Four palaeoceanographic proxy measures vary in consonance with the main lithological glacial-interglacial cyclicity at the site. Interglacial intervals are characterised by high d13C and colour reflectance (a proxy for carbonate content), and low gamma-ray (a proxy for clay content) and d18O; conversely, glacial intervals exhibit low d13C and reflectance, and high gamma ray and d18O. Early interglacial intervals are represented by silty clays which enclose intervals of 10-65 cm thick, sharp-based, Chondrites-burrowed, shelly, graded, very fine sands. The sands are rich in foraminifers, including species of warm water affinities, and were deposited distant from the shoreline under the influence of longitudinal flow in relatively deep water, as the palaeo-STC passed shorewards across the upper slope. The enclosing glacial units, which comprise mostly micaceous silty clay, though with some thin (3-25 cm thick) sands present also at peak cold periods, contain the cold-water scallop Zygochlamys delicatula.

The 1119 core records the seaward movement of the STC during glacial periods, accompanied by the incursion then of warmer subtropical water (STW) above the site, and landward movement during interglacials, resulting in a dominant influence then of colder subantarctic surface water (SAW). Intervals of thin, sharp-based, graded sands-muds occur within cold periods MIS 2-3, 6.2 and 7.4, and indicate the onset at times of peak cold of intermittent bottom currents which correspond to strengthened and expanded frontal flows along the STC, which at this time lay east of site 1119 in relatively close proximity to seaward-encroaching subantarctic waters within the Bounty gyre.

PP12B MCC: 270 Monday 1330h

Understanding Pre-Quaternary Climate Using Models and Data *(joint with A, OS, GC)*

Presiding: **R T Pierrehumbert,** University of Chicago

PP12B-01 1330h

Feedback of atmospheric chemistry, via CH4, on the Eocene climate

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Atmospheric CH4 is a potent greenhouse gas, but it lacks a geochemical or paleobiological proxy for the pre-Quaternary. So the concentrations of CH4 prescribed in Mesozoic and early Tertiary paleoclimate modelling studies have tended to depend on simple approximations and assumptions. To move towards more realistic attempts at setting the global CH4 levels in paleoclimate models, we developed a new process-orientated approach to defining them. Our approach is based on modelling terrestrial ecosystem distributions and productivity, and the emissions of trace gases, particularly the volatile organic carbon (VOCs) compounds isoprene and monoterpene, for a given paleoclimate. The effects of the trace gas emissions on the chemistry of the atmosphere are assessed using a three-dimensional atmospheric chemical transport model coupled to the UK Meterological office (UKMO) ocean-atmosphere general circulation model of global climate. Results for simulations in the early Eocene indicate atmospheric CH4 concentrations in excess of 3000ppb, with VOC and climate reaction feedbacks being especially important. The feedback of this level of CH4 on climate in the early Eocene was assessed in separate sensitivity experiments with the UKMO GCM. The results indicate strong seasonal warming (up to 5oC), particularly of continental interiors in the Northern hemisphere during the winter months.

PP12B-02 1345h

Paleoceanography in Northwest Pacific during Early Albian: Global Carbon Cycle and the Related Ocean Environments

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The major components (organic carbon and carbonate) and inorganic elements are analyzed in the sediments from the Okusakainosawa and Chirashinaigawa sections in the middle to north Hokkaido, Japan. It is estimated that the Yezo basin was located on a continental slope at the middle latitude of the northwest Pacific from late Aptian to early Albian. Total organic carbon contents vary from 0.30 to 1.12 wt. %, averaging 0.79 wt. % in the Okusakainosawa section, and from 0.32 to 0.95 wt. % in the samples of the Chirashinaigawa section. The black shale is not recognized at the studied area. The mean $C_{organic}/N$ atomic ratios of samples reveal about 20, which shows that most of the organic matter was terrigenous in origin at the Okusakainosawa section, while the organic matter is a mixture of marine and terrestrial organic carbon in the Chirashinaigawa section. Namely, terrestrial organic matter had been a main contributor in both sections and labile organic matter, which could reduce dissolved oxygen content very little in the bottom water, hardly deposited during early Albian. On the other hand, both sections are characterized by very low occurrence of carbonate due to dissolution through the water column and/or on the seafloor. As the cause of low content of marine organic carbon in both sections, the primary records of carbonate preservation were affected by seawater chemistry rather than by local rain of organic matter. Based upon the organic carbon content at the Tethys, the severe dissolution of carbonate is attributed to the degraded intermediate and deep seawater rather than the released carbon dioxide by the local rain. Hence, there is some possibility that the intermediate-deep water at the northwest Pacific Ocean was one of the oldest during mid Cretaceous. Nevertheless the dissolved oxygen in the bottom water had not been completely consumed during early Albian from the behavior of Mn in the sediment. In contrast, dissolved oxygen is completely consumed in the northwest Atlantic although all carbonate is well preserved. If any possibility is adopted, big differences exist between the north Pacific and Atlantic during early Albian. Actually, the organic rich strata were only deposited at the limited area in the Pacific as compared with the Atlantic. It is suggested that the Pacific seldom experienced the reduced conditions spatially and/or temporally in contrast to the Tethys Sea. These observations point out one possibility that the Pacific and Atlantic had each original chemical composition of intermediate and deep water and different conveyor belt thermohaline circulation may exist at least during early Albian.

PP12B-03 1400h

Ice Sheet Stability during the Late Ordovician: Obliquity Forcing with 8-12x Pre-industrial Levels of Atmospheric pCO_2

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Coupled ice sheet and atmospheric general circulation model results show that the formation and persistence of ice sheets during the Late Ordovician were sensitive to atmospheric pCO_2 levels and orbital forcing at the obliquity timescale (30 to 40 k.y.). Without orbital forcing, ice sheets develop with pCO_2 levels as high as 10x PAL. However, with orbital forcing permanent ice sheets that survive warm summer orbits develop only with atmospheric pCO_2 levels of 8x PAL. The ice sheet model results further indicate that during exceptionally long periods of low summer insolation and low atmospheric pCO_2 (8-10x PAL), large ice sheets could have formed that were able to persist under subsequently higher pCO_2 values. If atmospheric pCO_2 is a main driver for the timing of the Late Ordovician glaciation, our results have implications for the pCO_2 levels necessary to begin and end the Late Ordovician glaciation. In order to initiate growth of a permanent ice sheet in the Late Ordovician, atmospheric pCO_2 must have fallen to at least 8x PAL. Thus, the pCO_2 threshold for the initiation of glaciation in the Late Ordovician was on the lower end of previously published estimates of 8-20x PAL. Moreover, in order to end glaciation pCO_2 levels must have risen beyond the 8x PAL threshold for ice sheet formation. The model predicts multiple equilibria with respect to changes in atmospheric pCO_2 levels and amplitudes of the orbital perturbations. These sharp bifurcations can be attributed to small ice sheet instability.

PP12B-04 1415h

Glacial Flow of Floating Marine ice in 'Snowball Earth'

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An intense debate is underway over whether the Earth's oceans were globally ice-covered during parts of the Neoproterozoic. Ice-free regions generally persist in GCM simulations of glaciated Neoproterozoic climates; however, these models have not considered the tendency of thick layers of floating marine ice to deform and spread laterally.

We have constructed a simple model of the production and flow of marine ice on a planetary scale, and determined ice thickness and flow in two situations: when surface air temperature is everywhere below freezing, and when tropical temperatures rise above freezing. In both cases, ice flow strongly affects the distribution of marine ice. Flowing ice probably carries enough latent heat and freshwater to significantly affect the transition into a Snowball Earth climate. We speculate that flowing marine ice, rather than continental ice sheets, may be the erosive agent which created some Neoproterozoic glacial deposits.

URL: http://geosci.uchicago.edu/~goodmanj/snowball_ice_sheets.pdf

PP12B-05 1430h

Towards a Composite $\delta^{13}C$ reference section for the Neoproterozoic

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We present a high-resolution $\delta^{13}C$ record of marine carbonates, which spans much of the Neoproterozoic Era (~850 to 543 Ma). Constructing a $\delta^{13}C$ reference curve for this time period has proved difficult because of poor radiometric age control, discontinuities in shelf carbonate sedimentation, and ambiguous global correlations. Furthermore, much scatter and uncertainty in composite Proterozoic isotopic records are imposed by inclusion of multiple, poorly-correlated, stratigraphic successions. We avoid these pitfalls by utilizing only two well-studied carbonate-dominated sections for the bulk of the new curve : the Otavi Group of northern Namibia and the upper Hecla Hoek Succession of northeastern Svalbard. The key to the composite record is the correlation between the two successions, which is based on common isotopic and stratigraphic features, most notably a prominent pre-glacial $\delta^{13}C$ anomaly and the character of distinctive cap carbonates. The fortuitous overlap between the two successions yields a nearly continuous $\delta^{13}C$ record (excluding glaciations) from the base (~850 Ma) of older, Akademikerbreen Group carbonates in Svalbard through the top (~600 Ma) of the younger Abenab and Tsumeb group carbonates in Namibia. Because the latest Neoproterozoic is not preserved in northern Namibia, continuity of the record to the Precambrian/Cambrian boundary requires a connection with the Witvei and Nama Groups in central and southern Namibia. Though we stress that this composite reference section is a work in progress, it is an important first step towards a new framework into which radiometric dates and major global events (e.g. glaciations and associated sea level fluctuations) can be fit and upon which other marine geochemical proxies (e.g. $^{87}Sr/^{86}Sr$ and $\delta^{34}S$), biostratigraphy, and paleomagnetic data can be hung. In this manner, data from many fragmentary sections may be incorporated (albeit interpretively) into a single, integrated geochronology. Several interesting features of the record already stand out, including evidence for three major glaciations between ~745 and 570 Ma and a variable relationship between these events and associated negative $\delta^{13}C$ anomalies. Also of note are the occurrence of other major isotopic variations both prior to 745 Ma and after 570 Ma, which appear unrelated to glaciation. A more complete, but also more complex, picture of Neoproterozoic Earth history is emerging.

PP12B-06 1445h

Possible Isotopic Evidences of Post Marinoan of Neoproterozoic III in Three Gorges Area, China

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Well world widely correlated Neoproterozoic III, upward includes Doushantuo Formation and Dengying Formation, overlays tillite of Nantou Formation and Gucheng Formation in Three Gorges area, China. The section has well controlled on biostratigraphy and sedimentology, such as complex of small shelly fossils yield around Precambrian-Cambrian boundary at the top of the section, Vendotaenids yield in the lower part of Dengying Formation, acritarches in Doushantuo Formation, and cap dolomite at the base of Doushantuo Formation which overlay tillite unit of Nantou Formation at the base of the section. Strontium, carbon oxygen isotope presents significant excursions in this well-developed carbonate section that is located at Wuhe near Zhigui in the area. 1) Carbon isotope (δ_{13}C) dramatic dropped from $4^o/_{oo}$ to $C8^o/_{oo}$ (PDB in this paper) near the boundary of Doushantuo and Dengying Formation, and elevates around $4^o/_{oo}$ at lower part of Dengying Formation where oxygen isotope (δ_{18}O) raises to $0.5^o/_{oo}$ from $C7^o/_{oo}$ at the upper part of Doushantuo Formation. Strontium isotopic ratio ($^{87}Sr/^{86}Sr$ in this paper) is discovered a peak as high as 0.7100 in the base of Dengying Formation, and exhibits important excursions across the boundary from 0.7077 on the upper part of Doushantuo Formation and 0.7084 on the lower part of Dengying Formation. 2) A world widely typical excursion of carbon and strontium isotopes are confirmed span the boundary of Precambrian-Cambrian where controlled by a complex of small shelly fossils at the top of the section. 3) Abnormally isotopic excursions around the boundary of Doushantuo and Dengying Formation may be the possible evidence of post Marinoan ice age.

PP12C MCC: 270 Monday 1530h

Interhemispheric Climate Change II

(joint with A, OS, GC)

Presiding: **J R Toggweiler,** NOAA Geophysical Fluid Dynamics Laboratory**; P U Clark,** Oregon State University

PP12C-01 1530h INVITED

Coupling of the hemispheres in observations and simulations of glacial climate change

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We combine reconstructions, climate model simulations and a conceptual model of glacial climate change on millennial time scales to examine the relation between the high latitudes of both hemispheres. A lead-lag analysis of synchronised proxy records indicates that temperature changes in Greenland preceded changes of the opposite sign in Antarctica by 400-500 years. A composite record of the Dansgaard-Oeschger events shows that rapid warming (cooling) in Greenland was followed by a slow cooling (warming) phase in Antarctica. The amplitudes, rates of change and time lag of the interhemispheric temperature changes found in the reconstructions are in excellent agreement with climate model simulations in which the formation of North Atlantic Deep Water is perturbed. The simulated time lag between high northern and southern latitudes is mainly determined by the slow meridional propagation of the signal in the Southern Ocean. Our climate model simulations also show that increased deep water formation in the North Atlantic leads to a reduction of the Antarctic Circumpolar Current through diminishing meridional density gradients in the Southern Ocean.

We construct a simple conceptual model of interhemispheric Dansgaard-Oeschger oscillations. This model explains major features of the recorded temperature changes in Antarctica as well as the general shape of the north-south phase relation found in the observations including a broad peak of positive correlations for a lead of Antarctica over Greenland by 1000-2000 years. The existence of this peak is due to the regularity of the oscillations and does not imply a southern hemisphere trigger mechanism, contrary to previous suggestions. Our findings thus further emphasise the role of the thermohaline circulation in millennial scale climate variability.

PP12C-02 1550h INVITED

Chronology of Millennial-Scale Climate Change at Siple Dome, West Antarctica

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Ice core paleoclimate records from both hemispheres can be placed on common chronologies using records of long-lived atmospheric gasses. We used records of methane from 11-45 ka and δ^{18}O of O_2 from 11-90 ka to place the Siple Dome stable isotope record on a common time scale with GISP2. This record allows us to compare the relative timing of millennial-scale events in Greenland and Antarctica and specifically to test the "see-saw" pattern of Greenland/Antarctic warming and cooling inferred primarily from the Byrd and GISP2/GRIP ice cores. The precision of the comparison varies, but is as good as 0.3-0.4 ka at times of rapid change in atmospheric methane. During the last deglaciation, the main warming at Siple Dome preceded the onset of the Blling period in Greenland by approx. 5 ka. A plateau in the warming trend from approx. 15-13 ka appears to be the expression of the Antarctic Cold reversal (ACR) at Siple Dome and ends at the onset of the Younger Dryas in GISP2. This plateau starts at approx. 15.3 ka in our chronology. Its onset is either synchronous with, or slightly leads, the onset of the Blling period in Greenland, although interpretation is complicated by evidence for a depositional hiatus at Siple Dome. During MIS-3 the gradual warming associated with Antarctic events A1 and A2 at Siple Dome preceded, by approx. 1.3-1.5 ka, the rapid onset of warming at D-O events 8 (38.5 ka) and 12 (45.5 ka) at GISP2. The cooling phase of these Antarctic events started at about the time that Greenland warmed. Smaller Antarctic warmings following A1 apparently preceded D-O events 7, 6, and 5 by approx. 0.6-1.0 ka. The chronology of millennial-scale events in the older section of the Siple Dome record (45-90 ka) is currently less precise but strongly suggests that Antarctic events A3 and A4 preceded D-O events 14 (52.3 ka) and 16/17 (58.5 ka) by 3.5 and 2.4 ka, respectively. This suggestion will be tested with higher resolution comparison offered by the methane record for this section of Siple Dome (now in progress). The pattern and timing of millennial warming and cooling in the Siple Dome record are very similar to that at Byrd. This similarity strengthens the argument for dynamically important interhemispheric differences in timing of millennial-scale climate change, although new ice core records with adequate chronology are necessary to understand the spatial pattern of this phenomenon in Antarctica.

PP12C-03 1610h INVITED

Deuterium excess at Siple Dome, West Antarctica: A role for the Pacific in millennial-scale climate change?

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Deuterium excess is a parameter measured in ice cores that tracks changes in the conditions of the ocean surface during evaporation, primarily sea surface temperature and to a lesser extent, wind speed and humidity. Based on simple and complex atmospheric models, as well the presence of strong ENSO signals, Siple Dome in West Antarctica appears to get its moisture predominantly from the sub tropical Pacific, in contrast to ice cores from East Antarctica which are fed primarily with moisture from the Atlantic and Indian oceans. The Siple Dome ice core, therefore, is one of the first ice cores to contain a record of the Pacific Ocean surface conditions over the past 100,000 years. The Siple Dome ice record of climate has been placed on a common time scale with GISP2 using records of long-lived atmospheric gasses, methane and d18O of O2 (see Brook and others, this session). The delta D record from Siple Dome appears to reinforce the observation that millennial scale climate changes are not in phase between Antarctica and Greenland (including the presence of an Antarctic Cold Reversal in Siple Dome), and confirms the robust observation that the magnitude of millennial scale climate changes in Antarctica are very small compared to those seen in Greenland. Scaled to the glacial-interglacial delta D change, D-O events in Greenland are 5 to 10 times larger than the stage 3 oscillations in Antarctica. In contrast, deuterium excess changes in Siple Dome are very large. Using the same scaling, XS changes in Siple Dome are comparable in magnitude to the delta D changes seen in Greenland. In addition, the XS changes are out of phase with delta D at Siple Dome, and thus appear to be in phase in Greenland delta D. XS peaks in the Siple Dome ice core, suggesting warmer Pacific SSTs, correspond with nearly all of the D-O events, raising the potential for a role for the sub-tropical Southern Pacific Ocean in millennial scale climate change, with phasing coherent with the Greenland records. In addition, during the transition and into the Holocene, XS continues the strong 1,500 and 3,000 year oscillations it has during the older parts of the record. Notably, there are relatively large increases in XS at 11.9 kybp (near the end of the Younger Dryas) and at 14.7 kybp (near the beginning of the Bolling-Allerod warming).

PP12C-04 1630h

Gulf Stream Variability, Ice-Rafting Events and Greenland Record Between 24 and 64 kyrs

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We present detailed results obtained from ODP Leg 172 Site 1060, from the Black Bahamas Outer Ridge at 74°W, 31°N, 3500 meters water depth. This site is at present under the influence of the Gulf Stream and the North Atlantic Deep Water.

At this location the foraminiferal faunas demonstrate a clear millenial-scale variability during MIS3. Faunas are dominated by warm species during interstadials, typically 60% associated with the warm water of the Gulf Stream, while this group only makes up about 30% of the fauna during stadials. An age model has been constructed by correlating abrupt shifts in the relative abundance of this faunal group with abrupt changes in the isotopic composition of ice in Greenland (time scale of Johnsen et al. 2001).

On this time scale, the benthic oxygen isotope record for MIS3 at Site 1060 is similar to that generated