Mechanisms of Abrupt Climate Change:

A. The Thermohaline Circulation in the North Atlantic

Rapid transitions between fundamentally different climate regimes have commonly occurred over the last 400,000 years (Figure 1; see Clark et al., 2001 for a review), inspiring scientists to try and grapple with their possible likelihood of future occurrence. Two specific climate change surprises have been given special attention. The first involves trying to determine the probability of a collapse of the West Antarctic Ice sheet — an event that would lead to a 6m global sea level rise over a relatively short period of time. The second involves assessing the likelihood of a complete shutdown of the North Atlantic conveyor — if this were to occur, the global oceanic deep circulation would be reorganized and the amount of heat transported northward in the North Atlantic by the ocean would be substantially reduced; this would tend to affect the climate over land downwind of the ocean (i.e., Europe). In its Third Assessment Report, the IPCC (IPCC 2001) concluded that the former was very unlikely (1-10% chance) to occur over the 21st century and noted that it was too early to determine whether an irreversible change in the conveyor is likely or not over this same period.

Publication of the first Summit, Greenland, ice core results detailing abrupt climate change during the last glaciation (Johnsen et al., 1992) motivated an intensive investigation for evidence of similar climate instability occurring elsewhere on the globe and its causes. The resulting paleoclimate records clearly reveal the global extent of millennial-scale climate variability, with varying responses that are consistent with atmospheric and oceanic changes associated with changes in the Atlantic THC. With respect to cause and effect, however, our understanding of abrupt climate change remains incomplete. Insofar as the paleoclimate record provides the fundamental basis for evaluating the ability of models to correctly simulate possible nonlinear behavior of the THC, additional information is urgently needed to address these issues. In particular, several (but by no means all) areas that we consider needing immediate attention include: an increase in the distribution of sites in the Pacific and Southern Oceans to evaluate their role in abrupt climate change; development of novel tools to synchronize paleoclimatic records and constrain phasing relations; continued improvements in quantifying the climate signal from proxy records to evaluate climate sensitivity; and further analysis of the $\Delta^{14}C_{atm}$ record for the last 50 kyr BP as a measure of changes in the global

A variety of simulations from coupled models of varying complexities are beginning to simulate the temporal evolution and global signature of millennial-scale change revealed by the paleoclimate record, and provide important insights as to the mechanisms of change. In particular, paleoclimate records and modelling experiments are providing a framework for the possible magnitude of future warming and the response of the interconnected Earth systems to such a warming. Moreover, coupled GCM experiments incorporating geologic data (e.g., continental runoff history — Fanning and Weaver, 1997; Rind, et al., 2001) give new insights into the mechanisms of abrupt climate change and will lead to model improvements and knowledge that is essential for achieving the ability to model future climate.

Nevertheless, modelling past abrupt climate change completely remains one of the greatest challenges for modellers. Further progress will likely be realized as fully interactive and non-flux adjusted coupled earth system models are developed that treat the full range of climate feedbacks. As a step in this direction, recent experiments have been conducted using a fully interactive ice sheet model coupled to a climate model of intermediate complexity to explore the feedbacks between the continental ice sheets and the THC that may account for the D/O timescale and provide an explanation for the rapid warming following a Heinrich event (Schmittner et al., 2002).

Some modelling experiments have suggested that during the next few centuries, the THC may significantly reduce in response to increasing greenhouse gases (Stocker and Schmittner, 1993; Manabe and Stouffer, 1993; Rahmstorf and Ganopolski, 1999). Such a change could have consequences for the climate in the circum-Atlantic region by modifying long-established regional air-sea temperature contrasts, seasonal variations, locations of storm tracks and others. While in these areas a reduction of the THC would partially compensate the warming due to the increase in greenhouse gases, model simulations suggest substantial changes in the direction and strength of wind patterns (Mikolajewicz and Voss, 2000) and the location of convective areas (Wood et al., 1999). The implication of such changes on regional climate remains unexplored.

Reorganizations in the THC would also change the distribution of water masses and hence the density in the world ocean. A warmer and more stratified North Atlantic would also take up less anthropogenic CO_2 (Joos et al., 1999). On the other hand, other experiments suggest little or no THC reduction to the same greenhouse gas forcing (Cubasch et al., 2001). This indicates the dominance of negative feedback mechanisms such as changes in the amplitude and frequency of ENSO (Latif et al., 2000), or modifications of atmospheric variability patterns in the northern hemisphere (Delworth and Dixon, 2000).

The fate of the THC in the coming century largely depends on the response of air-sea heat and freshwater fluxes to the increased load of greenhouse gases. Uncertainties in modeled responses are particularly large for the latter (Cubasch et al., 2001). Moreover, the threshold for the occurrence of an abrupt change in a particular climate model depends on poorly constrained parameterizations of sub-grid scale ocean mixing (Schmittner and Weaver, 2001). Because a complete THC shutdown is a threshold phenomenon, the assessment of the likelihood of such an event must involve ensemble model simulations (Knutti and Stocker, 2001), as well as continued efforts to simulate past abrupt climate changes that so remarkably affected the global climate system.

In February, 2002 the WCRP Working Group on Coupled Models (WGCM) approved a new activity termed: “Coordinated Coupled Model Experiments”. A. Weaver is currently a member of the WCRP WGCM and is acting as the contact for the intermediate complexity modelling community for participation in the “Coordinated Coupled Model Experiments”. The first such coordinated experiment involves examining an intermodel comparison of Abrupt climate changes associated with a collapse of the thermohaline circulation. Specifically, the coordinated experiment is broken down into two parts:

1. Response to time-dependent climate change on the century timescale

Two initial experiments will be done form a control equilibrium: (a) CO2 increasing at 1% per year compounded for 140 years (up to 4xCO2), and (b) a corresponding control run. Daily surface water fluxes will be saved from each run, and two further runs will be then done: (c) like (a), but with the daily water fluxes from (b) used instead of those generated by the model, and (d) like (b) with the daily water fluxes from (a). This design of c) and d) was developed by Dixon et al.(1999) and Mikolajewicz and Voss (2000). As shown by these papers, the GFDL and ECHAM3/LSG models differ in the relative importance of changes in surface water fluxes and surface heat fluxes (caused by raising CO2). Various modelling groups have made different choices regarding whether the surface water flux in sea-ice regions is taken to be at the surface of the ice (i.e. the P-E) or at the underside of the ice (in which case it also includes ice melting and freezing).

A further aim is to find a diagnostic of the density field which can be used as a predictor of the overturning strength, such as the steric height gradient identified by Hughes and Weaver (1994). In particular, diagnostics for the rate of change of temperature and salinity in the ocean due to advection, diffusion and vertical mixing, will be examined on decadal timescales. These can then be used to relate changes in the density field back to the surface flux changes, as by Thorpe et al. (2001).

2. Sensitivity to surface water flux forcing

This experiment aims to establish a benchmark for the sensitivity to an imposed surface freshwater flux. The design is to apply a surface flux of 0.1 Sv and 1.0 Sv in total, uniformly distributed over the Atlantic between 50N and 70N, for a period of 100 years, starting from a control state. This additional flux is a net addition of freshwater to the ocean; it is not compensated for by removal elsewhere. The “Atlantic” may include parts of the Labrador Sea and North Sea within the latitude band. After 100 years, the imposed water flux will be switched off, and the experiment continued to run, so that any recovery can also be investigated.

Through the analysis of the timeseries of maximum of the Atlantic overturning streamfunction, maps of surface air temperature differences and of differences in surface fluxes (heat, freshwater and windstress), it is hoped to shed light on model differences concerning the reestablishment (if at all) of the THC once an external forcing is removed.
A. Weaver (UVic ESCM), W. Peltier (NCAR CSM) and G. Flato (CCCma) will all be active participants in this project. As a further addition to the CMIP coordinated experiment, both A. Weaver and W. Peltier will further repeat the “water hosing” experiments under different initial mean climate states (LGM, $2XCO_2$, $4XCO_2$) in order to determine whether the CMIP coordinated experiment results depend on the mean climatic state.

B. The Arctic Freshwater Budget

A. Weaver recently applied to NSERC under the Operating Grant proposal to support a major new collaborative research focus aimed at trying to understand the Arctic Freshwater budget and its potential to influence the North Atlantic Thermhaline circulation and climate.The amount requested and received is insufficient to complete the task and so additional funds are requested under this Polar Climate Stability Network to complete the research

The freshwater balance of the Arctic exerts a strong control on the salinity of the polar ocean and subsequently the global thermohaline circulation. Runoff from the land surface represents the single largest input of freshwater to the Arctic Ocean. Coupled ice-ocean models indicate that trends in both arctic precipitation and river runoff have the potential to exert broad-scale impacts on the arctic sea ice regime (Weatherly and Walsh 1996) and to affect decadal variability of the ocean circulation (Holland et al. 2000). The variability of freshwater fluxes in the Arctic Ocean also controls the rate of outflow through Fram Strait relative to fluxes through the Canadian Archipelago (Steele et al. 1996). Some have argued that a large increase in freshwater flux to the convective gyres in the Greenland and Iceland Seas through Fram Strait could even stop convection, and the thermohaline circulation (Aagaard and Carmack 1989).

The Great Salinity Anomaly (GSA) of the late 1960s accompanied large changes in Arctic/North Atlantic freshwater exchange. The upper 500 m of the northern North Atlantic experienced a freshwater excess of approximately 2000 km^3 (or 0.032 Sv over a two year period). Dickson et al. (1988) traced advection of this fresh anomaly around the subpolar gyre for over 14 years. Delworth et al. (1997) described a coupled ocean-atmosphere GCM study of long-term thermohaline variability associated primarily with oceanic processes. They found salinity anomalies in the surface layer of the Arctic Ocean precede anomalies of the thermohaline intensity by 10-15 years. In agreement with the proposed climate cycle of Wohlleben and Weaver (1995), these arctic freshwater anomalies are connected to the North Atlantic through SLP anomalies in the Greenland Sea resembling the pattern that Walsh and Chapman (1990) report preceded the GSA.

Given the importance of the fluxes of freshwater into the Arctic Ocean on global climate, changes in the climate and hydrologic cycle of the Arctic are of considerable concern. All climate models suggest that substantial warming should occur at high latitudes over the next century. Chapman and Walsh (1993) show that there has already been a pronounced warming over the land areas of northern Eurasian and most of North America (excepting the northeastern portion) since the early 1970s. Reductions in sea ice thickness and extent in the Arctic Ocean have been well documented (e.g., Cavalieri et al., 1997; Rothrock et al., 1999). Recent studies suggest that the arctic land areas, which have long been a significant sink of carbon as a result of accumulation in peat areas, may now have shifted to being a source due to increased winter soil respiration (Oechel et al., 1993; Zimov et al., 1996).

The arctic land surface also displays certain interesting and unique characteristics. In comparison with other global river basins, both precipitation and runoff are quite low, and indeed much of the area would be classified as desert if it were at lower latitudes. Net radiation is small and highly seasonal, as are other terms (e.g., evapotranspiration) in the surface water and energy balances. Snow plays a major role in the water balance of the region, and is the dominant source of streamflow, much of which is concentrated in a short period during and following spring snowmelt and ice breakup. Yet over much of the region, precipitation occurring as rainfall is large relative to that occurring as snowfall, and in parts of the region (particularly those in the central and southern portions of the drainage basins of the large Arctic rivers) can account for the majority of annual precipitation. Over most arctic river basins, summer rainfall is the primary source of annual evaporation, and for all but the smallest rivers, runoff response to summer precipitation is small. Given the critical role of the arctic freshwater balance in global climate, changes in its constituent fluxes are of major interest and concern.

Although numerous studies have hypothesized effects on the global climate system of changes in the arctic freshwater balance (e.g. Manabe and Stouffer 1993; Wood et al., 1999), the more specific effects of temporal and spatial changes have yet to be examined. For instance, one argument holds that because the transport time for sea ice out of the Arctic Ocean is several years, changes in seasonality and to some extent spatial distribution of river discharge will be damped out in terms of their broader scale effects on climate. On the other hand, changes in freshwater discharge almost certainly will have effects on the distribution of sea ice in the estuaries and continental shelf waters, and in turn on albedo and the general energy exchanges over the ocean surface. Whether such local changes, when integrated over the major rivers and numerous smaller ones discharging to the Arctic could affect climate at regional and global scales is an unknown that this proposal addresses.

The most recent version of the UVic coupled climate model will be applied to investigate the partitioning of oceanic transport of freshwater (both in liquid and solid form) via Fram Strait and through a well-resolved Canadian Arctic Arcipelago. Most global coupled climate models do not allow flow of water through the Canadian Archipelago, so that the validity of this approximation will be directly addressed. Furthermore, an objective is to examine the change in partitioning of the Arctic freshwater export through these two different routes over the last glacial cycle and into the future. Most coupled models fail to capture realistic Denmark Strait out flow waters, likely due to poor representation of the bottom boundary layer flow, especially over steep topography, as well as poor horizontal and vertical resolution in the region of outflow. The UVic model's rotated coordinate structure will allow us to isolate each of these potential causes and determine to what extent a more realistic overflow can be attained. This will be further tested under a variety of surface boundary layer and energy-conserving mixing schemes (see Simmons et al., 2003).

To further address the issue of the freshwater budget of the Arctic Ocean, a more realistic land surface model will also be needed. The University of Washington/ Princeton University's Variable Infiltration Capacity (VIC) land surface model (Liang et al., 1994; 1996; Cherkauer et al, 2002) will be incorporated into the UVic ESCM. VIC has been tested extensively for high latitude applications, mostly in off-line applications. It includes recent parameterizations of frozen soil and permafrost, lakes and wetlands, including lake ice freeze-thaw processes, and snow redistribution and sublimation (Cherkauer et al, 2002). Furthermore, it has a strong hydrological heritage, and has been used in a number of previous applications to simulate discharge of large continental rivers (e.g., Nijssen et al, 1997; Nijssen et al, 2001), including arctic rivers and the pan-arctic region (see in particular Bowling et al, 2000). The realistic simulation of the space-time variability of arctic river discharge, which has already been demonstrated with VIC (see Bowling et al, 2000) is central to this project's scientific inquiry.

In collaboration with Dr. D. Lettenmaier (University of Washington) and Dr. E. Wood (Princeton University), A. Weaver intends to start, in parallel, off-line simulations that will allow us to inter-compare and evaluate the current ESCM bucket and simplified MOSES land surface models in the context of a pan-Arctic application. Two versions of MOSES participated in PILPS-2e, the Arctic Hydrology Model intercomparison project. Both versions tended to overestimated sublimation, and consequently underestimated spring snow accumulations, and streamflow. Some of these problems may have been attributable to unrealistic snow roughness lengths, which was a common difficulty with many of the participating models (by contrast, VIC, along with a few other models, simulated winter snow accumulations and streamflow quite well). We will compare off-line simulations over the pan-Arctic domain using VIC, the UVic 'bucket' and the MOSES land schemes. The objective of this multi-model assessment will be to help us interpret results of early UVic coupled model simulations, that utilize a version of the MOSES land scheme.

The overall goal of this research, to be realised through the development and intercomparison of a hierarchy of land surface models as well as ocean sub-grid parameterisations, is to attempt to quantify changes in the Arctic freshwater budget over the last glacial cycle and hence to understand what changes might be in store over the next century.

C. Vegetation feedbacks on Climate

Funded through a CFCAS grant, we have recently added the Hadley Centre dynamic global vegetation model (TRIFFID — Cox et al. 2000, 2001) to the UVic model 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., 2002), and the other being a simplified one-layer version of the Hadley Centre MOSES land surface scheme. TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) defines the state of the terrestrial biosphere in terms of the soil carbon, and the structure and coverage of five plant functional types (PFT; broadleaf trees needleleaf trees, C3 grass, C4 grass, and shrub) within each model grid box. Vegetation dynamics (areal coverage, leaf area index and canopy height of each PFT) are driven by net primary productivity, which is calculated interactively as a function of climate and CO_2. Carbon fluxes for each of the vegetation types are derived using the coupled photosynthesis-stomatal conductance model developed by Cox et al (1998), which utilises existing models of leaf-level photosynthesis in C3 and C4 plants (Collatz et al 1991; Collatz et al 1992).

Recently, Yoshimori et al (2001) examined the issue of glacial inception at 116 kyr BP in both the UVic ESCM as well as the CCCma AGCM. Initially, we integrated the UVic ESCM under both present-day and 116 kyr BP orbital forcing and atmospheric levels of CO_2. We then integrated the CCCma AGCM with prescribed SSTs and sea ice mask taken from the UVic ESCM. We 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. Our results suggested that the capturing of glacial inception at 116 kyr BP requires the use of *cooler* sea surface conditions than the present. In addition, we showed how feedbacks induced through changes in vegetation type were important in capturing a more realistic representation of glacial inception. 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 was 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 double 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 increases the surface area with perennial snow significantly.

Weaver will integrate the UVic ESCM under 116 kyr radiative forcing to examine whether or not vegetation feedbacks will allow ice sheets to begin to grow (where land ice will be modelled using the Marshall/Clarke thermomechanical model already coupled into the UVic ESCM).

The introduction of a new dynamic vegetation model into the UVic coupled model has set the stage for a sensitivity study as to future changes in terrestrial vegetation as atmospheric carbon dioxide levels increase. Particular focus will be given to the likelihood of expansion of the Boreal forest and prairie regions northwards. Exploratory research will also be conducted to examine means of addressing methane and carbon dioxide feedbacks on climate as permafrost melts in northern tundra regions.

D. Methane Hydrate Instability

Methane hydrates, wherein methane gas is trapped in solid form, are known to occur throughout the world's oceans. Gornitz and Fung (1994) estimate a volumetric range of between 26.4 to 139.1 x 10^{15} m^3 of methane in oceanic gas hydrates, and 0.014 to 34 x 10^{15} m^3 of methane trapped in continental permafrost. Put another way, Hecht (2002) gives the total amount of carbon in the hydrates as about 10,000 gigatonnes, compared with the 750 gigatonnes of carbon that exist in the atmosphere today as carbon dioxide.

The abrupt climate change associated with a catastrophic release of large amounts of methane hydrates is an issue that has never before been looked at in a coupled climate model. Some have hypothesized on an approximate amount of methane release which is dependant on a projected ocean sea level rise or fall, and subsequent deep ocean pressure changes, and also on the accepted theories of methane and hydrate production. According to Gornitz and Fung (1994), a 1° or 2° warming (combined with a 48cm sea level rise [which is likely an overestimate]) would release bacterially-produced methane volumes of 0.93-1.86 x 10^{12} m^3 and 3.16-6.32 x 10^{12} m^3 respectively. Using the alternative theory of the fluid migration methane production, Gornitz and Fung (1994) predict releases of methane volumes of 0.014 x 10^{12} m^3 and 0.047 x 10^{12} m^3 during a 1° or 2° warming, respectively. Acknowledging the date of these estimations, and given the current acceptance of methane production being a combination of these two methods of methane creation, a more accurate estimate would likely involve a combination of these two techniques

The methane gas would be released mainly through gas hydrate dissociation, although small quantities would also be released from the free gas pockets that have been proven to exist throughout the hydrate layer and beneath the hydrate [US Department of Energy, 2003]. The estimated and discovered amounts of free gas are found to be insignificant in comparison to the hydrate deposits, and are commonly disregarded in calculations of triggered methane release.

The possibility of a catastrophic methane release is also thought to have occurred many years ago in the late Paleocene period. Deep-sea thermohaline circulation switching is thought to have resulted in massive gas hydrate dissociation (Kennett et al., 2000). Further evidence has given rise to the possibility that the resulting abrupt climate change occurred over periods of only decades, and not over the supposed long time scales of tens of thousands of years or more (Kennett and Peterson, 2002). Paleoclimate studies of Greenland ice cores revealed the rapidity of these climate changes.

In order to investigate the methane hydrate instability question, a data field will be generated as to the location of all known hydrate deposits. This will then be added to the UVic coupled model and the hydrates will be allowed to melt under changing deep ocean temperatures and pressure. A wide variety of future scenarios of greenhouse gas emissions will be used in an attempt to try and quantify a threshold for methane instability, and to further examine the climatic consequences if such an instability threshold were to be crossed. The experiments will be done both with and without the recently incorporated ocean and terrestrial biosphere carbon cycle model included.

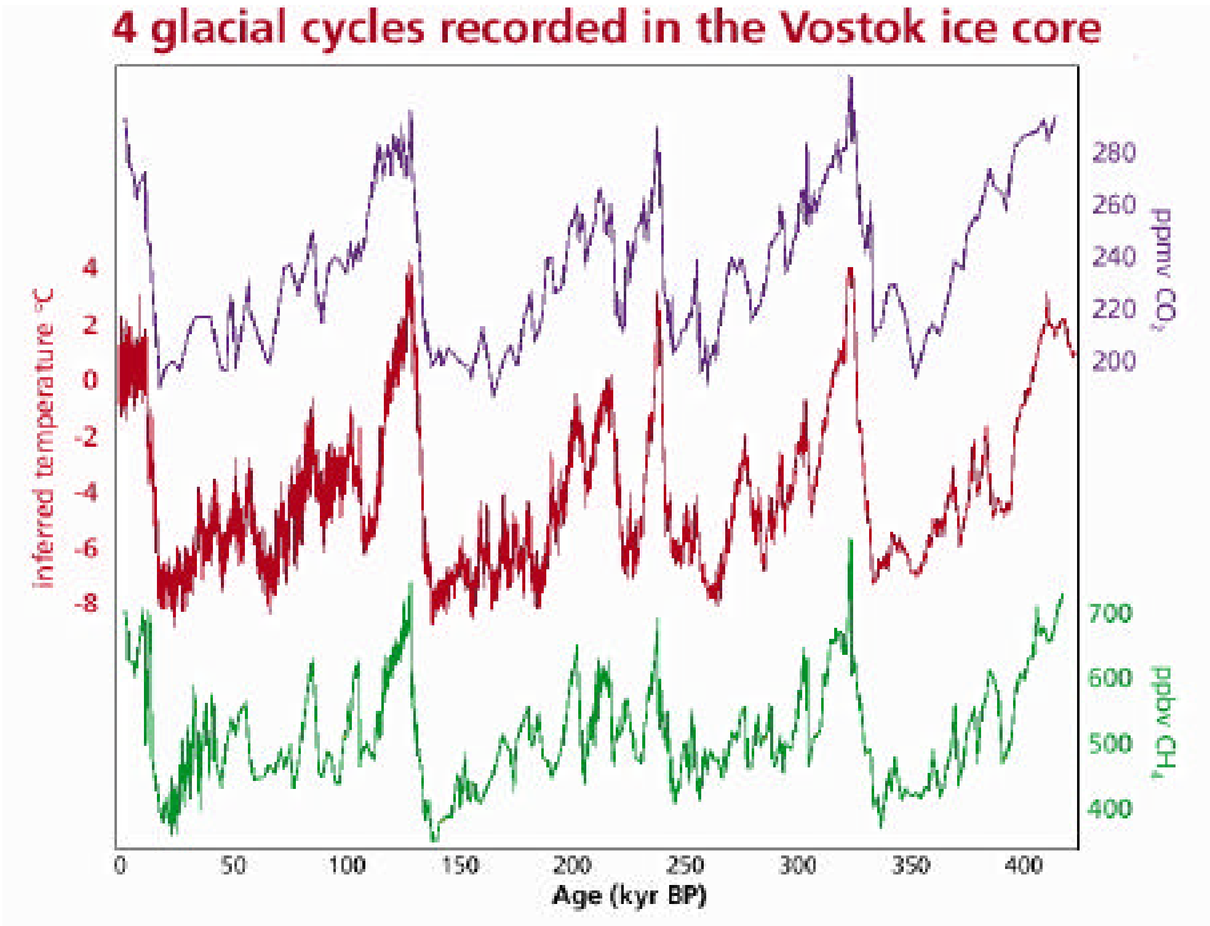

Figure 1: Variations in local Antarctic atmospheric temperature, as derived from oxygen isotope data, as well as concentrations of atmospheric carbon dioxide and methane from Vostok, Antarctica ice core records. The fact that cold climates aren't maintained without a depletion of greenhouse gases, and that warm climates aren't maintained without an excess of these greenhouse gases is evident. Notice also that the current level of atmospheric CO_2 (370 ppm) is >20% larger than at anytime during the last 400,000 years. Similarly, current levels of atmospheric methane CH_4 (1750 ppb) are more than double the maximum value found in the 400,000 year record. Notice also that the increase in CO_2 from 280 ppm to 370 ppm over the last 150 years, primarily due to fossil fuel burning, is about the same as the increase from the depths of the last ice age (21,000 years ago) to 1750 (190 ppm to 280 ppm). Figure redrawn from Petit et al. (1999).

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