# CLIMATE VARIABILITY:

# ITS CAUSES AND PREDICTIBILITY

## PART II: PROPOSAL

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## Executive Summary

The accelerated global warming of the last decades, and the predictions of more warming to come, have brought the need for climate research to the forefront of the national agenda in most developed countries. The atmospheric scientific community has reached a consensus on the prediction for continued warming, but many other important issues are still in pressing need of attention. At the forefront are: (1) the need to better estimate the relative contributions of natural variability and anthropogenic causes in the observed and predicted climate change, and (2) the need to determine the extent to which climate variability can be predicted, and for what timescales. Research progress on both of these fronts holds promises of major societal benefits.

Nineteen specialists covering a broad range of climate research expertise are joining forces to collaborate in a coordinated research project on climate variability. They come from 6 Canadian universities and 3 Federal Government laboratories The goals of the proposed research are: (1) to clarify the physical mechanisms responsible for the natural climate variability on timescales ranging from a season to a century, (2) to determine the extent to which this variability is predictable, (3) to develop tools to predict that variability, and (4) to develop and apply tools to distinguish natural from anthropogenic contributions in observed and predicted global warming.

A research agenda in climate variability is proposed that will make a major Canadian contribution to the International Climate Variability Program, a component of the World Climate Research Program. The proposed research is structured along the lines of the international program in that it has three central themes focusing on three different timescales: the seasonal to interannual time frame, the decadal to inter-decadal timescale, and the century timescale.

The first theme focuses on determining the skill that can be achieved in predicting the year-to-year variability in the mean-seasonal climate. This work is a significant extension and expansion of a successful on-going project that has already reaped benefits for operational seasonal forecasting at the Meteorological Service of Canada. Supported by observational and modelling studies, the research will proceed through an ordered sequence of steps that will lead to the development of a fully-coupled atmosphere-ocean model designed for seasonal predictions. This will require that a special effort be devoted to properly modelling the tropical Pacific Ocean, a major source region of seasonal predictability for North America.

In the decadal to inter-decadal timescale the interactions between the atmosphere and the surface and deep oceans are of the essence, particularly over the North Atlantic. An eddy-resolving ocean model will be developed to examine the interaction between the atmosphere and the North Atlantic Ocean to clarify the phase relationship between the atmospheric forcing and the deep-Atlantic circulation. Coupled atmosphere-ocean model studies will look at whether atmospheric predictive skill can be derived from the oceans on decadal timescales. The maintenance of atmospheric climate regimes and the mechanisms responsible for transitions from one regime to another will be investigated though observational studies and model simulations. Special attention will be given to the dynamics of the Arctic and North Atlantic Oscillations.

The third theme will be looking at the detection and attribution of climate change on the century timescale. Innovative methods will be sought to discriminate between anthropogenic climate change and natural variability in observations and model predictions. There will also be considerable work on regional climate modelling. An existing Regional Climate Model will be improved and coupled with regional ice and ocean models to examine how regional air/ sea/ ice in-

teractions affect climate on scales smaller than those simulated by the Canadian Climate Model used for century timescale scenarios.

The research results will be widely disseminated nationally and internationally in order to make a significant and visible contribution to the national needs for climate information, and to the International Climate Variability Research Program (CLIVAR).

# 1. THE INTERNATIONAL CLIVAR PROGRAM

The International Climate Variability Program (CLIVAR) is a component of the World Climate Research Program sponsored by the World Meteorological Organisation, the International Council of Scientific Unions and the Intergovernmental Oceanographic Commission of UNESCO.

The International CLIVAR objectives include (WCRP No. 103, 1998):

- "To describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial timescales …
- To extend the range and accuracy of seasonal to interannual climate prediction through the development of global predictive models.
- To understand and predict the response of the climate system to increases of radiatively active gases and aerosols and to compare these predictions to the observed record in order to detect the anthropogenic modification of the natural climate signal."

The program is structured around three sub-programs:

- CLIVAR-GOALS: the variability and predictability of the Global Ocean Atmosphere Land System on the seasonal to interseasonal timescale;
- CLIVAR-DecCen: the climate variability and predictability on the Decadal to Centennial timescale.
- CLIVAR-ACC: Anthropogenic Climate Change – modelling and detection.

As a component of the World Climate Research Program, CLIVAR emphasizes the physical climate system, as opposed to the biological and chemical processes which are at the heart of the International Geosphere-Biosphere Program.

Focusing on the interactions between the atmosphere and the oceans, ice and land on seasonal and longer timescales, CLIVAR is distinct from the Global Energy and Water Cycle Experiment (GEWEX), which is concerned with the faster timescales associated with the turbulent transfers of energy and water within the atmosphere.

## 1.1. The Canadian scene

The research to be described in this application will be a major Canadian contribution to this international program. It is structured around three themes that closely parallel the above three subprograms of the International CLIVAR program. As is the case internationally, the present CLIVAR proposal is distinct from the Canadian GEWEX project MAGS (Mackenzie GEWEX Study) as none of the proposed research is concerned specifically with the Mackenzie basin. Interaction will continue, however, with some members of the MAGS group, such as M. MacKay for water budget studies in our proposed regional modelling work.

The proposed research is also distinct from that of CRYSYS (The Cryosphere System in Canada) group in that none of the research proposed here focuses specifically on ice or the Arctic. While there is a keen interest in the Arctic on the part of several members of the present group, their proposed research will not focus on Arctic processes per se, but rather on the influence of the Arctic on the mid-latitudes, and in particular on the North Atlantic Ocean. There is proposed work also on the Arctic Oscillation, a large-scale mode of atmospheric variability, but the emphasis will be on understanding the atmospheric dynamics, not the interaction between the Arctic atmosphere and the underlying ice-ocean boundary, as might be expected in a CRYSYS project. Nonetheless, it will be important to maintain frequent contacts between the CLIVAR and CRYSYS Groups to keep each other informed of progress and quite likely to stimulate increased understanding of the climate system in both groups. It is our understanding that the CRYSIS group is planning to assemble and manage an ice-related data bank. The present co-PIs will keep close contacts with their CYSIS colleagues both to take advantage of the CYSIS data bank and to contribute to it if possible.

# 2. THE ORIGIN OF THE PRESENT CANADIAN CLIVAR GROUP

## 2.1 The last six years

The Canadian Climate Variability (CLIVAR) Research Group was created about six years ago as a component of the Climate Research Network of the Canadian Institute for Climate Studies (hereafter “the Institute”). It is one of a series of university-based research groups created at the initiative of the Institute to address a wide range of climate problems.

The specific mandate of the CLIVAR group is to improve our understanding of the mechanisms leading to the variability of the earth’s climate on seasonal to century timescales and to examine the level of predictability of the climate fluctuations. Three other groups funded by the Institute have been conducting research that is closely related to that of the CLIVAR group, namely, the North Atlantic Modelling Group, the Regional Climate Modelling Research Group and the component of the Arctic Research group working on the role of the Arctic in climate variability.

With time, the interconnections between the topics researched by the different groups and the need for coordination and collaboration became manifest. For example, the Regional Climate Modelling Group has developed a model to simulate regional conditions in a $CO_2$-enriched, warmer atmosphere, by regionalizing the simulations produced by a General Circulation Model (GCM). The CLIVAR Group, on the other hand, has shown that two Canadian global atmospheric models have some skill in predicting mean-seasonal conditions over Canada. The coming together of these two groups would make it easier to collaborate and see if the Regional Climate model can be used to regionalize the seasonal forecasts of the large-scale models.

After discussion among the group leaders and with the Network Scientific Advisory Panel of the Institute, it was decided to join forces under the umbrella of an enlarged CLIVAR Group. Such a merger of research talent is necessary to establish the critical mass required for continued progress in developing our understanding of the variability and predictability of climate. The merger will enhance the co-ordination of the research, improve the interaction among the scientists and increase the breadth of exposure offered to our graduate students and postdoctoral fellows. Importantly, it will also allow the Group to attack new problems that draw on the expertise developed in the separate groups.

The funding by the Institute of the CLIVAR Group, the Regional Climate Modelling Group and the North Atlantic Modelling Group all end on 31 March 2001. As of that date they will be integrated into the Climate Variability Group. The Institute funding of the Arctic Research Group is due to end on 31 March 2003. It was consequently decided that it would continue to function as a separate group until that date, but that its climate-variability component would be expanded and included in the new CLIVAR Group as of April 1, 2001. The funding requested for the latter in this proposal is only for the expanded activities. The Regional Climate Modelling Group will be incorporated in the Climate Variability Group, but because its infra-structure needs are much larger than that of the other components of the Group, it will seek infra-structure funding separately from this proposal, from the Institute and/or the Canadian Foundation for Climate and Atmospheric Sciences. Thus for this group, based at the Université du Québec à Montréal, funds are requested only for students, postdoctoral fellows, publication page charges and travel to conferences and workshops so that there will be no overlap in funding.

**2.2 The applicants**

The group is composed of 10 full-time academics from 6 Canadian universities and 9 scientists who have Adjunct Professor appointments in a Canadian university (7 of whom are from the Meteorological Service of Canada (MSC) and one from the Department of Fisheries and Oceans (DFO)). The group also includes Research Associates, Postdoctoral Fellows and graduate students. In addition, it benefits from the collaboration of at least 10 federal government scientists who do not require funding from the proposed CLIVAR network (J. Côté, B. Dugas, E. Carmack, S. Lambert, L. Lefaivre, W. Perrie, J. Sheng, D. Verseghy, C. Tang and D. Wright).

**2.3 Planning for the proposal**

On March 27 and 28, 2000 a workshop was held at McGill University to lay the foundations of the new CLIVAR Group, and to prepare a research project for the next five years. All but three of the applicants for this proposal participated in the workshop. The participants confirmed the decision to come together as one group and to expand the range of activities to take advantage of the new synergy that the merger would create and to better reflect the priorities of the International CLIVAR Science Plan (WCRP No. 103, 1998). In view of this increased range of activities and of the increasing pressures on the Institute's budget, it was decided to seek funding for future activities both from NSERC and the Institute.

The new CLIVAR group brings together the necessary expertise required to make a major Canadian National contribution to the International CLIVAR Program, a component of the World Climate Research Program (WCRP). Consequently, the planning meeting decided to structure the proposed five year research project around the three main themes of the International CLIVAR Science Plan (Op. cit), while placing special emphasis on those climate topics that will benefit Canada the most. This will ensure the highest possible relevance of the research to the international program and to the needs of Canadians.

**2.4 Advantages of a network**

The breadth of the proposed research, encompassing the seasonal to the century time scales, requires a correspondingly broad range of expertise that can only be assembled through a network of scientists. A network provides the ideal environment for specialists of different time scales to inform each other of the links between their areas of specialization. For example, those working on inter-seasonal variability and predictability need to know from their colleagues how phenomena like the El Niño, at the centre of their interest, are influenced by decadal oscillations in the Pacific. Similarly, those working on the detection and attribution of climate change on the century time scale need to be thoroughly familiar with the characteristics of decadal and multi-decadal natural variability. The network will foster a flow of information and stimulation among specialists of different time scales that would not otherwise be possible.

Climate research of the type proposed here requires a broad range of human resources, and considerable resources. For example, the seasonal forecasting project that is proposed could never be undertaken within a single university, or even a group of universities. The required computer, human and data resources are such that a major government laboratory involvement is absolutely essential. The network will make such a project possible by involving researchers from three government laboratories and two universities, for the greater benefit of all those involved, in particular the graduate students and postdoctoral fellows, who will receive a high level of training that would otherwise not be available in Canada. As a further example of the needed interaction among scientists from different institutions, the ocean model development to be done at Dalhousie University will rely heavily on the sub-gridscale parameterization work at the University of Waterloo and McGill University. Other examples of this required interaction will be seen in the project descriptions below. We expect that the sharing of resources and the synergy that will be generated by the interaction among the scientists will allow us to make a significant and visible contribution to the international CLAVAR program.

Finally, as mentioned earlier, the network will offer our students and postdoctoral fellows a breadth of scientific exposure, in terms of ideas, techniques and stimulation, that would otherwise not be available anywhere in Canada. The network will give them a unique environment in which to start a scientific career in climate research.

## 3. HIGHLIGHTS OF RECENT PROGRESS

### 3.1 Research

During the last 6 years the 19 Principal Investigators have published 350 papers in first-rate international journals. The publications are listed in the accompanying personal data forms for each co-applicant. In view of the space limitation only a few of the most relevant highlights, and only those funded by the Canadian Institute for Climate Studies as part of the Climate Research Network, will be summarized here.

*Boer, Brunet, Derome, Zwiers.* They conducted a series of seasonal predictions for each of the four seasons over a 26-year period with two Canadian global models, a project termed the Historical Forecasting Project (HFP). They demonstrated that the ensemble means of the predictions have statistically significant skill in predicting mean-seasonal surface air temperatures over Canada. Two methods for blending the two model ensemble predictions were compared. The forecast system developed during the HFP is now used operationally by the Canadian Meteorological Centre (CMC).

*Brunet*. He developed a dynamically-based method of orthogonal function analysis, called the Empirical Normal Mode method. With Derome he supervised a Ph.D. student who applied it to NCEP (National Centers for Environmental Prediction) analyses and global model simulations.

With French collaborators he tested a statistical seasonal forecasting technique based on Space-Time Principal Component Analysis and showed that it is superior to the widely used Canonical Correlation Anomaly approach.

*Derome*. He supervised Post-doctoral Fellow N. Hall who developed a global atmospheric model driven by time-independent empirical forcings. The model was shown to have a remarkably good climatology both in terms of the time-mean flow and the transient eddies. It was used to study the response to both tropical and midlatitude sea surface temperature anomalies. The role of linear and nonlinear mechanisms was clarified. In the case of the midlatitude sources, the position of the atmospheric jet in relation to the sea surface temperature anomaly was also clarified.

*Greatbatch.* He and his group investigated decadal oscillations in an ocean model. They showed that boundary waves that propagate around the ocean basin are a feature of the model oscillations. They also showed that variable bottom topography in coarse-resolution ocean models strongly inhibits self-sustained interdecadal variability by affecting the boundary waves.

In a number of numerical experiments with coworkers he demonstrated the possibility that low frequency variability internal to the atmosphere can drive significant low frequency variability in the ocean, including interdecadal variability of the thermohaline overturning circulation.

He designed new ways to represent the transport and mixing of heat and tracers by mesoscale eddies. He has also developed a new, non-Boussinesq version of the parallellized ocean model from the Geophysical Fluid Dynamics Laboratory (GFDL).

*Laprise and Caya.* They developed the Canadian Regional Climate Model (CRCM) and associated diagnostics package. Numerous refinements were incorporated in the model over time. They produced simulations over western Canada, eastern Canada and the tropical Atlantic as well as three 10-year simulations with transient increases in $CO_2$ and aerosols. Different nesting strategies were examined. The output of simulations were made available to users and in particular the latest climate change projection runs are available on the CCCma web site.

*Lin and Greatbatch.* In collaboration with Derome they developed two coupled global ocean/atmosphere models of intermediate complexity, the first based on a quasi-geostrophic atmospheric model, and the second based on a primitive equations model. Long simulations with these models and work by Greatbatch and Delworth (GFDL) confirmed the view that interdecadal variability internal to the atmosphere can generate low frequency variability in the ocean.

*Mysak (recent group member)* and Venegas analysed century-long records of North Atlantic sea-ice concentration and sea level pressure and found four dominant signals in the frequency domain and found that the 9-10 year oscillation especially stands out as a winter phenomenon.

*Pandolfo (recent group member).* He has developed storm track statistics and looked at their relation to time-mean anomalies, in particular the North Atlantic Oscillation. He has shown that a gradual north-eastward extension of the Atlantic storm track leads to the establishment of the positive phase of the oscillation. NASA colleagues and he have analysed a model simulation and found that the trend in the Arctic Oscillation time series can be induced by an increasing concentration of greenhouse gases.

*Weaver.* He developed an Earth System Climate Model (ESCM) and used it, in particular, to simulate the influence of Arctic sea ice on the variability of the North Atlantic climate, to study the influence of horizontal resolution and parameterized eddy processes on the thermohaline circulation.

In a study of extratropical subduction he found that it caused the El Niño to modulate on decadal-interdecadal timescales, consistent with observations.

Intrinsic modes of decadal variability driven by constant surface buoyancy were analysed using a box-geometry ocean model. The importance of numerical boundary waves in sustaining decadal oscillations was tested. In a study based on the ocean component of the GFDL coupled model he concluded that the interdecadal variability found in the coupled model was either a damped-oscillatory ocean mode or a mode of the full coupled system.

*Zwiers.* He investigated the extreme of atmospheric variables simulated by the CCCma GCM2 and how they might change in a warmer world. He presented improvements to the extreme value analysis methodology. This body of work is cited extensively in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report.

Using the output of the Historical Forecasting Project he showed that the forecast skill can be improved by statistically optimizing the information derived from the initial conditions and from the sea surface temperature anomalies.

In a series of studies he performed analyses of variance on ensembles of simulations with specified sea surface temperature to separate the variability due to the oceans from that due to the internal dynamics. These studies provide extremely useful guidance on the potential predictability of the atmosphere, and justify the group's efforts in seasonal forecasting.

### 3.2 Training

During the last 6 years the 19 co-applicants have supervised or co-supervised 53 different Master's students, 63 Ph.D. students and 57 postdoctoral fellows. The vast majority are either continuing with advanced studies or have found employment in their specialization, as the job opportunities for climate specialists are exceptionally good.

### 3.3 Other signs of achievement

Numerous awards and marks of recognition have been bestowed on Group members. These include: 3 NSERC/MSC Chairs, a Steacie Fellowship, 3 Patterson medals of the MSC, a membership in the Royal Society of Canada, a Fellowship in the American Meteorological Society and in the American Geophysical Union, an Editor's award from the latter Society, 2 Fellowships in the Canadian Meteorological and Oceanographic Society (CMOS), and 5 CMOS President's Prizes. The current memberships in international research committees are mentioned in section 5 as part of the group's contributions to international science.

## 4. THE PROPOSED RESEARCH

The proposed research is structured around the three themes of the International CLIVAR Program, namely, (i) the seasonal to interannual variability and predictability, (ii) the decadal to century variability and predictability, and (iii) anthropogenic climate change on the century timescale. Research in each of the three theme areas will be co-ordinated by two theme leaders, one a full-time academic, and one a senior government scientist with an adjunct appointment. The proposed research for each of the three themes will be presented separately. In each case the presentation begins with an overview of the research issues and of the proposed research. Then follow the individual research projects grouped under sub-themes.

The proven approach of using both observational and modelling studies to develop our understanding of the climate system will be adopted here. On the modelling side, a hierarchy of models will be used, from relatively simple ones to state-of-the-art global coupled atmosphere-ocean models. In each case the level of complexity and sophistication will be carefully selected to get the best solution to, and understanding of, the problem at hand, with the appropriate level of computer resources and manpower.

One component of the proposed research is an extension of work initiated during the last few years, but most of the research represent new initiatives. On the seasonal and interannual time scale, the proposed seasonal forecasting work builds on experience gained recently on a very successful pilot project. It is therefore with confidence that we propose to embark on a major new effort that will lead to the development of a coupled atmosphere-ocean model suitable for operational seasonal forecasting. The proposed regional climate modelling work will involve some necessary improvements to an existing model, but the bulk of the research represents new initiatives, such as downscaling seasonal forecasts and coupling the model to an ice model. All the work on the detection and attribution of climate change is entirely new.

## 4.1 THEME I: SEASONAL TO INTERANNUAL VARIABILITY AND PREDICTION

*Theme leaders: G.J. Boer (CCCma; U. Victoria) and J. Derome (McGill U.)*

### 4.1.1 The scientific issues

We deal here directly with one of the main scientific objectives of International CLIVAR-GOALS (Global Ocean-Atmosphere-Land System), namely "to improve the accuracy of seasonal to interannual climate prediction through programs of coupled modelling of the upper ocean, atmosphere, land and ice" (CLIVAR Science Plan, 1995).

**a. Prediction and predictability**

A prediction provides information about a future value of some quantity based on information available at some earlier time. The predictive system, the climate system in this case, is chaotic so that uncertainties in initial and boundary conditions, or in the predictive models and methods used, grow with forecast range. Nevertheless, there may be useful skill under several circumstances: (1) special initial conditions and/or flow situations which are inherently more predictable than others and which, if identified, would allow skilful prediction at long lead times (e.g., the phase of the Pacific North America Pattern (PNA), or the AO/NAO); (2) boundary conditions which give rise to a forced atmospheric signal which provides skill at longer timescales (e.g., anomalous tropical SSTs, snow and/or sea-ice, soil moisture).

**b. Signal and noise in seasonal to interannual predictions (SIP)**

The possibility of SIP depends on the existence of a "signal" beyond the usual natural variability of the weather. The temporal variance in a time-mean variable can then be written as the sum of two components, one associated with the signal to be predicted, and one associated with a chaotic component. As the latter is unpredictable, several features of SIP must be kept in mind, namely:

- it is impossible to systematically have perfect climate forecasts (even if the signal is perfectly forecast)
- the signal must be of sufficient strength compared to the natural variability noise
- there must be skill in predicting the signal.

No amount of effort or cleverness can overcome the fact that useful SIP is impossible if the signal is weak, the natural variability noise large, and/or the signal cannot be reasonably well predicted.

**c. Climate signals and "potential predictability"**

Knowledge of the important direct effect of the El Niño/Southern Oscillation (ENSO) phenomenon on tropical climate variability, and its less direct effect at Canadian latitudes, has grown rapidly (Horel and Wallace, 1981, Boer, 1983, Ropelewski and Halpert, 1989, Livezey et al., 1997, Gershunov, 1998, Trenberth et al., 1998). The extra-tropical response to tropical sea surface temperature variations is the main source of the "potential predictability" (e.g., Zwiers, 1996, Rowell, 1998, Martineu et al., 1999, Zwiers et al., 2000) that we strive to realise in SIP. The robustness of the ENSO mechanism leads to practical, although currently modest, skill in prediction. Because of the very large direct and indirect societal and economic affects associated with ENSO and seasonal variability in general, even modestly skilful forecasts have value, and changes in the ENSO mechanism with global warming could have far reaching consequences. Other boundary effects may provide additional predictability but these are less well understood. These include extratropical sea surface temperature anomalies (SSTAs), snow and sea-ice anomalies, and possibly soil moisture, although the latter is not widely observed (e.g., Graham et al., 1994, Déqué and Servain, 1989, Groisman et al., 1994, Fennessy and Shukla, 1999).

**d. Ensembles and reliability**

The natural variability that constitutes "noise" in the seasonal to interannual prediction system is present in both the climate system and the forecasts. The noise in the forecasts may, however, be reduced by ensemble methods, where a group of forecasts is made using the same boundary conditions but with slightly different initial conditions. The forecast signal is the same in each case but the noise differs and so may be averaged out over the ensemble.

Ensembles composed of results from different models may also be used to improve SIP (Krishnamurti et al., 1999, Derome et al., 2000). The idea here is that a combination of model results reduces noise as before but also overcomes some of the model errors in so far as they are uncorrelated.

A SIP is by itself of little use without some information on its likelihood of being correct. Both diagnostic and prognostic measures of reliability are needed. Diagnostic measures give skill levels based on past performance of the forecast system, which requires a set of historical forecasts so that past skill can be evaluated. Prognostic skill measures depend on using ensemble forecast information to assess the expected skill of the forecast.

### 4.1.2 Overview of the Theme I research

This section presents an overview of the proposed research on the seasonal to interannual timescale. The different contributing projects will be presented in more detail in the following sections.

**a. Predictability research with a model of intermediate complexity**

Predictability research, which expanded into the topic we now know as chaos, began with and exploited the possibilities of simplified models of the full atmosphere. Provided it captures the essential physics, a model of intermediate complexity may be used to investigate and illustrate aspects of predictability comparatively easily and economically compared to the overhead of a full GCM. In this project, each of the aspects (a-d) above will be investigated using the simple general circulation model of Hall (2000).

The ultimate goal is to see whether this economical model can contribute positively to a superensemble of models. This subproject will also serve as support for the following subprojects on seasonal forecasting based on state-of-the-art models in that it will be used to answer questions related to the skill of the forecasts as a function of ensemble size, and on a possible spread-skill relationship.

**b. HFP - Seasonal forecast research**

Canadian expertise in climate modelling and analysis (CCCma), developed for climate change research, and expertise in weather forecasting (RPN) has been leveraged and combined with University research (McGill) resulting in a state-of-the-art research, development, and operational activity (CMC) in first-season climate forecasting. The first phase of the Historical Forecasting Project (HFP1) is described in Derome et al. (2000). In it the persisted effects of ocean temperature anomalies were used as a basis to make seasonal forecasts using modern climate and forecast models. Ensembles of forecasts were produced and analysed for all seasons for the period 1969-1994 with two GCMs. This allowed the ensemble and reliability measures discussed above to be investigated and applied. This has led to a first-season forecast being issued operationally by CMC indicating a significant direct return on a modest investment in resources. The successful HFP reflects the combination of the difficult intellectual challenge of predictability research, the melding of available expertise developed for other purposes, and a practical result which would not have otherwise been attained within the MSC.

This successful approach will be continued in several extensions and with several partners. HFP2 aims to extend the productive cooperative research into SIP between university and government researchers. HFP2 extends the HFP1 research using improved and higher resolution versions of the climate model, the CCCma GCM3, and of the weather forecasting model, Global Environmental Model (GEM) developed at the Division de Recherche en Prévison Numérique (RPN). Results from these integrations will be made available for analysis of improvements in first-season forecasts and the reasons for such improvements. Additional skill made possible with a four model multi-ensemble will also be investigated. The data will also be available for ensemble approaches and for probabilistic measures of reliability.

Discussions are also underway with researchers in NOAA (National Oceanographic and Atmospheric Administration) to share results of experiments where they would adopt the HFP experimental protocol. There is also the potential of sharing results with a consortium of forecast producers through the International Research Institute (IRI). Both of these possibilities would widen the ensemble of model results and would also widen the "intellectual ensemble" applied to SIP. Finally, we have been invited to participate in the second stage of the Seasonal Prediction Model Intercomparison Project (SMIP), an undertaking of the CLIVAR Working Group on Seasonal-to-Interannual Prediction (WGSIP). SMIP currently uses and idealised AMIP-like experimental protocol. We have suggested an additional SMIP component using the HFP protocol and this will be discussed at the next WGSIP meeting.

**c. Multi-season 2-tier prediction**

The current approach using persisted SSTAs is suitable only for first-season forecasts. Multi-season forecasts demand that the SSTAs evolve with time. One approach is to use the robustness of the El Niño phenomenon to make tropical SST predictions either statistically or with some simplified tropical model. The atmospheric models are then used as before, with these SSTAs as lower boundary conditions, to make multi-season predictions, hence the “2-tier” approach. One project will investigate this 2-tier approach to multi-season predictions.

**d. Empirical and dynamical prediction and analysis**

Neural networks are nonlinear generalizations of the usual multivariate statistical methods. They have been applied to forecasting equatorial Pacific sea surface temperatures as reported, for instance, in the Experimental Long-lead Forecast Bulletin (see Kirtman, 2000). The objective here is to develop a hybrid model using the simplified Lamont tropical ocean model and a neural network statistical representation of tropical atmospheric behaviour. The aim is to provide forecasts of SSTAs for 2-tier SIP as discussed above.

**e. Downscaling of seasonal predictions**

Typical SIP results are available at GCM resolutions with grid intervals of several hundred kilometres. It may be possible to generate useful information at smaller scales by downscaling the GCM results using the CRCM (Canadian Regional Climate Model). For instance, the effects of the Great Lakes in the east and of the mountains in the west of Canada offer the possibility that local forcing and forecasts of seasonal flow anomalies will generate enhanced information.

The feasibility of using the CRCM for downscaling SIPS will be investigated. The ability of the model to reproduce observed seasonal anomalies when nested within objective analyses will first be assessed. A range of approaches and methods to dynamic downscaling will be investigated.

### f. Coupled model predictions and predictability

The ultimate tool for multi-seasonal prediction is a realistic global coupled atmosphere/ocean model. Such a model must include the controlling physics, especially of the ENSO mechanism. The CCCma CGCM (Flato et al., 2000) will be used as the basis for the development of a coupled multi-seasonal forecast system and for studies of the mechanisms of multi-seasonal climate variability.

The requirements for a coupled model which is useful for SIP are generally different from that for climate simulation and the development of such a model, while drawing on CCCma expertise, would not normally be undertaken at CCCma for climate change purposes. The proposed development therefore again represents a leveraging of expertise in several areas in the university and government communities.

Several steps are necessary to begin the research leading to fully coupled global multi-seasonal predictions:

*i. Improvement of the representation of the tropical ocean in the coupled model*
From the results of the CLIVAR ENSIP (ENSO Intercomparison Project) it may be claimed that none of the contributed models exhibits a satisfactory simulation of ENSO, indicating a lack of both modelling and perhaps theoretical understanding of this most important component of variability and predictability. Enhanced tropical resolution, mixed layer dynamics, and coupling approaches may all be required to improve the behaviour of the coupled system in the tropics. This is the main goal of this subproject.

*ii. Initialization of the coupled system*
Basic initialization methods of the coupled model will be investigated and the possibility of obtaining ocean analyses from other sources will be reviewed.

*iii. Experimental coupled predictions*
The goal is to perform experimental ensemble predictions on one or more well-observed ENSO events to prove the utility of the improved model and techniques. In addition and importantly, comprehensive analyses of ocean, atmosphere, and coupled behaviour for the system will be carried out. The ultimate aim is a coupled climate forecast system which could be used for a fully-coupled HFP and potentially for operational use.

Well-financed international efforts in SIP using coupled models are underway in the European Union and the USA. We are discussing participating in organized coupled model SIP experimentation with a number of US groups organized through the International Research Institute.

### g. Diagnostic studies of time-mean anomalies and storm statistics

In addition to the above modelling studies, diagnostic studies will examine the interaction between time-mean flow anomalies and the storm track statistics. In particular, this should help clarify the extent to which these anomalies are controlled/influenced by their interaction with the transient eddies, as opposed to being forced by anomalies in the lower boundary conditions.

### h. Summary of seasonal to interannual timescale research

Seasonal to inter-seasonal prediction is a rapidly developing area of scientific research and practical application. SIP will be investigated using a variety of approaches and methods representing a melding of available expertise and interests from a range of researchers made possible through this proposal. A broad and organized collection of projects deals with: (1) basic and potential predictability studies, (2) attainable first-season prediction methods involving ensemble and multi-model approaches, (3) potential second- and multi-seasonal prediction through 2-tier forecast approaches, (4) the potential for downscaling these results, and (5) the research needed to produce experimental SIP based on global coupled GCMs.

These projects are intertwined both within Canada and potentially with the US and the international community through the IRI, SMIP, and the CLIVAR initiatives.

### 4.1.3 The individual research projects

#### A) Seasonal to interannual prediction

#### Subproject 1: Seasonal predictability and predictions with a simple general circulation model

*J. Derome (McGill U.) and G. Brunet (RPN; McGill U.)*

Seasonal forecasting is generally done with sophisticated dynamical models or statistical methods. The dynamical approach has the advantage of not needing long time series to be "trained", as statistical methods do, and it should be better able to cope with a slowly changing atmosphere. The statistical approach, on the other hand, is far less computer-intensive, an advantage that is attractive considering the modest forecast skill that is currently achievable with either method. The present project aims to investigate an intermediate approach, based on a numerical model, but of a simpler and more economical type than those commonly used. Because the model is economical to use, it will be possible to perform numerous controlled experiments which should help understand results obtained with more complex models.

**Objectives**

1. To investigate how the size of ensembles of forecasts affects the forecast skill of the ensemble mean.
2. To investigate a possible forecast spread-skill relationship.
3. To seek the best method of combining the predictions made with different models to maximize skill.
4. To see if a simple global dynamical model can have practical skill in seasonal forecasting.
5. To do the above in an environment where sufficient data are available to obtain reliable results.

**Methodology.** It is proposed to use a simple general circulation model (SGCM) developed at Reading U. and McGill and described in Hall (2000). The model is a global spectral model driven by empirical *time-independent* forcing functions. The model has been integrated for several thousand days and has been shown to have a good climatology, both in terms of the time-mean variables and of the transient eddy statistics. Hall and Derome (2000) have used it to study the atmospheric response to a tropical heat source of the El Niño type, and Hall et al. (2000a,b) have used it to investigate the response to mid-latitude Pacific Ocean heat sources. The model can be run in perpetual Northern Hemisphere winter mode, or with an annual cycle, with specified sea surface temperatures, or coupled to a global ocean model developed in R. Greatbatch's group at Dalhousie.

This subproject will proceed through the following systematic steps:

*A potential predictability study.* We will begin by performing an ensemble of simulations with the SSTs specified from observations over a 50 year period covered by the NCEP reanalyses (Kalnay et al., 1996), in the spirit of the AMIP experiments (Atmospheric Model Intercomparison Project). We will perform an analysis of variance to determine the level of atmospheric variance forced by the SSTs and that due to the internal dynamics. A comparison with published results based on full GCMs (e.g., Zwiers et al., 2000) will allow us to see if the model is responding with the right amplitude to the SST forcing, and, if needed, to adjust the parameterization of the surface heat flux to obtain a signal to noise ratio similar to that of the best GCMs. From the simulations described in Hall and Derome (2000) we can expect that the model will generate a realistic PNA response to tropical heating of the El Niño type.

*Seasonal predictions of GCM simulations with simpler models.* We will then use the SGCM to produce seasonal forecasts. Instead of attempting to predict observed mean-seasonal states, as normally done, we will attempt to “predict” (hindcast) those generated by the GCM3 in a series of AMIP-type simulations forced by observed SSTs. The individual members of this AMIP2 ensemble will be used as proxies for atmospheric realizations and will thus provide a much longer record of states to be predicted than is available from observations. The forecast protocol will be the same as in the HFP1, i.e., the SST anomalies will be specified from the month before the start of the predictions, and kept constant in time through the 4-month predictions, to simulate operational conditions. We will investigate, among other questions the influence of the size of the ensembles on the forecast skill and a possible spread-skill relationship.

We will also use the GCM2 as a prediction model. The model is economical and allows running large ensembles. We will then investigate the best way to combine the predictions of the two models. In particular we will investigate the properties of the BLUE (Best Linear Unbiased Estimate) method and compare it to simper approaches. Of special interest is the length of the data record required to gain substantial benefits from the BLUE method.

*Seasonal predictions of observed states.* We will produce large-ensemble seasonal predictions with the SGCM of observed atmospheric conditions for the same period as in the first phase of the HFP. Building on the experience gained with this model we will test whether, with suitably large ensembles, it has some practical forecast skill. If so, we will investigate the best way to combine its predictions with those of the more complex models.

**Relationship to other projects and to themes.** This work is directly related to the next subproject on seasonal forecasting with more complex models, both being complementary contributions to the seasonal forecasting theme.

**Networking.** There will be continual interaction with all those working on the seasonal forecasting project, and in particular with G. Boer and F. Zwiers. The results will contribute to a better understanding of the results obtained with the other project, based on more complex models but shorter time series and smaller ensembles.

**Training.** A graduate student will contribute to each phase of the project. Research Associate H. Lin will be responsible for running the model and doing some of the analyses, but a graduate student will be involved in each phase of the project, mainly in the analysis of the predictions. Dr. H. Lin will work half-time on this project and half-time on the analysis of HFP results.

### SUBPROJECT 2: THE HISTORICAL SEASONAL FORECASTING PROJECT (HFP)

*J. Derome (McGill U.), G.J. Boer (CCCma; U. Victoria), G. Brunet (RPN; McGill U.) and F.W. Zwiers (CCCma; U. Victoria)*

The first phase of the Historical Forecasting Project (HFP1) is described in Derome et al. (2000). It investigates the first-season climate signal at Canadian latitudes that may be predicted with two current General Circulation Models using persisted sea surface temperatures as boundary conditions. Ensemble methods are used including a novel "superensemble" approach, albeit with only two models. A considerable body of analysis has been undertaken and is ongoing (e.g., Derome et al., 2000, Kharin and Zwiers, 2000, Kharin et al., 2000, Gagnon and Verret, 2000).

The HFP design has been very successful both intellectually and practically. It has permitted the modest Canadian effort to compete effectively in terms of presentations and publications in gaining new knowledge of short-term climate variations, their simulation with GCMs, and the use of this information for the production of first-season forecasts.

The melding of Canadian expertise in climate modelling and analysis (CCCma), weather forecasting (RPN), and atmospheric dynamics (McGill), together with modest CRN support, has catalyzed research and development in seasonal forecasting, has trained both students and research associates, has bolstered international interaction and cooperation, and has directly resulted in a state-of-the-art operational first-season climate forecasting system. The intent is to continue and expand this activity in several new directions.

**Objectives**

1. To investigate the utility and skill of seasonal forecasts produced each month.
2. To investigate and analyse the potential of two-tier multi-seasonal forecasts.
3. To investigate the promise of new atmospheric models for seasonal forecasting via HFP2.
4. To develop and apply ensemble and superensemble approaches.

**Methodology.** The HFP approach depends on a blending of expertise and activity leading from global analysis, predictions with state-of-the-art GCMs, to sophisticated analysis of results, and to the production of a range of forecast products including realistic seasonal forecasts. The initial successful HFP effort offers several extensions as well as new approaches which can provide new information on the climate system, on model behaviour, and on forecast product generation.

**1. "Monthly " seasonal forecasts**

HFP1 produced a superensemble of forecasts for the usual four seasons (DJF, MAM, JJA, SON). It is quite feasible, and of theoretical and practical interest, to produce seasonal forecasts every month (i.e., DJF, JFM, FMA, MAM, etc.). From a theoretical view-point, this offers the possibility of learning how predictability varies with the annual cycle and searching for an understanding of why this might be so. It also offers the possibility of a "lagged superensemble" approach where some combination of previous seasonal forecasts would be used to enhance available skill (e.g., the MAM forecast would be a suitable combination of the M, A, and M predictions from the JFM and FMA prediction cycles). From the practical point of view, new predictions for the next three months would be available every month and would provide more information than the current approach.

**2. Two-tier multi-season forecasts**

The HFP group has performed preliminary research into two-season prediction of DJF using a 2-tier approach with GCM2 and separate tropical SSTA forecasts from the LDE04 model (Chen et al., 1995, Chen et al., 2000). This work will be extended to other seasons and, if deemed appropriate, to other prediction models. The results will be analysed more completely and the utility of this approach, and potentially a parallel approach using Neural Network predicted SSTAs (see Subproject 6), will be assessed. Data will be made available for evaluation and analysis with the potential of multi-seasonal operational forecasts as a result.

**3. HFP2**

New generations of both the climate and forecast models used in HFP are now available. These new models represent a considerable investment in development directed initially toward climate change and short-term forecast production. HFP2 aims to capitalize on these model improvements also for SIP. The new climate model, AGCM3, is characterized by higher vertical and horizontal resolution and improvements in the representation of many critical physical processes (e.g., optimum topography, CLASS land surface scheme, boundary layer treatment, convection, radiation, and cloud representation). The new forecast model, GEM, represents an increase in resolution, a very different numerical approach, and many improvements also to the representation of physical processes.

These improved models hold the promise of improved first-season forecasts and it is of considerable interest both to exploit this promise and to understand which aspects of model improvement have led to forecast improvement (or, in the unhappy case that there is no improvement, why this is so). New understanding of the short-term behaviour of the climate system and of seasonal predictability should also flow from the HFP2.

### 4. Ensemble and superensemble approaches

While forecast production and the assessment of skill are basic to the SIP effort, the HFP design encourages further sophisticated analysis and the development of ensemble, superensemble, and probabilistic methods of treating forecast information. Data will be made available for investigation of ensemble approaches, including a possible 4-member superensemble with HFP1 and HFP2 models, and for probabilistic measures of reliability and other statistical approaches. The development of these approaches is, we believe, basic to progress in SIP. The possibility and potential of sharing results with a consortium of forecast producers through the International Research Institute (IRI) leading to an international superensemble will also be explored.

**Relationship to other projects and to themes.** This work is itself important and integral to the broad SIP research effort under Theme I. It is directly related to, and will be informed by the results the previous subproject based on a simple GCM. It will produce applicable results at an earlier stage than the next subproject on the development of a coupled atmosphere-ocean predictive system.

**Networking.** The people involved in the Theme I projects are closely interconnected, although widely separated geographically, and there will be continued and enhanced interaction with the SGCM predictability investigations (previous subproject) and the coupled model predictability project. As mentioned also in 4.1.2b there is both actual and potential relationships with international SIP activities

**Training.** A research associate will undertake the forecast production and analysis basic to the extended HFP that is the core of this proposal. This will involve training in CCCma and RPN models, computer methods, and analysis procedures using the country's most advanced supercomputer complex. This represents academic and professional development of a high level. Research Associate H. Lin will also work half-time on this subproject (the other half on the previous subproject). Results will also be available for analysis by students and other researchers. Based on the use of HFP1 forecast data this will be an important and worthwhile aspect of education and training.

## SUBPROJECT 3: COUPLED MODEL PREDICTION AND PREDICTABILITY

*G. J. Boer (CCCma; U. Victoria), G. Flato (CCCma; U. Victoria) and J. Derome (McGill U.)*

As stressed in the CLIVAR Science Plan (1995), the ultimate tool for multi-seasonal prediction is a realistic global coupled atmosphere/ocean/land/ice model, commonly termed a coupled global climate model (CGCM). The last 5 years has seen the rapid development of a Canadian CGCM and it application to a broad variety of scientific questions. Many of the results are discussed elsewhere in the document and are mentioned only briefly here. The atmospheric component of the CGCM has been well documented (McFarlane et al., 1992), and "intercompared" in

AMIP and other intercomparison projects (Gates et al., 1999, Boer, 2000). It has been used to study an array of atmospheric processes (e.g., Pointe et al., 1994, D'Andrea et al., 1998, Gleckler et al., 1995). In particular it has been used for predictability studies on monthly and seasonal timescales (Boer, 1993, Zwiers, 1996, Zwiers et al., 2000, Kharin and Zwiers, 2000, Kharin et al., 2000) and is one of the two models used in HFP1 as discussed above (Derome et al., 2000).

An intermediate version of the coupled model where the atmospheric component is coupled to a simplified mixed layer ocean and thermodynamic sea ice component is also well documented and used. Climate change investigations have contributed to the IPCC process (e.g., Boer et al., 1992, IPCC 1995), and to studies of a variety of aspects of climate change (e.g., Boer, 1995, Reader and Boer, 1998, Arora and Boer, 2000). More recently, two versions of the fully-coupled version of the model have been documented and intercompared (Flato et al., 2000, Lambert and Boer, 2000, Boer and Lambert, 2000, Flato and Boer, 2000, Covey et al., 2000, IPCC 2000 Chapter 8), and used for historical and projected climate change simulations (Boer et al., 2000a b). The results have been widely used for impact studies (IPCC Data Distribution Centre, CCCma website, US National Assessment) and for the IPCC (IPCC 2000, Chapters 9, 10, 12) and for several other studies.

**Objectives**

1. To improve and extend the representation of the tropical ocean in the coupled model for the purposes of seasonal to interannual predictions
2. To analyse ENSO and other coupled behaviour in the improved system
3. To investigate a hierarchy of initialization-methods of the coupled system
4. To undertake experimental coupled seasonal to interannual predictions.

**Methodology.** The CCCma CGCM provides the basis for the development of a coupled multi-seasonal forecast system and for studies of the mechanisms of multi-seasonal climate variability. However, several steps are necessary in the research leading to fully-coupled global multi-seasonal predictions and these are the objectives of the project.

*1. Improvement of the tropical ocean.* The improvement and extension of the representation of the tropical ocean in the coupled model for the purposes of SIP is a major aspect of the project. The CLIVAR ENSIP (ENSO Intercomparison Project) and STOIC (Study of Tropical Oceans in Coupled GCMs) studies show a wide variety of model behaviour in the tropical region in general and particularly terms of modelled ENSO. It may be claimed that no current model exhibits a satisfactory simulation of ENSO. This indicates a lack of modelling understanding but also a lack theoretical understanding of this most important component of variability and predictability.

There will be a step-by-step attempt to improve the tropical ocean component as follows:
*(a) Enhancement of horizontal tropical resolution.* Higher resolution should better represent the tropical oceanic wave modes involved in ENSO and the horizontal resolution of the ocean model will be increased in the tropical/equatorial region. However, ENSIP has shown that this is certainly not a sufficient condition and may not even be a necessary condition. Optimum approaches for varying resolution are not available and the nature of the implementation can impact the result. Careful planning and analysis of results is required.

*(b) Mixed layer representation.* Although standard in atmospheric models, boundary layer representations are only now becoming a standard part of global ocean climate models. The KPP parameterization will be investigated with special attention given to vertical resolution, mixing parameters and their effects on tropical ocean dynamics and thermodynamics.

*(c) Coupling methods.* Ocean models typically have higher resolution than atmospheric components and this requires a "coupling strategy". This is comparatively straightforward when the ocean resolution is a simple multiple of that of the atmosphere but becomes much more difficult when the ocean resolution varies with position. A coupling strategy which properly conserves interfacial energy, moisture, and momentum exchange between the atmosphere and ocean is required.

*2. Coupled system behaviour.* The coupled system has modes of variability which arise as a consequence of the coupling and which are not a feature of the atmospheric or oceanic system alone. ENSO behaviour is a major but not the only example. An analysis of coupled system behaviour will show if increased horizontal resolution and mixed layer parameterizations give better results in general and better ENSO results particularly. Cloud processes, characterized as cloud feedbacks, are undoubtedly important, as are aspects of the surface energy budget. Analyses of energy and variance budgets will be used in an effort to quantify the determinants particularly of ENSO behaviour, but of the coupled behaviour in general. The ENSIP and STOIC analysis / intercomparison projects are not able to clearly delineate the reasons for the very different modes of behaviour of current models nor were they able to list the necessary conditions for acceptable behaviour. This remains a difficult area of ongoing research. The reality of the simulated ENSO is important not only for seasonal to interannual prediction but also for global warming simulation and for climate change detection.

*3. Initialization.* Coupled system initialization methods are in their infancy although progress, based largely on methodologies developed for the atmosphere, is rapid and impressive. For some purposes relatively simple methods (such a as surface nudging) may be surprisingly effective. Understanding why this is the case, and the limits of such methods is important. More sophisticated objective analysis methods are also available for ocean analysis and modern variational methods are being developed. Simpler methods will be investigated first including the simplest of all, namely accepting analyses directly. While initialization is not a major interest of this project, it is important that reasonable initial conditions be used so that the SIP experiments are not compromised.

*4. Experimental coupled prediction.* The ultimate goal is to perform experimental predictions on one or more well observed ENSO events to prove the utility of the improved model and techniques. In addition and importantly, comprehensive analysis of ocean, atmosphere, and coupled behaviour for the predictions would be carried out. This is a step toward the ultimate goal of a coupled climate forecast system which can form the basis for a coupled HFP and, if sufficiently skilful, to form the basis of an operational system.

**Relationship to other projects and to themes.** This work is an integral part of the continuum of season to interannual predictability and prediction research under Theme I of the proposal. The project described here is directly connected to of the SGCM predictability investigations and the HFP seasonal predictability project representing the longer timescale, and complete coupled-model approach to SIP. This latter approach must ultimately prevail but at the current level of knowledge all approaches in the hierarchy can provide useful information and insight into the complex processes governing, and limiting, seasonal-to-interannual prediction.

**Networking.** The people involved in this theme are closely interconnected, although widely separated geographically, and there will be continued and enhanced interaction with an organized seasonal forecasting program

**Training.** A research associate will be recruited for model development, analysis, and for the experimental predictions that are part of this proposal. Training in CCCma/CRN models, computer methods, and analysis procedures has proved rewarding and valuable for previous RAs both academically and professionally. Although not explicitly part of the proposal, the results will be available for analysis by students and other researchers. Based on the use of climate change data on the CCCma web site, this can be an important and worthwhile aspect of education and training.

### SUBPROJECT 4: ACCURACY OF DOWNSCALING OF SEASONAL PREDICTIONS

*D. Caya (UQAM) and R. Laprise (UQAM)*

It is a goal of this sub-project to test the feasibility of using a RCM for operational downscaling of seasonal to interannual predictions (SIP). We first propose to study the ability of the CRCM to reproduce observed seasonal anomalies when nested with objective analyses of atmospheric observations. This is a necessary preliminary scientific test that the CRCM must past before attempting the downscaling of SIP ensembles.

The Project to Intercompare Regional Climate Simulation (PIRCS) has made the first attempt to answer this question. However the lack of soil moisture measurements to initialize the short two-month-long simulations and the implicit underlying assumption that climate anomalies would dominate over model biases, have limited the usefulness of the Project. Both difficulties are related to the length of the simulations, which are not long enough to be free from the initial value problem or to provide enough data to build stable climatologies.

The proposed project will produce nested simulations in excess of 10 years with the newly developed version of the CRCM. These simulations will be driven by the best sets of available gridded objective analyses. Seasonal anomaly correlations will be calculated for a number of predicted quantities, including near-surface temperature and precipitation amounts that are observed at surface stations. If these tests prove successful we may attempt to downscale ensemble SIP of global models.

**Relationship to other projects and to theme.** This project is directly related to the above subprojects (2) and (3) on seasonal forecasting in that it is meant to test the possibility of downscaling the predictions made with the global models used in these projects.

**Networking.** Close ties will be kept with all those involved in the seasonal forecasting project, and in particular G. Boer, G. Brunet, J. Derome, and F. Zwiers.

**Training.** One Graduate Student will work on this topic for his research throughout the subproject, working under the joint supervision of D. Caya and R. Laprise. The surface station data analyses will be done in collaboration with MSC meteorologists W. Hogg and A. Bourque, and the downscaling of ensemble seasonal prediction in collaboration with J. Derome and MSC scientist B. Dugas.

### SUBPROJECT 5: EVALUATION OF APPROACHES TO DYNAMICAL DOWNSCALING

*R. Laprise (UQAM) and D. Caya (UQAM)*

The validation of RCMs has been severely hampered by the lack of high-resolution gridded observed climatologies. It is well known that RCMs develop structures in their simulations that are more detailed than what is produced by GCMs because of their increased spatial resolution, but the value of these added details has still to be demonstrated. In particular, the relative importance of initial, lateral and surface conditions in controlling the fine-scale structures in RCM needs to be thoroughly evaluated. The importance of initial conditions has been studied already (e.g., Caya and Biner 2000).

*Lateral forcing.* The importance of lateral boundary conditions has begun to be studied by Ph.D. student B. Denis using a perfect-prognostic approach nicknamed the Big Brother Experiment. This experimental protocol consists in first establishing a reference climate using a high-resolution reference simulation called the Big Brother. The simulated results are degraded by removing scales that are unresolved in today's global objective analyses and/or GCM output. This filtered reference is then used to drive a high-resolution RCM. Finally, the climate statistics over the regional area of the regional model are compared with those of the Big Brother. Differences can thus be attributed without ambiguity to errors associated with the downscaling technique from prescribed lateral boundary conditions, and not to model errors or to observation limitations.

*Nesting strategy*. We will expand the test carried out so far comparing the traditional lateral boundary conditions nesting technique and the newly developed nudging of large scales (also referred to as spectral nesting). We also want to compare the limited-area nested and the variable-resolution global approaches, to determine the strengths and limitations of both approaches, as alternatives to regional climate modelling. The newly developed operational Canadian variable resolution model GEM and a limited area version of it will constitute an excellent environment for carrying out these tests.

*Surface forcing*. The contribution of the surface representation to the development and evolution of the fine-scale details in a simulation of a Regional Climate Model is another aspect of this sub-project. The forcing over the land surface is produced through the topography (mountains and valleys) and land cover (type of soil, vegetation, urbanization, etc.), while that over water surface depends on the sea (lake) surface temperature and ice distribution. The aspect we want to investigate is the relation between the spatial resolution of the surface characterization and the spatial resolution of the simulated atmospheric patterns. The CLASS scheme (Canadian Land Atmosphere Surface Scheme) will represent interactively land surface processes in the Canadian Regional Climate Model, while the observed SST will be prescribed from climate archives. It will be of interest to study the effect of the resolution of SSTs and of geophysical fields that enter CLASS on the downscaling ability of the regional model.

**Relationship to other projects and to theme.** This project is directly related to the above sub-projects (2) and (3) on seasonal forecasting in that it is meant to test the possibility of downscaling the predictions made with the global models used in these projects.

**Networking.** The work involving the GEM model will be done in collaboration with MSC scientists J. Côté and B. Dugas as well as with Michael Fox-Rabinovitz (U. Maryland). The work involving CLASS will be done in collaboration of MSC scientist D. Verseghy. Close ties will be kept with all those involved in the seasonal forecasting project, and in particular G. Boer, G. Brunet, J. Derome, and F. Zwiers.

**Training.** These sub-projects will proceed through the work of a PDF R. de Elía under the direct supervision of R. Laprise and of one graduate student working under the joint supervision of D. Caya and R. Laprise.

### SUBPROJECT 6: COMBINING EMPIRICAL AND DYNAMICAL APPROACHES TO ANALYSE AND PREDICT CLIMATE VARIABILITY

*W. Hsieh (U. British Columbia)*

Over the last few years, our group has developed neural network models which are nonlinear generalization of the multivariate statistical methods widely used in meteorological-oceanographic research - regression, principal component analysis and canonical correlation analysis. These nonlinear empirical methods have been applied to forecasting the equatorial Pacific sea surface temperatures for El Niño-La Niña events, and to analysing both real data and numerical model output. The next step in the evolution of this approach is to combine the empirical neural network approach with dynamical models in the network to improve our ability to analyse and predict climate variability.

**Objectives**

1. To develop a hybrid coupled model using the Lamont ocean model and a neural network atmospheric model, with data assimilation and a forecast error correction system.
2. To provide tropical Pacific SST forecasts as lower boundary conditions for the atmospheric GCMs (from CCCma and CMC) to improve their seasonal prediction skills.
3. To improve the hybrid coupled model by using an ocean GCM (MOM from GFDL).
4. To assist other GCM groups in the nonlinear analysis of their data, using neural networks for nonlinear regression, nonlinear principal component analysis and nonlinear Canonical Correlation Analysis.

**Methodology and Data.** 1. The hybrid coupled model will use the Lamont ocean model and a neural network model for the wind stress. The neural network nonlinear canonical correlation analysis model will estimate the wind stress field from the upper ocean heat content or the SST from the ocean model. Some parameterizations in the Lamont model (e.g., thermocline depth and subsurface temperature anomaly) may also be replaced by neural network parameterization schemes.

The next stage is to develop variational data assimilation schemes for the coupled model, first with 3-D-VAR (3-dimensional variational method), and then with 4-D-VAR. Finally, a model forecast error correction system will be developed to further enhance the forecast skills. A neural network will be used as a nonlinear Model Output Statistics system, and the error correction system will be developed using an Extended Kalman filter.

2. The HFP has used two global models, with ensembles of 6 forecasts produced from each model. These are then blended statistically. Because the MSC has not yet developed a tropical Pacific SST forecast model, bottom boundary conditions for the models were supplied by persisting the global SST observed in the month prior to the forecast period. We propose to supply tropical Pacific SST forecasts as bottom boundary conditions for the models to improve their seasonal prediction skills. The first SST forecast model will be a neural network nonlinear canonical correlation analysis model, with tropical sea level pressure as predictors for SST. The second will be the hybrid coupled model. The predicted SST from different models can also be blended by the Best Linear Unbiased Estimate method (Derome et al., 2000) to yield a better predicted SST field.

3. Extend the hybrid coupled modelling in (1) to more complex ocean models (e.g., the MOM – GFDL model). As the hybrid model will now cover the extra-tropics, this would allow us to test the hybrid modelling strategy for the extra-tropical regions.

4. With our neural network tools for nonlinear principal component analysis and nonlinear canonical correlation analysis, we will assist other groups in nonlinearly analysing their dynamical model outputs, either for extracting features and relations, or for downscaling GCM variables to local variables. The nonlinear principal component analysis and nonlinear canonical correlation analysis codes will be made publicly available.

**Expected results**. Improvements in forecasting the tropical Pacific SST and the seasonal climate over North America are expected. The nonlinear principal component analysis and nonlinear canonical correlation analysis will be a new paradigm in multivariate data analysis, augmenting the traditional Principal Component Analysis and Canonical Correlation Analysis techniques.

**Relationship to other projects and to themes.** This project is done in direct support of subproject (2) of Theme I on seasonal forecasting in that it will seek to provide the global models with improved SST predictions.

**Networking**. There will be close interactions with all those involved with the seasonal forecasting project (G. Boer, G. Brunet, J. Derome and F. Zwiers) and with G. Flato, J. Fyfe, L. Pandolfo, L. Mysak and C.A. Lin.

**Training:** 1 Ph.D. student and 1 post-doctoral fellow will be in training for each year of the project.

### B) SYNOPTIC-DYNAMIC CLIMATOLOGY OF LOWER-TROPOSPHERIC STORM-TRACK REGIONS

*L. Pandolfo (U. British Columbia)*

Extra-tropical cyclone activity is concentrated in three regions around the globe. In the Northern Hemisphere, these are the Atlantic and Pacific storm-track regions. The Atlantic storm-track extends north-eastward from Florida to the Norwegian sea, while the Pacific one extends eastward from Japan to British Columbia. In the Southern Hemisphere, an elongated storm-track circumvents Antarctica. The climate of these regions is strongly controlled by variability in storminess.

Numerous studies have shown how climate indices (e.g., the North Atlantic Oscillation or NAO) can be used to describe the variability of weather patterns in these regions (e.g., Hurrell and van Loon, 1997, Rogers, 1990, Cayan, 1992). For instance, they have shown clearly how the NAO modulates cyclone activity, wind strength, precipitation, temperature and air-sea fluxes over the North Atlantic. However, this modulation effect is always presented as a simultaneous (on a monthly timescale) correlation between the NAO and the weather field being considered. The synoptic and dynamic conditions leading to the simultaneous climate-weather correlations have not been defined.

Cayan (1992) hypothesized that extra-tropical cyclones could link upper-ocean dynamics to atmospheric climate variability through their control of air-sea heat fluxes. But again, his presentation of a relationship between the variability of the NAO, heat fluxes and storm activity (represented by intra-monthly flux variance) is a consistency check of the simultaneous occurrence of corresponding extreme values for those fields. Relationships of cause and effect between upper-ocean conditions, storm activity and short-term climate variability have not been definitely established.

This project will develop a synoptic climatology of the near-surface storm-track regions in order to understand their intra-seasonal and inter-annual dynamics. Such an understanding will provide the physical basis upon which to investigate how climate change will affect the storminess of coastal regions.

**Objectives**

1. Develop a synoptic climatology of the world's storm-track regions.

The goal is to assess weather variability in stormy regions in relation to a meaningful frame of reference. In our case, this reference will consist of a new kinematic set of low-frequency, planetary, atmospheric circulation types. Insight into the climate of storm-trackregions will be gained by examining the simultaneous and lagged relationships of various storm statistics (or indices), individually and collectively, to the large-scale dynamical processes described by our set of circulation types.

2. Establish the dynamic climatology of the world's storm-track regions.

The goal is to determine the physical and dynamical processes that act to create the observed variability in weather patterns in the storm-track regions. In the process, we will establish a dynamical model of extra-tropical air-sea interactions that can explain the synoptic climatology characteristic of storm-track regions.

**Methodology and data**

1. Synoptic climatology of storm-tracks

There are two stages to this part of the proposed research. Both stages involve diagnostic analyses using the NCEP reanalysis dataset and our storminess dataset developed in previous work. First, we will categorize low-frequency atmospheric circulations into types that best describe the regimes of climatic flow in a given storm-track region. Our preliminary investigations of the Atlantic region used the NAO index to discriminate between extreme climatic flows. We found a physical link between the NAO and storm activity. However, every major storm track region is located in a different oceanic basin. For instance, the greater width of the North Pacific with respect to the North Atlantic results in a storm-track region with two distinct maxima in storm activity (one east of Japan and the other in the Gulf of Alaska). It is not obvious that the NPO (North Pacific Oscillation) will prove useful for discriminating among patterns of storm activity simultaneously in both the Asian and the Gulf of Alaska storm tracks. Hence, for each storm-track region, we will define the low-frequency circulation types or regimes by applying Nonlinear Principal Component Analysis (NLPCA) to geopotential height fields. Second, we will assess and classify weather patterns in relation to these regimes. For this purpose, weather variability in a storm-track region will be represented concisely using our storminess dataset (see progress report) extended to cover all areas of the globe.

2. Dynamic climatology of storm-tracks

Our synoptic climatology will yield a classification of weather elements according to climatic flow regimes. The particular combination of weather elements present in a given climatic flow situation will provide clues about the physical processes that led to this particular weather-climate configuration. This will be quantified using various multi-variate statistical analysis techniques to determine the cause and effect relationships between upper-ocean variability, storm variability and climatic flows. From this we will infer dynamical models able to explain the synoptic climatology of storm-track regions.

**Anticipated results.** The proposed work will provide a synoptic climatology of all storm-track regions of the world based on our storminess dataset and on a classification of climatic flows. Our research will also establish a thermo-dynamical model of extra-tropical air-sea interaction to explain the coupled variability of storm activity and climatic flows on intra-seasonal and/or inter-annual timescales.

**Relationship to other projects and to themes.** Results from this work will shed light on the mechanisms responsible for the variability and predictability of the coupled climate system in storm-track regions. This is of direct relevance to the objectives of Theme I on seasonal variability and predictability.

**Networking.** The network approach is important for the realization of this project. The climatic flow regimes that will be used to develop the synoptic climatology of storm-tracks will be constructed in collaboration with the DecCen investigators involved in the project "Northern Hemispheric Circulation Modes and Regimes" (see 4.2.3A). In addition, the thermo-dynamical model will be compared with results from the CCCma coupled GCM and the CRCM.

**Training.** One graduate student will be involved continuously in this research. (M.Sc. first, then Ph.D.).

## 4.2 THEME II: THE DECADAL TO CENTURY TIMESCALE

*Theme leaders: J. Fyfe (CCCma; U. Victoria) and R.J. Greatbatch (Dalhousie U.)*

As with the corresponding international CLIVAR program, the overall scientific objective of this component of the network is to describe and understand long-time-scale variability and predictability through analysis of observations and modelling of the climate system. The primary goals of the proposed work are: (i) to extend our understanding of Northern Hemisphere modes and regimes of atmospheric variability on inter-annual to inter-decadal timescales, (ii) to characterize the decadal timescale response of the North Atlantic Ocean to forcing by the North Atlantic Oscillation, as well as the potential predictability of the latter, (iii) to understand the linked tropical and extratropical decadal variability in the Pacific (and potential interbasin influences) and (iv) to describe and understand the sources and mechanisms of Southern Ocean decadal variability. This work will utilize all relevant observational datasets and a range of climate models from simple atmospheric models to a state-of-the-art coupled global climate model (GCM). The research team involves government (CCCma, Victoria) and university scientists from five institutions spanning the country (U. Victoria, U. British Columbia, U. Waterloo, McGill U. and Dalhousie U.). Below is a summary of the scientific issues to be addressed followed by a summary of the research approaches.

### 4.2.1 The scientific issues

#### a. Northern Hemisphere circulation modes and regimes

In recent years there has been an enormous interest in the so-called "Arctic Oscillation" (Thompson and Wallace, 1998). The Arctic Oscillation, defined as the leading empirical orthogonal function of Northern Hemisphere sea-level pressure, describes a fairly zonally symmetric pattern of variability interpreted as representing a shifting of mass from polar latitudes to the midlatitudes and back again (on monthly, interannual and longer timescales). There is also evidence that the Arctic Oscillation has been changing in recent decades (Thompson et al., 2000), and some GCMs predict continued change into the 21$^{st}$ century as a result of increasing greenhouse gas forcing (Fyfe et al., 1999, Schindell et al., 1999). While proving to be a very useful description of Northern Hemisphere circulation variability and change, there has been debate recently as to whether the Arctic Oscillation is fundamentally a statistical entity or a true dynamical mode of variability (Deser, 1999, Wallace, 2000, Monahan et al., 2000b). Related to this issue is the question of the relationship between the hemispheric Arctic Oscillation and the regional North Atlantic Oscillation (which itself has long been studied). Researchers at the CCCma and the U. British Columbia have been addressing these important scientific issues using a newly developed analytical technique called nonlinear principal component analysis (Monahan, 2000a,b). When applied to observational and GCM data this new technique reveals that the Arctic Oscillation is the optimal linear approximation to a more physically representative and dynamically consistent nonlinear structure of Northern Hemisphere atmospheric variability. This nonlinear mode of variability is much less zonally-symmetric than the Arctic Oscillation and involves transitions in and out of various regional variability states or regimes. It has also been shown that under global warming the spatial structures of the underlying regimes remain essentially unchanged but their occupancy statistics alter (e.g., North Atlantic blocking episodes becoming less frequent). The proposed work continues this line of investigation by specifically addressing the following two scientific issues: 1) what are the dynamics which maintain regimes and cause transitions between them and 2) what is the relationship between linear modes of variability, such as the Arctic Oscillation, and nonlinear regimes of variability?

**b. North Atlantic Oscillation dynamics, predictability and forcing of the North Atlantic Ocean**

This research concerns the North Atlantic Oscillation, which is the most important mode of atmospheric variability in the North Atlantic and surrounding area. This work is organized along three main research lines addressing the following issues. 1) Understanding the dynamics of the regionally focused North Atlantic Oscillation in relation to the hemispheric Arctic Oscillation and, additionally, how the low index state of each is related to North Atlantic blocking events. 2) Describing and understanding the response of the North Atlantic ocean to the North Atlantic Oscillation. This line of research will quantify the influence of the North Atlantic Oscillation on North Atlantic deep water renewal and identify the specific oceanic pathways through which this influence is felt. Necessarily this line of investigation will involve the development of a high resolution ocean climate model including hitherto undeveloped parameterizations of certain important unresolved processes. One such parameterization to be developed will represent important diapycnal oceanic mixing which converts deep water back to surface water, while another parameterization to be developed will represent ageostrophic processes involved in cascading gravity wave modes. 3) Assessing the seasonal to interdecadal predictability of the North Atlantic Oscillation in the context of the coupled atmosphere-ocean climate system. Here the specific research question is how much predictive skill in the North Atlantic Oscillation can be derived from the oceanic influence on the North Atlantic sea-surface-temperatures? This line of a research will involve making significant improvements to an existing coupled atmosphere-ocean model.

**c. Pacific decadal variability**

Interannual variability in the Pacific Ocean is clearly dominated by El Niño/La Niña variability and its associated teleconnection through the atmosphere to the North Pacific. It is also clear that the North Pacific possesses significant decadal to interdecadal variability with the most notable recent event being the apparent climate regime change, which occurred from late 1976 through to 1988. During this period SSTs in the central and western North Pacific Ocean were cooler than normal and the Aleutian Low was deeper than normal (see Trenberth, 1990, Trenberth and Hurrell, 1994). A number of theories exist to help understand decadal variability in the North Pacific, for example; 1) decadal modulation of El Niño through non-linear tropical atmosphere-ocean coupling and subsequent teleconnection to the North Pacific (Trenberth and Hurrell, 1994), 2) oceanic subduction of extratropical thermal anomalies (generated through the atmospheric teleconnection response to tropical SST anomalies) which propagate along isopycnals towards the equator, potentially reversing the sign of equatorial SST anomalies (Gu and Philander, 1997) and 3) midlatitude coupled atmosphere-ocean interactions involving the subtropical gyre and its associated northward heat transport (Latif and Barnett, 1994, 1996).

In this general context, work will be directed along two lines: 1) the development of an improved equatorial Pacific Ocean representation in the CCCma coupled GCM (joint with subproject 3 of section 4.1.3) followed by a systematic and progressive analysis of the various mechanisms of decadal variability supported in the improved model and 2) an examination of oceanic subduction of South Pacific extratropical thermal anomalies and their role in tropical Pacific decadal variability. In a related vein it is also proposed to quantify the role of South Atlantic extratropical subduction on tropical Atlantic variability in order to test the hypothesis that tropical Atlantic variability is linked to low frequency variability in the Antarctic circumpolar current. Also to be addressed is the question of whether or not changes in the Pacific to Atlantic freshwater transport during different phases of El Niño are of sufficient magnitude to cause low-frequency variability in North Atlantic deep water formation.

**d. Southern Ocean decadal variability**

Preliminary analyses of two versions of the CCCma coupled GCM reveal interesting differences in decadal and longer timescale variability in the Southern Ocean. As an example, in the latest version of the CCCma coupled GCM there is a significant spectral peak in Southern Hemisphere ice extent variability at periods around 25 years, whereas an earlier version of the coupled GCM exhibits little low-frequency variability. This difference in decadal variability between model versions is likely related to the parameterization of oceanic processes, involving ocean mixing for example. The general scientific issue addressed here is the sensitivity of Southern Ocean decadal variability to parameterized and resolved ocean processes in a state-of-the-art coupled GCM. This assessment will be made in light of available observations and as such will help modellers identify those oceanic processes which are key to the successful reproduction of the observed record of Southern Ocean decadal variability.

### 4.2.2 Overview of the Theme II research

The general strategy under the "decadal to century timescale theme" is to analyze available observations and to employ a hierarchy of climate models and analytical techniques each suited to the particular observed phenomenon and scientific issue at hand.

Under subtheme (a) dealing with Northern Hemisphere modes and regimes the plan is to compare results obtained through the application of nonlinear principal component analyses to NCEP reanalyses and long control (with fixed pre-industrial greenhouse gas forcing) and stabilization (with enhanced greenhouse gas forcing) integrations of the CCCma coupled GCM (Flato et al., 2000). The CCCma coupled GCM has been shown to quite realistically represent hemispheric linear modes and nonlinear regimes from the surface to above the tropopause (Fyfe et al., 1999, Monahan, 2000a). Further, a simplified atmospheric GCM will be employed in order to relatively easily assess the influence of various key physical processes (e.g., topographic mean-flow interactions). The simple GCM is based on the dry primitive equations and is integrated with imposed time-independent forcing derived to reproduce realistic climatology and variability (described in detail in Hall, 2000). The model was developed at Reading and McGill Universities and is currently being successfully run on MSC computers under the configuration planned for this work. This research project networks scientists at the CCCma, the Universities of British Columbia and Dalhousie and external collaborators in France and Germany.

Under subtheme (b) dealing with the North Atlantic Oscillation, the plan includes the use and improvement of an existing coupled GCM developed jointly by C. Lin and J. Derome at McGill U. and R. Greatbatch at Dalhousie U. The model couples the simple atmospheric GCM (as described above) and a coarse resolution global ocean model developed in R. Greatbatch's group. The improvements include adding a moisture equation to the atmospheric component of the coupled model and replacing the ocean model with the POP (Parallel Ocean Program) model, a parallel version of the GFDL ocean model. Being a parallel code, it can be run on the MSC supercomputers and the NEC at the University of Toronto, as well as multiprocessor servers at Dalhousie U. and McGill U. This research project networks scientists at the Dalhousie U., McGill U., U. Waterloo and U. British Columbia, as well as with government scientists at the CCCma and RPN.

Under subtheme (c) dealing with Pacific decadal variability and interbasin transport the plan is to use the CCCma coupled GCM and the U. Victoria coupled model. The CCCma coupled GCM (Flato et al., 2000) is a fully three-dimensional climate system model which will have its Pacific

Ocean representation improved as part of the work of this network proposal. The U. Victoria model consists of a three-dimensional ocean model coupled to a thermodynamic/dynamic sea ice model, an energy-moisture balance atmospheric model and a thermodynamic land ice model (Weaver et al., 2000), and is ideally suited to idealized atmospheric flux forcing experiments planned as part of this work. This research networks government scientists at the CCCma and A. Weaver at the U. Victoria.

Under subtheme (d) dealing with Southern Ocean decadal variability the plan is to analyse existing control, stabilization and transient integrations of two versions of the CCCma coupled GCM.

### 4.2.3 The individual research projects

#### A) NORTHERN HEMISPHERE CIRCULATION MODES AND REGIMES

*J. Fyfe (CCCma; U. Victoria) and L. Pandolfo (U. British Columbia)*

Northern Hemisphere low-frequency atmospheric variability is highly complex yet can be usefully simplified in terms of separate linear "modes" of variability, such as the AO (Thompson and Wallace, 2000 and references therein), the Pacific North America Pattern (PNA; Wallace and Gutzler, 1981 and references therein) and the North Atlantic Oscillation (NAO; Walker and Bliss, 1932, Greatbatch, 2000 and references therein). These linear modes are known to operate on intermonthly, inter-annual and inter-decadal timescales, and longer. Alternatively, low-frequency atmospheric variability can be described in terms of nonlinear "regimes" of variability such as obtained through cluster analyses (Cheng and Wallace, 1993, Smyth et al., 1999 and references therein) or recently developed nonlinear principal component analyses (NLPCA; Monahan et al., 2000a,b). These regimes also vary over a wide spectrum of timescales describing, for example, the time spent in a given regime (i.e., occupancy time) or time spent in transition between regimes (i.e., transition time). The dual purposes of this investigation are to: 1) analyse the maintenance and transition dynamics of observed and modelled circulation regimes and 2) to study the relationship between these circulation regimes and the dominant linear modes of variability (such as the AO, PNA and NAO). A broad range of timescales will be explored from inter-monthly to interdecadal (and longer, if such scales are found to be important).

**Objectives:** (i) Dynamics of atmospheric circulation regimes: Monahan et al. (2000a,b) found that the low-frequency variability of the atmosphere can be characterized by distinct quasi-stationary states with one of the states bearing a strong resemblance to the extreme negative phase of the NAO, or "blocked" state south of Greenland. Interestingly, in transient integrations with the CCCma coupled GCM the frequency of occurrence of this regime decreases with enhanced greenhouse-gas forcing (Monahan et al., 2000a), which appears to be consistent with what may be occurring in nature (Corti et al., 1999, Monahan et al., 2000b). We propose to continue along this line of research by studying the dynamics involved in the maintenance and transition of these circulation regimes. This will be approached both with a simple atmospheric GCM developed at Reading and McGill Universities and the CCCma coupled GCM. Composite potential vorticity and wave activity density analyses will be performed to help separate the roles of high- and low-frequency dynamics in the formation and maintenance of these climate regimes and the transitions between them. Selectively adding and removing certain key dynamical processes in the simple GCM will help clarify the results obtained with the full GCM and from observations. Analyses of the simple GCM and the CCCma coupled GCM output under different climatic forcing conditions (say under enhanced greenhouse gas forcing) will also be performed, and in this regard the present proposal links to the ACC theme of this network.

(ii) Relationship between regimes and dominant linear modes of variability: Monahan et al. (2000b) note a resemblance between the spatial patterns of NLPCA-derived regimes and the spatial patterns of particular phases of the leading regional linear modes of atmospheric variability (notably the PNA and the extreme negative phase NAO). Additionally, they interpret the AO (which is by definition derived from a hemispheric analysis) as arising as the optimal linear compromise between the preferred quasi-stationary regimes. Indeed there appears to be some convergence of opinion that the characterization of the AO as an "annular mode" of variability is somewhat misleading (Deser, 1999, Wallace, 2000, Monahan et al., 2000). We propose to explore the relationship between the nonlinear and linear modes of variability through carefully conceived experiments with the simple GCM (once again, by selectively manipulating key dynamical processes).

**Methodology and data.** This subproject will involve linear and nonlinear Principal Component Analysis of NCEP reanalyses, CCCma coupled GCM output (Flato et al., 2000), as well as output generated with a simple GCM (Hall, 2000). The latter is a global spectral model driven by empirical time-independent forcing, ideally suited to the mechanistic studies proposed here due to its economy and ease of modification and analysis. Preliminary results with the simple GCM show that it is capable of reproducing realistic mean states and variability structures when driven with either NCEP reanalyses or CCCma coupled GCM output. Further composite analyses will be performed with high- and low-pass filtered potential vorticity and wave-activity density diagnostics.

**Anticipated results and relevance to themes**: The proposed research will advance our understanding of inter-monthly to interdecadal high latitude atmospheric variability. Such variability is directly experienced across Canada and further understanding of the processes involved will contribute to improved seasonal forecasting and climate change detection. It contributes to Theme II of this network, with links to L. Pandolfo's Theme I subproject 4.1.3.C and potential linkages to Theme III.

**Training.** One Ph.D**.** student and one PDF will be in training throughout this subproject, jointly supervised by L. Pandolfo and J. Fyfe.

**Networking.** This proposal primarily involves interactions between J. Fyfe at the CCCma and L. Pandolfo at UBC, who will share equal responsibility for the budget and for meeting the objectives of the proposal. The student and PDF funded under the proposal would alternate time between the two institutions. The student funded by the MSC has begun her Ph.D. studies at the U. Victoria. Present collaborative ties will be maintained with G. Flato (CCCma), N. Hall (McGill U.) and A. Monahan (Humboldt U.), and new collaborative ties will be forged with R. Greatbatch (Dalhousie U.).

## B) NORTH ATLANTIC OSCILLATION DYNAMICS, PREDICTABILITY AND FORCING OF THE NORTH ATLANTIC OCEAN

### SUBPROJECT 1: NORTH ATLANTIC CLIMATE VARIABILITY AND THE NORTH ATLANTIC OSCILLATION

*R. J. Greatbatch (Dalhousie U.) and H. Ritchie (MSC; Dalhousie U.)*

The North Atlantic Oscillation (NAO) is the most important mode of variability of the atmospheric circulation over the North Atlantic Ocean, and is a major influence on winter surface air temperature over the Northern Hemisphere as a whole (Hurrell, 1995, 1996; see Greatbatch, 2000, for an overview). Indeed, the NAO is closely related to a hemispheric mode of variability known as the Arctic Oscillation (AO; Thompson and Wallace, 1998). This proposal is concerned with exploring the atmospheric dynamics of the AO/NAO, the response of the North Atlantic Ocean to forcing by the AO/NAO, and the predictability of the AO/NAO on the seasonal and interdecadal timescales.

**Objectives.** (i) to understand the strong projection of the AO on the NAO and the role of atmospheric blocking and quasi-stationary regimes of the atmospheric circulation in the dynamics of the AO/NAO; (ii) to develop models of the North Atlantic Ocean and to use these models to study the response of the North Atlantic to forcing by the AO/NAO and (iii) to develop coupled ocean/ atmosphere models that can be used to study the AO/NAO within the coupled system and the predictability of the AO/NAO on a broad range of timescales.

**Methodology.** (i) Atmospheric Dynamics of the AO/NAO: On a planet with no zonal variations in its geography, the modes of variability are, of necessity, zonally symmetric about the pole. The observed zonal asymmetries of the AO in the troposphere, and the strong projection of the AO on the NAO, must therefore be associated with the zonal asymmetries of the Northern Hemisphere geography, notably the mountains ranges that cut across the eastward flow of the jet stream, and the land/ocean contrast. We propose to use the quasi-geostrophic model of Marshall and Molteni (1993) to explore the connection between the hemispheric AO and the regionally focused NAO, including the role of atmospheric blocking and quasi-stationary regimes of the atmospheric circulation. This model has a realistic looking AO/NAO, and has already been used by the McGill group for climate variability studies. We shall apply the technique of Non-linear Principal Component Analysis in collaboration with J. Fyfe and L. Pandolfo. We shall also investigate the connection between AO/NAO variability and blocking. In particular is blocking a symptom of the low index AO/NAO state or is blocking fundamental to the dynamics of the low index AO/NAO state? The link with the quasi-stationary regimes identified by Vautard (1990) will be investigated with help from Brunet.

(ii) AO/NAO driving of the North Atlantic Ocean: The NAO was identified as an important forcing for the North Atlantic Ocean in the classic paper of Bjerknes (1964). Bjerknes examined the relationship between sea surface temperature (SST) anomalies and the sea level pressure field and hypothesized that on timescales of interannual and shorter, SST is locally driven by the atmosphere but that on longer interdecadal timescales, ocean dynamics, and, in particular changes in the ocean heat transport play a role. Bjerknes' hypothesis has been confirmed by many subsequent studies. On the interdecadal timescale, Eden and Jung (2000) have shown that a model of the North Atlantic has skill at capturing the observed evolution of SST anomalies and have demonstrated the important role played by changes in the model's meridional overturning circulation (MOC). The North Atlantic is also one of the few places in the global ocean where the deep waters of the ocean are known to be renewed and therefore have contact with the atmosphere. Deep water renewal in the North Atlantic is strongly modified by the NAO (Dickson et al., 1996). The early 1990's saw the coldest and freshest Labrador Sea Water ever recorded at a time when the NAO was in an unusually strong positive phase, and deep convection was extending down to 2000m depth (Marshall and Schott, 1999).

We propose to develop models of the North Atlantic with resolutions ranging from 1 degree x 1 degree horizontally (the same resolution as used by Eden and Jung) to 1/3 degree x 1/3 degree (i.e., eddy permitting), and perhaps higher resolution depending on the availability of computer resources. The models will be used to study the response of the ocean to forcing by the NAO, including the pathways of newly ventilated water from the sources regions (the Labrador and the Greenland/Norwegian Seas), the sequestering of heat and other tracers, and the dependence on model resolution. Related work by Lamb and Straub (this proposal) will address the issue of parameterizing unresolved processes in the models. Lamb's proposal addresses the issue of where the important diapycnal mixing takes place in the ocean that converts the deep water back to surface water, and Straub's proposal addresses the role played by ageostrophic processes. The sensitivity of the strength of the MOC, and ability of the ocean to transport heat, is known to depend strongly on the strength of the diapycnal mixing (Munk, 1966, Bryan, 1987). An eddy resolving model is also required to better understand the role of mesoscale eddies in transporting heat and other tracers.

Related to the above is the question of the phase relationship between the strength of the forcing driving the ocean (e.g., the NAO) and the strength of the MOC. In the coupled ocean/atmosphere model of Delworth et al. (1993), the strength of the MOC lags the forcing by about two years, whereas in the new coupled model at GFDL, which has about double the resolution, the MOC lags the forcing by between 10 and 20 years, in keeping with the lag found by Eden and Jung. Clearly if we are to understand how the MOC and its associated poleward heat transport respond to forcing, e.g., from global warming, the issue of the phase relationship must be addressed. We propose to do this using ocean models of varying complexity.

(iii) Coupled Ocean/Atmosphere Modelling and Atmosphere/Ocean Prediction: With funding from CICS, a coarse resolution global ocean model has been coupled first to the Marshall/Molteni model and subsequently to the atmospheric model of Hall (2000). There is a strong need to improve the ocean component of the coupled model. This effort will allow us to investigate any possible predictability of the AO/NAO in the coupled system on both the seasonal and decadal timescale, an issue central to international CLIVAR. Given the success of the Eden and Jung model at capturing the interdecadal evolution of SST in the North Atlantic, we aim to replace the current global ocean model (which has 4 degree x 4 degree horizontal resolution) with a 1 degree x 1 degree model; that is the same resolution as the Eden and Jung model. To begin, the basic atmosphere model will be the model of Hall (2000). Plans to add moisture to this model are included in the proposal under Lin, and eventually we would want to use the moist version in coupled experiments.

An important question is how much predictive skill for the AO/NAO can be extracted from the influence of ocean dynamics on SST at the decadal timescale? There is evidence that in some atmospheric GCMs, the AO/NAO is responsive to SST (Rodwell et al., 1999), although Bretherton and Battisti (2000) point out that this does not necessarily imply predictive capability. This is because the underlying SST is itself being driven by variability intrinsic to the overlying atmosphere and originating from the fundamentally unpredictable synoptic variability. However, on decadal timescales, processes internal to the ocean play a role in the evolution of SST, and Bretherton and Battisti's argument no longer applies. We plan to use the coupled models developed here to test predictive skill at seasonal and decadal timescales by conducting ensembles of experiments.

**Anticipated results and relevance to themes**: The anticipated results are: 1) improved understanding of the strong projection of the AO on the NAO and the role of atmospheric blocking and quasi-stationary regimes of the atmospheric circulation in the dynamics of the AO/NAO; 2) greater understanding of how the North Atlantic Ocean responds to forcing by the AO/NAO; 3) an analysis of the AO/NAO in coupled ocean/atmosphere models, and improved knowledge of the predictability of the AO/NAO on timescales of seasonal to interdecadal. The results are of direct relevance to the DecCen component of CLIVAR, but because the AO/NAO is important on all timescales, is also of relevance to the GOALS and ACC component.

**Training.** Funding for 1 Research Associate, 1 PDF, 2 Ph.D. students and the half salary of a computer support person is requested for each year of the project.

**Networking.** 1) Work on the atmospheric dynamics of the AO/NAO will be done in collaboration with G. Brunet, J. Fyfe and L. Pandolfo, and with help from J. Derome and C.A. Lin. 2) The development of models of the North Atlantic Ocean is linked to the companion proposals by K. Lamb and D. Straub who are developing parameterizations for use in the models. 3) The coupled ocean/atmosphere modelling and predictability studies are linked to the proposals of C.A. Lin, who is developing a moist version of N. Hall's model (next subproject) and J. Derome and G. Brunet (Theme I, subproject 4.1.3.A.1) who will look at predictability of the AO/NAO on seasonal timescales.

### SUBPROJECT 2: PRECIPITATION EXTREMES AND INTERDECADAL VARIABILITY

*C.A. Lin (McGill U.)*

**Objectives.** The objective of the proposed work is to examine the statistics of extreme precipitation events and interdecadal variability in a global atmospheric model of intermediate complexity, and to couple the model to an ocean model. The coupled model will be examined for extreme precipitation events and interdecadal variability as well, and the results compared to the atmosphere-only model, to determine the role of the ocean.

**Methodology.** N. Hall of McGill U. has formulated and tested a dry dynamics atmospheric model (Hall, 2000). The model is based on the dry primitive equations of motion with time-independent sources of heat and momentum prescribed from observations. The model simulates well the time-mean fields and transient eddy covariances and runs much faster than a general circulation model. However, the model, being dry, does not resolve explicitly the hydrologic cycle. We propose to add a moisture tracer equation, with condensation and convection represented physically. Condensation will take place when the relative humidity exceeds a threshold, and convection will be parameterized using moist convective adjustment. This then will allow for precipitation in the model. Surface evaporation will be parameterized using the humidity gradient at the surface. Such an approach to represent the hydrologic cycle has been successfully used in a quasi-geostrophic climate model (Hanna et al., 1984).

The proposed project builds upon ongoing work where we examine the use of vertical motion in the dry model as an indicator of precipitation. We are examining NCEP reanalyses to develop a statistical relation between vertical motion and precipitation for the NCEP forecast model. Such a relation will then be applied to the dry model to see how well the large scale precipitation is simulated. These results will be compared with the precipitation obtained with moisture included in the model. We will also examine the validity of the statistical relation in the CCCma coupled GCM.

We propose to examine two problems, using both the atmosphere-only and coupled atmosphere-ocean models. The first problem deals with the statistics of extreme precipitation events. As the models are computationally efficient, we can perform simulations of order several thousand years. This gives a long precipitation record for a statistical analysis of extreme events. The second problem concerns interdecadal variability. We have experience with coupling the dry model with R. Greatbatch's global ocean model. The exchange of heat across the air-sea interface is presently parameterized through an exchange coefficient and the low level wind speed and air-sea temperature difference. This exchange includes both the sensible and latent heat as a single entity. This is thus a limitation of the existing coupled model. The introduction of a moisture equation will allow for the separate representation of sensible and latent heat exchanges through an explicit hydrologic cycle. This could well modify the results of the coupled model on interdecadal timescales.

The addition of moisture in Hall's dry model is a natural step in the model development. It would still be much more computationally efficient compared to a general circulation model. The proposed project is thus in the spirit of developing a hierarchy of models of differing complexity for climate studies.

**Anticipated results and relevance to themes**: The coupled atmosphere-ocean model using Hall's atmospheric model with an added moisture equation will resolve explicitly the hydrologic cycle, and thus heat and moisture exchanges at the air-sea interface. Interdecadal variability will be better represented compared to our earlier CLIVAR project where only heat exchange is taken into account. The results are relevant to the Decadal to centennial variability and predictability (DecCen) theme of CLIVAR. The analysis of extreme precipitation events using long runs of the atmosphere-only and coupled models will provide a baseline for comparison with climate change experiments, and is thus of relevance to the ACC theme. Comparison of the atmosphere-only and coupled model results will determine the role of the ocean in extreme precipitation events and interdecadal variability.

**Training.** 2 graduate students and 0.5 postdoctoral fellow.

**Networking.** The analysis of the CCCma coupled GCM output for a statistical relation between precipitation and vertical velocity will involve CCCma scientists. The atmospheric model will be coupled to the oceanic model developed by R. Greatbatch in collaboration with his group.

### SUBPROJECT 3: TIDALLY INDUCED MIXING AND THE MERIDIONAL OVERTURNING CIRCULATION IN THE NORTH ATLANTIC

*K.G. Lamb (Waterloo U.)*

The sources for the renewal of deep water in the North Atlantic are relatively well known. In contrast, the global distribution of the compensating upwelling, and its implications for the meridional circulation in the North Atlantic, is unclear (Munk and Wunsch, 1998). Over the past few years there has been some speculation that tidally induced diapycnal mixing in the abyssal ocean may play an important role in determining the strength and spatial structure of the upwelling from the abyssal ocean and consequently of the meridional circulation (Munk and Wunsch, 1998, Ledwell et al., 2000). Recently, horizontally inhomogeneous vertical diffusivities, based on a crude parameterization, have been shown to affect the horizontal distribution of upwelling (Hasumi and Suginohara, 1999).

**Objectives.**

The objective of this research is to understand how the mixing levels over rough topography depend on the strength of the barotropic tidal currents, the stratification and on the character of the topography and how these horizontally inhomogeneous mixing levels affect the meridional overturning circulation in the North Atlantic.
We will:

1. Develop parameterizations of abyssal mixing caused by the interaction of barotropic tidal currents and sub-grid topographic features in the deep ocean.
2. Incorporate the mixing parameterizations into models of the North Atlantic and global oceans being developed by R. Greatbatch's group.
3. Develop an understanding of the spatial and temporal variations of abyssal mixing induced by tides and their role in the meridional overturning circulation in the North Atlantic.

**Methodology.** The effects of horizontal inhomogeneities of vertical diffusivities on the meridional overturning circulation in the North Atlantic will be studied using the POP model. This model has a free surface but presently lacks tides. Tidal forcing terms will be added to the model. High resolution process studies will be done using idealised domains and a variety of topographies. The latter will include continental shelves, seamounts and an idealised mid-Atlantic Ridge. The simulations will resolve long internal waves, including the internal tide, however parameterizations of the mixing induced by smaller scale internal waves and topographic features (horizontal wavelengths of less than 10km), will be required. These model runs, in conjunction with some theoretical work, will provide a basis for the development of parameterizations to be used in a 1/3 degree North Atlantic model and in a 1 degree global ocean model.

Flow over topography can be very complicated. Mixing is associated with a number of flow phenomena including the bottom boundary layer, flow separation, hydraulic jumps, overturning isopycnals, and internal waves. The latter may break near the obstacle if sufficiently large, and will also propagate vertically and may subsequently interact nonlinearly with the other internal waves and induce localised mixing events at large distances from their generation site. This latter mechanism has been hypothesised to be responsible for the enhanced mixing levels observed up to 2 km above the edge of the Mid-Atlantic Ridge in the Brazil Basin (Ledwell et al., 2000).

Parameterizations of the effects of subgrid-scale (SGS) topography in atmospheric numerical models have a long history and have been recognised as a necessary component of an accurate model (Gregory et al., 1998). Relatively little attention has been paid to parameterizing the effects of SGS topography in ocean models. In atmospheric models the goal of the parameterization is to model the form drag associated with the SGS topography and its implications on mean atmospheric flows. For this project the focus will be on parameterizing buoyancy changes due to diapycnal mixing. A key nondimensional parameter used in parameterizations for atmospheric models is $Nh/U$, where $N$ is the buoyancy frequency, $h$ is the height of the topographic feature, and $U$ is the wind speed (Baines, 1995). For nonrotating flows there is a radical difference in the flow characteristics for $Nh/U$ greater or less than about 1.05. For small values of $Nh/U$ the air flows over a three-dimensional hill whereas for large $Nh/U$ flow splitting occurs and air at low levels moves around the hill. Oceanographic studies of oscillating flow over 3-D topography have focussed on linear models $Nh/U \ll 1$) (Bell, 1975), and on seamounts ($Nh/U \gg 1$), for which the Rossby number is very small (Boyer and Davies, 2000). Values of $Nh/U$ in the abyssal ocean range between about 2 and 20 for obstacle heights of 100-1000 m. At mid-latitudes, Rossby numbers are of $O(1)$ on length scales of a few hundred metres. These values imply that mixing parameterizations based on linear internal wave theory will be inadequate, and that rotational effects will be important.

**Anticipated results and relevance to themes**: The anticipated results are: 1) the development of parameterizations of mixing associated with barotropic tidal flow over rough topography; 2) the incorporation of tidal forcing terms and mixing parameterizations in the POP model; 3) an understanding of how mixing levels over rough topography depend on the strength of the barotropic tidal currents, the stratification and on the underlying topography; and 4) an understanding of the effects of horizontal inhomogeneities of diapycnal mixing on the meridional overturning circulation in the North Atlantic. These results are relevant to decadal and centennial variability because of the key role played by the meridional overturning circulation on long timescales.

**Training.** One PDF, supported by funds from this grant, will work on this project. The level of expertise in geophysical fluid dynamics that is required exceeds that of a graduate student. If the output from this research is to be useful in the development of R. Greatbatch's ocean model, progress has to be relatively fast, requiring the help of a PDF.

**Networking**. The work proposed here complements that of D. Straub (next subproject). He is interested in parameterizing the flux of energy into the internal wave field from larger scale flow features. Parameterizations developed by this work will be implemented in the North Atlantic and global ocean models being developed by R. Greatbatch as part of this proposal. There will also be interaction with N. McFarlane who has worked on parameterizations of wave drag in atmospheric models.

### SUBPROJECT 4: SUBGRID-SCALE PARAMETERIZATIONS FOR OCEAN EDDY RESOLVING GCMS

*D. N. Straub (McGill U.)*

While there has recently been considerable progress (e.g., Gent and McWilliams, 1990, Greatbatch, 1998) in the parameterization of mesoscale eddies for non-eddy resolving models, modelling unresolved effects in eddy permitting models appears less successful. Moreover, mesoscale eddies play a central role in shaping the wind driven circulation, which, in turn, helps determine the meridional overturning cell. For example, a more zonally oriented Gulf Stream extension is likely to be associated with a reduced thermohaline cell. Because of this, and given the ever increasing computer power available, it seems clear that explicit representation of mesoscale eddies will become increasingly standard in ocean models designed to address decadal, and even longer scale ocean variability. Credible models will require subgrid-scale closures to represent interactions between the eddy field and higher order dynamics, such as small scale gravity waves. This is especially important since eddy permitting models, unlike their coarser resolution counter-parts, do not cascade energy forward to dissipation scales. Thus, while the value of a viscous coefficient in a coarse resolution GCM is likely to affect only the details of boundary layers, it is well documented that this is not the case for eddy permitting models. Instead, these models are disturbingly sensitive to the precise values of the tunable coefficients (e.g., Pedlosky, 1996).

**Objectives and Methodology.** (i) To further develop arguments leading to an improved parameterization for the transfer of energy from the geostrophic eddy field to forward cascading gravity wave modes. The theory is based on stability of 2D hydrostatic flows to 3D perturbations and extends recent work by Leblanc and Cambon (1998), borrowing ideas from Lapeyre et al. (1999) and Warn (pers. com.). It predicts an exact criterion, similar to the Weiss-Obuko criterion, for a fairly wide class of steady homogeneous flows. The stability parameter depends not only on the deformation and vorticity fields (as does the Weiss criterion), but also on Coriolis frequency and the rate at which the compressional axis rotates following a Lagrangian parcel. Our work to date for growth of unbalanced modes in a stratified chaotic base state suggests that gravity waves with vertical length scales comparable to $U/N$ (2D velocity to Väisälä frequency) are strongly excited when the modified Weiss-Obuko parameter is near zero or positive. We propose, through a combination of theory and modelling, to further quantify the growth rates of gravity modes, given the statistics of the (geostrophically) balanced flow. The rate at which energy is transferred to the gravity modes will then depend on these growth rates and on the background level of unbalanced energy--i.e., the gravity wave field.

(ii) Incorporate our parameterization into quasigeostrophic models of mid-latitude ocean circulation. The most straight-forward way to do this will be to use a variable viscous coefficient. The viscous coefficient will be small, except where our instability criterion is met. This should assure a vigorous eddy field, while still allowing the system to deal with, for example, a net vorticity input without "running away" (e.g., Ierley and Sheremet, 1995). A comparison of how the system responds to variable (interdecadal) forcing with and without the new subgrid-scale model will be carried out. The effects of adding a stochastic component to the forcing will also be considered. This should affect the statistics of the resolved flow in a way that increases extremes (locally large Rossby numbers, etc.). In particular, the portion of the flow over which our viscous coefficient is large should increase relative to a similar experiment without stochastic forcing. This, in turn, should allow for solutions that remain closer to those predicted by classic Sverdrup theory than might otherwise be the case.

(iii) Incorporate our parameterization into a more complete general circulation model. This will be done in collaboration with R. Greatbatch. Because his model is based on the POP model, we will be able to make use of state-of-the-art parallel computers that will be available to us through a recent grant. The basic idea of these experiments will be to see whether these considerations can improve results in more realistic settings, where "truth" is more constrained by data. In particular, we plan to concentrate on modelling the Atlantic Ocean, paying particular attention to the influence of our parameterization on the influence of the Gulf Stream extension (North Atlantic Drift), its variability, and relationship to the meridional cell.

**Anticipated results and relevance to themes**: The principal goal of the proposed work is to develop and test closure schemes that are both less sensitive to the choice of parameters and physically more realistic than those currently used. These will be implemented, first in relatively simple quasi-geostrophic models, and then in more realistic ocean GCMs. We anticipate that "twin experiments" will show models run with our parameterization to be less sensitive to, say, an increase in the net wind stress curl, than those models using the more standard, eddy viscosity, closure. The success of closure schemes, such as that proposed here, will be a prerequisite to the success of eddy permitting models as predictive tools on long timescales. Without insensitivity to poorly known coefficients, it becomes difficult to distinguish between variability that is real, and that which is associated with models simply drifting into and out of the parameter regimes for which they were tuned.

**Training**. One Ph.D. student and one postdoctoral fellow will work on this project. The postdoctoral fellow will be shared with C.A. Lin (subproject 4.2.3.B.2).

**Networking.** This project complements that proposed by K. Lamb. His project is concerned with the influence of the gravity wave field on diapycnal mixing, whereas this one is concerned with interactions allowing gravity waves to extract energy from the larger scale flow (in regions where an appropriately defined Rossby number becomes O(1)). In both cases, the interest is in an accurate description of the gravity wave field. Further, we both propose to incorporate our parameterizations into the momentum and tracer equations, respectively, of a primitive equation GCM being developed by R. Greatbatch.

### C) PACIFIC DECADAL VARIABILITY

The Pacific Ocean possesses a rich mixture of decadal-interdecadal variability modes (see reviews of Trenberth, 1990, Nakamura et al., 1997). Notable amongst these is the apparent climate regime change in the North Pacific which occurred from late 1976 through to 1988. During this period the SSTs in the central and western North Pacific Ocean were cooler than normal, while SSTs along the western coast of North America were warmer than normal and the Aleutian Low was deeper than normal (see Trenberth, 1990, Trenberth and Hurrell, 1994). In attempting to explain this departure from normality, Trenberth (1990) pointed out that during this period there were three warm El Niño events with no intervening cold La Niña events. Thus tropical temperatures were warmer than average and so, through teleconnections to higher latitudes, the Aleutian Low was deeper than normal on average.

A number of theories exist to explain the observed decadal variability in the North Pacific. Because El Niño is a non-linear coupled tropical atmosphere-ocean phenomenon, it is possible that decadal modulation of El Niño and its subsequent teleconnection to the North Pacific could explain the observed low frequency variability there (Trenberth and Hurrell, 1994). Gu and Philander (1997) pointed out that a delayed negative feedback can be achieved through extratropical oceanic subduction of thermal anomalies (generated through the atmospheric teleconnection response to tropical SST anomalies) which slowly propagate along isopycnals towards the equator where they reverse the sign of equatorial SST anomalies. Finally, Latif and Barnett (1994, 1996) have suggested a mode of decadal-interdecadal North Pacific variability solely involving midlatitude coupled atmosphere-ocean interactions and the strength of the subtropical gyre and its associated northward heat transport. As pointed out by Nakamura et al. (1997), subtropical gyre SST variability on the decadal-interdecadal timescale is not solely explained through the tropical source, and some combination of the mechanisms may exist in reality.

While El Niño may modulate midlatitude thermal anomalies, a question arises as to how such anomalies persist through to the decadal timescale. Indeed, one would expect that thermal anomalies must ultimately be dissipated either by ocean-atmosphere interactions (Alexander, 1992a,b) or by internal oceanic processes. Ocean surface anomalies created over the deep mixed layer in winter could be preserved below the summer thermocline and reappear at the surface during the following winter when the mixed layer deepens and intersects the anomaly (e.g., Namias and Born, 1974, Alexander and Deser, 1995). Persistent atmospheric features, such as the anomalous reoccurrence of an intense Aleutian Low over decadal timescales, reinforce and further inject thermal anomalies into the deep mixed layer. As noted, these anomalies then subduct into the main pycnocline where they flow southward and potentially re-emerge and alter the tropical Pacific SSTs. In this manner, El Niño variability could yield a decadal-interdecadal signal in the extratropical Pacific temperature, which in turn could give rise to a modulation of El Niño on a similar timescale and explain the major phase shifts seen in the climate record.

The subprojects that follow propose to explore these various mechanisms of Pacific decadal variability via an improved version of the CCCma coupled GCM, and through perturbation experiments with the U. Victoria GCM.

### SUBPROJECT 1: PACIFIC DECADAL VARIABILITY IN THE CCCMA COUPLED GCM

*G. Boer, G. Flato and J. Fyfe (CCCma; U. Victoria)*

Like most other coupled GCMs of its generation the current CCCma coupled GCM has El Niño/ La Niña variability which is unrealistically weak owing in part perhaps to insufficient horizontal and vertical resolution in the tropical Pacific. It is also known that while the CCCma coupled GCM supports interdecadal modes of oceanic variability that have some correspondence to those found in nature, here the patterns are far from perfect (pers. comm. S. Yukimoto and B. Yu).

**Objectives and methodology**. In conjunction with Theme I, it is the primary objective of this work to improve the representation of tropical Pacific Ocean dynamics in the CCCma GCM. The first step towards this will involve increasing the horizontal and vertical resolution in the model initially via the implementation of a non-uniform ocean computational grid. With expected improvements to the El Niño/La Niña variability it is hoped that improvements in the model's Pacific Ocean decadal variability will follow. The individual to be funded under this proposal will undertake a progressive and systematic analysis of the Pacific Ocean and atmosphere variability in the current and future versions of the CCCma coupled GCM. This will also involve developing the relevant diagnostic tools such as those required in tracking the three-dimensional evolution of temperature anomalies in the North Pacific (e.g., in terms of isotherm depth and potential vorticity as in Schneider et al., 1999).

**Anticipated results and relevance to themes**: This work will help advance the capability of the CCCma coupled GCM, and through careful analysis in comparison to available observations will help with our understanding of the various modes and Pacific decadal variability.

**Training**. One PDF for each of the 5-years of the proposal.

**Networking**. This work is above and beyond that which would ordinarily be conducted at the CCCma and will involve several CCCma scientists in collaboration.

### SUBPROJECT 2: THE SOUTH PACIFIC SUBDUCTION PROCESS

*A. J. Weaver (U. Victoria) and J. Fyfe (CCCma; U. Victoria)*

**Objectives and methodology.** The South Pacific subduction process will be examined in this proposal through the use of both the U. Victoria GCM (of intermediate complexity) and the CCCma coupled GCM (fully three-dimensional). The literature on subduction processes has predominantly focussed on Northern Hemisphere subduction and its role on tropical variability, with little attention given to Southern Hemisphere phenomena. Weaver (1999) provided some evidence to suggest that anomalies imposed in the Southern Hemisphere were in fact more effective than similar anomalies in the Northern Hemisphere at modulating the pycnocline depth in the eastern equatorial Pacific through the subduction pathway. The student and research associate working on this project will conduct a series of experiments using the U. Victoria GCM to examine the role of subgrid-scale mixing parameterizations, as well as the effects of applying idealized forcing perturbations over different regions of the South Pacific Ocean on the resulting tropical pycnocline perturbations. Knowledge from these experiments will then aid in analysis of long control simulations performed with various versions of the CCCma coupled GCM. In addition, the potential role of extratropical subduction on tropical Atlantic variability will be examined to test the hypothesis that tropical Atlantic variability is linked to low frequency variability in the Antarctic circumpolar current via changes in Antarctic intermediate water formation.

**Anticipated results and relevance to themes**. These investigations will provide insight that will then be used as the basis for diagnostic studies of long control simulations performed with various versions of the CCCma coupled model.

**Training.** One student and one research associate.

**Networking**. This work will network CCCma and U. Victoria researchers.

### SUBPROJECT 3: INTERBASIN FRESHWATER TRANSPORT AND NORTH ATLANTIC DEEP WATER FORMATION

*A. J. Weaver (U. Victoria) and J. Fyfe (CCCma; U. Victoria)*

It has recently been proposed that the changes in interbasin freshwater transport during the different phases of El Niño may be of sufficient magnitude to cause variability in the strength of North Atlantic deep water formation as well as mitigate against its weakening, as usually found in coupled models, as the earth warms under the influence of greenhouse gases (Latif et al. 2000). Schmittner et al. (2000) estimated the change of the total Atlantic freshwater balance to be 0.05 Sv due to a change in the Southern Oscillation Index by one standard deviation, which is about half of the freshwater export from the Arctic to the North Atlantic via Fram Strait.

**Objectives**. We propose to have an M.Sc. student examine this mechanism for the variability of North Atlantic deep water formation in the CCCma coupled GCM.

**Anticipated results and relevance to themes**. This project will contribute to our understanding of a potentially powerful mechanism for low-frequency North Atlantic deep water variability.

**Training**. One M.Sc. student.

**Networking**. This work will network CCCma and U. Victoria researchers.

### D) SOUTHERN OCEAN CLIMATE VARIABILITY

*G. Flato, G. Boer and J. Fyfe (CCCma; U. Victoria)*

The first two versions of the CCCma coupled model, CGCM1 and CGCM2, have been used to conduct 1000-year control integrations with unperturbed climate forcing. CGCM1 is described in Flato et al. (2000) and CGCM2 in Flato and Boer (2000). Preliminary analysis reveals interesting differences in low-frequency (decadal and longer time-scale) variability in the Southern Ocean. In particular, CGCM2 exhibits a significant spectral peak in Southern Hemisphere ice extent variability at periods around 25 years. Since the ice in the Southern Hemisphere is almost entirely seasonal, this low-frequency variability is very likely related to ocean processes, and differences between the two models must arise from differences in physical parameterizations (ocean mixing and sea-ice dynamics).

**Objectives**. We wish to understand the source of this low-frequency variability, the mechanisms responsible, and the reasons for the apparent difference between the two model versions. By comparison to available observations (ice extent, surface temperature) we wish to evaluate the model's behaviour (i.e.: Is the variability realistic? Is one version demonstrably more realistic?) and inquire if the mechanisms involved in this variability might change as the climate warms.

**Methodology**. Results from the two long control integrations will be studied in detail, and comparisons with available observations used to evaluate the model's representation of relevant processes. Global surface air temperature data, available from 1900 onward (albeit with sparse coverage at high southern latitudes), NASA sea-ice concentration data (1978 onward), and "GISST" ice and sea-surface temperature (1903-1994) fields will be the primary data used in this study, but other data sets, such as ocean temperature and salinity, atmospheric reanalyses, etc., are also available in-house to supplement these. The mechanisms for Southern Ocean climate variability, the apparent connection between sea-ice extent variations and other climatic quantities, and the connections to mid-latitude variability will be investigated. This will involve use of available diagnostic programs developed at the CCCma to analyse and visualize model output and observational data. Initial analysis will be exploratory in nature (e.g., correlation maps, cross-spectra, EOFs), with more detailed analysis, and perhaps simplified "mechanistic" model studies, as particular mechanisms are identified. Results from the two model versions will be analyzed in parallel to highlight the effect of differences in model parameterizations and to gauge the `robustness' of mechanisms identified. Once the variability in the control simulations is better understood, transient climate change simulations will be subjected to similar analysis to examine changes in Southern Ocean variability as the climate warms.

**Anticipated results and relevance to themes.** The climate system is global and interconnected, and the Southern Ocean plays an important role in this system. This project will contribute to understanding climate variability, climate processes, and the ability of the CCCma coupled model to simulate them. This project affords an opportunity to highlight similarities and differences between Northern Hemisphere and Southern Hemisphere climate variability. Results from this project will yield insight into the recently-observed trends in quantities like air temperature over the Antarctic Peninsula, will contribute to studies of global climate change detection and attribution, and will contribute to studies of variability of physical controls on oceanic carbon sequestration in this biologically productive region.

**Training**. One Ph.D. student to be trained at the U. Victoria.

**Networking**. This work is above and beyond that which would ordinarily be conducted at the CCCma and will involve several CCCma scientists in collaboration.

## 4.3. THEME III: THE CENTURY TIMESCALE

*Theme leaders: A. J. Weaver (U. Victoria) and F. W. Zwiers (CCCma; U. Victoria)*

### 4.3.1 The scientific issues

The detection and attribution of anthropogenic climate change depends critically upon four components. First and foremost is the availability of a high quality historical climate record. Most of the detection effort to date (see Zwiers, 1999 for a review, see also Barnett et al., 1999, Hegerl et al., 2000, Tett et al., 1999) has focussed on a very carefully scrutinized instrumental surface temperature record (Jones et al., 1999) that extends back to about 1860. In addition, considerable attention has been focussed on the shorter post-war vertical temperature record from the international radiosonde network (e.g., Karoly et al., 1994, Allen and Tett, 1999). Satellite data, principally from a series of Microwave Sounder Unit (MSU) instruments, has augmented this record for the past two decades. After careful scrutiny and adjustment, the MSU record has been found to be consistent with the longer radiosonde record (Jones et al., 1997, Christy et al., 1998, Gaffen, et al., 2000).

A discrepancy remains between temperature trends during the past 2-4 decades observed in the lower troposphere and at the surface, with the surface warming more quickly than the troposphere. Climate models do not exhibit this behaviour. This has recently been reviewed by the U.S. National Academy of Sciences (National Research Council, 2000) and is the focus of recent research (e.g., Santer et al., 2000). A combination of sampling error, natural variability, and the effects of volcanic forcing (such as from the Mt. Pinatubo eruption) provide a plausible, but not complete explanation.

Recent palaeo climate reconstructions of global and hemisphere mean temperature (Crowley and Lowrey, 2000, Mann et al., 1999, Free and Robock, 1999, Bradley and Jones, 1993) extend the record backwards to as early as 1000 AD. These reconstructions provide additional evidence of the unusual nature of the 20$^{th}$ century warming, but cannot be used in formal detection and attribution studies because they do not provide the necessary information on the patterns of temperature variation. An area of increasing interest is to extend the search for an anthropogenic influence on climate to other aspects of the recent record. These include diurnal temperature range, precipitation, surface pressure (Paeth et al., 2000), and large scale circulation features such as the Northern and Southern Hemisphere annular modes (Thompson and Wallace, 1998, 2000, Fyfe et al., 1999, Monahan et al., 2000b).

A second component required for all detection and attribution studies is a reliable estimate of the climate's natural variability that arises from internal sources (as opposed to external anthropogenic or natural forcing). Two difficulties here are that the observational record is presumably contaminated with the effects of external forcing and that in any case, variability on the 30-50 year timescales important for detection is difficult to estimate from the available instrumental record. Consequently, most detection studies (e.g., Tett et al., 1999, Barnett et al., 1999, Hegerl et al., 2000) use estimates of internal variability obtained from coupled climate models.

Detection and attribution studies also require estimates of anthropogenic and naturally forced external signals that are hypothesized to be present in the climate record of the past century. Signals with patterns that remain constant with time can be derived from model projections of future climate change (e.g., Hegerl, et al., 1997, 2000). However, it is increasingly recognized that anthropogenic and natural signals in the observed record can be better discriminated if studies use estimates of the time dependent response to historical external forcing (Tett et al., 1999).

Finally, the statistical methodology itself is an important aspect of detection and attribution studies. This is an area in which there has been considerable advancement since IPCC (1996). In particular, it is now recognized that the “optimal detection” technique (Hasselmann, 1993, 1997) is a form of multiple regression (Allen et al., 1999, Allen and Stott, 2000, Allen et al., 2000). This realization has increased the rigour of detection studies and has provided the detection community with a range of sophisticated diagnostic techniques for assessing detection results (e.g., Allen and Tett, 1999, Tett et al., 1999).

While there is increasing confidence in detection results on a global scale, there also remain substantial and important uncertainties. Differential trends in surface and lower troposphere temperatures are not yet fully understood. The response to external forcing differs considerably between models. The pattern and magnitude of the response to aerosol forcing remains very uncertain. Regional details of the response to anthropogenic forcing and regional mechanisms of change also remain uncertain.

### 4.3.2 Overview of the Theme III research

This proposal is designed to focus attention on a number of issues outlined above in areas where the investigators either have the necessary expertise or feel that they are able to develop it efficiently. Effort will be focused in three broad areas; the detection and attribution of anthropogenic climate change, improved delineation of the response to natural and anthropogenic forcing of the climate system, and model development and enhancement focussed on processes important for the study of anthropogenic climate change.

Subtheme (A) below is focused on the detection and attribution of climate change. In addition to contributing on the global scale and by further improving the methodologies used for detection and attribution, we hope to make substantial inroads on the detection of an anthropogenic influence on climate on the regional (specifically North American) scale. This is an area where there has, as yet, been little attention because signals are relatively weaker on the regional scale, and because dynamical and statistical downscaling tools are only now entering a mature phase. This subtheme networks scientists at CCCma, U. Victoria and UQAM and also engages students and postdoctoral fellows and a collaborator at Texas A&M Univeriesty. This work leverages the coupled modelling efforts at CCCma and other centres by making extensive use of available coupled control and transient change simulations.

Subtheme (B) deals with diagnostic studies of the response of the climate system to external forcing. Here we will examine the discrepancy between surface and tropospheric temperature trends (Weaver and Zwiers) and consider the influence of natural external forcing and land surface change (Weaver). Also, we will examine elevation dependence of the climate change signal (D. Caya and R. Laprise) and continue to develop tools for the analysis of regional climate change (R. Laprise and D. Caya). This subtheme also links researchers at CCCma, U. Victoria and UQAM, provides extensive training opportunities and makes extensive use of available and planned coupled and regional climate model simulations.

Subtheme (C) deals with modelling studies that focus on processes important for regional climate change. Here we will study the impact of new state of the art parameterizations of clouds and related processes in the CRCM (N. McFarlane). Considerable effort will also be given to the development of a coupled ocean-atmosphere regional model with particular emphasis on eastern Canada and surrounding upper coastal ocean (F. Saucier, D. Caya, R. Laprise and collaborators). In addition, we will also focus attention on the interaction between the Arctic, the North Atlantic thermohaline circulation, and regional climate (Mysak). This subtheme links researchers at CCCma, UQAM, Institute Maurice-Lamontagne, the Bedford Institute of Oceanography and McGill. It provides considerable training opportunities in coupled modelling and leverages expertise at a number of government laboratories and universities.

### 4.3.3 The individual projects

#### A) DETECTION AND ATTRIBUTION STUDIES

**SUBPROJECT 1: DETECTION WITH NON-TRADITIONAL VARIABLES**

*A. J. Weaver (U. Victoria) and F. W. Zwiers (CCCma; U. Victoria)*

Several coupled climate modelling groups have now been able to reproduce the general features of the trend in the surface air temperature instrumental record over the 20$^{th}$ century (e.g., Mitchell et al., 1995, Hasselmann et al., 1995, Haywood et al., 1997, Emori et al., 1999, Meehl et al., 1999, Boer et al., 2000a,b). These studies have found that the inclusion of the direct effect of sulphate aerosols is important since the radiative forcing associated with 20$^{th}$ century greenhouse gas increase alone tends to overestimate the 20$^{th}$ century warming. These same models have more difficulty representing the details of the variability observed within the 20$^{th}$ century instrumental record such as the "early century" warming that occurred between 1925 and 1944. Some modelling studies suggest that the inclusion of variability in external natural forcing (i.e., solar and volcanic aerosol forcing) may improve aspects of this simulated variability. Delworth and Knutson (2000), on the other hand, note that one of their six 20$^{th}$ century integrations bears striking resemblance to the observed 20$^{th}$ century warming without the need for additional natural external forcing. In addition, all coupled models have shown a trend towards increasing global precipitation, with an intensification of the signal at the high northern latitudes, consistent with the observational record. Nevertheless, CGCM simulations have yet to be systematically analysed for the occurrence of other key observed trends, such as the reduction in diurnal temperature range over the 20$^{th}$ century and the associated increase in cloud coverage. We plan to address this point in this proposal within the context of the CCCma coupled model.

**SUBPROJECT 2: DETECTION OF "MULTI-MODEL" ENSEMBLE MEAN SIGNAL**

*F. W. Zwiers (CCCma; U. Victoria)*

Detection, and particularly attribution, results remain sensitive to the model that is used (Barnett et al., 1999, 2000, Hegerl et al., 2000). The multi-model ensemble approach has been demonstrated to be effective for seasonal forecasting (Krishnamurti et al., 1999, Derome et al., 2000, see also section 4.1.3A). It has been proposed that this might also be a useful approach for detection in that it may be able to account for model and other sources of uncertainty in the anthropogenic signals that are used for detection. Several ensembles of transient climate change simulations using historical greenhouse gas and sulphate aerosol forcing are now available from the IPCC Data Distribution Centre and are thus potentially available for a multi-model ensemble approach to detection and attribution.

The timescales important for detection and attribution (~30-50 years) and the limited length of the instrumental record (~100 years) dictate that studies must use model estimates of natural internal variability. These estimates are obtained from long model control runs whose lengths (~1000 years) dictate that detection and attribution studies must be performed in a space of reduced dimension that is typically spanned by the first 10 Empirical Orthogonal Functions (EOFs) of a control run. Anthropogenic signals can generally be well represented in such a space when they are simulated with the same model that is used to estimate natural internal variability (see, e.g., Hegerl et al., 1997, 2000, Tett et al., 1999). A difficulty encountered with the multi-model approach is that the ensemble signal can not be well represented in the EOF reduced natural variability space of any one model (G. Hegerl, pers. comm.). Thus successful application of this approach requires re-examination of the method that is used to select the reduced dimension detection space. Recent studies (e.g., Berliner et al., 2000, Schneider, 2000) take a different approach to covariance estimation that should lead to a different solution to this problem.

Our research will focus on developing an understanding of how these new approaches represent the space-time modes of variation important for detection and whether they provide a means for identifying a reduced space that adequately represents the internal variability simulated by models participating in a multi-model detection exercise. We will then examine whether this reduced space can adequately represent multi-model ensemble greenhouse gas and sulphate aerosol signals. Ultimately, we will perform a global scale detection and attribution study in the reduced space using multi-model ensemble signals. While it would also be desirable to consider signals from natural external forcing in this study, the very limited availability of simulations taking these sources of variability into account preclude this possibility.

### SUBPROJECT 3: BAYESIAN DETECTION AND ATTRIBUTION

*F. W. Zwiers (CCCma; U. Victoria) and A. J. Weaver (U. Victoria)*

The current detection and attribution paradigm (Hasselmann, 1997, Tett et al., 1999, Hegerl et al., 2000) is hampered by the attribution consistency test that is used to determine whether the amplitude of a model's response to anthropogenic forcing is consistent with the amplitude of the signal that is estimated from observations. The error rate of this test is not known because the test is designed to search for evidence of inconsistency rather than consistency. Thus even though inconsistency may be found at a given significance level, say 5%, the analyst can always find consistency by reducing the significance level to a lower level. The Bayesian approach to detection and attribution (Hasselmann, 1998, Berliner et al., 2000, see also Leroy, 1998) provides a more satisfactory solution to this problem. However, there has not yet been a full scale Bayesian detection and attribution study. Berliner et al. (2000) demonstrated the feasibility of the method, but they were hampered by the availability of a short control run and a single forced run. We intend to gain experience with the Bayesian approach to detection and attribution by repeating the Berliner study with simulations performed with CCCma's CGCM1 (Flato et al., 2000, Boer et al., 2000a,b) and CGCM2. These include two long control integrations (1000 years each), two ensembles of three greenhouse gas plus aerosol simulations, and a greenhouse gas only simulation. If time permits we will also extend the study so that it includes other models and possibly signals from natural external forcing. The latter could be simulated with the CCCma model but could also be obtained from the UVic ESCM (Weaver et al., 2000, see also North and Stevens, 1998 and North and Wu, 2000).

### SUBPROJECT 4: CONTINENTAL-SCALE DETECTION AND ATTRIBUTION

*F. W. Zwiers (CCCma; U. Victoria), A. J. Weaver (U. Victoria) and R. Laprise (UQAM)*

While detection and attribution on a global scale will affect high-level energy policy, the global warming issue will remain abstract for local, regional and national governments until detection and attribution is accomplished on smaller scales. Thus a further goal is to attempt detection and attribution on a regional (continental scale) during the 5-year period covered by this proposal. The “region” of interest for this study will be North America, which possesses a dense, high quality and well studied instrumental record of temperature, precipitation, surface pressure and near surface wind speed. An initial step will be to assemble the necessary data sets with the assistance of contacts at the Climate Monitoring Division of the Climate Research Branch and at the US National Climate Data Center. In the first instance, the necessary climate signals and estimates of natural internal variability will be obtained from existing global coupled model runs, such as those performed with CCCma’s CGCM1 and CGCM2. We will also attempt to use downscaled signals, both produced dynamically with the Canadian Regional Climate Model (CRCM; Laprise et al., 1998, Caya and Laprise, 1999) and with statistical downscaling procedures (Wilby et al., 1998, von Storch et al., 2000), and regional signals from the UVic ESCM (Weaver et al., 2000). CRCM time slice simulations, particularly those with a large scale forcing scheme (von Storch et al., 2000), will provide a useful means for validating the statistical downscaling approach. An advantage of the statistical downscaling approach is that it may then be possible to consider the use of a multi-model signal on a regional scale. Potential difficulties with regional detection include the lack of long simulations with which to estimate internal variability on the regional scale, and the possibility that it may be necessary to perform detection in a reduced space of relatively high dimension. Experience gained on the global scale with regularization issues and application of Bayesian techniques has a direct bearing on the work that is proposed here for the regional scale.

**Training and Networking.** These projects (1 through 4) will engage 1 Ph.D. student and 1 post doctoral fellow (jointly supervised by Weaver and Zwiers). Interaction will take place between researchers at CCCma (F. Zwiers, G. Boer, G. Flato), U. Victoria (A. Weaver) and UQAM (R. Laprise, D. Caya). Statisticians at U. Victoria will be consulted. F. Zwiers will collaborate with G. Hegerl (Texas A&M).

### B) IMPROVED DELINEATION OF THE CLIMATIC RESPONSE TO EXTERNAL FORCING

#### SUBPROJECT 1: DIFFERENTIAL SURFACE AND LOWER TROPOSPHERIC TEMPERATURE TRENDS

*A. J. Weaver (U. Victoria) and F. W. Zwiers (CCCma; U. Victoria)*

As noted earlier, surface temperatures show a greater rate of warming than do lower tropospheric air temperatures over the last 20 years. Models tend not to show such a differential trend. While noting uncertainties in the observational records, NRC (2000) pointed out that models need to better capture the vertical and temporal profiles of the radiative forcing especially associated with water vapour, tropospheric and stratospheric ozone, aerosols, and the effects of the latter on clouds. Santer et al. (2000) provide further evidence to support this notion from integrations they conducted with the ECHAM4/OPYC CGCM (Roeckner et al., 1999, Bengtsson et al., 1999) that includes a representation of the direct and indirect effects of sulphate aerosols, as well as changes in tropospheric ozone. They showed that the further inclusion of stratospheric ozone depletion and stratospheric aerosols associated with the Pinatubo eruption lead to a better agreement with observed tropospheric temperature changes since 1979, although discrepancies still remain.

We shall examine both the geographical and temporal distribution of this differential trend in surface versus lower tropospheric temperatures through the analysis of presently available and anticipated 20$^{th}$ century integrations conducted with the CCCma model. It is hoped that this analysis will lead to an understanding of key processes that may need to be better resolved in the coupled model.

### SUBPROJECT 2: NATURAL (SOLAR AND VOLCANIC) FORCING OF THE CLIMATE SYSTEM

*A. J. Weaver (U. Victoria)*

None of the aforementioned simulations examined the potential climatic effects of stratospheric aerosols associated with volcanic emissions. Crowley (2000) has estimated that changes in solar irradiance and volcanism may account for 41% to 64% of pre-industrial, decadal-scale surface air temperature variations. Cubasch et al. (1997) demonstrated that when solar variations were included in the ECHAM3/LSG model, their simulation from 1700 through the $20^{th}$ century showed enhanced low frequency variability. The implication of climate change detection and attribution studies (Hegerl et al., 1997, Tett et al., 1999) is that it may be important to account for changes in the natural external forcing of the climate system.

Energy balance/upwelling diffusion climate models and earth system models of intermediate complexity, when forced with volcanic and solar variations for the past 400 years, capture the cooling associated with the Little Ice Age (Crowley and Kim, 1999, Free and Robock, 1999, Bertrand et al., 1999). While they are not capable of assessing regional climatic anomalies associated with local feedbacks or changes in atmospheric dynamics, these models do produce the observed warming of the past century when forced with anthropogenic greenhouse gases and aerosols**.** The UVic ESCM (Weaver et al., 2000) will be used to explore the large-scale features of climate variability associated with the change in anthropogenic and natural forcing from about 1600 to the end of the $20^{th}$ century. These experiments will be useful for later comparison with the more realistic experiments that we anticipate CCCma will conduct with its CGCM, as they will elucidate potential sea ice and ocean feedbacks and will allow for detailed sensitivity analyses to be conducted.

### SUBPROJECT 3: INFLUENCE OF LAND SURFACE CHANGES

*A. J. Weaver (U. Victoria)*

Changing land use patterns affect climate in several ways. The impact of land use changes on radiative forcing is thought to be small (e.g., Hansen et al., 1998). Nonetheless, Brovkin et al. (1999) demonstrated that the CLIMate and BiosphERE model, CLIMBER (Petoukhov et al., 2000), was able to capture the long term trends and slow modulation in the Mann et al. (1999) reconstruction of northern hemisphere temperatures over the past 300 years by taking changes in land use patterns, atmospheric $CO_2$ and solar forcing into account. Some recent model results suggest that land cover changes during this century may have caused regional scale warming through local reforestation (Chase et al., 2000, Zhao et al., 2000) but this remains to be examined with a range of climate models.

The UVic Earth Climate System Model (Weaver et al., 2000) will be extended to incorporate land surface and dynamic vegetation subcomponent models to assess the climate response to historical land use changes as well as future dynamic vegetation changes (on the multi-century timescale).

### SUBPROJECT 4: STUDY OF CLIMATE CHANGE SIGNAL HEIGHT DEPENDENCE IN CRCM

*D. Caya (UQAM) and R. Laprise (UQAM)*

An observational analysis of Beniston and Rebetez (1996) and a model study of Giorgi et al. (1997) over the Alps, and a GCM simulation diagnostics by Fyfe and Flato (1999) over the Rocky Mountains have shown that the climate-change signal is stronger in high-altitude areas than in regions with low topography. We propose here to extend the study of Fyfe and Flato over the Rocky Mountains but for CRCM projections. It is expected that we will find a clearer elevation-dependent signal over the Rockies in the CRCM simulation than the one observed in the GCM because of the better resolved topography. This increased topography allows higher elevations and also increases the number of mountainous gridpoints in the database therefore permitting a better sampling of the elevation signal.

Fyfe and Flato at CCCma will develop a glacier mass-balance model for the GCM, this permitting an improved representation of land ice evolution on long timescales. When available this scheme will be adapted for use in the CRCM.

### SUBPROJECT 5: DIAGNOSTICS BUDGET STUDIES OF CRCM

*R. Laprise (UQAM) and D. Caya (UQAM)*

Beyond the simulation of anthropogenic climate changes, there is the understanding of the processes that are responsible for these changes. This is accomplished by computing diagnostic budgets from observed and simulated data sets.

The understanding of the physical processes that maintain the current climate equilibrium and control its possible changes requires the study of the balance of forces that prevail in the atmosphere and their simulated counterpart in climate models. This is generally referred to as budget analysis of the cycles of most important fields, such as atmospheric mass, heat, momentum, and water in its various forms, as well as derived quantities such as angular momentum and vorticity. The analysis can be made for the mean state as well as higher moments such as the variance (e.g., kinetic energy for winds, enstrophy for vorticity). A deeper understanding is further gained when the budgets are performed separating the contributions from different spatial scales on global analyses and GCM-simulated results. Recent progress made by Ph.D. student B. Denis toward the development of an algorithm based on shifted-cosine transforms to decompose spatial scales permits a computationally effective way of achieving the scale decomposition.

**Training and Networking.** Subprojects 1-3 will engage 1.5 PhD students and 1 postdoctoral fellow with supervision provided by Weaver (subprojects 2 and 3) and Weaver and Zwiers (subproject 1). Interaction with occur between scientists at CCCma (Zwiers, Flato) and U. Victoria (Weaver). Subproject 4 will constitute the research topic of 1 graduate student for each of the five years of the proposal, co-supervised by D. Caya and R. Laprise. Collaboration will be maintained with Fyfe and Flato at CCCma for glacier modelling aspects. Subproject 5 will engage 1 graduate student under the principal supervision of R. Laprise, coordinating with the rest of the UQÀM team and D. Caya and CCCma scientist G. Boer for general budget and scale decomposition aspects. Existing linkages will continue with MSC scientist M. MacKay for water budget studies as they relate to Mackenzie GEWEX Study (MAGS) and GEWEX, and with M. Slivitzky of INRS-Eau for validation with river run-off measurements.

## C) MODEL DEVELOPMENT AND ENHANCEMENT FOR THE STUDY OF CLIMATE CHANGE PROCESSES.

### SUBPROJECT 1: SENSITIVITY OF CLIMATE TO PHYSICAL FORMULATION

*N. A. McFarlane (CCCma; U. Victoria)*

The simulation of climate changes associated with anthropogenic release of greenhouse gases and aerosols requires the representation of many thermodynamical processes that contribute for some as positive feedback and others as negative one. An accurate representation of these processes is required to obtain a reliable estimate of the subtle balance between the feedbacks.

The importance of the treatment of clouds and related processes in climate models is widely recognized. The focus of the proposed project consists in evaluating the impact of the parameterizations recently developed in the fourth generation Canadian GCM on climate simulations made with the CRCM. These simulations will include documented case studies using observed data to specify CRCM lateral forcing and simulations using GCM4 output to force the CRCM. Some of these simulations will repeat earlier studies made with less sophisticated treatments of clouds and related processes, including the BALTEX study currently being carried out by V. Lorant. These earlier studies provide a basis for comparison and identification of elements in the new parameterizations that give rise to the largest impact and/or most significant improvements in climate simulations. The best documented of the proposed case studies will be used to validate the CRCM simulations.

**Training and Networking:** This sub-project began last year by PDF V. Lorant working under the supervision of McFarlane at CCCma, in collaboration with the UQÀM team, and will be continued for the first two years of this proposal.

### SUBPROJECT 2: DEVELOPMENT OF A COUPLED OCEAN-ATMOSPHERE CANADIAN REGIONAL CLIMATE MODEL FOR UPPER COASTAL OCEANS

*F. Saucier (IML; UQAR), D. Caya (UQAM) and R. Laprise (UQAM)*

The simulation of climate changes requires a representation of the interaction between the components of the Earth system: the atmosphere, the hydrosphere, the cryosphere, the biosphere and the lithosphere. Each component has its own response time, and depending on the timescale of interest, it can be either specified to current values or must be modelled interactively. Oceans respond on a vast range of timescales, depending on the depth and geographical location. Coastal waters respond particularly rapidly to atmospheric and fresh water forcing.

The purpose of this project is to construct a coupled ocean-ice-atmosphere modelling system for eastern Canada, including the north-western North Atlantic, the Gulf of St-Lawrence and Hudson's Bay to further our understanding of regional-scale coastal climate processes. Feedbacks associated with air-sea fluxes, clouds, shelf fronts, mesoscale oceanic features and sea-ice will be investigated for improving the needed downscaling of large-scale ocean climate models and improve coastal climate change projections. We propose to construct a composite modelling system to study regional-scale climate processes in the northwest Atlantic and related coastal regions of eastern Canada.

The system will be built from various components that are available to us: i) the ice-ocean regional model of Saucier and Dionne (1998) and Saucier et al. (2000) for enhanced resolution of the CRCM over eastern Canada and inland sea waters, Hudson's Bay and the Gulf of St-Lawrence, ii) the Kraus-Niiler mixed-layer model (MLM) for offshore waters, and iii) the 3-dimensional Princeton Ocean Model (POM) for the Labrador Sea. The implementation of a generic ice-ocean model for application to other basins will follow developments using the Modular Ocean Model (MOM), phasing in at Institut Maurice-Lamontagne (IML), or those at CCCma using the NCAR model. Air-sea flux calculations will be based on wave models such as the WAM model (e.g., Janssen and Viterbo, 1996), to have an explicit coupling of the upper ocean to the atmosphere through the momentum, heat and vapour fluxes.

The aim of this sub-project is to gain further insight on the strengths and limitations of each approach to regional ocean modelling. The coupling of the various ocean modules will be done using a mosaic approach in which each module may be switched on or off at each grid point, to ease the testing and evaluation.

**Training and Networking.** This work is the continuation of a project underway for the past two years by PDF P. Gachon at IML and Ph.D. student M. Faucher. For this project 1 Graduate student will study this topic for the 5 years of the proposal, co-supervised by F. Saucier and R. Laprise, as well as a PDF for the last 3 years of the project, co-supervised by F. Saucier and D. Caya. Linkages will be made with C. Tang and W. Perrie at Bedford Institute of Oceanography (BIO/DFO, Halifax) for WAM- and MLM-related aspects.

## SUBPROJECT 3: THE INFLUENCE OF A CHANGING ARCTIC SEA ICE COVER ON THE ATLANTIC THERMOHALINE CIRCULATION AND NORTHERN HIGH LATITUDE CLIMATE

*L. A. Mysak (McGill U.)*

### Introduction

Recent analyses of areal sea ice extent and ice thickness in the Arctic Ocean have shown dramatic decreases of the polar ice cap in recent years. Cavalieri et al. (1997) have shown that for all categories of ice, the sea ice extent anomalies have a downward trend over the 1980-1997 period, at a rate of about 3% per decade, whereas Johannessen et al. (1999) have established that the central Arctic perennial ice cover is shrinking at a rate of 7% per decade. From the ice thickness records taken from submarine-borne instruments, Rothrock et al. (1999) have estimated that the present Arctic ice cover is about 40% thinner than it was 20-40 years ago. Thus it is apparent that if these downward trends continue, which is a likely response of the Arctic to continuing global warming due to increasing greenhouse gases in the atmosphere, the Arctic Ocean could be nearly ice-free by the end of the century.The influence of the above changes on the climate of the North Atlantic sector could be substantial, with potential impacts on deep water formation, the thermohaline circulation (THC), and consequently the climate in the Atlantic sector.

### Objectives

1. To develop a coupled atmosphere-sea ice-ocean model of intermediate complexity which focuses on Arctic-North Atlantic interactions.
2. To run the model developed in (1) under current climate conditions and future global warming scenarios, with the aim of determining the impact of sea ice retreat on the THC and regional climate.
3. To apply the model developed in (1) to past (Holocene) climate time slices in order to investigate the nature of earlier Arctic-THC interactions.

**Methodology.** In the proposed research, a state-of-the-art sea ice model (Tremblay and Mysak, 1997) will be coupled to a recently developed 3-D global ocean model (R. Greatbatch, pers. comm.) and an energy moisture balance model (EMBM) for the atmosphere (Fanning and Weaver, 1996). The ocean part of this three-component model, developed by R. Greatbatch, is a modification of the Modular Ocean Model of GFDL. At McGill this model been successfully coupled to a coarse resolution atmospheric model by H. Lin, who is a research associate in the CICS CLIVAR network. This ocean model (in a parallelized version developed at Los Alamos) will first be coupled to a spherical coordinate form of the Tremblay-Mysak ice model, which is now under development (B. Tremblay, pers. comm.). Then the EMBM will be coupled to the ice-ocean model. The EMBM has been used in our group (Wang and Mysak, 2000) in another, zonally averaged coupled climate model, and thus we have the experience to add this EMBM to a global coupled ice-ocean model.

The three-component model forced by observed winds will first be validated by comparing the results with observed Arctic ice exports shown in Arfeuille et al. (2000) and with those of Mauritzen and Hakkinen (1997) and Holland et al. (2000b) who investigated the influence of varying ice exports on the strength of the North Atlantic THC. Next, a slowly decreasing Arctic ice cover will be imposed on the model and the ensuing impact on the THC and regional climate will be investigated. These results will be compared with those of Holland et al. (2000a) who used a model of similar complexity to study the impact of rising atmospheric $CO_2$ on the THC variability. Our results on the THC will also be compared with those from the CCCma coupled GCM run under greenhouse warming scenarios. Finally, we shall use the model to explore a variety of Arctic-THC interactions that may have occurred during past anomalous climate periods, such as during the warm period in the middle of the Holocene (Bauch et al., 2000) and during early Holocene times when there were restricted outflows from the Arctic (Forman et al., 2000).

**Anticipated results and relevance to themes.** The work on the effects of a decreasing ice cover on the thermohaline circulation will give us an estimate of the expected regional climate change that could be expected in a "greenhouse" Earth. The proposed Holocene simulation work will test the robustness of the model for different eras and relates to the PAGES-CLIVAR (Past Global Changes) overlapping theme of climate DecCen variability during the Holocene.

**Training and Networking.** During the course of this work (5-year period) 2 PDFs and 2 Ph.D. students will be trained in climate dynamics (one PDF and one Ph.D. student at any one time). Interactions with colleagues will occur both within the network and elsewhere. Within the network, we shall consult R. Greatbatch on ocean modelling and A. Weaver on coupling issues. In addition, we plan collaboration with B. Tremblay at Columbia University on ice-ocean coupling, and anticipate consultation with R. Gerdes and H. Brix from Alfred Wegener Institute in Bremerhaven, and F. Schott from University of Kiel. As convener of an IAPSO symposium on the Arctic and the THC (to be held in Argentina in Oct. 2001), Mysak will also be well positioned to become aware of the latest advances in the topic of the proposed research.

## 5. THE NETWORK'S NATIONAL AND INTERNATIONAL CONTRIBUTIONS

Canadian policy makers need to make climate-related decisions that have profound socio-economic consequences. Decisions on mitigation and/or adaptation to climate warming, for example, will impact the lives of all Canadians for several decades to come. Whether these decisions relate to internal Canadian policies, or to international agreements, they must be supported nationally by the best scientific information available. Numerous segments of the Canadian economy (e.g., agriculture, energy, health, tourism) also have to make climate-related decisions, some related to global warming, others related to shorter-term climate fluctuations, all of which will have maximum value if they are science-based.

The CLIVAR network will make major contributions to the national need for climate information in several areas:

1. The seasonal forecasting research, a significant extension of a successful ongoing project, will provide Canadians with a state-of-the-art predictive system that will be transferred to the Meteorological Service of Canada for operational forecasting, a public service to the Canadian population. This research builds on expertise and models developed for other purposes. It capitalizes on a spirit of collaboration among three components of the Meteorological Service – the climate modelling and analysis group (CCCma), the numerical weather prediction group (RPN), the Canadian Meteorological Centre – and the university sector (McGill). The proposed project will leverage $0.8M of computer time and a full-time meteorologist from the Canadian Meteorological Centre, a clear sign of the importance that the latter attaches to the research.

2. On the decadal timescale the research will clarify the extent to which the slowly evolving ocean temperature can be used as a predictor of the atmospheric temperature some years later. A capacity to predict the climate on the decadal timescale, even with modest skill, could be of major socio-economic value to the country.

3. On the century timescale the research will give a firmer scientific basis to the interpretation of the observed and predicted global warming. Policy makers will have information of the highest available quality on the respective contributions of natural variability and anthropogenic factors to the global warming, past and predicted.

Structured as it is around the Science Plan of the International CLIVAR Program, and bringing together an important fraction of Canada's scientists active in climate variability research, this proposal is meant to be a major part of the country's contribution to the international program. The Canadian CLIVAR Group is fully committed to making a visible contribution to the international effort.

The group's contributions will take many forms: scientific papers in the best international journals, presentations in international workshops and conferences on climate variability sponsored by the International CLIVAR Office and other organizations, participation in international CLIVAR scientific committees and working groups, and in the Intergovernmental Panel on Climate Change. The HFP Group has offered to contribute its research results to an international multi-group effort designed to compare the skill of different models world-wide at predicting mean-seasonal conditions. It has also accepted an invitation to collaborate with colleagues from the National Centers for Environmental Prediction in the next phase of its seasonal prediction research, described in section 4.1.3A. The Group will take part in workshops and conferences organized on this international project. For example, a presentation will be made in October 2000 at the Climate Diagnostics Workshop to be held at the International Research Institute (Lamont-Doherty Earth Observatory) and the Group will participate in others as they become known.

The group proposes to hold a "Stanstead Seminar" on climate variability during the summer of 2003. The Stanstead Seminars are a series of workshops, the first of which was held in 1955, organized by McGill University. Over the years the series has acquired an international reputation for the quality of the presentations and the stimulating scientific environment that it recreates time after time. The PI has organized or co-organized eight of these since 1973 on different topics dealing with large-scale dynamics, all of them held at Bishop's University in Québec's Eastern Townships. From the popularity of the previous Seminars and comments received on them, there is every reason to think that a Stanstead Seminar on climate variability would draw the very best speakers from around the world. The organizers would seek the sponsorship of the International CLIVAR Office and would coordinate the scientific program with that office to ensure that the Seminar makes a substantial and visible contribution to the international program. The Seminars have always been held with the interest of graduate students in mind. A number of seats is always reserved for them, and keynote speakers are asked to provide overview as well as cutting-edge research presentations. From comments received, it is evident that the Seminars have had a profound influence of a large number of graduates. The 2003 Seminar will proudly continue that tradition.

The Group will also contribute to the international climate research effort and its management through the work of some of its members on international science committees and workgroups.

Some of the contributions already made include the following activities and memberships on international committees during the period 1995 - 2000:

*G. J. Boer*: Contributing author and Canadian representative, Inter-government Panel on Climate Change (IPCC) 1995 Scientific Assessment.

*G. M. Flato*: With G. J. Boer, contributed CCCma model output to the IPCC Data Distribution Centre for use in international climate change impact studies.

*J. Fyfe*: Contributing author to two chapters of the IPCC Third Assessment Report.

*L. A. Mysak:* Co-convenor, Interdecadal Ocean Climate Symposium, IUGG Assembly, Hawaii.

*A. J. Weaver*: Lead author, Chapters 5 and 6, Inter-government Panel on Climate Change (IPCC) 1995 Scientific Assessment. Member, University Corporation for Atmospheric Research (UCAR) Climate System Modeling Program Project on Decadal-Centennial Variability of the Oceanic Thermohaline Circulation. Member, North Pacific Marine Sciences Organization (PICES) Working Group 7: Modeling of the Sub-Arctic North Pacific Circulation. Member, Pacific WOCE Workshop Organizing Committee. Member, Scientific Organizing Committee of the WCRP Arctic Climate System Study Second Science Conference. Member, U.S. National Academy of Science / National Research Council Ocean Studies Board, Committee on Major U.S. Oceanographic Research Programs.

This important type of international contribution is continuing through the following current activities:

G. *J. Boer*: Contributing author, Inter-government Panel on Climate Change (IPCC) 2000 Scientific Assessment.

*G. M. Flato*: Chair, Climate and Cryosphere Project, World Climate Research Program Numerical Experimentation Group. Lead scientist, cryospheric subcomponent of the international Coupled Model Intercomparison Project (CMIP) and its follow-on, CMIP2. Contributing author to 3 chapters of the IPCC Third Assessment Report.

*R.J. Greatbatch:* Co-convenor, Marginal Seas Symposium, IUGG Assembly, Hawaii.

*W. Hsieh*: His Neural Network model forecasts of the tropical sea surface temperature are published quarterly in the Experimental Long-Lead Forecast Bulletin published by the Center for Oceans Land and Atmosphere (COLA).

*R. Laprise*: Chairman, Panel on Regional Climate Modelling, Working Group on Numerical Experimentation, World Meteorological Organization.

*L.A. Mysak*: Convenor, IAPSO Symposium on the Arctic and the Thermohaline Circulation, Argentina., 2001.

*A.J. Weaver*: Lead author, Chapter 8 (Model Assessment), IPCC TAR. Member, United Nations World Climate Research Programme, Joint Scientific Committee/CLIVAR Working Group on Coupled Modelling. Member, National Academy of Science/National Research Council Board on Atmospheric Sciences and Climate, Climate Research Committee. Member, Steering Committee, Arctic System Science / Ocean-Atmosphere-Ice Interactions, NSF, Arctic Systems Science Program. Member, Scientific Steering Committee, Climate System History and Dynamics Project.

*F.W. Zwiers*: Lead author, Chapter 12 (Detection and Attribution), IPCC TAR, Member, International CLIVAR Scientific Steering Committee. Member, Atmospheric Model Intercomparison Project Panel. Member, Advisory Committee, NCAR Geophysical Statistics Project. Chair, Steering Committee, International Meetings on Statistical Climatology. Member, NOAA Climate Change Data and Detection Panel.

## 6. THE NETWORK'S CONTRIBUTIONS TO TRAINING

The training of graduate students and postdoctoral fellows (PDFs) will be at the core of the group's activities. Each year 20.5 graduate students and 11 postdoctoral fellows will be in training under the supervision of the group members. Of the funding being requested, 57% will be directed to their stipends and 6% to allow them to participate in conferences and workshops.

The students and PDFs will take an active part in the regular workshops held by the group and will be expected to make presentations on their research. They will also be expected to make presentations at international conferences and workshops. Travel funds are requested to allow students and PDFs to visit and interact with members of the group at other universities and government research laboratories. Their training in the group will provide them with an ideal preparation for a career in climate research in an academic environment or government laboratory, such those of the MSC. Funds have been allocated to allow students and PDFs to spend some time in other laboratories and campuses within the network.

The Meteorological Service of Canada hires university graduates in atmospheric sciences on a regular basis, and discussions with MSC management confirmed that the need for new personnel over the next several years will be substantial. This applies not only to operational meteorologists, but also to research assistants (usually with M.Sc. degrees) and research scientists (with Ph.D. degrees). There is every reason to expect that there will be positions available for graduates and postdoctoral fellows trained in the CLIVAR group. The type of research and computer expertise they will acquire in the group is very much in demand now and should remain in demand in the foreseeable future.

## 7. THE MANAGEMENT STRUCTURE

The Network will adopt a management structure that will ensure the most responsible use of the resources and the most effective communication with the funding organizations, the users, the Canadian public, the international scientific community as well as among the researchers themselves. This will be achieved by establishing a Board of Directors and a Scientific Steering Committee. A Network Manager will be responsible for the day-to-day administrative duties.

**Board of Directors**

The Board of Directors will have the responsibility for the overall management of the Network and will provide the financial accountability to the funding organizations. It will ensure that the Network meets its commitments and will report on research progress to the funding organizations. To maximize the dissemination of the research results, it will foster communication between the Network on the one hand, and the users, the public and the international scientific community, on the other.

The Board will be composed of six members. It will have two members from the main user of the research, the Meteorological Service of Canada, one from the other users, one representative from NSERC, the Network Principal Investigator and a scientist of international stature from outside the Network. Dr. Allyn Clarke, who just ended a term as Co-Chair of the International CLIVAR Scientific Steering Committee, has agreed to serve on the Board in the latter capacity.

The Board will meet at least once a year in person and every two months by telephone or other electronic conference means. The minutes will be recorded by the Network Manager and published on the Network web site.

**Scientific Steering Committee**

The Scientific Steering Committee will provide the research leadership and coordination. It will assess progress annually on the different projects and make recommendation to the Board on the re-allocation of resources if such is deemed necessary. The assessment will be made, in particular, on the basis of presentations made at the annual workshops, at conferences (in particular the CMOS Annual Congresses) and on the basis of the written semi-annual reports submitted to the Scientific Steering Committee by the project principal investigators. It will promote the exchange of graduate students and postdoctoral fellows among the different subgroups of the Network. It will liaise with international research programs and foster the participation of the Network in the international research effort and the dissemination of the results. It will organize the scientific aspects of the Network workshops and of the Stanstead Seminar to be held in 2003.

The Scientific Steering Committee will be composed of the six theme leaders plus R. Laprise, whose research spans a broad range of timescales. The Committee will meet twice a year in person and every other month through telephone conferences or other electronic means. The minutes of the meetings will be recorded by the Network Manager and published on the Network web site.

**Network Manager**

The Network Manager will be responsible for the day-to-day administrative duties of the Network. His/her responsibilities will include: organization of the Network workshops, maintenance of the web site, assisting the Chairs of the Board and of the Scientific Steering Committee in the preparation of meetings, writing of the meeting minutes, acting as the first-line of interaction with the public and the users, keeping a record of the financial activities, performing all other Network duties of an administrative nature. The Network Manager will work in close collaboration with the Principal Investigator but will report to the Board of Director.

## 8. DISSEMINATION OF RESEARCH RESULTS

The dissemination of the research results will be done both by the individual researchers and by the group as a well-identified entity. The individual researchers have an excellent record of publishing in leading international journals and in contributing presentations at national and international conferences; they will naturally continue to make their work known through these channels. The graduate students and postdoctoral fellows will be expected to make presentations at national and international conferences and to publish their results. Many of the group's members are frequently solicited by the public media for interviews, and it is fully expected that they will continue to inform the public through their contributions to radio and television programs, as well as newspaper and magazine articles. Climate and global change are very much in the news, and the group will ensure that the public receives the most accurate scientific information available.

The group will continue to hold annual workshops of a scientific/technical nature for its own benefit, but it will also invite other climate scientists to participate, in particular, from the Department of Fisheries and Oceans and from the Meteorological Service of Canada. For example, the members of the CRYSYS (Arctic Climate System) group would both benefit from and contribute to the scientific discussions of the present group. The group will also make a significant contribution to the scientific program of the Annual Congress of the Canadian Meteorological and Oceanographic Society, and it will offer to organize special sessions on climate variability. This will serve as an excellent platform to keep the Canadian community, including the operational meteorologists, well informed of the group's research progress.

The Stanstead Seminar mentioned in section 5 will be a very special occasion for the dissemination of the group's research, and for the enhancement of the group's national and international visibility. The Seminar series has acquired an enviable reputation that will help make the next Seminar an international success.

The principal investigators working on the seasonal to interseasonal prediction theme will continue to take part in the regular meetings of the "Forum on Seasonal Forecasting" organized by the Canadian Meteorological Centre. It is at these meetings that decisions are made on the transfer of the research from the CLIVAR group to the operational suite of the Centre. The dialog that takes place at these meetings informs the group of the needs of the Centre, and conversely it informs the Centre of the research products that can reasonably be expected on the medium term.

The group will maintain a Web site that is informative for both the scientific community and the public at large. The site will highlight the scientific achievements of the group in a language that is accessible to the public and the media. It will also contain the minutes of meetings of the Board and of the Scientific Steering Committee. While a section of the Web site will be reserved for network members to exchange data and results, an important section will be directed to the public at large and the media, both in French and English.

The group will publish a brochure, also bilingual, describing the network and its activities. With time, the network's most significant achievements will be added. The network manager will take the necessary steps to ensure that both the group's Web page is referenced by a braod spectrum of Web site, and the brochure is broadly distributed.

Many of the co-applicants have been frequently solicited in the past by the media for interviews on climate questions, and have responded with enthusiasm. Just recently the PI was interviewed for a radio program by Radio-Canada following a presentation made at the "Entretiens Jacques Cartier" in Montreal on seasonal forecasting and hydrology. The group members will continue to welcome these interactions with the media, realizing that there is considerable interest in the public in climate issues, and that they are in a position, as a group, to respond to a very broad range of questions on the subject. The Group's Web site will give the public and the media all required information on how to reach the experts, and on their areas of special expertise.

*Intellectual property.* The intellectual property from the research will be governed by the policies of the co-investigators' universities. It will also respect the policy of the Canadian Foundation for Climate and Atmospheric Research as described in its Funding Agreement with the Government of Canada.

## 9. SUMMARY OF BENEFITS TO CANADA

The benefits to Canada that will be derived from the network's research have been described elsewhere in the proposal, in particular in section 5 on the network's national and international contributions, and in section 6 on its contributions to training. These benefits can be summarized as follows:

1. The research will be a major national contribution to the international CLIVAR program of the World Climate Research Program. Without the network, the level of research coordination and cohesion that is proposed would not be possible. The network will also increase the visibility of the Canadian effort both nationally and internationally.

2. The network will provide Canadians with a state-of-the-art predictive system for mean-seasonal conditions that will be transferred to the Canadian Meteorological Centre for operational forecasting.

3. The research will clarify the extent to which climate fluctuations on the decadal time scale are predictable. Even if modest, a predictive capacity on that time scale could be of major socio-economic benefit to Canada.

4. The research on the detection and attribution of climate change will give a firmer scientific basis to the interpretation of observed and predicted global warming. The results of the research will be made available to the policy makers, in particular through the meteorological Service of Canada.

5. Each year 20 graduate students and 11 postdoctoral fellows will be in training in the network. This will make a significant contribution to the national need for trained climate scientists.

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# APPENDIX

## LIST OF ACRONYMS

| | |
|---|---|
| ACC | Anthropogenic Climate Change |
| AGCM3 | Atmospheric GCM, Third Generation |
| AMIP | Atmospheric Model Intercomparison Project |
| AO | Arctic Oscillations |
| BLUE | Best Linear Unbiased Estimate |
| CCCma | Canadian Centre for Climate Modelling and Analysis |
| CGCM | Coupled global climate model |
| CICS | Canadian Institute for Climate Studies |
| CLASS | Canadian Land Atmosphere Surface Scheme |
| CLIVAR | Canadian Climate Variability Research Group |
| CMC | Canadian Meteorological Centre |
| CRCM | Canadian Regional Climate Model |
| DecCen | Decadal to Centennial climate variability and predictability |
| DFO | Department of Fisheries and Oceans |
| EMBM | Energy moisture balance model |
| ENSIP | ENSO Intercomparison Project |
| ENSO | El Niño/Southern Oscillation |
| EOF | Empirical Orthogonal Function |
| ESCM | Earth System Climate Model |
| GCM | General Circulation Model |
| GCM4 | Fourth Generation GCM |
| GEM | Global Environmental Model |
| GEWEX | Global Energy and Water Cycle Experiment |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GFDL_R30_c | A GFDL model with Rhomboidal 30 truncation |
| GIN | Greenland-Iceland-Norwegian Sea |
| GISST | Global ice and sea-surface temperature data set |
| GOALS | Global Ocean-Atmosphere-Land System |
| HFP | Historical Forecasting Project |
| IPCC | Intergovernmental Panel on Climate Change |
| IRI | International Research Institute |
| MLM | Mixed-layer model |

**LIST OF ACRONYMS CONTINUED**

| | |
|---|---|
| MOC | Meridional overturning circulation |
| MOM | Modular Ocean Model |
| MSC | Meteorological Service of Canada |
| NAO | North Atlantic Oscillations |
| NLPCA | Nonlinear principal component analysis |
| NOAA | National Oceanographic and Atmospheric Administration |
| PIRCS | Project to Intercompare Regional Climate Simulation |
| PNA | Pacific North America Pattern |
| POM | Princeton Ocean Model |
| POP | Parallel Ocean Program |
| RCM | Regional Climate Model |
| RPN | Recherche en Prévision Numérique |
| SGCM | Simple general circulation model |
| SGS | Subgrid-scale |
| SIP | Seasonal to Interannual Prediction |
| SMIP | Seasonal Prediction Model Intercomparison Project |
| SST | Sea surface temperature |
| SSTA | Sea surface temperature anomaly |
| STOIC | Study of Tropical Oceans in Coupled GCMs |
| THC | Thermohaline circulation |
| WAM | Wave model |
| WGSIP | Working Group on Seasonal-to-Interannual Prediction |