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The Oceans

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Article abstract

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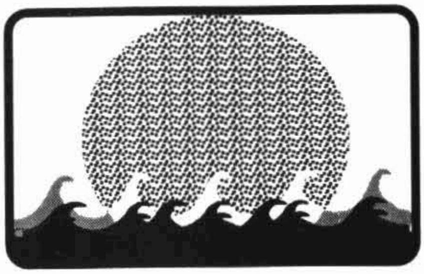
Additionally, new developments in acoustic sensors and signal processing will greatly enhance our ability to imagethe oceans and the sea floor, and advances in data collection and data dissemination (networking) will significantly change the way we do globalscience. Arrays of autonomous sensors, satellite links, and global data networks may eventually reduce the cost of large-scale ocean-related research programs. Canada must be well-positioned both to contribute to, and to benefit from, these programs. Our challenge will be to ensure that the mechanisms (and funding levels) are available to support Canadian participation without compromising the efforts of the talented researcher who prefers to work independently, and to find the means to train excellent "earth system scientists" without compromising the high levels of specialized expertise needed to explore even small components of the system.



The Oceans

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ABSTRACT

The oceans play a pivotal role in the earth system matrix and will thus be a critical component of future earth system research. This research will be driven by both technological advances and the need for an interdisciplinary approach. The scale (both spatial and temporal) of ocean-related problems often requires expensive, large-scale, international programs. These programs are evolving into interdisciplinary looks at manageable sub-components of the system including: 1) investigations of global patterns of ocean and atmosphere circulation through networks of moorings, satellites and drifting sensors (*e.g.*, World Ocean Circulation Experiment), 2) investigations of the role of the oceans in the global CO_2 system through deployment of sophisticated chemical and biological sensors, satellite observations, and flux measurements (*e.g.*, Joint Global Ocean Flux Study), 3) establishment of a global database of high-resolution paleoclimatic time-series for investigations of the response of the earth/atmosphere system to known forcing functions and to changes in boundary conditions (*e.g.*, Ocean Drilling Program (ODP) and Nansen Arctic Drilling paleo-oceanography), 4) investigations of mid-ocean ridge dynamics and the complex and linked processes of magmatism, hydrothermal circulation, vent community development and lithosphere evolution (*e.g.*, RIDGE and ODP crustal drilling).

Additionally, new developments in acoustic sensors and signal processing will greatly enhance our ability to image the oceans and the sea floor, and advances in data collection and data dissemination (networking) will significantly change the way we do global science. Arrays of autonomous sensors, satellite links, and global data networks may eventually reduce the cost of large-scale ocean-related research programs. Canada must be well-positioned both to contribute to, and to benefit from, these programs. Our challenge will be to ensure that the mechanisms (and funding levels) are available to support Canadian participation without compromising the efforts of the talented researcher who prefers to work independently, and to find the means to train excellent "earth system scientists" without compromising the high levels of specialized expertise needed to explore even small components of the system.

RÉSUMÉ

Les océans jouent un rôle central dans l'écheveau des réactions du système-Terre (la Terre comme un ensemble organisé), et à ce titre seront un sujet de première importance dans les prochaines recherches sur le système-Terre. Ces recherches seront réalisées grâce à des percées technologiques, et naîtront de la nécessité d'approches interdisciplinaires. L'échelle même des problèmes reliés aux océans, aussi bien temporelle que spatiale, requière l'élaboration de programmes internationaux de grande envergure et coûteux. En ce moment, ces programmes évoluent vers des approches qui portent sur des sous-composantes du système — leur dimension les rend plus facile à gére — et qui comprennent: 1) l'étude des patrons de circulation dans l'atmosphère et dans les ocèans au moyen de réseaux de capteurs qui sont ammarrés, dérivants, ou embarqués sur satellites. Par ex. l'Experience sur la circulation océanique mondiale;
2) l'étude du rôle des océans dans le cycle planétaire du CO_2, grâce au déploiement de capteurs chimiques et biologiques perfectionnés, de satellites d'observation, et à des mesures de flux. Par ex. *Joint Global Ocean Flux Study* (étude conjointe des flux océaniques du globe);
3) la création d'une base de données à l'échelle du globe de suites paléoclimatiques très précises et définies en fonctions du temps, afin d'étudier la réponse du système terre-océans (continents et océans comme système) à des fonctions de forçage connues, de même qu'à des changements des conditions ambiantes à l'interface. Par ex. le Programme de sondage des fonds marin (PSDFM) et le *Nansen Arctic Drilling* (projet de sondage du plateau polaire à Nansen);
4) l'étude de la géodynamique des rides

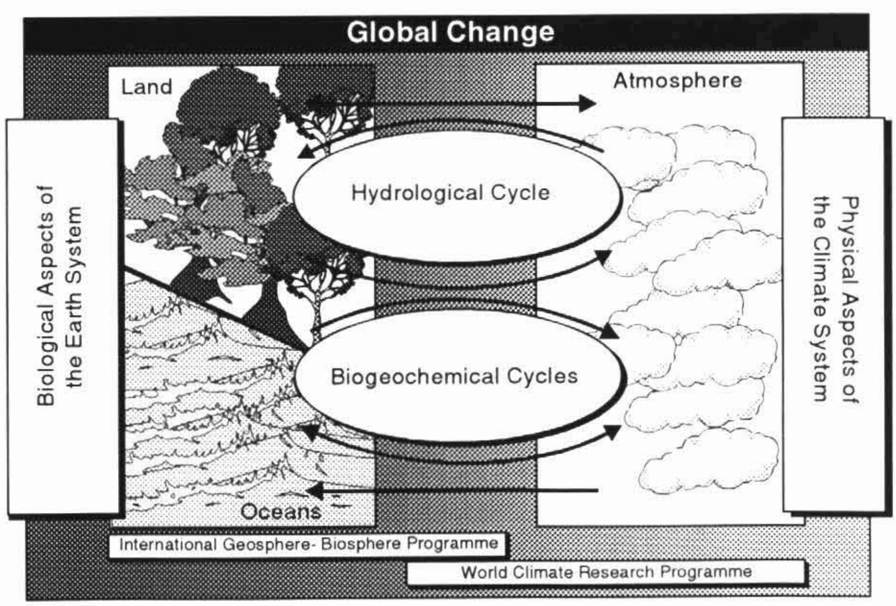

Figure 1 *Conceptual picture of linkages among chemical, biological and physical processes critical to our understanding of global change (from IGBP, 1990).*

mid-océaniques ainsi que des géomécanismes complexes du magmatisme, de la circulation des fluides hydrothermaux, de la mise en place de réseaux d'évents volcaniques, et de l'évolution de la lithosphère. Par ex. les projets de *RIDGE* et du PSDFM).

De plus, les dèveloppements récents dans les domaines des capteurs acoustiques et du traitement des signaux amélioreront grandement nos capacités à mettre les océans et les fonds océaniques en image. Également, les progrès dans les techniques de cueillette et de dissémination des données (leur mise en réseau) changeront considérablement nos façons de traiter des problèmes scientifiques globaux. Les ensembles de capteurs autonomes, les liaisons par satellites, et les réseaux planétaires de données pourraient entraîner une réduction de coût des grands programmes de recherches sur les océans. Le Canada doit s'assurer de participer à ces grands programmes et de profiter de leurs retombées. Notre défi consistera à nous assurer que les mécanismes ainsi que les moyen de financement seront disponibles pour assurer la participation canadienne sans pour cela entraver les efforts de chercheurs talentueux qui préféreraient travailler de façon indépendante. Nous devrons également trouver les moyens de former des «scientifiques du système-Terre» sans que cela ne compromette l'existence des spécialités nécessaires à l'étude de quelques composantes particulière du système.

INTRODUCTION

One of the most exciting advances of the last few decades has been the recognition of the complex connections of the global earth system (Fig. 1). We have come to realize that we can no longer think of the Earth in terms of independent, distinct systems, but rather, if we are to gain a predictive understanding of Earth processes, we must think about these Earth processes in a globally consistent manner that incorporates the interactions and feedbacks of the Earth's various subsystems.

Coupled with these conceptual advances have been major breakthroughs in instrumentation and analytical techniques. These advances have allowed us, for the first time, to develop qualitative and even numerical models that begin to describe (albeit in a very simple manner) the complex "inter-workings" of the earth system (Fig. 2). Despite these breakthoughs, the system is so vast and our understanding of it still so primitive that we are forced to break down the system into more manageable subcomponents. Our challenge is to develop research and training approaches that are sufficiently specialized and focussed to provide a detailed understanding of a particular component, but at the same time take into account the interconnections of the system. As our models evolve, 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. This discussion will focus on future research trends in this key component of the earth system.

The ocean system is too large for an all-inclusive discussion and, despite some effort to objectively discuss the topics presented, the perspective is inevitably a personal one, biased by my background as a deep-water marine geologist. And so, from the outset I apologize for my omissions: most notably, the lack of discussion of coastal, nearshore and margin programs. There is no question that these areas represent critical components of the ocean system, but rather than risk misrepresenting fields that I am unfamiliar with, I have chosen to focus on topics that I am more comfortable with, hoping that their discussion will serve as examples of the approach that future marine geoscience may take.

THE OCEANS

The remote and opaque nature of the oceans have made marine science a field 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, global access, and 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 to 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

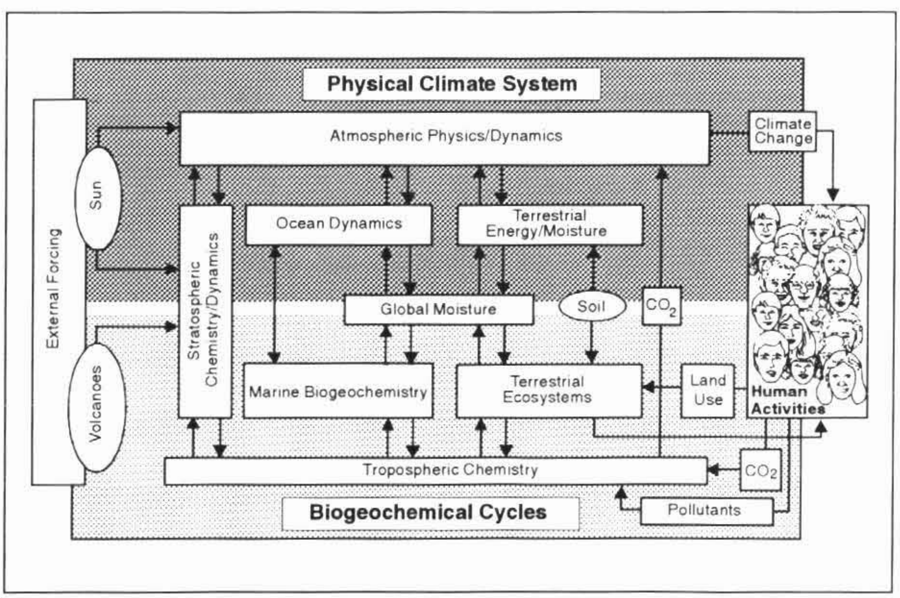

Figure 2 *Interconnections of identifiable subcomponents of the earth system (from IGBP, 1990).*

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.

RESEARCH FOCUS AND TECHNOLOGICAL ADVANCES

As examples of the approach outlined above, four 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, these being 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 focussed on the World Ocean Circulation Experiment (WOCE), 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 focussed 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 that use satellite links to automatically telemeter their position and data to shore-based labs will be deployed.

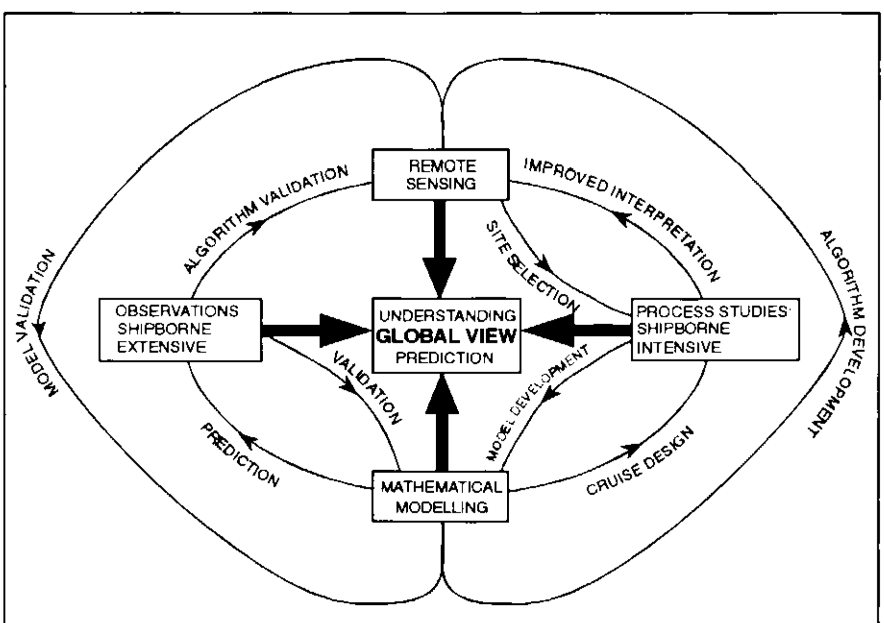

Figure 3 *Schematic diagram outlining JGOFS approach to integrating subcomponents of the system (from SCOR, 1987).*

Oceans in the Global CO_2 System

During 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 parts per million (ppm) to a present day value of 350 ppm. The ultimate climatic effect of this "greenhouse" experiment is unknown, with predictions ranging from catastrophic to negligible. We do know, however, that the ocean stores approximately 50 times more CO_2 than the atmosphere and thus plays 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 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 the Joint Global Ocean Flux Study (JGOFS) 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 modelling scheme (Fig. 3). Satellite-borne sensors will produce the global distribution of variables such as wind speed and chlorophyll (from colour 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 interface, as well as within the water column. Most importantly, critical links with the modellers 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 to accurately 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 with 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 paleo-oceanographic "proxies", each recording the behaviour of a particular component of the global climate system (*e.g.*, the $\delta^{18}O$ signal preserved in the skeletons of benthonic micro-organisms is a good indicator of global ice volume, the distribution of eolian sediments is an indicator of aridity, as well as of past wind speeds and directions). Sediment cores recover a multichannel time-series of the history of earth system change, and the paleo-oceanographer'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 paleo-oceanographic 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 that 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 that can extend back millions of years. Just as importantly, ODP has provided the structure and focus for planning global experiments aimed at exploring: the nature of short period climate change; longer period climate change; the history, causes and effects of changes in sea level; the history of the carbon cycle and paleoproductivity; and 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) paleo-oceanographic records with temporal resolution on the order of thousands of years. In special environments (*e.g.*, fjords), these techniques can produce long records with annual to decadal resolution.

In planning global paleo-oceanographic 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 (approximately 20 km^3/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 seawater 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 multi-disciplinary program called the International Ridge Interdisciplinary Global Experiment (InterRIDGE) has evolved. This program calls upon a hierarchical investigative strategy for mapping and sampling the ridge system including: reconnaissance surveys of poorly known components (*e.g.*, back-arc basins); more detailed surveys of the spatial and temporal evolution of ridge "segments" (30-100 km long pieces of the ridge typically characterized by a single bathymetric high; and very detailed investigations within single segments of the ridge system.

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

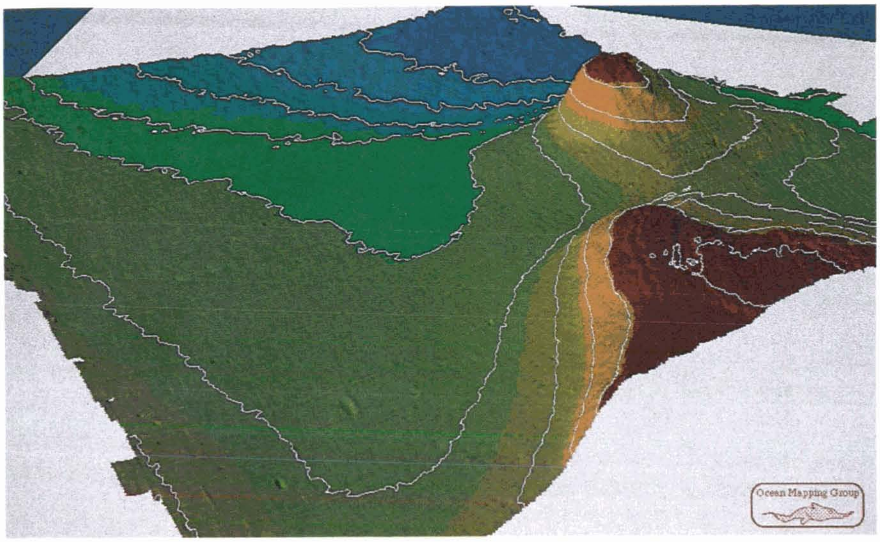

Figure 4 *Newly developed sonar systems and visualization techniques are providing unprecedented views of the sea floor allowing the simultaneous display of both topography and acoustic backscatter. Image is of approximately 3×3 km area of sea floor off Conception Bay, Newfoundland. Data was collected with Simrad EM-100 multibeam sonar system and processed by the University of New Brunswick's Ocean Mapping Group.*

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

A CANADIAN PERSPECTIVE

As demonstrated by these examples, I envision a future for marine science that revolves around large-scale, interdisciplinary programs that focus on manageable sub-components of the earth system. The spatial and temporal scale of ocean-related problems requires this approach. Let us look again to ODP and its predecessor, the Deep Sea Drilling Project, as one of the very first examples of this type of program. After twenty-five years of operation and a long list of impressive results (*e.g.*, confirmation of the theory of plate tectonics, discovery that the Mediterranean dried up, critical insights into crustal structure and ocean history) the international drilling program is going strong, and still producing exciting results. Most relevant to our discussion here, a program of this magnitude (and thus many of these results), could not have come to fruition without a large-scale, globally focussed, globally funded initiative. While the magnitude of these programs is often intimidating, future developments in data acquisition techniques, telemetry, and networking technologies should make such programs more efficient and manageable. The key question is: How well is Canada positioned to contribute to, and benefit from, these programs?

The potential role that Canada can play in these programs is evident if we look at the level of involvement of individual Canadian scientists in the initial formulation and planning of each of these programs. Canadian scientists have been key players in the organization of many of these programs, and others have been sought out to serve on their international advisory panels. Clearly, the international community recognizes the contribution that the Canadian scientific community has to make. It has been more difficult, however, to establish *official* Canadian representation in some of these programs and, in particular, to establish official Canadian national research efforts.

For example, while Canada is now a member of ODP, the Deep Sea Drilling Project operated for more than fifteen years without official Canadian representation. The Canadian geoscience community suffered from this and is only now beginning to recover. A small Canadian WOCE program has been funded, and after a long and sometimes painful process, a Canadian JGOFS program has just been funded, though many years behind the international community. Individual Canadians are active participants in InterRIDGE and NAD, but at present their involvements are ad hoc with little official sanction.

The problem seems to lie in identifying a clear mechanism or agency for establishing official Canadian participation and programs. 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 under the direction of several different departments. As multidisciplinary programs evolve, we are thus faced with the task of co-ordinating the interaction of several federal departments. Past experience has shown that this can lead to lots of buck passing and finger pointing; everyone is interested, but each thinks that another department should pay.

The problem appears to be getting worse lately. Our government labs have a number of very talented ocean scientists. Unlike their academic colleagues, however, they work for departments with specific and often evolving mission statements. There is no question that the mandates of these departments incorporate many of the objectives of the large-scale interdisciplinary programs such as those described. Over the past few years, however, there has been a growing trend for the work of the government labs to become more focussed and "client-oriented". Given the current distribution of ocean researchers in Canada, this process is creating a serious void, leaving only a small number of relatively poorly funded and equipped researchers who are free to take the long-term outlook necessary for addressing global research issues. This problem is further compounded by the fact that almost all of the rapidly diminishing fleet of research vessels and the major ocean-related facilities are operated by the government labs. This process is seriously threatening Canada's ability to play a viable role in the marine sciences.

What can be done about this? I believe that there must be a concerted effort to co-ordinate and solidify the links between the academic community and government researchers. We need to identify a body that can serve to co-ordinate Canada's role in international earth system research programs, act as the focal point for the organization of Canadian national programs, and serve to lobby the highest levels of government for worthwhile research causes. This body should be made up of representatives of the various constituencies (government departments, academia and perhaps industry) and have a budget of its own, but not be dependent on or responsible to any one department. Ideally there would be new (perhaps Green Plan) money, for this effort, but if a zero sum game must be played, funds could be tithed from the supporting departments. The body would review proposals for Canadian participation in (or initiation of) various interdisciplinary earth system projects and, for those deemed meritorious, establish a budget and maintain some oversight authority. The body should not be charged with managing the Canadian national programs, but should rather facilitate their organization. Once established, the Canadian national programs would have a management structure of their own.

Within such a body, the Natural Sciences and Engineering Research Council (NSERC) should be a representative of the academic community. We must encourage NSERC to accept its responsibility as the primary sponsor of basic research along with the fact that many of these interdisciplinary programs *are fundamentally basic re* search. NSERC should also attempt to encourage an occasionally insular academic community to participate actively in these programs. NSERC has taken a very important step in this direction by its recent announcement of the Collaborative Research Grants Program.

While large, interdisciplinary programs are essential for addressing the most fundamental earth system questions, and our funding agencies must be proactive in directing efforts in this direction, we must also remember that there will inevitably be some talented members of the academic community who are are not comfortable working within the framework of large projects. Canadians are quite fortunate in this regard in that these people should be able to continue their work under the Operating Grant program. The freedom and flexibility allowed by Canada's Operating Grant program is the envy of the international community and nothing should jeopardize this.

Finally, we are faced with the question of training. How can we train scientists who will be both willing to address and capable of addressing the complex task of approaching the earth and ocean sciences in an integrated manner, and, for that matter, should we? These are difficult questions to answer. If we accept the need for an integrated approach to earth science, then we should certainly be training "earth system scientists". But how do we do this without so diluting their background that they cannot make productive contributions to the field? We can do this by creating an environment of integration, an educational and research environment where the focus is on system integration, but staffed by individuals who are fully expert in their particular field. Students should be trained in an atmosphere where ocean scientists of all disciplines work together on common problems and where the boundaries between the sub-disciplines are both physically and spiritually diffuse. Within this atmosphere, however, the student must obtain a complete and detailed background in at least one of the basic subdisciplines of marine science (physics, math, biology, chemistry, geology, engineering, *etc.*). Only with this background as a basis can the productive system scientist develop. And so we must encourage the further develop*ment of the oceanographic centres that* we now have, and we must emphasize the need within these centres for collaborative and interdisciplinary research coupled with first-rate training in at least one of the basic disciplines. After a (student) generation or two in this sort of environment, we will see new courses and disciplines evolve that no longer fit within the bounds of the traditional fields, but rather are detailed and complete looks at areas of interaction among the fields. We will be seeing the birth of new "earth system scientists."

CONCLUSIONS

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 pivotal 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 focussed on manageable subcomponents of the system. In order to contribute to, and benefit from, this conceptual revolution, Canada must maintain a critical mass of of world-class ocean scientists and provide them with the tools and infrastructure necessary to participate in these programs and to initiate programs of their own. Canada already has a small corps of visionaries and revolutionaries who are willing to take on this challenge, but we must train new generations of ocean scientists to bring to their trade high levels of specialized expertise that have been tempered in an environment of interdisciplinary study.

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