in detail how life and climate are linked; how science relating to weather and climate is conducted; the role of the sun in the climate system; the complex interactions between spheres and processes within the system; natural variability and change; human activities and related change; and how people can make informed decisions relating to climate.

The Essential Principles of Climate Literacy, and the related Essential Principles of Atmospheric Science Literacy (http://www.eo.ucar.edu/asl/) were developed through similar community-based processes, and provide authoritative frameworks of principles and concepts to help guide educators, scientists conducting outreach, and institutional communicators in framing climate and atmospheric science. Through use of the Essential Principles, teachers can identify the climate science concepts that are developmentally appropriate for their students and lead to a thorough understanding. Educators can see explicit alignment between climate science and the National Science Education Standards, and curriculum and professional development providers may define and align their offerings within the scope of the Essential Principles.

There are a number of substantial challenges involved in fostering a climate-literate society through education. As noted previously, textbooks and traditional teaching materials relative to climate science are often lacking. Standard curriculum and textbook adoption cycles that are often slow and subject to protracted state and local review and debate (Stein et al., 2001). Meanwhile, the field of climate science evolves quickly as new evidence arises. For example, observed sea ice melt and changes in ice sheets are occurring faster than models had predicted (e.g., Stroeve et al., 2007) and a steady stream of reports (e.g., Karl et al., 2008) and studies (e.g., Domingues et al., 2008) update and enhance the findings conveyed in reports such as the Intergovernmental Panel on Climate Change. Staying current with the latest findings is difficult for scientists and well nigh impossible for educators and the general public.

Finally, as Moser and Dilling note in their article "Making Climate Hot" (2004, p. 35), "in the absence of an adequate mental model, lay listeners will make up or seek their own framework to help them make sense of the issue." Their own framework may be sociocultural or it may be from a prior misconception. Ideally, the Climate Literacy framework and mental models that tie to specific fundamental concepts within the framework will contribute to broader climate and science literacy, although specific misconceptions about climate science will need to be addressed for this effort to be successful.

IDENTIFYING MISCONCEPTIONS

In his article in Science Magazine, "Risk Communication on Climate: Mental Models and Mass Balance," John Sterman (2008, p. 532) notes that "the strong scientific consensus on the causes and risks of climate change stands in stark contract to widespread confusion and complacency among the public," and that the mental

models of policymakers and citizens, who by strong majorities believe climate change is occurring and support action to address it, do not have an effective mental model of the lag-time and nonlinear dynamics of accumulation to appreciate how challenging it will be to stabilize and reduce anthropogenic carbon dioxide emissions in the atmosphere. "Even if people sincerely wish to mitigate the risks of climate change, wait-and-see will seem prudent if they misunderstand basic concepts of accumulation and erroneously believe that stopping the growth of emissions will quickly stabilize the climate" (Sterman, 2008, p. 532). In calling for new methods to develop individuals' intuitive systems thinking capabilities, Sterman identifies an important misconception that will need to be addressed in order to more fully inform and engage the public. It should be noted, however, that there are others educators should be aware of in order for climate science literacy to be improved.

In fostering effective mental models that will promote climate literacy through education, outreach, and communication programs and strategies, one challenge stands out: how to successfully convey the complexity and process of the science (Grotzer and Lincoln, 2007) and to identify and address core misconceptions about natural climate processes and anthropogenic forcing and the resulting "enhanced" greenhouse effect. As Cordero et al. (2008, p. 865) have observed: "an improved understanding of students' ideas and how they develop can lead to better instructional methods and ultimately enhance the public's understanding of science." From mistaken ideas of the "reason for the season" to the common confusion that people have about global warming and the ozone layer, these "naïve theories" or "misconceptions" have proven difficult to counter. These misconceptions become deeply rooted among even highly educated adults (Sterman and Sweeney, 2007) and as Rule (2005, p. 309) has noted, teachers hold many of the same misconceptions about fossil fuels as their younger students, "confirming the importance of addressing younger students' ideas during instruction," and affirming the importance of professional development.

Following is a preliminary summary of 10 concepts (Table 1) relating to climate, atmospheric science and fossil fuel energy use, and the common misconceptions or preconcepts researchers have identified, which can leave students, adults, and teachers confused and ill-informed. The primary means used by researchers to identify these misconceptions is via observations and interviews, questionnaires and surveys, and more recently (e.g., Rebich and Gautier, 2005) through the use of concept maps. Further research will be required to determine the relative importance of these concepts among various audiences; the existing best practices for addressing the misconceptions; new ways of conveying the science; and to evaluate the effectiveness of specific mental models and strategies.

Axial Tilt as the "Reason for Seasons"

The well-known "Private Universe" study of Harvard Graduates as well as eighth grade students demonstrated how difficult it is to convey the fundamental cause of seasonal change. While students may be taught this concept in middle school or even earlier (Morrow, 2000), the AAAS Project 2061 research (2007, p. 118) notes

Table 1. Climate Concepts, Misconceptions, Research Evidence, and Literacy Principles

Climate science concept	Naïve and misconception	Research evidence	Relevant science literacy principles and concepts
(1) Axial Tilt as the "reason for seasons."	Earth gets closer to sun in summer, and is further away in winter.	Schneps, 1985; AAAS, 2007	The tilt of Earth on its axis causes solar energy to fall more directly on different parts of Earth during different times of the year, resulting in seasonal changes. (CL-3C)
(2) Gas/air has mass and takes up space.	Gas makes things lighter; air seems to have no weight, color or odor and is in effect invisible.	AAAS, 2007	The atmosphere is a mixture of gases with small, but important quantities of liquid and solid particles. (ASL-1.1, 1.2)
(3) Plants acquire mass from carbon dioxide via photosynthesis.	Plants derive their mass from water and nutrients through roots.	Schneps, 1985; Hershey, 2004; AAAS, 2007	The carbon cycle influences climate in a variety of ways, including seasonal interactions between the atmosphere, biosphere, and hydrosphere, and the formation and consumption of fossil fuels. (CL 4D)
(4) Fossil fuels are "buried solar energy" originally captured by living organisms.	Fossil fuels have been around since the origins of Earth.	Rule, 2005	The energy in fossil fuels such as oil, natural gas and coal comes from energy captured long ago from the sun. (CL 3F)
(5) Difference between and significance of incoming UV and outgoing Infrared radiation.	The sun's energy reflects off the surface of the Earth.	Gautier, 2006	The Earth receives energy in the form of short-wavelength electromagnetic radiation from the Sun. (ACL- 2.1)
(6) Greenhouse effect allows liquid water and life to exist on earth, and human activities are "enhancing" the greenhouse effect.	Human activities cause the greenhouse effect, which is like global warming.	AAAS, 2007; Rebich, 2005	Gases in the atmosphere, such as carbon dioxide and water vapor, temporarily trap infrared radiation from the warmed surface of Earth. The additional warmth … allows liquid water … to exist on much of Earth's surface. (CL 3E)
(7) Ozone layer's role in Earth system.	Global warming caused by ozone hole created by chemicals.	Gowda, 1997; Gautier, 2006	We … rely on ozone in the stratosphere to protect us from harmful radiation from the Sun. (ASL, EP7.1)
(8) There are significant differences between weather and climate processes and time scales, and how they are studied.	Climate is simply long-term weather, and therefore can't be predicted.	Gowda, 1997	Weather is understood as the atmospheric conditions at any given time or place…. Climate is understood as the atmospheric conditions (i.e., weather variables) averaged over a long period of time … and over a large area. (CL 5A/B)

(*table continues*)

Table 1. Continued

Climate science concept	Naïve and misconception	Research evidence	Relevant science literacy principles and concepts
(9) Small changes (atmospheric composition or temperature increase) can have a large and nonlinear effect.	The atmosphere is large and small amounts of CO2 can't make much of a difference.	Gowda, 1997; Chi, 2005	Relatively small increases in amounts of greenhouse gases … can magnify the greenhouse effect. (CL 4G) Interactions between components of the Earth's climate system result in changes to the system and produce emergent phenomena unique to the system. (CL 4G/H)
(10) The Carbon Cycle and Human Dimension.	Carbon is destroyed when fossil fuels are burned and CO2 is released into the atmosphere; carbon released from combustion and other human activities doesn't have an impact on the climate system; global warming, if it is occurring, is the result of natural cycles we can't do anything about.	Madsen, 2007	([T]he observed increase in global average temperatures since the latter part of the 20th century is very likely due to documented increases in human-induced greenhouse gas concentrations, primarily from the burning of fossil fuels. (CL 6E) Carbon dioxide, an important greenhouse gas, is removed from the atmosphere in the ocean and other parts of the Earth system through biologic and geologic processes. (CL 4D) The atmosphere plays an important role in biogeochemical cycles in the Earth system. For example, the atmosphere is a reservoir of carbon in the Earth system, storing carbon released from natural processes and fossil fuel burning, and transferring carbon to the plants through photosynthesis. (ASL EP5.3)

that students of all ages, including college students and adults, "have difficulty understanding what causes the seasons." In addition to the axial tilt, factors that come into play in people's mental models include the belief that Earth orbits the sun in an elongated elliptical path; confusion about the relative size, motion, and distance of the Earth from the sun; how light travels; the length of the Earth's revolution around the sun; and even the period of rotation. One strategy to mitigate again this common misconception is to ensure that the concept is adequately addressed in high school, when students have sufficient background in geometry and physics to grasp the concept.

Gas/Air Has Mass and Takes Up Space

In our everyday lives, we do not experience the pressure of air, which is made up of invisible, odorless gases, and thus the concept that air has mass and exerts pressure is nonintuitive and counter to our perceptions. Research by AAAS Project 2061

(2007, p. 118) for their Weather and Climate strand map indicates that recognizing "air has weight may be challenging even for high-school students. Students of all ages (including college students) may believe that air exerts force or pressure only when it is moving and only downwards." On a related note, they also call out the difficulty many students have with the concept that through evaporation water is converted to an invisible form. "With special instruction, some students in 5th grade may be able to identify the air as the final location of evaporating water, but they must first accept air as a permanent substance" (AAAS, 2007, p. 18).

Plants Acquire Mass from Carbon Dioxide Via Photosynthesis

Also noted in the Harvard Private Universe study (Schneps and Sadler, 1985), the commonly held concept—that plants derive their mass from nutrients drawn up with water through the roots—is deeply rooted and difficult to dislodge. The nonintuitive concept—that plants derive their mass "out of thin air" via photosynthesis, which pulls carbon out of the atmosphere and releases free oxygen—is taught in middle and high school, but the concepts often are not retained. Hershey (2004) in his study of photosynthesis misconceptions focuses on five causes: oversimplifications, overgeneralizations, obsolete concepts or terms, misidentifications, and flawed research. One team reports that using an interactive CD-ROM entitled "Photosynthesis In Silico," reduced common misconceptions by 70% by helping students visualize the complex process of photosynthesis (Russell et al., 2004).

Fossil Fuels Are "Buried Solar Energy" Originally Captured by Living Organisms

In her study "Elementary Students' Ideas Concerning Fossil Fuel Energy," Rule (2005) identifies numerous misconceptions and gaps in students' understanding of fossil fuels, how they are used, and where they originate. Average and gifted students both fared poorly on understanding the basics of fossil fuels, suggesting that

> a reason for this may be that fossil fuel energy is an unfamiliar topic to these students and therefore, they have a general lack of knowledge and fewer preconceptions in this area than they might have concerning other, more familiar, topics. (Rule, 2005, p. 313)

She also examined the understanding of pre-service teachers and found they held many of the same misconceptions as their students. In summary, she offers:

> The persistence of misconceptions about fossil fuels into adulthood indicates the critical nature of helping younger students understand the scientific concepts involved. Students must understand how fossil fuels originate to comprehend their nonrenewable nature and uneven distribution worldwide with ensuing political consequences. Students need to know the main uses of petroleum and other fossil fuels to comprehend their impact on global relationships and ecology. (Rule, 2005, p. 317)

Differentiating Between and Understanding the Significance of Incoming Ultraviolet and Outgoing Infrared Radiation

In a study of misconceptions about the greenhouse effect using questionnaires and concept maps, Gautier et al. (2006) noted:

> In most instances, longwave radiative processes did not appear to play any part in students' models of the greenhouse effect. This indicates that students have difficulties viewing the Earth (let alone greenhouse gases) as radiating bodies. Many students were not aware of the natural greenhouse effect produced by atmospheric gases that maintains a habitable temperature on Earth and that the issue of global warming is related to the enhanced greenhouse effect. (Gautier et al., 2006, p. 387)

Addressing this misconception will require that teachers understand and convey to their students the difference between and the significance of incoming short-wave ultraviolet and visible radiation and outgoing infrared radiation, and take the time to emphasize the basic physics and chemistry involved to their students.

The Greenhouse Effect Allows Liquid Water and Life to Exist on Earth, and Human Activities Are "Enhancing" the Effect

AAAS Project 2061 (2007, p. 118) reported that "students have difficulty linking relevant elements of knowledge when explaining the greenhouse effect and may confuse the natural greenhouse effect with the enhancement of that effect." Rebich and Gautier (2005) also recognized that there is substantial confusion around the greenhouse effect and how it works, noting that some of the confusion "may result in part from the direct analogy to a greenhouse maintaining heat by trapping warm air inside," and adding that there was a

> great deal of confusion about what greenhouse gases are and the nature of their role in climate and climate change. The term "aerosol" was very often used to describe a type of greenhouse gas, which we considered to be evidence that many students were making colloquial use of the word aerosol (to mean CFC). (Rebich and Gautier, 2005, p. 363)

Ozone Layer's Role in Earth System

The common confusion between the ozone layer and the greenhouse effect is well documented (Jeffries et al., 2001; Rebich and Gauthier, 2005; Gautier et al., 2006; AAAS, 2007). Gowda et al. (1997, p. 2233) noted that

> while CFCs are greenhouse gases and do have some role to play in climate change, they are a significantly smaller cause of global warming that fossil fuels use, industrial air pollution, or deforestation. Nevertheless,

> students prominently identified CFCs and ozone layer depletion as causes of climate change.

Gautier et al. (2006, p. 386) suggest that

> based on previous experiences with both teaching and assessing student learning about global climate change, we propose key principles that we consider minimum knowledge. . . . Earth science educators should focus on identification of key principles in all areas of the discipline and use those as the basis for curriculum development.

Gautier and her colleagues studied misconceptions about 21 key principles relating to the greenhouse effect through surveys and experience, concluding:

> When planning lectures and course activities that are intended to help students overcome their misconceptions about a topic, a common-sense approach might involve presenting inappropriate conceptions students are likely to have, emphasizing that these ideas are not correct, and then presenting the information students would need to correct their misconceptions. In the educational research literature, this approach is referred to as the cognitive conflict approach. (Gautier et al., 2006, p. 394)

Significant Differences Between Weather and Climate Processes and Time Scales, and How They Are Studied

Gowda et al. (1997) found that the majority of students studied were unable to distinguish between weather and climate or aware of the long-term nature of climate change.

> The inability to distinguish between weather and climate apparently leads students to make other mistakes, such as expecting that climate change signals will be manifest in short-run weather patterns and that it will be possible to sense them directly. Scientists, in contrast, isolate climate change patterns by statistical analysis of long-term climatological data. (Gowda et al., 1997, p. 2236)

The short-term, linear cause and effect described in weather reports about particular weather events may contribute to the confusion and misconception that Sterman (2008) has identified relating to the accumulation over time of carbon dioxide and other greenhouse gases in the atmosphere.

Small Changes (Such as Atmospheric Composition or Temperature Increase) Can Have a Large and Nonlinear Effect

It is no surprise that, given the general lack of general scientific literacy, students, adults, and teachers will have difficulty accepting how small changes—such as the

increase over a century of a hundred parts per million of carbon dioxide in the atmosphere or the impacts triggered by a few degrees increase in the global temperature (Gowda et al., 1997)—can have a massive impact on the climate system. Such nonlinear processes with nonintuitive emergent properties pose a particular challenge to educators. As Chi (2005) describes in her study "Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust," some processes are direct and more easily understood, while some are emergent, and much more challenging to address:

> Students' misconceptions of emergent processes are robust because they misinterpret emergent processes as a kind of commonsense direct processes. To correct such a misconception requires a re-representation or a conceptual shift across ontological kinds. Therefore, misconceptions of emergent processes are robust because such a shift requires that students know about the emergent kind and can overcome their (perhaps even innate) predisposition to conceive of all processes as a direct kind. (Chi, 2005, p. 161)

Carbon Cycle Confusion

After the water cycle, the carbon cycle is arguably the most important biogeochemical cycle related to the climate system. Often, education and outreach programs emphasize carbon without providing much background about the basic physics and chemistry involved. The plethora of carbon calculators and programs designed to promote the reduction of carbon emissions do little or nothing to address widespread confusion and misconceptions about the basics of the carbon cycle and its role in climate. In a study of university students' ideas on the carbon cycle, Madsen (2007) reports:

> The results show a remarkable lack of understanding of the some of the basic components of the carbon cycle and of how humans may affect this cycle. For example, there was a general lack of understanding of how carbon moves between reservoirs. A popular alternative conception was that carbon, like water, is involved in processes of evaporation, associated with clouds, and falls as precipitation back to the oceans or land. In terms of how human activities might affect the carbon cycle, the most common alternative conception was that human activity is causing pollution and that pollution would disturb the carbon cycle. In only a few cases was the type of pollution or how the pollution would actually disturb the cycle defined. These results demonstrate the crucial need to continue to educate the public about even the most basic concepts underlying the science of climate change and, when engaged in these educational activities, to be aware of the level of prior knowledge of the audiences so as to maximize their learning experience.

Gowda et al. (1997) suggest that misconceptions arise due to problems in: (1) information availability (the multidisciplinary nature of climate does not fit within traditional disciplinary boundaries); (2) having the news media as the primary source of information that blurs nuances and is not readily able to communicate complex details; (3) judgmental heuristics or mental shortcuts that may lead people to jump to conclusions (a heat wave is caused by global warming) rather than weighing probabilistic information; and (4) "fuzzy environmentalism," based on opinion or ideology rather than good science. Misconceptions arise in virtually any subject, and the misconceptions noted above are perhaps the tip of the iceberg. But given the high-stake risks associated with climate change, addressing these misconceptions and related systemic holes and pedagogical gaps should be a high priority in order to facilitate societal mitigation and adaptation.

CONCLUSION

In the 50 years since the International Geophysical Year, the human population has more than doubled, fossil fuel emissions have tripled (Marland et al., 2008), and energy demand is forecast to increase by 50% between 2005 and 2030 (EIA, 2008). Our economy is influenced by weather and climate—up to 40 percent of the approximately $10 trillion U.S. economy is affected by weather and climate events annually (NRC, 2003)—yet our societal literacy around climate is remarkably low. A robust campaign to promote climate science literacy through formal and informal education and broad communication channels will help in clarifying climate confusion, addressing the systemic holes, cognitive gaps, and misconceptions that are currently widespread. But the challenges are significant.

Addressing misconceptions will require first an awareness of the misconceptions, tools, such as effective mental models, and strategies to identify and overcome them, proper training and professional development for educators, and the conceptual framework and high quality resources to inform and engage the learners. New resources to explain basic climate concepts are becoming more sophisticated, avoiding representations that lead to misconceptions or employing visualizations and animations that explain concepts in a new way.

In order to teach climate science effectively and address their own knowledge gaps and misconceptions, teachers must be properly trained through pre- and in-service professional development, and must be provided current, accurate learning tools and resources that specifically identify and address misconceptions and cognitive deficiencies. Scientists are slowly learning to become more effective in communicating the complexities of the science to nontechnical audiences. Stephen Schneider on his "Mediaology" website (2008) suggests that scientists drop superiority judgments, explain how they arrived at their expert opinion, summarize specific peer-reviewed studies, use metaphors and accessible language, and avoid jargon (e.g., such terms as "enhanced greenhouse effect" may to an untrained ear sound like a good thing).

It is important to acknowledge that even with an ideal climate education system in place, individual and collective decisions are complex and may not be fully rooted in logic or rationale thought. As discussed in "Creating a Climate for

Change" (Moser and Dilling, 2007) the "knowledge deficit" model, whereby people are assumed to make informed decisions once their cognitive deficiencies and gaps have been filled, is not well supported by social science theory and empirical research. Chess and Johnson (2007, p. 223) noted that "more knowledge does not necessarily lead to more appropriate behavior" and that "information is not entirely inconsequential, but it is much overrated as a change agent." However, Bord et al. (2000, p. 205) found that "knowing what causes climate change, and what does not is the most powerful predictor of both stated intention to take voluntary actions and to vote on hypothetical referenda to enact new government policies to reduce greenhouse emissions." But informed decision-making is complex and more research is needed to delve into the role of fostering a climate-literate and science-savvy society.

A revised version of the Essential Principles of Climate Science Literacy finalized in March 2009 contains two principles relating to anthropogenic change: "Human activities are impacting the climate system" (Essential Principle Six) and "Climate change will have consequences for the Earth system and human lives" (Essential Principle Seven). Moreover, the entire set of principles is geared for helping inform climate decisions and is framed by a guiding principle: "Humans can take actions to reduce climate change and its impacts." Vetted by climate experts, endorsed by numerous federal agencies and science organizations, this conceptual framework will evolve as needed over time. In the meanwhile, by providing the nation with an authoritative document so all relevant parties are "on the same page," it will help address decades of climate science misconceptions, pedagogical gaps, and public confusion.

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