J. Korean Earth Sci. Soc., v. 37, no. 5, p. 309−322, September 2016
http://dx.doi.org/10.5467/JKESS.2016.37.5.309
ISSN 1225-6692 (printed edition)
ISSN 2287-4518 (electronic edition)

Developing a Framework of Conceptual Understandings of Earth Systems

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Abstract: This paper presents an analytical framework of Conceptual Understandings of Earth Systems (CUES) that shows a relationship between disciplinary knowledge of Earth systems and the specific thinking skills required to understand that knowledge. This framework is developed through an extensive literature review of students' and teachers' understandings of earth systems concepts and systems thinking in earth science context. This study first presents the categories of disciplinary knowledge of Earth systems, Earth System Knowledge (ESK). This study then illustrates a relationship between categories of ESK and the ontological categories (Matter, Process, Systems) that has been used to study students' conceptual understandings of Earth systems. Finally, this study presents the CUES framework to show the relationship between disciplinary knowledge and thinking skills. The implications of using this framework for curriculum development, assessment, and teacher education and ESS research are discussed.

Keywords: Earth system science, structure of a discipline, systems thinking, ontological categories.

Introduction

Over the last three decades, knowledge of the traditional earth science disciplines has been integrated to form the new discipline of Earth System Science (ESS) (Finley, Nam, and Oughton, 2011; Johnson, Ruzek, and Kalb, 1997). As a result, the necessity of transforming a traditional approach of teaching earth science to an earth systems approach has been advocated by many earth science educators and reflected in the efforts to develop numerous system-oriented education projects (e.g. Global Learning and Observation to Benefit the Environment [GLOBE]) as well as international science standards (e.g. *Next Generation Science Standards [NGSS]* (NGSS Lead States, 2013)).

However, in spite of this stated interest in integrating earth systems concepts into earth science education, there has been increasing concern about teaching earth science to K-12 students with an earth systems approach. In fact, several studies have indicated that the depth and breadth of both students' and teachers' knowledge of earth systems are limited and often include misconceptions (Libarkin and Kurdziel, 2006; Sell et al., 2006).

The recently released national science education standard in the U.S., NGSS (NGSS Lead States, 2013), recommended 'Earth as System' as one of three 'Disciplinary Core Ideas (DCI)' of the earth and space science discipline. The disciplinary knowledge under the *Earth as System* DCI was structured and organized in a way that builds students' understandings of earth system science content through repeated exposure to the concepts over multiple years. This approach, which presents sequential development of conceptual understanding of a topic, has been recently spotlighted in science education as 'Learning Progression.' Learning progression is not merely a sequence of science topics or concepts but also a sequential development of thinking: "successively more sophisticated ways of thinking about a topic that can follow and build on one another as children learn about a topic over a broad span of time" (National Research Council, 2007, p. 217).

Studies of earth system education have also supported the idea that understanding the earth as a

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system requires not only knowledge about earth systems but also specific thinking skills such as systems thinking. Systems thinking is characterized by different types of cognitive ability including finding feedback loops, defining patterns of interrelationship, and multivariate reasoning skills (e.g. Ben-zvi-Assaraf and Orion, 2005a; Kali, Orion, and Eylon, 2003). In addition, studies show that different levels of students' understanding of systems exist depending on their prior knowledge relevant to the specific system context (Ben-zvi-Assaraf and Orion, 2005a). Thus, to better understand how people conceptualize the earth as a system, we need to consider the progression of the understanding of disciplinary knowledge of earth systems in conjunction with thinking skills.

Thus the primary purpose of this study is to develop a framework to show the relationship between the progression of the conceptual understandings of the earth as a system and different types of thinking skills associated with it. Within this framework, first, the core concepts of earth system were defined to categorize disciplinary knowledge of ESS. Then a number of international documents on science education (e.g. NGSS (NGSS Lead States, 2013) were analyzed that deal with students' and teachers' conceptual understandings of the earth as a system. Second, the levels of thinking skills that is required to understand domain specific knowledge of earth systems were defined based on the studies on ontological categories of conceptual understanding of a scientific concept and Systems Thinking literature in an earth system education context. The integration of the progression of both domain specific knowledge and thinking skills resulted in a framework called Conceptual Understandings of Earth Systems (CUES) that can be used to assess understandings of Earth as a system at four different levels.

To develop a valid framework to show the relationship between ESK and required thinking skill, three research question has been answered:

First, what are the core concepts of ESK defined by authorized documents?

Second, what kinds of thinking skills are required to understand the concept of earth as a system?

Third, how these two concepts; core concepts of ESK and the progression of thinking skills are meaningfully interconnected and structured as a conceptual framework?

Method

This paper is a position paper that suggests a conceptual framework to show a relationship between earth system knowledge and the required thinking skills to understand the knowledge. An intensive literature review has been conducted by utilizing combined content analysis methods (Patton, 2002). To construct validity of each suggested ESK concepts and framework, the scope or the reviewed literature and the analysis method for each research question has been addressed in the following to build validity of the result.

Earth System Knowledge Category

1) The scope of the literature review

To find fundamental categories of Earth System Knowledge, the review of literature has been conducted with two main key-words; 'earth system science' and 'earth system education'. To construct the validity of the sources and literature; first, the quality of the sources was evaluated by two categories; peer-reviewed or been passed by authorized educational panel such as published in a national or international peer reviewed journal in science education, certified National education boards or documents published by National Research Council; second, three researchers evaluated the validity of the papers by checking the quality of the paper. If two of the researchers disagree with a source or literature, it has been deleted from the review list. Finally one hundred and ten literatures have been selected that have been published from 1970s to 2010s.

2) Validity

From the selected literature, a coding scheme was established and validated by the three researchers.

First the researchers analyzed a smaller number of literatures to establish coding categories. Based on these initial categories, all of the literature data were analyzed by the three researchers to discern emerging patterns in the literature. To support the reliability of the analysis, analysis results were peer reviewed; inter-rater reliability was above 80% for all categories.

Conceptual Understandings of Earth System (CUES)

1) The scope of the literature review

CUES framework is combined from the literature review in three important categories of earth science education; literature review to define categories in ESK which is explained above, ontological categories, and systems thinking. Ontological categories were adopted by Chi et al. (1994)'s study and Libarkin and Kurdziel (2006)'s study. Systems thinking literature was reviewed to understand the ontological category of *System* and to find a relationship between ESK and thinking skill. To support the idea that students understand natural phenomena through the lens of three ontological categories, literature dealing with misconceptions in earth science (from 1980s to 2010s) has been reviewed with key words including; misconceptions, earth science, climate change, earth system, alternative conceptions, etc. Systems thinking literature also reviewed with key words including system thinking, complex thinking, etc. To construct the framework, literature that suggested a relationship between knowledge and thinking were reviewed. Systems thinking literature support the idea, particularly when it discusses about the difference between naïve and expert thinking in system context. In addition, Liberkin and Kurdziel (2006) argued the relationship between the depth of ESK and the ontological categories of earth system concepts.

2) Validity

From the selected literature, a coding scheme was established and validated by the three researchers. Due to the lack of literature about the ontological categories, Liberkin and Kurdziel (2006)'s idea was adopted with higher rate of agreement with the researchers (95%). Then the researchers first analyzed a smaller number of literatures about misconceptions in earth science and system thinking skills to establish the relationship between the ESK knowledge and thinking skill. Based on these initial categories, all of the literature data were analyzed again to discern emerging patterns in the literature. CUES framework was finally constructed by the analysis of the literature by three researchers. To support the reliability of the analysis, the analysis results were peer reviewed; inter-rater reliability was above 90%.

A Paradigm Shift: Key Features of Earth Systems Science

Earth System Science (ESS), as a new discipline has been defined based on a paradigm shift in understanding the earth as a system that occurred more than 50 years ago. ESS is a new approach of integrating earth science knowledge through an interdisciplinary framework to create better explanations of natural phenomena and recognize that humans have enormous and often self-destructive impacts on local, regional, and global scales. A new Systems Thinking paradigm and our relatively new ability to study the Earth on a global scale using advanced technologies played a significant role in this paradigm shift. These realizations seemed to require the articulation of many ideas from more traditional earth science disciplines as well as the biological and social sciences. The global scale of the information obtained from these technological innovations and a broader, more integrated perspective prompted the scientific community to begin examining Earth systems.

In the early 1980's, scientists tried to develop earth system models to understand the impact of human society on the physical planet. One of these, the "Bretherton Diagram," shows a complex network of interactions between Earth's physical systems and human dimensions. It includes three important components of the earth system: human activities, physical climate systems, and biochemical cycles. In the diagram, Bretherton separated humans from other life forms in the biochemical cycle by placing them within a black box due to the high uncertainty of humans' impact on earth systems. The necessity of discovering humans' impact on earth systems accelerated the development of Earth System Knowledge.

In the 1990's, computer technologies allowed earth system scientists to calculate and predict human impact on earth systems and to develop a field for the mathematical analysis of earth systems called Earth System Analysis (Schellnhuber, 1998). Schellnhuber (1999) proposed the Earth System Equation, which is a formula that expresses the elementary insight that the overall system contains two main components: the ecosphere, N, and the human factor, H. The equation is E=(N, H), where N=(a, b, c, ...); H=(A, S). Schellnhuber explains:

> N consists of an alphabet of intricately linked planetary sub-spheres (a) atmosphere, (b) biosphere, (c) cryosphere; that is, all the frozen water of Earth, and so on. The human factor is even more subtle: H embraces the 'physical' sub-component A ('anthroposphere' as the aggregate of all individual human lives, actions and products) and the 'metaphysical' sub-component S reflecting the emergence of a 'global subject.' This subject manifests itself, for instance, by adopting international protocols for climate protection. (Schellnhuber, 1998, p. C20-C21)

For example, to describe future climate patterns, earth system scientists need to understand N: physical laws that can describe atmospheric circulations, chemical components of the atmosphere, historic data for Earth surface temperature, how atmospheric circulations are affected by Earth surface characteristics, and how Earth's rotation is also affected by the solar system. But equally important, they need to precisely predict H: how human lives and society's decisions affect earth systems. In other words, human activity on the level of individual lives as well as within societies is considered one of the main factors that could change earth system phenomena. Schellnhuber (1998) emphasized that studying the interactions between humans and Earth ecosystems is the main purpose of the discipline of ESS.

While there is still uncertainty, earth system scientists can make reasonable predictions about the Earth's future environment using an interdisciplinary approach that includes computer science, mathematical modeling using probability, and physical and chemical analysis to study Earth's physical structures. Schellnhuber (1999) described these sophisticated techniques and scientific activities, including simulation modeling, as "a second 'Copernican' revolution that will enable us to look back on our planet to perceive one single, complex, dissipative, dynamic entity, far from thermo-dynamic equilibrium -- the Earth system" (p. C20).

The above provides the overall specifications for what must be considered in ESS. The discipline requires a global perspective and systems-based interdisciplinary models (often probabilistic simulations) that describe, explain, and predict the interactions between the physical (sometimes called natural) systems and human systems. The physical system involves the subsystems of the geosphere, atmosphere, hydrosphere, cryosphere, and biosphere. The human system is a unique feature of the earth systems and includes agriculture, the economy, transportation, politics, culture, communications, natural resource extraction, and other subsystems. While the critical importance of human interactions are recognized, I minimize the extent to which I address those interactions here. I do so as an acknowledgement of the complexity of social systems and the limitations of what can be accomplished in one paper. Thus I focus on investigating what is needed to understand the Earth's physical systems and a limited aspect of human impact on the earth system.

The complex nature of each of these subsystems in their own right, let alone the incredibly complex nature of their interactions, certainly contributes to the difficulty teachers and students have in understanding earth systems. However, there are not enough studies to show how teachers and students understand the Earth as a system. Perhaps the lack of studies about K-12 teachers' and students' understanding of earth system behaviors is because the discipline of ESS is relatively new and even newer in earth science education. More specifically, it is possible that I do not have a comprehensive set of ideas about how to define earth system knowledge for K-12 students to guide further research. In the following section, I define the boundary of earth system knowledge for K-12 levels and define the core concepts of earth systems to categorize disciplinary earth system knowledge.

Five Core Concepts of Earth System Knowledge (ESK)

Understanding Earth as a system requires different kinds of domain-specific knowledge. In fact, one of the primary efforts of researchers in the disciplines of earth science and earth science education is to identify the domain-specific knowledge that is critical to understanding Earth as a system. (e.g. Earth Science Literacy Initiative, 2009; Finley & Enochs, 2006). In particular, many NASA earth system education projects (e.g. Earth System Science program, 2016; NASA Innovations in Climate Education. 2016) and recently released Next Generation Science Standards (NGSS Lead States, 2013) emphasize the importance of understanding earth as a system. This is an enormous and complex task due to the complexity of Earth System Science and its inclusion of many disciplines (Finley et al., 2011). Therefore, researchers have created several different models of what domain-specific knowledge is required. For example, NASA (1986) provided an initial conceptual model for the earth system interactions in the Bretherton diagram of the biospheric cycle. Mayer (2002) has focused more on the aesthetic aspects of the earth system and suggested a set of “Understandings of Earth System.”

The details of critical domain-specific knowledge vary depending on the purpose and the philosophy of various earth system education programs and educators (e.g. AAAS, 1993; NASA, 2000; NRC, 2012). In the previous study, a set of analytic concepts to describe natural systems in the earth science context has been suggested: systems, materials, boundaries, structures, intra-system process, inter-system process, form of energy, variables, variable values, relational rules for variables, and models (Finley et al., 2011). These analytical concepts show a meta-level conceptual structure of the discipline of Earth System Science (ESS) and are directly related to domain-specific knowledge that is important to understanding the earth as a system. Based on these analytical concepts, the current study further analyze disciplinary knowledge of earth systems and important concepts involved in a number of science education standards documents that indicate what students and teachers should know and in research on what students and teachers understand about ESS (see Table 1). Five categories of disciplinary knowledge of earth systems are repeatedly mentioned as important and necessary knowledge for understanding Earth as a system and thus form the basis for

Table 1. Five Categories of Earth System Knowledge (ESK)

	Physical Structure and Components	Physical and Biochemical Interaction	Energy	Time and Space Scale	System Behavior
AAAS (1993)	•	•	•	•	
Ireton et al. (1996)	•	•		•	•
NRC(1996)	•	•	•	•	
NASA(2000)	•	•	•	•	•
Mayer et. al (2002)	•	•		•	
Earth Science Literacy Initiative (2009)	•	•	•	•	•
US Climate Change Science Program (2009)	•	•	•	•	•
Ocean Literacy Network (2011)	•	•	•	•	•
Authors (2011)	•	•	•	•	•
NRC (2012)	•	•	•	•	•
NGSS Lead States (2013)	•	•	•	•	•

organizing Earth System Knowledge (ESK). These categories are not entirely independent of each other, as would be expected given the myriad components and processes that interact in the earth system.

As Table 1 presents, advocates of earth system education agree that understanding an earth science concept as *System* requires not only knowledge of the physical structure and components of the Earth, but also knowledge about physical and biochemical processes, time and space scale (Orion and Ault, 2007), energy (Liu and Hu, 2003), and system behaviors such as feedback loops.

Ontological categories: conceptualizing earth system concepts as *Matter, Process,* or *System*

An important aspect of understanding the Earth as a system is found in the ontological categories to which people assign earth science concepts in their minds in order to understand earth system phenomena. Chi, Slotta, and Leeuw (1994) suggested that people conceptualize entities in the world within three distinct ontological categories: *Matter, Process*, and *Mental States*. According to Chi et al. (1994), objects have different ontological attributes. For example, objects in the *Matter* category, like rocks and lakes, have ontological attributes such as "having weight" or "having volume." Objects in the *Process* category, like seasons and weather, have their own distinct set of attributes such as "occurring once a year" or "resulting in" (p. 29). In other words, the meaning of a concept is determined by the ontological category to which the concept is assigned. Objects in the *Mental States* category might have intensions and purposes guiding how they function.

To define the ontological categories in the context of earth system science, two paper has been selected as a main source; Chi, Slotta, and Leeuw (1994) and Libarkin and Kurdziel (2006). Chi et al. (1994) was the first study that tried to interpret how human conceptualize natural phenomena as different ontological entities. Based on three ontological categories, they explain a reason of why students develop misconceptions about natural phenomena. Two ontological categories Matter and Process have been adopted in this study to explain how students conceptualize concepts in earth systems as different ontology. Based on Chi et al., (1994)'s work, Libarkin and Kurdziel, (2006) suggested five ontological categories in earth system context which are *Matter, Transformation, Proto-process, Process, and System.* The categories of *Transformation* and *Proto-process* would generally be placed in the *Process* categories, respectively, in the original schema of Chi et al. (1994) but indicated a lower level of understanding in terms of systems thinking perspective (Libarkin and Kurdziel, 2006). Libarkin and Kurdziel (2006) contributed to the earth system education literature by adopting more detailed level of ontological category in conceptualizing earth system concepts. Libarkin and Kurdziel (2006)'s study was the only study that investigate how students conceptualize earth system concepts as a different ontological entities. In a study about college students' understanding of an earth science concept, fossilization, Libarkin and Kurdziel (2006) found that students most often conceptualized earth system concepts as *Matter* rather than *Process*, and only a few students conceptualized them as *System*. They further suggested that the *Process* category can be divided into two different levels, *Proto-Process* and *Process*, based on the depth of students' understanding of earth science concepts. Ben-zvi-Assarf and Orion (2005b) also showed that more detailed ontological categories would exist in how people conceptualize an earth science concept as a *Process.*

Based on Libarkin and Kurdziel (2006), I suggest using the terms *Linear Process* and *Multiple Processes* to distinguish conceptualization of an earth science concept as *Process* within different levels of understanding of the complexity of a natural phenomenon. A *Linear Process* has a similar meaning with *Transformation* and *Proto-Process* in Libarkin and Kurdziel (2006), implies that people simply conceptualize earth system phenomena as a single step or multiple chains of a linear process. *Multiple Processes* has a similar meaning with *Process* in Libarkin and Kurdziel (2006), meaning that people conceptualize earth system phenomena as a complex process with multiple causes and effects and understand the specific mechanisms of its interactions with other earth system components. For example, if a person conceptualizes the water cycle as a linear process, he/she may know that water moves in a certain direction from one place to another (e.g. from rain → soil → river). However, the person cannot conceptualize how each step of the process interacts with other components of the earth system. If a person conceptualizes the water cycle as multiple processes, he/she may know how each step of that cycle interacts with other components of the earth system (e,g. rain → soil → plant → atmosphere, or rain → soil → groundwater) within a short or long-term period.

Similarly, other studies have shown that students tend to conceptualize water and rock in earth systems as static objects rather than as part of complex earth system processes (Ben-zvi-Assaraf and Orion, 2005b; Raia, 2005). However, it is unclear why most students categorize Earth objects in the ontological category of *Matter* rather than *Process (Linear or Multiple)* or *System* (e.g. Libarkin and Kurdziel, 2006; Sell et al., 2006). One possible explanation is the limitations of humans' ability to observe natural phenomena through micro or macro scales of time and space. People often try to understand complex natural phenomena by interpreting it through knowledge from similar situations they experience in their everyday lives. This explanation was often argued by advocates of Systems Thinking in education (e.g. Forrester, 1993).

Another possible explanation for the different ontological categories is that a higher level of understanding of ESS concepts, such as *Process* or *System* rather than *Matter*, requires extensive domain-specific knowledge. Libarkin et al. (2005) showed that if students lack knowledge about the process and timeframe of how fossils are formed, they might simply conceptualize fossils as *Matter*, such as a type of rock formed a long time ago that holds living things from the time when it was formed. On the other hand, a paleontologist would probably conceptualize fossils as *System*, an outcome of complex interactions between living things and non-living environments or places and the process as part of on-going *Systems* (Libarkin and Kurdziel, 2006).

Researchers studying the differences between novice and expert thinking in a Systems context argue that domain-specific knowledge is a key factor that differentiates thinking between these groups. Experts have more knowledge in a specific domain, allowing them to incorporate information into a broader causal framework (Jacobson, 2001). Researchers studying Systems Thinking also explain that understanding of *System* is very different from how people understand a science concept as *Process*, as conceptualizing earth science phenomena as *System* requires not only concrete content knowledge but also Systems Thinking skills including multivariable reasoning ability (e.g. Hmelo-Silver and Pfeffer, 2004; Jacobson, 2001; Kuhn et al., 2008).

In short, research on ontological categories of earth science concepts and recent research on expert and novice understandings of systems implies that there are four distinct categories of how people understand earth system phenomena: *Matter, Linear Process*, *Multiple Processes*, and *System*. More importantly, these four ontological categories are related to the depth of an individual's disciplinary knowledge of earth systems related to a certain topic.

Educational researchers in earth science argue that a Systems Thinking approach can help students understand earth system behaviors more holistically (Ben-zvi-Assarf and Orion, 2005a; Herbert, 2005; Raia, 2005). An understanding of systems requires higher levels of thinking skills including scientific reasoning skills (Chen and Stroup, 1993; Forrester, 1993; Kuhn et al., 2008). In the following section, important characteristics of Systems Thinking are addressed to argue that it is a key, along with the domain-specific knowledge of earth system behaviors, to conceptualizing earth science phenomena as a System.

Systems Thinking

Systems Thinking has been applied in many disciplines such as sociology, management, computer science, engineering, and natural science (Chen and Stroup, 1993; Forrester, 1993; Jacobson, 2001; Roberts, 1978; Senge, 1990; Weinberg, 1975). While researchers in different disciplines have tried to represent Systems Thinking within various disciplinary contexts, essential components of this approach have been proposed.

The founder of System Dynamics, Forrester (1968), proposed that natural and social processes could be conceptualized as the big, overarching concept of Systems. Forrester (1993) argued that feedback loops are the most important principle of systems and are the process within a system through which all changes occur, going on to suggest that "people seldom realize the pervasive existence of feedback loops in driving everything that changes through time" (p. 6). He also argued that our intuitions and experience of simple systems (those that can be interpreted as simple cause and effect) obstruct the complete understanding of the structure of complex systems: "Complex systems behave in ways entirely different from our expectations derived from experience with simple systems. Because intuition is based on simple systems, people are misled when making decisions about complex systems" (p. 10). Other Systems Thinking advocates have also emphasized the importance of the ability to recognize ongoing and interdependent interactions between system components (Richmond, 1993; Roberts et al., 1994; Senge, 1990).

Forrester's ideas have been elaborated and extended via research on expert/novice thinking. That research indicates that explanations of systems phenomena or solving problems in a system context require the cognitive skill of multivariate reasoning, in addition to the simpler linear single-cause single-effect reasoning (e.g. Hmelo-Silver and Pfeffer, 2004; Jacobson, 2001; Khun et al., 2008) in conjunction with domain-specific knowledge. Multivariate scientific reasoning is used to find how multiple variables are causally interdependent and how the interactions among multiple variables affect system behaviors and outcomes. One can understand the importance of multivariate reasoning in conjunction with recognizing the importance of feedback loops in systems. In the feedback process, any one variable affects multiple outcomes and can change the direction of the feedback loops as well as increase or decrease the process. Feedback loops are such that we cannot always see the final outcome but only the directions of the outcomes from the sequential change of the multiple variables.

We know empirically that understanding multivariate systems and feedback loops is difficult for students, who often fail to reason about the interactions of variables (Sins, Savelsbergh, and Joolingen, 2005). Instead, they tend to think about each variable separately and try to find a linear cause and effect (e.g. Fugelsang and Thompson, 2003; Löhner, Van Joolingen, and Savelsbergh, 2003; Schauble, Klopfer, and Raghavan, 1991). If the variables are dependent in time, which means that there is another factor that can change the condition of the variable, students hardly ever determine how a variable affects the feedback process (Sins et al., 2005).

Other aspects of Systems Thinking are also referred, for example, thinking of systems in terms of chaos. Chaotic systems change over time, are aperiodic and often non-repeating, are non-linear, sensitive to initial conditions, non-additive, involve synergistic reactions in which the whole is not equal to the sum of its parts, and are deterministic but not necessarily predictable. The other closely related aspect of Systems Thinking is that systems are complex. According to Valle (2000):

> A complex system is one in which numerous independent elements continuously interact and spontaneously organize and reorganize themselves into more and more elaborate structures over time. Complexity is characterized by: (1) a large number of similar but independent elements or agents; (2) persistent movement and responses by these elements to other agents; (3) adaptiveness so that the system adjusts to new situations to ensure survival; (4) self-organization, in which order in the system forms

> spontaneously; (5) local rules that apply to each agent; and (6) progression in complexity so that over time the system becomes larger and more sophisticated. (p. 4)

In summary, understanding feedback loops, interdependent interactions between system components, multivariate thinking, chaos, and complexity is critical components to understanding system behaviors. Students' thinking skills cannot be separated from their domain-specific knowledge (Greeno, 1989). In other words, each component of systems thinking requires certain level of domain-specific knowledge.

A Framework for Conceptual Understandings of Earth Systems (CUES)

As the above literature demonstrates, five categories of ESK are critical for conceptualizing earth science concepts as a *System*. In particular, knowledge of system behaviors is important for such conceptualization. In other words, knowledge of concrete objects in earth systems, such as of Earth's physical structure, components, and materials, is not enough to conceptualize earth science concepts as a *Process* or *System*. Similarly, knowledge related to natural processes and variables in the earth system (physical and biochemical processes, energy, and energy transformations) might not be enough to conceptualize an earth science concept as a *System*. Conceptualizing an earth science concept as a System requires all five categories of ESK. Figure 1 presents this simple but important relationship between the categories of ESK and the different ontological categories: *Matter* and *Process* (*Linear and Multiple*).

As Fig. 1 shows, to assign an earth system concept to the *Process* category, people need knowledge for the *Matter* category as well as specific knowledge for the *Process* category. Likewise, the *System* category requires knowledge for both the *Matter* and *Process* categories as well as specific knowledge for *System* structure and behavior. For example, the concept of "ocean" can be assigned an ontological category of *Matter* if a person has knowledge that an ocean is part of Earth's physical structure and is a reservoir like a lake or a river. If a person conceptualizes an earth science concept as *Linear or Multiple Processes*, that person interprets the process based on simple causality or declarative scientific facts (e.g. water moves in ocean because of gravity or water stays longer in deep ocean circulation). If a person understands that the ocean contains currents or that it is part of the water cycle through the processes of evaporation and rain, that person might conceptualize it as *Linear Process*. The concept of "ocean" can be conceptualized as *Multiple Process* if a person understands that an ocean wave is not the movement of water molecules but instead the movement of energy and that different levels of interactions (the macro level of ocean waves and the particulate level of a water molecule) exist. If a person understands that the ocean interacts with the atmosphere above it through an interchange of chemicals and energy, such as water molecules and carbon dioxide, and explains how the interaction

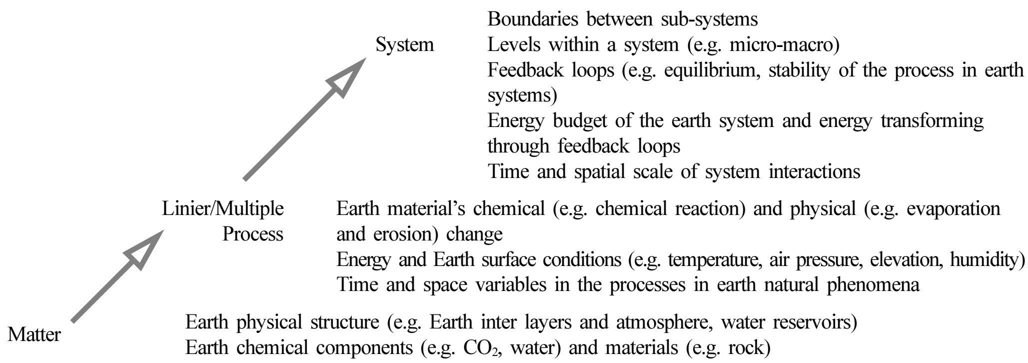

Fig. 1. Categories of ESK and conceptualization of an earth science concept into different ontology

Table 2. Conceptual Understandings of Earth System (CUES)

Thinking Skills	General Scientific thinking and reasoning			Systems Thinking Multivariate Reasoning
Ontological Category:	Matter	Process		System
		Linear process	Multiple process	
Category: Earth physical structure, components	Earth system is composed with earth physical structure such as earth surface and interior structure	The relationship between earth material and physical structure (e.g. water can be held in minerals and rocks)	Earth's structures as overlapped spheres (atmosphere, biosphere, hydrosphere etc.) Multiple variables (structural variables, time variable, energy variable, and so on) that cause the movement of earth material, physical and chemical change through networks between earth subsystems Human activity causes pollution and it affects many other aspect of ecosystem.	Molecular characteristics of the earth materials and its role in different sub-systems System behaviors through different system levels (micro or macro) and between systems (overlapping boundaries) Earth materials' physical and chemical change as part of earth system behavior The function of energy flow and transfer through earth system behavior and its effects on earth system energy budget Time and space scale of earth system behaviors (feedback loops) Human is part of the earth system and interacting with earth's natural environment
Earth physical and bio-chemical processes		Earth physical and bio-chemical change through linear process (water evaporation as part of water cycle)		
Energy in earth system		Energy transfer through linear chemical and physical processes (elevation change, gas pressure, temperature change)		
Time and space scale		Physical and bio-chemical process in earth system happen with different time and space scale		
Earth system behaviors				

between ocean and atmospheric system results El Niño and La Niña, that person may conceptualize ocean as *Systems*. If people cannot find concrete causality between two levels of behavior in ocean systems, they do not understand the connections between the two levels and neglect the fact that the ocean is behaving as a system (Wilensky and Resnick, 1999).

In addition, the investigation of the literature of general Systems Thinking revealed that the highest level of thinking skills requires understanding of feedback loops, interdependent interactions between system components, multivariate thinking, chaos, and complexity in an earth system context. Based on the relationships between ontological categories, categories of ESK, and Systems Thinking skills, the Conceptual Understandings of Earth Systems (CUES) is developed. This relationship is described as two dimensional (see Table 2). One dimension shows the ESK categories necessary to conceptualize ESS concepts into certain ontological categories. The second dimension shows the ontological categories and related Systems thinking skills required to conceptualize earth science concepts as a *System.* Table 2 also includes propositions using the categories of ESK.

Implications

The purpose of this paper was to explicate why understanding Earth as a system seems to be so difficult. I considered the problem in terms of the nature of the discipline of Earth System Science (ESS) and knowledge and thinking skills involved in the development of ESS. There have been many studies that address students' misconceptions regarding earth system concepts but not many of them answer the fundamental question of why students do not conceptualize earth system phenomena as system but as a simple movement of matters or linear process (e.g. Ben-zvi-Assaraf and Orion, 2005; Sell et al., 2006; Sibley et al., 2007) These studies imply that understandings of Earth as a system require not only domain-specific knowledge of ESS but also specific thinking skills including Systems Thinking (thinking about feedback loops, finding patterns of inter-relationship) and multivariate reasoning. According to a previous study (Finley et al., 2011) presenting important meta-level concepts of ESS, the framework showing a categorized domain-specific knowledge is necessary in order to conceptualize an earth science concept as a *System.* The CUES framework adds to our understanding of how people's grasp of Earth as a set of systems can be categorized as different stages or progression of knowledge and thinking. Specifically, CUES provides us an integrated model of what is required to understand the Earth as a set of systems in terms of the ontological perspectives, five categories of domain-specific knowledge, and a number of characteristics of general Systems Thinking. By illustrating the relationship between domain-specific Earth System Knowledge and ontological categories with specific thinking skills, the CUES framework could improve our ability to design alternative, well-grounded curricula, assessments, and teacher preparation programs for ESS education.

First, the CUES could improve our ability to generate alternative and well-grounded curricula for improving students' Earth System Knowledge by providing the relationship between the ontological categories and domain-specific Earth System Knowledge (ESK). The CUES shows that the depth of ESK is directly related to the ontological categories and progression of thinking skills. This suggests that young students who do not have deep knowledge of Earth systems probably cannot understand specific details of system interactions, but they can understand simple causality or simple matter cycles, which is fundamental for developing understandings about dynamic processes. To help students develop a higher level of earth system understanding, teachers need to design earth system curricula based on the learning progression suggested in the CUES. First, the CUES framework suggests that young students conceptualized earth materials and physical structures as they experience these in everyday life. In other words, students' understanding of earth material (e.g. water) is from their experience of it which is limited in a space and time. Second, introducing simple processes of matter moving between two different spaces they could not observe (e.g. lake → underground water) would provide young students a springboard for understanding a higher level of system concepts such as water cycle. According to NGSS (NGSS Lead States, 2013), first step placed in lower elementary level (K-2nd) and the second step is assigned for higher elementary grades (3rd-6th). Third step is to introduce a multiple process between earth subsystems by introducing energy flow through matter cycles or time scale related to the cycle process. This step is for middle school students since they understand abstract concepts in mathematics and science. Finally high school students are ready to understand systems concepts including system structure and behaviors because they understand more earth science concepts along with basic principles in chemistry and physics.

Second, the CUES provides us a blueprint to effectively assess students' understanding of the Earth system, particularly in the perspective of Systems Thinking skills. To date there are no studies of how Systems Thinking and domain-specific knowledge are related. Perhaps that is because there has been no model of what is needed in order to understand the Earth as a set of systems, which would serve as a basis for the development of the various forms of assessment that would be needed to conduct such studies. By providing the important relationship between Systems Thinking skills and categories of domain-specific knowledge (ESK), the CUES framework can be used to construct valid assessments for measuring students' and teachers' understandings of Earth systems.

Finally, the CUES could be used to develop ESS teacher education programs. The framework indicates what teachers need to know about ESS in order to plan curricula and instruction effectively. It may be possible to develop courses or workshops based on the CUES that teach educators background knowledge about ESS and ways the subject matter can be organized to improve their students' thinking skills and levels of ESS content knowledge. The study of earth science concepts held by K-12 teachers has been slow to shift from a focus on separate sub-disciplines to a focus on an integrated Earth system. Perhaps the use of the CUES framework in teacher education programs will promote the necessary shift to ESS education.

Currently, only the research about teachers' understanding of separate topics in ESS such as moon phases, seasons, and ozone depletion exist (e.g. Dahl, Anderson, and Libarkin, 2005; Ekborg, 2003; Jang and Nam, 2012; Jeong and Han, 2010; Khalid, 2003; Kikas, 2004). We do not have enough studies of teachers' understandings of the Earth as a system. The absence of research on pre-service and in-service teachers' knowledge of earth systems is problematic because how teachers think about their subject influences their teaching practice, such as selection of specific teaching strategies, content knowledge, and activities (Grossman, 1990; Kinach, 2002; Lee, 2010; Sperandeo-Mineo, Fazio, and Tarantino, 2005). If scientists and teacher educators are to help improve earth systems teaching, we have to understand the ways in which teachers think about the Earth as a system.

Given the acceleration of environmental change, such as that of the global climate system, understanding the Earth as a system has become essential in order to create a scientifically literate citizenry. However, our knowledge of teachers' and students' understanding of the Earth as a system is still in its infancy. Due to the interdisciplinary nature of Earth Systems Science, as well as the complexity of the Earth System Knowledge structure, there are few studies of what teachers and students should know and thus little grounding for curriculum design, science teacher education, and research. The CUES framework is well grounded and can be used to further our educational efforts with respect to Earth Systems Science.

Acknowledgment

This work was supported by Pusan National University Research Grant, 2016.

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Manuscript received: July 14, 2016
Revised manuscript received: September 18, 2016
Manuscript accepted: September 26, 2016