

the lattice solid model has been implemented. In order to guarantee portability over a wide range of computer architectures, a message passing approach based on MPI has been used in the implementation. Particular care has been taken to eliminate serial bottlenecks in the program, thus ensuring high scalability on systems with a large number of CPUs. Measures taken to achieve this objective include the use of asynchronous communication between the parallel processes and the minimization of communication with and work done by a central "master" process.

Benchmarks using models with up to 6 million particles on a parallel computer with 128 CPUs show that the program can achieve a high parallel efficiency. This makes it feasible to simulate multi-million particle models in a relatively short amount of time, enabling a step forward towards more realistic simulations.

- [1] <http://www.quakes.uq.edu.au/ACCESS/>
 [2] <http://www.es.jamstec.go.jp/>

U41A-0005 0830h POSTER

The Rotation of Non-rigid Earth

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The rotation of a deformable, energy-generating and dissipative Earth is much more complex than the rotation of a biaxial rigid body of revolution can represent. A review of the perturbation scheme for the generalized Eulerian equation of motion or the Liouville equation reveals that: (1) the reference frame needs to be physically located in the Earth, unique, consistent with observation, and always associated with polar motion; (2) relative angular momentum represents the perturbation in the Earth, which includes both motion and mass redistribution; (3) the instantaneous figure axis around which the rotation axis physically wobbles is not the Earth's principal axis; (4) the Chandler wobble is not of single frequency, but has multiple frequencies and is quasi-permanent; (5) the Earth's rotation after polar excitation is unstable; (6) the Earth in unstable rotation is axially near-symmetrical and slightly triaxial even if it was originally biaxial; and (7) the Earth can reach its stable rotation only after its rotation, principal, and instantaneous figure axis are completely aligned with each other to arrive at the minimum energy configuration of the system.

U41A-0006 0830h POSTER

A coupled method of spectral elements and modal solutions for seismic forward modeling in realistic D" layer models.

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The D" structure is believed to hold the key to many largely unanswered questions in deep Earth geodynamics and its study can be efficiently addressed by seismological forward modeling approaches. However, present global waveform modeling (based on normal mode perturbation or ray tracing) cannot handle wave propagation in this region due to the association of high velocity contrasts and diffraction, presence of topography on a solid-liquid interface, anisotropy, and also the need of high frequency simulations at the global scale (at least 0.1 Hz). To fill this gap, we have developed an extension of the coupled method of spectral elements and a modal solution (Capdeville et al., 2001) allowing us to use a relatively thin layer of spectral elements to represent a 3D D" layer model, "sandwiched" between two modal solutions for the rest of the Earth, assumed spherically symmetric.

The Spectral Element Method (SEM) is a high-order variational method that combines the geometrical flexibility of finite element methods together with the precision of pseudo-spectral methods. The SEM has been shown by different authors to provide an accurate solution to most of difficult 3D problems. However, when dealing with Earth models that are not fully 3D, the drawback of using the SEM is an unnecessary increase in both computer memory and CPU time, thus limiting the applications to long-period simulations. The coupled method presented here circumvents this problem by limiting the use of the SEM to only a small part of the Earth allowing higher frequency simulations. The coupling is performed using two Dirichlet to Neumann (DtN) operators, one on each interface. DtN operators are constructed in the frequency-spectral domain using modal solutions in the spherically symmetric sphere and spherical shell.

Using this new method, we are able to perform simulations in D" up to 0.1Hz on parallel computers of reasonable size and in time short enough to be suitable for forward modelling of specific S waveform profiles of interest.

Results of preliminary forward modelling of real data in realistic 3D D" models will be presented.

Capdeville Y, et al (2001). Coupling Spectral Elements and Modal Solution etc. submitted to Geophys. J. Int.

U41A-0007 0830h POSTER

A local grid refinement approach for the lithosphere and upper mantle in 3-D spherical mantle convection models

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High resolution mantle convection models have made great progress over the past years owing in large part to the rapid increase in computational resources. However, fully resolving Earth's upper thermal boundary layer, the lithosphere, in 3-D spherical convection simulations is still beyond the reach of even the most powerful supercomputers currently available.

Here we address the problem using the 3-D spherical mantle convection code TERRA. Applying a non-uniform computational grid with local mesh refinements concentrated into the lithosphere and the upper mantle, we are able to achieve grid point resolutions of less than 20 km in the low viscosity upper mantle allowing us to model highly vigorous mantle convection at Rayleigh numbers exceeding 10⁹. Our non-uniform mesh implementation also allows a drastic reduction in computational cost, which is decreased by an order of magnitude compared to convection models having a uniform grid point resolution throughout the mantle. We will show basic numerical calculations performed at Rayleigh number 10⁹ that exhibit Earth-like surface velocities and Nusselt number.

U41B MC: 134 Thursday 0830h

The Science of Abrupt Climate Change and the Implications for Public Policy I

Presiding: R. Alley, Pennsylvania State University; A R Isern, National Science Foundation

U41B-01 0830h

Abrupt Climate Change: Overview

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Paleoclimatic records show that large, rapid, widespread climate changes have occurred repeatedly. Thresholds and feedbacks in the Earth system impart abruptness and persistence, so it is likely that abrupt climate changes will occur in the future. A new National Research Council study of abrupt climate changes, sponsored by the U.S. Global Change Research Program, highlights the strong evidence for abruptness in past climate changes, regionally as well as globally and affecting water and other climatic variables in addition to temperature. Our understanding of mechanisms identifies many key areas and climate variables involved in abrupt changes, but does not provide predictive capability beyond the realization that further abrupt changes are likely. Abruptness increases the impacts of climate changes on societies and ecosystems. A targeted research program of paleo- and modern studies of climate change and impacts, including analysis of mechanisms and improved statistical characterization, would significantly increase understanding of abrupt changes and allow improved recommendations of mitigation or adaptation strategies.

U41B-02 0845h

Cholera, Climate and Complexity

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There is no abstract available for this presentation.

U41B-03 0905h INVITED

The Conveyor Fights Back

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Recent modeling efforts by Seager and by Battisti suggest that it is not the Atlantic conveyor which keeps northern Europe warm but rather the global air-flow pattern. If correct, does this finding knock the conveyor out of contention as the trigger for the abrupt climate changes recorded in the Greenland ice cores? I contend that it does not. In fact, this new modeling result eliminates one of a stumbling blocks namely observation that snowline lowerings for at 40°S were similar to those at for 40°N. It does, however, leave wide open the question as to how changes in ocean circulation create such profound impacts on continental climate.

U41B-04 0925h INVITED

Abrupt Climate Change and the Thermohaline Circulation: Concepts and Observations

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The ocean's thermohaline circulation (THC) consists of cooling-induced deep convection and sinking at high latitudes, upwelling at lower latitudes, and the horizontal currents feeding the vertical flows. In the North Atlantic, where most of the deep sinking occurs, the THC is responsible for the unusually strong northward heat transport, which results in the relative mildness of western European climate. Abrupt changes in the THC are a plausible cause of observed past climate changes and might occur again in the future. Climate models have demonstrated the possibility that globally rising temperatures will cause increased rainfall in high latitudes, disrupting deep convection and the THC. But the extant models differ widely in their estimates of current and future THC strength.

I will first use a very simple conceptual model to show why, at present, it is impossible to tell whether a temporary increase in greenhouse gases will lead to a temporary or a permanent change in the THC. The cause of the uncertainty is the role of the wind-driven circulation in transporting freshwater in the ocean; this effect is represented poorly in present climate models. Next, I will outline the dynamical ideas behind, and current planning work toward, efforts to observe the Atlantic THC on a continuous basis. Such monitoring will be a prerequisite for the ultimate goal of predicting THC variability.

U41B-05 0940h

A Discussion of Mechanisms Responsible for Abrupt Climate Change

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On millennial time scales, the paleodata suggests marked variability in the climate of Europe and Northern Africa that appears to be concomitant with changes in the strength of the thermohaline circulation in the N. Atlantic. Indeed, it has been suggested that the Little Ice Age and the Medieval warm period were the most recent manifestations of the extremes of this millennial-scale thermohaline-climate oscillation, and that this "mode" of climate variability extends throughout the majority of Northern Hemisphere and, perhaps, the globe. During glacial epochs, the global extent of these climate excursions is unambiguous and the climate changes are large in amplitude and often abrupt in time.

The leading hypothesis for the millennial-scale thermohaline-climate "mode" invokes a switch in the overturning circulation in the (N. Atlantic) ocean, say from "on" to nearly-off, which then causes an abrupt, large cooling over the whole northern hemisphere; the millennial time scales come from the adjustment time of the global ocean.

In this talk I will present observations and calculations that suggests the overturning circulation in the N. Atlantic today has only a modest effect on the winter-time climate of Europe, and an even smaller effect elsewhere. Our results, when applied to the conventional view of the millennial scale climate variability, suggests that the ocean thermohaline circulation changes may be a response to the abrupt climate change, rather than a driver. In support of this view, calculations will be presented that illustrate the potency for small changes in the tropics as the driver of large, abrupt global climate changes during glacial times.

U41B-06 0955h INVITED

Impacts of Abrupt Change: Lessons From Interannual Climate Variations

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Was the climate shift circa 1976 an abrupt climate change? I will first consider the issue of what constitutes an abrupt change, noting that definitions suggested by climate changes per se may have to be altered when the impacts on societies are considered. I will also touch on the relationship between abrupt changes and extreme events.

Seasonal to interannual climate variations, especially those associated with the ENSO cycle, often have strong impacts on societies and economies. Experience in applying forecasts and other knowledge of these events offer some cautionary tales and some successes. In the first world, information is likely to be widespread, and may be put to use by the individual. Farming in Australia is a successful example. In the less developed world, more developed institutions such as banks and corporations are likely to have greater information access than artisanal workers. In general, since climate forecasts are probabilistic, those such as commodities brokers who are able to spread risk over many transactions are most likely to cope best with climate change.

U41B-07 1010h

Clocking the Speed of Climate Change: The End of the Younger Dryas as Recorded by Four Greenland Ice Cores

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The warming at the end of the Younger Dryas (about 11,500 years bp) was the first large, rapid climate change to be studied in detail in ice cores, and remains the most recent, large, rapid climate change that we can study with near-annual resolution. Early studies examined this climate change using the DYE3 ice core in southern Greenland, and later studies compared this record to the GISP2 record in central Greenland. It is estimated that during this climate shift average, annual temperatures in Greenland warmed by about 15 degrees in less than a human lifetime, and ocean conditions such as sea ice extent and surface currents, changed even faster. We present here new results from the NorthGRIP ice core in northern-central Greenland. Measurements of stable isotopes, delta D, delta O18 and deuterium excess, have now been made with one to two year resolution across the end of the Younger Dryas in this core. These measurements are compared with those at DYE3, and the Summit cores, GRIP and GISP2. The structure of this large climate shift as recorded in these four cores is remarkably similar at the annual to biannual time scale, lending strong support to the hypothesis that the isotope shifts on this detailed time scale are climate shifts representative of a large region. The NorthGRIP results confirm the step like nature of this climate change that was seen clearly in the Summit isotope records, and somewhat less so in the DYE3 ice core. Most of the warming appears to have happened in two steps of roughly 7 to 8 degrees C each. Each of these steps lasted about ten years. The deuterium excess results from the four cores suggest that ocean conditions changed in ten to twenty years, with a rapid retreat in sea ice lasting 5 to 10 years being followed by a more gradual 10 to 30 year warming of surface water near Greenland. A warming of ocean waters in the sub-tropical North Atlantic appears to have preceded the abrupt climate shift by 20 years, suggesting that a precursor event may be present to help in prediction of such shifts. It is thought that this climate event was triggered by the re-establishment of warm surface currents flowing northward into the Atlantic, most likely tied to the re-establishment of North Atlantic Deep Water Formation. The speed with which these climate changes occurred, both in the ocean and

over the ice sheet, are truly challenging in terms of human adaptation and the design of workable climate policy. We note that the impact of changes in North Atlantic Ocean circulation are a concern today as polar ice melts and potentially changes the density structure of the ocean in this region. In addition, the Younger Dryas warming may provide clues as to the speed and magnitude of climate change that could accompany the current, observed loss of Arctic Sea ice.

U41B-08 1025h

Detecting a Potential Collapse of the North Atlantic Thermohaline Circulation: the Benefit of an Improved Ocean Observation System

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Many climate models predict a collapse of the North Atlantic thermohaline circulation (THC) as a result of anthropogenic climate change. The economic damages attending such a global change are likely to be non-negligible. Detecting such a THC collapse — should it happen in the future — would certainly affect climate policy. We argue that the present observation system would not detect a diminishing North Atlantic THC before it reaches a level below which models indicate it would not recover for centuries (we refer to this as the point of no return). Our simple analysis suggests that detection with 90% confidence would occur only after the point of no return because the present ocean observation system observes too infrequently and/or the inferred ocean circulation is too uncertain. This conclusion holds for a variety of analysis methods, both from a Bayesian and from a frequentist point of view. Detection of a THC collapse before the point of no return could be achieved in our model by more frequent observations. A crude cost-benefit analysis suggests that the benefits of such an improved ocean observation system would considerably exceed the costs.

U41B-09 1100h INVITED

Sensitivity and Thresholds of Ecosystems to Abrupt Climate Change

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Rapid vegetational change is a hallmark of past abrupt climate change, as evidenced from Younger Dryas records in Europe, eastern North America, and the Pacific North American rim. The potential response of future ecosystems to abrupt climate change is targeted, with a focus on particular changes in the hydrological cycle. The vulnerability of ecosystems is notable when particular shifts cross thresholds of precipitation and temperature, as many plants and animals are adapted to specific climatic windows. Significant forest species compositional changes occur at eotonal boundaries, which are often the first locations to record a climatic response. Historical forest declines have been linked to stress, and even Pleistocene extinctions have been associated with human interaction at times of rapid climatic shifts. Environmental extremes are risky for reproductive stages, and result in nonlinearities. The role of humans in association with abrupt climate change suggests that many ecosystems may cross thresholds from which they will find it difficult to recover. Sectors particularly vulnerable will be reviewed.

U41B-10 1115h

Abrupt Climate Changes Caused by a Collapse of the North Atlantic Thermohaline Circulation: Implications for Optimal Economic Climate Policies

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Climate modelers have recognized the possibility of abrupt climate changes caused by a collapse of the North Atlantic thermohaline circulation (THC). This circulation system now warms northwestern Europe and transports carbon dioxide to the deep oceans. The posited THC collapse could produce severe cooling in northwestern Europe, even when general global warming is in progress. Here we use a simple integrated assessment model to investigate the optimal policy response to this risk. Our analysis shows that significantly reducing carbon dioxide emissions may be justified to avoid or delay even small (and arguably realistic) damages from an uncertain THC collapse. Detecting a change in the THC before a potential collapse enables the policy maker to improve climate policy (as measured by an increased per-capita consumption). The considerable economic value of detecting a potential THC collapse early enough has implications for the design of an ocean observation system.

U41B-11 1130h

Regional Abrupt Climate Change in the U.S.: Comparing the Colorado and Columbia River Basins

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Paleoclimatic evidence and historical experience indicate the earth's climate system is capable of switching rapidly from one quasi-stable state to another. Current global assessments of anthropogenic climate change, however, do not fully account for such abrupt shifts, and instead generally assume the earth's climate will gradually warm over the next several centuries. Integrated assessments of abrupt climate change exist, but on a regional level. Here we discuss two examples where abrupt climate change information was applied to the management of natural resources, including water in the Colorado Basin and salmon in the Columbia Basin.

Tree-ring data imply that a massive 20-yr drought occurred in the Colorado Basin during the late sixteenth century. The Severe-Sustained Drought assessment (SSD) evaluated the socioeconomic impacts of this historically-unprecedented drought in the context of modern water allocation policy in the Colorado Basin. Based on semi-structured, open-ended interviews with assessment participants and regional stakeholders, the SSD clarified positions of competing water interests and expanded awareness of potential drought impacts, but did not modify Colorado River water management or policies. Assessment design characteristics had limited influence on effectiveness; the timing of publication and political and legal factors constraining alternative policy options for water distribution were more influential determinants. Absent a crisis, there are few incentives for water managers to implement SSD policy recommendations. The lack of a basin wide commission and long-term climate assessment group in the Colorado Basin appear to limit stakeholder ability to utilize technical information related to abrupt climate change.

In the Columbia River Basin, the crisis of declining salmon stocks motivated the consideration of alternative policies which recognize the role of unpredictable and abrupt decadal shifts in oceanic productivity. Although actual management strategies remain unchanged, the framing of the debate over salmon restoration shifted from one focused solely on freshwater habitat to one that more fully recognizes the oceanic influence on salmon mortality. The rapid assimilation of climate information into natural resource management in the Columbia Basin appears to be related to the sustained presence of the well-funded basin wide commission and an iterative climate assessment.

U41B-12 1145h

Warming in the Northern Great Plains: Impact and Response in the Agricultural Community

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Because agricultural production in the northern Great Plains contributes significantly to both domestic and international markets the impacts of climate

change, as well as the response strategies undertaken by the regions residents, will be felt throughout the nation and the world. The national assessment of Climate Change Impacts on the United States has pointed out that the northern Great Plains could be favored under global warming scenarios in that future climates could increase crop yields [Reilly, Tubiello, McCarl, and Melillo, 2000]. Yield, though, is only one measure of the consequences that rapid warming might have on this region. Challenges to a changing environment must be met by people. Producers here, as well as in other agricultural regions, already function under multiple stresses that are completely separate from climate variability and change. These include falling prices, globalization, complex trade relations, changes in government policy, environmental constraints, and changing consumer preferences. It is against the backdrop of these stresses that pending climate changes must be considered.

Interactions with stakeholders through the NGP Assessment workshops, held in 1997 and 1999, identified key concerns and outlined potential mitigation and optimization strategies for the consequences of climate change in this region. We will present examples of the successful implementation of some of these strategies: actions that farmers and ranchers are employing to 1) increase their awareness of environmental factors, 2) enhance their ability to respond quickly to environmental change, 3) improve their economic returns, and 4) decrease environmental degradation. We will also highlight other no regrets actions and policies under consideration that may offer individual producers greater flexibility in their management decisions and provide a healthier environment for society at large.

U42A MC: Hall D Thursday 1330h

The Science of Abrupt Climate Change and the Implications for Public Policy II

Presiding: R Alley, Pennsylvania State University; A R Isern, National Science Foundation

U42A-0008 1330h POSTER

Possible role of different helio-geophysical factors in abrupt climate change

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As shown by recent investigations, galactic cosmic rays (GCR) exert a considerable influence on physical and chemical processes in the troposphere, including development of cloudiness. More intense (less intense) GCR fluxes result in the increasing (decreasing) lower cloudiness (Palló Bagó and Butler, 2000; Marsh and Svensmark, 2000) and, as a consequence, in lower (higher) near-surface temperatures. Modulation of GCR fluxes can be caused by variations in solar activity (from days to thousands of years on time scale) and changes in the geomagnetic field (from hundreds to thousands of years on the time scale). The additive effect of these factors, together with effect of other climatic processes in the Earth's atmosphere (for instance, Henrich events), can lead to an abrupt climate change. Examples of the additive effect of changes in the geomagnetic field and solar activity can be the Younger Dryas cooling event and abrupt climate change around 2,700-2,800 years BP. Both these cooling events occurred, as follows from proxy data, during the minimum of quasi-2,400-year solar cycle and, hence, Gothenburg and Etrussia geomagnetic excursions. These effects lead to enhancement of the GCR flux, and, hence, to cooling of the lower troposphere. At the Holocene boundary, the additive effect of three factors contributing to climate warming was observed. The first was an abrupt increase in the geomagnetic field, which resulted in weaker GCR fluxes. The second factor was the growth in the activity of the 2,400-year solar cycle, which enhanced solar radiation and weakened GCR fluxes. The third was astronomical factors (the Milankovitch effect) which also contributed

to climate warming. The effects of the factors mentioned above enhanced each other, which could lead to the abrupt climate change at the Holocene boundary. Analysis has shown that abrupt climate change events occur as a rule, if several helio-geophysical and climatic factors are acting simultaneously in the same direction. This work was supported by EC (grant INTAS 97-3100 and IC 15CT98-0123 EXTRATERRESTRIAL) and RFBR (grant 00-05-64921).

U42A-0009 1330h POSTER

The Ice Core Correlation Game: What can we learn about global climate

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Prominent changes in oxygen and deuterium isotopic composition of the ice and in the methane concentrations in trapped atmosphere in ice cores allow a detailed correlation of ice core records from the arctic and antarctic.

U42A-0010 1330h POSTER

The Rapidly Diminishing Arctic Ice Cover and its Potential Impact on Navy Operational Considerations

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Observations made from U.S. Navy Fleet submarines during the 1990s have revealed a dramatic decrease in thickness, when compared to historical values, of the central Arctic Ocean pack ice cover. Estimates of this decrease have been as high as 40%. Remote sensing observations have shown a coincident decrease in the areal extent of the pack. The areal decrease has been especially apparent during winter. The overall loss of ice appears to have accelerated over the past decade, raising the possibility that the Northwest Passage and the Northern Sea Route may become seasonally navigable on a regular basis in the coming decade. The ice loss has been most evident in the peripheral seas and continental shelf areas. For example, during winter 2000-2001 the Bering Sea was effectively ice-free, with strong and immediate impacts on the surrounding indigenous populations. Lessening of the peripheral pack ice cover will presumably lead to accelerated development of the resource-rich regions that surround the deep, central Arctic Ocean basin. This raises potential issues with respect to national security and commercial interests, and has implicit strategic concerns for the Navy. The timeline for a significantly navigable Arctic may extend decades into the future; however, operational requirements must be identified in the nearer term to ensure that the necessary capabilities exist when future Arctic missions do present themselves. A first step is to improve the understanding of the coupled atmosphere/ice/ocean system. Current environmental measurement and prediction, including Arctic weather and ice prediction, shallow water acoustic performance prediction, dynamic ocean environmental changes and data to support navigation is inadequate to support sustained naval operations in the Arctic. A new focus on data collection is required in order to measure, map, monitor and model Arctic weather, ice and oceanographic conditions.

U42A-0011 1330h POSTER

Reconstruction of the Surface Temperature Change in Central Greenland During D/O 12, 45 Kyr B.P.

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Air bubbles preserved in polar ice cores are unique archives of past atmospheric composition. Recently, it has been shown that air bubbles isotopic composition (N-15, Ar-40) enables to quantify past abrupt changes in polar regions. In this study, a high resolution measurement of nitrogen and argon isotopes in an ice core from Greenland allows to determine past surface temperature variations and the ice age-gas age difference during the Dansgaard-Oeschger event 12 recorded around 45,000 years before present. These results imply a mean surface temperature change of 8.2 ± 0.8 °C and permit to determine a $\delta^{18}\text{O}_{\text{ice}}$ -temperature coefficient of 0.54 ± 0.05 ‰/°C and therefore bring a new constraint to calibrate the isotopic paleothermometer during glacial period. Moreover, a direct comparison with methane concentration will be presented to discuss the phase relationship between the warming and the methane increase.

U42A-0012 1330h POSTER

Rapid Climate Change at Siple Dome, Antarctica

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The 1004 m deep ice core from Siple Dome, Antarctica contains a paleoclimate record that spans at least the last 100,000 years. The most striking features of the paleoclimate record are two intervals at roughly 15 and 20 kyr BP. Both events are characterized by a transition period of reduced ice accumulation followed by an abrupt and persistent increase in surface temperatures. For the 15 kyr event the duration of the transition period was less than a few hundred years and ice accumulation dropped to zero or negative rates. The magnitude of the increase in surface temperature was at least 3 degrees and ice accumulation rates were similar before and after the event. For the 20 kyr event the duration of the transition period was less than 100 years and possibly as short as 50 years. The magnitude of the step increase in surface temperature was about 5 degrees and the ice accumulation rate was at least one-third lower after the event than before. Deuterium excess measurements indicate the two events had different

U42B MC: 134 Thursday 1330h

Virtual Earth Laboratories II (joint with NG, GP, S, T, DI, MR)

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Institute of Technology; R

Hollerbach, Univ. of Glasgow

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Prospects for Realistic Models of Planetary Dynamios

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