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Long Term Climate Change and a Deep Geological Repository in the Canadian Shield: Issues and Analyses

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Abstract

For the past million years of Earth history, the Canadian Shield has experienced a continuous process of glaciation and deglaciation, events that have significantly altered the landscape of the northern half of the North American continent. This sequence of events, ultimately due to small changes in received solar radiation due to the influence of gravitational many body effects upon the earths orbit around the sun, should they continue, constitute an important phenomena with respect to developing an understanding of groundwater flow system evolution in Shield terrain as it may influence the long-term performance of a Deep Geologic Repository for used nuclear fuel. In this paper a description is provided of the University of Toronto Glacial Systems Model, which is being applied to yield geophysically constrained predictions of the last Laurentide (North American) glacial event. In particular, the GSM is providing unique insight into the time rate of change, magnitude and uncertainty of surface boundary conditions and permafrost occurrence at a hypothetical Shield repository site. These predictive estimates of boreal, peri-glacial and ice-sheet history are offering an innovative and reasoned basis to explore flow system characteristics and attributes that govern hydrodynamic and geochemical stability within deep-seated Shield flow domains.

1. Introduction

An issue that immediately arises in connection with the possible development of a repository for spent nuclear fuel in a Canadian Shield setting concerns the safety of the vault in the event of a re-glaciation. Since this region of the Earth's surface has been repeatedly subjected to extreme surface loading by continental ice sheets of maximum thickness 4 km throughout the latter half of the Pleistocene epoch, there is clearly a need to understand the highly time dependent nature of the boundary conditions on the surface of the Earth above a repository that would obtain if this cyclic process of glaciation and deglaciation were to continue. That it would be strongly expected to continue in the absence of the ongoing anthropogenic perturbation to surface climate due to fossil fuel burning should be clear on the basis of the fact that the shield has been re-glaciated approximately every 100,000 years over the past million years of Earth history. It is fortunate for the purpose of assessing the impact that such an event might have upon repository safety that there have been major advances recently in our ability to quantitatively assess the transient variations in surface boundary conditions that such an event would involve, and to assess the degree of non-uniqueness that is inevitably involved in such an assessment.

A series of analyses has been performed in order to provide a detailed assessment of the expected change in boundary conditions as input to detailed regional scale modeling of the impact upon hydrological flow system evolution that such an event would involve. These analyses make use of the University of Toronto Glacial Systems Model that has been developed over the course of the past decade (Deblonde and Peltier 1991,1993; Tarasov and Peltier 1997, 1999, 2002, 2004). The current version of the model includes a 3-dimensional thermo-mechanically coupled ice sheet model, a bed thermal model that extends to a depth of several kilometers and which may be employed to predict the occurrence and evolution of permafrost depth, a sub-glacial till deformation model, a temperature dependent positive degree day mass-balance model with a physical refreezing parameterization, a spherically symmetric visco-elastic isostatic response model and a fast drainage routing solver that may be employed to accurately determine the routing of meltwater to the sea produced during episodes of deglaciation.

A key input to the GSM model concerns the climate forcing that is assumed to operate during the process of ice sheet advance and retreat. In accord with the current state-of-the-art in this area, the Greenland Ice Core Project (GRIP) ice core $\delta^{18}O$ record is used to define the time variation of surface climate (temperature and precipitation) as a means to interpolate between a glacial maximum climate determined by an average of an ensemble of the highest resolution subset of the models developed in the context of the international Paleoclimate Modelling Intercomparison Project (PMIP) collaboration, and a modern climate determined on the basis of the National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) reanalysis project. Because the millennial scale variations of the extent of glacial cooling revealed in the GRIP core are expected to be of at least hemispheric scale, it is expected that this methodology should deliver a reasonable approximation to the climate variability that actually forces the advances and retreats of glacial ice.

A crucial aspect of the analyses that have been performed has involved the computational apparatus designed to aid in the assessment of the uniqueness of the time dependent boundary conditions that are inferred on the basis of the GSM model. This aspect of the analysis involves an extensive Bayesian calibration of the model against a wide range of the constraints that may be invoked to ensure that the model accurately reproduces, within observational error, the variations in observables that characterize the aftermath of the most recent glacial cycle. Because the model is expensive to run, a neural network which may be employed to emulate the statistics that it generates has also been developed with which it has been possible to extensively probe the phase space of solutions to the nonlinear problem of ice sheet advance and retreat so as to ensure that predictions are not trapped in a local and non-physical equilibrium. Using this apparatus it is possible to provide a rigorous assessment of the issue of non-uniqueness which is clearly critical in demonstrating confidence in predictive model results.

In the remainder of this paper to follow I will first provide a cursory review of the mathematical structure of the model that is being employed as basis for determination of the surface boundary conditions that will influence the hydrogeological environment experienced by a subsurface repository (Section 2). In Section 3 I provide a number of examples of the results that have been obtained, including an assessment of the evolution of permafrost depth through a typical glacial cycle, and the time dependence of the normal stress due to the thickness of continental ice that would be expected to over-ride a representative site during a next glacial episode. The expected time variation of surface temperature is also discussed. Conclusions are presented in Section 4.

2. The University of Toronto Glacial Systems Model

Although the detailed characteristics of this model have been previously reviewed at length in the course of developing the apparatus required for the nuclear repository safety application (Peltier 2002, 2003, 2004b), it will be useful for completeness sake to discuss this structure briefly here. The key components of the structure are described in the sub-sections to follow.

2.1 The evolution equation for continental ice thickness

Vertical integration of the equation of continuity for ice substance delivers the standard nonlinear diffusion equation for the evolution of ice thickness in the "shallow ice approximation" as:

$$\frac{\partial H}{\partial t} = \nabla_h \bullet \left[2A(T)(\rho_i g)^m H^{m+2} (\nabla_h h \bullet \nabla_h h)^{(m-1)/2} \nabla_h h \right] + G(r, t) \qquad (1)$$

In equation (1) "H" is the ice thickness, A(T) is the temperature dependent factor that accounts for the thermally activated nature of the creep process in ice, "h" is the height of the surface of the ice sheet above sea level, "m" is the power law exponent in the relationship between the differential stress acting within the volume of the ice and the strain rate thereby induced, and G is the mass balance function that determines the local rates of accumulation and ablation that act locally so as to cause the ice sheet to grow or to decay.

2.2 The evolution equation for the temperature of the ice

Since the horizontal advection of heat with the evolving ice sheet strongly dominates the process of horizontal diffusion, we may accurately compute the evolution of the temperature field within the ice sheet by solving the following simple advection-diffusion equation:

$$\rho_i C(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[k(T) \frac{\partial T}{\partial z} \right] - \rho_i C(T) V \bullet \nabla T + Q_d \qquad (2)$$

In equation (2) as in (1) "T" is the absolute temperature, r_i is the density of the ice, C(T) is the temperature dependent heat capacity, k(T) is the temperature dependent thermal conductivity, V is the vector ice velocity and Q_d is the heating due to ice deformation. This evolution equation for the temperature field within the ice is solved subject to boundary conditions on the temperature at the surface of the evolving ice mass delivered by a model of climate evolution, and at the base of the evolving ice mass determined by the specification of a spatial distribution of the heat flow into the base of the ice mass from the deep interior of the Earth.

2.3 The evolution equation for the vertical deflection of the surface of the solid Earth in response to ice sheet loading and unloading

During a typical glacial cycle the timescale over which the surface load is applied is sufficiently long that the "solid" mantle of the Earth responds to the surface load in a visco-elastic fashion. The viscous component of the response is such that approximately 2/3 of the total response is accommodated by this essentially fluid behaviour. In the current version of the UofT Glacial Systems Model this visco-elastic component of the response is computed using the full theory of this process most recently reviewed in Peltier (1998). In this theory the time dependent vertical deflection of the surface of the solid Earth is expressed in the form of the following three dimensional convolution integral, in which "R" is the time dependent radial displacement, "L" is the surface mass load per unit area and Γ is the visco-elastic radial displacement Green function (Peltier, 1974) in which γ is the angular separation between the "source point" with co-ordinates (θ', φ') and a "field point" with co-ordinates (θ, φ):

$$R(\theta, \phi, t) = \int_{-\infty}^{t} dt' \iint_{\Omega} L(\theta', \phi', t')\, \Gamma(\gamma, t - t')\, d\Omega' \tag{3}$$

There is a subtlety in this representation of the response of the solid Earth to the glaciation-deglaciation process because the surface load is a composite of a part associated with the time dependence of ice thickness and a part associated with the time dependence of ocean bathymetry. These two parts of the composite surface load are linked by the requirement that the net surface load must be mass conserving such that when ice melts, for example, the mass of water that is added to the ocean basins is precisely equal at all times to the mass of melted ice. The composite structure of the surface mass load is expressed in the expansion:

$$L(\theta, \phi, t) = \rho_I I(\theta, \phi, t) + \rho_w S(\theta, \phi, t) \tag{4}$$

in which "I" is the space and time dependent ice thickness and "S" is the space and time dependent "relative" sea level, that is the change in the level of the sea relative to the deforming local radius of the solid Earth. The field "S" must be determined by solving an integral equation that is discussed at length in the review paper of Peltier (1998). No purpose will be served by recounting the detailed mathematical methods that have been developed to solve this equation here.

3. Results of Analyses Performed in Support of Repository Safety Assessment

In Figure 1, I show a sequence of time slices in the calculation of the evolving thickness of the Laurentide Ice Sheet (LIS) from an illustrative model of a typical 100,000 year cycle of glaciation and deglaciation, one that has been strongly constrained so as to enable the model to reconcile the geophysical, geological and geodetic data that may be brought to bear on the problem. The time slices shown are those for the deglaciation phase of the cycle that began approximately 20,000 years ago. The data employed to constrain the calculation include ^{14}C dated relative sea level histories, ice margin positions as a function of time through the deglaciation phase of the ice age cycle, and geodetic observations of the present day rates of vertical motion of the land based upon absolute gravity measurements or measurements based upon the application of Very Long Baseline Radio-Interferometry (VLBI). Also shown on this Figure are the predicted locations of the pro-glacial lakes that are known to have formed during the retreat phase of the ice-age cycle. It is a characteristic of all such models of the process that fit the totality of the available data (e.g. Peltier, 2004a) that the present Hudson Bay is a local minimum of ice thickness at the Last Glacial Maximum (LGM) 21,000 years before present. This is a consequence of the continuous action of the Hudson Strait Ice Stream during the glacial period, a feature of the LIS that acted so as to “draw down” the maximum in thickness over this region that would otherwise form.

Figure 2 shows time series of the history of North American continental ice volume variations from this and a series of comparable models constructed so as to approximately span the space of allowed solutions to this complex problem (see Tarasov and Peltier, 2004 for detailed discussion). The individual time series in this set are expressed in terms of the eustatic history of sea level that would be caused by the evolution of this continent scale ice mass. Inspection of these time series demonstrates that of the total eustatic rise of sea level of approximately 120 m that occurred across the most recent glacial interglacial transition (e.g. Shackleton, 2000), approximately 80 m or 2/3 of the total was derivative of the collapse of the LIS.

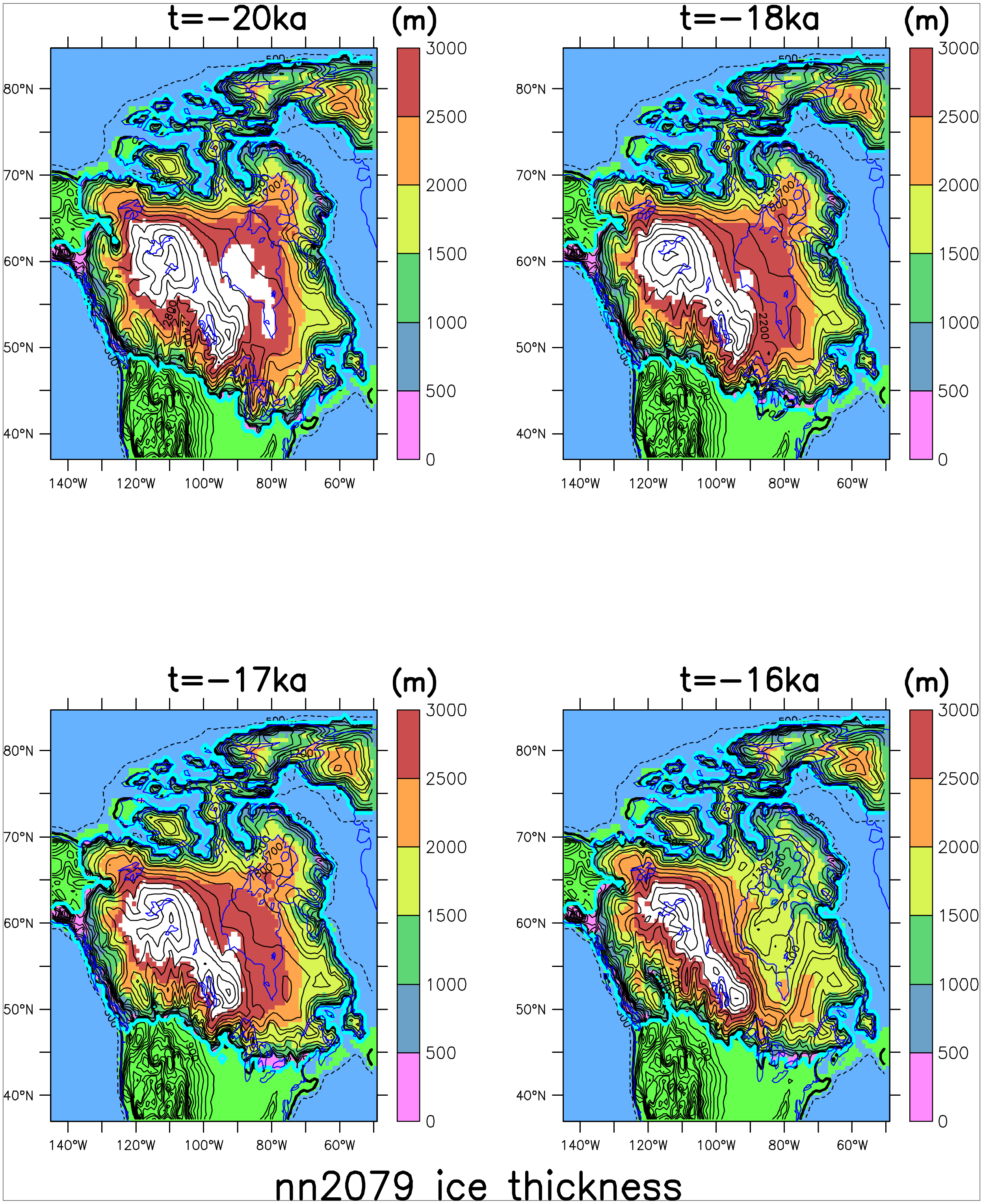

Figure 1: Deglaciation chronology and meltback sequence for the high velocity model from the ensemble that best fits the totality of the observational data over the time interval from 20,000 calendar years before present and 8,000 calendar years before present. The Figure also shows the time dependent ice-thickness, as well as the pro-glacial region that is expected to be water covered during the retreat phase.

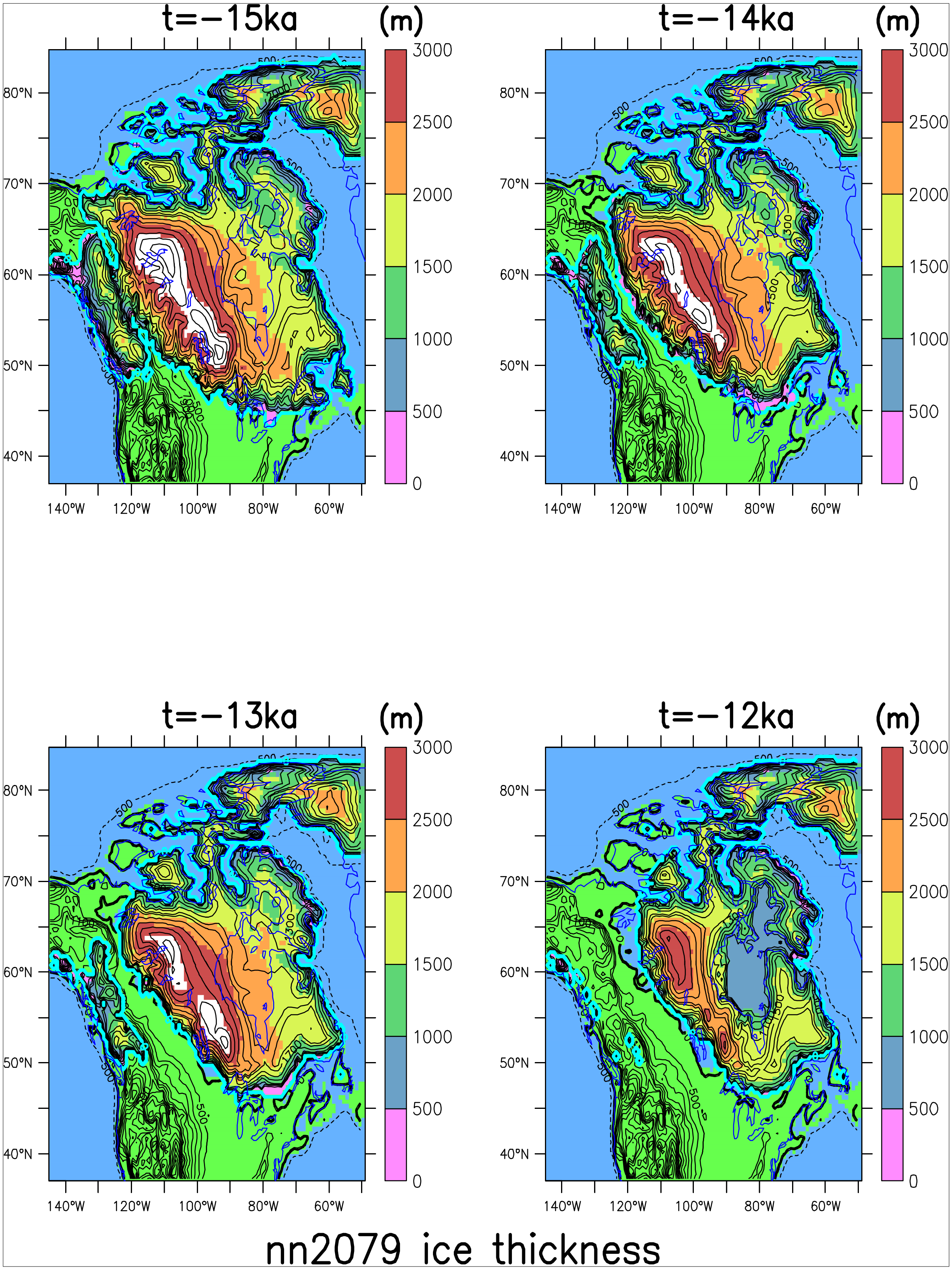

Figure 1: *Continued.*

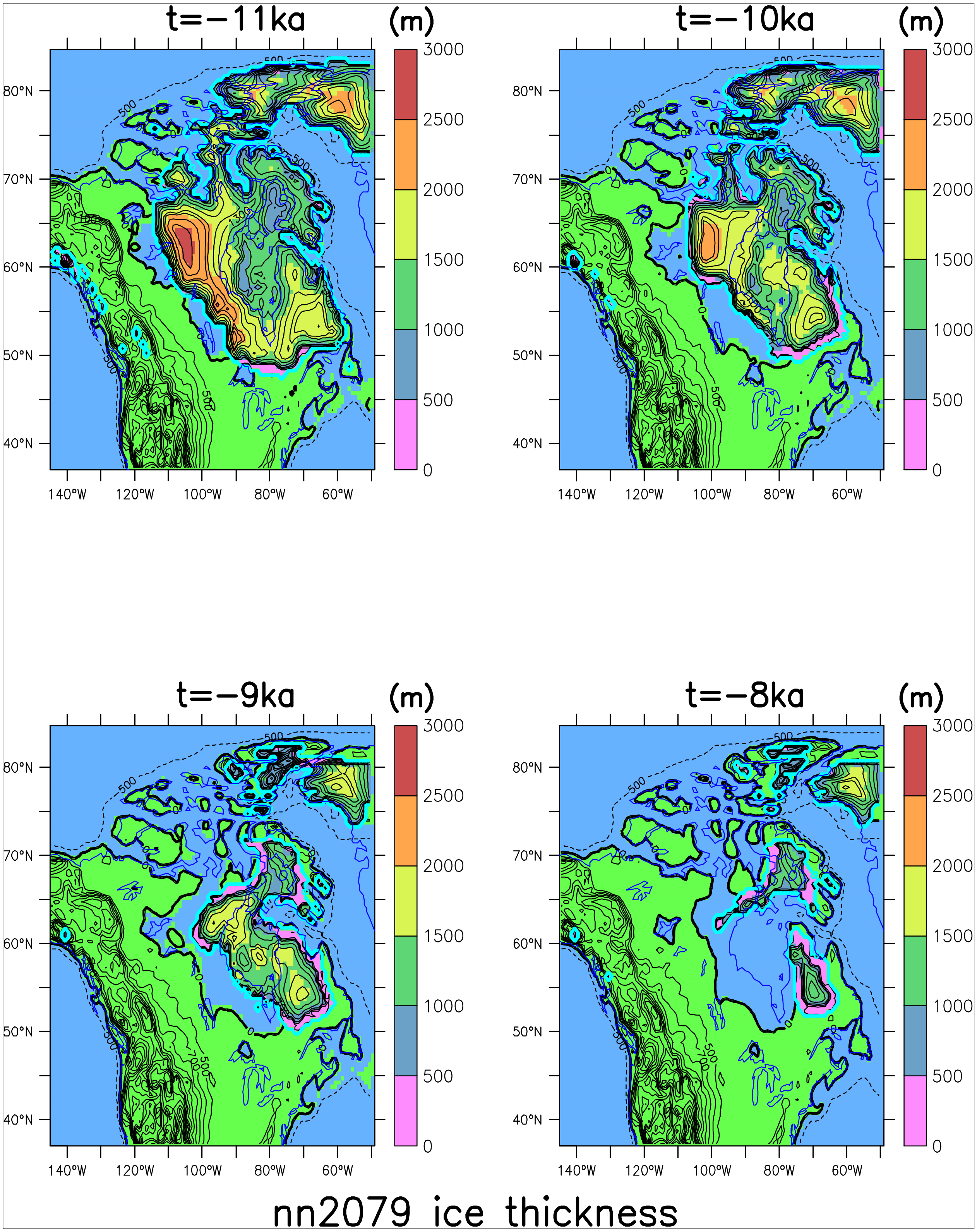

Figure 1: *Continued.*

Of particular interest from the perspective of Shield flow system evolution and long-term repository performance is the time dependent depth and areal extent of permafrost that would have existed during the cycle of glaciation and deglaciation. The GSM is designed to make rather accurate predictions of this sub-surface manifestation of glacial advance and retreat when sufficiently high vertical spatial resolution is employed to describe the subsurface thermal regime. Figure 3 shows a sequence of maps of the predicted thickness of permafrost on the North American continent as a function of time through the glacial cycle. Notable is the fact that during the inception phase of the cycle during which the LIS is expanding there is predicted to exist an extensive "halo" of permafrost surrounding the advancing ice sheet. Under the ice sheet itself, however, the surface of the Earth is predicted to be at or very close to the pressure melting point of the overlying ice, a consequence of the insolating effect of the ice sheet which acts so as to trap the heat flowing into the base of the ice sheet from the solid Earth. The quality of these predictions of the model may be assessed by comparing the present day permafrost depth predictions to field observations over the continent, a test that the model passes with reasonable accuracy especially considering that permafrost depth has been approximated simply as the depth to the zero degree Centigrade isotherm, thereby neglecting the impact that might be expected due to the finite salinity of pore waters. It has also proven possible to test the quality of this prediction of the model for times other than the present by making use of ground surface temperature inferences for earlier times derived from the formal inversion of borehole temperature records (e.g. Rolandone et al., 2003). Their inferences of surface temperature for LGM at several sites in Manitoba and Quebec are also in close accord with the predictions of the GSM.

As a final series of examples of the analyses being performed with the GSM, I show in Figure 4 the results of a number of relevant time series for a representative Ontario shield location. In Figure 4a, the normal stress (MPa) at the site due to ice loading is shown as a function of time during the 100 kyr cycle of glaciation and deglaciation. Inspection will make clear the fact that at this site, for this particular model, the location is overrun by ice advance in three primary phases, the final phase of advance being the one in which the ice reaches its greatest thickness.

Figure 4b shows the history of the evolution of surface temperature at the site which suggests that permafrost conditions would have prevailed at all times prior to the final deglaciation of the site except for the two periods of thickest ice cover that occurred at approximately 60,000 years ago and at LGM 21,000 years ago. At these latter times the ice cover is predicted to have been sufficiently thick that the insolation effect worked in such a way as to raise the temperature of the base of the ice sheet to a value close to the pressure melting point. On each of Figures 4a and 4b the multiplicity of curves shown differ from one another only to the degree that the climate forcing employed to drive the development of the ice sheet model has been smoothed from the direct result obtained by using the oxygen isotope record of the GRIP ice core from Summit, Greenland to provide time control on the general circulation model derived climate fields. It is the results for the 3 kyr smoothed fields that I believe to be the most accurate. The result presented on Figure 4c shows the time series of local meltwater production at the site and this is seen to become significant only during the final deglaciation phase of the cycle for this particular model of the glaciation-deglaciation process. Figure 4d shows the evolution of subsurface temperature at the site as a function of time, a result that implies permafrost conditions to prevail for much of the glacial cycle. Other data equally useful and important insofar as inputs to the modeling of the groundwater flow regime consist of the time series of the components of ice velocity. In the interest of space these additional results will not be detailed here.

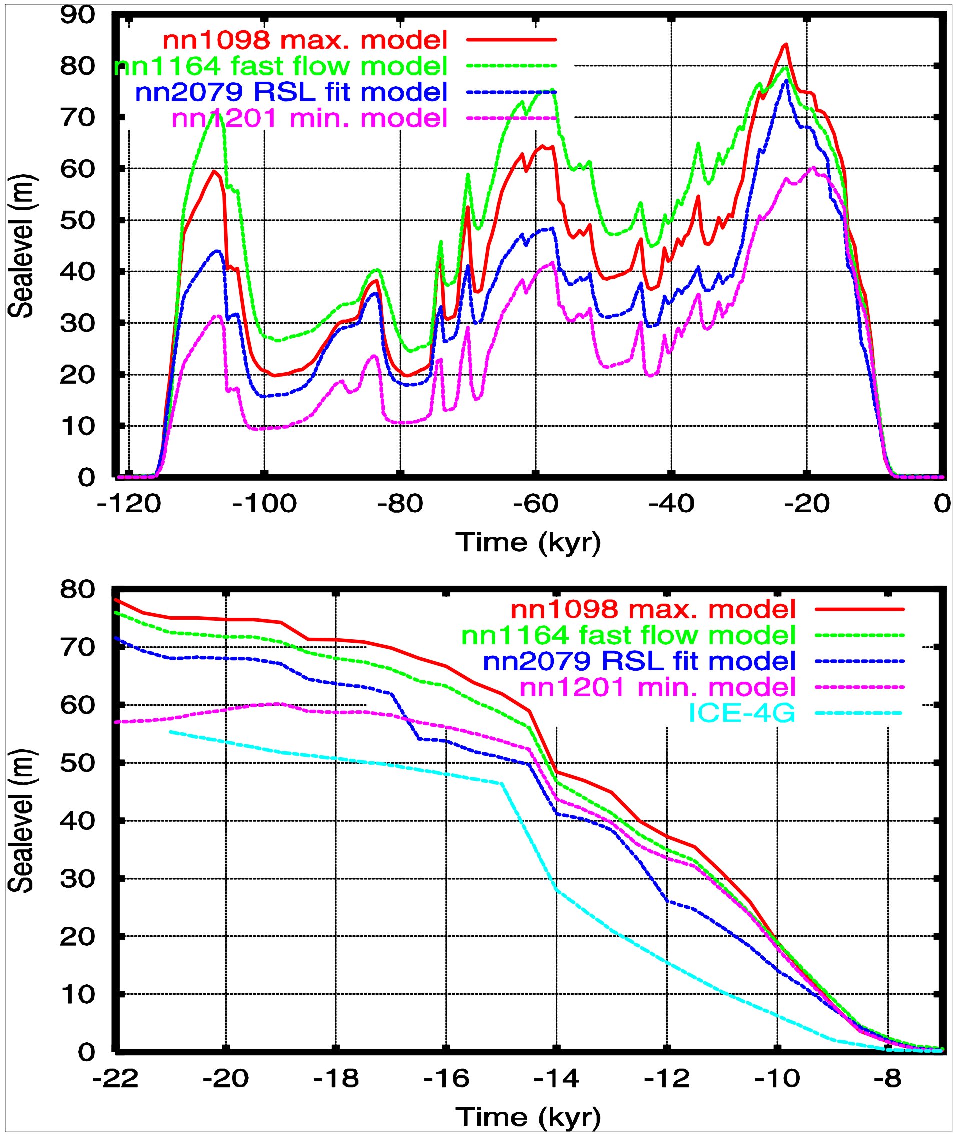

Figure 2: (top) Variation of eustatic sea level equivalent variation of the mass of the North American ice sheet complex as a function of time beginning at the time of glacial inception and continuing through the deglaciation event. (bottom) blow-up of the deglaciation portion of the complete time series shown in the top frame, superimposed upon which is the equivalent result for the ICE-4G (VM2). Results are shown for four models that appear, on the basis of the large ensemble analysis, to extend over the range of uncertainty of models that adequately reconcile the observations. These include a maximum LGM volume model, a model characterized by the greatest impact of fast flow, a minimum volume model and a model that best fits the RSL constraints.

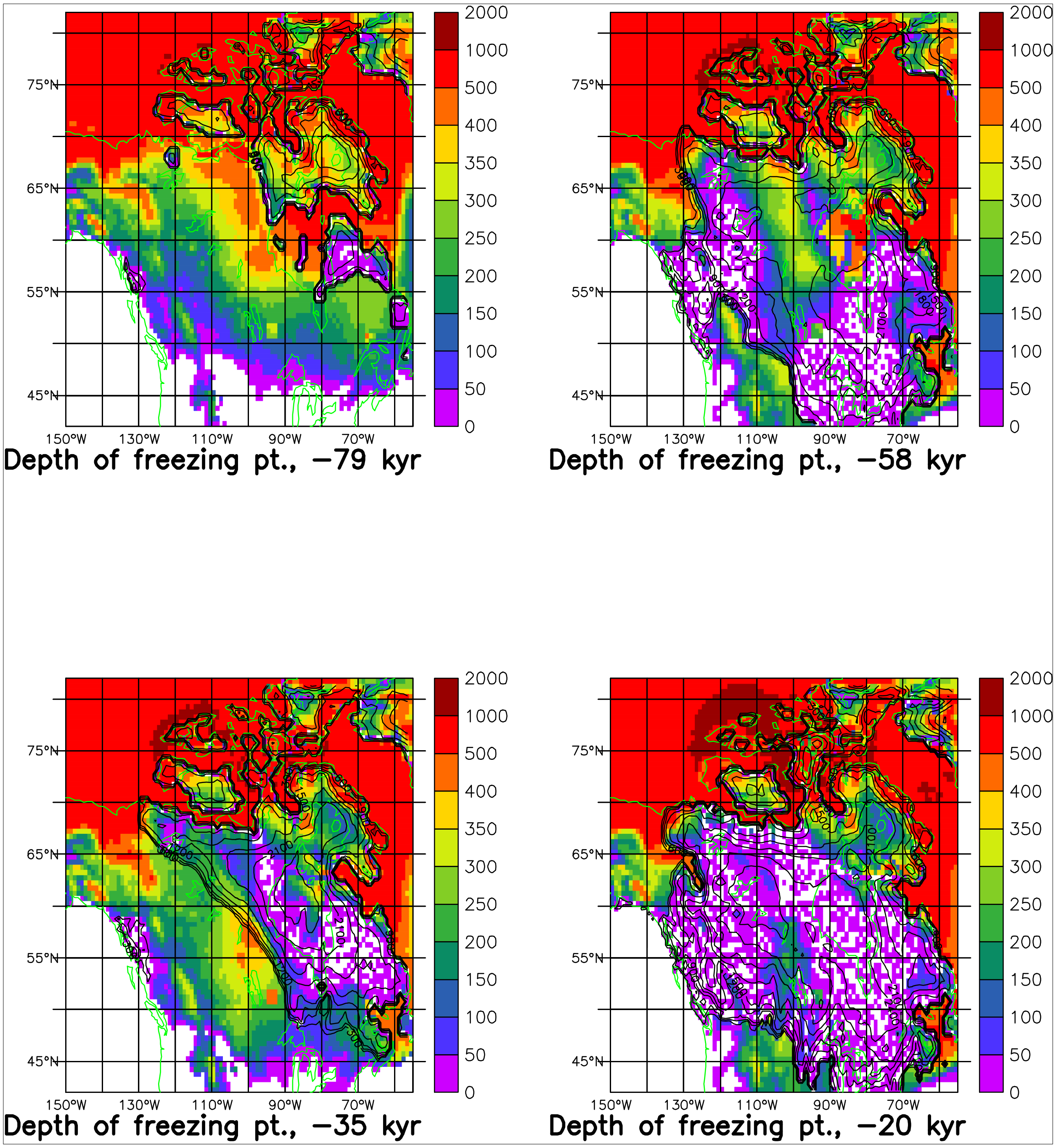

Figure 3: Permafrost depth as a function of time over the entire North American continent from a typical version of the 100 kyr ice-age cycle as represented by the University of Toronto Glacial Systems Model. The colour bars represents depth of penetration of permafrost in metres.

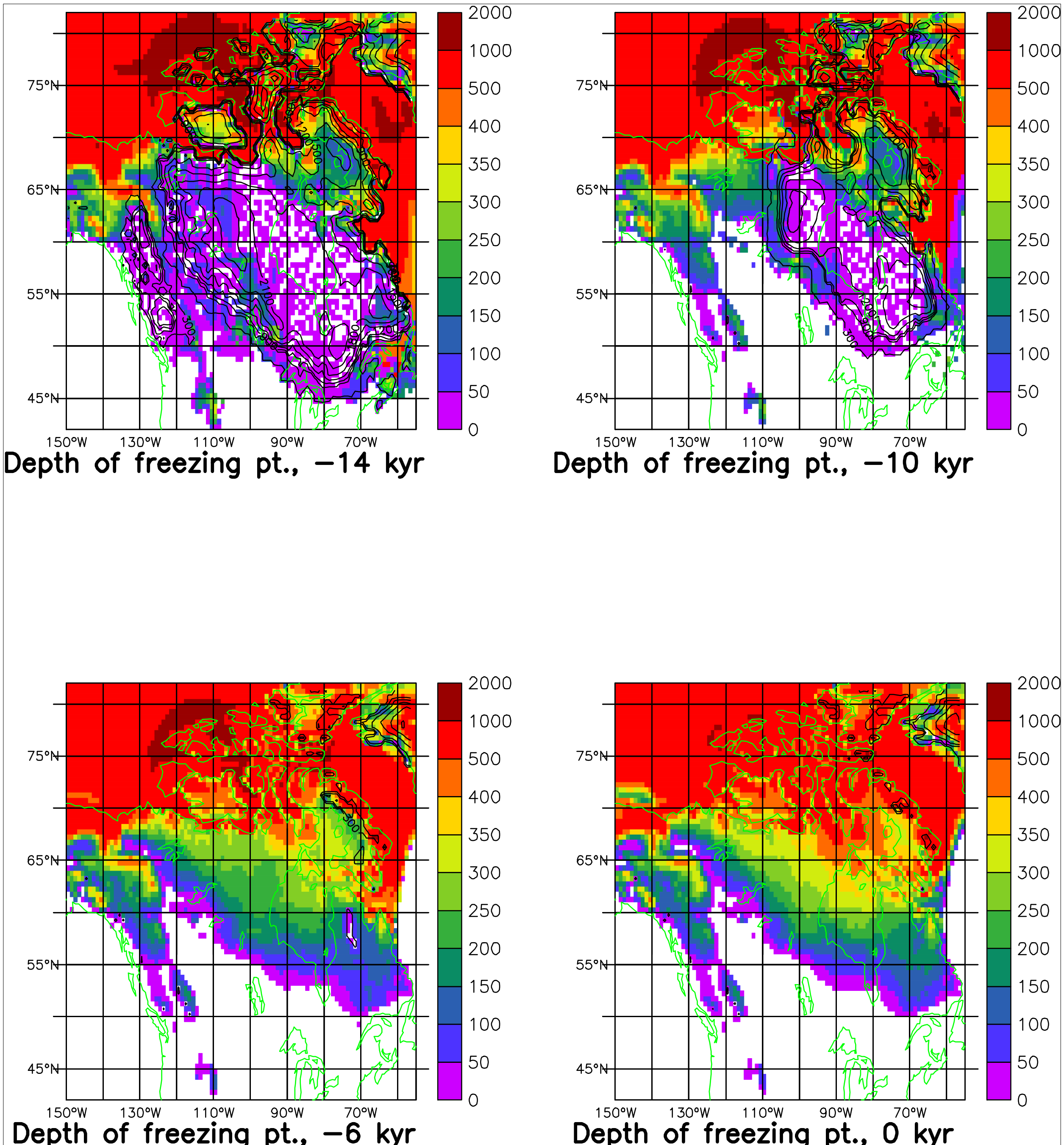

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Figure 3: Continued

4. Summary and Conclusions

A detailed model of long timescale climate change has been developed, the University of Toronto Glacial Systems Model, which is yielding geophysically constrained predictions of the process of continental glaciation and deglaciation that has occurred in the past due to the small changes in the effective intensity of the Sun on the Earth. This model is being applied to develop a reasoned geoscientific basis that conveys an understanding of the magnitude and rate of change in surface boundary conditions (i.e. temperature; normal stress (ice thickness); permafrost) likely to have affected, and to affect, a representative crystalline Canadian Shield site. This understanding is providing a more comprehensive basis with which to explore issues of Shield flow system hydrodynamic and geochemical stability as it relates to the long-term performance of a hypothetical Deep Geologic Repository for nuclear used fuel. In so doing it is contributing to an improved knowledge of site-specific factors that influence or govern the evolution of crystalline Shield groundwater flow domains and, hence, the development of a DGR Safety Case.

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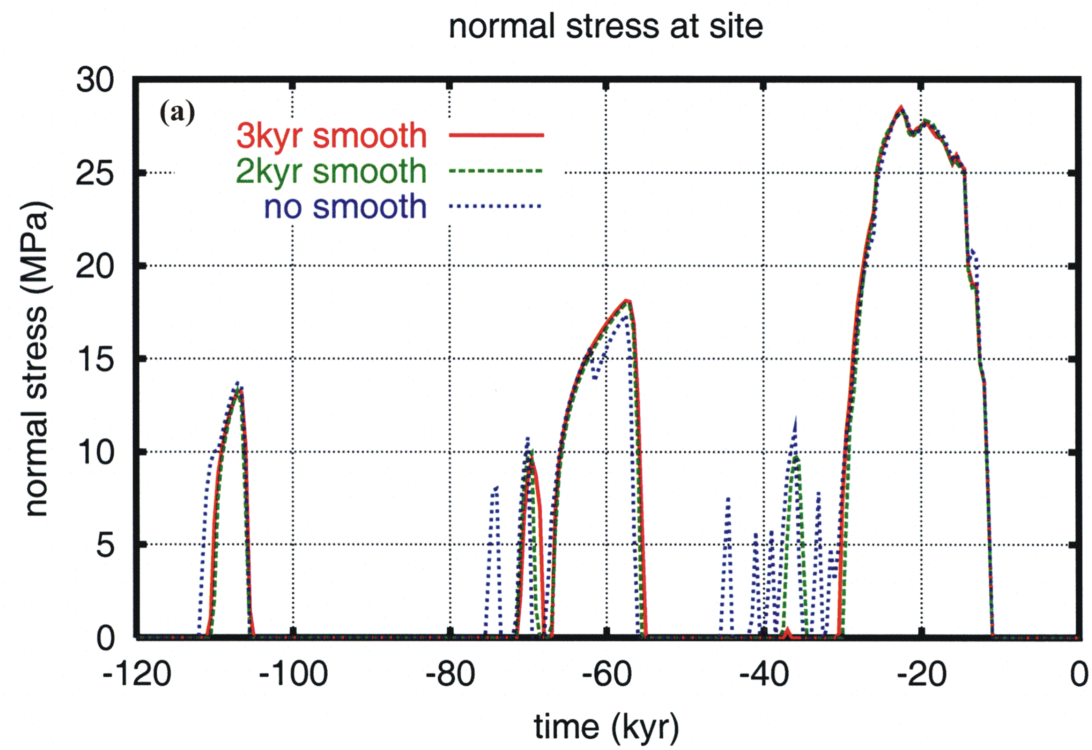

Figure 4a. Time evolution of the normal stress on the surface of the Earth during one model realization of a 100 kyr cycle of ice sheet advance and retreat. The three different time series shown have been produced by applying various degrees of smoothing to the GRIP ice core d^{18}0 time series employed to control the temporal evolution of surface climate.

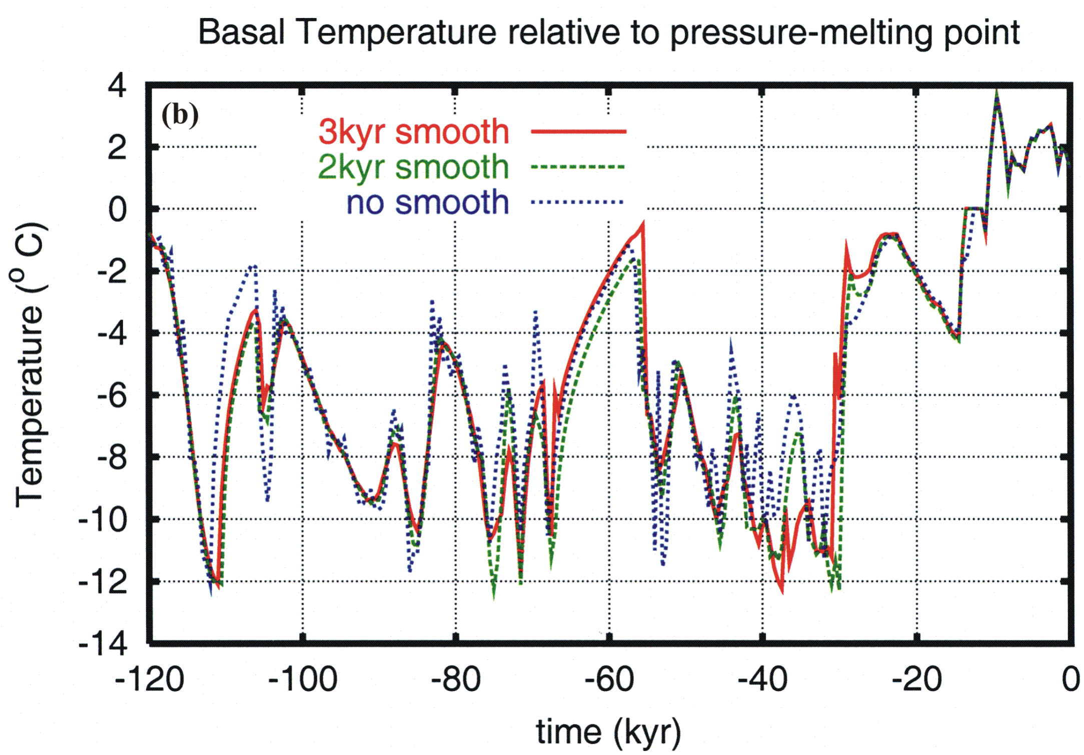

Figure 4b. Same as for Figure 4a but for the evolution of the temperature at the surface of the Earth

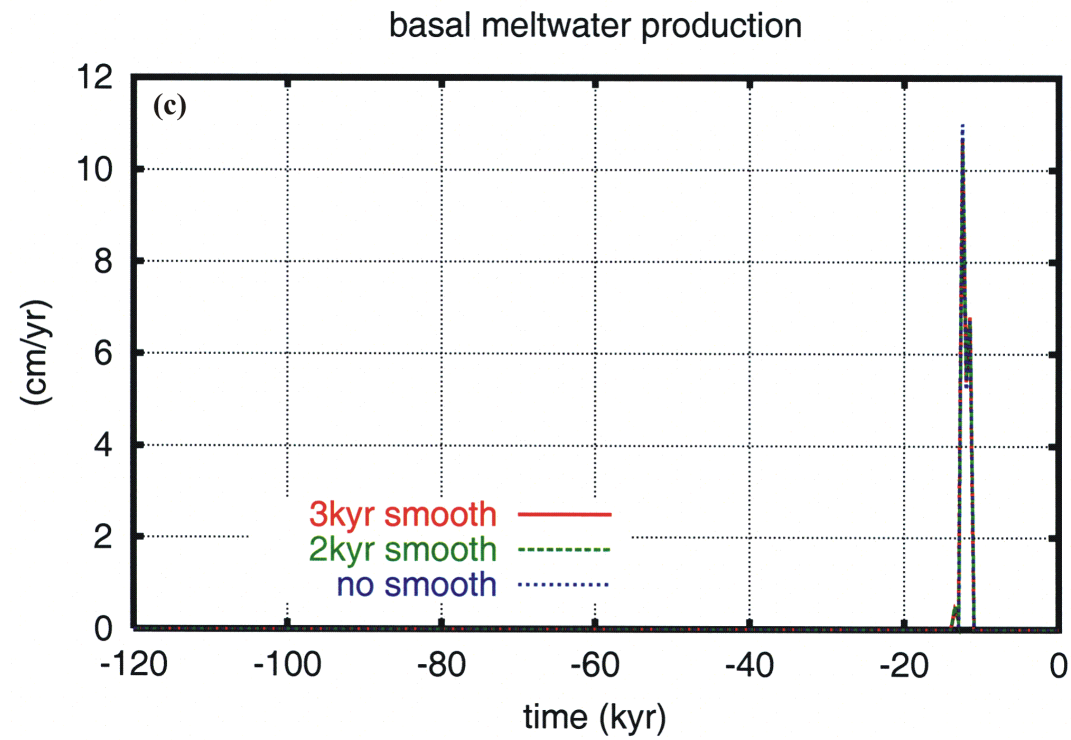

Figure 4c. Same as for Figure 4a but for the rate of meltwater production at the base of the ice sheet.

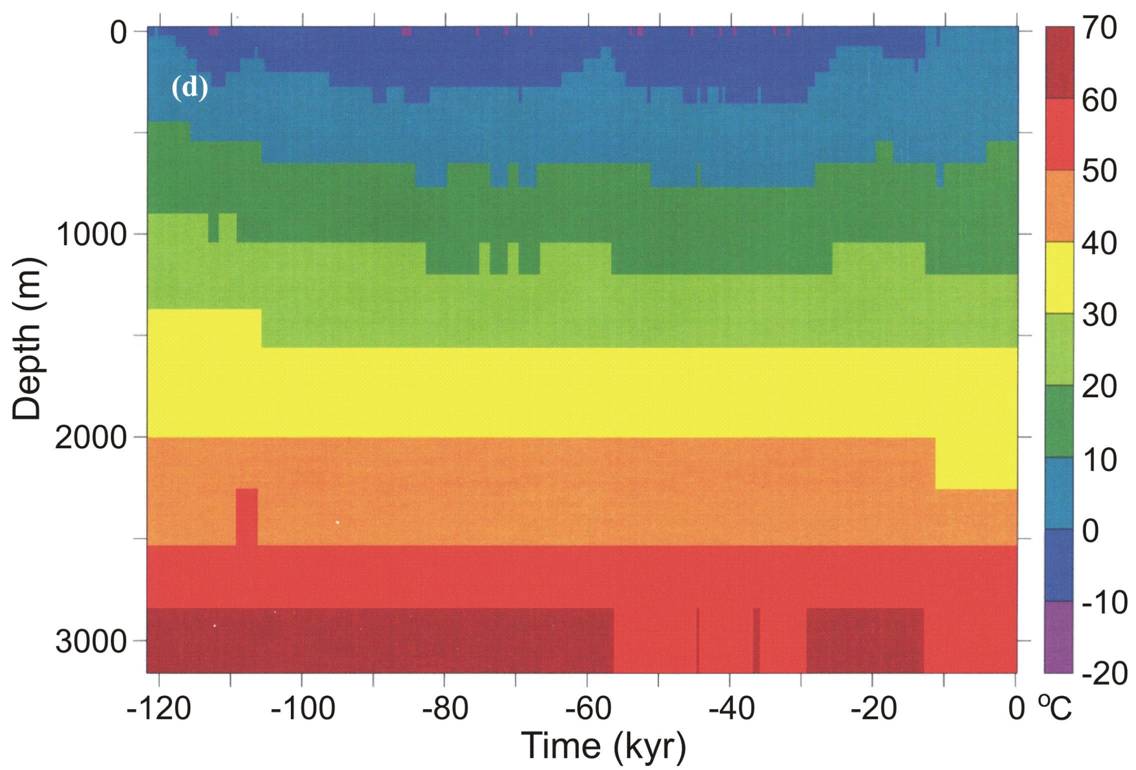

Figure 4d. Depth-Time plot of the evolution of subsurface temperature at a representative repository site.