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Conceptualizing climate change in the context of a climate system: implications for climate and environmental education

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Today there is much interest in teaching secondary students about climate change. Much of this effort has focused directly on students' understanding of climate change. We hypothesize, however, that in order for students to understand climate change they must first understand climate as a system and how changes to this system due to both natural and human influences result in climatic and environmental changes and feedbacks. The purpose of this article is to articulate a climate system framework for teaching about climate change and to stimulate discussion about what secondary students should know and understand about a climate system. We first provide an overview of the research on secondary students' conceptions of climate and climate change. We then present a climate system framework for teaching about climate and climate change that builds on students' conceptions and scientific perspectives. We conclude by articulating a draft conceptual progression based on students' conceptions and our climate system framework as a means to inform curriculum development, instructional design, and future research in climate and environmental education.

Keywords: climate change; conceptions; understanding; curriculum

The Intergovernmental Panel on Climate Change (IPCC) has concluded that global warming is inevitable and that human activity is likely to be the main cause (IPCC 2007a). According to the IPCC, human activities continue to modify landscapes and alter atmospheric composition of greenhouse gases – carbon dioxide, methane, and nitrous oxides – to the Earth's atmosphere, and global temperatures are expected to rise, causing the Earth's climates to change. These changes may affect precipitation patterns, severe and extreme weather events, and over time environmental systems. Furthermore, human health and agricultural productivity may be sensitive to climate change. Additionally, the effects are expected to exacerbate over the next decades and are expected to drive policies and regional and global economies (IPCC 2007a). Thus, it is vital that students learn about climate change. Climate change is by far the most important environmental issue facing society and as such is an important environmental education topic (Jickling 2001). We

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hypothesize, however, that in order for students to understand climate change they must first understand climate as a system and how changes to this system due to both natural and human influences result in climatic and environmental changes and feedbacks. The purpose of this article is to articulate a climate system framework for teaching about climate change and to stimulate discussion about what secondary students should know and understand about a climate system. We present our climate system framework as a means to inform curriculum development, instructional design, and future research in climate and environmental education.

We first provide an overview of the research on secondary students' conceptions of climate and climate change. We then present a climate system framework for teaching about climate and climate change. We articulate a draft conceptual progression based on our climate system framework and the research on students' conceptions. We acknowledge that climate change education is both complex and challenging. The complexity of the Earth's climate and the uncertainty of climate science (Andrey and Mortsch 2000) coupled with the long time scale, the inability to directly observe climate change – unlike day-to-day weather change (Schreiner, Henriksen, and Hansen 2005) leads to difficulties in developing students' conceptualization of climate change. Additionally, we believe there is also difficulty due to scales, and complex cause and effects – one region affecting changes in another region or at a different time. Also, the seemingly opposite effects – e.g. heavy snowfall due to 'global warming' – and the highly varied media depiction of climate change makes teaching about the issue extremely challenging.

Review of the literature

Over the past several years many international studies have been conducted in an effort to identify secondary students' knowledge, conceptions, and conceptualizations of the greenhouse effect, global warming, climate change, and related scientific concepts. These studies have provided invaluable data about student learning that informs curriculum development, instructional design and teacher professional development. At the same time the research findings clearly indicate the challenges facing teachers and science educators in developing students' conceptualizations of climate change. They clearly show the gap between students' conceptualizations and scientific perspectives on climate change.

Our summary of the research is intended to describe the range or diversity of students' conceptions about topics relative to a climate system and climate change; it is not an attempt to draw conclusions about individual students, age or grade level understanding or even ethnic, social, and cultural differences. Furthermore, Rickinson (2001) noted that television, movies, and other informal learning experiences influence students' understandings of environmental issues. Thus, we acknowledge that students' understandings will vary by social and cultural context and educational experiences, including both formal and informal education. We have focused our review of the literature to research studies set in secondary schools. We have grouped the studies into six categories as follows: (1) causes of global warming and climate change; (2) greenhouse gases and the greenhouse effect; (3) global warming and climate change; (4) climate and weather; (5) the carbon cycle and the greenhouse effect; and (6) impacts of global warming and climate change. We conclude the section by presenting a general student model of climate change, built from the research literature.

Causes of global warming and climate change

Students believe that air pollution causes global warming and climate change. Forms of air pollution that students believed caused climate change included acid rain (Boyes, Chuckran, and Stanisstreet 1993; Boyes and Stanisstreet 1993; Pruneau et al. 2001); dust (Pruneau et al. 2001); harmful and unnatural gases (Gowda, Fox, and Magelky 1997); and air pollution in general (Andersson and Wallin 2000; Shepardson et al. 2009; Boyes and Stanisstreet, 1997; Gowda, Fox, and Magelky 1997). Studies also highlight students' belief that 'ozone depletion' is an effect of global warming (Shepardson et al. 2009; Boyes, Chuckran, and Stanisstreet 1993; Boyes and Stanisstreet 1993, 1998; Fisher 1998; Gowda, Fox, and Magelky 1997; Kilinc, Stanisstreet, and Boyes 2008; Pekel and Ozay 2005; Pruneau et al. 2001). A commonly held idea was that the ozone hole allows more solar energy or ultraviolet radiation to reach the Earth, causing global warming (Andersson and Wallin 2000; Shepardson et al. 2009; Boyes, Stanisstreet, and Papantoniou 1999; Boyes and Stanisstreet 1994, 1997; Koulaidis and Christidou 1999; Österlind 2005; Pruneau et al. 2003; Rye, Rubba, and Wiesenmayer 1997). Yet, some students believed that global warming and climate change is caused by an increase in solar radiation (Boyes, Chuckran, and Stanisstreet 1993; Boyes and Stanisstreet 1993; Pruneau et al. 2003) or because the Earth gets closer to the Sun (Shepardson et al. 2009; Pruneau et al. 2003), a seasonal variation. But ultimately these results highlight the students' view that humans affect the Earth's climate – the processes or pathways, however, are poorly understood.

Greenhouse gases and the greenhouse effect

Students may not consider carbon dioxide as a greenhouse gas (Boyes, Chuckran, and Stanisstreet 1993; Boyes and Stanisstreet 1993, 1997; Pruneau et al. 2001) and even when students identify carbon dioxide as a greenhouse gas they rarely consider other gases such as methane, water vapor, or nitrous oxides as greenhouse gases (Boyes, Chuckran, and Stanisstreet 1993; Boyes and Stanisstreet 1993; Fisher 1998; Shepardson et al. 2009). Furthermore, students believe that the greenhouse gases exist as a 'layer' (Shepardson et al. 2009; Koulaidis and Christidou 1999; Pruneau et al. 2003) or a 'lid' or 'roof' (Andersson and Wallin 2000) in the atmosphere that forms a 'barrier' (Andersson and Wallin 2000) that 'bounces' the heat from the Earth back toward the Earth or 'traps' the Sun's energy (Shepardson et al. 2009, 2011).

Some students are not even aware of the greenhouse effect (Shepardson et al. 2009; Andersson and Wallin 2000; Pruneau et al. 2001) or they make no distinction between the greenhouse effect and global warming (Andersson and Wallin 2000; Boyes, Chuckran, and Stanisstreet 1993). For some students the greenhouse effect is the trapping of solar rays by the ozone layer (Shepardson et al. 2009; Boyes and Stanisstreet 1997; Pruneau et al. 2003) or the result of ozone depletion, caused by greenhouse gases, allowing more solar radiation to reach the Earth (Shepardson et al. 2009; Boyes, Chuckran, and Stanisstreet 1999; Boyes and Stanisstreet 1994, 1997; Gowda, Fox, and Magelky 1997; Koulaidis and Christidou 1999; Rye et al. 1997), confusing stratospheric ozone with the greenhouse effect.

For students who know about the greenhouse effect their understanding is fairly simplistic. It is the trapping of the Sun's energy by the Earth's atmosphere (Shepardson et al. 2009; Kilinc, Stanisstreet, and Boyes 2008) or the bouncing of the

Sun's energy back and forth between the atmosphere and the Earth's surface (Shepardson et al. 2009). Shepardson et al. (2011) identified five mental models that students hold about the greenhouse effect (Table 1). Students do not make any distinction between the types of solar radiation, generally referring to solar radiation as 'ultraviolet rays,' 'solar rays,' 'sun rays,' 'heat,' and 'heat rays' (Shepardson et al. 2009; Boyes and Stanisstreet 1997, 1998; Fisher 1998; Koulaidis and Christidou 1999; Österlind 2005). Furthermore, students often do not differentiate solar radiation from terrestrial radiation (Shepardson et al. 2009; Koulaidis and Christidou 1999). The greenhouse effect is often viewed as a human-caused phenomenon vs. a natural process that has been enhanced by human activity; or something that is central for survival of life on the Earth.

Global warming and climate change

For the most part, students think that global warming will only affect temperature and to a lesser degree precipitation (Shepardson et al. 2009), predicting much higher temperatures (Gowda, Fox, and Magelky 1997; Kilinc, Stanisstreet, and Boyes 2008). Few students considered the possibility that global warming will affect the frequency, variability, and severity of weather events (Shepardson et al. 2009). In essence, students do not consider the difference between global warming and climate change (Shepardson et al. 2009), or that global warming might impact climate differently in various regions of the United States or the world (Shepardson et al. 2009, Boyes and Stanisstreet 1993). Furthermore, climate variability is not considered by students; that is, abnormal weather events are considered to be examples of climate change vs. a variation in climate; they do not consider long-term trends (Shepardson et al. 2009).

Climate and weather

Although there is a lack of research on students' conceptualization of a climate system (Schreiner, Henriksen, and Hansen 2005), research has shown that students fail to understand that climate is the long-term changes in weather patterns (Gowda, Fox, and Magelky 1997; Pruneau et al. 2003). This often leads students to think that climate change will be observable and directly experienced in short-term weather patterns (Gowda, Fox, and Magelky 1997). Thus, many students link observed and experienced weather events, such as unseasonably cool summers, as evidence supporting or refuting climate change.

Table 1. Secondary students' mental models of the greenhouse effect.

Model 5. Sun's rays are 'bounced' or reflected back and forth between the Earth surface and greenhouse gases, heating the Earth (may or may not identify specific greenhouse gases)
Model 4. Greenhouse gases 'trap' the Sun's rays, heating the Earth (may or may not identify specific greenhouse gases)
Model 3. Greenhouse gases, but no heating mechanism; simply gases in the atmosphere
Model 2. Greenhouse gases cause ozone depletion or formation, causing the Earth to warm
Model 1. 'Greenhouse' for growing plants

Carbon cycle and the greenhouse effect

Students' understanding of the carbon cycle as linked to the greenhouse effect has been little investigated. Most past research takes an ecological perspective. For example, Smith and Anderson in Driver et al. (1994) reported that students make no connection between oxygen/carbon dioxide cycle and other biological processes. More recently, Mohan, Chen, and Anderson (2010) have investigated students' understandings of the carbon cycle by incorporating the combustion of fuel, connecting environmental systems with human systems. They found that students held rudimentary ideas about how deforestation and the burning of gasoline affect the carbon cycle. For these students the decrease in trees resulted in reduced levels of atmospheric oxygen which allowed more of the Sun's rays to reach the Earth, causing temperature to rise. These students also believed that the burning of gasoline converted matter to a gas that polluted the air which impacted the ozone layer causing more heat, warming the Earth. These findings are similar to the research on students' conceptions of the greenhouse effect where students overwhelmingly attribute the increase in atmospheric carbon dioxide levels to vehicles and factories polluting the air or affecting the ozone layer (Shepardson et al. 2009, 2011; Andersson and Wallin 2000; Kilinc, Stanisstreet, and Boyes 2008). Shepardson et al. (2009, 2011) found that students think of respiration, volcanic eruption, and changes in photosynthesis (deforestation/forestation) as natural processes that affect atmospheric carbon dioxide levels. In essence, these students have an 'everyday' conception of the carbon cycle as linked to the greenhouse effect. They see sources and sinks in a simplistic way.

Impact of global warming and climate change

For the most part students only see increasing temperatures as the major effect of global warming (Shepardson et al. 2009; Gowda, Fox, and Magelky 1997; Kilinc, Stanisstreet, and Boyes 2008), with only a few students thinking about changes in precipitation (Shepardson et al. 2009). This increasing temperature will cause polar ice to melt, resulting in a rising ocean and increased flooding (Shepardson et al. 2009; Kilinc, Stanisstreet, and Boyes 2008). Students tend to believe that increasing temperature will cause plants, animals, and humans to die because of heat or loss of drinking water – drought (Shepardson et al. 2009). At the same time, the degree to which students are willing to engage in mitigating actions to reduce global warming and its impact is related to perceived convenience and usefulness of the action (Skamp, Boyes, and Stanisstreet 2009). For the most part, students were more willing to engage in convenient actions then inconvenient actions even though they perceived those actions to be less useful than inconvenient actions (Skamp, Boyes, and Stanisstreet 2009).

General student model of climate change

Based on the above studies we present a general student model of climate change. We have built the model based on the student ideas described in the research literature. We acknowledge that individual students may hold a different model and that the above studies involved different student populations, conceptual focus, and methodological approaches; however, the similarities among studies provide a degree of confidence in constructing a general student model of climate change. We believe that this model serves as a starting point in understanding students' conception of climate change. It also informs our framework for conceptualizing climate change within a climate system (Figure 1).

The model clearly shows the limited conceptual understanding students have about climate change. Students' understanding of climate change is built on the greenhouse effect and the sources of greenhouse gases, and to a lesser degree changes in stratospheric ozone. They lack an understanding of climate as a regulator of the Earth's energy budget through the reflection (albedo), absorption, and radiation of the Sun's energy within the climate system. They do not see the interconnections or feedbacks among the components of the climate system (i.e. atmosphere, ice, vegetation, land surface, and oceans). Their thinking is essentially linear in nature. For example: burning fossil fuels increases atmospheric greenhouse gases which causes the Earth's temperature to increase which causes climate change and plants and animals to die. They link changes in vegetation (deforestation) to the greenhouse effect via reduced photosynthesis and reduction in the sink, but not to changes in land surface, surface emissions, and albedo. This lack of understanding regarding feedbacks and the inter-relation between climatic components is a significant stumbling block for understanding not only the causes and effects of

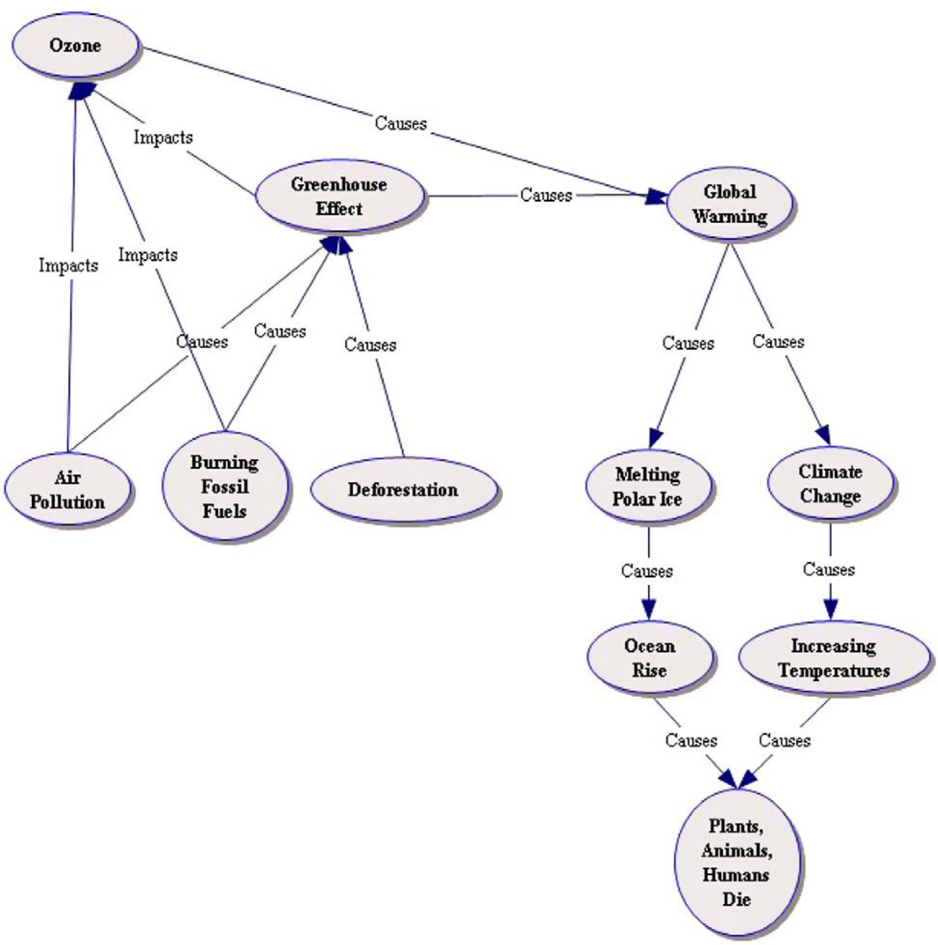

Figure 1. General student model of climate change.

climate change, but also the adaptive and mitigation strategies that can be devised. Therefore, it appears that in order to develop students' conceptualization of climate change, requires that the teaching and learning about climate change be contextualized within the climate system.

Climate system framework

Although there are many models of a climate system available, we use Ruddiman (2001) as one basis for our climate system framework. It simply illustrates the external causes of climate, the internal causes of climate, and their interconnection, and the linkage to external responses or climate variability. Embedded in this model are the elements associated with the cycling of water and carbon, land surface and ice changes, the Earth's energy budget, the greenhouse effect and greenhouse gases, and to some degree longer term climatic factors associated with the orbit and rotation of the Earth, and changes in solar intensity. It incorporates natural causes of climate variability such as El Niño and La Niña and volcanic eruptions. It illustrates how human changes to the system affect climate: changes in land cover impacts albedo, deforestation impacts the carbon cycle and albedo, and burning fossil fuels impacts the greenhouse effect. It indicates that climate change involves more than burning fossil fuels and enhancing the greenhouse effect. It shows how melting ice or changing land cover influences albedo, altering the Earth's energy budget. It illustrates that change in one component of the system impacts other components of the system, changing the Earth's climates. We also draw from the IPCC (2007a, 2007b) and the texts of Peixoto and Oort (1992) and Marshall and Plumb (2008) in developing our climate system framework.

Indeed, our proposal of the climate system framework also builds off of NOAA's (2009) *Climate Literacy: The Essential Principles of Climate Science*, which organizes the interconnections of a climate system into seven essential principles with concepts:

(1) The Sun is the primary source of Earth's energy for Earth's climate system.
(2) Climate is regulated by complex interactions among components of the Earth system.
(3) Life on Earth depends on, is shaped by, and affects climate.
(4) Climate varies over space and time through both natural and man-made processes.
(5) Our understanding of the climate system is improved through observations, theoretical studies, and modeling.
(6) Superimposed over natural variability, human activities are impacting the climate system.
(7) Climate change will have consequences for the Earth system and human lives.

The NOAA climate literacy document acknowledges that the 'full comprehension of these interconnected concepts will require a system-thinking approach, meaning the ability to understand complex interconnections among all of the components of climate system' (3).

We also ground our climate system framework on The *National Science Education Standards* (NRC 1996) system standard, which demonstrates how the development of a curriculum in climate science can provide opportunities for students and teachers to explore and analyze climate change from a systems-based perspective rather than in isolated segments (Table 2). Finally, we draw from American Association for the Advancement of Science (AAAS) 'Weather and Climate' strand map (AAAS 2007) and *Benchmarks for Science Literacy* (AAAS 1993).

In essence our framework is driven by three guiding questions:

- What is a climate system and what are the components of the system?
- What happens to the system when components within the system change?
- What are the impacts of these changes?

Central to our framework is the notion that weather, climate variability, and climate change are different components of the Earth system that are manifested within the atmosphere, in particular the troposphere. This emphasizes temporal scales for change in weather patterns and events over time as climate variability and change (Figure 2). We change the drivers in the atmosphere that can alter the weather by modifying the components of the Earth's system: for example, enhancing the greenhouse effect and/or changing the Earth's surface and energy budget. We enhance the greenhouse effect by changing the carbon and the broader biogeochemical cycles through changes such as burning fossil fuels or changing land cover (deforestation), which increases atmospheric carbon dioxide, warming the troposphere (global warming) and further impacting climate, including regional weather. Changing regional meteorology leads to changes in the hydrologic cycle and the distribution of water (e.g. rain and snow events). At the same time changes in land cover (e.g. vegetation and urbanization) and land surface impacts albedo and the Earth's energy budget. A warming troposphere results in melting polar ice which not only affects the oceans, but also changes the albedo, influencing the Earth's energy budget. These secondary changes or climate feedbacks may have a greater impact on regional climate and global warming than carbon dioxide and other greenhouse gas emissions alone due to the non-linear nature of the climate system. Our framework then presents climate as an interaction among the components of a climate system. Changes to one component of the system may cause changes to other components of the system, affecting the Earth's ability to absorb or reflect the Sun's energy. Below we describe each component of the climate system framework, providing a conceptual overview of what students should know and understand.

Table 2. The relationship between the NRC system standards and a climate system framework.

NRC system concepts	Climate system
Function	Distribute Sun's energy, water, and plant and animal life
Feedback/ equilibrium	Hydrologic and biogeochemical cycles; energy budget; interactions among atmosphere, ocean (e.g. La/El), land, vegetation, and ice
Boundaries	Local, regional, and global; geographic, topographic (relief/elevation), scales of time (e.g. seasons, 30 years) and space
Components	Sun, atmosphere, ocean, land, vegetation, and ice
Resources (inputs/outputs)	Radiative energy, water, greenhouse gases, weather

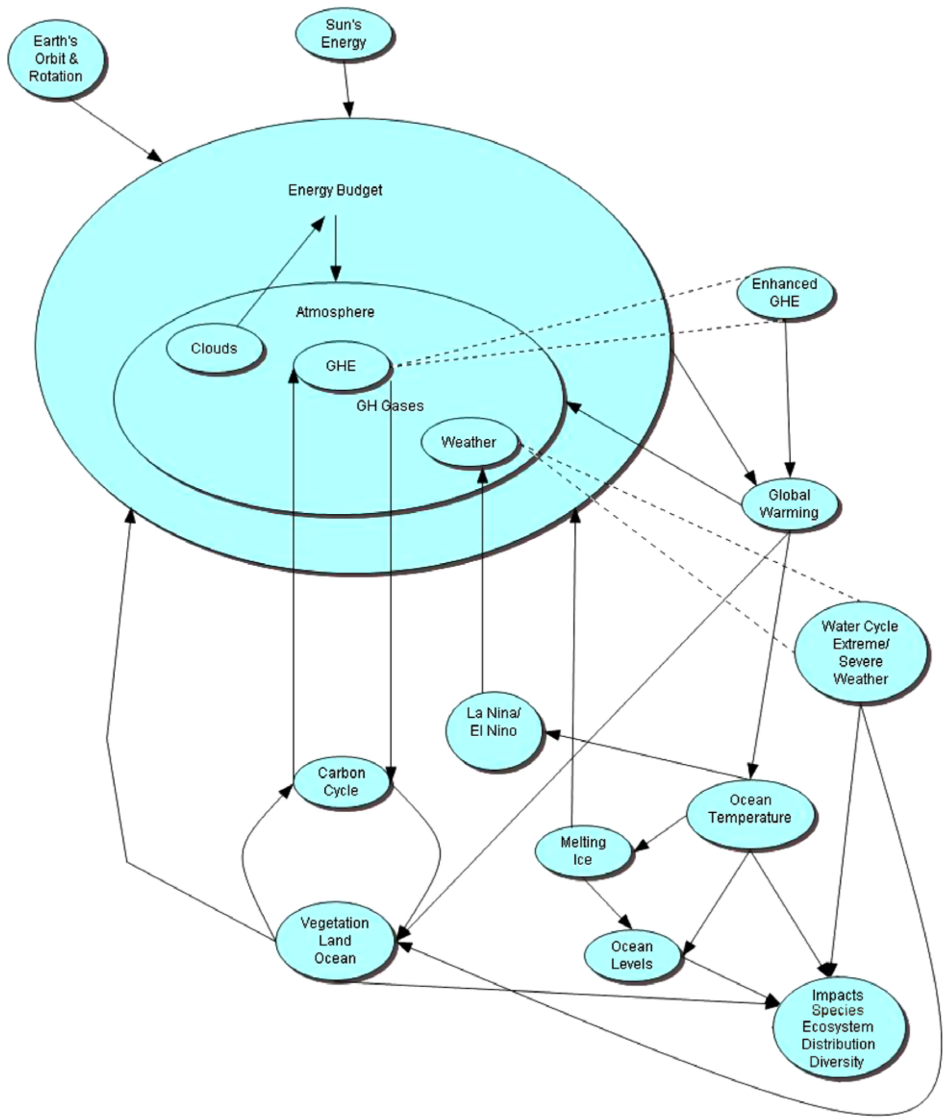

Figure 2. Climate system (Ruddiman 2001).

Natural causes and changes to the climate system, climate variability

The Earth's land, oceans and atmosphere absorb the Sun's energy, providing the surface energy that helps drive the Earth's climates. Because the Earth is like a sphere (i.e. oblate spheroid or geoid), more energy is received by the equatorial regions than the polar regions. The amount of solar energy reaching the Earth also varies at middle and high latitude from season to season. This imbalance in heating is modulated by the oceans and the atmosphere through evaporation, convection, precipitation, pressure changes, winds, and ocean currents. This energy is redistributed from the equator to the poles and from the Earth's surface to the troposphere and back to space, helping balance the Earth's energy budget. Any increase or decrease in the amount of incoming solar energy and/or outgoing energy alters the Earth's energy budget components, causing global temperatures to rise or fall accordingly. The climate system attempts to balance the Earth's energy budget. The Sun's energy is reflected and absorbed by the clouds and particles in the troposphere, as well as by the Earth's surface. The reflected energy (about 29%) does not directly participate in the Earth's climate system. (The percentages are estimates of the Earth's global annual mean energy budget based on a number of scientific works, including Kiehl and Trenberth 1997.) The Sun's energy that reaches the Earth's surface (about 48%; 23% is absorbed by the atmosphere) is differentially absorbed by the land and oceans. This energy is lost through evaporation or latent heat (25%), convection (5%), and as infrared energy (17%). Of the infrared energy radiated from the Earth, about 12% escapes to space. The remaining 5% is absorbed by the greenhouse gases, which increases their temperature, warming the troposphere. The greenhouse gases also radiate infrared energy in all directions, some of which is directed back toward the Earth's surface and absorbed, further warming the surface. Because the oceans cover more than 70% of the Earth's surface and are closely coupled to the atmosphere, they play a major role in the climate system (see Atmosphere and Oceans below).

The Earth's climates change naturally; past climates or paleoclimates indicate periods of warming and cooling (ice ages). These past global climate changes were due to variations in solar radiation (Shindell et al. 2003). Natural changes in the Earth's orbit and rotation alter the amount or intensity of the solar radiation that reaches the Earth's surface. Natural variations in the Sun's irradiance also influence the amount of solar energy that reaches the Earth. The Sun's output varies about every 11 years, which causes natural cycles of warming and cooling. Volcanic eruptions release particles into the troposphere that reflect a portion of the Sun's energy, cooling the climate over short time periods. For example, El Chichon in 1982 and Pinatubo in 1991, released sulfur dioxide and other particles into the troposphere which reflected a portion of the Sun's energy, causing a short-term drop in global temperature (Stenchikov 2009). These natural variations continue today, but their influence does not explain the rapid warming, geologically speaking, experienced over the past decades (IPCC 2007a).

Atmosphere (troposphere)

Human activities that influence or force changes in the Earth's energy budget due to perturbations introduced into the troposphere include: (1) particle/aerosol loading, which both absorb and reflect incoming solar energy depending on their chemical composition and size and (2) through the burning of fossil fuels and land use alterations, which releases carbon dioxide and other greenhouse gases, increasing the atmospheric concentration of greenhouse gases (IPCC 2007a). An increase in greenhouse gas molecules results in an increase in the absorption of the infrared energy emitted by the Earth's surface. Since the greenhouse gas molecules radiate this energy in all directions, some energy warms the troposphere and some reaches the Earth's surface causing temperatures to rise. The amount of human-caused greenhouse gas emissions, particularly carbon dioxide, far surpasses that of volcanic eruptions. Water vapor in the troposphere is the largest feedback component because of its abundance, accounting for about two-thirds of the greenhouse effect or natural warming. Increasing temperatures alter the water vapor feedback and cause more evaporation/transpiration, transferring water from the Earth's surface to the troposphere (IPCC 2007a). An increase in water vapor can further increase the temperature differentially through the atmosphere (Solomon et al. 2010). As the water vapor encounters cooler temperatures water condenses around particles in the troposphere forming clouds. Clouds reflect solar energy, cooling the Earth. At the same time, clouds absorb infrared energy emitted by the Earth's surface, causing warming. Overall, it is thought that clouds will have a cooling effect on the Earth's climate (IPCC 2007a).

Carbon dioxide and other greenhouse gases remain in the troposphere for hundreds of years, thus even if greenhouse gas emissions are reduced today, their impact on global warming will continue for years (IPCC 2007a). It will also take years for the excess energy absorbed by the oceans to return to a natural state, thus the oceans will continue to warm the troposphere even as greenhouse gas emissions are reduced (IPCC 2007a). It is estimated that global warming will continue for decades, even if greenhouse gas emissions are held at the current levels (IPCC 2007a).

Global warming can impact regional meteorology and weather, changing precipitation patterns, and will result in an increase in the frequency of hot days and longer and more intense heat waves. While definitive evidence is still not available, some studies suggest that a warmer planet can cause more frequent and severe storms, flooding and drought conditions (IPCC 2007a). Although no single weather event can be linked to global warming, long-term (30+ years) patterns or changes in weather may be caused by the warming of the troposphere (Richard and Soden 2008).

Snow and ice

Global warming has caused polar snow and ice to melt, exposing lower albedo water and land surfaces (IPCC 2007a). Darker surfaces reflect less of the Sun's energy than snow and ice and thus absorb more of the Sun's energy, warming the water and land. These warmer surfaces then radiate more energy into the troposphere, thereby causing more warming. Melting glacial ice also releases stored water, causing ocean levels to rise (Bahr, Dyurgerov, and Meier 2009; IPCC 2007a). Thus, glaciers and oceans are linked through the atmospheric and hydrologic cycle.

Oceans

The world's oceans absorb a large portion of the Sun's incoming energy, and thus have the capacity to store and release significant amounts of energy. Thus, the oceans provide energy to the climate system and serve as a major driver of climate and weather. Much of the ocean's energy is transferred to the troposphere through evaporation (latent heat) and convection, which warms the troposphere. The warming creates a temperature gradient, causing pressure gradients and winds. The winds exert forces on the ocean surface creating ocean currents and mixing. For this reason, the oceans and troposphere are closely linked, and changes in one result in changes in the other. Although the oceans change slowly, in terms of months, years, and decades, the troposphere changes quickly – minutes, hours, and days. As ocean water warms it expands. This thermal expansion may cause ocean levels to rise (IPCC 2007a).

The coupling of oceans and troposphere also causes La Niña and El Niño events, which results in natural variations in climate (Philander 1990). During La

Niña periods the Pacific Ocean is cooler than normal and the trade winds are stronger. This prevents the formation of rain clouds over the eastern region of the Pacific and increases the formation of rain clouds over the western region of the Pacific. This also affects the position of and weakens the jet stream, affecting storm events in the northern hemisphere. El Niño events are typically opposite that of La Niña events. During El Niño events the Pacific Ocean is warmer than normal and evaporation increases, adding more water vapor to the troposphere, and the jet stream may shift eastward, resulting in more intense winter storms in the northern hemisphere. La Niña and El Niño events also impact the severity and tracking of tropical storms in the United States (e.g. Bove et al. 1998; Tartaglione, Smith, and O'Brien 2003). They cause our climate to vary naturally over time.

The oceans also serve as a major carbon sink, absorbing almost twice as much carbon than the Earth's vegetation and land combined. It also releases a similar amount of carbon to the troposphere; however, phytoplankton absorbs some of the carbon dioxide through photosynthesis. Fecal matter from ocean organisms and decomposition provide a slight net increase in carbon concentration of the oceans. The increase in carbon dioxide has resulted in a slight acidification of the oceans (Anthony et al. 2008; IPCC 2007a). This, along with warming waters has adversely impacted coral reefs and life in the oceans (Hughes et al. 2003; IPCC 2007b).

Land and vegetation

Changes in land surface and vegetative cover affects reflectivity (albedo) and the carbon cycle (IPCC 2007a). For example, deforestation not only reduces a carbon sink, but decreases the albedo of the land surface, increasing the amount of the Sun's energy that is absorbed (Pielke et al. 2002). In the Arctic, as soils warm and the tundra thaws, carbon dioxide and methane are released into the troposphere (Christensen et al. 2004; IPCC 2007a). A warming climate is likely to increase forest fires and insect infestations, releasing more carbon dioxide into the troposphere as trees burn or die and decay (Aber 2001; IPCC 2007b). Increased carbon dioxide levels may stimulate some plants to grow, removing carbon dioxide from the troposphere (Ainsworth and Long 2005). This 'extra' growth may be limited by the availability of water, nitrogen, and temperature, and thus the removal of carbon dioxide from the troposphere is likely to stabilize or level out (IPCC 2007b). Although this land–vegetation–carbon cycle is complex, it is thought that land/vegetation sinks will decline or become less efficient (Oren et al. 2001). Thus, changes in albedo and carbon cycling will increase global temperatures, lengthening the growing season in some regions (IPCC 2007a, 2007b). This longer growing season may result in an increase in food production at the mid and high-latitudes, assuming the availability of water (IPCC 2007b). At the same time, it would result in a decrease in food production at lower latitudes (IPCC 2007b; Parry et al. 1999).

The greatest increases in warming will occur over land, in the northern hemisphere (IPCC 2007a). This warming will impact the plants and animals found in the different climate zones. A longer growing season and an earlier spring may change migration patterns or disrupt lifecycles. A disruption in lifecycles could affect the ability of some pollinators and plants to survive and reproduce, reducing the available food in a food chain depending on the soils (Lal 2004). Warmer temperatures will result in drier soils, thus plants will need more water to survive and with less water wildfires may increase. Shorter and milder winters may allow more insects to survive, causing infestations to occur (IPCC 2007b). Warmer temperatures may exceed the tolerance level of indigenous plants and animals, causing increased mortality and a change in geographic distribution. Plants and animals will migrate toward the poles and species that cannot migrate or adapt may go extinct (Walther et al. 2002).

Human impacts

Coastal regions will be impacted by rising oceans and according to some studies a possibility of more frequent hurricanes (Trenberth 2005). Prolonged heat waves and drought conditions will stress water and food resources and cause more heat-related deaths (IPCC 2007b). Hotter days will result in poorer air quality and increased ozone alerts (Mickley et al. 2004). Tropical temperature zones will expand northward increasing the risk of infectious diseases, including the spread of malaria (Martens et al. 1999). People may be required to change their lifestyles and practices to mitigate global warming, and communities may need to become climate ready, preparing for increased flooding and storm and drought conditions, which may require changes in zoning, land use practices, and agriculture (Pielke et al. 2007).

The climate system framework and student conceptions of climate change

Comparing our general student model of climate change to our proposed climate system framework reveals several key elements or constructs that need to be addressed in order to develop students' conceptualizations of climate change within the context of a climate system. These include:

- What is a climate system?
- Climate and weather
- The Earth and Earth's energy budget
- System feedbacks
- The Sun (solar radiation)
- Atmosphere (troposphere)
- Ice and snow
- Oceans
- Land and vegetation.

By addressing these key constructs, instruction challenges students' understanding of global warming and climate change as being driven by the greenhouse effect alone. Instead, it emphasizes the Earth's energy budget, the transfer of energy, and the cycling of water among the Earth's systems, climate as a regulator of the Earth's energy budget through the reflection (albedo), absorption, and radiation of the Sun's energy. In this way, the greenhouse effect is also contextualized within the Earth's energy budget. This challenges and builds on students' conceptions that global warming and climate change are simply a factor of greenhouse gas emissions. This would extend students' understanding beyond a simple 'burning of fossil fuels as a carbon transfer model,' contextualizing the carbon cycle within the climate system. It builds the interconnections or feedbacks among the components of the climate system (i.e. atmosphere, ice, vegetation, land, and oceans) and it incorporates human changes to the climate system (e.g. burning of fossil fuels, land use, and land cover changes).

Based on our general student model of climate change and our climate system framework, we present a first articulation of these conceptual elements across three levels of understanding in Appendix 1. We acknowledge that this conceptual progression is based on sparse research about students' conceptions of a climate system and thus reflects our best perspective of students' understandings. The progression, however, provides a starting point for developing curriculum and designing instruction, as well as setting a direction for future educational research on students' conceptualization of a climate system.

Conclusion

Teaching and learning about climate change is conceptually challenging. Although students can collect local weather data and relate this data to local climate, they cannot monitor climate change due to time and scale issues. Therefore, in order to learn about climate change it is necessary for students to interpret, analyze, explain, and evaluate historical data and model-based data projections, which are also challenging classroom activities (Shepardson et al. 2009). Thus, as identified in various studies and our prior research, there is no set way that climate literacy can be achieved or misconceptions associated with climate science can be reduced. This is particularly challenging within the limited scope and the time that can be realistically dedicated for climate and weather activities within the curriculum. Given these challenges, it is important that students be given the opportunity to develop the knowledge and skills to analyze historical and current climate data and data-based projections and to think about climate change in the context of a climate system; to communicate about and contextualize climate data and ideas from a climate system perspective. As we and others (e.g. Clewett 2003; George et al. 2005) have asserted, this provides students the opportunity to analyze the variability in the Earth's climate, the frequency, severity and duration of extreme weather events. It is essential that students make informed decisions concerning their own personal actions and behaviors as part of the climate system. Ultimately it is the responsibility of superintendents, principals, science teachers, science educators, and scientists to develop curriculum that informs classroom practice and that nurtures climate science literacy. Therefore, we welcome and invite comment and discussion about our approach to conceptualizing climate change in the context of a climate system. We have established a website, http://iclimate.org/ccc, to foster this dialog and have sought participation from both the formal and informal educational community.

Given the lack of research on students' conceptions of the climate system, we encourage future studies in this area. Indeed, it is important to test our hypothesis and draft a climate system conceptual progression that can be adapted at different grades and ability levels. There is a need to either validate or reduce the conceptual elements in developing students' conceptual understanding of a climate system. It is essential to identify and further develop the levels of understanding that students construct over time. In addition, what instructional approaches and experiences are needed to promote students' learning about a climate system also needs to be investigated. Finally, does developing students' understanding of a climate system foster a deeper understanding about global warming and climate change? These questions and others can only be answered through a collaborative research agenda that is needed to be pursued by partnering with classroom teachers, education researchers, and climate scientists.

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