limitation and reduced metabolic rates typical in deep-sea ecosystems may also limit the ability of many organisms to tolerate changes in pH (i.e. pH compensation) or CO_2 (e.g. metabolic depression).

We recently performed field experiments at depths from 3000 to 3600 m to evaluate the biological responses of representative deep-sea organisms to changes in seawater chemistry caused by carbon dioxide sequestration. Several small pools (ca. 15 l) of liquid CO_2 were deployed on the seafloor from the ROV *Tiburon* operated by the Monterey Bay Aquarium Research Institute, using a novel CO_2 release system. Rates of survival and aspects of the physiological condition of various elements of the seafloor faunal community were compared between sites near (<1 m) and distant (control sites >30 m away) from CO_2 pools. Tidally oscillating currents swept a plume of CO_2-rich water away from the pools as the liquid CO_2 dissolved, resulting in periodic reductions of pH around the pools to 6.0 to 7.0 units within 1 m.

Rates of survival for two common megafaunal echinoderms (echinoid 1 and holothurian 1) held in cages adjacent to CO_2 pools were very low compared were compared to control sites. Decalcification of urchin spines and skeletal elements was evident for animals near CO_2 pools. The abundances of infaunal worms and crustaceans were lower near CO_2 pools after 5 weeks than control sites. In addition, the physiological condition (gut fullness and tissue density) of infaunal amphipods exposed to CO_2 was poorer than in control groups. Additional studies of the response of sediment-dwelling meiofauna, the sediment microbial community, and mobile scavenger species (fishes, amphipods) to elevated CO_2 exposure are underway.

A wide variety of field and laboratory studies of a phylogenetically diverse suite of deep-sea species from benthic and midwater environments, coupled with careful estimation of the degree and areal extent of changes in seawater chemistry to be expected with any CO_2 disposal scenario, is required before any realistic estimate of the impacts of sequestration on deep-sea ecosystems is possible.

U32B-10 1600h

Greenland Ice Sheet Sublimation: Suface Mass Balance Implications with Climate Warming

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Maps of surface water vapor flux from the Greenland ice sheet are constructed using Greenland Climate Network (GC-Net) data spanning 1995-2001. Temperature distribution maps from 1950-1960 and the contemporary period indicate a general warming of 2 degrees C. The correspondance of water vapor fluxes with temperature anomalies suggest a reduction in the net water vapor loss from 1950-1960 to the 1995-2001 period of 10%. In a warmer climate, an increase in the water vapor deposition at high elevations offsets an increase of water vapor loss at low elevations. 87% of the ice sheet area is above 1000 m elevation. Using the best estimate of net annual surface water vapor flux based on GC-Net data (-73 Gt) and estimates for precipitation, melt runoff, direct runoff, and iceberg calving, the annual mass balance of the ice sheet is in negative balance by 9% of the annual precipitation input. Reducing the uncertainties of the ice sheet mass balance parameters is the focus of future work.

URL: http://cires.colorado.edu/steffen/sublimation/

U32B-11 1615h

Lunar Solar Power System and Minimization of Carbon Dioxide Emissions in the Production of Commercial Power for a Prosperous Global Economy

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A prosperous world requires at least 6.7 kWt/person of thermal energy or the equivalent of 2.5 3 kWe/person of electric energy (1, 2). Thus, a prosperous world of 10 billion people requires approximately 67 TWt or 25 to 30 TWe of commercial power that is low in cost, globally safe, and capable of providing 6,700 TWt-y/century to Earth for many centuries. These requirements preclude conventional terrestrial fossil-fuel, nuclear, and renewable systems. Cost-effective access of solar energy is required.

The Moon intercepts 13,000 TWs of solar power. The proposed Lunar Solar Power (LSP) System collects a small portion of this solar power at bases located near the Earthward limbs of the Moon, converts the power to low-intensity microwave power beams (less than 20 percent the intensity of sunlight), and delivers the microwave power to receivers on Earth. The LSP lunar components are manufactured on the Moon using lunar materials. The receivers on Earth output utility-scale power. By 2050 the LSP System can provide abundant, clean, and low-cost commercial electric power to Earth that is independent of the biosphere. LSP energy can decouple physical and most service industry from the biosphere, stimulate healthy net growth of the global economy, and establish a two-planet (Earth-Moon) economy.

1. World Energy Council (2000) Energy for Tomorrows World Acting Now!,175pp., Atalink Projects Ltd., London. 2. Criswell, D. R. 1998 (13 - 18 September) Lunar solar power for energy prosperity within the 21st century, 17th Congress of the World Energy Council, Division 4: Concepts for a sustainable future issues session, 4.1.23, 277-289, Houston, TX (Also on WEC98 web site. Search for lunar.)

U41A MC: Hall D Thursday 0830h

Virtual Earth Laboratories I

Presiding: **H Bunge,** Princeton University**; L Stixrude,** Univ. of Michigan**; J Tromp,** California Institute of Technology**; R Hollerbach,** Univ. of Glasgow

U41A-0001 0830h POSTER

Cretaceous Length of Day Perturbation by Mantle Avalanche

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These last tens years, numerical models of mantle convection including the effects of the main mantle phase changes have emphasized the role of the 670 km endothermic phase change in generating mantle avalanches. These events are characterized by catastrophic mantle mass anomaly perturbations. The influence of the mass transfers due to the avalanches on the Length of Day (l.o.d.) has been studied by resolving the reduced Liouville equation. The results shows that the inertia tensor of the mantle remains approximately constant during the partial layering periods while it is mainly sensitive to the global mass transfers through the 670 km discontinuity during the avalanches. In spite of a tidal secular trend to l.o.d. lengthening, the paleontological records can be interpreted as a l.o.d. shortening between 200 and 80 My which would be synchronous with a strong True Polar Wander and a global warming of the upper mantle as witnessed by recent geochemical results and isostasy considerations. A l.o.d. shortening during the Cenozoic and Cretaceous brings one more clue to the possible implication of a mantle avalanche in generating the concomitant large scale events which have occurred during this very particular period of the Earth's history.

U41A-0002 0830h POSTER

A 3D Spherical Model of Mantle Convection and Continental Drift

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It has long been speculated that continents affect the large-scale heterogeneity structure of the Earth's mantle. Unusually slow seismic velocity anomalies under South Africa, for example, suggest some impact from the former supercontinent Pangea. Much progress has been made in understanding the effects of continents in mantle convection models. However, the influence of continents on vigorous 3D spherical mantle convection has not yet been studied. We address this problem using the 3D spherical mantle dynamics code TERRA implemented on a high performance Beowulf cluster. Our parallelized, finite element model approximates continental regions as unsubductable rigid lids whose motion is determined from the dynamics of the flow, in line with earlier Cartesian experiments. We study the effects of continents for a number of different flow regimes, including models with and without a significant viscosity increase in the lower mantle and models having having either strong internal heating from radioactivity or strong bottom heating from the core. We find that the nature of the heating mode is particularly significant in determining how effectively a continent promotes the formation of long-wavelength heterogeneities in the mantle.

U41A-0003 0830h POSTER

Modeling 3D Wave Propagation in Global Earth Models Using a Spectral/Mortar Element Method

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The Spectral Element Method (SEM) has been shown in recent years to provide an efficient, accurate solution to wave propagation in the Earth at both regional and global scales. Based on a high order polynomial approximation of the weak form of the wave equation, the SEM naturally takes into account the free surface condition (which is crucial for surface wave propagation) and allows for considering localized density/velocity heterogeneities.

For global wave propagation the method requires to tile the 3-sphere with hexaedra. This is achieved by paving the Earth's major interfaces with quadrangles and connecting them radially, with a cube being set inside the inner core to avoid any singularity at the center of the mesh. However, such a process yields a non-uniform grid-points distribution that causes the seismic wavelengths to be largely over-sampled for increasing depth. This drawback is overcome by coarsening the mesh through some special "non-conforming" interfaces, which do not necessarily coincide with composition or phase changes. The matching between the fine and the coarse grids is achieved by the mortar element method which consists in relaxing the continuity conditions across the non-conforming interfaces. Examples of the method will be presented for some radial Earth models where the local effects of gravity are taken into account during wave propagation. The approximation is based on a formulation in displacement for the solid parts and in the velocity potential for the fluid regions, and the non-conforming interfaces can be set either in the solid or in the fluid.

For realistic applications of the method to 3D Earth models, the possibility of refining the spectral element mesh laterally must also be considered. A striking example illustrating this need is the discretization of the Earth's crustal structure, for which thickness variations of a factor up to 10 can be encountered. Adapting the grid-points sampling to these lateral contrasts is a key ingredient to study the propagation of surfaces waves in presence of topography on both the surface of the Earth and the Mohorovicic discontinuity. We will present how the mortar element method must be adapted in order to deal with such local refinements, and show some examples for models of increasing complexity.

U41A-0004 0830h POSTER

A parallel implementation of the Lattice Solid Model for large scale simulation of earthquake dynamics

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The particle based lattice solid model has been used successfully as a virtual laboratory to simulate the dynamics of faults, earthquakes and gouge processes. The phenomena investigated with the lattice solid model range from the stick-slip behavior of faults, localization phenomena in gouge and the evolution of stress correlation in multi-fault systems, to the influence of rate and state-dependent friction laws on the macroscopic behavior of faults. However, the results from those simulations also show that in order to make a next step towards more realistic simulations it will be necessary to use three-dimensional models containing a large number of particles with a range of sizes, thus requiring a significantly increased amount of computing resources. Whereas the computing power provided by a single processor can be expected to double every 18 to 24 months, parallel computers which provide hundreds of times the computing power are available today and there are several efforts underway to construct dedicated parallel computers and associated simulation software systems for large-scale earth science simulation (e.g. The Australian Computational Earth Systems Simulator[1] and Japanese Earth Simulator[2])". In order to use the computing power made available by those large parallel computers, a parallel version of

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/ACESS/
[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 10^9. 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 10^9 that exhibit Earth-like surface veocities 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 tartgeted reesearch 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 Atlantics conveyor which keeps northern Europe warm but rather the global airflow 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 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 wintertime 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 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.