OS31G-117 0830h POSTER

Coordinating a Fleet of Autonomous Underwater Glider Using a Decision Theoretic Approach in a Multi-agent System

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Autonomous underwater Gliders have the ability to patrol the subsurface Ocean for long durations. They surface at regular intervals to transmit data and download new sets of instructions. A small fleet of Gliders can improve efficiency and help scientists study the subsurface features of coastal waters around-the-clock and at controllable locations. A Glider fleet could be coordinated with a preset instruction set, but events measured from other scientific systems or model forecasts can change the sampling priorities. To direct the Glider Fleet to desirable locations there will be need for a scientist who studies data from various sources and provides new instructions for the Glider fleet to be downloaded. The focus of this research is to automate the coordination of the Glider Fleet given the information from the components of regional observation network to minimize direct human involvement.

It is proposed in this research to develop a flexible, autonomous and a responsive software tool to coordinate a Glider Fleet. The coordinating software design is based on a Decision Theoretic Expert System. The field of Decision Analysis studies the application of Decision Theory to solve actual decision problems. The system will make optimal decisions based on available evidence. This software will be both adaptable and adaptive. The adaptable behavior will allow it to take instructions from the user and change the download instructions for the Gliders accordingly. The ability of the software to change the instruction set for the Gliders without human intervention provided some evidence is available demonstrates adaptivity. The advantage of using Decision Theory over other approaches is its ability to incorporate uncertainty in the environment and taking into account the value of information before making decision.

URL: http://marine.rutgers.edu/cool

OS31H HC: 317 B Wednesday 0830h

Quantification and Regionalization of Benthic Flux Rates: Implications for Ocean Budgets I

Presiding: **C Hensen,** Fachbereich Geowissenschaften Universitt Bremen **; M Zabel,** Fachbereich Geowissenschaften Universitt Bremen **; C E Reimers,** Oregon State University

OS31H-01 0830h INVITED

Implications of deep-sea benthic oxygen demand on the sinking organic matter flux, its reactivity, and the relationship to overlying productivity.

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Benthic oxygen fluxes in deep-sea sediments reflect both the influx of utilizable organic matter and the supply of oxygen from the bottom waters. When organic matter influx rates are low, oxygen penetrates relatively deep into the sediments and aerobic respiration predominates in the consumption of organic material. Under greater organic carbon rain rates, the supply of oxygen may become limiting and anaerobic metabolism may result. A simple diagenetic model of pore water oxygen was developed to look at the relationship of organic matter influx to the proportioning of aerobic versus anaerobic oxidation. The model is sensitive to the organic matter decay coefficient and where the incoming organic matter has material of different reactivities, the relationship may become more complex.. Under conditions where sediments are predominantly aerobic, measured benthic oxygen fluxes, reflecting the time-integrated rain rate, were correlated with overlying primary productivities estimated from recent global maps. The results suggest greater carbon input to the deep-sea than predicted from past sediment-trap relationships. The linkage of the model and the data correlations suggest the possibility for examining global distributions of greater aerobic or greater anaerobic metabolism, or for investigating global distributions of sinking organic matter reactivity.

OS31H-02 0850h

Quantification and Regionalization of Benthic Silicate Fluxes along the Continental Margin off W-Africa, California and Chile - a Case Study in Upwelling and low Lateral Transport Regions

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The quantification of benthic flux rates across the sediment-water-interface by identifying their control parameters and regional distribution patterns plays an import role in understanding the global ocean cycles.

Within a large database of control parameters the primary productivity, water depth or the total organic carbon content (TOC) were combined with the available determinations of benthic silicate flux rates to generate regional distribution maps of the benthic silicate release. The investigated areas comprise the continental margins of W-Africa, Chile and California because they belong to the most intensively investigated regions at present.

Generally, there exists a reasonable but not strong correlation of TOC with benthic silicate fluxes. But regionally, they are affected by other factors like currents induced a lateral transport process, which, however, complicates the relation between benthic processes and the upper water column. To overcome this problem, finally, we have defined five biogeochemical provinces along the continental margin of W-Africa. Therefore independent geographical and oceanographically boundary conditions, like climate regions of the hinterland, distances to the coast, current systems, fluviatil input or location of oxygen minimum zones have been considered. These regions are known as high productive areas and different terrigenous input.

At first, we can show that there is a strong and significant relation between the benthic silicate release and the TOC, which is specific in each province and characterize them. Regression analyses verify the high significance of these relations by a regression coefficient of more than r^2=0.92. Based on this findings a Siflux(TOC) function could be formulated for every biogeochemical province. The empirically determined transfer functions were applied on a new generated TOC grid in a $0.2^\circ \times 0.2^\circ$ resolution grid via kriging interpolation method and provide a high-resolution benthic silicate flux grid.

However, the definition and the comparison of five biogeochemical provinces along the continental margin of W-Africa gives us the possibility to transfer and apply the developed Siflux(TOC) functions on comparable biogeochemical regions in the world ocean with a low database of measured benthic silicate fluxes. The results are very promising and put us in the position to receive benthic silicate release distribution maps on a global scale, based on a high-resolution database of the control parameter TOC.

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OS31H-03 0905h

In situ Measurements of Solute Transport Velocities in Permeable Shelf Sands

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Solute transport rates within the uppermost 2 cm of the sediment column of a continental shelf sand deposit, with a mean grain size of 450 μm and permeabilities of 1-2.5E-11 m^2, have been measured *in situ* by detecting the breakthrough of a pulse of dissolved iodide after its injection into the bottom water. These tracer experiments were conducted in the Middle Atlantic Bight at a water depth of $\sim$13 m from a small tethered tripod that carried a microprofiling system for positioning and operating a solid-state voltammetric microelectrode, close-up video camera, acoustic current meter and a motorized 1-liter "syringe". When triggered by a switch operated on shipboard, the syringe delivered a solution of 0.21M KI and red dye through five nozzles positioned around and above the buried tip of the voltammetric sensor for 1 to 5 minutes. Mixing by bottom turbulence quickly dispersed the tracer, and a timed sequence of repetitive voltammetric scans was used to monitor the subsequent migration of iodide into the sand. The average one-dimensional vertical velocity, expressed as the depth of the sensor tip in the sand divided by the breakthrough time, was found to vary from 0.002 to 0.005 cm s^{-1} and to generally decrease with depth. Because of dispersion and episodic sediment transport associated with the greatest 5% of wave heights and current speeds recorded, some concentration versus time responses showed evidence of uneven solute migration. Pore water advection was also evident in oxygen profiles measured before and after tracer injection with the voltammetric sensor. These profiles showed irregular distributions and oxygen penetration depths of 4 to 4.5 cm.

OS31H-04 0920h

Quantification of Erosion Rates of Particulate Organic and Inorganic Matter in a Continental Shelf: Implication for Biogeochemical Cycles

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In most nearshore and continental shelf areas, the combination of high surface productivity and relative shallow water column depth results in high carbon sedimentation rates. Only a small fraction of the deposited organic matter becomes permanently buried whereas a significant fraction is influenced by resuspension processes. Thus sediment transport processes play an important role in the biogeochemical cycles in continental margin regions. If prediction of non-cohesive sediment transport is quite reliable, it is not the case for cohesive sediment because of the large number of parameters involved and their highly complex interactions. Modeling of sediment erosion and transport requires a description of erosional properties of the bed. For instance the two main variables of interest are critical shear stress and erosion rate. Unlike most experimental and modeling studies considering total particulate matter, we included the organic fraction in our resuspension process study. Resuspension experiments were performed in a recirculating flume using natural sediments from continental shelf of Gulf of Lion (Marseille, France) to assess their stability against erosion. Cohesive sediments were collected with a multi-corer at 3 sites (40, 100, 160 water depth) situated along a transect from the Rhne river mouth to the shelf break. Several sediment parameters, critical shear stress of erosion and erosion rates of both inorganic and organic particulate matter were measured. A high frequency sampling during the bloom revealed that erosion rates and critical shear stress vary temporally. Variations of critical shear stress were correlated with clay contents and those of erosion rates with silt contents. The sampling period presented two maximums of erosion rate of particulate organic matter, which are related to high sediment organic contents. An increase from coast to offshore areas in critical shear stress (0.031-0.048 N.m-2) was observed along the transect. This can be related to the observed increase in bulk density (1286-1561 kg.m-3). Consequently a decreasing erosion rates of particulate matter (63- 40 g.m-2 .h-1) and particulate organic matter (17-7 g.m-2.h-1) was measured. These results suggest that sediments located near the river mouth, which are more easily eroded, are likely to play an important role in transferring particulate organic matter through the water column. Indeed, first assessment shows that after one hour erosion at 0.2 N.m-2 corresponding to a frequently observed wind induced bottom stress, the input of organic phosphorous and nitrogenous particles represents around 10% of the stock within the overlaying water column. A resuspension model was used to reproduce the suspended

sediment concentration in the flume. Considering different erosion rate formulae, best results were obtained using Parchure and Mehtas relationship for soft beds. Simulations were highly sensitive to the definition of erosion threshold. This confirms the necessity to focus further works on modeling critical shear stress in order to develop predictive models for exchange processes of particulate matter in the benthic boundary layer.

OS31H-05 0935h

Enhancement of Fine Particle Deposition to Permeable Sediments

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Predictions of deposition rate are integral to the study of the transport of many constituents including contaminants and organic matter. Generally, fine particle deposition rates are assumed to be equivalent to the suspension settling velocity, therefore, deposition rates in excess of settling are considered enhanced. Flume observations of deposition were made using treatments that covered a wide range of flow, particle, and bed conditions. Specific treatments demonstrated large enhancements (up to eight times settling). Delivery of particles to the interface is important, but models based on delivery alone failed to predict the observed enhancement. This necessitated the development of a new model based on a balance between delivery and filtration in the bed. Interfacial diffusion was chosen as a model for particle delivery. Fluid flow predictions by the model, such as slip at the sediment water interface and fluid penetration into the sediment, appear to be supported by flume experiments. Filtration of particles by the bed is a useful framework for retention, but the shear in the interstitial flow may introduce additional factors not included in traditional filtration experiments. The magnitude of enhancement was attributed to far greater filtration efficiencies for the sediment water interface than those previously reported in sediment columns. The observation of enhanced deposition to flat sediment beds reinforces the importance of permeable sediments to the mediation of transport from the water column to the sediment bed.

OS31H-06 1010h

Significant Slope Sediment Bio-Irrigation: Sediment-Water Exchange Rates from the Western U.S. Margin

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Any biogeochemical model which incorporates sea floor processes must parameterize solute-overlying water exchange. We are providing a data-based model that suggests bio-irrigation, the pumping of bottom water through the sediments by biological mechanisms, is important at water depths far greater than previously assumed and therefore must be considered as a transport mechanism in margin sediments. Bio-irrigation rates, modeled as a non-local exchange process, are presented from California Borderland basins (900-3700 m), Central California margin (100-3600 m), and the vicinity of Hydrate Ridge on the Cascadia margin (700-1800 m). Combined flux chamber deployments and sediment pore water analysis were made at each California site. Bio-irrigation rates were calculated by modeling the uptake of the conservative tracer Br^- injected into the chamber and the flux of natural ^{222}Rn. The depth of irrigation was based on Br^- and ^{222}Rn modeling utilizing chamber data. On the Cascadia Margin, high-resolution ^{222}Rn profiles were measured in near-surface pore waters extracted with a whole core squeezer, and bio-irrigation rates were calculated by fitting a one-dimensional transport-reaction model to the data. Comparison between calculated flux rates and the result of a nearby benthic chamber deployment allowed the bio-irrigation depth to be constrained. The Borderland basin sediments were variable, with some characterized as diffusive systems and others showing bio-irrigation. At the central California coast, bio-irrigation rates decreased with increasing water depth, and were negligible at the 3600 m site. On the Cascadia Margin, high bio-irrigation rates were found at Hydrate Ridge, with lower values at surrounding sites. On the Central California and Cascadia margins, bio-irrigation rates remain large within the oxygen minimum zone and are comparable to those reported for shelf and estuarine environments. At all sites below 100 m, the calculated bio-irrigation depth was less than 5 cm. Although pore water nutrient profiles from the California margin demonstrate that bio-irrigation can extend to depths of 1 m or more, bio-irrigation rates below 5 cm must be too low to influence short-lived tracer transport.

OS31H-07 1025h

Spatial and Temporal Variability of Benthic Fluxes in the North-Western Black Sea

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In-situ flux chamber experiments and sediment analysis in the North-Western Black Sea in summer 1995, spring 1997 and 1998 show spatial and temporal variability in the benthic nutrient recycling. The spatial variability reveals a region of high benthic fluxes near-shore within 20 km from the coast (about 2400 km2) and a region of low benthic fluxes on the offshore shelf (about 45600 km2). Near-shore, the intense benthic recycling and high benthic nutrient fluxes are triggered by high productivity and high sedimentation caused by river input of organic matter and nutrients. The anticyclonic circulation near-shore, driven by river influx and wind, keeps water with high nutrient and particle load near-shore, moving the water masses south along the Romanian and Bulgarian coast. Here, benthic fluxes are about one order of magnitude higher (1.24 mmol ammonia m-2 d-1) than on the off-shore shelf (0.16 mmol ammonia m-2 d-1). Lower nutrient content in the near-shore sediments (0.6-2.2% POC of dry weight sediment) than in the deep basins sediments (2.8-4.4% POC) might be a hint to intense nutrient recycling near-shore and a better preservation of organic matter in the deep basin sediments. In the low flux region off-shore, the low benthic fluxes are due to low productivity induced by low nutrient concentrations in the water column.

Seasonal variability was observed both in high and low flux regions, triggered by the sedimentation of organic matter. Benthic fluxes are higher in summer than in spring, on average. However, inter-annual variability has to be considered as well. We suspect that inter-annual variability is driven by the oxygen concentration of the water due to wind induced mixing and oxygen penetration into the sediment and by the sedimentation rate of organic matter.

Comparison of the Danube input with the benthic fluxes reveals that the Black Sea shelf is a sink for the riverine nitrate load. Since the river input is phosphate deficient, the benthic recycling of phosphate is an important factor sustaining high productivity in the coastal zone of the Black Sea.

OS31H-08 1040h

Laboratory, Field and In situ study of Metal behaviour and Oxygen Flux within a North Sea Drill Cuttings Pile.

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This paper presents results of dissolved (<0.2 micron grain size) and total (>0.2 micron grain size) metal (Cd, Co, Cr, Cu, Mo, Ni, Pb, U, V, Zn) concentrations with concurrent in-situ oxygen and sulphide micro-profiles from a North Sea offshore drill cuttings pile. The simultaneous analysis of geochemical carrier substances (Mn and Fe oxyhydroxides), ^{210}Pb (to assess sediment mixing) and an indicator of drill cuttings (Ba) are presented. These are used in conjunction with the oxygen and sulphide measurements to examine processes controlling metal behaviour within the cuttings piles. The in-situ data were collected using a Remotely Operated Vehicle (ROV) in conjunction with a microelectrode benthic profiling system capable of measuring rapid biogeochemical changes close to the sediment water - interface. Data obtained give evidence that the most rapid biogeochemical reactions and fluxes take place near the centre of the cuttings pile. Here the largest total metal concentrations occur along with a rapid rate of organic matter decomposition (43.6 g C $m^{-2}y^{-1}$) and oxygen consumption (233 mol m^{-3}. m^{-1}). The precipitation of metal mono- and disulphides were directly observed within the pile. Metal fluxes determined suggest that low exchange rates of metals with overlying seawater are observed under the low energy conditions persisting in the cuttings pile when sampled. There was no sediment mixing at the station closest to the platform but mixing in the surface sediment increases with increasing distance from the platform.

OS31H-09 1055h

Sediment Community Oxygen Consumption Variability in the SW Gulf of Mexico

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Recent studies illustrate that tropical seas can have a large variability in the structure and function of their benthic communities in spite of the persistent oligotrophy of their waters. This variability occurs at the local, regional and temporal scales. This variability can be attributed to a complex set of sediment environmental variables and the changes of the ratio between the different infaunal components. Estimates of sediment community oxygen consumption (SCOC) at 16 localities of soft-bottom sediments of the shelf, slope and abyssal plain in the SW Gulf of Mexico showed significant differences at the regional level, which can be attributed to the major processes that define the habitats. The approach for measuring oxygen demand were ship-board incubations of recovered soft-bottom sediment with overlying water at in situ temperature using replicated experimental incubation chambers that were maintained in the dark and at constant temperature. SCOC in the abyssal plain was measured using a benthic lander. The SCOC rates were 4 times higher on the Yucatan shelf in contrast to Tamaulipas and the Bay of Campeche. The lowest SCOC mean rates occurred on the Sigsbee abyssal plain. Local significant differences were recorded on the Yucatan shelf and the Campeche shelf and margin. Seasonal changes were significant on the Campeche continental margin with the highest SCOC rates recorded during the summer rainy season, two times higher than rates recorded in the winter storm season. Depth, and sediment factors mean sediment grain size, and nitrogen content in sediment accounted for 95.3% of the total variance. SCOC and the infaunal biomass were positively correlated on the shelf, as was the bacterial biomass. The meiofaunal biomass was significantly correlated with the SCOC both in the Campeche and the Tamaulipas regions. The variability of SCOC characterises the SW Gulf of Mexico as highly complex responding at the local, regional and seasonal scales. At the local scale the biological activity is responsible of redistribution of organic carbon and dispersion observed. At the regional and seasonal scales, upwellings and outwellings affect the fate of organic carbon and SCOC. The continental margin was considered a relevant feature for tropical basins where high biological activity takes place.

OS31H-10 1110h

Organic Carbon Cycling in Diatom-Inhabited Muddy Sediments

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The diatom-inhabited sediments of the North Adriatic Sea are characterised by different trophic conditions shifting over time from photoautotrophy to heterotrophy. In these areas a significant fraction of the photosynthetically fixed carbon is released by benthic

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microalgae as extracellular carbohydrates that apparently tightly coupled to heterotrophic dynamics. Sedimentary organic carbon utilization by benthic consumers is strictly influenced by its biochemical composition mainly consisting of proteins followed by lipids and water-soluble carbohydrates. Potential organic carbon (OC) turnover is generally rapid (7-14 d^{-1}) suggesting freshly produced material to the sea floor. The faster turnover times corresponde to greater DOC benthic efflux confirming an efficient bacterial decomposition. On the other hand, vertical fluxes provide very low OC inputs that cannot explain the values of benthic production observed. The microphytobenthic production is a potentially important alternative OC source for benthic consumers. Total autochthonous production however is unable to sustain the benthic community metabolism neither in net photoautotrophy conditions therefore important allochthonous inputs (i.e. material brought from the river or by lateral advection) must be present.

OS31I HC: 318 A Wednesday 0830h

Paleoceanography of Warm and Cold Climates During the Cenozoic Cooling Trend

Presiding: **D Seidov,** Pennsylvania State University**; E Barron,** Pennsylvania State University**; L Sloan,** University of California, Santa Cruz Cruz

OS31I-01 0830h

What can we Learn About the Oceans Role in Climate From the Cenozoic Cooling Trend? An Introduction

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The Cenozoic contains a rich record of climate change, including a cooling trend occurring over tens of millions of years and a number of abrupt steps or transitions. Observations suggest that the Late Cretaceous and Early Cenozoic deep ocean temperatures were as high as 15 degrees C, a condition not to be found subsequently. Transitions at key intervals, such as the Paleocene/Eocene boundary, provide strong evidence of large-scale changes in ocean circulation, its biota and in indicators of the character of the atmospheric circulation. The development of continental scale glaciation coincides with significant changes in the character and intensity of the ocean circulation. The mechanisms responsible for the cooling trend remain the subject of intense debate, but the role of the ocean is central in the majority of the hypotheses. This introduction provides an overview of the modeling efforts designed to simulate the global change in response to the evolution of the Earths surface since the Cretaceous. Three factors are considered: (1) Both land-sea distribution and the role of ocean gateways are key elements of model studies and in hypotheses of long-term climate change, (2) Carbon dioxide is believed to be a major contributor to the evolution of the Earths temperature and carbon dioxide is likely to be closely coupled to global tectonics. (3) Freshwater impacts in high latitudes could accompany and strongly influence cryosphere development during the Cenozoic cooling trend. Recent computer simulations indicate that these impacts could be an important element of the long-term climate change. These studies emphasize the role of the coupled ocean-atmosphere system in transporting heat poleward and the role of changes in continental configuration or freshwater inputs in altering the nature of the ocean circulation.

OS31I-02 0900h INVITED

Tropical Temperatures in Ancient Greenhouse Climates

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There is abundant geological evidence for warm, mostly ice-free poles in ancient warm climate phases such as in the Late Cretaceous and Paleogene periods. Two broad classes of explanation may account for this, namely a more efficient system of atmospheric and oceanic circulation and/or higher overall global temperatures, possibly due to an enhanced greenhouse effect. Previous investigations of sea surface temperatures (SSTs) in the tropics using the oxygen isotope ratio of planktonic foraminifer shells have tended to suggest relatively cool values (typically around 20 degrees or less), leading to the suggestion that a different arrangement of ocean currents may have warmed the poles while cooling the tropics. Such a climate system has been difficult to model, however. This "cool tropic paradox" and has forced all investigators to reconsider their data. For example, it has long been known that most planktonic foraminifer shells from deep-sea cores are recrystallized on a micron scale, a process that could potentially bias palaeotemperature measurements toward "cool" values. Recent investigation of exceptionally well-preserved Cretaceous and Eocene assemblages from Tanzania and elsewhere suggests much warmer temperatures than previously obtained (around 30 degrees or more). Furthermore, we have obtained very large inter-species carbon isotope differentials between species, which is consistent with the idea that the more normal recrystallized assemblages from deep sea chalks are generally affected by a very substantial diaagenetic overprint. The warm tropical SST values we have measured are consistent with climate models under enhanced greenhouse conditions and some other proxy data from exceptionally well preserved carbonates, and suggests that ancient warm climates may be a better analogue for future global warming than generally believed.

OS31I-03 0915h INVITED

Coupled Atmosphere-Ocean Models of the Cretaceous

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We will present results from a coupled atmosphere-ocean climate model simulation of the Cretaceous. We use the low resolution version of the latest Hadley Centre climate model. Realistic paleogeography, topography, and bathymetry were used. Carbon dioxide concentrations were set to 4 x pre-industrial concentrations. The ocean component was spun-up for 7000 years, and then run coupled to an atmosphere. The model simulates a very warm ocean, with tropical sea surface temperatures exceeding 33C in places. In addition, the deep ocean reaches temperatures in excess of 10C. The processes involved will be explained, and the implications for the terrestrial and marine data will be discussed.

OS31I-04 0930h

Model predicted ocean and atmosphere heat transport 50 million years ago: Implications for role of the ocean heat transport changes in past climates.

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One mechanism by which the oceans have been proposed to be important for understanding the nature of past climates is through the impact of ocean circulation changes on poleward heat transport. Ocean heat transport has been especially implicated in attempts to understand the presence of polar warmth and small meridional thermal gradients found in the Early Paleogene (65-40 Mya). We compiled datasets for topography, bathymetry, and vegetation for early Paleogene conditions and incorporated these in two simulations of early Paleogene climate using the latest version of NCARs CSM (v. 1.4), a fully coupled (ocean, atmosphere, land surface, sea-ice) general circulation model. The simulations were integrated for several thousand years in the deep ocean. For the first time, Paleogene climate has been simulated with a fully coupled model, and atmospheric and ocean heat fluxes are predicted in a self-consistent and coupled manner. Numerous differences between the early Paleogene cases relative to modern conditions, including the presence of a circumtropical seaway, the absence of an Antarctic Circumpolar Current, and concentrations of carbon dioxide twice pre-industrial values, have little effect on the general pattern of poleward heat transport in the ocean or the atmosphere. Sensitivity tests reveal that this prediction is extremely robust with respect to changes in initial conditions and even to between-simulation differences in the general flow patterns. These results do not support the role of major changes in ocean heat transport as causing past global climate changes, although support for regional climatic effects is found. Results from previous studies that used uncoupled ocean models may need to be reexamined in light of these results. These results challenge existing paradigms about the role of ocean heat transport in past warm climates.

OS31I-05 0945h

The Warm Deep?Ocean Conveyor During Cretaceous Period Driven by Surface Salinity Contrasts

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The warm deep ocean during the Cretaceous (65–130 Ma ago) has traditionally been explained by increased poleward oceanic heat transport. However, increased heat transport is difficult to explain in itself. It is unlikely that a heat transport far stronger than today existed with reduced oceanic thermal contrasts, causing a weak meridional overturning in the ocean. The presence of a warm, ice–free ocean during the Mesozoic–Cenozoic time period thus presents the most challenging problem in explaining of how a warm polar climate with very small meridional and vertical thermal gradients in the world ocean could be maintained by ocean circulation. Usually, atmospheric feedbacks in conjunction with increased atmospheric concentrations of greenhouse gases are employed to explain the warm equable Cretaceous–Eocene climate. The assumption of equatorially symmetric high–latitude sea surface temperatures is often used in atmospheric modeling and implicitly in data interpretation. However, no feasible physical mechanism – sea–water density depends on both temperature and salinity – could maintain warm subpolar surface oceans in both hemispheres. Our study exploits new interpretations of the geologic record as well as results of paleoclimate modeling, which indicates that the southern subpolar ocean was warmer than the northern oceans. We show that, assuming an asymmetry in sea surface thermohaline conditions between the Northern and Southern Hemispheres, a warm deep ocean could coexist with a relatively cool subpolar (high–latitude) sea surface in one hemisphere and a warmer subpolar sea surface in another hemisphere. The presence of a relatively cool high–latitude sea surface in at least one hemisphere is sufficient to drive the strong meridional overturning and corresponding poleward heat transport that kept the abyssal ocean warm during the Cretaceous and other warm–climate periods in geologic history.

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Warm Low-Latitude Temperatures in the Eocene: Evidence from the Oxygen Isotopic Compositions of Mollusks

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Oxygen isotopic data from planktonic foraminifera suggest that tropical sea-surface temperatures in the Eocene, a time of high-latitude warmth, were cooler than at present. This temperature distribution has been difficult to explain by climate models invoking high pCO2 or increased latitudinal heat transport. The "cool tropics paradox" has lead authors to question the fidelity of the planktonic foraminiferal isotopic record and to propose diagenetic influences (Pearson et al., 2001, Nature 413:481-487). To evaluate Eocene low-latitude temperatures and Paleogene cooling, we produced isotopic records of seasonal temperature variation in serially-sampled mollusks from the U.S. Gulf Coast (Mississippi, Alabama). We analyzed fossils from ten stratigraphic units ranging in age from about 54 to 30 Ma. The depositional environment for all but two units is confirmed as shallow based on foraminiferal assemblage and lithology. More than 2600 analyses were performed on 51 specimens of the gastropods *Conus, Turritella,* and *Mesalia*, and the bivalve *Venericardia* from normal marine salinity waters. Deposition in normal marine salinities is supported by carbon isotopic compositions.

Oxygen isotopic values increase roughly $1.5^{o}/_{oo}$ from middle Eocene to early Oligocene and