Broadening Student Horizons:
A perturbation to Earth System Science Education

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ABSTRACT

Earth System Science is an exceptionally interdisciplinary field requiring knowledge and skills from multiple scientific disciplines. Many important questions lie at the intersection of traditional disciplines and require a systems level approach. The emerging educational challenge is to train the next generation of scientists to address these topics. Here, we describe the development, delivery, and assessment of a new course in Earth System Science designed for advanced undergraduates and beginning graduate students. The course was designed to meet specific learning objectives, delivered in an inquiry-based learning environment, and assessed to determine the extent to which the learning objectives had been attained. The course consisted of readings from both texts and primary literature, lectures by UNH professors and NASA scientists, computer modeling labs, and interdisciplinary team-research projects. Results emphasize the importance of pre-planning and resources, establishing clear and concise student learning objectives, creating of an inquiry-based learning centered environment, role-modeling how Earth System Science research is done, and meeting student demand and institutional challenges. This class can serve as a model course for upper level undergraduates and beginning graduate students to expand their disciplinary scope, skills, and readiness to address Earth System Science questions.

INTRODUCTION

Earth System Science requires skills and perspectives that cross-cut traditional educational disciplines (Jacobson et al., 2000; Falkowski et al., 2000; Moore et al., 2001; Steffen et al., 2003; Pielke et al., 2003). Improving our understanding of the interactions connecting the major components of the Earth System including the atmosphere, hydrosphere, cryosphere, biosphere, and lithosphere is critical for understanding basic properties and dynamics of the Earth and requires more emphasis than can be obtained by studying the component spheres or isolated interactions alone.

Major national and international research organizations have identified the need for broader interdisciplinary approaches to Earth system questions. The eleven core projects of the International Geosphere-Biosphere Program are all interdisciplinary and include such projects as the Biospheric Aspects of the Hydrological Cycle, Land-Ocean Interactions in the Coastal Zone, Global Analysis Integration and Modeling, Past Global Changes, and most recently the Surface Ocean-Lower Atmosphere Study. The concluding chapter of the International Panel on Climate Change's Third Assessment Report states that "Understanding the components of the Earth System is critically important, but insufficient on its own to understand the functioning of the Earth System as a whole" (Moore et al., 2001). Within the U.S., major research organizations now also foster an interdisciplinary perspective. For example NASA specifically has fostered this view for over a decade and currently supports several major interdisciplinary programs including the Interdisciplinary Science Program, the Large-Scale Biosphere-Atmosphere Program, and others. Moreover, the five fundamental questions of NASA's Earth Science Enterprise (NASA, 2000; NASA 2002) focus on the Earth System as a whole and are:

- "How is the global Earth System changing?"
- "What are the primary forcings of the Earth system?"
- "How does the Earth System respond to natural and human induced changes?"
- "What are the consequences of change in the Earth System for human civilization?"
- "How well can we predict future changes to the Earth System?"

The NSF has several interdisciplinary programs including Biocomplexity and the Integrative Graduate Education and Research Training.

In contrast to the growing recognition of the need for interdisciplinary research and education, the educational experience of many undergraduate and graduate science students is one of decreasing breadth (increasing specialization) with increasing level of advancement (Fig. 1a). University curricula in science departments typically encourage or require students to begin by taking introductory courses that expose them to a broad range of scientific principles, concepts, and skills. These are then followed by increasingly advanced courses and research experiences on increasingly specialized topics. Culminating in the PhD, this approach to science education yields scientists who are highly trained on specific, often disciplinary topics. While this approach has been effective in training scientists with expertise and knowledge in traditional disciplinary fields, the approach may need to be modified in order to effectively train students to address the complex interdisciplinary topics of Earth System Science (Jacobson et al., 2000; Falkowski et al., 2000; Moore et al., 2001; Steffen et al., 2003; Pielke et al., 2003).

National research agencies and universities across the country are beginning to respond to the need for interdisciplinary Earth System Science research and education.

The NASA/ Universities Space Research Association (USRA) Program in Earth System Science Education (ESSE) has lead to nation-wide collaborative effort with universities to bring ESS to the classroom (Johnson and Ruzek, 2003). The University of New Hampshire (UNH), a participant in the ESSE program, is among the leaders in this trend. In 1985, UNH established the Institute for the Study of Earth, Oceans, and Space (EOS) to foster interdisciplinary studies. In 2001, UNH and NASA-Goddard Space Flight Center joined to establish the Joint Center for Earth Sciences. In 2002 the cross-college Natural Resources and Earth System Science (NRESS) Ph.D. Program was established to replace the Ph.D. programs previously offered by the Department of Earth Sciences (College of Engineering and Physical Sciences- CEPS) and the Department of Natural Resources (College of Life Sciences and Agriculture - COLSA). At the undergraduate level, CEPS and COLSA have developed an inter-college multi-departmental program in Environmental Sciences. This interdisciplinary program is concerned with the interaction of biological, chemical, and physical processes that shape our natural environment.

At UNH, numerous courses in multiple disciplines support these academic programs. For Interdisciplinary offerings in ESS, EOS has offered a seminar-style graduate level course titled “Earth System Science: Understanding Our Global Environment.” This course introduced students to Earth System Science through a series of lectures by a sequence of university professors whose research interests collectively spanned a wide range of relevant science topics. UNH currently offers three introductory classes offered at the undergraduate level that explicitly use an Earth System science approach – Global Environmental Change (ESci405) and Introduction to Climate

(ESci514) offered by the Department of Earth Sciences, and Global Biological Change (NR415) offered by the Department of Natural Resources.

In this paper, we describe the development, delivery, and assessment of a new advanced undergraduate / beginning graduate course in Earth System Science (ESS). Like previous offerings of ESS, the course provided an introduction to the study of Earth as an integrated system to relatively advanced students. Unlike previous offerings, the course was designed from the ground-up to meet specific learning objectives, led by a pair of professors, and assessed to determine the extent to which learning objectives had been attained. Experience teaching the course emphasized the importance of pre-planning and resources, creation of an inquiry-based learning centered environment, role-modeling how Earth System Science research is done, and meeting student demand and institutional challenges. By providing an interdisciplinary educational experience for relatively advanced students that is both broad and rigorous, this course can be considered a perturbation to Earth System Science education (Fig 1b).

A NEW COURSE IN EARTH SYSTEM SCIENCE

Course Development

From 2003-2005 we developed a new advanced undergraduate/beginning graduate course in Earth System Science, offered for the first time in Fall 2005. The course focused on the characterization of the components that make up the Earth System (atmosphere, hydrosphere, biosphere, cryosphere, lithosphere), and the dynamic interaction between these components (energy balance, water cycle, biogeochemical cycles, climate). Below, we describe the course development process.

Defining the scope: Because Earth System Science is a broad and relatively young field, the course development process was designed to be informed by a large set of scientists on an ongoing basis. We established a course design team that was interdisciplinary, multi-departmental, and multi-institutional. It included both faculty and graduate students, whose backgrounds ranged from ecology and paleoclimatology to mathematics and geophysics. Within UNH, the team involved scientists from two research centers and two departments spread over three colleges/institutes. These included the Climate Change Research Center and the Complex Systems Research Center in the Institute for the Study of Earth Oceans and Space, the Department of Earth Sciences from the College of Engineering and Physical Sciences, and the Department of Natural Resources from the College of Life Sciences and Agriculture. The team also included a Senior Scientist from the NASA Goddard Space Flight Center, a higher education specialist from the UNH Center for Teaching Excellence, three science graduate students with an interest in science education.

The design team shared a commitment to developing an effective active learning environment (Chickering and Gamson, 1987). We reached an early consensus to meet criteria for good course design (e.g., Fink, 1999), and to focus on addressing specific learning objectives. Course design proceeded through steps of establishing learning objectives, developing an assessment plan for those objectives, and creating course structure and content . The planning period (>1 y) enabled us to poll the ESS community to determine the essential skills, concepts, and approaches students should have. In all, more than 100 scientists from UNH, NASA-GSFC, and other members of the ESS community were polled to gather input. Actively engaging the scientific community at these institutions and involving all interested faculty enabled us to incorporate the latest research, and ensure the course design reflected the most current understanding of the Earth System. The long planning period also allowed for feedback from presenting at two ESSE21 conferences in the development stage (Wake et al., 2003; Hurtt et al., 2004).

Learning Objectives: The first concrete step in course design was the identification of a clear set of student learning objectives explicitly stated in the course syllabus. Student learning objectives were created to span the range of levels of understanding articulated by Bloom (1984), and are:

1. Describe key components, interactions, and concepts that characterize the modern earth system (knowledge, comprehension)
2. Analyze the causes of change in the Earth System over varied temporal and spatial scales (analysis)
3. Build simple models of key Earth System interactions; apply this knowledge to key scientific questions in Earth System Science (application)
4. Read, discuss, and evaluate Earth System Science papers in the primary literature (synthesis, evaluation)
5. Relate knowledge of Earth System Science to the human condition (application)

6. Develop peer-to-peer learning/teaching skills and effectiveness at working in groups (skills)
7. Evaluate the role of uncertainty for Earth System Science research and decision making (evaluation)

Assessment: Once learning objectives were defined, the next step in course development was to develop an explicit assessment plan. In collaboration with the Teaching Excellence program at UNH, we developed a plan consisting of multiple methods and approaches to determine the extent to which students met learning objectives, and to solicit feedback from the students regarding the course material, course format, and the effectiveness of the instructors. We included both traditional and non-traditional methods for both formative and summative assessments. Tables 1 and 2 provide an overview of assessment methods used by learning objective and course characteristic, respectively.

The first part of our assessment plan was based on several standard methods used to evaluate student learning and satisfaction. This part of the plan included exams (one at mid-semester and one at the end), laboratory exercises, and end-of-semester university course evaluations. Exams were structured to assess understanding across a range of levels of understanding (Bloom, 1984), and consisted of a set of 15-20 short answer questions, 3-4 medium answer questions, and 1-2 long answer questions. Weekly lab exercises during the first half of the semester were designed to assess student learning on the application and synthesis of core concepts. Weekly oral updates on student projects and final presentations during the second half of the semester were used to assess application, synthesis, and the effectiveness of students working in teams. Standard university end-of-semester course evaluations were used to assess students' opinions of the course.

The assessment plan also included several non-traditional methods to increase feedback between students and instructors. These methods included classroom assessment techniques (CATS, Angelo and Cross, 1993), interviews, concept maps, questionnaires, and discussions. Throughout lectures and labs, student learning was assessed using CATS that included minute papers, muddiest point exercises, empty outlines, as well as seeking answers from students to direct questions. Student interviews provided additional means of assessing student learning. During the first week of class, each student was interviewed by staff from the Teaching Excellence Program (Appendix 1). The initial interview was designed to provide background information on the student's view of Earth System Science before the course. At the end of the semester, staff from the Teaching Excellence Program gathered similar information from the students during a videotaped focus group discussion (Appendix 2). All interviews were confidential and not shared with professors until after class was completed. Students were tracked anonymously to enable connecting initial interviews with other anonymous assessments over the course of the semester, without identities being jeopardized.

Concept maps were also included in the assessment plan. Concept maps are diagrams that represent an individuals understanding of a particular topic or concept (Angelo and Cross, 1993; Dorough and Rye, 1997; McClure et al., 1999). Three times during the semester (beginning, middle and end), students were asked to draw concept maps of the Earth System. The series of concept maps from each student was used to help assess changes in the conceptual understanding of the Earth System over the duration of the course.

Questionnaires at the middle and end of the semester consisted of 20 questions (Appendix 3) related to the lecture and laboratory sections of the class. We also requested that the students provide two specific suggestions on how the class could be improved. These were collected by the TA and sent to the Teaching Excellence office for analysis. Only the summarized and anonymous results were shared with the professors.

Course Structure and Content

The structure of the course consisted of four linked elements: Readings, Lectures, Labs, and Student Projects described in the course syllabus (Appendix 4). Each of these elements provided an important resource for students, and integration between them reinforced important concepts without unnecessary repetition. Given the broad scope of Earth System Science, it quickly became clear that the vast set of potential content on Earth System Science had to be reduced to an effective sub-set. The challenge of selecting content arose from:

- A commitment to designing toward course objectives,
- Anticipation of the diversity of student background knowledge and interests,
- Realistic estimate of student time commitment,
- Consideration of the learning value of varied repetition,
- Awareness of the foundational nature of an ESS orientation for graduate students

Given these considerations, a sequence of basic and advanced topics and case studies were selected to illustrate particular frameworks, approaches, concepts, and tools in Earth System Science. Selecting course content was a difficult task, as many important examples had to be dropped. However, the process provided us with a rich list of potential topics for student research topics.

Readings: The anticipated range of student backgrounds influenced our selection of a broadly accessible intermediate-level textbook (Kump et al., 2004). Students were responsible for using this text and other resources to meet a consistent level of preparation throughout the course. Readings were chosen to provide essential background, and to promote informed discussion of key Earth System Science issues. We stratified all reading assignments into basic and advanced categories Basic readings from the textbook were combined with advanced readings that consisted of peer reviewed journal articles on specific studies (Appendix 5 and 6). In addition, optional resources were provided on each topic to provide additional resources for students with less previous exposure, and for those with special interests in particular topics.

Lectures: Lectures were designed to provide background on the components (atmosphere, hydrosphere, cryosphere, biosphere, and lithosphere), dynamics (e.g., energy budget, water cycle, biogeochemical cycles), and changes within the Earth. Lectures in the first part of the course focused on ESS concepts, components, and cycles. The second part of the course focused on case studies emphasizing interactions, feedbacks, and change over.

Examples of both positive and negative feedbacks were presented and discussed. Phenomena such as coupled ocean-atmosphere circulation systems (e.g., ENSO, Arctic Oscillation), the complex role of clouds in the water cycle, and important interactions between the biosphere and atmosphere (e.g. deforestation and energy balance) were examined. All lecture materials were developed in an electronic format (e.g., MS Word, PowerPoint). This allowed for rapid incorporation of recent research, data, models, and visualization into the lectures, and provided a means to archive the lectures and to share our learning resources with others.

All lectures were given using modern teaching methods that embraced good practice principles and an active learning-centered paradigm (Bonwell and Eison, 1991; Barr and Tagg, 1995; Cross 1998; Chickering and Gamson, 1987; Chickering and Gamson 1999). Concepts were presented in short blocks (<15min) separated by activities such as minute papers, empty outlines, think-pair-share exercises, and discussions that engaged students in the material presented. Because different students learn differently (Anderson and Adams, 1992), presentations were flexible, addressed student feedback, and often described concepts using more than one approach.

NASA-GSFC participation provided a special degree of enrichment by exposing students to the breadth and depth of implementing space-borne observational projects and the application of data from such projects/missions in Earth System Science. A seminar series of 5 NASA scientists was required, and open to the wider university community. Presentations were coordinated with course content. Keynote speakers also met informally with students giving them opportunities to discuss key ESS issues, learn about NASA activities, and ask about career opportunities.

Computer Labs: A computer lab formed a fundamental component of the class. Both previous research (Angelo, 1993) and our experience have shown that students retain far more of the course material when they are active participants instead of passive learners. We paid special attention to developing a series of computer labs that encouraged students to develop the skills to build and run simple models of Earth System dynamics. Topics covered in lab were integrated closely with topics covered in lectures and readings. Student preparation for modeling was built on foundation of basic problem solving, and mathematical skills relating to differential equations established early in the semester. Examples from Harte (1998) helped to inform these exercises.

Computer models were developed using Stella© software. Stella provided a graphical user interface that made coding, running, and visualizing dynamic models easy and accessible. The modeling environment provided a linkage between student's conceptual understanding (e.g. concept maps) and the need for quantification and analysis of change over time. Modeling exercises progressed from simple representations of the Earth's energy budget with no atmosphere, to more complex representations that included multiple atmospheric layers, greenhouse gases, biogeochemical cycles, and land surface dynamics. Some exercises were new. Others were derived from available published examples (Harte, 1998). A previously developed lab on the energy balance of "Daisy World" was also utilized (Menking, 2004). Key mathematical concepts emphasized throughout included dynamic equilibria, steady state, stability, forcing, perturbation, and feedbacks.

<u>Team Projects:</u> For the second half of the semester, the lab portion of the course was dedicated to student team research projects. Small student teams (3 per team) were formed through a combination of self-selection and oversight to ensure that each team comprised a diverse group with complimentary skills. Each team completed an eight-week modeling-based research project on a topic in Earth System Science. Student teams gave weekly 5 minute oral reports on their progress on a schedule of milestones that progressed from: topic/motivation, model development, results, and conclusion. All team members were required to participate in each presentation. Following each presentation, teams were asked to respond to questions and suggestions from students and professors. At the end of each period, team participants were encouraged to ask rest of the class and/or instructors for input on projects. Student projects culminated in American Geophysical Union (AGU)-style oral presentations in class at the end of the semester, and AGU-style poster presentations at the UNH Undergraduate Research Conference the following spring.

<u>Integration into the Curriculum</u>: From initial considerations of a large set of specific prerequisites that included prior-preparation in all relevant areas, prerequisites were ultimately simplified down to consist of advanced student status (Junior or Senior) in any science major or graduate student status in any scientific field, one-semester of calculus, and permission of instructor. Because of the courses interdisciplinary nature, and the diverse team of instructors from different colleges/departments, the course was cross-listed in multiple departments/colleges. It was listed at the undergraduate and graduate levels in the Department of Earth Sciences and Natural Resources and was approved for

majors therein. In addition, it was listed at the graduate level in EOS. The course formed a key advanced offering in the new cross-departmental B.S. in Environmental Sciences major in Earth System Sciences and Natural Resources. Institutional approval at the program/department level for this new course provided crucial incentive for interested student to enroll.

RESULTS

The Assessment Plan we developed provided the basis to evaluate how well the students met the seven learning objectives outline above. We also identified several key lessons learned from developing and delivering the course.

Meeting learning objectives

1. Knowledge-based comprehension and understanding aspects of this course were assessed using both traditional and more contemporary assessment methods (Table 1). Student performance on exam questions was summarized by calculating the mean score and standard deviation for each set of questions that related to a particular course objective (Figure 2). The high averages on all exam questions indicate that the students had a practical understanding of key concepts, components, and interactions. Concept maps also revealed an improved understanding of the complex web of interactions that characterize the Earth System. For example, the initial concept maps drawn by the students reveal an incomplete, disorganized, and confused mental map of the Earth System (Figure 3 and 4). In comparison, concept maps drawn later in the course are more

logical, more detailed, and capture an improved understanding of the system (Figure 3, 4).

2. Analyzing the causes of change over varied spatial and temporal scales was more challenging to assess. Student mean exam question scores were the lowest on this topic out of all course objectives (Fig. 2). However, both lab exercises and student team projects revealed marked improvement in understanding of system dynamics.

3. Exam questions, laboratory exercises, concept maps, and student team projects all illustrated marked improvement on application of knowledge from ESS models to key scientific questions. The exam questions relating to this learning objective had mean score of 8.8, tying for the highest score. Student team projects documented progression from initial research questions to successful oral and poster presentations of Earth System topics using dynamical computer models.

4. Reading, discussing, and evaluating assigned primary literature was allotted approximately 1/3 of the lecture time. The effectiveness of achieving the learning objective was evaluated through exam questions, final project development, and in-class student discussions. The mean exam question score for this objective was relatively high (Fig. 2). In addition, in-class discussion was invaluable for helping the students learn the process of advanced literature synthesis and evaluation and develop critical thinking skills. Students prepared their own summaries, handouts, and critical thinking questions to promote discussion. Student-led discussions were credited with helping students better comprehend and analyze scientific papers. Exam questions pertaining to the assigned literature indicated students gained critical reading, and synthesis skills.

5. Relating ESS to the human condition represents one of the important student learning objectives for this course. We used multiple assessment methods to evaluate student performance on this objective (Table 1). Assessment techniques included both short and long questions on Exam 1, short and medium questions on Exam 2, weekly student project updates, final projects, and concept maps. The most impressive illustration of students' progress appeared in the progression of their concept maps (Figures 3 and 4). Initial concept maps typically omitted human interactions. The second (mid-term) concept maps typically included some human element. More fully integrated human interactions were typically included in the end-of-semester concept maps. One student created the "anthroposphere" to depict that humans represent a key component of the Earth System. The inclusion of the anthroposphere by this student illustrates an appreciation of the large role that humans are playing in ESS.

6. Student's demonstrated peer-to-peer cooperation in learning and research by effectively working with increasing efficiency in team study-groups, lab exercises, and successful interdisciplinary research projects. By the end of the course, students readily formed groups to address challenging interdisciplinary topics when they arose without instructor's provocation, an generally produced results that were better than any student could have produced alone. Student team research projects were highly successful, and exceeded instructor's expectations.

7. Uncertainty is a key concept in ESS and was the basis of Objective 7. Exam assessment results show that the course was effective in conveying the ESS nature of uncertainty. This objective tied with Objective 3 for the highest mean score while additionally receiving the lowest standard deviation value (Fig. 2).

Creating an Inquiry-Based Learning Environment

The creation of an inquiry-based learning environment to empower and motivate student learning was an important characteristic of the course. Students recognized the importance of this environment. Initial student interviews yielded responses such as students being "interested in the unique way of learning that he/she expects to experience taking this class, including peer learning" and students preferring lectures coinciding with topic discussion and concept application in a cooperative environment. Student feedback from the mid-semester course evaluation indicated that we were successful facilitating an effective social arrangement in the classroom. Most notably, students became comfortable enough to request changes in the course format. For example, one of the twenty questions on the mid-semester evaluation asked students to respond to the statement "I would like more discussions of readings". Options for answers ranged from strongly agree (1) to strongly disagree (5) The average numeric response was 2.3 (s.d. 1.6), suggesting that the students were seeking more discussion. Follow up informal conversations indicted they also were also interested in assuming a larger role in leading the discussions of the advanced readings. This suggestion was implemented immediately by having the students voluntarily assign themselves discussion leaders for specific articles on the reading schedule, direct discussions, and provide short written summaries of each article to their classmates. Through informal discussion, we learned that students met outside of class to study advanced readings for the mid-term exam. Additionally, question 19 on the mid-term and end-of-semester course evaluation (same set of questions) asked students to respond the statement "The instructors create an inquiry based learning environment". The average of their responses shifted from 2.3 to 1.7, reflecting a shift towards agree.

Student responses from end-of-semester group discussions also suggested that this course was effective in creating a learning environment. Student comments proclaim that the uniqueness of the course originated from "advanced readings and subsequent discussion that…made us more accountable", adding that "[the students] got to hear what peers had to say" which led to the students feeling "somewhat empowered by the student-driven discussions." The feeling of ownership of their learning environment was appreciated by the students and led to more effective teaching-learning alliances in the classroom. Moreover, the students agreed that having the students lead the discussions made them "more accountable for doing the readings [and so we did more than they might have done otherwise] because peers were going to ask us questions." They also enjoyed having multiple instructors with different backgrounds and student-driven discussions not only because the professors worked "synergistically" in presenting the material, but also "joined-in and asked questions" during discussions and were available for "ample professor input" while still providing plenty of "opportunity…for all of us to participate." Overall, the students expressed their approval of the class format.

Role-Modeling How Earth System Science is Done

Student team-research projects provided evidence that students worked together applied their ESS knowledge. The process of project development and feedback from instructors and peers modeled how teams of scientists approach key scientific questions, incorporate feedback, and make formal presentations. During interviews students described this as one of the most important aspects of the course. One student commented that "this course works with your strengths but also develops your weaknesses" after mentioning that "the idea [of this course is to become] well-rounded and have an expanded outlook to be a better scientist." Others made statements that they "know a lot more about how the system works and can really talk about current events [in science]" when referring to the informal discussions they engaged in with visiting NASA scientists. Another student reflected on "how this class has broadened my perspectives a lot about science and what the questions are in our science." The absence of any student comment or response contrary to the above statements indicate that the methods and format of this course were successful in meeting course learning goals, and were effective in teaching upper-level undergraduate and entry-level graduate students not only about "what ESS is", but also "how ESS is done."

Meeting Student Demand and Institutional Challenges

To be successful, new courses must address both student interests and institutional challenges. Students were aware of the benefits to studying ESS and the need to broaden their view and become more. Initial interviews recorded student desire to learn about the Earth System. When students were asked why learning about ESS was important and why are they interested in pursuing ESS, numerous comments represented their desire for a more comprehensive outlook. One student exclaimed that the "future of the world depends on us being able to predict and understand how these system operate" and that it is important to "understand a larger picture of the Earth Systems because we [humans] need to figure out the effects of [our] influence", explaining that "since all the Earth Systems are integrated they must be studied on a broad scope" in addition to previously more focused studies. Students explained that their "field of study is too narrow and future research would be more useful with an understanding of ESS." Many students cited their research as motivation for learning about ESS "because it goes along with his/her undergraduate work" and because "science [is] not…divided into cut and dry areas but rather all [areas] must be integrated [as] the earth systems interact with each other" and "this will help in his/her approach to research and how it can be applied to the world."

Despite student demand for new courses, significant challenges remain in making students and advisors aware of new courses, and fitting new courses into degree requirements and scheduling conflicts. Our efforts publicizing the course through course flyers, and getting course approval, and acquiring approval for degree credits were key to achieving our initial enrollment. More work in these areas including an expanded student recruiting effort, permanent course approval, and catalogue listing are needed to more fully integrate the course into the curriculum, and grow enrollment in the future.

DISCUSSION

The understanding of the Earth System has progressed markedly through history from early conceptions of the earth at the center of the universe under external control, to modern understandings of the universe, Earth System dynamics, and concepts for global environmental management (Schellnhuber, 1999). Today, many of the most important questions in Earth System Science lie at the intersection of traditional disciplines, and must be addressed through an integrated systems perspective (Jacobson et al., 2000; Falkowski et al., 2000; Moore et al., 2001; Steffen et al., 2003; Pielke et al., 2003). The educational challenge is to train the next generation of scientists to address interdisciplinary questions (Sung et al., 2003).

In this study, we have described the development, structure, and results of a new course designed to enhance the teaching of Earth System Science. The course exposed advanced undergraduate / beginning graduate level students to a course in Earth System Science that was simultaneously broad and deep. Considerable effort was placed on the selection, organization, coordination, and development of course materials (readings, lecture, labs, etc.). These resources were essential to delivering an effective course. However, the most important lessons learned from this course were not about content, but about how the course was taught. Earth System Science is such a vast topic, that it is easy to see that any conceivable course would necessarily omits important content. Early realization of this fact helped us to design from the outset the creation of an inquiry-based learning-centered approach. As a result, students were not overwhelmed with information in lectures and assigned readings, but motivated and empowered to build on essential concepts covered in class with independent readings, study, and research. This approach was perhaps the single most important aspect to the success of student learning in the course.

To gauge student learning and to provide feedback on course attributes, a substantial effort was dedicated to assessment. Because of the difficulty of collecting and evaluating relevant assessment information, the lack of control groups, and because of the small class size, we were not able to use statistical tests as a means of formal hypothesis testing. Rather, we have based our conclusions on the largely qualitative standard of identifying lessons learned from what a reasonable person would conclude from our data. Exams and student interviews documented that students broadened their understanding of key Earth System concepts and interactions. Student research projects demonstrated their enhanced ability to effectively address interdisciplinary Earth System topics quantitatively and in teams. To add to these metrics, new assessment methods are needed to assess the extent to which students exposed to this course are successful at addressing Earth System Science long-term. Post-tests and surveys could lend insight into the long-term retention of Earth System Science knowledge and concepts.

It is our hope that this course provides a general and customizable model for how to enhance Earth System Science education at the post-secondary level. To ensure quality, we have submitted all course materials that we have developed (lectures, labs, assessments, etc…) to external peer review by NASA Education Product Review. To expand the number of students engaged, we have both solidified the integration and continue offering of the course at UNH, and successfully obtained new support to extend these resources and methods to faculty at a large set of Historically Black Colleges and Universities (HBCUs) nationally. Over the next three years, we plan to expose dozens of instructors and hundreds of students to the content and approaches described here. Expanding the number instructors and students involved in this effort to perturb Earth System Science Education will lead to further improvements in course design, and expand the pool of Earth System Scientists able to address issues in ESS.

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Table 1. Assessment of student learning by student-learning objective.

Student Learning Objective	Assessment of Student Learning											
	Exam 1			Exam 2			Lab Exercises	Project Updates	Final Project	Student Discuss.	Concept Maps	CATs
	S	M	L	S	M	L						
1. Concept Comprehension, Knowledge, and Understanding	√	√	√	√	√	√	√				√	√
2. Analysis of Change Over Varied Spatial and Temporal Scales	√			√	√	√						
3. Application of Knowledge from ESS Models to Key Scientific Questions	√		√	√	√	√	√	√	√		√	
4. Synthesis and Evaluation of Literature	√	√		√	√	√		√	√	√		
5. Relate Knowledge of ESS to the Human Condition	√		√	√	√			√	√		√	
6. Develop Peer-to-Peer Learning and Group Skills							√	√	√	√		
7. Role of Uncertainty		√			√		√	√	√	√		

Exam "S", "M", and "L" represent the breakdown for short, medium, and long answer questions.

Table 2. Student course assessment by course characteristic.

Course Characteristic	Course Assessment by Students					
	Course Evaluation Mid-Semester	Course Evaluation End-Semester	UNH End-of-Semester Evaluation	Interview 1	Interview 2	Informal Discussions
Course Content	√	√	√		√	√
Course Structure and Format	√	√	√		√	√
Course Relevance and Importance				√	√	√
Preparation and Resources	√	√	√			
Inquiry Based Learning Environ.	√	√			√	√
Modeling real-world approach to Earth System Science					√	√

FIGURE CAPTIONS

Figure 1. (a) The educational experience of many science students is one of decreasing breadth with level of advancement. (b) The educational experience of science students is perturbed (shaded box) with an advanced interdisciplinary course that will better prepare them to address interdisciplinary topics in the future (dashed region).

Figure 2. Mean student exam scores (+ std. dev.) categorized by learning objective.

Figure 3. Examples of student concept maps of the Earth System dawn at the (a) beginning, (b) middle, and (c) end of the semester. The series of maps illustrates a progression of conceptual understanding of the Earth System.

Figure 4. Examples of concept maps of the Earth System from a second student dawn at the (a) beginning, (b) middle, and (c) end of the semester. The series of maps illustrates a progression of conceptual understanding of the Earth System.

Figure 1 (a)

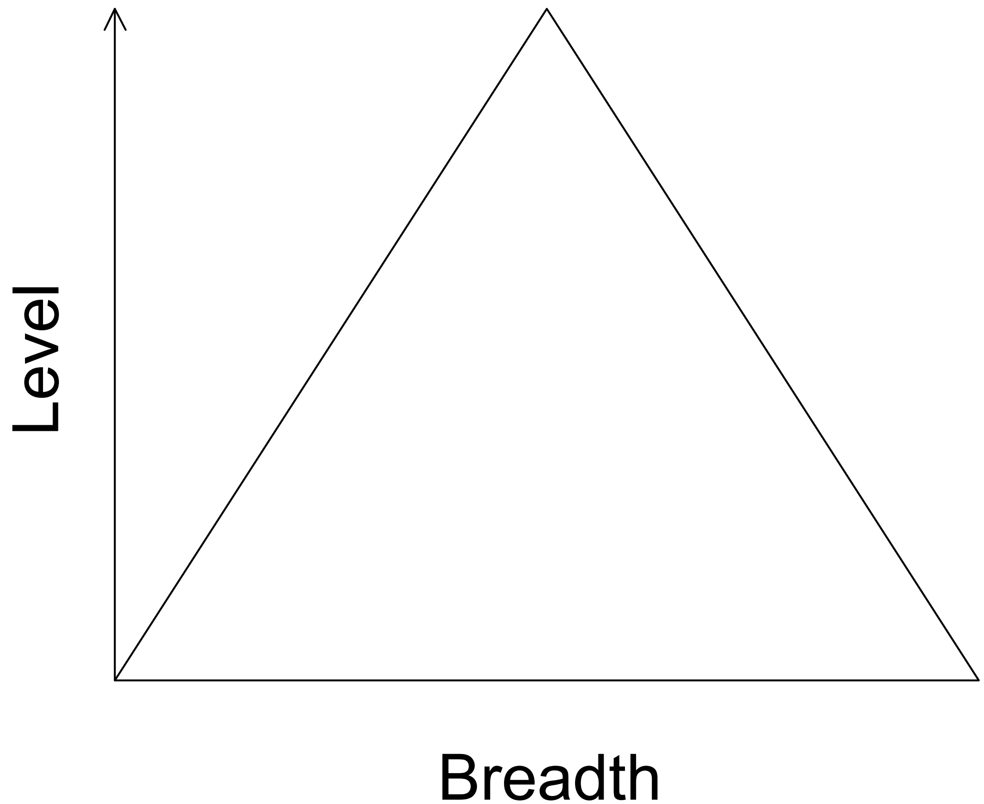


Figure 1 (b)

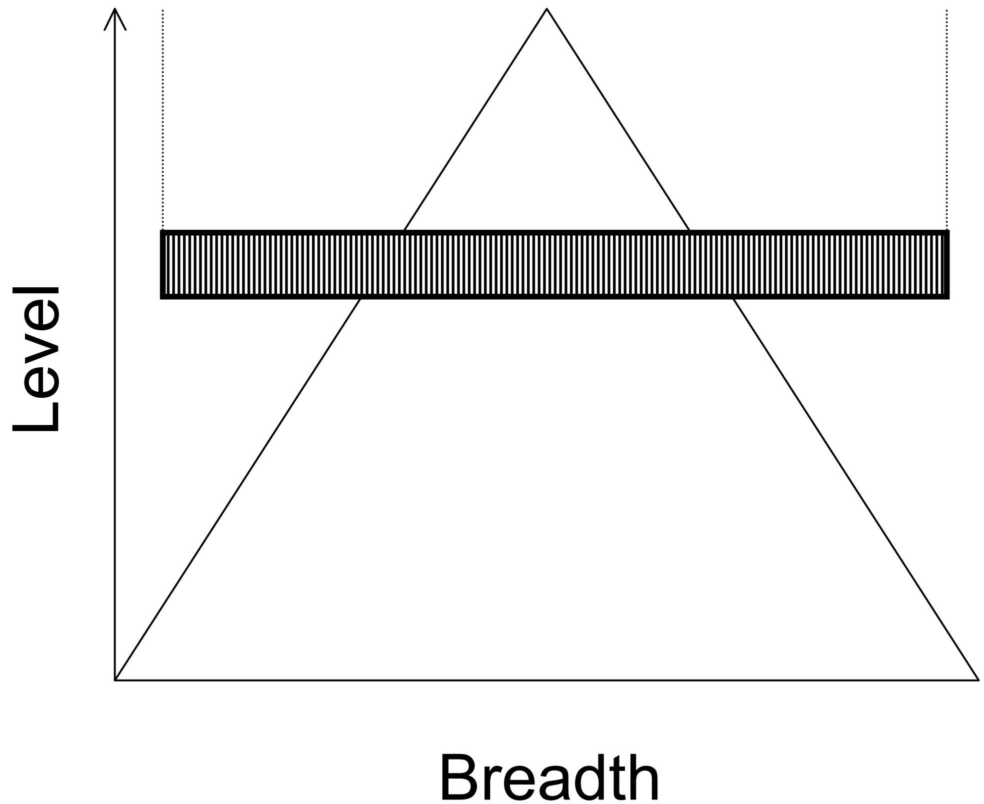


Figure 2

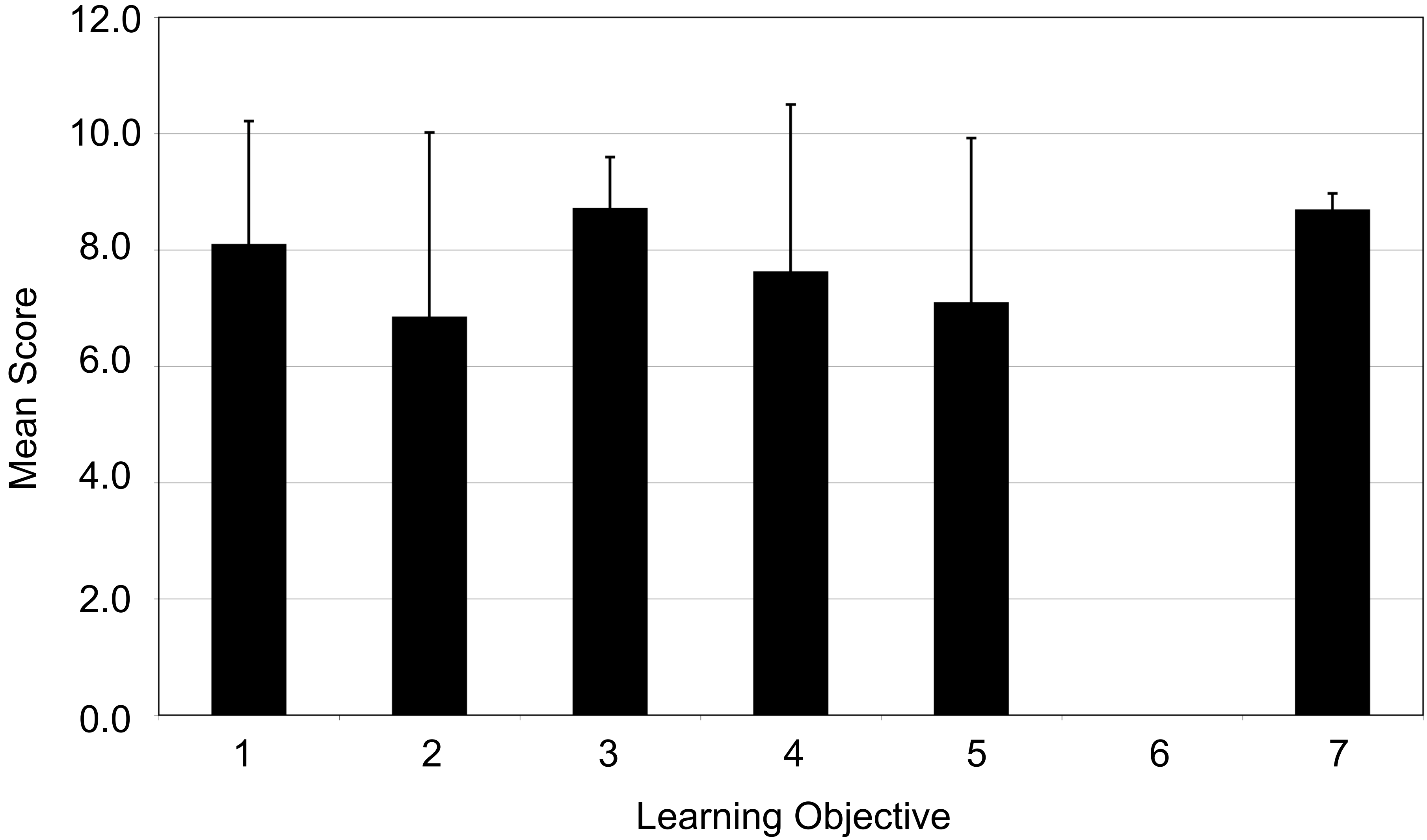


Figure 3 (c)

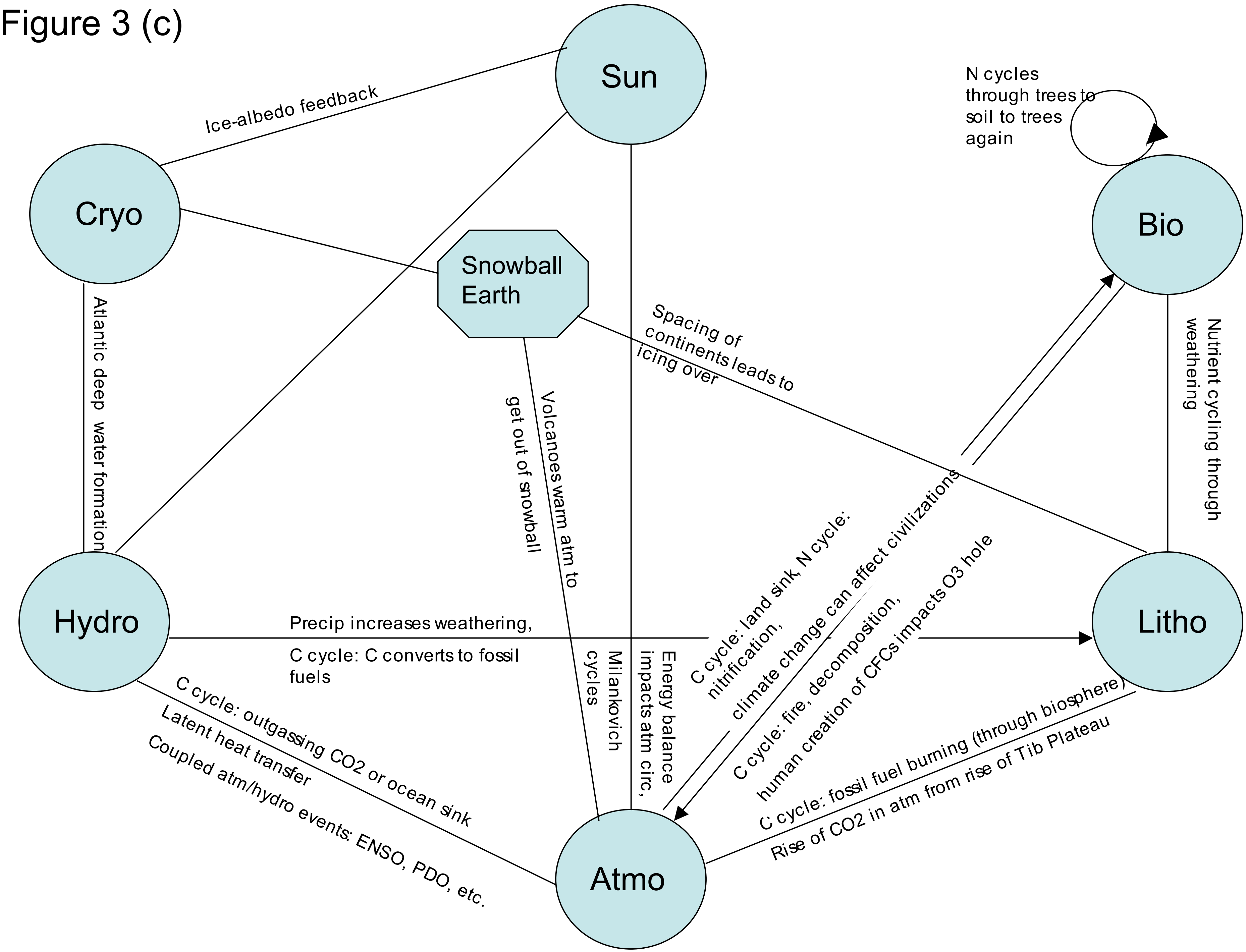

Sun
Cryo
Bio
Hydro
Litho
Atmo
Snowball Earth
Ice-albedo feedback
N cycles through trees to soil to trees again
Atlantic deep water formation
Volcanoes warm atm to get out of snowball
Spacing of continents leads to icing over
Nutrient cycling through weathering
Precip increases weathering,
C cycle: C converts to fossil fuels
Milankovich cycles
Energy balance impacts atm circ,
C cycle: land sink, N cycle: nitrification,
climate change can affect civilizations
C cycle: fire, decomposition,
human creation of CFCs impacts O3 hole
C cycle: outgassing CO2 or ocean sink
Latent heat transfer
Coupled atm/hydro events: ENSO, PDO, etc.
C cycle: fossil fuel burning (through biosphere)
Rise of CO2 in atm from rise of Tib Plateau

Figure 3 (a)

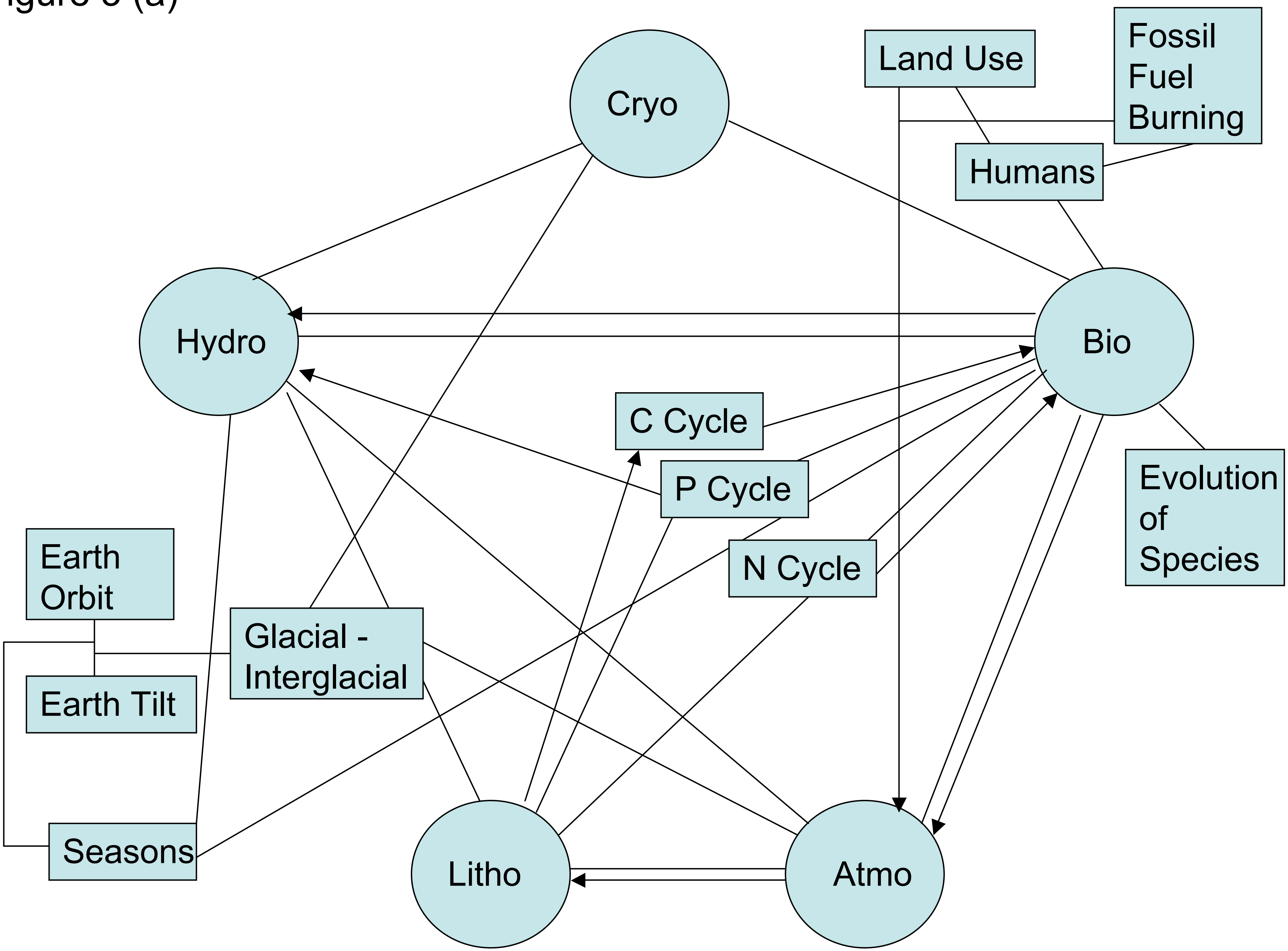
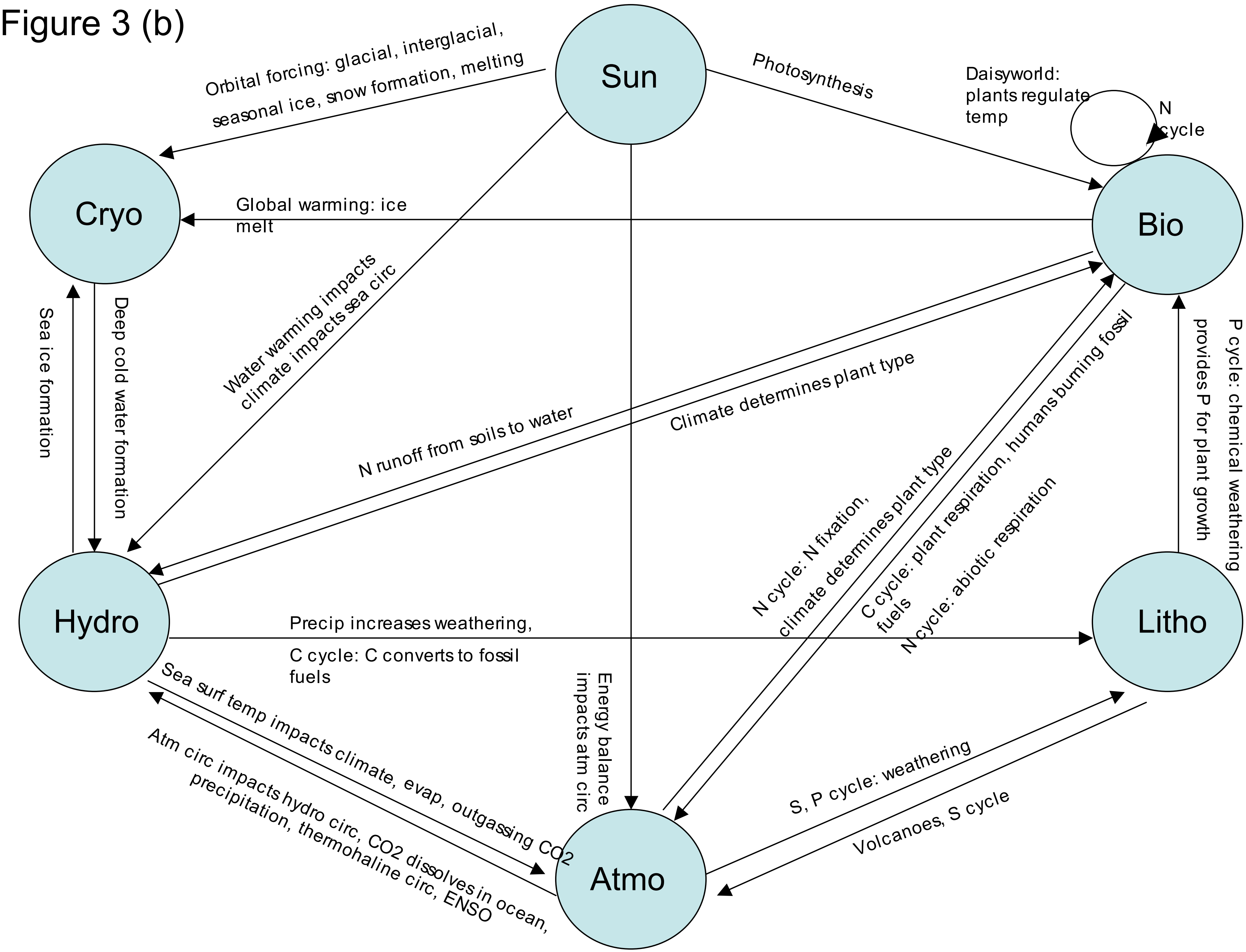

Cryo
Land Use
Fossil Fuel Burning
Humans
Hydro
Bio
C Cycle
P Cycle
N Cycle
Evolution of Species
Earth Orbit
Glacial - Interglacial
Earth Tilt
Seasons
Litho
Atmo

Figure 3 (b)



Sun
Cryo
Bio
Hydro
Litho
Atmo
Orbital forcing: glacial, interglacial, seasonal ice, snow formation, melting
Photosynthesis
Daisyworld: plants regulate temp
N cycle
Global warming: ice melt
Water warming impacts climate impacts sea circ
Sea ice formation
Deep cold water formation
Climate determines plant type
N runoff from soils to water
P cycle: chemical weathering provides P for plant growth
N cycle: N fixation, climate determines plant type
C cycle: plant respiration, humans burning fossil fuels
N cycle: abiotic respiration
Precip increases weathering,
C cycle: C converts to fossil fuels
Energy balance impacts atm circ
Sea surf temp impacts climate, evap, outgassing CO2
Atm circ impacts hydro circ, CO2 dissolves in ocean, precipitation, thermohaline circ, ENSO
S, P cycle: weathering
Volcanoes, S cycle

Figure 4 (a)

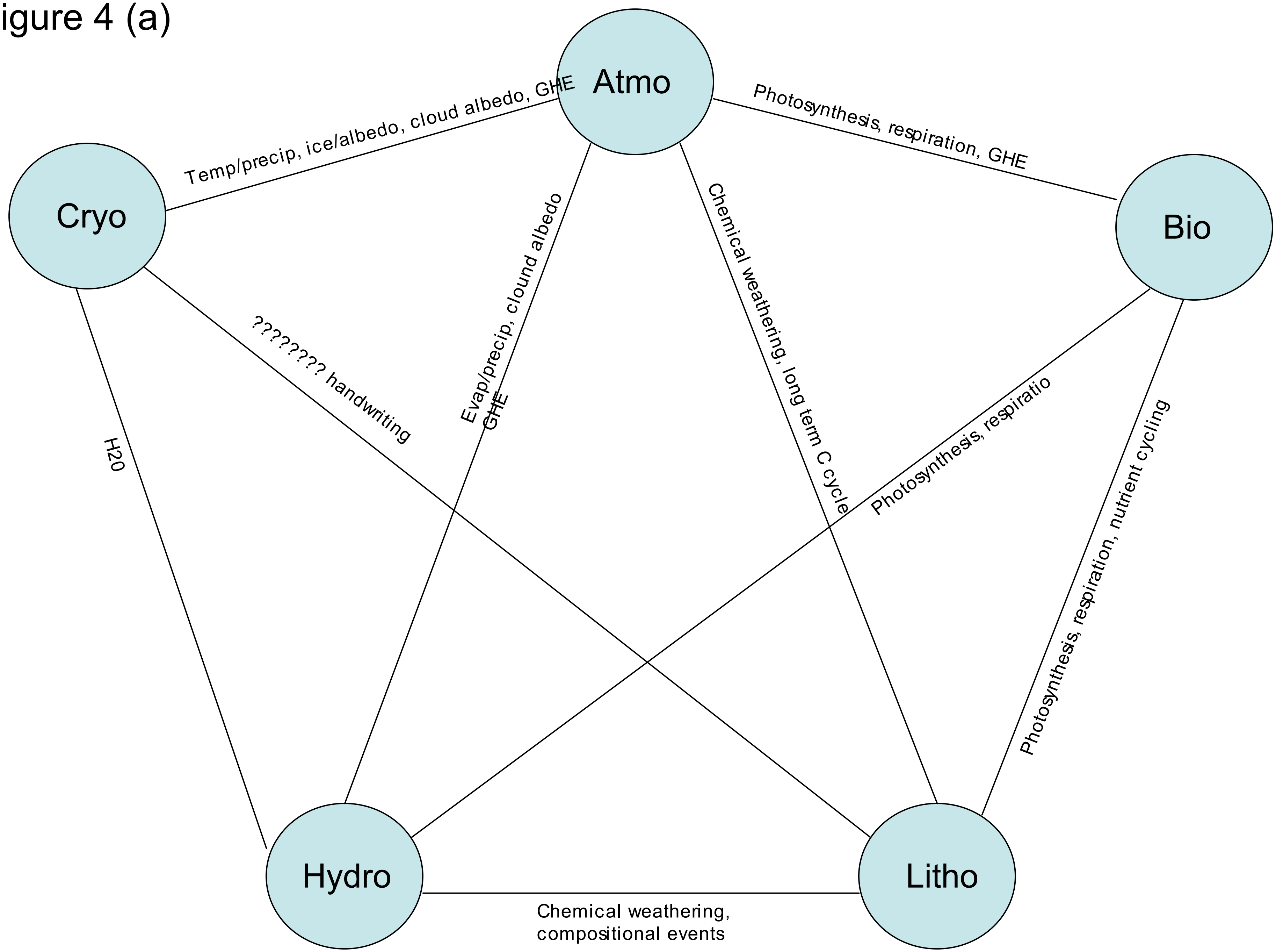

Atmo
Cryo
Bio
Hydro
Litho
Temp/precip, ice/albedo, cloud albedo, GHE
Photosynthesis, respiration, GHE
Evap/precip, clound albedo
GHE
Chemical weathering, long term C cycle
???????? handwriting
H20
Photosynthesis, respiratio
Photosynthesis, respiration, nutrient cycling
Chemical weathering,
compositional events

Figure 4 (b)

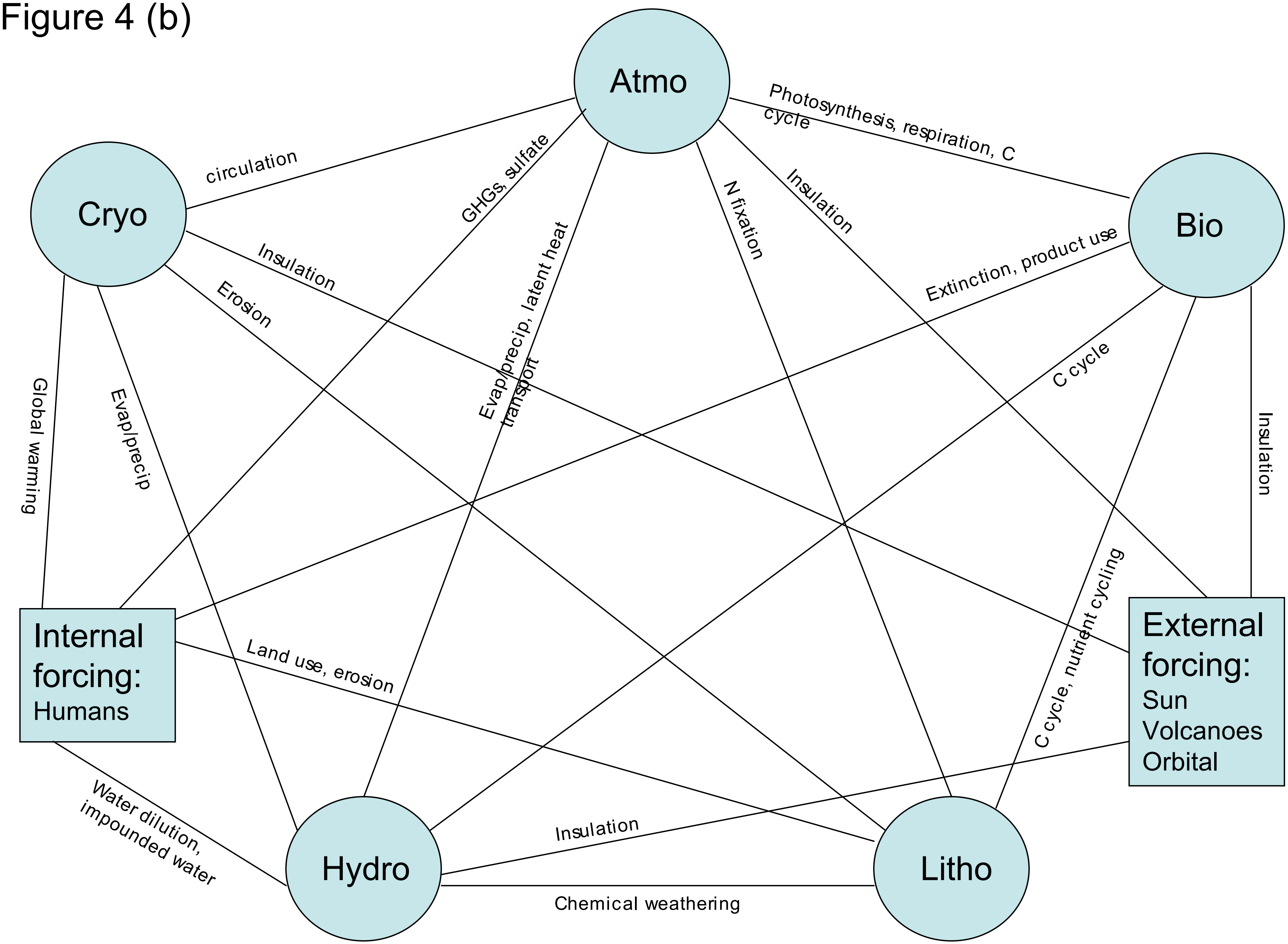
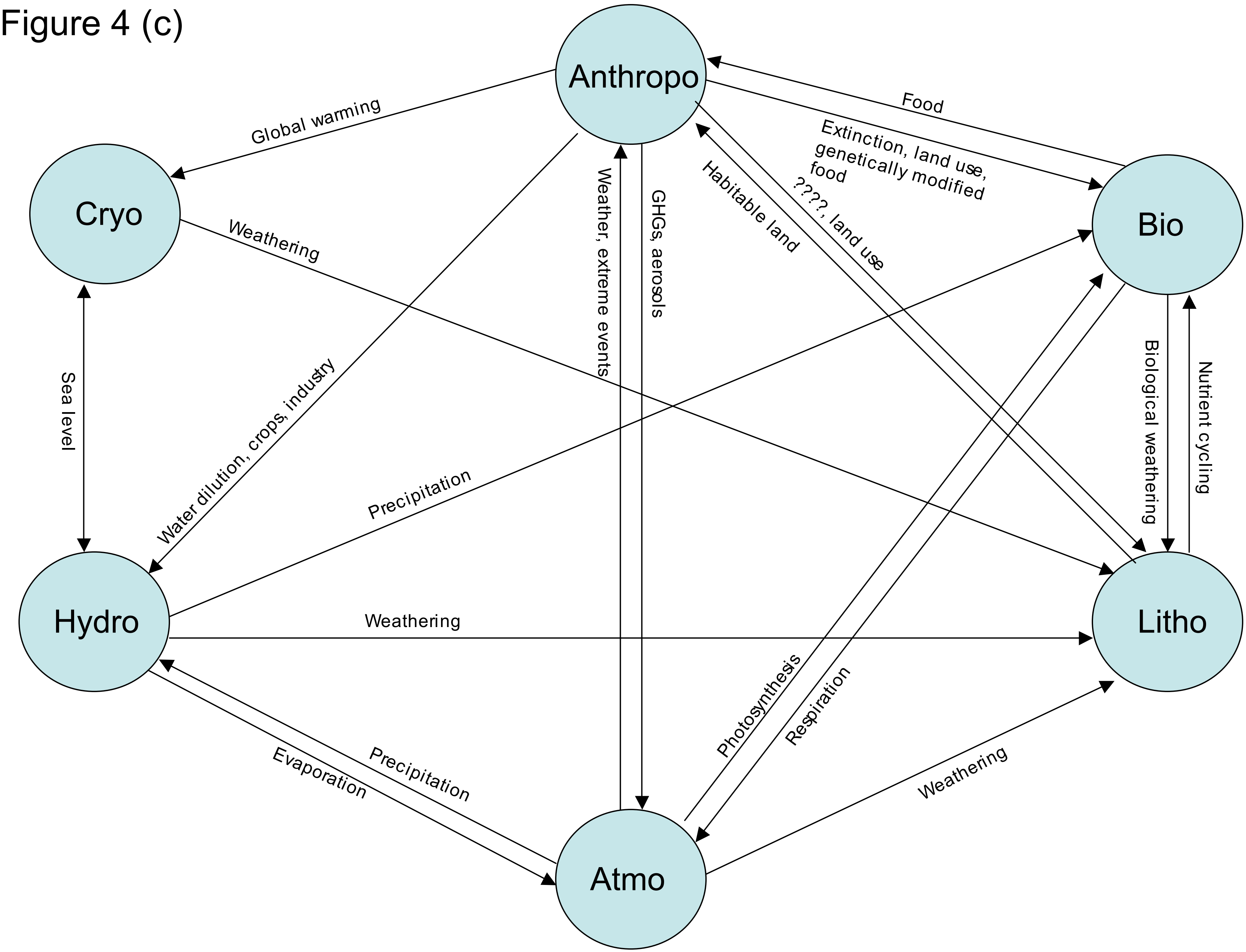

Atmo
Cryo
Bio
Internal forcing:
Humans
External forcing:
Sun
Volcanoes
Orbital
Hydro
Litho
circulation
Photosynthesis, respiration, C cycle
GHGs, sulfate
Evap/precip, latent heat transport
N fixation
Insulation
Insulation
Erosion
Extinction, product use
C cycle
Global warming
Evap/precip
Insulation
C cycle, nutrient cycling
Land use, erosion
Water dilution, impounded water
Insulation
Chemical weathering

Figure 4 (c)



Anthropo
Cryo
Bio
Hydro
Litho
Atmo
Global warming
Food
Extinction, land use, genetically modified food
????, land use
Habitable land
Weather, extreme events
GHGs, aerosols
Weathering
Water dilution, crops, industry
Sea level
Precipitation
Biological weathering
Nutrient cycling
Weathering
Photosynthesis
Respiration
Evaporation
Precipitation
Weathering

APPENDIXES

Appendix 1. Questions asked of students during interviews at beginning of semester.

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1. How and why is an understanding of Earth System Science important?
2. Why are you interested in this course?
3. What really excites you about "science?"
4. If you could change how "science" is taught, what changes would you recommend?
5. What one word best characterizes your scientific education to date? (explain)

Appendix 2. Questions asked of students during end-of-semester focus group discussion.

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1. Was this a unique course?
2. Did you like having multiple (2) instructors?
3. Were student driven discussions a positive or negative aspect of the course?
4. What are your thoughts on concept mapping?
5. What was the most interesting topic in the course?
6. What pieces of the course should be dropped or de-emphasized?
7. Describe specifics about the way instructors presented the course material.
8. Would the class be different with more students?
9. What motivates students to take this course?
10. Describe any specific strengths and weaknesses of the course not already mentioned.
11. How would this course have to change to appeal to non-science majors?
12. Is Earth System Science a discipline such as chemistry, math, physics, biology?
13. Would a series of courses in ESS be appealing to undergraduates?
14. Define your experience of this course in one word. (explain)

Appendix 3: 20 Question Evaluation Summary

Evaluation Questions (Middle and End of Semester)
ESCR 795/895; NR 797/897; EOS 895

Favorite high school teacher name: ____________________

1 Stongly Agree 2 Agree 3 Neutral 4 Disagree 5 Strongly Disagree

	Mean (std dev) Middle	End
1. I generally read the assigned readings before class	1.7 (0.8)	1.7(0.8)
2. Having the class slides before/during class is helpful	2.0 (1.5)	2.3(1.2)
3. Kump is an acceptable primary textbook	1.3 (0.5)	1.5(0.5)
4. I would like more discussion of readings	2.3 (1.6)	3.3(1.6)
5. The Blackboard features of the course work well	1.8 (0.8)	1.7(0.5)
6. This course decreases my interest in Earth system science	4.8 (0.4)	4.7(0.5)
7. Overall, the course is effective	1.8 (0.4)	1.7(0.5)
8. The course is too easy and does not challenge me	3.8 (1.5)	4.0(1.3)
9. This course repeats too much from my undergraduate courses	3.8 (1.4)	3.5(1.1)
10. This course is about what I expected	2.5 (1.1)	2.2(1.0)
11. Use weekly quizzes instead of midterm and final	3.5 (1.2)	3.8(1.2)
12. Too much emphasis on broad topics; I need more specifics	2.8 (1.2)	3.3(1.2)
13. This course helps me place my research into context	2.6 (0.9)	2.2(0.1)
14. The readings are useful for helping learn the material	2.0 (0.9)	2.2(0.9)
15. The lab reinforces concepts introduced in the lecture	2.2 (0.4)	2.0(0.0)
16. The lab introduces new concepts not covered in lecture	2.0 (0.6)	2.3(1.0)
17. I am learning useful computer skills in the lab	1.6 (0.7)	1.5(0.6)
18. The lab is too difficult	3.2 (1.2)	3.2(1.2)
19. The instructors create an inquiry based learning environment	2.3 (0.8)	1.7(0.8)
20 The interdisciplinary emphasis of the class is a valuable approach	1.5 (0.8)	1.5(0.8)

21. How could the class be improved (please give one or two specific suggestions).

Appendix 4: Syllabus

Earth System Science ESCI 795/895; NR 797/897; EOS 895
Syllabus for Fall 2004

Professors:
Dr. Cameron Wake, 354 Morse Hall, 603-862-2329, cameron.wake@unh.edu
Dr. George Hurtt, 451 Morse Hall, 603-862-1792, george.hurtt@unh.edu
TA:
Ms. Tracey Wawrzeniak, 346 Morse Hall, 603-862-4046, tlp5@unh.edu

Lectures: James 116 W/F 8:40 –10:00am
Lab: Tischler Computer Lab, James 20 Friday 1:00-3:00 pm
Environmental Sciences Lecture Series: Th 3:30-5:00pm, James 303

Student Learning Objectives:

1. Describe key **components, interactions, and concepts** that characterize the modern earth system (knowledge, comprehension)
2. Analyze the causes of change in the Earth System over varied temporal and spatial scales (analysis)
3. Build simple models of key Earth System interactions; apply this knowledge to key scientific questions in Earth System Science (application)
4. Read, discuss, and evaluate Earth System Science papers in the primary literature (synthesis, evaluation)
5. Relate knowledge of Earth System Science to the human condition (application)
6. Develop peer-to-peer learning/teaching skills and effectiveness at working in groups (skills)
7. Evaluate the role of uncertainty for Earth System Science research and decision making (evaluation)

Reading for Lecture

1. Background Reading: Kump LR, Kasting JF, Crane RG (2004) The Earth System, 2nd edition, Pearson Education Inc., Upper Saddle River, New Jersey, ISBN0131420593.

2. Primary Literature including articles both for background (to enhance textbook reading) and for advanced concepts have been compiled into an electronic course packet posted on the blackboard site. There will be 2-5 readings from the electronic course packet each week.

Readings for Lab:

Laboratory readings and exercises will be posted on Blackboard. Background reading (material from Harte, J. (1988) Consider a Spherical Cow. A Course in Environmental Problem Solving, and Harte, J. (2001). Consider a Cylindrical Cow: more adventures in environmental problem solving) will also be posted on the blackboard site.

NOTE: Course lectures, information, readings, and student presentations will be posted online at: http://blackboard.unh.edu

Course Prerequisites: Calculus I and permission of instructor

For undergraduate students, our goal is to attract juniors and seniors from CEPS and COLSA who have already taken a progression of courses in their field of study. Our main criteria for selecting students will be evidence of this progression in a science based major. We also expect to attract incoming M.Sc and Ph. D. students with a Earth Science background/plan-of-study.

COURSE CONTENT

NOTE: Each class will include a segment providing background information and a segment on advanced concepts (AC) of particular relevance to the Earth System. Students will be expected to have read both the background material and advanced concepts articles so that they can participate in class exercises and discussions in a meaningful way. This class participation will provide one means of student assessment.

In addition to the lectures, students are required to attend the five Environmental Science Lectures by NASA Goddard scientists. Four of the five lectures will be on Thursday from 3:30 to 5:00 pm in James 303. One lecture (Michael King on Tuesday Sept 28) will be from 12:40 to 2:00 pm in the MUB Theater II.

PART 1: Earth System Science (ESS) Concepts, Components, and Cycles

L1: 9/1 Course structure, class objectives, motivation for class, intro to concept mapping
L2: 9/3 Earth System Components
Initial exercise in developing concept map of the Earth System
AC: Spatial and temporal scales of analysis
L3: 9/8 Earth System Concepts: Interactions and Processes
AC: Why is ESS important for humanity?
L4: 9/10 Solar Luminosity and the Role of the Sun in the Earth System
AC: solar and orbital variability
L5: 9/15 Earth's Energy Balance and the Greenhouse Effect
AC: Why is the Earth's temperature just right?
L6: 9/17 Earth's Energy Balance and the Greenhouse Effect (con'd)
AC: Uncertainty: Climate Feedbacks
L7: 9/22 Atmosphere (temperature, pressure, circulation)
AC: Semi-permanent high and low pressure cells
L8: 9/24 Hydrosphere I: The Water Cycle, evaporation and precipitation
AC: Human influence on the global water cycle

9/28 **Environmental Sciences Lecture:** Michael King (NASA Goddard)
12:30 – 2:00 PM, MUB Theater II

L9: 9/29 Hydrosphere II: Ocean Structure and circulation
AC: NADW and thresholds; non-linear feedbacks
9/30 **Environmental Sciences Lecture:** David Adameck (NASA Goddard)

L10: 10/1 Coupled Ocean-Atmosphere circulation systems (ENSO, NAO and Monsoons)
AC: teleconnections and climate forecasting
L11: 10/6 Cryosphere: Snow and Ice
AC: short-term temporal variability of sea ice and mountain glaciers

10/7 **Environmental Sciences Lecture:** Robert Bindschadler (NASA Goddard)

L12: 10/8 Lithosphere: Plate Tectonics, Paleogeography, and Volcanoes
AC: Pinatubo cooling; Tibetan Plateau and global cooling
L13: 10/13 Biochemistry: Carbon Cycle
AC: Approaches and uncertainty in modern carbon budgets
10/15: NO CLASS mid –semester break
L14: 10/20 Biochemistry: N,S,P Cycles
AC: Linkages among biogeochemical cycles

10/21 **Environmental Sciences Lecture:** Compton Tucker (NASA Goddard)

L15: 10/22 Biophysics: Land Cover Influence on Climate
AC: Biophysics and climate simulations
L16: 10/27 Biosphere and Biodiversity
AC: Role and value of major ecosystem services

Oct 28: 12:30 – 2 PM: Review for Exam
10/28 **Environmental Sciences Lecture:** R. Calahan (NASA Goddard)

10/29: EXAM 1

PART II: ESS Interactions and Feedbacks – Case Studies

L17: 11/3 2nd exercise in developing concept map of the Earth System
Rise of Atmospheric Oxygen
L18: 11/5 Snowball Earth
L19: 11/10 Rapid Climate Change Events over last glacial cycle
L20: 11/12 Holocene Climate Change and Civilization
L21: 11/17 K-T Boundary Extinction Event
L22: 11/19 Last 100 years of climate change
L23: 11/24 Threshold response: Ozone Hole
11/26 NO CLASS: THANKSGIVING
L24: 12/1 Recent Land Use, Fossil Fuel Burning and the Carbon Cycle

L25: 12/3 Recent Biosphere Feedbacks
L26: 12/8 Scenarios of Climate Change in the Future
L27: 12/10 Review and 3rd exercise in developing concept map of the Earth System
12/16 Final Exam (during final exam period)

LABORATORIES – BUILDING COMPUTER MODELS

•Models will be developed using Stella™ Software.
•Lab work will be graded and discussed each week to measure student progression.
•Labs will utilize and apply information covered lecture & reading materials.

Part I: Introduction to Modeling:

This part of the course will consist of student interviews, and an introduction to the structure and use of models as tools for scientific analyses/investigation. Topics addressed will include: order of magnitude estimation, box models, units, lifetimes, equlibria, timescales to reach equlibria, differential equations, integration, feedbacks, stability, and an introduction to Stella computer modeling software. As we expect to have students with varied backgrounds taking this course, we will pay special attention to students who require additional assistance (both via pairing students with strong numerical skills with those whose numerical skills are not as strong and focused help from the TA and the Professors).

Lab 1: 9/3 Student Interviews
Lab 2: 9/10 Earth System Science Critical Thinking 1
Lab 3: 9/17 Earth System Science Critical Thinking 2 & Introduction to Stella

Part II: Modeling Earth System Dynamics:

Lab 4: 9/24 Earth System Dynamics I: Energy Balance
Lab 5: 10/1 Earth System Dynamics II: Variable Forcing
Lab 6: 10/8 Earth System Dynamics III: Potential Biospheric Feedbacks
10/15: NO LAB – MID SEMESTER BREAK
Lab 7: 10/22 Earth System Dynamics IV: GHG Dynamics
Lab 8:10/29 Synthesis

Part III: Student Case Studies Using Computer Models

Student teams will identify and address important cases studies in Earth System Science using computer models, and present results in the form of oral, PowerPoint, and poster presentations. The major goals of this section of the lab are threefold: (1) the development and application of quantitative skills for addressing key problems in Earth System Science, (2) an increased understanding of important case studies in Earth System Science using models, and (3) the development and application of professional skills for presenting scientific information. Student teams will provide weekly presentations on progress and issues.

Lab 9: 11/5 Identification of case study and student teams
Lab 10: 11/12 Presentations and theoretical background for model development
Lab 11: 11/19 Presentations and Model Development
11/26 NO LAB: THANKSGIVING
Lab 12: 12/3 Progress Reports and Continued Model Development
Lab 13: 12/10 Presentation of student projects

Student Project Topics (Examples):

40 million year cooling
Snowball Earth
Biodiversity
Rapid Climate Change Events
Quaternary Glaciations and the Carbon Cycle
Paleocene/Eocene

GRADING

Exams (2) 20% each	40%
Weekly class exercises:	10%
Labs:	30%
Research Paper/Presentation:	20%

Weekly class exercises include short oral summaries of required readings, short in class exercises, discussions, and debates. The laboratories will be graded based on material handed in for grading as well as oral updates of research and the final oral/poster presentations.

Graduate students will be expected to produce additional material and efforts in several areas on which they will be graded accordingly. This includes leading discussions and exercises during lectures, an additional essay question on the two exams, an additional critical thinking problem in each of the first seven laboratory exercises, and providing leadership to the student teams working on the laboratory case studies.

Appendix 5. Course schedule and reading assignments.

Date	Topic	Background Reading	Advanced Reading
W 9/1	1 Intro to course (Hurtt/Wake)	Syllabus, Course Objectives	Concept Mapping
F 9/3	2 Earth System Components (Wake)	Kump Ch. 1, 2	IGBP Science #4
W 9/8	3 Earth System Interactions (Hurtt)	Kump Ch. 1, 2, cont'd.	Jacobson 2000 Pielke 2003 Schellnhuber 1999
F 9/10	4 Sun-Earth System (Wake)	Kump p. 303-308; Kump p. 274-280	Lean 1996 Eddy 1976
W 9/15	5 Energy Balance I (Hurtt)	Kump Ch. 3	Kump p.42-43
F 9/17	6 Energy Balance II: (Hurtt)	Kump Ch. 3, cont'd.	Kump p. 48-53 Cess 1995
W 9/22	7 Atmosphere (Wake)	Kump Ch. 4	
F 9/24	8 Hydrosphere I (Wake)	Kump Ch. 4, +++	Vorosmarty 2000
T 9/28	King Lecture		King and Herring, 2000
W 9/29	9 Hydrosphere II (Wake)	Kump Ch. 5	Broecker 1997 Alley 2003
Th 9/30	Adamec Lecture		
F 10/1	10 Ocean-Atmosphere Circulation (Wake)	Kump p. 308-316	Hurrell 2001 Philander 1998 Kerr 1999 CPC web page
W 10/6	11 Hydrosphere: Snow & Ice (Wake)	Selections from Physics of Climate (Wake)	IPCC p123-130 Johannessen2004
Th 10/7	Bindschadler lecture		Bindschadler and Bentley 2002
F 10/8	12 Lithosphere (Wake)	Kump Ch 7	Ruddiman 1991 Raymo 1993 Zielinski 1992
W 10/13	13 Biogeochemistry Carbon cycle (Hurtt)	Kump Ch.8	Sigenthaler & Sarmiento,1993,
F 10/15	Mid-semester Break - No Classes		
W 10/20	14 Biogeochemistry N,S,P (Ollinger)	Schlesinger 1997 ch 12,13	Vitousek & Howarth 1991
Th 10/21	Tucker Lecture		
F 10/22	15 Biophysics (Hurtt)	Peixoto & Oort 1992 Physics of Climate, p. 216-240	Pielke et al 1997
W 10/27	16 Biosphere and Biodiversity (Hurtt)	Kump 9	Costanza et al, 1997
F 10/29	Concept Map; Review		

F 11/3	18 Rise of Atmospheric O2 (Hurtt)	Kump CH. 11, Holland HD. 1995.	Kasting JF. 2001. Catling et al., 2001.
W 11/10	19 Snowball Earth (Wake)	Kump 240-244	Hoffmann 1998, 2000
F 11/13	20 K-T Boundary Extinction Event (Hurtt)	Kump ch. 13	
W 11/17	21 RCCE's (Wake)	Kump Ch. 15, Steffen, Ch. 2.6	Mayewski 1993 Alley 1993; 1997 Bond 1993
F 11/19	22 Holocene Climate Change & Civilization (Wake)	Kump Ch. 15	Steffen, Ch. 5 and TBD
W 11/24	23 Climate System-Last 100 years (Wake)	IPCC Exec Summary; Kump ch. 16	Stott et al. 2000
F 11/26	Thanksgiving Day No classes	-	-
W 12/1	24 O3 Hole (Wake)	Kump Ch. 17	Solomon 2001
F 12/3	25 Land Use (Hurtt)	Steffen, Ch. 4 (tentative)	Hurtt et al 2002, Roy et al 2003l
W 12/8	26 Biosphere Feedbacks (Hurtt)		Cox et al, 2000,
F 12/10	27Scenarios of Change (Hurtt)	Climate Change 2001, Chapter 13, Climate Scenario Development	

Appendix 6. Course Reading List.

ESS Electronic Course Packet Readings

1. IGBP Science Series No. 4. 2001. Global Change and the Earth System: A planet under pressure. The Global Environmental Programmes. Ed.Will Steffen and Peter Tyson. Stockholm: IGBP, 32pp.
2. Jacobson, M.C., R.J. Charlson and H. Rodhe. 2000. Introduction: Biogeochemical cycles as fundamental constructs for studying earth system science and global change. Ed. M.C. Jacobson et al. *Earth System Science: From Biogeochemical Cycles to Global Change*. Academic Press: Boston.
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18. IPCC. 2001. "Glaciers and Ice Caps." In IPCC 2001 *Climate Change 2001: The Scientific Basis*: 647-655.

19. Johannessen, O.M. 2004. "Arctic Climate Change: Observed and Modeled Temperature and Sea-ice Variability." *Tellus* 56A: 328-341.
20. Bindschadler, R. and C. Bentley. 2002. "On Thin Ice?" *Scientific American* December 2002: 98-105.
21. Raymo, M.E. and W.F. Ruddiman. 1992. "Tectonic Forcing of Late Cenozoic Climate." *Nature* 359: 117-122.
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23. Zielinski, G.A., et al. 1994. "Record of Volcanism Since 7000 B.C. From the GISP2 Greenland Ice Core and Implications for the Volcano-Climate System." *Science* 264: 948-952.
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