ALLOCATION REPORT OF THE ENVIRONMENTAL EARTH SCIENCES GRANT SELECTION COMMITTEE (COMMITTEE 09)

This Committee is responsible for research in Earth surface and near-surface processes, encompassing Quaternary geology and paleoecology, geomorphology. soil science, hydrology, glaciology, limnology, oceanography, meteorology and climatology, environmental chemistry and physics, and remote sensing. A total of 304 grantees is currently studing in these fields.

Canadian research in environmental Earth sciences has substantial impact. Table 1 summerizes a survey of the research papers published during 1989-93 in international journals identified by the members of the Committee as the most authoritive in various subfields. Canadians ranked first in numbers of papers published, relative to GERD, in 10 of 15, and second in another 3, of these stringently reviewed journals. Thus, Canadian Earth scientists have a dominating influence in terms of the numbers of high quality refereed papers, relative to the total expenditure on research, in the leading journals in environmental Earth sciences. This evidence sustains the picture of relative prominence enjoyed by all of Canadian Earth sciences, documented in this report.

The Quality of Canadian Research

Interactions of the atmosphere, biosphere, hydrosphere and lithosphere at the Earth's surface comprise the central processes of environmental Earth sciences. The recent public and political interest in the environment has caused a major expansion of work in this area. Research is focused not only on current environments, but also on the evolution of ecosystems during the Quaternary period (the

Table 1. Percentage of the total number of first-authored papers by members of G-7 countries and Australia (1989-93) in top international journals in solid Earth sciences

Journal	Canada	Australia	France	Germany	Italy	Japan	UK	USA
Geochim Cos Acta	**1.07**	*0.98*	0.22	0.11	0.04	0.04	0.26	0.40
Geology	**1.66**	*1.50*	0.20	0.06	0.00	0.02	0.32	0.40
Geophys Res Lett	**0.48**	0.41	0.25	0.15	0.13	0.09	0.19	*0.43*
Geophysics	**1.53**	*0.64*	0.19	0.07	0.12	0.01	0.20	0.37
Int J Remote Sens	0.60	**1.17**	0.37	0.14	0.44	0.03	*0.94*	0.15
J Climatology	*0.70*	**1.23**	0.14	0.15	0.03	0.01	0.18	0.46
J Fluid Mechanics	0.35	**1.10**	0.16	0.10	0.13	0.04	*0.90*	0.33
J Glaciology	**1.80**	0.45	0.26	0.10	0.09	0.02	*0.80*	0.27
J Geo Res (Oceans)	**0.98**	*0.63*	0.21	0.14	0.08	0.03	0.18	0.44
J Sedim Petrology	**1.73**	*0.89*	0.05	0.04	0.17	0.00	0.34	0.40
Quaternary Research	**1.38**	*1.26*	0.31	0.04	0.04	0.04	0.21	0.37
Rev Palaeobot Pal	*0.89*	**1.60**	0.48	0.11	0.08	0.02	0.63	0.14
Soil Sci Soc Am J	**1.05**	*0.92*	0.06	0.04	0.05	0.02	0.03	0.48
J Atmos Science	**0.69**	*0.44*	0.10	0.08	0.12	0.04	0.22	*0.44*
Water Res Researc	*1.02*	**1.58**	0.06	0.03	0.24	0.01	0.09	0.40

Note: Data are normalized to GERD. Figures in bold are first rank; and, italics are second in rank.***

**GERD = Gross Expenditure of Research and Development in $PPP billion (Purchasing Power Parity) for 1990 (latest year of complete data) from Main Science & Technology Indicators, OECD Paris, 1993, Part 2.*

*** The same result is obtained if population is used for normalization* last 1.6 million years), to provide the appropriate long-term perspective within which to evaluate the significance of environmental change.

Hydrological sciences

Of particular interest to society at all levels is the study of the Earth's water balance, and the physical and chemical processes associated with the water cycle. About 8% of Canada's area is lakes, amongst which are some of the largest in the world, and another 20% of the area is wetland; Canadian rivers discharge about 9% of the world's annual freshwater circulation. To better manage this resource, it is imperative to buttress Canada's long tradition of major engineering projects with deeper insight into the hydrological cycle and the impacts of human activity.

Studies of the chemical, physical and biological aspects of the water cycle have gained momentum from emerging concerns for long-range transport of atmospheric pollutants, soil salinization, and the contamination of rivers and lakes. The importance of groundwater behaviour has become evident with the recognition of problems such as landfill leachates, fuel tank leaks, water supply quality, and radioactive waste management. Canada is strong in groundwater studies, with world leadership particularly in monitoring and modelling local and regional groundwater movement and the chemical evolution of groundwater. Studies of regional groundwater fields were pioneered at the University of Alberta by J. Toth. At UBC, pioneering work on physically based groundwater flow modelling was completed by R.A. Freeze and is continued by J.L. Smith. At Waterloo, J.A. Cherry has made important field and model studies of flow in fractured media, while E. Frind and E. Sudicky provide world leadership in numerical modelling. Students from these groups are making an international impact academically and industrially.

A major international focus in surface water hydrology is the construction of distributed models of the water balance for drainage basins. M.-K. Woo (McMaster) and J. Stein (Laval) have made important contributions with respect to northern forest and Arctic regions. (Canadian researchers are integrating hydrology into large-scale climate programs such as the Northern Wetlands Study and BOREAS (Boreal Ecosystem – Atmosphere Study). This expertise is important because water is the major mediator of the impact of climate on ecosystems, including human societies.

Snow, ice and permafrost

With about 185 000 km^2 of perennial ice cover, Canada has by far the largest extent of ice outside the two major ice caps. Sea ice, freshwater ice, ground ice in northern permaffost regions, and seasonal snow cover everywhere, exert a profound influence over economic activity and define our unique ecosystems. There is a long tradition of study of snow hydrology at Laval and McMaster universities, and in the group led by D.M. Gray at Saskatchewan. Spectacular work has been completed by G.K.C. Clarke (UBC) to place instruments beneath glaciers to measure water flows and material properties at the ice base, thereby providing information on the physical constraints of glacier motion. University scientists, for example, E. LeDrew at the Waterloo Centre for Remote Sensing also lead work in remote sensing of snow and ice. Naturally, Canada has a long tradition of excellent work in the development of permafrost and associated landforms, with a major focus of activity in the Ottawa-Carleton Geoscience Centre.

Geomorphology and glacial geology

Canada has a great diversity of landscapes due to the size of the country and, because of glacial and tectonic history, the relative youth of many of its landforms. Interest in landforms stems from the constraints imposed on human activities by events such as landslides, floods, and coastal recession. But the landscape presents that aspect of the Earth sciences most immediately accessible to most people, so its interpretation holds substantial cultural value.

The study of glacial landforms, which cover most of the land surface, is a traditional and continuing strength in Canada, with major leadership contributed by the Geological Survey of Canada. The largest and most influential university school is that of N. Rutter at Alberta. He and his colleagues have led an international effort to understand the environment of the last interglacial episode in order to better understand the current (Holocene) epoch. A radical reinterpretation is in progress, led by J. Shaw (Alberta), of the genesis and glacial implications of landform suites, which complements rapidly changing views about ice cap stability and glacial hydrology in the last ice age. In this work lies promise of a major revolution in our understanding of ice sheet behaviour. Basin-wide approaches to the interpretation of glacial stratigraphy, pioneered in Canada by N. Eyles (Toronto) and by GSC staff, are also making an exciting new contribution by integrating glacial episodes into the general stratigraphic record.

Canadian geomorphologists have for many years been among the international leaders of the field. Field and experimental measurements of erosion on natural surfaces are conducted by R Bryan and S.-H. Luk (Toronto) with international collaboration from Israel and China. A. Hay (Memorial) and A.J. Bowen (Dalhousie) have formed one of the world's leading coastal sediment transport groups, and are currently participating in the most extensive observing program for many years at the U.S. Army Corps of Engineers observatory in the U.S.A. Innovative programs of coupled field and experimental observations in fluvial (*e.g.*, P. Ashmore, Western), coastal (B. Greenwood, Toronto, with Hay and Bowen) and aeolian sediment transport (*e.g.*, W. Nickling, Guelph) are ongoing. A.D. Miall (Toronto) and D.G. Smith (Calgary) have made major contributions to the

J. ROSS MACKAY, O.C., is Research Professor in the Department of Geography, The University of British Columbia. He is the preeminent student of permafrost in the world. He has given the standard classification for ground ice, but his major contribution lies in his observations, unparalleled in duration and detail, of the evolution of ground ice and permafrost features in the Mackenzie delta, some including experimental manipulations of the surface. Among his awards are FRSC (1959), Miller Medal (RSC), Logan Medal (GAC) and Vega Medal (Swedish Society for Anthropology and Geography), and he is a Foreign Fellow of the Russian Academy of Natural Sciences (1992).

study of fluvial sedimentology, including founding the influential series of International Conferences on Fluvial Sedimentology. Canadian studies of the stability of natural slopes are well recognized, supported by substantial strength in engineering studies of slope stability: D.M. Cruden (Alberta) is leading an international effort to systematize studies of landslides and the work of J. Locat (Laval) on marine slope stability is well known. In 1993, Canada hosted the Third International Conference on Geomorphology.

Soil science

Quaternary geologists and engineers regard unconsolidated material as soil, regardless of its thickness, whereas soil scientists consider soil to be the biologically active surface layer, differentiated from the parent geological material by physical, hydrological and biological processes. Terrestrial life depends on soil, and soil is the real resource that underlies agriculture and forestry. All engineering structures must contend with soils and most are actually founded in them. Virtually all of the world's drinking water passes through the soil. Nationally and globally, understanding soil dynamics and evolution is critical to sustaining society.

Less than one-third of Canada, and much of that climatically marginal, has soils that can support commercial agriculture and forestry. The management of soil for agriculture has a strong history in Canada, making Canadian farmers among the most efficient. D.A. Rennie (Saskatchewan) has questioned summer-fallow on the prairies. This led to the now widespread practice of "zero-tillage" to conserve soil moisture. Soil genesis is of great significance to Canada. Work by S. Pawluk (Alberta) on Gray Luvisols and Solonetz soils, and the application of micromorphology to the study of soil fabric is internationally acclaimed. The understanding of Podzolic soils, the "true" forest soils of Canada, has been advanced by A.J. McKeague (Ag.Can.), the Guelph group, S. Arp (New Brunswick) and K. Klinka (UBC). Soil biology is an internationally neglected field: there are probably more species in the soil than above it. D. Parkinson (Calgary), A. Fortin (Laval) and W.B. McGill (Alberta) have provided important insights into the intricate and essential role of soil organisms. Similarly, Canadian research is second to none on soil fungi (mycorrhizae) and their role in the phosphorus cycle. Environmental soil chemistry has a long tradition in soil science. Work on the effect of sewage sludge and other human effluents on soil and groundwater quality was pioneered by L. Weber (Guelph) and contributed to the formation of the Wastewater Technology Centre at Burlington. Activities at Guelph on effects of road salts, chemical spills, and landfills, as well as at Alberta on effects of petroleum spills on land, sulphur stockpiles, heavy metals and fly-ash (M.J. Dudas) have affected the way Canadians conduct business.

Soil scientists make important international contributions. Through the efforts of C.F. Bentley (Alberta), organizations such as ICRISAT (International Crop Research Institute for the Semiarid Tropics) have evolved. Canadians have had a major impact in developing sustainable soil resource principles. Following the Rio de Janeiro conference of 1993, the definition of sustainable land management developed at a Canadian Conference has been accepted by the International Board for Soil Research and Management and its member organizations, including the French Ministry of Foreign Affairs, the Overseas Development Agency of the United Kingdom, and the U.S. Agency for International Development.

Oceanographv

The oceans cover 71% of the Earth's surface and regulate Earth's climate and its hydrological cycle. They supply food and mineral resources, they are important for transportation, and are increasingly used as a waste repository. The discipline is developing rapidly as understanding of the physical and chemical behaviour of the oceans matures and as multi-disciplinary studies, often using new technologies (e.g., satellite and acoustic remote sensing, autonomous free-diving vehicles), produce new discoveries. Some of this activity is driven by concern over the effects of human activity on the seas. This concern is critical for Canada, which has an extensive coastline.

Canada is strong in ocean science despite the relatively small research community. Our understanding of the exchanges of heat, water and momentum between the sea surface and the atmosphere was largely established by the influential school at UBC led by R.W. Stewart, many of whose students are prominent researchers around the world. [1]. LeBlond (UBC) and L.A. Mysak (McGill) have published the definitive treatise on the subject of waves, while C.J.R. Garrett (Victoria) is a leading authority on internal waves and mixing in the ocean, and N. Oakey (Dalhousie and Fisheries and Oceans) and B. Ruddick (Dalhousie) are carrying out novel measurements of turbulence at sea. Ocean acoustics is an area of particular strength; D.M. Farmer (Victoria, UBC and DFO), who was this year awarded the second Walter Munk Medal in this discipline by The Oceanography Society, has carried out pioneering studies of the uses of sound in the ocean, and A.E. Hay (Memorial) is well known for his work on the acoustic remote sensing of suspended sediment. A world centre for studies of sea ice was established by E. Pounder at McGill, where there is currently a refocussing of effort on the role of the Arctic in climate change. Work on the physical and chemical controls on primary production in the ocean by T. Platt (Dalhousie and DFO) and his former students, notably M.R. Lewis (Dalhousie), is internationally recognized. In marine sediment geochemistry, significant contributions to our understanding of ferromanganese nodules on the deep-sea floor have been made by S.E. Calvert (UBC), and A. Mucci

DEREK C. FORD, Professor of Geography in McMaster University, is the leading authority on karst. The originator of a major modern theory of cave development, he has also contributed fundamental work on paleoenvironments by developing uranium series dating and stable isotope studies for speleothems (with H. F. Schwarcz). He received the Gold Medal of the International Speleological Union in 1973 and was its President in 1985-89. He has made major contributions to international science and development, particularly in central and eastern Europe, and has advised extensively on cavern conservation. In 1990, he was awarded the Dumont Medal of the Geographical Society of Belgium. He was elected FRSC in 1988.

(McGill) is one of a small international group of experts on carbonate mineral precipitation and dissolution in sea water media B.P. Boudreau (Dalhousie) is well known for his work on the mathematical modelling of chemical processes in sea-floor deposits. In paleoceanography, C. Hillaire-Marcel (UQAM), T.F. Pedersen (UBC) and L.A. Mayer (New Brunswick) have provided insights into changing oceanographic and atmospheric conditions in the Atlantic and Pacific over glacial – interglacial timescales from detailed studies of deep-sea cores, including those obtained in the ODP. Mathematical modelling of ocean circulation is a vigorous area of investigation by L.A. Mysak (McGill), R. Greatbatch (Memorial) and A. Weaver (Victoria). The University of New Brunswick Ocean Mapping Centre has recently been established by L.A. Mayer through cooperation between NSERC, ACOA, the Canadian Hydrographic Service and private industry to work at the leading edge of technology. There has already been considerable industrial spin-off from university research in ocean sciences, and vigorous marine and environmental consulting enterprises attest to this influence.

Recognition of the key role played by the ocean with respect to weather, climate and atmospheric chemistry have greatly increased the demand for information on the ocean system. The result is a proliferation of large, international scientific programs. Canadian oceanographers are heavily involved in the World Ocean Circulation Experiment (World Climate Research Program) and the Joint Global Ocean Flux Study (IGBP), with support from the NSERC Collaborative Special Projects program, and are poised to begin work in several other international collaborative programs, such as PAGES (Past Global Changes) and LOICZ (Land-Ocean Interactions in the Coastal Zone) of IGBP.

Atmospheric sciences

The atmosphere is our source of oxygen and freshwater. The stratospheric ozone layer protects the Earth from harmful ultraviolet radiation; winds disperse pollutants; while the natural greenhouse effect maintains the planet's average temperature above freezing. Climate governs human activity, while severe weather wreaks social havoc. The atmospheric scientist seeks to understand these phenomena, to predict their occurrence and, increasingly, to anticipate the effects that human activities have upon the atmosphere.

In Canada, the Atmospheric Environment Service of Environment Canada leads a strong national research effort that is closely tied to weather and climate forecasting requirements. There is close collaboration with the university community, so that the total research effort can fairly be said to be optimized. The broad scope of Canadian atmospheric science is fostered by recognition of the role of mass and energy exchanges between the atmosphere and other components of the environment. This has led to strength in the atmospheric boundary layer, with special attention to forest (e.g., P. Schuepp, McGill) and tundra (W.R. Rouse, McMaster) environments, agricultural and forest biometeorology (T.A. Black, UBC and a group at Guelph, amongst whom D. Thurtell is noted for his contributions to instrumentation). T. Oke (UBC) is the world's leading student of urban climate; notably, he has placed understanding of the urban "heat island" on a sound physical basis. Mesoscale circulation is studied by several groups, including that of J. Derome and colleagues at McGill which is investigating the limits of predictability. Canadians have been world leaders in developing high performance algorithms and models, a notable success being the "breaking-internal-wave" theory for Chinook windstorms (W.R. Peltier, Toronto), which has received wide international recognition. A cooperative McGill/UQAM/AES project has led to a world-class mesoscale community model for weather prediction. Canadian expertise has also focused on the use of radar to "see" the rain and now the wind. These and other instrument systems have been brought together in a sequence of studies to understand Canadian winter storms which has also involved extensive oceanographic studies of hazardous marine conditions brought on by storms. H.-R. Cho (Toronto) and D.L. Zhang (McGill) have contributed important work in this area, as has P. Taylor (York). Strong leadership is provided for study of the dynamics and chemistry of the middle atmosphere by CIRAC (Canadian Institute for Research in Atmospheric Chemistry), at York, while important contributions to understanding the status of stratospheric ozone have come from W. Evans (Trent).

A "global warming crisis" is predicated on the observed increase in the atmospheric concentration of greenhouse gases. The effect will be greatest in high latitudes, so is crucial to Canada. But, as yet, climate variations remain entirely within the realm of natural variability. Canadians are leading contributors to studies of the larger spatial and longer time scales of the global climate system necessary to resolve this problem: Roger Daley (AES) in particular designed the Canadian spectral general circulation model, universally recognized as one of the best in the world. Uncertainty about the feedback between clouds and radiation still limits current climate models. Work on the solar radiation budget at the surface includes that of H. Leighton (McGill), whose satellite-based estimation methods will be used to interpret EOS data. Research in this area is expanding rapidly, and the results will contribute substantially to improvement of the Canadian Climate Model of the AES, which will enable Canada to make more informed decisions regarding the impact of climate change.

Remote sensing and mapping

Canada has the second largest land mass of all countries, but has only a relatively small population. One of the most cost-effective approaches for resource exploration,

P.M. HUANG, Professor of Soil Science in the University of Saskatchewan, is an environmental geochemist investigating surface chemistry and mineralogy of soils. He has pioneered study of the interaction of mineral colloids and organic material in soil-water systems, hence connecting biochemistry and mineralogy. He also studies trace heavy metals in soils, thence food chain contamination. He has been elected Fellow of the American Society of Agronomy and of both the Canadian and American Soil Science Societies, and is Honorary Professor in the universities of Huangzhou and Guanxi. His work is comparable with that of Dr. Udo Schwertmann, soil mineralogist at the Institut fur Bodenkunde, Freiburg, Germany.

environmental monitoring and research in cold and remote regions is by use of airborne and spaceborne platforms. Accordingly, remote sensing is a highly developed field in Canada, having grown out of Canadian leadership in the use of air photography for mapping and resource appraisal.

In 1995, Canada will launch RADARSAT. Canadian scientists have made major developments in interpretation methods in anticipation of this satellite, notably at the centre CARTEL at Sherbrooke, led by F. Bonn. Algorithms for automatic data reduction, including the application of fuzzy logic and Bayesian decision procedures to interpret imprecise or transitional features, are actively pursued by groups led by C. Gold at Laval and W. Moon at Manitoba. Geographic information systems, closely allied with remote sensing for data storage and analysis, were first conceived in Canada. Canadian university scientists continue to contribute basic algorithms that underlie developments in GIS and to investigate methods for use of GIS to update spatial data rapidly (P. Howarth, Waterloo Centre for Remote Sensing). Developments in GIS have generated a substantial private sector industry.

Geophysical methods for imaging the solid Earth are also remote sensing techniques. Methods for high resolution, shallow penetration of surficial materials have not been well developed, but a major innovation in the 1980s was the development in Canada of ground penetrating radar by Peter Annan. This instrument is an important new tool for field studies of groundwater and Quaternary stratigraphy. Similarly, L. Mayer (UNB) was co-developer of the CHIRP marine sub-bottom sonar, and an innovative shallow seismic reflection technique has been developed by J.A.M. Hunter and S. Pullan (GSC), initially for mapping permafrost.

Environmental chemistry

There is growing concern about rapid changes in the chemistry of the environment and their potential impact on humankind. Canadians are exposed to acid aerosols and urban smog, polluted water and contaminated soil. A growing number of studies have linked air pollutants to respiratory problems and contaminants to chronic or even acute community health problems. The Canadian university centre for work in this area is at York, which hosts CIRAC, built under the guidance of H. Schiff.

The use of isotopes to understand the spatial dispersion of contaminants, and the historical evolution of Holocene environment, is pursued in a number of Canadian laboratories, notably GEOTOP, at UQAM. A particular focus of Canadian work is the carbon budget of northern wetlands. This has been approached by phytological (T. Moore, McGill), hydrological (N. Roulet, McGill) and micrometeorological measurements (W.R. Rouse, McMaster) in the Northern Wetlands Project of CIRAC, BOREAS and other programs. Studies of peat accumulation over Holocene time (B. Warner, Waterloo) give a unique long range perspective.

Chemical binding of substances affects their reactivity and thus is fundamental in dissolution studies, pollution, toxicity, and waste reclamation. Most metals bind at surfaces affected by natural organic matter, calling for new biogeochemical approaches. Canadians are among the world leaders studying many aspects of the complex transformations that occur in soils (*e.g.*, L. Evans, Guelph), in lake and river waters and their suspended sediments (J. Kramer, McMaster, Y.K. Chau, McMaster), and in groundwaters (E. Reardon and S. Frape, Waterloo). A. Campbell and A. Tessier (INRS-Eau) lead a major effort to understand the chemistry of the water/sediment interface, a significant sink for mobile aqueous contaminants. On the global scale, satellites are invaluable for observing pollutants. The Canadian designed MOPITT (Measurement of Pollution in the Troposphere) instrument of J.R Drummond (Toronto) is the sole Canadian payload scheduled to be launched into space on NASA's EOS (Earth Observing System) satellites. It will measure the concentrations of CO and CH^4 in the atmosphere.

Paleoenvironmental studies

The surface of the Earth provides the substrate for life while itself being shaped by biological activity; the resulting interactions are a fundamental part of both Earth science and the life sciences. Greater understanding of these interactions is essential if we are to assess and manage the impact of human activity on the environment. The environments of the past provide a wide spectrum of changes in response to primary climate variation, and the diversity of our landscape reflects a range of environmental histories. Paleoenvironmental analysis therefore is concerned with the history of climate and the record of environmental response.

Fossil pollen analysis provides one of the best means of acquiring empirical information on the possible long-term response of ecosystems to climate warming. Under the influence of J.C. Ritchie (Toronto) Canada has developed several world-class palynological laboratories. That led by R. Mathewes at Simon Fraser is concentrating on late Pleistocene changes and Holocene vegetation history on the west coast, while L. Cwynar, at New Brunswick, is similarly studying the east coast. G.M. McDonald (McMaster) is studying the boreal ecotone using palynological and dendrological methods, while P. Richard (Montreal), a world leader in the field, is developing a systematic picture of postglacial vegetation history in Quebec. Tree rings hold vital information on the natural range of climatic variation over the last 1000 years; S. Payette, L. Filion and Y. Begin at the Centre d'etudes nordiques (Laval) have made a major

CHRISTOPHER J. R. GARRETT moved from the Department of Oceanography in Dalhousie University to become Landsdowne Professor in the School of Earth and Ocean Sciences in the University of Victoria. He is one of the foremost authorities on ocean waves, including internal waves and tides, and mixing processes in the ocean. He has made seminal contributions to our understanding of turbulence and circulation in straits, and has made important contributions to the prediction of iceberg trajectories and the potential consequences of radioactive waste disposal in the deep ocean. He has been a Steacie Fellow (1977-78) and a Guggenheim Fellow (1981-82). He was elected FRSC in 1977 and FRS in 1993. His work is broadly comparable with that of Stephen Thorpe, University of Southampton, U.K.

contribution to understanding Holocene climate and tree-line fluctuations in northeastern North America. History in the Western Cordillera is the subject of long-term studies by B.H. Luckmnn (Western).

Closely allied with this work is investigation of the neoglacial history of the mountains, led by Luckman and G. Osborne (Calgary). Holocene history can also be recovered from physical and chemical studies of lake deposits, and this is an important method on the Canadian prairies. W. Last (Manitoba) is an acknowledged world leader in the study of saline lakes. D. Huntley and E. Nelson (SFU), N. Rutter (Alberta) and the groups at GEOTOP and McMaster have made important contributions to dating techniques pertaining to the last two million years.

Industrial Impact of Canadian Research

The traditional industrial orientation of the Earth sciences is toward the mineral and hydrocarbon industries. The Environmental Earth sciences retain this orientation. Most reconnaissance mineral prospecting today takes the form of soil, plant or water sampling for chemical signatures. Sampling and interpretation are based on knowledge of regional Quaternary history, and contemporary geomorphology and hydrology. As well, engineering and environmental problems at mine sites rely for resolution on similar knowledge at a local scale.

However, the applications of environmental Earth science extend far beyond these traditional industries. In many provinces, a terrain map — depicting topography, drainage and surface materials — is now the basis for land use planning, particularly in forestry and agriculture, and in planning major communication routes. The recently legislated *Forest Practices Code* of British Columbia requires the production of such a map, by a professional geoscientist, as the first step in forest land planning. Soil maps are, of course, the traditional basis for agricultural land assessment. The industrial value of such activities is not separated from the general costs of resource development, and so value to the economy cannot separately be assigned. These activities have, however, spawned dozens of consulting companies within the past decade.

Another important area of industrial application is the control of mine and industrial wastes, rehabilitation of contaminated soil and remediation of wastewater, particularly ground water. This has become a major focus of research in several university departments. For example, the Waterloo Centre for Groundwater Research (WCGR) has been particularly successful at creating marketable products as an outgrowth of its groundbreaking research. Six spin-off companies have been created over the last 6 years, and 21 technologies developed at the centre by members or their technicians have had patent applications filed; 10 of these have been granted. There are also 17 commercially available software packages that have been developed in the centre. The application of the results, again, commonly occurs in the context of larger projects for which no breakdown of costs and benefits isolates the Earth science contribution.

Weather and marine forecasting are of immense commercial value and in addition, are of vital importance for safety in the transportation and communications industries, as well as for general public security. In these areas, the relations between research and operational forecasting are virtually seamless. The need for improved forecasting methods directly drives a substantial part of the atmospheric science research agenda

Costs of Research

The requirements and *modus operandi* of research in Earth sciences are especially stringent. Canadians have been world leaders in the transition from descriptive to analytical Earth science. This has required substantial funding for new field instruments and the analytical facilities that are necessary to study collections from the field are sophisticated and costly. Realistic modelling of Earth systems requires the fastest and often the largest computing facilities available. And the discipline also requires extensive field programs, often in adverse and remote environments and sometimes requiring large, expensive platforms. Canada is internationally known for its highly productive, field-based research programs.

Information on the Price Index for Research Grant expenditures (NSERC Cost of Research Report (COR) Table 1) shows that Earth scientists used the bulk of their grants for laboratory costs (materials), technical assistance (other salary) and for travel. The latter including field work. Researchers in other disciplines have used more of their funds to support students and post-doctoral fellows, where the

W. RICHARD PELTIER is University Professor of Physics in the University of Toronto. His polymathic work in geophysical fluid dynamics (GFD) and mathematical geophysics involves the dynamics of atmospheres and oceans and of the Earth's deep interior. He writes widely on the mantle convection process and on the theory of ice ages. He was a Steacie Fellow (1978), a Canada Council Killam Research Fellow (1980-82), Guggenheim Fellow (1986-88), and was elected FRSC in 1986. His work on viscoelastic Earth models has been compared to that of Freeman Gilbert of the Scripps Institution of Oceanography, while that in GFD is similar in style to that of Richard Lindzen of MIT.

CLAUDE HILLAIRE-MARCEL holds the NSERC/Hydro Quebec Research Chair in the Environment at the Universite du Quebec a Montreal. He is a world authority on the application of stable isotopes to study past climates as recorded in lake and marine sediments. He established GEOTOP, Canada's foremost environmental isotope research laboratory, and is now deeply involved in studying biogeochemical systems and the ways in which they are affected by global change. He was elected FRSC in 1991 and received the Prix Michel-Jurdent in 1992. His work is comparable with that of Jean-Claude Duplessy, Director of the CNRS Centre des faibles Radioactivites Gif-sur-Yvette, France.

inflation rate apparently has been much higher (COR Table 3). However, the price index for travel is derived from the Statistics Canada transportation and travel price index, which poorly reflects inflationary trends for field work in remote regions .

A sample of 30 of the leading 1095 of researchers in Environmental Earth sciences (selected on the basis of their impact on the discipline and their international stature, rather than grant size) showed that they average $232,176 total in research support annually, including $56,936 in the form of a Research Grant (ratio = 3.9). During 21 years of NSERC support, they have educated a total of 24 graduate students each and have worked with 4 post-doctoral fellows. They currently have 6 graduate students and one post-doctoral fellow in their group. In comparison, a random sample of 46 established researchers (middle to late career scientists with established and stable research programs, excluding the top 10%) averages a total of $205,842 in research support, including $29,232 in the form of a Research Grant (ratio = 7.0). After 15 years of NSERC support they have educated a total of 17 graduate students each and have worked with 2 post-doctoral fellows. They currently supervise 5 graduate students and one post-doctoral fellow each.

There is relatively little difference in total research funding between the two groups. However, the Top Researchers (COR Table 6; not the same comparison group) devote more of their funds to personnel (other salary and post-doctoral stipends) and somewhat less to travel compared with the whole community. Representative annual budgets (not including major equipment) for leading researchers in Environmental Earth sciences are shown in Table 2. The data are generalized from the actual budgets of leading individuals. The data show that these researchers spend 54% to 74% of the budget on personnel. This reflects the increasing requirement for laboratory and field assistance amongst those engaged in larger programs. The availability of funds to support more post-doctoral fellows and research assistants would accelerate research programs significantly, but Earth scientists cannot afford to devote more of their budget to this end because of high field and laboratory costs.

Earth scientists have been very successful in obtaining grant support for their research programs from a wide range of sources. Table 3 shows that for both groups of Environmental Earth Sciences researchers surveyed, the current average ratio of total funding to Research Grant awards exceeds 3; it commonly lies between 4 and 6. This shows that Earth scientists have been very successful in diversifying the sources of research funds.

Vision for the Future

Continued participation of environmental Earth scientists in the resource industries is inevitable due to the requirement of Canadian industry to optimize resource extraction and to maintain sound environmental practice and awareness. Environmental geology is consequently a growing sub-discipline in this context, and Canada is exceptionally well placed to lead the field. This country is already the international leader in the field of mine and polluted groundwater control and remediation and in operational terrain mapping.

Global events, including natural and anthropogenic hazards and environmental change, whether they occur within or outside our national frontiers, affect Canadians directly. Canada's comparatively pristine state offers some of the best field sites to document the current condition of a large, high-latitude landmass. Its social stability promises some of the best opportunities in the foreseeable future to study the effects of environmental change. It is imperative, therefore, that Canadian scientists continue to exercise leadership in understanding northern environments. At the same time, our more polluted agricultural and industrial heartland is in need of remediation before the effects of pollution become irreversible. This will require novel strate-

Table 2. Representative annual budgets required by top researchers in solid Earth sciences specializing in laboratory-, field-based and theoretical studies

			Laboratory		Field		Theoretical	
Category	**Item**	**Unit Cost**	No.	Total Cost	No.	Total Cost	No.	Total Cost
Personnel	Undergrads	4000	1	4000	1	4000	1	4000
	Grads	15000	5	75000	4	60000	5	75000
	PDFs	27500	3	82500	3	82500	2	55000
	Technicians	30000	3	90000	2	60000		
	Res Assts [1]	7500			2	15000		
	Res Assocs	55000					1	55000
Equipment	Capital [2]			15000		15000		25000
	Maintenance			25000		15000		35000
Materials [3]				35000		50000		45000
Travel	Field Work [4]					20000		
	Conference			10000		10000		35000
Others	Computing			3000		5000		20000
Totals:				**$339,500**		**$336,500**		**$349,000**
Special Field Logistics (ships, aircraft, etc.)						**$130,000**		

[1] *Field-based research requires student assistants for individual field projects*
[2] *Items costing less than $7000*
[3] *Materials includes materials, supplies, analytical costs, publication costs*
[4] *Field work includes laboratory visits but does not include access to remote regions*

TABLE 3. Funding leverage in Environmental Earth Sciences

Sample	Avg Total Funding	Avg Res Grant	Ratio T/RG	Range of Ratios
Leading 10%	232,176	56,936	3.9	1-15
Random established	237,367	29,077	8.1	1-30*

**One extreme outlier at 76.8. (The ratios reported differ from the historical average figure reported in the* Introduction *for the entire Earth Sciences group because they are based on subsamples of the group and only one reporting year)*

gies and technical innovations founded in our understanding of Canadian conditions.

An emergent trend in environmental Earth science is for increased interaction between observational scientists and modellers to produce physically well-constrained models of the atmosphere/hydrosphere/cryosphere system. These models will increasingly incorporate the chemical cycles of the Earth system, hence they will also incorporate biospheric processes. As a consequence, traditional subdiscipline boundaries are collapsing. A significant dimension of observational and modelling efforts is the extension of modelling to regional scale. An important specific goal is to incorporate chemistry and cloud physics into GCMs. Another important goal of direct collaboration between observers and modellers is the development of mesoscale weather and hydrological forecast models that are continually tuned by new observations.

Nonlinear modelling will become more pervasive at all scales, from local groundwater flux, through ocean and atmosphere models, to models of the Earth's core and mantle. Computing power and observing ability now make it possible to incorporate the inhomogeneity of the Earth matrix into the models as well. Allied with these developments will be studies of the limits to predictability in Earth systems. It is now recognized that certain effects in the atmosphere and oceans are unpredictable because they are coupled with higher frequency phenomena which cannot be forecast out to the requisite time scale. Mixed stochastic deterministic models of phenomena, particularly at the regional scale, will be the result.

There will be an increased emphasis on all aspects of environmental chemistry, with the emergence of biogeochemistry as a signiffcant field of study in the atmosphere and hydrosphere, and in the study of microbial activity in the soil and rocks. This will be a significant area of joint activity with solid Earth scientists. A specific goal will be understanding the role of biota in the evolution of groundwater chemistry and application of this knowledge to contaminant remediation.

Observational Earth science will be strongly influenced by improvements in sensors and instruments over the next five years. Examples include the development of microprobes to study the chemistry of water/sediment interfaces; the growth of acoustic methods for probing the oceans; the launch of RADARSAT; and developments in geodesy and navigation which will yield centimetre precision in location. GC-C-IR mass spectrometry provides molecular resolution for study of the organic chemistry of the environment. Toward the end of the decade the EOS satellites will begin to yield a mammoth volume of new data for analysis. At the same time, the science will become more deliberately experimental. It is always difficult to conduct an experiment *sensu stricto* at full scale in the environment because the achievement of experimental control over the variates is virtually impossible. By careful selection of the location or timing of observations, however, discriminating results may be obtained. A particularly important question is how to apply the results of experiments necessarily conducted at relatively small scale to understand large-scale phenomena of the Earth system. Closer fusion of observation and modelling will generate systematic attention to the problem of scaling observations up from local to regional to global scales.

The science of the Earth's history will benefit by the development of methods to obtain near continuous high resolution records of former environmental conditions over long portions of the Quaternary period from oceanic and terrestrial sediments. At favorable sites, Holocene history will be resolved to within a few years. Very high resolution palynological records will permit stand to landscape-scale vegetation dynamics to be studied, placing the interpretation of Quaternary vegetation history on a firmer footing. It must be recognized, however, that unravelling the history of the Earth and the evolution of the biota – including humankind – depends in substantial degree upon the serendipitous discovery of key evidence. The ability to support the search for and analysis of such discoveries is a key feature of the NSERC Research Grants program.

Summary

The environmental Earth sciences in Canada are in a phase of dynamic growth. New tools, new concepts, and rapidly expanding interest in protecting our environmental heritage are opening up new questions and demolishing old

LOUISE FILION is Professor in the Centre d'etudes nordiques (Director, 1987-1992) at the Universite Laval and President of the Commission de la recherché of the university. She has pioneered the study of interactions between vegetation and landform dynamics. She studies Holocene paleoclimate and paleoecology using dendrological and geomorphological evidence, and has specialized in the history of wind deposits in the difficult terrain of subarctic Quebec. She is vice-Chair of the Canadian Polar Commission and was recipient of the Prix Leon-Lortie (1991) for science of the Societe Saint-Jean-Baptiste.

disciplinary barriers. The concept of the "Earth system" is effecting a synthesis of work on the contemporary environment complementary to that achieved a generation ago by plate tectonics for deep geological time. The community is building from a position of substantial strength, as can be attested by the international dominance of Canadian contributions, relative to research investment; by the high leverage attained for research funding; and by the recognition accorded our leading scientists. We gain additional strength from our secure and close collaboration with solid Earth scientists. And we have a vigorous cohort of younger scientists who, given adequate support, will certainly increase Canadian contributions and strength in this socially important field.