Earth System Science Undergraduate Program Proposal

Earth System Science

What is Earth System Science?
Earth System Science (ESS) views Earth as a single integrated system that provides a unifying context to examine the interrelationships between all components of the Earth system. The approach concentrates on the nature of linkages among the physical, chemical, biological, and human subsystems of the Earth. ESS primarily involves studying the cycling of matter and energy through the biosphere, atmosphere, hydrosphere, cryosphere, and solid Earth. ESS examines the dynamics and interrelationships among these processes at time scales that range from billions of years to days, and seeks to understand how these interrelationships have changed over time.

Earth System Science within the Faculty of Science
Substantial expertise in Earth System Science exists within the Faculty of Science. Within the Faculty, the Departments of Geography, Earth and Planetary Sciences, and Atmospheric and Oceanic Sciences teach courses and conduct research in the fundamental disciplines of earth science, systems ecology, and the human dimensions of global change. Scholars within these departments, combined with the Faculty’s partnership in the McGill School of Environment, provide a solid foundation upon which to build an innovative ESS program.

Earth systems science complements the existing compartmentalized examination of Earth system components. The ESS program will offer students a synthetic, holistic approach. To do Earth System Science requires both depth in core disciplines and breadth of exposure to concepts integrating them.

We believe so strongly in the necessity of teaching Earth System Science to all McGill undergraduates that the three departments will jointly offer an elective course in Earth System Science for freshman (U0) students entitled “The Earth System” (ATOC/EPS/GEOG 104) beginning in the 2004-2005 academic year.

Objectives of Earth System Science at McGill
With the resources of several departments, we developed an Earth System Science program that prepares students to tackle global scientific problems of the 21st century. We will address six “grand challenges”, each related to a fundamental scientific problem, that are crucial to humanity. They are:

- Global cycles
- Climate variability and change
- Land use and land cover change
- Energy and resources
- Earth hazards
- Earth-atmosphere observation, monitoring, analysis and prediction

Earth System Science problems are among the most complex and challenging global issues facing society. Many students are drawn to these challenges. Providing the

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knowledge and inspiring them requires instilling a passion for research and an ability to develop practical approaches to address global problems. Imbuing students with an appreciation of the breadth of the Earth system coupled with a solid foundation in at least one disciplinary component will give students informed insight into the complex world they inhabit.

Earth System Science
The program will provide students with an integrated knowledge of how the Earth system, composed of the atmosphere, the oceans and the solid Earth, operates. Students will be taught the fundamental tools, techniques and concepts of Earth Systems Science. The program will equip students to address the six “Grand Challenges” of Earth System Science, which are listed above.

The undergraduate program will lead to either a Majors or an Honours B.Sc. degree. The latter is in draft form only. It will incorporate the core requirements of the Majors program. It requires only a higher GPA and an undergraduate research project. Both B.Sc. programs will be unique at McGill because of their integrated approach to understanding the processes of the Earth System as integrated whole.

This proposal includes five new courses (ESYS courses indicated in **bold** below; ATOC/EPS/GEOG 104 has already been approved) that will each need additional professorial staff from each of the three departments involved in the joint majors program. The best method for these joint courses to be taught is if all professors are always present in the classroom. Thus, each year, 15 professors need to be provided with teaching release time equivalent to one course. Additionally, these 15 professors will need extra teaching release time the first year the courses are offered in order to prepare for these new courses.
### Earth System Science Undergraduate Program Proposal

**B.Sc. Majors in Earth System Science**

<table>
<thead>
<tr>
<th>Required credits:</th>
<th>36</th>
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<tbody>
<tr>
<td>Complementary credits:</td>
<td>24 or 25</td>
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<tr>
<td>Total credits:</td>
<td>60 or 61</td>
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#### U1 Year

**Autumn**
- **ENVR 200** The Global Environment 3
- **ATOC 214** Introduction: Physics of the Atmosphere 3
- **GEOG 203** Environmental Systems 3
- **EPSC 210** Introduction to Mineralogy 3  
  *or*  
  **EPSC 220** Principles of Geochemistry 3
- **BIOL 215** Introduction to Ecology and Evolution 3

**Winter**
- **ESYS 200** Earth System Processes 3
- **MATH 222** Calculus 3 3
- **EPSC 212** Introductory Petrology 4  
  *or*  
  **GEOG 272** Earth's Changing Surface 3  
  *or*  
  **ATOC 215** Weather Systems and Climate 3

#### U2 Year

**Autumn**
- **ESYS 300** Investigating the Earth System 3
- **ESYS 301** Earth System Modeling 3
- **BIOL 308** Ecological Dynamics 3
- **MATH 203** Principles of Statistics (or equivalent) 3
- Complementary 3

**Winter**
- **ATOC 308** Principles of Remote Sensing 3
- Complementary 3

#### U3 Year

**Autumn**
- **ESYS 500** Earth Systems Applications 3
- Complementary 6

**Winter**
- Complementary 6
Earth System Science Undergraduate Program Proposal

Complementary Courses

18 complementary credits, taken from following lists, with at least 3 credits from each of ATOC, EPSC, and GEOG.

Courses from Atmospheric and Oceanic Sciences
ATOC 309 Weather radars and satellites
ATOC 315 Water in the Atmosphere
ATOC 412 Atmospheric Dynamics
ATOC 419 Advances in Chemistry of Atmosphere
ATOC 512 Atmospheric and Oceanic Dynamics
ATOC 513 Waves and Stability
ATOC 530 Climate Dynamics 1
ATOC 531 Climate Dynamics 2
ATOC 540 Synoptic Meteorology 1
ATOC 541 Synoptic Meteorology 2

Courses from Earth and Planetary Sciences
EPSC 312 Spectroscopy of Minerals
EPSC 320 Elementary Earth Physics
EPSC 331 Field School 2
EPSC 334 Invertebrate Paleontology
EPSC 341 Field School 3
EPSC 350 Tectonics
EPSC 423 Igneous Petrology
EPSC 425 Sediments to Sequences
EPSC 445 Metamorphic Petrology
EPSC 455 Sedimentary Geology
EPSC 519 Isotope Geology
EPSC 530 Volcanology
EPSC 542 Chemical Oceanography
EPSC 549 Hydrogeology
EPSC 580 Aqueous Geochemistry
EPSC 590 Applied Geochemistry Seminar

Possible Courses from Geography
GEOG 305 Soils and Environment
GEOG 306 Raster Geo-Information Science
GEOG 307 Socioeconomic Applications of GIS
GEOG 321 Climatic Environments
GEOG 322 Environmental Hydrology
GEOG 350 Ecological Biogeography
GEOG 372 Running Water Environments
GEOG 495 Field Studies: Physical Geography
GEOG 499 Subarctic Field Studies: Schefferville
GEOG 505 Global Biogeochemistry
GEOG 506 Perspectives of Geographic Information Analysis
GEOG 522 Advanced Environmental Hydrology
GEOG 535 Remote Sensing and Interpretation
Earth System Science Undergraduate Program Proposal

GEOG 536  Geocryology
GEOG 537  Advanced Fluvial Geomorphology
GEOG 550  Quaternary Palaeoecology

Courses From Other Units
ABEN 319  Applied Mathematics (M)
BIOL 309  Mathematical Models in Biology
BIOL 432  Limnology
BIOL 441  Biological Oceanography
BIOL 465  Conservation
BIOL 534  Theoretical Ecology
BIOL 540  Ecology of Species Invasions
MATH 314  Advanced Calculus*
MATH 315  Ordinary Differential Equations*
MATH 317  Numerical Analysis
MATH 319  Partial Differential Equations*
MATH 323  Probability Theory
MATH 326  Nonlinear Dynamics and Chaos
MATH 423  Regression & Analysis of Variance
MATH 437  Mathematical Methods In Biology
MATH 447  Stochastic Processes
MATH 525  Sampling Theory & Applications
NRSC 540  Socio-Cultural Issues in Water
PHYS 331  Topics in Classical Mechanics
PHYS 332  Physics of Fluids
PHYS 340  Electricity and Magnetism
PHYS 342  Electromagnetic Waves
SOCI 461  Quantitative Data Analysis
SOCI 504  Quantitative Methods 1
SOCI 505  Quantitative Methods 2
SOCI 580  Social Research Design & Practice
Earth System Science Undergraduate Program Proposal

ESYS 200 Earth System Processes

Course Description (50 words max):
Earth system science examines the complex, intertwined interactions among the geosphere, hydrosphere, biosphere, and atmosphere. It focuses upon physical, chemical, and biological processes that extend over spatial scales ranging from microns to the size of planetary orbits, and spans time scales from fractions of a second to billions of years.

Long:
New fields of synthetic science are increasingly emerging. Many of these fields are focused on the environment, due to the growing realization that the survival of modern civilization is linked to the fate of the environment, and that understanding environmental change requires an integrated understanding that draws upon many disciplines. One of the strongest, defined new synthetic sciences is Earth System Science. Earth System Science has emerged from the combination of new technical abilities for viewing and modeling the whole Earth with a new awareness of global environmental problems.

The Earth has been transforming itself ever since it formed. People have been altering the Earth ever since our earliest ancestors appeared, but in the 20th century humanity became a significant driver of global change. Earth system science seeks to understand these anthropogenic transformations in the context of the history and dynamics of the Earth System.

Upon finishing the course, the students will have a scientific understanding of the Earth system and how key interactions among anthropogenic, atmospheric, ecologic, geologic, and processes shape the dynamics of the Earth System.

A team of Earth system scientists from the departments of Atmospheric and Oceanic Sciences, Earth and Planetary Sciences, and Geography will teach the course. They will incorporate recent scientific discoveries, debates, and policy issues from the perspective of Earth System Science.

Course Syllabus

The Earth System: an integrated introduction (EPS/AOS/GEOG)
1. The Earth can be viewed as a dynamic, interacting system of life, soil, atmosphere, and ocean. Earth is open energetically but largely closed materially. While it incorporates life, it does not evolve in a Darwinian sense. Earth functions according to its own rules. Understanding these rules is the goal of Earth Systems Science.

Plate Tectonics (3 weeks) EPS
Questions?
Why is the Earth Blue and Green? Why are there continents? Why does the Earth move?
Topics:
2. Formation of the Earth; Location of Earth; Differences among Planets. Composition of the Earth, internal rock dynamics; volcanoes; earthquakes
3. The Rock cycle; reducing planet to oxidizing planet; origins of life Feedback loops in the earliest Earth system, stability and cyclicity versus stochasticity in
Earth System Science Undergraduate Program Proposal

the Earth system
4. Links to atmosphere (out-gassing & climate change); ocean (ocean composition & circulation); and life (biogeography; mass extinctions)
   Atmosphere far from equilibrium. Lovelock and looking for Life on Mars.
   Energy budgets of atmosphere

Ice Ages (2 1/2 weeks) AOS/EPS/GEOG
   Why are there Ice Ages?
   Why is the Earth not a ball of ice? Why is it sometimes more icy?
5. Ice in history; Snowball Earth; Past Ice Ages and Greenhouses. Why are there ice ages? Plate tectonics; Milankovich cycles.
6. Oceanic circulation and Ice Ages; flickers (Heinrich events).
7a. Effect on CO₂; effect on life.

El Niño-Southern Oscillation (ENSO) (2 1/2 weeks) AOS/GEOG/EPS
   Why isn’t the weather normal?
7b. Difference between weather & climate.
8. Coupling of atmospheric and oceanic circulation; basic climate system; atmospheric cells & teleconnections; jet stream fronts.
9. ENSO as a giant oscillator; feedbacks; cause & effect vs. emergence. Impacts of ENSO on weather, on life and on people.

Primary Production and Respiration (2 weeks) GEOG/AOS
   What is the metabolism of the Earth? Is the Earth alive?
   Keeling’s annually oscillating curve of atmospheric carbon dioxide in Hawaii reflects the alternating photosynthetic and respiratory cycles of continental vegetation in the Northern Hemisphere. Why do we see these dynamics? The answer involves Earth’s orbit, plate tectonics, climate, and biomass.
10. Coupling between biosphere and atmosphere; N-S gradients in CO₂ oscillations; Gross and Net Primary Productivity
11. Regional coupling; ecological appropriation
   Human action and vulnerability, largely at the regional level.
   Coupling of atmosphere and vegetation. Cases of urban environments, deforestation.
   Vulnerability: ability to cope with and adapt to change.

Week 12: Transformations of the Earth System (EPS/AOS/GEOG)
   Transformations in the Earth System: co-evolution (EPS/AOS)
   Co-evolution of life with the geosphere and the hydrosphere. Changes in atmosphere, changes in weathering rates, biogenic production of calcium carbonate; changes in C fixation (C3, C4)

Week 13: Transformations in the Earth System: People (GEOG)
   The Anthropocene: Earth as transformed by human action; greenlash
   Human Dimensions of Global Change; vulnerability and adaptation.
   Understanding human impact: industrial ecology & material flows, ecological appropriation, land use land cover change, and modification of global biogeochemical cycle
   Geoengineering and its dangers. Who owns the Earth? Kyoto, Montreal, etc…
Earth System Science Undergraduate Program Proposal
ESYS 300 Investigating the Earth System

Objective: This course provides students with an understanding of the fundamental physical, chemical and biological processes of the Earth system and how different components and reservoirs of the system interact. Interactions between reservoirs and the mechanisms that control the interactions will be discussed and quantitatively investigated. A special emphasis will be placed on studying the development and response of the Earth system and its reservoirs to perturbations.

Lecture 1
Introduction
Scope of the course including illustrations of which factors of the Earth system will be covered in the course.

Lectures 2-7
Reservoirs in the system
Overall bounds for the system (radiation, water, etc.)
Types of reservoirs (physical, chemical, biological)
Fundamental chemical and physical properties of the reservoirs and how we characterize them
Changes in the reservoirs through time. Timescales of change

Lectures 8-17
Interfaces and interactions between reservoirs
Biogeochemistry and physics of the interactions
examples include, but are not limited to: lithosphere/hydrosphere, atmosphere/ocean, biosphere/atmosphere, biosphere/lithosphere
Diffusion and propagation
Stability/instability
Development of perturbations, thresholds and extremes in the Earth system
Linear vs. non-linear response to perturbation

Lectures 18-26
Putting it all together
Whole system: Integrated global examples (typical, unusual cases and feedbacks)
Regional examples and their comparisons: Integrated regional examples (variety of systems from cold to hot, etc.)
Extremes on global and regional scales (development and roles involving all components of the Earth system, e.g. Drought)
Time and space scales of global and regional responses through physical, chemical and biological examples
Stable and unstable features and states of the Earth system

Textbook

Marking:
Problem sets 20 %
Term paper 30 %
Midterm exam 20 %
Final exam (cumulative) 30 %
Key concepts:
Systems: boundaries, components, connections; (in)stability; feedback loops;
The course will begin with lectures on the theory and practice of modeling. Following
this, the remainder of the course will be conducted in a computer laboratory where
students will interactively create and analyze Earth System Science models.
Enrollment probably limited to less than 40 due to lab space.

Course organization:
Four themes: mass balance, negative feedback, positive feedback, fast/slow dynamics
1) Mass balance
System definition
J. Harte type back of the envelope calculations– estimation of fluxes: e.g. amount of
water on earth; heat flux; water flowing through watershed
2) Negative Feedbacks
Stability
Homeostasis (e.g. Daisyworld, C cycle)
Dampening, overshoot, oscillations
3) Positive feedback;
Resilience; alternative stable states
e.g. Abrupt climate change; fire and vegetation interactions; coral reefs
4) Coupling of cycles (fast/slow dynamics)
e.g. CO₂ and different uptake rates; ocean and atmospheric
e.g. eutrophication and soil P change

Method:
The course combines lectures on modeling with instruction in a computer laboratory
where students interactively experiment with systems models. Students will recreate and
analyze existing models that illustrate how different topics in Earth System Science can
be viewed from a modeling perspective. They will use Stella modeling software to create
and analyze models. This approach allows students to focus on model concepts without
requiring them to learn a programming language.
During the course, students engage in a small group (5-6 students) project and will write
a report that critiques an existing computer simulation model. This project will enable
students to explore and discuss an Earth System Science model in depth, and learn how to
write a group report.
Homework: For each module, students will be given a set of homework questions that
will require them to use Stella to reproduce and then analyze a computer model that
explores the dynamics discussed in each module. The goal of these homework
assignments is to develop student’s individual ability to create and analyze models.
Tests: There will be two short tests that will cover basic modeling concepts and systems
thinking. The first will be midway through the course, after the first two modules, and
the second at the end of the course, following the final two modules. These tests will
evaluate the student’s understanding of modeling concepts.

Evaluation
Model Critique 20%
Tests 2 x 10 20%
Homework 4 x 15 60%
ESYS 500 Earth System Applications

Objective: This is the “capstone” course in the ESYS program, which draws together what has been learned in the other courses. The course will focus on projects, either individual or group, which draw upon the evolving interests of the students and on the faculty teaching the course.
In particular, these projects will address the six “Grand Challenges” that are fundamental scientific problems crucial to humanity. These are: the global water cycle, climate variability and change, land use and land cover change, energy and resources, earth hazards, earth-atmosphere observation, monitoring, analysis and prediction.
Combining instructor and student interests, projects will be designed to contribute to these issues, through the integration of literature reviews, experiments and modeling. Students will undertake two projects, one jointly with other students and the other an individual project. In both projects, integration of what has been learned in the program with specific issues will be stressed. Both projects will be presented to the class, to inform others and to gain experience in presenting research material.

Suggested marking scheme:
Joint project: Overall project 20%
Individual contribution 20%
Individual project: 40%
Oral presentations and general class participation: 20%