years. We found that the difference between the SSTs of the NE and NW Pacific margins (ΔSST) reflected an orbital-controlled ENSO-like variability, and the ΔSST can be used as an indication of the long-term ENSO. The variation of ΔSST was large and pronounced at the 23-kyr cycle during 0-60 ka (MIS-1 to MIS-3) and 120-145 ka (MIS-5e to MIS-6), which agreed well with the long-term ENSO behavior predicted by the Zebiak-Cane ENSO model (Clement et al., 1999), as regards both the timing and frequency. In contrast, the variation was relatively small and pronounced at the 41-kyr cycle during 60-120 ka (MIS-4 to MIS-5d), which disagreed with the model prediction. Our observation also demonstrated that a strongly El Niño-like SST pattern prevailed in the mid-latitude North Pacific during the last two deglaciations. The synchronous warming of the Antarctica (Petit et al., 1999) and the tropical Pacific (Lea, 2000; Koutavas et al., 2002; Visser et al., 2003) prevailed within these strongly El Niño-like intervals during deglaciations. These findings are concordant with Cane (1998)'s hypothesis that a long-term El Niño must have resulted in global heating. Both meridional heat transport and pCO_2 increases might have been accelerated under a strongly El Niño-like condition during the last two deglaciations. These new findings suggest that a strongly El Niño-like condition was essential to the global warming that induced glacial terminations.

PP22A-1204 1330h POSTER

Evidence of Arid to Semi-arid Climate Near Western Pacific Warm Pool During Sea-Level Lowstands: Caliche Surfaces in Late Cenozoic Carbonates of Nansha Islands, South China Sea

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Whether the climate of tropical seas during glacial periods became cold and dry has been an open debate. Models by different authors proposed the tropical sea-surface temperature (SST) during the Last Glacial Maximum (LGM) to be about 2° lower, or 5-6° lower than present. The controversy partly arise from disparate reconstructions of temperature from stable oxygen isotope archives of marine sediments. In this paper, we provide field evidence of semi-arid or arid climate during late Cenozoic sea-level lowstands from an atoll located in central South China Sea near the Western Pacific Warm Pool (WPWP). Lower rainfall and higher evaporation associated with the dry conditions might have resulted in less meteoric water component in the surface sea-water, and this factor should be taken into considerations in deciphering temperature from isotopic records. Taiping Islet (Itu Aba), located at N10° 23' and E114° 22' is part of the Nansha (Spratly) Islands near the northwestern margin of the Western Pacific Warm Pool. Rock cores of a borehole at Taiping became accessible to the authors in the recent years. We identified at least four subaerial exposure surfaces (SES) in the late Cenozoic carbonates. Caliche deposits are recognized on each of the four surfaces on the basis of alveolar texture, micro-rhizolith, caliche glaebules and corroded limestone nodules in reddish matrix (terra-rossa). Caliche developed on limestones typically forms in semi-arid to arid areas with annual precipitation from about 500 to 1000mm, while the modern annual rainfall of Nansha Island is 1800-2100mm. The occurrence of the Nansha caliche suggests the climate was much drier than present during the sea-level lowstands represented by the four SES. During the sea-level falls, reduced surface area of South China Sea with continental shelves exposed might have resulted in less moistures in the atmosphere and therefore less precipitation and higher evaporation rates. As a result, the reduced amount of meteoric fresh water in the surface sea-water may yield heavier oxygen isotopic compositions. We suggest that paleo-SST interpretations based on oxygen isotope archives in or near South Chine Sea should take the precipitation factor into consideration. Previous studies in Southeast Asian land regions and offshore northern Australia have proposed a scenario of a drier WPWP during LGM. Our data suggest such dry condition may not only occur in LGM but also in the previous glacial periods or sea-level lowstands; may not only in lands, but also in the central South China Sea.

PP22A-1205 1330h POSTER

Simulated Response of Tropical Climate to Changes in ice Sheet and Carbon Dioxide Forcings

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Proxy records indicate that the tropical climate has experienced substantial changes that appear to coincide with Dansgaard-Oeschger and glacial-interglacial climate changes in the northern hemisphere. The source of the tropical climate variability is debated. To date, climate models have exhibited a relatively minor tropical climate response to northern hemisphere extratropical forcing. To further explore the influence of northern hemisphere extratropical forcing on tropical climate, a series of coupled ocean-atmosphere experiments using the Fast Ocean-Atmosphere Model have been performed to test the influence of the Laurentide Ice Sheet, and the post-glacial CO2 rise on tropical climate. The control experiment is a Last Glacial Maximum simulation (including ice-sheet configuration, orbital parameters, land surface characteristics, and trace gas concentrations appropriate for 21k). Two additional experiments have been conducted, the first with an 11k ice-sheet configuration and the second with an 11k ice-sheet configuration and 280 ppm CO2. All other boundary conditions remain constant in these sensitivity experiments. Preliminary model results indicate that the extratropical forcing has a substantial effect on tropical climate and the ITCZ. Deglaciation causes a pronounced (5-10°latitude) northward shift in the position of the ITCZ. This in turn has an effect on SST and thermocline structure in the Pacific, leading to changes in the periodicity and magnitude of interannual and interdecadal variability. The tropical Pacific warms 2-3°C in the LGM simulation compared to the 11k ice-sheet experiment, whereas a cooling of 10°C in the Southern Ocean, south of Australia, occurs between the same two experiments. Furthermore, the Asian monsoon appears to be affected by the change in glacial boundary conditions with stronger convective precipitation during times of full glaciation. Model results demonstrate that extratropical forcing may have caused significant climate changes in the tropics.

PP22A-1206 1330h POSTER

A Meta-analysis of Tropical Surface Temperatures at the Last Glacial Maximum

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Based on direct measurements of gas trapped in ice cores, we know that fluctuations in CO2 levels and glacial periods are highly synchronous. However, we have no direct means of measuring past temperature, so we must rely on proxies that correlate with temperature to infer temperature variability through time. A concerted effort to measure the change in global temperature since the Last Glacial Maximum (LGM) was undertaken by CLIMAP (1980) who estimated tropical sea surface temperatures during the LGM to be 1.5° ± 1.2 C cooler than today. Since the first estimates of temperature at the LGM, numerous biological, chemical and physical temperature proxies have been developed. Estimates of tropical surface cooling at the LGM from these proxies have varied considerably (0-8°C). Here we conduct a meta-analysis of proxy estimates to arrive at an impartial approximation of tropical cooling at the LGM: 3.3° ± 2.0 C. This approximation of tropical surface temperature would suggest a mid-range climate sensitivity of about 3.5 ° C for the anticipated doubling of CO2. Developing more paleo-temperature proxies and evaluating existing proxies is critical to our understanding of how Earth's temperature responds to changes in CO2.

PP22B MCC: 3001-3003 Tuesday 1340h

Evolution of Earth's Greenhouse Effect II *(joint with A, GC)*

Presiding: **J Kiehl,** National Center for Atmospheric Research**; L C Sloan,** University of California, Santa Cruz

PP22B-01 1340h

Evolution of Earth's Greenhouse Effect

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The major factors contributing to Earth's greenhouse effect are discussed along with various quantitative methods for determining the greenhouse effect. Earth's greenhouse effect has evolved over geologic time scales and continues to evolve. The magnitude of Earth's greenhouse effect is explored for particular time periods of Earth's evolution from the Neoproterozoic to present. Coupled climate model simulations for these various time periods are used to estimate the magnitude of the greenhouse effect. A comparison is made between the present greenhouse effect and those of past times. The connection between the greenhouse effect and Earth's hydrologic cycle is also discussed. Finally, a comparison is made of between past greenhouse effects and that predicted for the end of the twenty-first century.

PP22B-02 1345h INVITED

Methane Greenhouses and Anti-Greenhouses During the Precambrian

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Methane was arguably an important greenhouse gas during the Archean and early Paleoproterozoic Eras, prior to the rise of O2 at 2.3 Ga (1,2). Atmospheric CH4 concentrations of 1000 ppmv or more are predicted, assuming that methanogenic bacteria evolved early and that they were widely distributed in the prevailing anaerobic biosphere (2,3). Indeed, previous models (1-3) may have underestimated both the concentration of CH4 and the greenhouse effect itself at this time. Knauth and Lowe (4) have used oxygen isotopes in cherts to argue that the mean surface temperature at 3.2-3.5 Ga was between 55oC and 85oC. The Sun is thought to have been some 23 percent dimmer at that time (5), so this would have required substantial greenhouse warming by both CH4 and CO2. Further constraints are imposed by the formation of hydrocarbon haze, and an accompanying "anti-greenhouse effect", if the CH4 concentration exceeds that of CO2 (2). Thus, only certain combinations of CH4 and CO2 are possible. The rise of O2 at 2.3 Ga destabilized the methane greenhouse, leading to widespread (possibly global) glaciation (1,6). The next 1.5 billion years were warm, however, as evidenced by the absence of glacial deposits and the continuing high temperatures implied by O isotopes in cherts (7). CH4 levels could have remained relatively high during this time, 20-100 ppmv, as a consequence of low concentrations of dissolved O2 and sulfate in the deep oceans, and increased recycling of organic matter by fermentation and methanogenesis (8,9). An increase in either O2 or dissolved sulfate at around 0.75 Ga may have once again decreased atmospheric CH4 levels and triggered the widespread Neoproterozoic glaciations.
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PP

PP22B-03 1405h INVITED

CO_2 as a Primary Driver of Phanerozoic Climate Change

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Recent studies have purported to show a closer correspondence between Phanerozoic records of cosmic ray flux and temperature than between CO_2 and temperature. The role of the greenhouse gas CO_2 in controlling global temperatures has therefore been questioned. Here we review the geologic records of CO_2 and glaciations and find that CO_2 was low during periods of long-lived and widespread continental glaciations and moderately-high to high during other, warmer periods. The CO_2 record is likely robust because independent proxy records are highly correlated with CO_2 predictions from geochemical models. The Phanerozoic shallow water $\delta^{18}O$ temperature record has been used to quantitatively test the importance of potential climate forcings, but it fails several first-order tests relative to well-established paleoclimatic indicators: both the early Paleozoic and Mesozoic are calculated to be too cold for too long. We explore the possible influence of seawater pH on the $\delta^{18}O$ record and find that a pH-corrected record matches both the glacial and CO_2 records much better. Periodic fluctuations in the cosmic ray flux may be of some climatic significance, but are likely of second-order importance on a multi-million year timescale.

PP22B-04 1420h INVITED

Global warming in the early Eocene: was it driven by carbon dioxide?

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A wide variety of geological evidence indicates Earth experienced extreme global warmth 50 million years ago. But proxy indicators generally suggest carbon dioxide levels similar to today's value. What, then, drove global warming in the Eocene ? We present a process-based earth systems modelling analysis of this Eocene climatic puzzle. In our atmospheric chemistry calculations, trace gas emissions from terrestrial ecosystems lead to significantly higher atmospheric methane and tropospheric ozone levels compared to the pre-industrial situation. Climatic feedback experiments, quantifying the radiative forcing of these gases, and stratospheric water vapour, demonstrate substantial land surface warming. We suggest therefore that the trace gas composition of the ancient atmosphere provides a coherent climate forcing mechanism accounting, in large part, for the global warmth of the early Eocene.

PP22B-05 1440h

Continental Break-up And Global Climatic Evolution

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The global cooling of the Earth at the end of the Proterozoic (750-550 Ma), possibly resulting in successive global glaciations, has been linked to the concomitant fragmentation of the long-lived supercontinent Rodinia. By coupling an ocean-atmosphere climate model to a global carbon cycle model, we show that the breakup of Rodinia induces a significant decrease in atmospheric pCO2 of 1320 ppm due to the intense runoff occurring in a dispersed continental configuration, and results in a progressive transition from a greenhouse' to an icehouse' climate.

PP22B-06 1455h

A Prominent Rise in Tropical SST during the Paleocene-Eocene Thermal Maximum as inferred from Mg/Ca, Isotope, and other data

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The Paleocene-Eocene Thermal Maximum (PETM) has been attributed to a rapid rise in greenhouse gas levels, possibly via extensive dissociation of marine clathrate. If so, warming should have theoretically occurred at all latitudes, though amplified toward the poles. Oxygen-isotope records reveal that high latitude sea surface temperature (SST) warmed by as much as 10°C, while worldwide bottom water temperatures increased by 5°C. To date, however, the character of the tropical SST response during the PETM remains unconstrained. Here we address this deficiency by measuring both the oxygen isotope and minor element (magnesium/calcium) ratios of planktonic foraminifera from a tropical Pacific deep-sea core to estimate changes in SST and sea-surface salinity (SSS). The core is from ODP Site 1209 located on Shatsky Rise. The P/E boundary layer is represented by a dark horizon imbedded in a carbonate-rich nannofossil ooze. Samples were collected at high-resolution across this layer for a variety of analyses. Stable isotope analyses of single specimen mixed-layer foraminifera, *Morozovella velascoensis* and *Acarinina soldadoensis* show the classic -3.0‰ $\delta^{13}C$ excursion as well as a -0.7‰ $\delta^{18}O$ excursion. Minor element analyses of the same species reveal a prominent excursion in Mg/Ca ratios from 3.6 to 5.5 mmol/mol. The excursions in the isotope and Mg/Ca records appear to initiate a few cm below the sharp lithologic contact that marks the base of the clay rich layer, peak about 20 cm above. Sr/Ca ratios on the other hand remain constant. Other proxies of preservation show no correlation to the Mg/Ca. Thus, the combined isotope/minor element proxies imply a 4.5-5.0°C rise in Pacific SST during the PETM. From the residual in the oxygen isotope record, we estimate an SSS increase of 1-2 ppt. These results, when considered with SST data for high-latitudes, are consistent with model simulated tropical SST response to roughly a doubling of atmospheric pCO_2.

PP22B-07 1510h

Equilibrium Tropical Climate Sensitivity Determination from Paleoclimatic Data

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The key scientific uncertainty in the global warming debate is the equilibrium climate response to a doubling of atmospheric carbon dioxide. Coupled atmosphere-ocean general circulation models predict a wide range of equilibrium climate sensitivities (2.0 to 5.1 deg C), with a consequently large spread of societal implications. Comparison of models with instrumental data have not been able to reduce the uncertainty in climate sensitivity. An alternative way to gauge equilibrium climate sensitivity is to use paleoclimatic data. Two recent advances, the development and application of proxy recorders of tropical sea surface temperature (SST) and the synchronization of the deep-sea and Antarctic ice-core time scales, make it possible to directly relate past changes in tropical SST to atmospheric carbon dioxide levels. A detailed 360 ky record of past tropical SST variations in the warm (modern SST = 26.2 deg C) eastern equatorial Pacific waters north of the Galapagos Islands was previously obtained from core TR163-19 (2 deg N, 91 deg W: 2348m) (Lea et al., 2000). A new age model has been developed for this record by aligning the benthic O18 record of TR163-19 to nearby core V19-30, which itself has been aligned to Vostok air O18 (Shackleton, 2000). Using this age model, the coherency between the TR163-19 SST record and Vostok CO2 is 0.98 at 100k and 0.94 at 41k (0 phase lag). The strong correspondence of tropical Pacific SST and Vostok CO2 leads to the hypothesis that atmospheric carbon dioxide variations are the dominant control on tropical climate on orbital time scales (100k, 41k). Calibration of the influence of past greenhouse gas variability (CO2 and methane) on tropical SST indicates a tropical climate sensitivity equivalent to 4.4 plus/minus 1 deg C for a 4 W per sq. m radiative increase from doubling of atmospheric pCO2. This result suggests that the equilibrium response of tropical climate to atmospheric CO2 changes might be similar to the upper end of available predictions from coupled models. The two key uncertainties in this study are: 1) the degree to which factors other than greenhouse gases (e.g., ice volume) affect tropical SSTs, which could be tested by GCMs; and, 2) the reliance on a single site with potential regional sensitivity, which could be improved by using multiple tropical SST records.

URL: http://www.geol.ucsb.edu/faculty/lea/

PP22B-08 1525h

Estimating climate sensitivity from paleo-data.

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For twenty years estimates of climate sensitivity from the instrumental record have neen between about 1.5-4.5°C for a doubling of CO2. Various efforts, most notably by J. Hansen, and M. Hoffert and C. Covey. have been made to test this range against paleo-data for the ice age and Cretaceous, yielding approximately the same range with a "best guess" sensitivity of about 2.0-3.0°C. Here we re-examine this issue with new paleo-data and also include information for the time period 1000-present. For this latter interval formal pdfs can for the first time be calculated for paleo data. Regardless of the time interval examined we generally find that paleo-sensitivities still fall within the range of about 1.5-4.5°C. The primary impediments to more precise determinations involve not only uncertainties in forcings but also the paleo reconstructions. Barring a dramatic breakthrough in reconciliation of some long-standing differences in the magnitude of paleotemperature estimates for different proxies, the range of paleo-sensitivities will continue to have this uncertainty. This range can be considered either unsatisfactory or satisfactory. It is unsatisfactory because some may consider it insufficiently precise. It is satisfactory in the sense that the range is both robust and entirely consistent with the range independently estimated from the instrumental record.

PP22C MCC: 3001-3003 Tuesday 1600h

Old World Social Responses to Holocene Abrupt Climate Change Events I *(joint with B, GC, PA, HG)*

Presiding: **H Weiss,** Yale University**; L Ristvet,** Cambridge University

PP22C-01 1600h

Work More? The 8.2 kaBP Abrupt Climate Change Event and the Origins of Irrigation Agriculture and Surplus Agro-Production in Mesopotamia

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The West Asian archaeological record is of sufficient transparency and resolution to permit observation of the social responses to the major Holocene abrupt climate change events at 8.2, 5.2 and 4.2 kaBP. The 8.2kaBP abrupt climate change event in West Asia was a three hundred year aridification and cooling episode. During this period rain-fed agriculture, established for over a millennium in northern Mesopotamia, suddenly collapsed. Irrigation agriculture, pastoral nomadism, or migration were the only subsistence alternatives