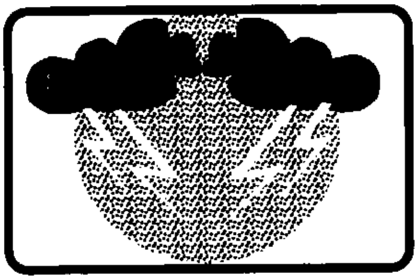


The Atmospheric Sciences

W.R. Peltier
Department of Physics
University of Toronto
Toronto, Ontario M5S 1A7

ABSTRACT

Current research in the atmospheric sciences has come to be heavily influenced by the growing need to understand increasingly evident changes taking place in the earth system. The research agenda includes issues involving processes that span the full range of space and time scales relevant to atmospheric behaviour. A common theme that links the separate strands of this activity concerns the inter-relationships among distinct atmospheric subsystems and, indeed, the mechanisms through which the atmosphere as a whole interacts with other elements of the total environment. I expect this trend to become increasingly evident in the future. It is imperative, however, that as these interdisciplinary activities develop, the core research areas continue to receive strong support, for it is upon them that the integrity of the field will continue to rely.

RÉSUMÉ

Les recherches actuelles dans le domaine des sciences de l'atmosphère ont été très influencées par la nécessité croissante de comprendre de mieux en mieux les changements qui ont lieu dans le système-Terre (la Terre comme ensemble organisé). Le programme des recherches portent entre autres sur des problèmes qui comportent des mécanismes qui existent à tous les niveaux du spectre des échelles spatiales et temporelles du comportement de l'atmosphère. Les interrelations entre des sous-systèmes atmosphériques distincts constituent un thème de recherche commun et qui lie les différents faisceaux de cette activité de recherche, de même que les mécanismes d'interaction entre l'atmosphère elle-même et les autres éléments de l'ensemble de l'environnement. Je m'attends à ce que cette tendance s'affirme de plus en plus. Cela dit, il est absolument nécessaire que le soutien dans les domaines de la recherche fondamentale demeure fort car c'est d'elles que dépend la cohésion de ce champ de recherche.

INTRODUCTION

Although past research in the atmospheric sciences was often quite rigidly partitioned into a number of rather weakly linked subdisciplines (cloud physics, atmospheric radiation, atmospheric chemistry, atmospheric dynamics, micrometeorology, numerical weather forecasting, climatology, *etc.*), pressing environmental issues are driving the research agenda of the discipline as a whole in a refreshingly integrative direction. During the past decade, there has also been a considerable broadening of the spectrum of research activity itself.

In order to better appreciate the emerging trends in atmospheric research, it is useful, I think, to be reminded at the outset of developments in the recent past. The modern era of research in this field was initially guided at the international level by the World Meteorological Organization (WMO), which successfully sought to build an international capability in numerical weather prediction, a theme that dominated the research agenda through the decades of the 1950s, 1960s and 1970s. This development, made possible by rapid advances in the design of digital computers, is one in which Canada participated fully, leading to the establishment of the existing numerical weather prediction group (Recherche en Prévision Numérique or RPN) of the Atmospheric Environment Service at Dorval, Quebec. This group remains one of the very best in the world in this area. The WMO-sponsored Global Atmospheric Research Program (GARP) provided the main vehicle for the establishment of research priorities through this period, a program that led to important increases in understanding of the atmospheric general circulation (culminating in the First Garp Global Experiment or FGGE) and of problems related to air-sea interaction (expressed, for example, in the Garp Atlantic Tropical Experiment or GATE). With the establishment of the World Climate Research Programme (WCRP) jointly by WMO and the International Council of Scientific Unions (ICSU), the research agenda shifted to the physical climate system, first through development of the ongoing Tropical Ocean-Global Atmosphere program (TOGA) — focussed upon El Niño and the Southern oscillation — and, more recently, through the World Ocean Circulation Experiment (WOCE). Each program emphasizes issues fundamentally concerned with the impact on the global climate system of atmosphere-ocean interactions. In the late 1980s, ICSU mounted, through its own sole sponsorship, a much larger program, the International Geosphere-Biosphere Program (IGBP), that complements the World Climate Research Programme's (WCRP) emphasis on the physical climate system, with an array of scientific projects focussed upon the chemical and biological components of the total earth system. Current IGBP core projects include the International Global Atmospheric Chemistry Program (IGAC), the Joint Global Ocean Flux Study (JGOFS) that is focussed on the role of the oceans in the carbon cycle, Global Change and Terrestrial Ecosystems (GCTE), Past Global Changes (PAGES), and Global Analysis Interpretation and Modelling (GAIM). It is in the midst of this sometimes bewildering array of major environmental programs and projects that the research agenda for the atmospheric sciences is being continually developed and refined. Clearly, both for want of space and by personal inclination, I will not be able to fully survey here the complete range of issues that will drive future research initiatives. What I will try to do, rather, is to review a sampling of ideas in a way that is intended to provide a sense of the range of the work that will be undertaken. In order to impose some order on the discussion, I have elected to address a sequence of focal themes that have been arranged in ascending order of the space and time scales of the phenomenology that is of interest, and which may be especially relevant in the Canadian research context.

MESOSCALE, CLOUD SCALE AND BOUNDARY LAYER

Just as the decades 1960-1980 might justifiably be seen as the era of synoptic scale meteorology, it seems rather clear, even from this rather early vantage point, that the decade prior to the new millennium will be something of a golden era in mesoscale research. Notable recent achievements by the Canadian community include work on the origin of Chinook windstorms, which demonstrate that these events, common in the lee of the Rocky Mountains, are induced by the "breaking" of internal waves forced by topography. The general circulation model of the Canadian Climate Centre (CCC) was one of the first in the world to be employed to demonstrate that the drag on the mean-flow associated with the momentum deposition caused by this process plays a critical role in determining the component of the large-scale circulation that is controlled by stationary planetary waves (McFarlane, 1987). A fast-developing research trend is toward the design and use of non-hydrostatic large-scale models that are capable of explicitly resolving such small-scale processes, often through implementation of techniques for two-way grid nesting. This effort will continue to be supported by intensive local observing programs such as the recently completed Canadian Atlantic Storms (CASP) and CASP II experiments off the east coast of Canada that focussed upon the mesoscale substructure within evolving marine cyclones and polar lows (Stewart, 1991). These observational programs involve intensive use of modern research instrumentation, not only that deployed on aircraft platforms, but also arrays of modern weather radars with doppler capability and satellite imagery, such as that available from satellite-borne radiometers, including the National Oceanographic and Atmospheric Administration (NOAA), Advanced Very High Resolution Radiometer (AVHRR). The upcoming (1994) Beaufort and Arctic Sea Experiment (BASE) will be the next Canadian undertaking in this area, an experiment that will constitute one contribution to the WCRP enterprise called GEWEX, which will focus on the Global Energy and Water Cycle. An extremely interesting aspect of the meteorological environment in the Mackenzie Valley area, where the Canadian contribution to GEWEX will be focussed, is the issue of the detailed mechanism whereby lee cyclogenesis occurs. Important work remains to be done in the general area of the interaction of the atmospheric flow with topography, work that will increasingly demand significant improvements in the understanding of boundary layer processes and of cloud physical/dynamical feedbacks onto the large-scale flow.

SYNOPTIC SCALE RESEARCH

In mid-latitudes, the dominant synoptic scale process concerns cyclogenesis and the influences that govern its occurrence and control its intensity. Recent European research, as well as that undertaken in both Canadian and United States laboratories, has quite clearly demonstrated the important role that water vapour plays in governing the rapidity of development of those intense marine cyclones called "bombs". This work has also led to a marked increase in understanding the potentially important role that non-modal baroclinic instability may play in the development process. Much remains to be done by way of careful comparison of the extent to which intermediate model approximations to the primitive equations are capable of explaining the detailed characteristics of a typical baroclinic wave life-cycle and the concomitant wave, mean-flow interaction process. Although a great deal of effort has already been invested in such analyses in order to develop parameterizations of baroclinic adjustment that are suitable for use in simplified climate models, I think it fair to say that no fully satisfactory means has yet been discovered whereby this may be achieved (in the context of a global energy balance model, for example). Of great current interest in the context of understanding continental cyclogenesis is the impact that land surface processes may have on a typical baroclinic wave life-cycle. Considerable improvements to the design of synoptic scale numerical weather prediction (NWP) models have been achieved through the implementation of the same detailed models of land surface processes that are central to the operation of the general circulation models employed for much longer timescale climate system analyses. We may expect to see increasing convergence of models employed in NWP applications and General Circulation Models (GCMs), the former becoming simply higher spatial resolution versions of the latter. Upcoming projects (such as BOREAS, which has been designed to enhance understanding of the impact of boreal forest ecosystems upon atmosphere-landsurface exchange processes, a joint Canadian-American (National Aeronautic and Space Administration) undertaking), are expected to strongly influence future research directions.

CLIMATE AND GLOBAL DYNAMICS

In the past five years, modern research on the global climate system has come to be dominated, reasonably, by work on the design and application of models of the coupled ocean-atmosphere system. The atmospheric components of these coupled models are now second generation implementations that are run, whether spectral or grid-point in technical design, at a spatial resolution corresponding to triangular truncation 42 (mesh point separation of approximately 5°). The Canadian model developed at the CCC (Boer *et al.*, 1984a, b), based upon an early spectral implementation by the Recherche en Prévision Numérique (RPN) group at Dorval, is rather widely acknowledged to be one of the best in the world. Because no equivalent ocean circulation model is yet available with which this atmospheric module may be coupled, however, Canadian research on the climate system is rapidly falling behind that in the rest of the international community. For this reason, considerable resources are being directed toward advancing this research in Canada, especially in the context of the development under CCC auspices of a Climate Research Network. It is an interesting fact that existing global ocean models (such as the Cox-Bryan model of Princeton's Geophysical Fluid Dynamics Laboratory) are based, for the most part, on three-decade-old numerical technology. The future will undoubtedly see the development of a next generation of finite element-based software that will most probably rely on unstructured multi-grid methods for speed and efficiency. It also seems likely that Atmospheric General Circulation Models (AGCMs) will switch from semi-spectral technology to the same Finite Element Method (FEM)-based multi-grid methods, since these appear to offer the greatest opportunity for the large further increase in speed that is required, and that will be possible with the massively parallel supercomputers that will soon dominate the machine-rooms at the main modelling centres.

Applications with the next generation of coupled Atmosphere-Ocean General Circulation Models (AOGCMs) will include not only the continuation of current experiments relating to prediction of the impacts to be expected due to global warming of the lower troposphere caused by increasing atmospheric concentrations of greenhouse gases (*e.g.*, IPCC Report, 1990), but many others as well. Hopes are high that the observational data from WOCE and JGOFS will enable us to achieve a much clearer understand of the carbon cycle, for example. Even in the context of soon-to-be-conventional transient CO_2 increase experiments, the higher spatial resolution that will be enabled by the next generation of supercomputers should allow us to achieve a much better understanding of the regional effects of global warming than has been possible with the existing generation of models. Of all of the processes that large-scale models handle badly, probably those most urgently in need of more systematic and detailed analysis are those related to water. The proper representation of the feedback of clouds onto the physics of the large scales of atmospheric behaviour, especially through the radiation budget, will receive highest priority attention in the context of the Global Change research programs of many nations in coming years, this problem having been identified as the main impediment to the improvement of our understanding of the climate system in general. The GEWEX experiment mentioned previously is expected to provide one further impetus to advance in this area, as has the National Aeronautics and Space Administration's (NASA) Earth Radiation Budget Experiment (ERBE). Late in the present decade, we will (probably!) see the launch of the first satellites in the constellation that will constitute NASA's Earth Observing System (EOS), a system that is rather widely expected to revolutionize our understanding of the earth system in its entirety. It is to be hoped that the Canadian Space Agency will see fit to invest its resources in promoting the involvement of university-based scientists in the creative use of the huge volumes of data that will be forthcoming from these platforms.

Probably the most exotic of the emerging research foci in the atmospheric sciences concerns the extraordinary increase in the level of research in the area of paleoclimate and earth system history that has been occurring since the early 1980s. This stream of activity, exemplified by the Past Global Changes (PAGES) project of the IGBP and the ongoing Paleoclimate Model Intercomparison Project (PMIP), is driven by the recognition that paleodata may provide the best means possible whereby the robustness of the parameterization schemes of typical AOGCMs may be tested. Such investigations focus upon the ability of the models to properly reconcile climate data relating to times when the system was forced in a markedly different fashion than is the modern system. A main focus concerns the sequence of changes in climate state that is observed to have been obtained during the most recent glacial cycle of the present ice age, which began approximately 120,000 years ago and ended approximately 10,000 years ago. Based upon the analysis of $\delta^{18}O$ data from deep sea sedimentary cores, it is quite clear that the 10^5 year cycle of ice advance and retreat is driven by the small changes of effective solar insolation caused by variations of the Earth's orbit around the sun. Since the orbital forcing has no significant power at the 10^5 year period on which orbital eccentricity varies, the dominant climate response at this period appears to involve significant internal system nonlinearity. The specific physical processes that govern this nonlinearity have yet to be unambiguously identified. One candidate involves the thermohaline circulation of the oceans, which seems to have reversed its sense of overturning in the critical Atlantic basin from full glacial to interglacial (*e.g.*, Broecker and Denton, 1989). Although limited analyses of this phenomenology with full coupled AOGCMs have begun, it is expected that a greatly enhanced effort in this area will develop in coming years. In many ways, the challenge of understanding the long time-scale variations of planetary climate, revealed by measurements in ice cores, deep sea sedimentary cores, lake cores, *etc.*, is as great and the implications as wide ranging, concerning our understanding of the planet, as was the issue of continental drift that dominated the geophysical research agenda for the three decades that began in approximately 1960.

ATMOSPHERIC CHEMISTRY AND THE STRATOSPHERE

The discovery of the ozone hole over Antarctica in the mid-1980s, and the subsequent demonstration that the ozone depletion observed was a direct consequence of the release of chlorofluoro-carbons (CFCs) into the atmosphere by human activity, has led to greatly increased levels of research into the coupled chemistry and dynamics of this part of the atmosphere. Aside from the vital importance of the stratosphere as the region of the atmosphere within which the photochemical production of ozone occurs, the region is especially interesting because of the extent to which its dynamics are driven by planetary wave and internal wave-induced interactions with the mean flow. It has, therefore, become an arena of choice for theorists interested in wave, mean-flow interaction processes, and much work remains to be done in the development of models of such effects. Because of the important role that dynamics plays in determining the spatial distribution of ozone, the stratosphere is also a region in which chemistry and dynamics are strongly coupled. In Canada, as elsewhere, the immediate future will quite probably see 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, this decade will see the development, in connection with the EOS of NASA, of a new generation of satellite remote sensing systems of unprecedented accuracy. Of special importance to the Canadian community will be the MOPITT instrument (Drummond, 1989) that is designed to measure both CO and CH_4, the former in profile, the latter in column, and which will constitute Canada's main contribution to the EOS program. The CO measurement is especially important to understanding the global impact of biomass burning, and also the chemistry of the hydroxyl radical, which plays a vital role in tropospheric chemistry as a whole. This work in remote sensing will require continuing support through intensive ground-based measurement programs such as the recently completed Northern Wetlands Project, whose goal was to accurately measure the emission of methane from the Hudson Bay lowlands over a full annual cycle. A special (Summer 1992) issue of the *Journal of Geophysical Research* devoted to papers describing the results of this joint Canada-United States project is an interesting early example of the sort of focussed collaborative effort that is a sure harbinger of what the research future has in store.

CONCLUDING REMARKS

The above discussion of future research trends in the atmospheric sciences has, of necessity, been less than exhaustive and is probably less well balanced between experimental and theoretical research than I would have liked. It should be seen as an attempt to convey something of the flavour and the range of considerations that are now shaping the research agenda in this area of science. If atmospheric science is to continue to advance vigorously in Canada, it is important that certain conditions be met. These conditions would include the delivery of adequate supercomputing capacity to university-based scientists, a deepening of the involvement by the Canadian Space Agency in funding the application (as well as the collection) of atmospheric data from space, and a strengthening of the funding base of the Natural Sciences and Engineering Research Council research grants program in environmental earth sciences. The investment by the Canadian Climate Centre in the development of a Network for Climate Research should play an important role in the immediate future by way of galvanizing work across the community on large-scale climate-related problems. It is an example of the sort of initiative that will be required to more fully link scientists in government laboratories with those in the universities in order that the country may continue to deliver the leadership in the atmospheric sciences that has most often characterized its contributions in the past.

REFERENCES

Boer, G.J., McFarlane, N.A., Laprise, R., Henderson, J.D. and Blanchet J.-P., 1984a, The Canadian Climate Centre Spectral Atmospheric General Circulation Model: Atmosphere-Ocean, v. 22, p. 397-429.

Boer, G.J., McFarlane, N.A. and Laprise, R., 1984b, The climatology of the Canadian Climate Centre spectral atmospheric general circulation model as obtained from a 5-year simulation: Atmosphere-Ocean, v. 22, p. 430-475.

Broecker, W.S. and Denton, G.H., 1989, The role of ocean-atmosphere reorganization in glacial cycles: Geochimica et Cosmochimica Acta, v. 53, p. 2465-2501.

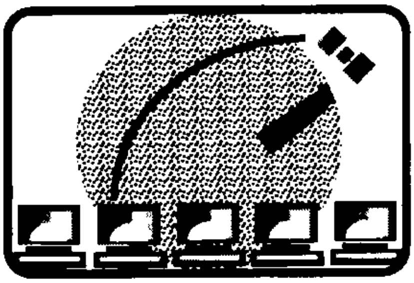
Drummond, J.R., 1989, Novel correlation radiometer: the length modulated radiometer: Applied Optics, v. 28, p. 2451-2452.

Intergovernmental Panel on Climate Change, 1990, Climate Change: The IPCC Scientific Assessment, *in* Houghton, J.T., Jenkins, G.J. and Ephraums, J.J., eds.: Cambridge University Press, Cambridge, 365 p.

McFarlane, N.A., 1987, The effect of orographically excited gravity-wave drag on the circulation of the lower stratosphere and troposphere: Journal of Atmospheric Science, v. 14, p. 1175-1800.

Stewart, R.E., 1991, Canadian Atlantic Storms Program: Progress and plans of the meteorological component: American Meteorological Society, Bulletin, v. 72, p. 364-371.

Accepted 1 September 1993.



The Significance of Research Platforms for Future Advances in the Earth Sciences

Christopher R. Barnes
School of Earth and Ocean Sciences
University of Victoria
P.O. Box 1700
Victoria, British Columbia V8W 2Y2

ABSTRACT

Scientific advances in recent decades in space exploration, satellite observations, and supercomputing have resulted in an ability to undertake global studies that were formerly impossible. The change in applied earth sciences from supporting the resource exploration sector to including the environmental conservation and protection sector has added new requirements for regional and global baseline environmental studies. Many new initiatives have been launched as international collaborative programs in which Canada — given its large land area and its frontage on three oceans — has commonly had a special responsibility to play an important scientific role.

The means by which such science is undertaken has likewise adjusted to these changes in the discipline. In particular, the need for sophisticated scientific research platforms has become essential. These range from space platforms (space stations, satellites), to atmospheric research platforms (balloons, aerosondes, mobile field stations), to ocean research platforms (ships, ice islands, tethered and autonomous underwater vehicles, drill ships), to continental research platforms (field stations, drilling platforms, seismic platforms).

The management and funding of such