optical thickness look-up library using previously calculated single scattering data in conjunction with the Discrete Ordinates Radiative Transfer (DISORT) code. An algorithm was constructed based on this look-up library to infer the optical thickness of tropical cirrus clouds for each pixel in a MODIS image. We demonstrate the applicability of this algorithm using several independent MODIS images from NASA's Terra satellite. The method described here is complimentary to the MODIS operational cloud retrieval algorithm for the case of cirrus clouds.

U21A-14 0830h POSTER

Retrieval of the optical thickness of ice clouds from spaceborne high-spectral-resolution radiance measurements

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One of the primary goals of the Atmospheric Infrared Sounder (AIRS) is to retrieve atmospheric profiles. Beyond the clear sky sounding capability, the high spectral resolution infrared radiance contains useful information about clouds, particularly for high-level, optically thin cirrus. In the present research, we present methodology for the retrieval of cirrus optical thickness from AIRS high spectral resolution infrared radiances. A fast cloudy radiative transfer model is developed to simulate AIRS radiances when clouds are present. Calculations show that the brightness temperature difference between this fast cloudy radiative transfer model developed specifically to simulate clouds and a discrete ordinates (DISORT) radiative transfer model is within 0.5K for most cloud cases. However, the computing speed of the fast model is 1000 times faster than DISORT. The fast model for cloudy radiance simulations was merged subsequently with the clear-sky fast model for AIRS sounding purpose developed at the University of Maryland-Baltimore County. Various cirrus cloud studies have been conducted, which include: (1). the sensitivity of AIRS brightness temperatures to optical thickness and effective particle size, and (2) the sensitivity of simulated brightness temperatures to the microphysical properties of ice clouds for a range of wavenumbers in the IR region. Based on the sensitivity studies, methodology is suggested to retrieve the optical thickness of cirrus clouds from AIRS measurements. For the implemention of the retrieval algorithm, ECMWF atmospheric profiles and collocated MODIS cloud altitude data are used for forward modeling calculations. The applicability of the retrieval algorithm is demonstrated by a case study. The ice cloud optical thicknesses derived from the AIRS measurements are compared with those retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) 1.38 μm and 0.66 μm bands. The optical thicknesses inferred from the MODIS measurements are collocated and degraded to the AIRS spatial resolution. Results from the MODIS and AIRS retrievals are quite similar over a wide range of optical thicknesses.

U21A-15 0830h POSTER

Microphysical and optical properties of ice clouds derived from the Airborne Visible/Infrared Imaging Spectrometer measurements

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In this paper, we introduce a method to simultaneously retrieve ice crystal effective size and cirrus cloud optical thickness using 1.38- and 1.88-μm cirrus reflectance from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data. Atmospheric and surface effects are removed from this data to obtain isolated cirrus reflectance. An effective size and optical thickness look-up table has been produced for each case presented here using the Discrete Ordinates Radiative Transfer (DISORT) code and previously calculated single-scattering data. An algorithm has been developed based on the look-up tables to derive the effective size and optical thickness of cirrus clouds on a pixel-by-pixel basis. The applicability of this method is demonstrated using several independent AVIRIS images.

U21B CC: 517 A Tuesday 0830h

Extreme Environments of the Precambrian Earth I

Presiding: **G S Jenkins,** Howard University; **C Poulsen,** University of Michigan; **P McCausland,** University of Michigan

U21B-01 0835h INVITED

HOW STRONG IS THE CASE FOR PROTEROZOIC LOW-LATITUDE GLACIATION?

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The most recent global compilations of paleomagnetic depositional latitudes for Proterozoic glaciogenic formations indicate a dominant mode near the paleoequator (Evans 2000 AJS; Evans 2003 Tectonophysics). This result would therefore support either the snowball Earth or the large-obliquity hypotheses for Precambrian ice ages, but would reject the uniformitarian comparison to polar-temperate-restricted Phanerozoic glaciogenic deposits. The most reliable low-latitude results come from the Australian Marinoan succession, but a recent summary of these units has suggested that a glaciogenic origin is not yet demonstrated (Eyles and Januszczak 2004 Earth-Sci Reviews). It becomes useful, then, to review the global evidence for Proterozoic low-latitude glaciation. Eyles and Januszczak (ibid.) identified 13 Neoproterozoic deposits with "demonstrated" glacial influence. Among these, poor age constraints and lack of paleomagnetic data prohibit estimation of depositional paleolatitudes for the Fiq, Sturtian, Vreeland, Taoudeni, East Greenland, Port Askaig, and Zhengmuguan units. Moderate paleolatitudes are reasonably well supported for the South China, Gaskiers, Smalfjord, and Moelv units. Among the three remaining units, the Rapitan Group can be assigned a near-equatorial paleolatitude indirectly through use of the Galeros and Franklin-Natkusiak paleomagnetic results, as long as the Rapitan age lies within 750-720 Ma as generally expected. The Moonlight Valley Formation in northern Australia may be assigned a tropical paleolatitude according to high-quality paleomagnetic results from compellingly correlated Marinoan strata in southern Australia. Those strata, including the famous Elatina Formation, have yielded a robust paleomagnetic signature that is commonly interpreted to imply frigid climate (manifest in part by frost-wedge polygons) at near-equatorial latitudes. Concerns that the Neoproterozoic geomagnetic field was either nonaxial or nondipolar are valid in principle, but it should be noted that the degree of nonactualistic features required to produce polar or temperate glacial paleolatitudes is as shockingly nonuniformitarian to geophysicists as equatorial glaciation is to paleoclimatologists. Similarly, hypotheses invoking rapid paleolatitude shifts of continents to generate erroneous paleomagnetic latitudes due to lax age constraints require such motions at rates beyond what is normally considered reasonable for plate tectonics. Snowball Earth thus remains an attractive model to explain numerous anomalous features of the Neoproterozoic rock record.

U21B-02 0855h

On the Syn-glacial Sedimentary Record of Snowball Earth: Tales of Three Ice-mass Types

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We sketch a conceptual model of the glacial history of a snowball Earth, based on new field studies of Marinoan (c640 Ma), Sturtian (c710 Ma) and Huronian (c2.4 Ga) syn-glacial deposits, and informed by sea-ice dynamics modeling. If the oceans froze over from pole to pole, sea ice would thicken and flow glacially towards the Equator, maintained in dynamic steady state by sublimation-precipitation and melting-freezing (Goodman & Pierrehumbert, 2003). Flowage thickens tropical sea ice (and thins extratropical sea ice) relative to adjacent landfast sea ice, where ice thickness is set by one-dimensional thermal diffusion. The latter, called 'sikussak' on Greenland fjords, would occur on rimmed shelves, silled basins and inland seas that are physically protected from invasion by sea glaciers. Such areas have high preservation potential in the geological record and their stratigraphic development through a snowball cycle (CO2 hysteresis loop) ought to reflect an interplay between three distinct ice-mass types: (1) sea glaciers, (2) sikussak, and (3) grounded ice domes. The snowball stage begins when sea glaciers invade the tropics and sikussak prevents calving from outlet glaciers and associated shelf ice. The snowball onset might easily be mistaken for a glacial termination in the sedimentary record. Suspended sediment discharged from wet-base grounded ice may accumulate beneath the sikussak, producing deposits previously interpreted as interstadial or non-glacial. Despite tropical sea ice c450 m thick (GP2003), sea glacier movement ensures a perpetual habitat for photoautotrophy in grounding-line crack systems. After greenhouse forcing raises tropical sea-surface temperature to the melting point, sikussak is replaced by 'oases' of open water, but the tropical ocean remains ice covered due to sea glacial inflow from higher latitudes. If evolved snowball seawater is anoxic and charged with dissolved iron, banded iron-formation will precipitate in snowball oases due to air-sea exchange and oxygenic photosynthesis. Snowball oases that formed over carbonate rock or debris may become critically oversaturated upon warming, and the isotopic composition of precipitated carbonate may be dominated by the large atmospheric carbon reservoir. Snowball oases would cover only a few percent of global surface area, but glacier accumulation rates will be enhanced in their vicinity, leading to progradation of ice-proximal deposits (diamictite) over oasis and sub-sikussak formations. Very high tropical melting rates are required to beat back the sea glaciers, giving rise to an active hydrologic cycle and an erosive, wet-base, glacial regime. Ultimate collapse of the sea glaciers triggers terrestrial deglaciation, recorded by 'cap' dolostones that track the post-glacial transgression. Sections of the Polarisbreen Group (c640 Ma) in Svalbard, the Rapitan Group (c710 Ma) in the northern Canadian Cordillera, and the Gowganda Formation (c2.4 Ga) in central Canada exemplify the conceptual model described here.

U21B-03 0915h INVITED

Neoproterozoic Glacial Extremes: How Plausible is the

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The suggestion that the glaciation events of the Neoproterozoic could have been global in extent, so-called "snowball" glaciations, during which the oceans were entirely covered by sea ice and the continents by massive continental ice sheets, is an idea tha is recurrent in the geological and climate dynamics literature. It is an idea that haa both critics and defenders but concensus concerning it's plausiblity has yet to emerge. Previous work on this problem has led to the suggestion that a more likely scenario than the "hard snowball" is one in which open water continues to persist at the equator, thus enabling biological evolution into the Cambrian to proceed, perhaps stimulated by the transition from the cold conditions of the Neoproterozoic to the warm condition of the Cambrian, thus leading to the Cambrian "explosion of life". We will discuss recent extensions of our previous efforts to model the extreme climate of the Neoproterozoic, using both the University of Toronto Glacial Systems Model and the NCAR Community Climate System Model. With an appropriate choice for the albedo of sea ice, the former model conntinues to deliver hysteresis in the surface temperature vs. CO2 concentration space when solar luminosity is reduced by 6% below modern, and thus continues to suggest the existence of the previously hypothesized "CO2 attractor". We argue here that the system could be locked onto this attractor by the strong "out of equilibrium" effects of the carbon cycle recently discussed by Rothman et al. (PNAS, 2003). The open water solution is confirmed as the preferred mode of the system by the detailed CCSM integrations that we have performed.

U21B-04 0935h INVITED

Tectonics and Glaciation in the Neoproterozoic

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This presentation addresses the links between tectonics and glaciation in the Neoproterozoic. The global context of glaciation at that time is the massive reorganisation of the planet's land and ocean systems resulting from the break up and dispersal of the supercontinent Rodinia. Commencing about 750 Ma and lasting for at least 150 million years, global rifting was the overriding control on sedimentary basin formation, basin fill stratigraphies, and it is argued, glaciation. An initial phase of rifting began after 750 Ma along the paleo-Pacific margin of Laurentia with a later phase at about 600 Ma along its paleo-Atlantic Iapetan margin. It cannot be simply coincidental that these two rift phases are directly linked to episodes of glaciation; the first phase that of the Sturtian and equivalent Rapitan glacials, the second that of the Marinoan and Vendian glacial deposits. Precise dating of these glacial intervals has not yet been achieved but they occur within thick rift-related tectonostratigraphic successions. These consist for the most part of thick submarine slope and fan deposits reflecting rift basin formation and influxes of large volumes of clastic sediment, including large volumes of detrital carbonate debris, from uplifted rift shoulders. Successions are dominated by turbidites, olistostromes and debris flow facies (diamictites); some, where uplift or latitude were appropriate, are glacially-influenced but many are not. Deposits record a fully functioning hydrological cycle. Tectonically generated topography in the form of uplifted rift flanks may have been a key control on the growth of regional ice centers suggesting a diachronous climatic response to uplift as rifting progressed in a zipper-like fashion around the margins of Laurentia.

U22A CC: 517 A Tuesday 1030h

Extreme Environments of the Precambrian Earth II

Presiding: **G S Jenkins,** Howard University**; C Poulsen,** University of Michigan

U22A-01 1030h

Extreme carbonate super-saturation of the ocean and Neoproterozoic ice ages

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In the modern ocean, reduction in carbonate deposition on the continental shelves can be compensated for by the increased preservation in deep sea sediments of biogenic carbonate originating from planktic calcifiers living in the open ocean. The result is that ocean carbonate chemistry is strongly buffered and the carbon-climate system relatively stable. However, before the advent of metazoan biomineralization in the Cambrian and proliferation of calcareous plankton during the Mesozoic, carbonate deposition would have been largely restricted to shallow water photic environments. Such a system is highly susceptible to positive feedback between sea level fall, reduced shallow water carbonate deposition, increased carbonate saturation of the ocean, atmospheric CO_2 draw-down, and ice-sheet growth. This is consistent with the occurrence of ice ages of near-global extent during the Neoproterozoic. Both the widespread occurrence and observed thickness of cap' (dolostone) carbonate deposited during postglacial transgression are explicit predictions of this hypothesis. The enigmatic cap facies thus record the rapid removal of accumulated alkalinity from an ocean that has reached an extreme degree of carbonate super-saturation by the end of the glacial period.

URL: http://tracer.env.uea.ac.uk/e114/publications.html

U22A-02 1045h

Weathering History During Extreme Climate Conditions in Neoproterozoic Time: a Clay Mineral Study on the Nanhuan-Sinian Succession (South China)

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The Nanhuan-Sinian sedimentary rocks on the Yangtze Platform in South China represent a glacial succession of Neoproterozoic age. The succession of paleolow-latitude is assumed to be correlative to the global glacial "snowball Earth" event. This estimation is on the one hand based on sparse age determinations and on the other hand on in the simalarities of its consecutive occurence of tillites and warm-water carbonates similar to successions on other continents. One of the postulates of the snowball Earth hypothesis is that during glaciation chemical weathering on the continents was shut down and was followed by intense silicate weathering in the aftermath of the glaciation. Furthermore, as a result of the nearly complete ice-cover oceanic bottom waters allegedly became anoxic. Clay minerals are being produced among other things by weathering of silicate minerals. We evaluated the degree of chemical weathering by combining major and trace element analyses (incl. REE), XRD and TEM to recontruct the weathering history during the Nanhuan-Sinian time. Lithological records together with the application of geochemical weathering proxies indicate an inter- or at least intraglacial stage for the Nanhuan-Sinian succession. The values of paleoredox indices do not show anoxic bottom water conditions during the Nanhuan glaciation. Our results allow two possible implications: (i) The snowball Earth scenario did not occur exactly as postulated and needs to consider climate variability and long-term ocean-atmosphere interaction, or (ii) the Nanhuan glaciation evolved independently from the global glaciations considered by the snowball Earth hypothesis.

U22A-03 1100h

Biogeochemical susceptibility of Proterozoic oceans to extreme isotopic events

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It has been suggested that Proterozoic oceans contained an unusually concentrated pool of dissolved and suspended organic carbon [1]. This high concentration is traced to its accumulation in the water column, prior to the evolutionary innovations that caused organic matter to sink. Oxidation of a small part of this large reservoir can create a large isotopic signal in the smaller inorganic pool, thereby explaining the large Neoproterozoic fluctuations in the isotopic composition of carbonate. Here we construct a simple continuous model to analyze the mechanisms by which such an organic-rich ocean can be created and investigate its stability with respect to oceanic circulation and evolutionary changes. Our model describes the biological, geochemical, and physical interactions of oceanic organic carbon, dissolved oxygen, and dissolved nutrients as a function of depth. It is formulated as coupled advection-reaction-diffusion equations. We first verify that, in the presence of sinking organic matter, the model simulates modern depth profiles of oxygen, carbon, and nutrients such as phosphorus. We then explore the consequences of producing neutrally-buoyant organic matter. As expected, this case results in lower levels of oxygen at depth. We analyze the dynamic stability of this state, with particular emphasis on the effects of instability on the isotopic composition of carbonate. 1. Rothman D.H., Hayes J.M., Summons R.E. (2003) Dynamics of the Neoproterozoic carbon cycle. Proc. Nat. Acad. Sci., USA 100: 8124 - 8129.

U22A-04 1115h

High methane abundance throughout Precambrian.

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Decreased solar luminosity (Gough, 1981) and multiple lines of geologic evidence in favor of a "liquid" ocean in the Archean set a puzzle known as "Faint Young Sun" paradox. For several decades, elevated atmospheric CO2 levels were considered to be the most self-consistent solution for the warm Archean climate (Walker et al., 1977; Kasting et al., 1993). However, to offset a 25% decreased solar luminosity (at 3.5 Gyr ago) and keep the mean global surface temperature at 288K, CO2 should have been at a steady-state concentration of about 0.3 bars. At such high levels CO2 would condense (Mellon, 1996) in the Earth's polar regions (as it does on Mars today) and no longer could be considered as the only "stabilizer" of the Archean climate. Lack of siderite in paleosols (Rye et al., 1995) and lack of glaciations in Archean/Proterozoic also does not support large CO2 concentrations and pure CO2 greenhouse in the Precambrian. Climate simulations (Pavlov et al., 2000) show that 100-1000 ppm of methane would be sufficient to maintain warm climate under decreased solar luminosity without invoking huge CO2 levels. Therefore, the key question is how to maintain such high CH4 levels. In the anoxic Archean environment (Pavlov & Kasting, 2002), the lifetime of methane molecule would be long 10000 years. Previous photochemical calculations show that to maintain the "steady-state" 1000 ppm of CH4, the methane flux into Archean atmosphere should have been close to the present day biogenic methane flux (Pavlov et al., 2001) which is debatable. However, previous calculations assumed a high ("diffusion-limited") rate of hydrogen loss to space. If atmosphere was anoxic, hydrogen should have been lost at much (5-100 times) slower rate (Tian et al., 2003). Here we demonstrate that 100-1000 ppm could be maintained with much smaller methane flux in the hydrogen-rich Archean atmosphere. In the oxygenated Proterozoic atmosphere the lifetime of methane becomes much shorter. However, the biogenic flux from the oxygen/sulfate-poor Proterozoic ocean could have been even higher than the present total biogenic flux. The methane abundance in the oxygenated atmosphere is a non-linear function of methane source because methane molecules destroy their major sink - OH radicals (Prather, 1996). We showed (Pavlov et al., 2003) that 100 ppm of methane in Proterozoic could be maintained with only 7-10 times increased present biogenic flux. We conclude that methane was abundant throughout Archean and Proterozoic and most likely was responsible for lack of glaciations in the Precambrian.

U22A-05 1130h

High obliquity simulations of Proterozoic climate conditions

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Results from GCM simulations using boundary conditions (solar forcing, landmass position) for the Proterozoic Era (Palaeoproterozoic, Mesoproterozoic, Neoproterozoic) are presented. The primary purpose of this presentation is to determine from model simulations when high obliquity conditions are consistent or inconsistent with the implied climatic conditions from geologic rock record. The results suggests that high obliquity is a viable solution for most of the Proterozoic Era with the exception of the extreme events at the end of the Neoproterozoic when glacial deposits may have existed in high latitudes (>40 degrees). However, the high latitude glacial deposits have the largest uncertainties. A number of studies have suggested that the proposed mechanisms for restoring obliquity to the present day values at the end of the Neoproterozoic are not viable. However, the overall agreement with the implied climate conditions during the Proterozoic Era makes it difficult to dismiss the High Obliquity Hypothesis.