Executive Summary
In the most recent 2003 CFI Innovation competition, I was awarded a world-class NEC supercomputing facility with a total cost of about $6 million (32 CPUs of an upgraded NEC SX6). The research plan used to justify this award focused on climate and paleoclimate modelling and analysis over the last glacial cycle and model-based integrated assessment. While CFI has provided the necessary infrastructure to meet the goals of my proposed research, my challenge is now to acquire research grant funding to support the training of a new generation of highly qualified personnel with access to this world class facility. I am submitting two separate CFCAS proposals to seek funding for each of the two distinct areas of research. The developmental phase of this research proposal has been completed and I am now poised to make fundamental advances in our understanding of climate and its impact on human evolution in the past and the impact of humans on climate evolution in the future.

The overarching objectives of this proposal are to:

1) Integrate the UVic Earth System Climate Model for 116,000 years over a complete glacial cycle from the last interglacial (116kyrBP) with fully interactive carbon cycle, continental ice sheet dynamics and dynamic terrestrial vegetation to determine whether or not we are able to capture the statistics of glacial-interglacial transitions and the millennial timescale variability, including periodic Heinrich events which occurred over the last glacial cycle.

2) Assess the possibility of abrupt climate change associated with ice sheet-climate interactions under a variety of future scenarios of greenhouse gas emissions.

3) Investigate the existence of an atmospheric CO_2 threshold in the mass balance of the Greenland Ice Sheet under a wide range of CO_2 scenarios from 200 to 500 ppm.

4) Assess key policy-relevant issues concerning the potential climatic effects of major reforestation and ocean fertilization projects aimed at mitigating climate change through enhanced uptake of carbon in land and ocean-based sinks.

All research will be carried out at the University of Victoria using the UVic Earth System Climate Model of intermediate complexity. Researchers in my lab have a unique, highly collaborative relationship with researchers in the CCCma as they are located in the same hallway. Two of my past students/postdocs are now continuing employees in the CCCma (D. Robitaille and O. Saenko). While I have not listed anyone within the CCCma as a formal collaborator, informal collaborations will continue to be as frequent and extensive as they have been (clearly evident in my Form 100 publication list).

The present proposal aims at firming up our knowledge of climate feedbacks and hence climate science. Since models are being used to project future climate change associated with increasing greenhouse gases, paleoclimate modelling efforts are essential as means of model and climate feedback evaluation. By improving our science, we will play an even stronger role in the IPCC process, thus helping to build international respect for Canada's positions on these issues whereas by studying and evaluating carbon sequestration strategies using forests and the oceans we will assess new mitigation strategies for overall reduction of atmospheric CO_2 levels and gain new insights into the role of forests in the carbon cycle. Canada's forest resource may play an important role in Canada's future carbon strategy, although this has yet to be quantitatively examined.

Introduction

Coupled atmosphere-ocean general circulation models (GCMs) are frequently used to understand both past, present and future climate and climate variability. The computational expense associated with these models, however, precludes their use for undertaking extensive parameter sensitivity studies. It is important to conduct sensitivity studies, in parallel with the coupled GCM studies, using simpler models. Simple models, or models of intermediate complexity, allow one to explore the climate sensitivity associated with a particular process or component of the climate system over a wide range of parameters. In addition, they allow one to streamline the experiments that are performed using more complicated GCMs. These more idealised coupled models vary in complexity from simple one dimensional energy balance/upwelling diffusion models (Wigley 1988), to zonally-averaged ocean/energy balance atmosphere models (Stocker and Schmittner 1997), to models with more sophisticated subcomponents (Petoukhov et al. 2000; Weaver et al. 2001).

Simple and intermediate complexity climate models are designed with a particular class of scientific questions in mind. In the development of the model, only those processes and parametrisations are included which are deemed important (or are possible to incorporate) in the quest to address the scientific questions of concern. For example Wigley (1998) used an upwelling diffusion-energy balance climate model to evaluate Kyoto Protocol implications for increases in global mean temperature and sea level. While such a simple climate model relies on the climate sensitivity and other parameters obtained from coupled atmosphere-ocean GCMs, it nevertheless allows for a first-order analysis. Stocker and Schmittner (1997) used a three-basin zonally-averaged ocean circulation model coupled to a simple energy-balance atmospheric model, to undertake a systematic parameter sensitivity study of the response of the North Atlantic thermohaline circulation to both the rate of increase and equilibrium concentration of atmospheric CO_2. While the actual critical thresholds that arose from this study would need verification by more complicated models, their work clearly illustrated the importance of the rate of CO_2 increase on the North Atlantic thermohaline circulation, a result difficult, if not impossible, to achieve with the computationally expensive current generation of GCMs.

The UVic Earth System Climate Model (ESCM)

The philosophy underlying the development of the UVic ESCM is that on timescales greater than a decade, the ocean, its horizontal gyre structure, and its ability to transport heat and freshwater are key components of the climate system. As such, the model has been built to resolve as many processes and feedbacks as possible that affect climate sensitivity and oceanic heat uptake on long timescales. It is also constructed in a modular fashion so that only a subset of processes or subcomponent models may be included, depending on the particular scientific question of concern.

Since its original conception, the UVic ESCM has undergone significant development. It now consists of an ocean GCM coupled to a sophisticated sea ice model, an ocean carbon cycle model, a dynamic energy-moisture balance atmosphere model, a thermomechanical ice sheet model, a land surface model and a terrestrial dynamic vegetation/carbon cycle model (Weaver et al. 2001; Matthews et al. 2003,2004; Meissner et al. 2003; Ewen et al. 2004). A reduced complexity atmosphere model is used for computational efficiency. Atmospheric heat transport is parametrised through diffusion, and moisture transport occurs through advection and diffusion, with precipitation arising when the relative humidity is greater than 85%. The atmospheric model includes a parametrisation of the water vapour/planetary longwave feedback, while the radiative forcing associated with atmospheric CO_2 changes is externally imposed as a reduction of the planetary longwave radiative flux. A specified lapse rate is used to reduce the land surface temperature where there is topography.

The model uses prescribed winds to obtain its present-day climatology, and a dynamical wind feedback is included that exploits a latitudinally-varying empirical relationship between atmospheric surface temperature and density. The ocean component of the coupled model is a 3-D ocean GCM with a global resolution of 3.6° (zonal) by 1.8° (meridional) and 19 vertical levels. The coupled model incorporates a dynamic/ thermodynamic sea ice model (Bitz et al. 2001). Dynamics is represented by an elastic-viscous-plastic rheology and various sea ice thermodynamics and thickness distribution options are included.

The thermomechanical ice sheet model within the UVic ESCM comes from Marshall and Clarke (1997). It employs continuum mixture theory to incorporate ice streams (Yoshimori et al. 2001). We have also added the Hadley Centre dynamic global vegetation and terrestrial carbon cycle model (TRIFFID — Cox et al. 2000; Cox 2001) in which the relevant land-surface characteristics (vegetation fraction, leaf area index, albedo, etc.) are modelled directly (Foley et al. 1996), and two different land surface models: one being a simple bucket model (Matthews et al. 2003), and the other being a simplified one-layer version of the Hadley Centre MOSES land surface scheme (Meissner et al. 2003).

The coupled model has been extensively and successfully evaluated against both contemporary climate observations as well as paleo proxy records (Weaver et al. 1998, 2001; Schmittner et al. 2002; Meissner et al. 2003). One of the virtues of the coupled model is that we do not need to employ explicit flux adjustments to keep the simulation of the present climate stable. It also allows us to conduct many long timescale integrations in order to investigate climate processes through a wide range of parameter space. Our use of a rotated coordinate system also allows us to examine high latitude processes in detail without having to worry about numerical issues associated with converging meridians. Thus, it is well suited for both climate and paleoclimate modelling, and is especially useful for examining important high latitude processes.

The UVic ESCM has not only been used to investigate various scientific questions in contemporary and paleo climate, but also as a laboratory with which to build new subcomponent models, test new parametrisations, and develop intuition and coupling experience/technology for use by the CCCma). The efficiency of the simpler atmospheric component of the ESCM allows for a wide range of parameter space to be explored through long timescale integrations. For example, a new dynamic/thermodynamic sea ice model, developed by researchers in my group (Bitz et al. 2000), has recently been incorporated into the CCCma coupled atmosphere-ocean GCM, as well as the NCAR Climate System Model in the US.

Recently, Yoshimori et al. (2002) examined the issue of glacial inception at 116 kyr BP in both the UVic ESCM as well as the CCCma AGCM. They integrated the UVic ESCM under both present-day and 116 kyr BP orbital forcing and atmospheric levels of CO_2 and then integrated the CCCma AGCM with prescribed SSTs and sea ice mask from the UVic ESCM. They examined the sensitivity to specified vegetation changes in the land surface component of the CCCma AGCM, based on climate changes induced at 116kyr BP. In the CCCma model, perennial snow cover occurred over northern Canada under 116 kyr BP orbital and CO_2 forcing with present-day *warm* sea surface conditions, and further expanded when 116 kyr BP *cool* sea surface conditions were applied. Modifying vegetation based on cooling during the summer induced by 116 kyr BP sea surface conditions, lead to much larger areas of perennial snow cover. The results from these experiments clearly highlighted the importance of both SST and vegetation feedbacks on glacial inception.

In Meissner et al. (2003), the first results of the UVic Earth system model coupled to a land surface scheme and the TRIFFID dynamic global vegetation model were presented. A southward shift of the northern treeline as well as a global decrease in vegetation carbon were observed in the ice age inception run. In tropical regions, up to 85% of broadleaf trees were replaced by shrub and C4 grasses. These changes in vegetation cover had a remarkable effect on the global climate: land related feedbacks doubled the atmospheric cooling during the ice age inception as well as the reduction of the meridional overturning in the North Atlantic. The introduction of vegetation related feedbacks also increased the surface area with perennial snow significantly.

This proposal will build upon our demonstrated success of addressing fundamental questions in climate and paleoclimate. Here the theme of scientific inquiry concerns carbon and vegetation feedbacks in past climate change. Inspired by our examination of the past, we will study the future effects of human influence on the terrestrial and oceanic carbon cycle. In particular, we will assess the effectiveness of potential terrestrial and ocean carbon sinks in mitigating future greenhouse gas levels.

The Greenland Ice Sheet and Abrupt Climate Change

In Matthews et al. (2004), the behaviour of the terrestrial carbon cycle under historical and future climate change was examined using the UVic Earth System Climate Model, including a dynamic terrestrial vegetation and global carbon cycle model. When forced by historical emissions of CO_2, the coupled carbon cycle model accurately reproduced historical atmospheric CO_2 trends, as well as terrestrial and oceanic uptake for the past two decades. Under six 21st century illustrative IPCC SRES emissions scenarios, terrestrial and oceanic carbon sinks remained strong, though terrestrial uptake as a fraction of emissions declined over the 21st century. In these simulations, the negative feedback of CO_2 fertilization on vegetation growth was shown to exceed the effect of the positive feedback of climate warming on soil respiration. In this work, however, the thermomechanical Marshall/Clarke ice sheet model was not included since it had not yet been interactively coupled with the terrestrial vegetation model.

The numerous coupled models assessed in IPCC (2001) have a range in the magnitude of the hydrological cycle response, characterised by increased precipitation at middle to high latitudes and increased evaporation in the subtropics, with the UVic model in the middle of this range. Despite the fact that none of these models revealed a cessation of the North Atlantic thermohaline ciirculation during the 21^{st} century, although many show a slight reduction in its intensity, some have suggested, without quantitative support, that freshwater input to the oceans by melting land glaciers, ice sheets and permafrost, which is not included in the coupled model simulations assessed in IPCC (2001), could be sufficient to trigger a cessation of the AMO during the 21^{st} century.

The best estimate of sea level change over the 20^{th} century (IPCC, 2001) associated with the very slight net negative mass balance from Greenland (which itself is not significantly different from zero in a statistical sense) is 0.0-0.1 mm/yr. This converts to only about 0.0–0.001 Sv (1 Sv $\int 10^{12}$ m^3s^{-1}) of freshwater forcing. The maximum estimate, 0.001 Sv, is $1/100^{th}$ the size of the perturbation Weaver and Hillaire-Marcel (2004) used to collapse the thermohaline circulation in their simulations with an externally exposed freshwater source. In an additional experiment, they took this upper bound estimate (0.001Sv) and added it continually from 1950–2450 as an external perturbation to the North Atlantic between 50°N and 70°N. The resulting path of the North Atlantic thermohaline circulation was indistinguishable from their control experiment as was the globally-averaged warming at 2050.

The main goal of this subproject is to reexamine the work of Matthews et al (2004) and Weaver and Hillaire-Marcel (2004) but now to allow the ice sheets over Greenland and Antarctica to respond to a changing climate. The success of our use of the Marshall/Clarke ice sheet model in paleo equilibrium and transient climates (Yoshimori et al., 2001; Schmittner et al., 2002), as well our ability to capture the correct location and thickness of ice sheets in the present climate (Weaver et al., 2001), suggests that we will have success in examining transient future climates. The goal is to assess the possibility of abrupt climate change associated with ice sheet-climate interactions.

Climate Change over the Last 135,000 Years

Ice core records for the last glaciation have revealed variability on the millennial timescale characterized by abrupt warming events (interstadials) lasting from several hundred to several thousand years. These oscillations, known as Dansgaard/Oeschger (D-O) oscillations (Oeschger et al. 1984; Dansgaard et al. 1984) are also apparent in North Atlantic sediment records (Bond et al. 1993) suggesting a role or response of the ocean. The last such event, known as the Younger Dryas, took place between 12,700 and 11,650 years BP (Dansgaard et al. 1989) and terminated abruptly within a few decades (Alley et al. 1993). Evidence from the Santa Barbara basin (Kennett and Ingram 1995) and the northeast Pacific (Lund and Mix 1998) suggests that a signature of these D-O oscillations is also present in the Pacific, while further recent analyses suggest they may be an inherent part of late (Oppo et al. 1998) and early (Raymo et al. 1998) Pleistocene climate.

In an attempt to provide a mechanism for the observed D-O variability, Broecker et al. (1990) proposed that during glacial times, when the northern end of the Atlantic Ocean was surrounded by ice sheets, a stable mode of the "conveyor belt" for North Atlantic Deep Water (NADW) was not possible. They further suggested that when the NADW "conveyor" was weakened or shut down and there were growing ice sheets, there was little oceanic salt export from the Atlantic to the other world basins. Assuming a net evaporation over the North Atlantic, its salinity continued to increase with the moisture being deposited on land as snow thereby growing the ice sheets. Upon reaching a critical salinity, deep convection and subsequently the "conveyor" turned on, transporting and releasing heat to the North Atlantic and thereby melting back the ice sheets. The flux of fresh water into the North Atlantic from the melting ice sheets (or enhanced ice berg calving) eventually reduced or shut off the "conveyor" and the process began anew. Schmittner et al. (2002), on the other hand, used the UVic model to show that the mechanism proposed by Broecker et al. (1990) was in fact opposite to what occurred within the coupled system. During the cold, glacial climate, when the conveyor is on, the mass balance over continental ice sheets was positive. That is, rather than melting ice sheets, when the conveyor turned on they grew, since the warmer atmosphere allowed greater precipitation (in the form of snow). They also found a mechanism for D-O oscillations but it involved increased ice berg calving which provided the freshwater source to the ocean, several hundred years after the conveyor turned on.

In the present day climate, the mass balance over the Greenland ice sheet is slightly negative. The results of Schmittner et al. (2002) suggest the rather fundamental result that a threshold exists for atmospheric CO_2 between 200 and 300 ppm whereby the sign of the response of the mass balance to a warming perturbation changes. That is, in the present climate, the mass balance is negative as summer melting dominates over winter precipitation whereby in a glacial interstadial, the mass balance was positive as winter precipitation dominated over summer melting. We will investigate the existence of such a threshold through a systematic analysis of mass balance of the Greenland ice sheet under a wide range of CO_2 scenarios from 200 to 500 ppm.

Heinrich (1988), in analyzing marine sediments from the North Atlantic noted the presence of six anomalous concentrations of lithic fragments over the last glaciation. Since the source for these fragments was the land, he argued that this provided evidence for six anomalous surges of icebergs into the North Atlantic. MacAyeal (1993) developed a simple model to illustrate the mechanism for Laurentide ice-sheet instability which ultimately gives rise to an ice-sheet surge and a Heinrich event. He argued that the Heinrich cycle consisted of two phases. In the growth phase the Laurentide ice sheet grew through snow accumulation while remaining attached to the bedrock. In the purge phase, he suggested that the high pressures caused by the deep ice sheet caused thawing near the base of the ice sheet thereby allowing the ice sheet to surge seaward over a lubricated base through Hudson Strait. He pointed out that the resulting freshwater discharge into the North Atlantic would be of the order of 0.16 Sv (1 Sv ∫ $10^6 m^3 s^{-1}$) over a period as short as 250–500 years. Recent evidence (Hewitt et al. 1997) suggests that Heinrich events (and associated ice rafted debris) also have a signature in the northeast Pacific Ocean.

As noted by Bond et al. (1993) and Broecker (1994) the Heinrich events, appearing about every 10,000 years, occur at the end of a sequence of D-O cycles during a prolonged cold period. Bond et al (1993) further noted that the sequences of D-O oscillations tended to follow a saw-tooth cycle (now termed a Bond Cycle) with successive D-O oscillations involving progressively cooler interstadials. They argued that this Bond Cycle was terminated by a Heinrich event, after which a rapid warming occurred and the process began anew.

The melting of continental ice sheets during the last deglaciation provided a freshwater source to the ocean that also affected global sea level and the strength of the thermohaline circulation. An exceptionally large melting event, inferred from far-field relative sea level records, occurred ~14,600 yr BP wherein global sea level rose by about 20 m in less than 500 years. The ice sheet that served as the source for this event, known as meltwater pulse 1A (mwp-1A) has been the subject of some controversy since it was first identified from Barbados coral records (Fairbanks 1989*)*. The Laurentide Ice Sheet was commonly cited as the most likely source for mwp-1A, but this raised the apparent conundrum of reconciling a large freshwater forcing (~0.5 Sv over several hundred years) to the North Atlantic Ocean with an active Atlantic thermohaline circulation and associated warm climate of the Bølling-Allerød warm interval (Clark et al. 1996). Until recently, a satisfactory mechanism for the onset of the Bølling-Allerød event, conventionally considered as marking the termination of the last glacial period, had not been identified.

Clark et al. (2002) provided compelling evidence that the partial collapse of the Antarctic ice sheet was responsible for a substantial component of mwp-1A. They noted that the ice sheet ablation responsible for mwp-1A would lead to a sea level fingerprint, that is a dramatic departure from eustasy, due primarily to a reduction in the gravitational attraction of ocean water towards the location(s) of the source. A comparison of fingerprints predicted for various mwp-1A scenarios with available far-field relative sea level records strongly supported an Antarctic source for mwp-1A and ruled out a sole Laurentide source for the event. Further evidence for an Antarctic source for mwp-1A comes from South Atlantic records of ice-rafted debris (IRD) derived from the Antarctic ice sheet, where Kanfoush et al. (2000) document the existence of one such IRD event (SA0) that correlates to mwp-1A and the Antarctic Cold Reversal.

Using the UVic model, Weaver et al. (2003) demonstrated that with mwp-1A originating from the Antarctic ice sheet, consistent with the sea-level fingerprinting inferences of Clark et al. (2002), the strength of North Atlantic deepwater formation increased, thereby warming the North Atlantic region and providing an explanation for the onset of the Bølling-Allerød warm interval. The established mode of active NADW formation would then be able to respond to subsequent freshwater forcing from the Laurentide and Fennoscandian ice sheets, setting the stage for the Younger Dryas cold period.

Despite these fundamental advances over the last few years in paleoclimate modelling and analysis, many challenges remain. In particular, the capturing of millennial timescale (D-O) variability and its packaging into Bond Cycles in cold climates, its association with Heinrich events, and its dependence on the mean climatic state remains one of the greatest challenges for paleoclimate modelers. It is precisely this challenge that this project aims to address.

As noted in Prentice et al. (2001) “current thinking maintains that the oceanic uptake of anthropogenic CO_2 is primarily a physically and chemically controlled process superimposed on a biologically driven carbon cycle that is close to steady state”. However, this is not the case over millennial and glacial timescales. To this end, a biological ocean carbon cycle has recently been added to the UVic model following the guidelines set out by the Ocean-Carbon Cycle Model Intercomparison Project (OCMIP) research initiative of the Global Analysis, Interpretation, and Modeling (GAIM) Task Force of the International Geosphere-Biosphere Program (IGBP). The challenge of this proposal will then be to integrate the UVic ESCM for 116,000 years over a complete glacial cycle from the last interglacial (116kyrBP) with a fully interactive carbon cycle, continental ice dynamics and dynamic terrestrial vegetation to determine whether or not we are able to capture the glacial-interglacial transitions and the millennial timescale variability, including periodic Heinrich events which occurred over the last glacial cycle. While it might never be possible to exactly reproduce the proxy record over the last glacial cycle, reproducing the statistics of millennial timescale variability and Heinrich events, as well as the slow evolution of the glacial-interglacial cycle, is certainly within our grasp. This project should be viewed as extremely ambitious and high risk, although I believe I have a good track record of completing such projects. If successful, the knowledge gained would be fundamental.

The Potential for Reforestation as a Means of Mitigating Atmospheric CO_2

Through specified modification “forest/ocean policy management” of the terrestrial and oceanic bisphere within the UVic model we will be able to provide an assessment of key policy issues concerning the potential climatic effects of major reforestation and ocean fertilisation projects aimed at mitigating climate change through enhanced uptake of carbon in land and ocean-based sinks. This project is intimately linked to a number of existing and proposed research Networks. Of particular importance is its fundamental link with the FluxNet network. FluxNet will be producing a wealth of observational information concerning the exchange of CO_2 between the land surface and the atmosphere. Such observations will be instrumental in the validation of our terrestrial carbon cycle model. In addition, our results will aid the FluxNet team in terms of assessing the potential for Canada’s terrestrial biosphere to act as a sink for anthropogenic CO_2.

The ocean carbon cycle component of this full proposal will continue to be closely related to the Global Coupled Carbon Cycle Model (GC^3M) project and the national field-based SOLAS program aimed at exploring the role of iron fertilisation in enhancing oceanic carbon. Dr. K. Denman (CCCma), one of my collaborators in the CCCma, will be an instrumental link in this regard.

To my knowledge, no one in the world is either attempting to carry out research along these lines or is indeed able to do so. The UVic model is unique in that it is able to be integrated for many millennia and in that it represents all the main components of the climate system relevant for long timescale climate change/variability. While other groups are examining specific periods in the past with coupled models, no one has attempted or is able to attempt conducting a 135,000 year integration over the last glacial cycle.

CFCAS Selection Criteria

1) Science

I believe that the proposed research plan outlined above represents novel and highly topical science aimed at addressing fundamental problems in contemporary and past climate. I also believe that with the acquisition of the NEC facility, my group and I now have the necessary infrastructure in place to meet the ambitious goals of this project.

2) Expertise

I believe that I have a good track record of meeting all the milestones of all of my proposals (for example, please see the attached progress report on my last CFCAS grant). Frequently my proposals have been described by review committees as ‘overly ambitious’, yet it is precisely these ambitious questions that spark my keen sense of scientific inquiry. ‘Safe proposals’ conducting ‘safe science’ do not interest me as I like to try and push the frontiers of our knowledge.

I believe that I am positioned internationally to make significant steps forward in our understanding of climate science. I have been involved in the last two IPCC assessments as well as the scoping for the next IPCC Assessment. I have been a member of numerous international climate committees and currently co-chair the CLIVAR PAGES (Past Global Changes) Intersection Panel. I am also an Editor of the Journal of Climate and have been put forward as the next Chief Editor of the journal (January 2005) when David Randall steps down.

3) Targetted

While there are broad links with the various targeted criteria, the present proposal is central to the CFCAS category: “Understanding key climate system process including greenhouse gas sources and sinks”. In particular, our evaluation of the UVic model through its integration over the last glacial cycle will give us insight into our ability to understand natural mechanisms of climate variability and abrupt climate change associated with terrestrial vegetation and continental ice sheet processes. This will then allow us to assess the potential of the ocean and Canada’s terrestrial biosphere to mitigate increases in anthropogenic greenhouse gases. In addition, our investigation of the mass balance of the Greenland Ice sheet and its potential interaction with the North Atlantic thermohaline circulation will allow us to better assess the likelihood of a change in the strength of North Atlantic Deepwater formation in the future. This therefore is a mechanism that would lead to better marine environmental predictions.

4) National Context

Through the Kyoto Protocol, Canada has made a commitment to reduce its greenhouse gas emissions to 6% below 1990 levels for the period spanning 2008 to 2012. Canada has begun to move toward this goal by the introduction of several federal government programs, such as the Canadian Action Plan 2000 on Climate Change and the National Business Plan of the National Implementation Strategy. These programs, and their sibling programs from provincial government initiatives, are targeted at Canadian business and government agencies responding to the climate change problem. Fundamental to any policy option is a solid foundation in the science underlying that option. The present proposal aims at firming up our knowledge of climate feedbacks and hence climate science.

As models are being used to project future climate associated with increasing greenhouse gases, paleoclimate modelling efforts are essential as a means of model and climate feedback evaluation. By improving our science, we will play an even stronger role in the IPCC process, thus helping to build international respect for Canada’s positions on these issues whereas by studying and evaluating carbon sequestration strategies using forests and the oceans we will assess new mitigation strategies for overall reduction of atmospheric CO_2 levels and gain new insights into the role of forests in the carbon cycle. Canada’s forest resource may play an important role in Canada’s future carbon strategy, although this has yet to be quantitatively examined.

We will be able to provide an assessment of key policy questions concerning the potential climatic effects of major reforestation and ocean fertilisation projects aimed at mitigating climate change through enhanced uptake of carbon in land and ocean-based sinks. This project is intimately linked to a number of existing and proposed research Networks. Of particular importance is its fundamental link with the FluxNet network. FluxNet will be producing a wealth of observational information concerning the exchange of CO_2 between the land surface and the atmosphere. Such observations will be instrumental in the validation of our terrestrial carbon cycle model. In addition, our results will aid the FluxNet team in terms of assessing the potential for Canada’s terrestrial biosphere to act as a sink for anthropogenic CO_2. The ocean carbon cycle component of my full proposal will also be closely related to the emerging Carbon Cycling in Aquatic Systems BIOCAP network, the Global Coupled Carbon Cycle Model (GC^3M) project and the national field-based SOLAS program aimed at exploring the role of iron fertilisation in enhancing oceanic carbon. Dr. K. Denman (CCCma), one of my collaborators, will be an instrumental link in this regard.

As a member of the steering committee for the Canadian CLIVAR network and as co-Chair of the WCRP CLIVAR-PAGES Intersection project, there would be close linkages to these networks. CLIVAR Canada is focused on the contemporary climate and does not contain a paleo component in it. This is in fact not the case for the WCRP International CLIVAR program. As co-Chair of the relevant international organization that deals with paleo work in support of climate modelling and analysis efforts (as a means of model evaluation and as a mechanism of getting estimates of natural climate variability for climate change detection and attribution studies), I would hope to be able to contribute scientifically to these international efforts. This would not be possible within the existing CLIVAR Network given its current focus and the fact that it has already set its science plan for the next (second to last) year.

This project is also complementary, albeit independent, from the Polar Climate Stability project proposed by Dick Peltier at the University of Toronto.

5) Funding

As of October, 2004 I will only have two funding sources: 1) my NSERC Discovery Grant; 2) My CLIVAR network grant. Research grant support in my lab should be viewed as in a crisis at a time when infrastructure support should be viewed as world-class and never better. This is not because of a lack of productivity but solely a consequence of the fact that virtually all of my grants finished in the 2003-2004 fiscal year. My NSERC discovery grant provides modest funding to partially support my international collaboration with D. Lettenmeir (University of Washington) and E. Wood (Princeton) in the area of high latitude land surface processes (and in particular permafrost and hydrology). Eric Wood will be spending his sabbatical in Victoria from May to August, 2004. It also is required to support my computer technician. This project is completely unrelated to the present Proposal.

The CLIVAR grant supports my work in the area of climate change detection and attribution and climate variability in the contemporary climate. It is exclusively focused on the physical processes governing contemporary climate variability and involves extensive interaction with the CCCma (especially Francis Zwiers, John Fyfe and Greg Flato). This project is also completely independent from the present application. The review committee will notice that I received a large CLIVAR grant in 2004-2005. This was a one-time increase to allow me to bridge over my funding crisis. The grant reduces to $146,400 in 2005-2006, the last year of the CLIVAR project.

The Polar Climate Stability project concerns itself with mechanisms involving abrupt climate change. In particular, my component of this project is to assess the possibility of abrupt change in the North Atlantic Ocean through freshwater discharge. In addition, I will be assessing the potential for a widespread methane hydrate instability. Once more, this project, which exclusively concerns itself with high latitude processes, is unrelated to the present proposal. The specific component of this project dealing with the Greenland Ice sheet is not covered in the Polar Climate Stability project.

Finally, my CFI/BCKDF grant is intimately linked in with this proposal. As I have already noted, CFI/BCKDF/NEC granted me funding for a $6 million supercomputing facility (a 32CPU NEC facility). This facility will be the tool on which the young researchers funded under this proposal would work. In fact, my CFI proposal was justified as providing the equipment necessary for me to undertake the research I am proposing here. Here I am seeking salary support; in the CFI proposal I was seeking infrastructure support.

My publication record is such that I believe that I have a good track record in ensuring that research results are disseminated to the wider scientific community. What is not listed in Form 100 is my commitment to educating the public on issues concerning my research. I have conducted hundreds of media interviews over the last few years and my research has been written up in two Time Magazine articles. These articles highlighted the goals of my research over the last decade: 1) “to produce a detailed simulation of the earth’s climate for the past 135,000 years with unparalleled precision” (Time Magazine Canadian Edition, Nov. 18 2002, p. 79); 2) “to examine the influence of climate on human evolution over the past 130,000 years” (Time Magazine Canadian Edition, Feb. 17 2003, p. 49). Attaining the first of these two goals is the purpose of this proposal. In addition, my students, postdocs and I have given scores of lectures to schools, public forums, industry boards, societies, workshops, universities and conferences. In addition, my work (and career) has recently been the focus of a section of a Grade 10 Science Curriculum text book (by Pearson Press) used in Alberta and soon to be implemented in Ontario and British Columbia.

6) Collaboration

All of my research has been inherently collaborative (witness the extensive list of collaborators from around the world in my Form 100). I confess that I have some difficulty with the definition of collaboration often used by funding agencies. To me, collaboration and funding should be separated. For example, this proposal is seeking to support the salaries of several young researchers. These researchers will work in a highly interdisciplinary environment and will be engaged on a daily basis with researchers within the CCCma. All their work will be collaborative with researchers from around the world, yet I am the one who is responsible for ensuring that their salaries are paid, not the others. As a specific example, Katrin Meissner (who is now a faculty member in SEOS), was funded off my last CFCAS grant. She spent several weeks in England working with Peter Cox so that she could become familiar with TRIFFID. Peter, Katrin and I then wrote the first paper together on the use of TRIFFID in our model (the glacial inception paper).

I have published numerous papers with researchers in the CCCma, across Canada, and elsewhere. The mechanism by which these collaborations arose is that in moving to address the science in one of my proposals, we realize that we need to tap into some outside expertise. We approach an individual that we deem as the best able to assist us and we then spend a bit of time interacting with that individual. A collaboration then ensues. This has worked exceptionally well in the past for my group and is not something that I would like to change. As such, I have only listed myself as a PI on this project as it is almost exclusively aimed at funding the young researchers who would work at UVic (that is, I am responsible for their salary). With this said, we will continue to work with Peter Clark in the US, Shawn Marshall in Calgary, Claude Hillaire-Marcell at UQAM, Andy Ridgwell and Garry Clark at UBC, Peter Cox at the Hadley Centre, Jonathan Gregory in Reading, Martin Claussen and others at Potsdam, Andreas Schmittner at Kiel University etc.

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Progress report for CFCAS research Grant:

"Vegetation/Carbon Cycle Feedbacks on Quaternary Climate

I am in the final year of the above-titled three-year research project. Below I list the individual milestones for this project and the status of our efforts to meet them.

Milestone 1: Incorporation of inorganic carbon cycle into UVic ESCM

This milestone was completed very early on in the project. We expanded this area to examine the effects of increased anthropogenic carbon dioxide emitted into the atmosphere on climate feedbacks that could potentially reduce further uptake of carbon by the oceans. The most significant feedbacks acting on the system to reduce carbon sequestration by the oceans are reductions in the thermohaline circulation (THC) and increased sea surface temperatures (SSTs). Although changes in SSTs affect the solubility of atmospheric CO_2 across the ocean-atmosphere interface, changes to the THC lead to more fundamental modifications of the ocean circulation and hence transport and storage of carbon to the deep ocean. Using the UVic model which incorporated the new ocean carbon solubility pump, we projected atmospheric carbon dioxide levels under global warming scenarios. A transient weakening of the THC was found in most simulations and increased SSTs were found in all simulations. Although these positive feedbacks acted on the carbon system to reduce oceanic uptake, the ocean had the capacity to take up 65-75% of the anthropogenic CO_2 increase once the forcing was turned off. This reduced by about 5% for each 50 year period that anthropogenic emissions were maintained at a stabilised and elevated atmospheric CO_2 level, and converged to 0% if the system was forced with stabilised levels well into the future. The effects of climate feedbacks on carbon uptake were also examined and we found that the ocean stored 7% more carbon when there were no climate feedbacks acting on the system. Sensitivity experiments were conducted with respect to the representation of ocean mixing and sea ice dynamics. The inclusion of the Gent-McWilliams mixing parametrisation for mixing associated with mesoscale eddies led to a further 6% increase in oceanic uptake, whereas the inclusion of sea ice dynamics led to only 2% global variations in uptake.

Published in: Ewen, T.L., A.J. Weaver and M. Eby, 2004: Sensitivity of the inorganic carbon cycle to future climate warming in the UVic coupled model. *Atmosphere-Ocean*, **42**, 23-42.

Milestone 2: Incorporation of new land surface scheme into UVic ESCM

This milestone was also completed very early on in the project. The UVic model is designed to be modular with a c-preprocessor used to determine which options should be included in any given model configuration. We have now added two land surface schemes. The first is a simple bucket type model and the second is a reduced-complexity version of the Hadley Centre MOSES scheme. The latter must be used when the Hadley Centre TRIFFID dynamic vegetation code is chosen as an option.

Once more, we expanded this milestone in that we undertook a study to examine the radiative effect of changing human land-use patterns on the climate of the past 300 years through analysis of a series of equilibrium and transient climate simulations using the UVic Model. Land-surface changes were prescribed through varying land cover type, representing the replacement of natural vegetation by human agricultural systems from 1700 to 1992. All land cover simulations showed a cooling in the range of 0.09 to 0.22°C with larger regional changes caused by local positive feedbacks.

Published in: Matthews, H.D., A.J. Weaver, M. Eby and K.J. Meissner, 2003: Radiative forcing of climate by historical land cover change. *Geophys. Res. Lett.*, **30(2)**, 27:1-27:4, 1055, doi:10.1029/2002GL016098.

Milestone 3: Incorporation of TRIFFID into UVic ESCM

This milestone has also been completed. We went much further than our original proposal in that we also included a terrestrial carbon cycle model as part of this milestone. In particular, we explored natural and anthropogenic influences on the climate system, with an emphasis on the biogeophysical and biogeochemical effects of historical land cover change. The biogeophysical effect of land cover change was first subjected to a detailed sensitivity analysis in the context of the UVic Model. Our results showed a global cooling in the range of 0.06 to 0.22 °C, though this effect was not found to be detectable in observed temperature trends. We then included the effects of natural forcings (volcanic aerosols, solar insolation variability and orbital changes) and other anthropogenic forcings (greenhouse gases and sulphate aerosols). Transient model runs from the year 1700 to 2000 were examined for each forcing individually as well as for combinations of forcings. We found that the UVic Model reproduced well the global temperature data when all forcings were included. These transient experiments were repeated using TRIFFID coupled interactively to the UVic Model. We found that dynamic vegetation acted as a positive feedback in the climate system for both the all-forcings and land cover change only model runs. Finally, the biogeochemical effect of land cover change was explored using the dynamically coupled inorganic ocean (milestone 1) and terrestrial carbon cycle model. The carbon emissions from land cover change were found to enhance global temperatures by an amount that exceeds the biogeophysical cooling. The net effect of historical land cover change over this period is to increase global temperature by 0.15°C.

Published in: Matthews, H.D., A.J. Weaver, K.J. Meissner, N.P. Gillett and M. Eby, 2004: Natural and anthropogenic climate change: Incorporating historical land cover change, vegetation dynamics and the global carbon cycle. *Climate Dynamics,* in press.

In addition, we examined the behaviour of the terrestrial carbon cycle under historical and future climate change using the UVic Model, which included TRIFFID and a global carbon cycle model. When forced by historical emissions of CO_2, the coupled carbon cycle model accurately reproduced historical atmospheric CO_2 trends, as well as terrestrial and oceanic uptake for the past two decades. Under six illustrative 21st century SRES emissions scenarios, terrestrial and oceanic carbon sinks remained strong, though terrestrial uptake as a fraction of emissions declined over the 21st century. In these simulations, the negative feedback of CO_2 fertilization on vegetation growth was shown to exceed the effect of the positive feedback of climate warming on soil respiration.

Published in: Matthews, H.D., A.J. Weaver and K.J. Meissner, 2003: Terrestrial carbon cycle dynamics under recent and future climate change. *Journal of Climate*, submitted.

Damon Matthews, a PhD student funded to work on this project has recently submitted his thesis and will start an NSERC Postdoctoral Fellowship position working with Shawn Marshall at the University of Calgary shortly.

Milestone 4: Determine whether multiple equilibria exist through ocean carbon cycle/atmosphere interactions.

This milestone has also been completed and we have summarized its results in a paper that recently appeared in Quaternary Science Reviews. As discussed in my proposal, past climates, both before and after the Last Glacial Maximum, were marked by a series of abrupt transitions from cold to warm states associated with significant changes in atmospheric CO_2. The mechanisms that led to these transitions most likely include variability in the thermohaline circulation, as inferred from deep sea sediment records. We investigated the changes in atmospheric CO_2 concentration that arose during abrupt climate change events through our use of meltwater pulse scenarios applied to the UVic model coupled to an inorganic carbon component. We performed transient simulations with increased freshwater discharge to high latitude regions in both hemispheres from a glacial equilibrium climate to simulate meltwater episodes. We found that changes in ocean circulation and carbon solubility lead to significant increases in atmospheric CO_2 concentrations when we simulated meltwater episodes in both hemispheres. The magnitude of increase in atmospheric CO_2 was between 10-40 ppmv, which accounts for some of the changes in CO_2 as recorded in the ice core records. The equilibrium response of the climate system after the perturbation was invariably different from the initial condition which lead us to conclude that multiple equilibria could indeed exist through ocean carbon cycle/atmosphere interactions.

Published in: Ewen, T., A.J. Weaver and A. Schmittner, 2004: Modelling carbon cycle feedbacks during abrupt climate change. *Quaternary Science Reviews,* **23**, 431-448.

Milestone 5: Determine whether vegetation feedbacks contribute to glacial inception at 116 kyr BP

This milestone was completed (well ahead of scheule) when we published the first results of the UVic model coupled to a land surface scheme and TRIFFID. As a necessary first step we examined the present day climate simulation and compared it to observations. We then compared a simulation of an ice age inception (forced with 116 ka BP orbital parameters and an atmospheric CO_2 concentration of 240 ppm) with a preindustrial run (present day orbital parameters, atmospheric CO_2 of 280 ppm). Emphasis was placed on the vegetation's response to the combined changes in solar radiation and atmospheric CO_2 level. A southward shift of the northern treeline as well as a global decrease in vegetation carbon were observed in the ice age inception run. In tropical regions, up to 88% of broadleaf trees were replaced by shrubs and C4 grasses. These changes in vegetation cover had a remarkable effect on the global climate: land related feedbacks doubled the atmospheric cooling during the ice age inception as well as the reduction of the meridional overturning in the North Atlantic. The introduction of vegetation related feedbacks also increased the surface area with perennial snow significantly, leading us to conclude that indeed vegetation feedbacks contributed substantially to glacial inception at 116 kyr BP.

Published in: Meissner, K.J., A.J. Weaver, H.D. Matthews and P.M. Cox, 2003: The role of land-surface dynamics in glacial inception: A study with the UVic Earth System Model. *Climate Dynamics*, **21**, 515-537.

Milestone 6: Determine the relative role of changes in ocean SSTs, land surface moisture and vegetation feedbacks in causing observed change in African climate/biome at 6kyr BP

This is a milestone which is to be completed by September 2004. Jacob Burgess will be joining my lab on May 1 as an NSERC Summer Undergraduate Student and will work with me to undertake the necessary experiments to ensure completion of this project. We anticipate completion of the project on schedule and submission of a manuscript in the fall on this topic. I am hoping that I will be able to convince Jacob to stay with my group as a graduate student as he has an outstanding (straight A+) academic background. Of course, I would need to acquire funding to be able to offer him a graduate stipend in September 2005.

Milestone 7: Determine the role of inorganic carbon uptake in glacial to interglacial transitions

Tracy Ewen, a PhD student funded under this project, successfully defended her thesis on April 26, 2004. The last chapter of her thesis examined the response of the carbon cycle during glacial-interglacial transitions. An LGM initial equilibrium with orbital parameters set to 21 kyr BP and CO_2 radiative forcing to 200 ppmv was used and 8 kyr BP boundary conditions, namely orbital parameters for 8 kyr BP and CO_2 radiative forcing of 280 ppmv, were then imposed. Atmospheric CO_2 was allowed to evolve and we found an increase of only ~5 ppmv. Changes due to CO_2 radiative forcing alone account for almost all of the change in atmospheric CO_2, with effects of changing the orbital parameters almost negligible on global carbon uptake. We suggest that the inclusion of both biological and carbonate pumps must be important components to unlocking the mystery surrounding the glacial-interglacial cycles. A draft of a short paper for Geophysical Research Letters has been written and we will submit it shortly bringing conclusion to this milestone.

Milestone 8: Final report delivered to CCCma and CFCA documenting technology/knowledge

As the project finishes in September, this has yet to be done.