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# Health of the Discipline Statement for Earth Science

*The NSERC*
*Earth Sciences Committees*

## OVERVIEW

The solid Earth, the land surface, the hydrosphere, atmosphere and their constituent organisms are strongly interacting systems. For the past 200 years, there has been a steady growth of subdisciplines working within each of these systems. However, it is only in the past decade that quantitative integrated study has become feasible. Four factors have caused this recent development. Firstly, the global theories of plate tectonics and mantle convection have provided a theoretical framework for subdisciplinary work. Secondly, the deployment of remote sensing systems has revolutionized our view of the Earth; the surface of the planet is mapped at moderately high resolution, and the floors of oceans, seas and great lakes are also known at scales adequate for many purposes. Thirdly, increased computing power has stimulated global modelling in such areas as heat flow, climate and ocean circulation. Lastly, and perhaps most potent, is the realization that anthropogenic processes may be forcing overly rapid and unnatural change to many of the more fragile environments.

There are other themes of national significance. Canada is the largest country in the world. Half of its land area is Arctic and sub-Arctic, constituting 25% of all ice-free Arctic and sub-Arctic terrain on the planet, and exhibiting geological and ecological features that are truly unique. We cannot afford to waste the scientific opportunities offered by these resources; to do so would be globally irresponsible. In addition, we have a small population in a vast country; the most tangible evidence of sovereignty is the scientific study of the land that is Canada. This should have high national priority.

The recognition that Earth systems are not independent of each other raises the spectre that human activity may trigger disastrous and irreversible change. Ozone depletion, acid rain, loss of agricultural land, deforestation, groundwater contamination, oceanic pollution, global warming, and sea-level rise are not simply matters of scientific study, they are matters of deep concern for the future of the human race. Only scientific study can provide an understanding of these systems; without this, it will be impossible to predict and manage future change.

In order to respond to the challenge of society and its interaction with the Earth, a three-pronged attack is required:

1) We must be able to characterize environmental change as it occurs. Consequently, extensive field programs with sophisticated field instrumentation are essential; without them, we lack even the basic data. The geographic and climatic ranges of Canada mean that we are in an ideal position for such programs, but their magnitude provides significant logistical and financial problems.

2) Extensive field sampling requires extensive supporting analytical facilities, particularly in the areas of trace-element and isotopic analysis. We have the expertise, but we do not have the necessary instrumental resources or supporting infrastructure.

3) Amelioration or prevention of environmental degradation involves being able to predict the results of specific actions or processes. This involves building models based on the field and lab results of 1) and 2), and then using these to simulate numerically the effects of system perturbations. The community has the expertise, but the massive computational requirements of such a program far outstrip our current capabilities.

This effort needs significantly increased multi-disciplinary work on a large scale if the earth sciences are to develop a truly integrated view of the Earth, and to respond to the scientific and social demands posed by the increasing impact of society on the environment.

## DETAILED REVIEW

The Earth consists of six principal units: the core, the mantle, the crust, the land surface, the oceans, and the atmosphere. Historically, studies of these units have evolved as separate disciplines. However, the advent of plate tectonics as a unifying theory of the Earth, together with the current concern about global-scale environmental issues, have led to the integration of geological sciences, geophysics, physical geography, oceanography and atmospheric sciences into a single entity: earth science. There is a great intellectual challenge to understand Earth processes on a global scale. The urgency of much of this work is greatly increased by the immediacy of current environmental problems as society struggles to minimize the adverse environmental effects of human activity. Brief synoptic reviews of the principal units of our planet are given below. However, it needs to be emphasized that key work now transcends unit boundaries, and we are seeing a very rapid increase in the scale and multi-disciplinary nature of earth science activities.

## CORE

### *Current Status*

Although the Earth's deep interior is less accessible to direct observation than the far reaches of outer space, great advances have been made in recent years in inferring its properties from surface observations. The outer core is fluid, as evidenced by its inability to transmit seismic shear waves; in contrast, the inner core is solid. Studies of meteorites suggest the core to be primarily iron, and this is in accord with the bulk properties of the Earth. The outer core convects, typically with velocities of about one centimetre/year, and being electrically conducting, generates the geomagnetic dynamo. Conceptually, the origin of the dynamo is understood, but the actual mechanisms are matters of acute controversy.

Mechanical and thermal coupling between the core and overlying mantle contribute to a wide range of terrestrial phenomena: short-term changes in the length of the day, long-term polar wander, and the generation of topographic and thermal irregularities at the core-mantle interface. These irregularities may govern the frequency of reversals of the Earth's magnetic field, and cause the rise of molten material (mantle plumes) from the base of the mantle; they are the ultimate driving force of plate tectonics.

### *Future Directions*

While significant progress has been made on determining decade-period flow patterns in the outer core by inverting geomagnetic secular variation data, shorter period motions in the Earth's core can only be inferred from very precise measurements of fluctuations in the gravity and magnetic fields at the Earth's surface. Canada is developing two state-of-the-art installations capable of providing precise geodynamic data. A super-conducting gravimeter has been installed at the Absolute Gravity Station outside Ottawa. Observations will test the existence of oscillations in the Earth's fluid outer core, and provide more information on the decade-scale motions inferred from magnetic data. The Long-Baseline Interferometer involves the radio observatories at Penticton, British Columbia, and Algonquin Park, Ontario. Determination of the propagation and time delay of microwave radiation emitted by quasars between the two sites will reveal short-term changes in the magnitude and direction of the Earth's rotation, and provide information on global-scale tectonic motions. Major advances in our understanding of the properties of the core are expected in the next few years.

## MANTLE

### *Current Status*

The mantle surrounds the core; it transmits seismic shear waves and is rigid on short time scales. Over geological time scales, it convects with velocities on the order of one centimetre/year. The mantle is composed primarily of crystalline silicates of magnesium and iron, which undergo phase transitions as depth increases; hence, the mantle is layered. The upper layer is where substantial partial melting occurs, and is the source of much volcanic activity at the Earth's surface. Plate tectonics portrays this upper layer as a soft substratum on which the crustal plates move. Hot upper mantle material wells up at ocean ridges where the lithospheric plates move apart; it forms new oceanic lithosphere, which continues to move sideways from the ocean ridges. Eventually, the oceanic crust cools, becomes more dense, and sinks back into the upper mantle along subduction zones.

### *Future Directions*

To understand deep-seated processes, it has become imperative to know about the properties and behaviour of minerals under conditions that are present in the deep mantle and core. This has led to a major thrust to calculate the physical and chemical properties of minerals under specific external conditions. Theoretical models of the electronic structure are developing rapidly, and are becoming reliable for simple common minerals. These advances are paralleled by detailed measurements of physical properties to test the reliability of theoretical models. These also provide constraints on geophysically derived models of the mantle and core and, in turn, geophysical measurements also provide checks on the validity of the calculations.

Simulating high-temperature and high-pressure conditions deep within the Earth is a major endeavour in the earth sciences. Canada has one of three laboratories in the world in which ultra-high-pressure experiments are capable of simulating virtually any conditions within the Earth's mantle, a key feature of deep-Earth studies. Recent work has shown that there is inversion of density differences between melts (magmas) and minerals with increasing pressure. This may have resulted in "magma oceans" deep within the mantle, both today and early in the Earth's evolution. This magma ocean concept has major implications for ideas of how crust was originally formed and stabilized on the Earth and other planets.

## CRUST

The lithosphere comprises the Earth's crust and the solid upper mantle. It varies in thickness from 0 at the ocean ridges, to an average of 100 km below the continents. The crust is approximately 8 km thick beneath the oceans, and 30-70 km thick beneath the continents. A significant feature of Canadian research on the crust is the continuing megaproject, LITHOPROBE. This focusses a wide array of techniques on specific transects of the crust that are of particular tectonic interest. The program has been underway for approximately five years, and has had a major impact on our understanding of crustal processes and the geological evolution of Canada.

### Basement Crust

#### *Current Status*

The oldest part of the Earth's crust is in the northwest Canadian Shield (almost 4 billion years old). The initial Earth's crust resulted from melting and differentiation of the mantle, and has since been recycled by heating, melting, remobilization and weathering associated with mountain building. The source and age of emplacement of magmas of both mantle and crustal origins can be tracked using stable and radiogenic isotopic tracers, and trace-, minor- and major-element geochemistry of rocks and minerals. As mountain chains are uplifted, cooled and eroded, their mineral constituents re-equilibrate as temperature and pressure regimes change. These paleo-pressure and -temperature (PT) regimes are recorded by different metamorphic minerals. Coupling this information with geochronology, we are now able to decipher the paleo-thickness of crust, and the rates of uplift and erosion of ancient mountain belts.

The physical make-up of Canada offers an unrivalled natural laboratory: the largest expanse of Precambrian shield in the western world, flanked by two younger mountain belts, the Appalachians and the Cordillera. Great strides are being made in understanding the formation of continental crust, and the western and eastern LITHOPROBE transects are now providing a long-awaited look into deeper-seated parts of both ancient and modern (active) tectonic zones. These provide the opportunity to model and predict the role of water in crustal-scale fault zones, the thermal response of the crust to large-scale upheaval, and the response of the lithosphere to change in thermal structure. In addition, the lower crust has an electrical conductivity that is between one and three orders of magnitude greater than that expected from experiments on dry rock of lower crustal composition. The lower crust is also characterized by prominent sub-horizontal seismic reflectors, and much current discussion is focussed on the role of fluids *versus* carbon films as the cause of both phenomena.

#### *Future Directions*

High-resolution geochemical, geochronological, geophysical and tectonic techniques will be used to probe the crust to greater depths to gain understanding of modern and ancient subduction and accretionary processes. Models of crustal structure that emerge from LITHOPROBE transects will be tested, possibly by deep drilling and detailed surface mapping. In addition, it is critical that there be more laboratory measurements of seismic velocities in rocks at very high pressures and temperatures if we are ever to understand the physical characteristics of the prominent sub-horizontal seismic reflectors of the lower crust. More emphasis is needed on the deformational behaviour and physical properties of rocks, especially in the transitional semi-brittle to semi-ductile field, which is necessary to understand and predict deep seismic activity. More than 10% of Canada's population live under the threat of a major earthquake in British Columbia, a major social hazard requiring serious study.

### Sedimentary and Organic Record

#### *Current Status*

The sedimentary and paleo-biological records are inexorably intertwined. A powerful impetus for their study is the recognition that understanding past events is essential to test models and serve as indicators for future environmental change. Studies of periodicity of extinction, sedimentary cycles, and changes in latitude have provided data that give a long-term perspective to our understanding of global change, and complement the shorter-term views provided by surficial, oceanic and atmospheric studies.

Many of Canada's hydrocarbon-rich basins have been reinterpreted from the viewpoint of sequence stratigraphy. Diagenetic studies of minerals and documentation of the fluid history of basins have been vital in understanding the formation and migration histories of hydrocarbon and mineral deposits. Recent studies on modelling past climates have recognized that the influence of continental hydrological systems on oceanic circulation patterns may be recorded by late Quaternary terrestrial sediments, the best examples of which occur in Canada.

Interest in biogeographic distributions and global tectonic events remains strong. Canada has unrivalled occurrences of fossils, particularly from the Arctic and sub-Arctic regions. Much effort is devoted to taxonomic, biostratigraphic and paleoecologic studies. There are major fossil biotas still to be described, and these will provide major contributions to the interpretation of extinctions, evolutionary radiation, and past environmental change.

#### *Future Directions*

There is rapid expansion in attempts to understand past global events as recorded in sedimentary basins. In particular, future work will involve much greater integration of evidence from fossil biota, from physical and geochemical composition of sediments, from geochronology, and from magnetic reversals, focussing specifically on catastrophic change.

Such work is crucial to our understanding of the Earth and to our future. Because of Canada's enormous land area and abundant sedimentary basins, we have the opportunity and obligation to manage our landmass to ensure our future. The proxy record will therefore be examined in increasing detail to determine the nature and rate of change at periods of biotic catastrophe. Much emphasis must be devoted to Quaternary bio-events. However, other intervals in the geologic record indicate shifts from icehouse to greenhouse climate, and comparison of these events with the Quaternary period is critical to ensure the generality of our global models.

### Mineral and Petroleum Resources

#### *Current Status*

The input of heat into continental crust through magmatism and tectonic loading is usually accompanied by the loss of fluid originally incorporated into the rocks during sedimentation and low-temperature fluid-rock interaction. How these fluids migrate, how metals are carried in solution, what controls the location of hydrocarbons, and the precipitation of ores in different tectonic regimes, are all fundamental questions currently under attack. A major recent finding is the recognition that there can be fluid flow to great depths within the lithosphere, along the deep faults that mark the boundaries between segments of the lithosphere, and in basins produced as a result of differential loading. Changes in temperature and pressure, and the interaction between fluids of differing composition can result in the formation or modification of ore deposits. Fluids that are produced deep within the lithosphere from dehydration of rocks and minerals can migrate toward the top of the lithosphere, and precipitate gold, silver and other important metals. Much current work is focussed on the origin of such deposits, ancient and present-day hydrothermal systems, water-rock reactions, and fluid flow in the lithosphere.

The intensive exploration for hydrocarbons in the western Canada sedimentary basin and the frontier offshore basins has resulted in major advances in our knowledge of the formation and evolution of sedimentary rocks. Structural and stratigraphic controls of fluid flow and their impact on such areas as salt migration and dolomitization have been receiving increased attention, and will play a significant role in future hydrocarbon exploration strategies.

### *Future Directions*

As yet, we know very little about the structure and stability of metal complexes in hydrothermal fluids. Experimental and theoretical work in this area will be of great importance to our understanding of ore transport and deposition mechanisms. This must be coupled with field observations focussed on small-scale processes operative at sites of ore concentration. The source of many ore-forming hydrothermal fluids is deep in the lithosphere. The evolution of pressure and temperature within these deep regimes is key to our understanding of dissolution and long-range transport mechanisms, and requires coupled tectonic and geochemical work. For parts of the Canadian Shield and the Cordillera, such studies should afford refinement of exploration strategies for metallic ore deposits. For the sedimentary basins in Canada, such studies will be of assistance in identifying undiscovered petroleum reserves. In addition, the impact of basement structure on the creation of traps and conduits for fluid flow will have a major effect on future exploration strategies.

The evolution of sedimentary basins is an important aspect in the development and preservation of hydrocarbons and certain ore deposits such as potash, uranium, lead-zinc, and kaolin. Minerals within basins are susceptible to alteration by fluids which pass through the basin and, in turn, the fluids are altered by the same process. The entire pressure, temperature and timing of these fluid-flow events are recorded in the minerals within the basins. Future studies must involve unravelling the complex fluid histories of these basins so that those favourable to both the generation and preservation of ore and petroleum deposits can be identified and assessed as to their economic potential.

## LAND SURFACE

Interactions of the atmosphere, biosphere, hydrosphere and lithosphere at the Earth's surface are the central processes of environmental science, and fall squarely within the domain of earth science. The recent public and political interest in environmental questions has caused a major expansion of work in this area. This focusses not only on current environmental issues, but also on the evolution of ecosystems during the Quaternary Period (the last 1+ million years), as it is difficult to evaluate the significance of current change without long-term perspective. A wide variety of programs in environmental science are now offered at the undergraduate level in many universities, and there is rapid expansion in graduate studies in this area.

### Fresh Water

#### *Current Status*

Of particular interest to society at all levels is the study of the spatial and temporal character of the Earth's water balance, and the physical and chemical processes associated with the cycling of water on the planet. Per capita, Canada has the world's greatest supply of fresh water, and has a long tradition of major engineering projects associated with water resource development. However, in the last 15 years, there has been a shift away from the technological aspects of resource exploitation toward the more scientific aspects of the hydrological cycle.

Studies of the chemical, physical and biological aspects of the water cycle have gained momentum from emerging concerns for the long-range transport of atmospheric pollutants, the acid rain problem, and the contamination of rivers, lakes and groundwater resources by urban and industrial wastes. Topics particularly germane to Canada include snow chemistry, acid shock from snowmelt, infiltration and soil moisture in temperate and permafrost zones, groundwater movement, energy and mass balances of snow and ice, sediment erosion and transport, and salinization of agricultural soils. The importance of groundwater behaviour has become apparent with the onset of innumerable environmental problems (*e.g.*, landfills, gasoline tank leaks, water supply quality, low-level and high-level radioactive waste disposal).

#### *Future Directions*

There is growing recognition of the importance of co-ordinated programs to provide integrated descriptions of hydrological, meteorological and ecological processes on a wide range of spatial and temporal scales; the remarkable variability in the occurrence of water in the terrestrial environment cannot be understood without them. Progress in the interpretation of global circulation models to understand the nature of environmental change is currently stymied by the significant mismatch between the resolution of such models and the scales of natural variability of hydrological processes on the land surface. This problem is of major importance because water is the major mediator of the impact of climate on ecosystems, including human societies. The development of commensurable models of climate and of large-scale hydrological behaviour is an important topic that has scarcely been addressed as yet.

Understanding of fluid flow, solute transport, and water/rock interactions in the immense variety found in Canada is essential for sound environmental management. Two themes of continuing importance are the transport and fate of toxins and carcinogens (including pesticides, solvents and gasoline) in rivers, lakes and shallow aquifers, and the transport of all contaminants in deeper fractured or cavernous rock masses and glacial deposits. There is increasing realization that such processes are strongly mediated by microbiological interactions; the need for co-ordinated multi-disciplinary work on this topic is urgent.

### Landforms

#### *Current Status*

Canada has a great diversity of landscape types, due to the size of the land surface and the relative youth of many of its landforms (for reasons of glacial and tectonic influences). Interest in landforms stems from the many physical constraints imposed on human activities by such events as landslides, floods, glacier instability, and coastal regression. Of particular significance are geotechnical studies of landslides and rockfalls in the Canadian Cordillera, fluvial sediment transport and sediment budgeting, and coastal processes in the Great Lakes and the oceans.

The common linking factor is a concern with the genesis, form, physical properties, and stability of Quaternary materials. A major focal point of research is environmental change, as reflected in both the pace of landform development and the associated sedimentary record. Studies on time scales ranging from a few years to ten millennia have allowed an assessment of the relative influence of glacial processes, climatic fluctuations, and recent anthropogenic disturbances on landform development in Canada.

***Future Directions***

In the Canadian Cordillera — the most rapidly changing Canadian geomorphic region — much work is still needed on the present-day dynamics of rivers, hillslopes and glaciers, particularly with regard to linkages between these processes. In Arctic and sub-Arctic environments, extensive studies of periglacial processes and landforms are required. These environments are particularly responsive to climatic and anthropogenic change, and their detailed study will allow the past and potential impacts of global change to be characterized, modelled and anticipated.

**Soil Science**

***Current Status***

Soils are thinner in Canada than in many other countries, primarily because of low rates of soil formation due to unfavourable climatic conditions. As our soils are thin and fragile, they are easily degraded. Loss of organic matter, erosion, salinization, compaction and acidification currently cost the country billions of dollars annually due to loss of productivity and increased production costs.

The understanding of soil formation in temperate and Arctic regions is of particular importance to Canada. Soil formation processes have been studied in relationship to landscape, with emphasis on organic carbon dynamics, hydrological processes, and the resultant consequences for soil fertility. Recognition and documentation of soil degradation processes are essential, and have been instrumental in developing simulation modelling as an important predictive tool for soil management.

***Future Directions***

Emphasis will shift from data gathering and description to a more detailed understanding of soil formation and alteration processes. Inventories of soils, climate and landscape must be used to improve soil management systems for agriculture and forestry. Nutrient and tillage systems that avoid or minimize soil degradation, environmental pollution, and economic risk must be developed. Processes at the surfaces of mineral and organic materials must be characterized at the atomic level if we are to understand solute transport, release of greenhouse gases, chemical kinetics, and microbial processes. The role of soil micro-organisms in reclamation of soils and subsoils contaminated by organics will become increasingly crucial, as well as their role in stabilizing atmospheric $CO_2$ into humus, stabilization of soil structure, nutrient uptake by plants, and the control of root diseases. Based on a better understanding of such mechanisms, computer modelling will shift from using semi-empirical relations to more fundamental processes at the microscopic level.

**Biological Interactions**

***Current Status***

The surface of the Earth provides the substrate for life while itself being shaped by biological activity; the resultant interactions are a fundamental part of earth science. There is a direct linkage between the physical features and processes of earth science and the biological components of the environment that are also in the domain of life science. Further development of this linkage is essential if we are to adequately assess and manage the impact of human activity on the environment.

Modern relationships between organisms and the environment provide key knowledge in the reconstruction of past environments using the paleoecological record. These data include pollen, plant macrofossils, invertebrates, insects, diatoms and dinoflagellates, and tree-rings. In order to successfully investigate the evolution of landscapes and associated flora and fauna over such long time-scales, it is necessary to integrate knowledge of the atmosphere, the Earth's surface, and the solid Earth, along with expertise on the properties and functions of ecosystems.

***Future Directions***

Many areas of Canada remain *terra incognita*. Work is required in almost all ecosystems of Canada, but is particularly important in the Arctic, the prairies, and parts of intermontane and coastal British Columbia. In all regions, more detailed analysis of present relationships between organisms and the environment, and paleoecological studies with greater spatial and temporal resolution are required to address the complex questions being generated by disturbance ecology, landscape ecology, glacial and periglacial geomorphology, and paleoclimatic modelling.

The ever-growing concern regarding the impact of human activity on the environment provides a particularly strong impetus for increased research in Canada. Studies of diatoms have proven a very effective means of elucidating the impact of such anthropogenic disturbances as acid rain on lake ecosystems. Fossil pollen analysis provides one of the most practical means of acquiring empirical information on the possible long-term response of ecosystems to climate warming. Tree-ring analysis contributes vital information on both the natural range of climatic variation during the last 1000 years and on the impact of atmospheric pollutants and climate warming on the growth and reproduction of forests in the future. This emphasizes the direct link between the Earth, life and social sciences that is required to tackle the pressing questions of anthropogenic disturbance of the environment.

## OCEANS

The critical role of the ocean in moderating climate change, and the growing evidence for global sea-level rise, have added new areas of research to the more traditional topics of fisheries productivity, contaminant dispersion, ocean-atmosphere exchange processes, ocean circulation dynamics, and coastal-zone development.

***Current Status***

During the last 15 years, the study of the oceans has undergone rapid change, driven by technological advances and the greatly increased need for improved understanding of ocean dynamics. Technological developments, particularly in miniaturized low-power digital electronics, have made possible a wide range of new and powerful tools: supercomputers, workstations and microcomputers, satellite-borne instrument systems for passive and active measurements of the ocean surface, and accurate and reliable instrumentation for subsurface measurements from ships, submersibles and long-term moorings. These advances have allowed much more comprehensive experiments at sea, and the development of improved dynamic models.

The recent increase in demand for oceanographic knowledge was due, initially, to the requirements of offshore petroleum exploration, added to those of traditional users (the fisheries and naval defence). Subsequently, heightened concerns regarding the effects of greenhouse gases on global atmospheric temperatures, coupled with the recognition of the key role played by the ocean with respect to weather, climate and atmospheric chemistry, have increased the demand for information on the behaviour of the ocean system. The result has been a proliferation of large-scale international scientific programs. Such programs are a traditional part of oceanography because of the large physical scale of the system. However, the style of more recent programs is changing because of the increasingly important roles of mathematical modelling and the interdisciplinary nature of research required to answer key questions of interest. Thus, to determine the role of the ocean as a control on the rate of $CO_2$ build-up in the atmosphere, the pathways and rates of carbon transfer in the ocean need to be determined. This requires the combined inputs of geochemistry, geophysics, sedimentology and biology. Ultimately, it will be geological studies of past climate change on much longer time scales that will help test such global models and complete the understanding of global climate change.

### *Future Directions*

Principal scientific concerns will be the non-linear feedback mechanisms and thermohaline processes that effect the transfer, redistribution and storage of heat, greenhouse gases, and other substances in the oceans. The problems of oceanic heat transport, mixed-layer dynamics, and primary productivity will continue to dominate oceanic research. The pathways of freshwater flux, anthropogenic carbon, and chemical contaminants within the ocean need to be satisfactorily defined. Refinement of both conceptual and numerical models of the ocean's role in quasi-periodic interannual climate phenomena (*e.g.*, El Niño) is urgently required. Global sea-level rise associated with melting of land-based glaciers, regional tectonic processes, and the storage of heat in the ocean will continue to be of vital concern. The establishment of a world-wide sea-level monitoring network and the development of satellite-based levelling systems are essential to future sea-level research.

Continued improvements in satellite technology will allow more detailed examination of oceanic frontal zones, eddy variability, wave phenomena, and coastal upwelling zones. Proper management of coastal-zone resources requires further observation and modelling of upwelling dynamics, cross-shore exchange mechanisms, and bottom boundary-layer processes. The links between primary and higher trophic levels, such as fish, still need to be understood and quantified before stock productivity models can be reliably applied. Virtually nothing is yet known about offshore fisheries' productivity or the trophic interactions of organisms living in proximity to hydrothermal vents. Until recently, oceanic resources have been treated as inexhaustible. The dwindling northern cod stocks off the coast of Newfoundland provide a vivid example of the serious socio-economic disasters that may confront Canada, without adequate management of our natural resources.

## ATMOSPHERE

Recent awareness of climate and global change issues, acid rain, toxic chemicals in the atmosphere, and the hazards of severe storms have added new areas of research to the more traditional topics of weather forecasting, climate, boundary layer physics, cloud physics, and satellite and radar meteorology.

### *Current Status*

There is now a consensus that our climate is warming due to increased greenhouse gas emissions. However, the amount and rate of warming are open to debate, and the global climate models predicting these changes are evolving rapidly. In order to reduce uncertainties in global climate models, they need to be improved in the areas of ocean/land/atmosphere interactions and associated physical and chemical processes. These are now under active development, being driven by the need to improve the Canadian climate model of the Atmospheric Environment Service. This model will enable Canada to make more informed decisions regarding the impact of climate change.

Atmospheric chemistry is currently focussed on acid rain, toxic chemicals in the atmosphere, stratospheric ozone depletion, biological damage from increased oxidant levels, Arctic haze, and chemical instrumentation. There is growing international concern about rapid atmospheric chemical change and its potential impact on mankind. This has resulted in many international field projects documenting the atmospheric chemistry of particular regions, surface networks of chemical instrumentation, measurements from aircraft, balloon flights into the stratosphere, and instrumentation on board space shuttles. These have had a major impact on our knowledge of atmospheric chemistry in high-latitude regions.

Instrumentation is evolving rapidly, particularly in the areas of computer hardware and software. Reliable instrumentation, capable of measuring trace constituents at very low concentrations, is being developed and used in many field projects and at monitoring sites. New-generation weather radar systems using Doppler and polarization techniques are now being used with software necessary for the interpretation of the data. Other surface-based remote sensing devices, such as wind profilers, lidars (laser sounders), and acoustic sounders, are also being developed. Satellite-based instrumentation is producing data on a global scale, but the satellite imagery requires more sophisticated interpretation techniques and, in some cases, more extensive land- and sea-based verification.

Weather forecasting research and basic studies in tropospheric and stratospheric processes continue to be the backbone of atmospheric research. Without new knowledge in these areas, it would be very difficult to further develop such high-profile topics as climate change and atmospheric chemistry. Environment Canada has recently acquired the NEC supercomputer in Montreal, and Canada is now making great progress in developing state-of-the-art weather forecasting models. Using the latest data assimilation and numerical modelling techniques, it should be possible to improve our long-term forecasts, with accurate predictions for five days and beyond. The trend is also toward simulation of smaller-scale phenomena, with length scales of less than 50 km. In order to better understand these smaller-scale phenomena, supporting field projects are of critical importance.

***Future Directions***

Future work will involve sophisticated numerical models of Canadian and global weather, climate and air quality, with an emphasis on accurate prediction for smaller scales than has been possible in the past. This requires the largest supercomputers available, as well as improved schemes for parameterizing the physics and chemistry of these models. The ability to improve our knowledge about the atmosphere also requires new instrumentation that is currently being developed. Field projects that normally use such equipment are far beyond the capacity of single scientists or institutions. Large-scale co-operative projects are required, and many of these will be international in scope.

Canada must be in a better position to respond to environmental emergencies such as Chernobyl, Hagersville, Mount St. Helens, and the Kuwait oil fires. Rapid prediction of the impact of such events on Canadians is now being demanded. This requires increased research on global and regional models, particularly with regard to the unusual perturbations associated with natural and anthropogenic disasters.

## CONCLUDING NOTE

This report on the Health of the Discipline for Earth Science has been prepared with input from all members of the Solid Earth Science and the Environmental Earth Science grant selection committees and the Group Chairman. It has been written in a form readable by a wide audience, with some explanation of the nature of our planet and the nature of current and future research initiatives.

The great geographical variety and extent of Canada has allowed its earth scientists to make contributions to international scholarship that are out of all proportion to their small numbers. They have done so both as individual creative scientists, and as key participants in the many national and international programs that are essential if we are to truly understand the Earth and its global behaviour. The role of the federal government in maintaining research agencies with national mandates (*e.g.*, AES, CCIW, EMR), and in promoting curiosity-driven research through NSERC support to university researchers has been central to this achievement.

Given the space limitations, the report focusses on the scientific issues within our discipline. Our principal concern as earth scientists is to continue the development and integration of many hitherto disparate disciplines into a single unified view of the Earth. Not only is this exciting and essential for the development of our science, but it is crucial if we are to be able to solve the critical problems arising from the increasing impact of society on our environment.