CHAPTER 3

CURRENT STATUS AND PREDICTED DEVELOPMENTS AND TRENDS IN THE GEOSCIENCES

The future of the geosciences cannot be considered fully unless it is placed within the context of the current status of the discipline. Further, some earlier reviews focus on peripheral issues as opposed to the changes occurring in the actual discipline. This chapter attempts, allowing for necessary brevity, to outline the current scientific aspects of the component shells that comprise out planet (core, mantle, crust, biosphere, oceans, atmosphere). Since research is a dynamic intellectual process, this current status is expanded to include comments on predicted developments and trends in the geosciences.

The terrestrial planets, those nearest the Sun, are all chemically differentiated. The size of a planet, the source and magnitude of its energy sources, and the nature of the differentiation, are the basic factors that control the evolution and functions of a planet. The Earth is large enough so that much of the primordial heat energy remains from accretion and from gravitational preparation during differentiation. This initial energy, plus the continual addition of heat from the radioactive decay of elements distributed through the body of the Earth, keep the interior hot enough so that melting occurs locally and convection operates through most of its mass.

At the centre of each terrestrial planet is a dense metallic core and surrounding it is a thick mantle of silicate-rich rocks. In the case of the Earth the mantle is capped by a thin, highly-differentiated crust enriched in light elements such as aluminum, sodium and potassium. On and above the crust are even more highly differentiated zones, the biosphere, the hydrosphere, and the atmosphere. In this section we briefly discuss each of these compositional zones. Because this discussion is presented with Canadian interests in mind, we have consulted extensively the review articles by Crossley (1993), Hoffman (1993), Ludden and Francis (1993), Nowlan (1993), Mayer (1993), and Peltier (1993), each of which appeared in *Geoscience Canada* vol.20, no.3. Many of these aspects are also considered in the US NRC Report (National Research Council, 1993) and in the NSERC Allocation Report (Appendix 1).

3 (a) Core

Silicate-rich rock in the crust and upper mantle has a density near $3g/cm^3$. Under compression the density of a silicate rock increases, but the increases, even up to pressures postulated for those at the base of the mantle, are less than the overall density of the Earth, $5.52g/cm^3$. To account for the density disparity a metallic core has long been postulated. Geochemical evidence, such as the cosmogenic abundance of elements, and the existence of iron-nickel meteorites, has led to the near universal acceptance of the hypothesis that the Earth's core must be largely metallic iron with an admixture of several percent of nickel. However, high pressure melting experiments suggest that an entirely metallic core would be a little too dense and that a small admixture of some lighter elements must therefore also be present; likely candidates are oxygen (as FeO), sulfur (as FeS) or elemental silicon. The exact composition of the core therefore remains uncertain, but the importance of the core in many of the Earth's processes is certain.

Core studies are not undertaken for their immediate societal relevance or foreseeable economic gain. They are undertaken as a matter of enquiry into the innermost workings of our planet. Such studies must be carried out remotely using such tools as seismology, geomagnetism, geodesy, and high pressure physics.

Seismology

Seismology provides most of the data concerning the elastic (thermal) properties and from the elastic properties both the thermal and the compositional structure of the Earth can be inferred. However, seismic studies can only provide a snapshot of the Earth's thermal structure as it is today and so far no adequate way of studying the time evolution of the elastic properties has been discovered.

Body wave studies and the Earth's free oscillations are both employed in seismic studies of the Earth's deep interior; but of the two, body-wave studies are the most important. From body-wave records an outer, liquid core and a solid inner core of apparently identical composition had been discovered by 1936. Subsequent work has greatly refined details of the size and shape of the core but body wave studies provide little information about one of the most difficult of the still unanswered core questions - flow patterns in the outer core.

The boundary between the outer core and the overlying mantle is the most profound seismic discontinuity in the Earth. Very little can be discerned about the liquid outer core beyond its bulk properties. A good deal can be learned about the boundary between the outer core and the mantle, however. At the base of the mantle and the top of the core, there is a 200 kilometre-thick region that is interpreted as a region of marked chemical inhomogeneity. Known as the D" layer from a seismic classification of layers in the Earth, the D" region is thought to play an important role in the properties of both the core and the mantle. The D" layer influences the magnetic signal measured at the Earth's surface, and appears to play a role in the mantle convection and thereby in the way heat escapes from the deep interior.

Geomagnetic studies

Geomagnetic studies have a long and distinguished history - one of the first and most profound studies was published by Edmund Halley in 1691! The magnetic field is generated in the liquid outer core, but despite the long history of study, a great many details concerning the source of the magnetic field remain unresolved. The field is a product of dynamo action in the electrically conducting outer core, but exactly how the dynamo works is conjectural. In no small part, the uncertainly arises because the magnetic signal we measure at the Earth's surface has been filtered by the poorly conducting mantle. The filtering is so intense that even the most informed theories have so far provided only distorted and partial images of core processes. Flow in the core required to produce the dynamo is necessarily complex. Although the average flow velocity in the outer core is about 0.03 cm/s, there must be a broad range of flow velocities that are both chaotic and turbulent. At present there is no direct way to measure such flows.

Among the many challenges for geomagneticians is an explanation of the way the pattern and strength of the magnetic field has changed with time, and especially during polarity reversals. Reversals are known from paleomagnetic studies to have occurred many times in the past, but even though they almost certainly arise from turbulent flow, reversals cannot yet be demonstrated to be derived from any clearly identifiable physical cause. Polarity reversals happen irregularly and rapidly. Paleomagnetic records during a reversal are just now starting to be assembled from measurements in many parts of the world. A reversal event seems to take over 10^4 years or less, but even the time involved is still uncertain because details of field strength and pattern during reversal are still being assembled. Paleomagnetic studies of the polarity, field strength, and field pattern are of great importance in determining the age of seafloor sediments; they are also one of the few tools available for learning something about the nature of the Earth's interior backward in time.

Core studies in Canada occupy the attention of only a small fraction of the country's earth scientists. They are a distinguished group, however, and their contributions stand tall among the global community of scientists tackling the difficult and demanding task of core studies. If Canada is to play its role in global science, core studies should and must be supported.

3 (b) Mantle

If a poll were to be taken among earth scientists, and the question was what is the most important scientific challenge for earth scientists, one of the contenders for top spot would surely be the relationship between the mantle and the overlying crust. It is clear that almost everything that happens to the crust is controlled by the mantle. However, the controls exerted by the mantle composition and mantle convection on both the composition and structure of the oceanic and continental crusts can only be resolved through indirect methods such as seismic tomography, geochemical studies of mantle derived magmas, or by direct studies on hard-to-find mantle xenoliths and rare outcrops of upper mantle rocks in ophiolites and oceanic fracture zones.

Convection

Temperature rises steeply through the crust and uppermost mantle at a rate of approximately 13°C/km. Down to a depth of about 100 kilometres (equivalent to about 1300°C), rocks tend to be rigid and exhibit brittle properties; heat moves through this outer 100 kilometres principally by conduction and this is the reason for the steep thermal gradient. Below 100 kilometres, at temperatures in excess of 1300°C, rock strength decreases markedly, rocks become ductile and so convection is possible. The geothermal gradient through the mantle, from 100 kilometres down to the core-mantle boundary at a depth of about 2900 kilometres, is between 1° and 2°C/km. Although some details of mantle convection are now reasonably well understood, many key scientific questions are still unresolved. The principal ones are the vertical scale of mantle convection, that is, whether single, whole mantle overturn occurs or whether stacked cells are present, and the efficiency of the convective mixing process.

The hottest part of the mantle is at the base, adjacent to the core, but seismic studies suggest that the most ductile part of the mantle is at a top, the asthenosphere, a region that lies roughly between 100 and 350 kilometres below the Earth's surface. It is now accepted that the asthenosphere not only convects, but that it also transports the rigid outermost 100 km of the Earth, the lithosphere, and that the continental and ocean crusts are carried on the lithosphere.

The means by which convective processes in the mantle can be inferred are seismic tomography (an imaging process analogous to medical CAT scans), heat flow and gravity studies. Canadian earth scientists make important contributions to each of the study areas.

Mantle-crust interactions

The interplay between the conducting 100 kilometre-thick lithospheric cap, broken as it is into a series of fragments called plates, and the vast, slowly convecting mantle reservoir, produces our familiar landscape of continents and oceans and, through plate tectonics, causes earthquakes and volcanism. Why the crust has the composition and structure that it does, why earthquakes and volcanoes are distributed the way they are, where and why mineral resources have the locations they do are all tied, via plate tectonics, to convection in the mantle. It is hardly surprising, therefore, that the dynamics and composition of the mantle should be subjects of intense investigation for geologists around the world. A particularly challenging aspect of the mantle-crust interaction question concerns time variations. The only evidence available is that trapped in the crust, and Canada with its vast areas of geologically ancient crust has played, and will continue to play, a vitally important part in understanding the evolution of the mantle.

Arguably, the most important aspect of mantle studies for Canadian scientists is the differentiation and emplacement of the early crust. Canada has the most extensive and best exposed of continental terrains older than 2.7 billion years. How, when and where this earliest crust formed, how continents arose by aggregation of fragments of the most ancient crust, and how mineral resources became distributed through the ancient crust, are topics that can possibly be answered better in Canada than anywhere else in the world. The tools by which mantle evolution and mantle-crust interactions can be studied are mainly petrologic and geochemical. Radiometric dating, particularly U-Pb ages of zircon (a technique highly perfected in Canada), Sm/Nd, Re/Os and other isotopic fractionations are the principal study tools.

Mantle studies are believed to be entering a decade or more of major advances through interactive studies of geophysics, petrology and geochemistry. As Ludden and Francis (1993) state in the concluding remarks of their summary paper on the mantle:

> *"Crustal studies can no longer be fully understood without evaluating the role of the mantle in the metamorphism, uplift history, and metallogenesis and hydrocarbon production in orogenic and anorogenic zones."*

This means, of course, that because society, and therefore the earth science community, is principally involved with the crust, it is essential that a component of earth science research be devoted to the underlying mantle.

3 (c) Lithosphere - Crust

The lithosphere is a thermal and mechanical boundary layer at the top of the Earth's silicate mantle. It includes the crust and part of the upper mantle. Its thickness ranges from approximately 2 kilometres at oceanic spreading axes to approximately 150 kilometres beneath the Archean cratons. The crust, which is that part of the Earth above the Mohorovicic discontinuity, actually represents less than 1.1% of the total Earth's volume. The surface division into continental and oceanic crust is a distinctive feature of the Earth compared to the other terrestrial planets. Although the Earth was formed over 4.5 billion years ago, all of the present deep ocean areas are underlain by a thin crust formed within the past 200 million years.

Plate Tectonics revolutionized our understanding of the global systems. It has provided a basic framework for understanding not only how oceanic crust forms and how crust deforms but also how global systems interrelate. The theory has been one of the most unifying forces in the geological sciences. It has caused us to realize the interconnectivity of the earth processes and how dynamic the Earth is.

Just how much of the solid-earth sciences is related to the crust and its significance to humankind can be seen in the USNRC Report. Of five key research areas in solid-earth sciences (Table 3.1) three directly involve the crust, namely

Table 3.1 Key research outlined in the US NRC Report (1993)

Research Area	Objectives
I. Global Paleoenvironments and Biological Evolution	To develop a record of how the Earth, its atmosphere, its hydrosphere, and its biosphere have evolved on all time scales from the shortest to the longest. Such a record would provide perspective for understanding continuing environmental change and for facilitating resource exploration.
II. Global Geochemical and Biogeochemical Cycles	To determine how and when materials have moved among the geospheres crossing the interfaces between mantle and crust, continent and ocean floor, solid earth and hydrosphere, solid earth and atmosphere, and hydrosphere and atmosphere. Interactions between the whole solid-earth system and its fluid envelopes represents a further challenge. Cycling through the biosphere and understanding how that process has changed in time is of special interest.
III. Fluids in and on the Earth	To understand how fluids move within the Earth and on its surface. The fluids include water, hydrocarbons, magmas rising from great depths to volcanic eruptions, and solutions and gases distributed mainly through the crust but also in the mantle.
IV. Crustal Dynamics: Ocean and Continent	To understand the origin and evolution of the Earth's crust and uppermost mantle. The ocean basins, island arcs, continents, and mountain belts are built and modified by physical deformations and mass transfer processes. These tectonic locales commonly host resources introduced by chemical and physical transport.
V. Core and Mantle Dynamics	To provide the basic geophysical, geochemical and geological understanding as to how the internal engine of our planet operates on the grandest scale and to use such data to improve conditions on Earth by predicting and developing theories for global earth systems. A matrix of research opportunities including crustal studies was created with these research areas tabulated against four fundamental objectives for doing the research (Table 3.2). Although this report was prepared for US earth sciences to fulfill national and international operations, the research opportunities have generally worldwide significance.

Table 3.2 Matrix of Research Opportunities

Research Area	A. Understand Processes	B. Sustain Sufficient Resources Water, Minerals Fuels	C. Mitigate Geological Hazards Earthquakes, Volcanoes, Landslides	D. Minimize Global & Environmental Change Assess, Mitigate, Remediate
I. Global Paleoenvironments & Biological Evolution	• Soil development and contamination • Glacier ice & it's inclusions • Quaternary record • Recent global changes • Paleogeography & Paleoclimatology • Paleoceanography • Forcing factors in environmental change • History of life • Discovery and curation of fossils • Abrupt and catastrophic changes • Organic geochemistry	• Mineral deposits through time		• Environmental impact of mining coal • Past global change • Catastrophic changes in the past • Solid-earth processes in global change • Global database of present-day measurements • Volcanic emissions and climate modifications
II. Global Geochemical & Biogeochemical Cycles	• Geochemical cycles: atmosphere & ocean • Evolution of crust from mantle • Fluxes along ocean spreading centers and continental rift systems • Fluxes at convergent plate margins • Mathematical modeling in geochemistry	• Organic geochemistry & the origin of petroleum • Microbiology and soils	• Seismic safety of reservoirs • Precursory phenomena and volcanic eruptions • Volume-changing soils	• Earth-science/ materials/ medical research • Biological control of organic chemical reactions • Geochemistry of waste management
III. Fluids in and on the Earth	• Analysis of drainage basins • Mineral-water interface geochemistry • Pore fluids and active tectonics • Magma generation and migration	• Kinetics of water-rock interaction • Analysis of drainage basins • Water quality and contamination • Modeling water flow • Source-transport-accumulation models • Numerical modeling of depositional environments • In situ mineral resource extraction • Crustal fluids		• Isolation of radioactive waste • Groundwater protection • Waste disposal • In situ cleanup of hazardous waste • New mining technologies • Waste disposal from mining operations • Disposal of spent reactor meterial
IV. Crustal Dynamics: Ocean & Continent	• Landorm response to change • Quantification of feedback mechanisms for landforms • Mathematical modeling of landform changes • Sequence stratigraphy • Oceanic lithosphere generation & accretion • Continental rift valleys • Metasomatism & metamorphism of lithosphere • State of the crust: thermal, strain, stress • Convergent plate boundary lithosphere • History of mountain ranges depth, temperature, time • Quantitative understanding of earthquake rupture • Rates of recent geological processes • Real-time plate movements & near-surface deformations • Geological Predictions • Modern geological maps	• Sedimentary basin analysis • Surface & soil isotopic ages • Prediction of mineral resource occurrences • Concealed ore bodies • Intermediate-scale search for ore bodies • Exploration for new petroleum reserves • Advanced production and recovery methods • Coal availability and accessibility • Coal petrology and quality • Concealed geothermal fields	• Earthquake prediction • Paleoseismology • Geological mapping of volcanoes • Remote sensing of volcanoes • Quaternary tectonics • Densifying soil materials • Landslide susceptibility maps • Preventing landslides • Dating techniques • Real-time geology • Systems approach to geomorphology • Extreme events modifying the landscape • Geographic information systems • Land use and reuse • Hazard-interaction problems • Detection of neotectonic features • Bearing capacity of weathered rocks • Urban planning: underground space • Geophysical subsurface exploration • Detection of underground voids	
V. Core & Mantle Dynamics	• Origin of the magnetic field • Core-mantle boundary • Imaging the Earth's interior • Experiments at high pressures & temperatures • Geochemical dynamics • Geodynamic modeling			

(National Research Council, 1993)

global geochemical and biochemical cycles, fluids in and on the earth, and crustal dynamics-oceans and continents.

Canadian Perspective

Canada with one sixth of the world's continental crust, a long history of earth resource development, and a keen interest in crustal deformation and geological hazards, has had a traditional strength in lithospheric research. In a recent paper on "*The Crisis in Lithospheric Research*", Paul Hoffman (1993) has highlighted some of the more current major contributions made by Lithoprobe (Clowes *et al.*, 1992) to unravelling crustal structure in various parts of Canada through mainly the application of deep seismic reflection profiling. Phase IV of the megaproject has been approved and seismic has been shot most recently across the Alberta Basement Transect and the Trans-Hudson Orogen. Transects in which multi-disciplinary studies are active are: Abitibi-Grenville, Trans-Hudson Orogen, Alberta Basement, Eastern Canadian Shield Onshore-Offshore, Slave-Northern Cordilleran Lithospheric Evolution, and Western Superior.

Hoffman (1993) also points to the very important contributions that have been made recently to understanding the nature and origin of cratonic lithosphere and its implications for Archean plate tectonics and Holocene geodynamics, through the study of mantle xenoliths, particularly diamondiferous eclogites and harzburgites, combined with a variety of geophysical observations and high pressure experimental data.

There is no doubt that the seismic imaging of deep crustal events has considerably advanced our understanding of Precambrian and subsequent deformation and evolution of the Canadian continental crust, however ground-truthing geophysical interpretation requires drilling. If not, then the crustal seismic interpretations, and the suggested alternative interpretations, will remain just that: interpretation. Unlike the European scientific community, who elected to drill singularly deep holes in the continental crust, the Canadian community through the Canadian Continental Drilling Program has chosen to drill a series of shallow holes on different geologic problems across Canada, *e.g.*, the 1992 K/T (Cretaceous-Tertiary) boundary drilling project in western Canada. Certainly the Lithoprobe interpretation of the Kapuskasing Transect is drillable if funding could be secured. For the present the Committee is considering drilling tied to Global Change Studies.

Despite uncertain funding in recent years, Canadian scientists are actively involved with the Ocean Drilling Program. As most of the oceanic lithosphere is generated by mantle upwelling at mid-ocean ridges, and recycled into the mantle at subduction zones, understanding processes at these key areas in plate tectonics is essential to establishing a global review of the Earth dynamics, and to quantify fluxes of matter and energy between the mantle, the crust and the atmosphere. Understanding processes at mid-ocean ridges has been the main focus of the ODP lithospheric community. In a recent summary of ODP's Lithosphere Objectives (JOIDES, 1994) a major goal is still to understand the architecture of the oceanic lithosphere at mid-oceanic ridges and monitor hydrothermal circulation, and to obtain time-series data. Experiments will be designed at subduction zones to quantify geochemical fluxes and mass balances, investigate back-arc initiation and sources, as well as investigate massive sulfide deposits in this tectonic setting. ODP's Tectonic Objectives will be to continue to focus on the processes and products of Earth deformation, *i.e.*, the mechanisms, kinematics and dynamics of the deformation as well as the architecture of the resulting structures.

The field of earth environmental sciences is a broad description for a wide variety of geoscientific fields that involve the interaction between the geosphere, hydrosphere, atmosphere and biosphere, and the activities of humankind. This field includes all earth sciences that affect the viability of the human species. Earth environmental sciences include:

- **Natural geological hazards** including those from geological materials, exogenic geological (geomorphologic) processes, endogenic geologic (tectonic) processes; and extraterrestrial processes;
- **Water supply and quality,** including both groundwater and surface water, which are presently being pressured by increasing demand and decreasing supplies, due to over use, waste disposal, acid mine drainage and other types of environmental contamination;
- **Society-related activities** including those associated with the construction on, or under, the Earth's surface; the use of structural materials such as sand and gravel, crushed rock, building stone and cement; soil management, air pollution, acid rain, over extraction of materials or fluids from the ground, urban and land use geology and planning; and
- **Environmental and global change** including ice core research, paleoecology/paleobotany, Quaternary age dating, denchronology and archaeology.

Topics in this field have a couple of common characteristics, and those characteristics differ somewhat from those of traditional geology. Earth environmental sciences generally involve surface and/or near-surface processes (both terrestrial and marine), and they generally have the potential to affect a large number of people. In addition, the activities of our growing population have an increasing impact on these "natural" processes.

Traditional subdisciplines of the earth sciences associated with the environment include, but are not limited to: engineering geology, environmental geology, geochemistry, geomorphology, hydrogeology, marine geology, Quaternary geology and soil science.

The field of earth environmental sciences is not entirely new, but in the past several decades it has come into its own and grown rapidly, and in the future will likely become the fastest developing field within the earth sciences.

R.A. Price, former Assistant Deputy Minister of the GSC, in his presentation to the 1992 International Conference of Geological Surveys: stated under the heading "The Mission of a National Geological Survey":

> *"Geoscience information is required by governments for the development of sound policies on, among other things: the management of mineral, energy and water resources; the management of risk due to geological and geophysical hazards such as floods, landslides, earthquakes and volcanic eruptions; and the protection of the environment and human health, nationally and globally." (Price, 1994)*

Table 3.3 Summary of the top priority and high priority research opportunities for each identified research theme (National Research Council, 1993).

Research Theme	Top Priority	High Priority
A-I. Global Paleoenvironments and Biological Evolution	The past 2.5 million years	The past 150 million years Prior to 150 million years
A-II Global Geochemical and Biogeochemical Cycles	Biogeochemistry and rock cycles through time	Construct models of the interaction between cycles Establish how geochemical cycles operate in the modern world
A-III. Fluids in and on the Earth	Fluid Pressure and Fluid Composition in the Crust	Fluid flow in sedimentary basins Microbial influences on fluid chemistry
A-IV. Crustal Dynamics: Oceans and Continents	Active Crustal Deformation	Landform responses to climatic, tectonic, and hydrologic events Understanding crustal evolution
A-V. Core and Mantle Dynamics	Mantle Convection	Origin and variation of magnetic field Nature of core mantle boundary
B. To Sustain Sufficient Natural Resources	Improve the Monitoring and Assessment of the Nation's Water Quantity and Quality	Sedimentary basin research Thermodynamic and kinetic understanding of rock-water interaction and mineral-water interface geochemistry Energy and mineral exploration, production, and assessment strategies
C. To Mitigate Geological Hazards	Define and Characterize Regions of Seismic Hazard	Define and characterize areas of seismic hazard Define and characterize potential volcanic hazards
D. To Minimize and Adjust to the Effects of Global and Environmental Change	Develop the Ability to Remediate Polluted Groundwaters, Emphasizing Microbial Methods	Isolation of toxic and radioactive waste Geochemistry and human health

Predicted Developments and Trends

As part of the research framework for developing Solid-Earth Sciences, in the US National Research Council (1993) study selected research topics of top priority and high priority were developed from the matrix of research opportunities (Table 3.3). Again, the NRC Committee's consensus choices of top crustal research projects could apply equally well to Canada, or many other nations. The select topics involving crustal themes again could have direct significance for future Canadian lithospheric research. The Kobe earthquake in Japan, and relatively moderate Seattle earthquake several weeks later (both in January 1995) have focused for continued research on defining and characterizing regions of seismic hazard, especially understanding the physics of earthquake rupture.

So far in this century, there have been 8 earthquakes greater than magnitude 7 in Canada. It is estimated that a major earthquake in Vancouver could cost more than $30 billion dollars (GSC, 1994). Over the past several decades our knowledge about the seismic zones of Canada and the associated seismic hazards has increased dramatically. Geoscientific research, primarily by the federal government, continues to contribute to the National Building Code. Research will continue to better define the possibility of a major earthquake in areas of known seismicity, such as the west coast, and the consequences to urban areas and major facilities such as hydro-electric dams. Research will also continue to better define the seismicity of other less-seismically active areas of the country such as the Mackenzie Mountains in the Northwest Territories, and in certain areas of Quebec and New Brunswick. Associated with earthquake research will be the continuing efforts to better understand liquefaction potential especially in populated areas such as Richmond, B.C., and in association with large structures such as dams. Tsunami prediction and induced seismicity will also continued to be studied.

In 1989, annual losses from all types of landslides in Canada was estimated to be as high as $1 billion (Cruden *et al.*, 1989). Landslides of various types occur in almost all parts of the country and can potentially affect, either directly or indirectly, many hundreds of Canadians. Geoscientists from university, federal and provincial governments and industry are just beginning to inventory the extent of the problem. A great deal more effort is required to continue the inventory, investigate the causes and devise better mitigative measures. In some cases mitigation may simply be avoidance or better land use planning. The new *Forest Practices Code* for British Columbia is a unique regulation as it requires the input of geoscientists, knowledgeable in terrain stability, during the planning process for forest harvesting.

With our increased use of the nearshore and offshore in the next decades, research into marine slope stability will likely increase in importance.

There are no megaprojects like Lithoprobe on the horizon for lithospheric research. However, areas of lithospheric research close to fields high on the socio-political agenda which are likely to advance may include surface processes and the lithosphere, and groundwater and the lithosphere (Hoffman, 1993). Both research themes involve looking at the lithosphere via processes that operate from the top down.

Conclusion

Studies of the continental crust and its margins should be a priority for Canadian geological research in the 21st century. Deciphering the complex interplay between tectonism, volcanism, climate change, sedimentary deposition, and geomorphic processes is vital for understanding the nature of global change (*Solid-Earth Sciences and Society*, US NRC Report, 1993). In the future, surface and near surface geological processes will become a more important area of crustal research.

3 (d) Biosphere

The study of the Earth's ancient biosphere is of interest to a wide array of specialists and to the lay public, and it has a broad range of applications. Paleontology, or the study of ancient life (fossils), is increasingly incorporated in the term paleobiology, or the study of ancient dynamic biological systems. A review of future trends in paleobiology was given by Nowlan (1993), and other comments are included in the NSERC Health of the Discipline Statement (Natural Sciences and Engineering Research Council, 1993), the USNRC Report (National Research Council, 1993) and the NSERC Allocation Report.

Public interest in the field continues to expand as expressed in a wealth of popular articles, television series such as PaleoWorld, the phenomenal appeal of Jurassic Park in both book and film versions, and the success of the Royal Tyrrell Museum of Paleontology at Drumheller, Alberta. Fascinating scientific aspects include the origin of life; the Burgess Shale Cambrian fauna and the early diversification of metazoans; mass extinctions, especially those induced by meteorite impacts; the Eocene fossil forests of the Canadian Arctic; the discovery of DNA in fossil insects and bones; and the evolution of primates and humankind. The growing public concern over the issue of biodiversity (from the Spotted Owl of the Pacific Northwest and British Columbia to the biotic desecration of the tropical forests), the increased awareness of delicate ecologic interactions, and the impact of the massive current anthropogenically induced extinction have resulted in a balanced appreciation of the relationships between the existing and ancient life on Earth. This relationship has also been recognized by specialist researchers and is expressed in the appearance of several journals (*e.g.*, Paleobiology, Historical Biology) that create a communication bridge for those who study modern and ancient life.

The essence of paleontology and much of biology has been basic taxonomic studies. An estimated 3-4 million species exist today, of which only about 40% are formally described and named. Extending that diversity back through 4 billion years of Earth history indicates the magnitude of the taxonomic challenge to paleontologists who have described formally only a mere 250,000 species. The painstaking task of systematic taxonomy had fallen out of favour in the last few decades. However, the environmental concerns over biodiversity have clearly established the essential need for this basic research; it is the foundation of the knowledge from which so many other paleobiological interpretations or syntheses are based.

Interest abounds in the dynamics of past life, especially its origins, modification, and episodic demise. The origin and diversity of early life (prokaryotes, eukaryotes, metazoans) from the earliest Precambrian to the Early Paleozoic are clearly interrelated to the early physical and chemical evolution of the planet (lithosphere, oceans and atmosphere, particularly). New geochemical and isotopic studies (*e.g.*, C, Sr, S, Nd isotopes), combined with paleobiological data, will promote new models of early Earth evolution. The rich diversity of Precambrian and Early Paleozoic strata in Canada will assuredly yield important future discoveries with further field-based research, similar to the spectacular fossils recovered from, for example, the Gunflint, Mistaken Point, and Stephen (Burgess Shale) formations.

With all phyla established by the Early Paleozoic, later modifications to the global biota have provided a sensitive indicator to patterns of global change. As metazoans diversified, they exploited more widely the available niches through processes of tiering, niche-partitioning, and community specialization. Organisms penetrated further into the frontiers of the deep ocean, the ocean sediment or terrestrial substrate, and the air. Some major modifications of life, initially with profound negative consequences, have been produced by extinction events, of which those at or near the end of the Ordovician, Devonian, Permian, Cretaceous periods and those of today are the most acute. Future research trends will focus on the precise dynamics of the origin, modification, and extinction of global (and regional) biota. The fossil record preserves a database rich and sensitive enough to permit greater accuracy in timescales, determine patterns and causes of global change, and ultimately contribute to an understanding of recycling throughout most of Earth history.

A primary application of taxonomic data is biostratigraphy: establishing a progressively refined and accurate biochronologic scale. More recently isotope geochronologic work has been applied to fossil skeletal material from volcanic ash beds (zircons from bentonites) to provide improved correlations between the "relative" and "absolute" timescales. A future objective will be to increase such resolution in order to understand instantaneous and short-term processes and events in the geologic record (*e.g.*, the role and impact of orbital forcing). Paleobiological data are of increasing importance in resolving recent and anthropogenic changes. Palynology is widely used to record recent changes in vegetation or the onset of deforestation or agricultural development. The analysis of tree rings (by counts or by geochemical analyses of each ring) and similar approaches using annual growth layers of coral skeletons provide data on climate variability. These studies are being incorporated in, for example, the past global changes program (PAGES) of IGBP (Global Change Program).

With increasing paleobiological data through space and time, elaborate paleoecologic models are emerging. The ocean drilling programs (Deep Sea Drilling Project and Ocean Drilling Program) have provided a global marine coverage for the post-mid-Mesozoic (last 200 m.y.). Canadian paleobiologists will benefit from Canada's continued membership in ODP. Biotic data will be key to determining the state of oceanographic circulation, anoxia, and related climate change as the spatial-temporal distribution of taxa becomes known within an increasingly refined timescale. This work is spurring the development of global models of paleogeography, paleoceanography, and paleobiogeography. Biotic-isotopic studies will be able to test models of paleogeography developed from geophysical (paleomagnetic), tectonic, and sedimentologic data. Regional applications include the increasing application to (suspect) terrane analysis in orogenic belts (*e.g.*, the Canadian Cordillera).

A burgeoning field in paleobiology is the geochemistry and biochemistry of skeletal or organic matter. Isotopic work includes studies (and application) of C (for age dating; organic productivity flux), Sr (sea water history; chemostratigraphic correlative tool; tectonic processes), O (paleo-temperatures), N (trophic structures), and Nd (paleoceanography; crustal erosion rates). Biochemical work is in its infancy in examining the nature of organic matter preserved in skeletal tissue or as primary organic matter. Exciting DNA studies are developing within the field of molecular paleontology. Thermal alteration studies (*e.g.*, of palynomorphs, conodonts, organic matter) of increasing sophistication are valuable for regional studies of thermal crustal history and for predicting hydrocarbon potential. More quantitative index schemes can be predicted. Refinements in mass spectrometry technology are also allowing wider application of geochemical data from skeletal materials – an example being the development of the laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS), even used for tracking the migration patterns of modern salmon through analysis of individual fish scales.

Ancient life has contributed directly or indirectly to the composition of the atmosphere (O_2, CO_2), the composition of many marine (carbonates, reefs, black shales) and non-marine (coal) sediments, to the generation of hydrocarbons (oil, gas), to sedimentary diagenesis, and to a variety of other processes, especially at the microbial level. The future trends in the discipline will be influenced greatly by the integration of complementary datasets, by quantified application of the rich natural database (*e.g.*, graphic correlation), building on an expanded taxonomic foundation, and with increasingly diversified applications. Important challenges lie in greater communication with the biological and geochemical communities, improving interactions between the many subdisciplinary groups of specialists, and building more unified models of Earth history involving ancient and modern microbial, invertebrate, vertebrate, and plant data.

Future opportunities for significant advances in Canadian paleobiology abound given its large number of sedimentary basins, and that many basins in the Arctic and the northwest remain poorly explored. This will continue to encourage an emphasis in high-resolution biostratigraphy and chemostratigraphy. The remarkable repository of subsurface cores and cuttings from the Western Canada Sedimentary Basin and the offshore basins, and the repository of ODP cores, offers an unparalleled opportunity for detailed micropaleontological research. Canada also offers exceptional future opportunities in the fields of Quaternary paleobiology and Mesozoic-Cenozoic vertebrate and paleobotanical research. Canadian paleobiologists will continue to play important and lead roles in a variety of international programs such as ODP, BOREAS, the International Geological Correlation Project (IGCP), the International Geosphere-Biosphere Program (IGBP – Global Change Program), and the International Biodiversity Convention program.

The evolution and dynamic systems of the biosphere are of particular interest to the public since, being part of them, they can relate to them more closely than perhaps to any other part of the earth sciences. Communication and interpretation of scientific results to the public can be facilitated particularly well through museums and science centres. There are both federal and provincial museums as well as a network of provincial science centres. In Ontario, for example, the Royal Ontario Museum and the Ontario Science Centre (OSC) rank behind only the CN tower in Toronto in attracting the most tourists. In 1993-94, the OSC had nearly 1 million visitors (25% being school children). Likewise the Royal Tyrrell Museum of Paleontology at Drumheller is the leading tourist attraction in Alberta with over 440,000 visitors in 1993-94.

3 (e) Oceans

As our understanding of the Earth System evolves, it is becoming increasingly clear that, of the earth's subsystems, the oceans play the pivotal role in the evolution of the biosphere, atmosphere, and much of the geosphere. Despite this, study of the oceans has lagged behind many other components of the Earth System; this is because of the special challenges that the oceans present. The remote and opaque nature of the oceans has made marine science a field that is dependent on technology. In many instances advances in technology have led and even driven advances in understanding. Ocean-related problems also often involve vast (global) spatial scales and temporal scales ranging from fractions of seconds (*e.g.*, turbulence and gas exchange) to millions of years (*e.g.*, tectonic changes). Ocean studies thus often require expensive research platforms, need global access, and require a long-term commitment. These factors, coupled with the growing awareness of the need for an interdisciplinary approach to earth-science problems, have led to the evolution of a number of large-scale, often international, programs aimed at exploring manageable subcomponents of the Earth System.

To the dismay of some, but the benefit of many, and particularly to the benefit of our science, these large-scale, interdisciplinary programs are forming the foundation of our future research efforts. Though these programs may become bogged down in a bureaucratic quagmire, they can, if organized and managed properly, bring together specialists from often disparate disciplines and forge new alliances and lines of communications that would have been unimaginable ten years ago. This process of cross-fertilization can, with little extra effort, give rise to the critically needed system integration (often by just putting these people together in the same room) and, as this process is witnessed by younger scientists, can lay the groundwork of the training for future "system scientists". Taken to an idealistic extreme, the final output and impact of these large-scale, interdisciplinary programs may very well be greater than the sum of their individual contributions.

As examples of the approach outlined above, five areas of research that represent theoretically "manageable subcomponents" of the Ocean System, and for which large-scale, international programs (in varying states of maturity) already exist, will be discussed. This list is far from exhaustive and serves only to indicate future trends.

Global patterns of oceanic and atmospheric circulation

Despite the rapid growth of supercomputing capabilities (access to which has been a problem for some sectors of the Canadian scientific community), we are still unable to generate accurate long-term climate forecasts. Because of this, the last few years have seen a frenzy of international activity aimed at fostering research on those elements of the climate system that are expected to have the greatest impact on the accuracy of climate forecasts. The emphasis of this research has been on time-scales of weeks to decades, the time-scales most important to the critical decisions that must be made regarding agricultural, industrial, and governmental issues. The oceanographic component of this effort has focused on WOCE (World Ocean Circulation Experiment), a long-term international effort aimed at producing a global survey of ocean circulation.

The objectives of WOCE are to understand, on a global basis, the relationship of climate to: 1) the large-scale fluxes of heat and fresh water; 2) the dynamic balance of ocean circulation and its response to changes in surface fluxes; 3) the rates and nature of formation, ventilation, and circulation of water masses that influence the climate system on time-scales from ten to one hundred years and; 4) the components of oceanic variability on time-scales of months to years and spatial scales of megameters to global.

These objectives are to be met with a series of experiments involving a global data base of oceanographic data, as well as experiments focused on gyre dynamics and on the Southern Ocean (where the Antarctic Circumpolar Current links the Atlantic, Pacific, and Indian Oceans and transforms oceanic heat flux from a regional into a global phenomenon). These experimental programs will call upon traditional shipboard oceanographic techniques as well as an array of satellite-borne sensors that produce maps of sea-surface height and temperature. Additionally, several new generations of surface and subsurface drifters which use satellite links to telemeter automatically their position and data to shore-based laboratories will be deployed.

Oceans in the global CO_2 system

Over the past few hundred years mankind has undertaken a global geochemical experiment. Through the burning of fossil fuels and changing land use, the amount of CO_2 in the atmosphere has increased from a pre-industrial level of 270 ppm to a present day value of 350 ppm. The ultimate climatic effect of this "greenhouse" situation is unknown, with predictions ranging from catastrophic to negligible. We do know, however, that the oceans store about 50 times more CO_2 than the atmosphere and thus play an important regulating role in the global CO_2 system. The specifics of the nature, rates, and effects of ocean/atmosphere CO_2 exchange remain unresolved. Given the critical, yet poorly understood role that CO_2 plays in the global environment, an international program, titled Joint Global Ocean Flux Study (JGOFS), has been established to increase our understanding of the ocean carbon cycle, its sensitivity to change, and the regulation of the atmosphere-ocean CO_2 balance. The specific objectives of this program are: 1) to determine and understand, on a global scale, the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean; and 2) to develop a capability to predict, on a global scale, the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

The JGOFS program has adopted a "systems approach" to address these objectives by integrating a number of field and analytical methodologies with an interactive modeling scheme. Satellite-borne sensors will produce the global distribution of variables like wind speed and chlorophyll (from color sensors). Ship-borne measurements will provide the distribution and seasonal variations of key biogeochemical parameters, and long-term variability will be examined through a few dedicated time-series stations. Process studies will involve intensive analyses of the factors controlling rates and fluxes at the air-sea and sediment-water interfaces as well as within the water column. Most importantly, critical links with the modelers are built into the approach as the observational data are used to upgrade, redefine, and verify the predictive models.

Global high-resolution paleoclimatic database

If we are accurately to predict man's impact on the Earth System, we must fully understand the background signal of natural change upon which the anthropogenic signal is superimposed. To do this we turn to the history of earth processes as recorded in the geologic record. The geologic record also provides us the opportunity to examine the response of the Earth System to naturally occurring changes in boundary conditions, as well as to explore (at least for the past several hundred thousand years) the response of the Earth System to the only known external forcing function – variations in solar insolation resulting from periodic changes in the geometry of the earth-sun orbital configuration (the Milankovitch hypothesis).

The record of Earth System response to external forcing or varying boundary conditions is preserved through a number of paleoceanographic "proxies", each recording the behavior of a particular component of the global climate system (e.g., the $\partial^{18}O$ signal preserved in the skeletons of benthonic micro-organisms is a good indicator of global ice volume, the distribution of aeolian sediments is an indicator of aridity, as well as past wind speeds and directions). Sediment cores recover a multichannel time-series of the history of Earth System change and the paleoceanographer's goal is to collect a global array of proxy data, demultiplex the record, and attempt to reconstruct the state of the system at any given time along with the temporal and spatial relationships among the various components of the system. For example, by piecing together the timing and global response of changes in wind patterns, temperatures, ocean currents, and ocean chemistry to an event like the uplift of the Himalayas, we can begin to understand the fundamental workings of the Earth System.

The paleoceanographic record is best preserved in regions of the ocean that are relatively free from erosive processes and where high productivity results in the rapid accumulation of sedimentary components that are sensitive to changes in environmental conditions. These records are commonly recovered in short piston cores which represent a few hundred thousand years of the geologic record. A major international program, The Ocean Drilling Program (ODP), has provided the technology needed to collect high-resolution paleoclimatic records which can extend back millions of years. Just as importantly, the ODP has provided the structure and focus for planning global experiments aimed at exploring: 1) the nature of short-period climate change; 2) longer-period climate change; 3) the history, causes, and effects of changes in sea level; 4) the history of the carbon cycle and paleoproductivity; and 5) evolutionary biology.

To meet these objectives a number of long-term global experiments involving drilling sites in key areas (*e.g.*, equatorial oceans for short-term climate change, continental margins and atolls for the history of sea level) have been planned. Many of these programs will take advantage of newly developed coring technology and continuous core-logging techniques that can ensure the complete recovery of long (5 to 10 million year) paleoceanographic records with temporal resolution on the order of 1000 years. In special environments (*e.g.*, fjords) these techniques can produce long records with annual to decadal resolution.

In planning global paleoceanographic programs the Arctic has been identified as an area of critical importance to our understanding of the tectonic, oceanographic, and climatic evolution of the Earth. Unfortunately, despite the impressive capabilities of the ODP vessel JOIDES RESOLUTION, most of the Arctic is not accessible to the ODP drillship. To address this issue, a new organization, the Nansen Arctic Drilling Program (NAD) has formed in an effort to obtain the data required to document the climatic history and structural evolution of the Arctic Basin.

Mid-ocean ridge dynamics , magmatism, and hydrothermal circulation

The global mid-ocean ridge system, once solely the domain of petrologists, is now being viewed as a key component of the solid-earth geochemical cycle. This system dominates the earth's volcanic flux; the cooling of newly created lithosphere (about 20 cubic kilometres per year) accounts for most of the heat lost from the earth's interior. Hydrothermal circulation at the ridge crest significantly contributes to oceanic heat flux and acts as a key regulator of oceanic chemistry. This regulator may serve to counteract the effect of change in the composition of sea water due to variations in continental input (from climatic or tectonic events), as well as to provide the foundation for a chemosynthetic food chain. The role of these chemosynthetic vent communities in the evolution of life and the environment are key unresolved questions.

In order to address these and other related issues, a long-range multidisciplinary program (InterRIDGE – International Ridge Interdisciplinary Global Experiment) has evolved. This program calls upon an hierarchical investigative strategy for mapping and sampling the ridge system, including: 1) reconnaissance surveys of poorly known components (*e.g.*, back-arc basins); 2) more detailed surveys of the spatial and temporal evolution of ridge "segments" (30 to 100 km-long pieces of the ridge typically characterized by a single bathymetric high ; and 3) very detailed investigations within single segments of the ridge system.

These studies will take advantage of a number of technological advances, including: 1) multichannel seismic techniques which are now allowing definition of axial magma chambers; 2) improved drilling techniques to allow drilling on the bare rock of the ridge crest and in high-temperature environments; 3) the establishment of long-term instrumented "natural observatories," utilizing arrays of seismometers, tiltmeters, water samplers, temperature and conductivity probes, sediment traps, *etc.*; and finally, 4) , newly developed swath mapping side-scan sonar and visualization techniques, combined with highly accurate Global Positioning System satellite navigation, are producing an unprecedented view of seafloor morphology.

It is important to note that both the drilling and natural observatory aspects of the InterRIDGE program will also involve the Ocean Drilling Program as ODP's mandate also extends to fundamental questions of crustal evolution and tectonics.

Coastal Ocean Processes

Two factors–the growing pressure from a population base that is increasingly shifting to coastal regions, and the end of the cold war with its concomitant shift in the focus of naval research from anti-submarine warfare to mine-countermeasures – have heightened the focus on research in coastal ocean processes. The importance of coastal oceans extends far beyond their relatively small geographic extent; they are the locus of extremely high biological production and are becoming the repositories for a wide variety of pollutants and waste. The realization that successful coastal research will require a more interdisciplinary approach, combining studies of biological, chemical, physical, and geological processes runs in parallel with the changing paradigm of Earth System Science. Four key issues that will be of particular importance in future coastal-zone studies are: air-sea interactions; cross-margin transport; carbon cycles; and particle dynamics (Ocean Studies Board, 1992). Research programs will be designed to produce estimates of air-sea fluxes of momentum, heat, and gases in the non-equilibrium sea state that is typical of the coastal ocean. These estimates, along with an increased understanding of the biological, chemical, and geological processes that affect these fluxes, will be critical in establishing global CO_2 and climate models.

The diversity of coastal regions will require a long-term, global effort in order to eventually integrate the results of local studies into global models. The key to these studies will be to identify the most significant physical-meteorological processes that are, to some degree, common to all the world's coastal waters. Each of these processes should then be studied in a prototypical environment where the process dominates.

A Canadian Perspective

Canada is unquestionably a maritime nation. It borders on three oceans and has the world's largest continental shelf area with the offshore representing more than 30% of its territory. The wealth of many Canadian regions has been inextricably linked to the oceans. The economic activity generated annually off Canada's west coast exceeds $3 billion and has the potential to double within a decade (Science Council of BC, 1993).

The oceans have clearly played a critical role in the development of Canada – but will they continue to play an important role in the future? This is a difficult question to answer, for the Canadian marine geoscience community is facing some acute problems. In most developed nations doing serious ocean science, the majority of research is done at academic institutions. In Canada, however, the majority of ocean science is done in government laboratories, often under the direction of several different departments. Our government laboratories have a number of very talented marine geoscientists, but unlike their academic counterparts, the government scientists work for departments with specific and often evolving mission statements. Over the past few years there has been a growing trend for the work of the government laboratories to become more focused on short-term cost recovery. Given the current distribution of ocean researchers in Canada, this process is creating a serious imbalance with only a small number of relatively poorly funded and equipped researchers with the mandate to take the long-term outlook necessary for addressing global research issues and sustainable resource development.

This problem has been exacerbated because most of our research vessels and major ocean-related facilities (e.g., remotely operated vehicles) are also owned and operated by the government laboratories. Almost all of the ships available to the Canadian oceanographic community are run by the Department of Fisheries and Oceans (DFO) which, through a steady stream of budget cuts, has retired a number of vessels, leaving fewer and fewer available to the marine research community. Finally, ocean scientists in Canada have been hampered by the lack of a formal mechanism for becoming partners in major international collaborative projects like those described above (a more detailed discussion of this issue can be found in Chapter 9 – International Geoscience Programs).

Despite this bleak appraisal, there are positive signs on the horizon and, as has been a common theme throughout this document, they result from collaboration and cooperation designed to increase the efficiency of operations. Focusing on an area of Canadian strength (our development of sophisticated ocean-mapping technologies), a National Action Committee for Ocean Mapping (NACOM) has been formed to try to coordinate and rationalize the various national needs for ocean mapping. This group is made up of representatives from universities and every federal department with a stake in the ocean. The NACOM's efforts have led to the formation of an 11-company consortium which, working together with government and academia, has successfully undertaken several commercial projects. Canadian ocean-mapping technology is also being sought outside of Canada: a collaboration between the Canadian Hydrographic Service and The Ocean Mapping Group at the University of New Brunswick has generated of contracts worth significantly more than $1 million from the U.S. Navy and the U.S. Geological Survey.

There is also potentially good news with regard to shiptime. Negotiations are currently underway between several federal departments with regard to rationalizing ship use. Such negotiations can only lead to the more efficient and cost effective deployment of our limited marine platforms. In addition, the Natural Sciences and Engineering Research Council (NSERC), the primary funder of basic research in Canada, has acknowledged its responsibility to the oceanographic community and formulated mechanisms that will allow the academic community to write competitive proposals for shiptime costs. NSERC has also increased its Collaborative Special Programs funding, thereby providing a potential means of supporting for Canadian participation in major international research projects.

We are witnessing a conceptual revolution in the earth sciences. Earth System Science is more than a catchy phrase – it is an approach to studying earth sciences that, when coupled with advanced data acquisition and analytical techniques, holds hope that we may someday gain a predictive understanding of how the earth works. The oceans play a major role in this system and given the scale (both spatial and temporal) of ocean-related problems, ocean science often requires large-scale, international research programs focused on manageable subcomponents of the system. In order to contribute to, and benefit from, this conceptual revolution, Canada must maintain a critical mass of world-class ocean scientists and provide them with the tools and infrastructure necessary to participate in these programs and initiate programs of their own.

3 (f) Atmosphere

While the atmospheric sciences have historically been distinct from the geosciences, the growing acceptance of a system approach to earth science behooves us to consider the atmospheric sciences in our discussion of future trends in the geosciences. As has been the case for many natural science disciplines, the atmospheric sciences have recently undergone a radical transformation. Research that had historically been divided into distinct and only weakly linked subdisciplines is now being focused on an integrated approach involving processes that span the full range of space and time scales relevant to atmospheric behavior. As this approach develops, new subdisciplines that concentrate on the modes of interaction within the atmosphere as well as the interactions of the atmosphere with other components of the earth system, evolve. As has also been true for the ocean sciences, the growing effort in cross-disciplinary atmospheric research is being facilitated by large-scale, international, experiments and programs. This section, a précis of a report written by Prof. Richard Peltier of the Univ. of Toronto (Peltier, 1993), will briefly present a sampling of several of the research themes that will play a critical role in the future of atmospheric science.

Mesoscale and boundary layer scale research

The coming years will see a major shift from synoptic scale meteorology to a focus on mesoscale problems. A Canadian example of these efforts is provided by work on the origin of Chinook windstorms, which have been attributed to the "breaking" of internal waves forced by topography. Non-hydrostatic models are now being developed which are capable of resolving these kind of small-scale processes, and observational programs are being planned to look at the mesoscale substructure within evolving marine cyclones and polar lows. These observational programs require state-of-the-art airborne sensors, weather doppler radars, and satellite radiometry (e.g., NOAA's AVHRR). Canadians will be contributing to this research by looking at lee cyclogenesis in the Beaufort Sea and Arctic Ocean region as part of the World Climate Research Program's (WCRP) Global Energy and Water Cycle Experiment (GEWEX). In general, the study of the interaction of atmospheric flow with topography, and along with this, improvements in the understanding of boundary-layer processes and of cloud physical/dynamical feedbacks into large scale flow will be the focus of mesoscale research efforts.

Synoptic-scale research

The dominant research focus for synoptic scale processes is cyclogenesis, including the factors that control the intensity and occurrence of cyclones. Recent research has identified the importance of water vapor and non-modal baroclinic instabilities in controlling the speed at which intense marine cyclones develop. The impact of land-surface processes on baroclinic wave generation is being explored for continental cyclogenesis. Through the incorporation of these land-surface processes, synoptic scale, numerical, weather-prediction models (NWP) have been greatly improved and are beginning to converge with the larger-scale General Circulation Models (GCMs). Finally, projects like BOREAS, which are designed to enhance the understanding of the impact of boreal forest ecosystems on atmosphere-land surface exchange processes, will have a significant influence on future research directions.

Climate and global dynamics

The major advance in global climate research in the past few years has been the development and implementation of coupled ocean-atmosphere models. The atmospheric components of these models are now in their second generation, with spatial resolutions of approximately 5 degrees. The Canadian model developed at the Canadian Climate Centre and based on the earlier work of the Recherché en Prevision Numerique (RPN) group at Dorval, is acknowledged to be one of the best in the world. Canadian researchers are focusing their efforts on generating an ocean circulation model with equivalent resolution. The next generation of finite-element software (which uses unstructured, multigrid methods) will replace existing analytical techniques. As these techniques are perfected, Atmospheric General Circulation Models (AGCMs) will also adopt multigrid methods but these will require massively parallel supercomputers.

With the parallel development of AGCMs and ocean circulation models will come the next generation of Atmosphere-Ocean Coupled General Circulation Models (AOGCMs) which will be focused on predicting the impact on global climate of increased concentrations of greenhouse gases. Observational data from global experiments like WOCE and JGOFS (see Oceans section) will provide important insight into the workings of the carbon cycle. One area that is in particular need of investigation is the manner in which the models handle water vapor. The proper representation of the effect of clouds on the radiation budget and thus atmospheric behavior will be a high priority future research direction.

A relatively new and intriguing direction for atmospheric research is in the area of paleoclimate. This activity, which is exemplified by the programs of IGBP Past Global Changes (PAGES) and the Paleoclimate Model Intercomparison Project (PMIP), is driven by the recognition that paleoclimate data may provide the best (and perhaps only) means to test the results of AOCGMs. These paleoclimate programs use proxy climate data (*e.g.*, dust distribution for past winds; microfossil species distribution for past temperatures, and oxygen isotope ratios for past ice volumes and temperatures) to reconstruct the state of the global climate at critical times in the past when boundary conditions were significantly different from those of today. Studies of CO_2 trapped in ice-cores also provide a direct measurement of the state of the atmospheric carbon dioxide system at these times. These data can be used directly to test the AOGCMs ability to predict global climate in times when the system was forced in a markedly different manner.

Particular attention has focused on the most recent glacial cycle. The analysis of oxygen isotope and other paleoclimate proxy data has indicated that the glacial/interglacial signal appears to be related to forcing from changes in solar insolation that are related to periodic changes in the Earth-Sun orbit through time (supporting an hypothesis put forth many years ago by James Croll and later quantified by Milutin Milankovitch) and identifying a critical external forcing function for climate. Variations in solar insolation, however, have very little power at the 100,000-year frequency that dominates glacial/interglacial changes, indicating that there are non-linear internal processes involved in climatic response. It is the nature of these non-linear responses that will be the focus of future paleoclimatic research. While various hypotheses have been suggested (isostatic response of ice sheets, rapid changes in thermohaline circulation, *etc.*), their testing awaits the further development of the coupled Atmosphere-Ocean General Circulation Models.

Atmospheric chemistry and the stratosphere

The discovery of the ozone hole over Antarctica and the subsequent demonstration that ozone depletion was a direct consequence of the release of chloroflorocarbons (CFCs) into the atmosphere have led to a frenzy of research into the coupled chemistry and dynamics of the stratosphere. In addition to its role in the photochemical production of ozone, the stratosphere is also important because of the extent to which its dynamics are driven by planetary wave and internal wave induced flows. Because of the important role that dynamics play in the distribution of ozone and because of the intriguing (to the theoreticians) dynamics of the stratosphere, future research will be focused on the development of General Circulation Models that fully resolve the stratosphere as well as the troposphere, and which are coupled to fully interactive chemistry modules.

In the general area of atmospheric chemistry and composition, future efforts will focus on the development of a new generation of high-resolution satellite remote sensing systems. Of particular importance to Canada will be the MOPITT instrument that will measure both CO and CH_4 in the atmosphere. These remotely sensed measurements will have to be coupled with extensive "ground-truthing" programs, like the recently completed Northern Wetlands Project which was designed to measure the emission of methane from the Hudson Bay region.

Closing Comments

Canada has clearly made substantial contributions to atmospheric research, particularly in the development of Atmospheric General Circulation models. If these contributions are to continue, however, Canadian scientists must have access to state-of-the-art supercomputing facilities. Additionally, Canadian scientists must have access to atmospheric data from space. The Canadian Space Agency will play an active role in this field by developing the MOPPITT instrument, but access to the range of data needed to make real advances in the field will depend on Canadian support for and participation in large-scale international programs, like Mission to Planet Earth (see discussion in the technology section).