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The cause of the glacial / interglacial pCO_2 cycles remains elusive. What are we missing?

Direct effect of Fe fertilization. Pro: Iron deposition to Antarctica preceeds termination pCO_2 rise. Con: Might work in a box model but not in current GCMs. The difference, according to Toggweiler, is the extent of equilibration of high latitude surface waters. The processes that maintain disequilibrium in the GCMs operate even more strongly in the real ocean, so my unproven hunch is that the Fe fertilization would be insufficient in the real world, too. If not, the GCMs upon which CO_2 uptake calculations are based would be seriously in error.

Nutrient inventory of the ocean, driven by exposure of the continental shelves. Pro: pCO_2 broadly follows ice volume (with exception of terminations, where it leads). Con: If $CaCO_3$ production is stimulated along with organic carbon, then the $CaCO_3$ compensation response kills the pCO_2 drawdown.

Weathering vs. $CaCO_3$ deposition on continental shelves. Pro: We know that the flooding and exposure of the continental shelves must have perturbed the ocean $CaCO_3$ cycle profoundly. Con: The expected effects of this perturbation are not seen in deep sea $CaCO_3$ distribution.

Rain ratio shift, driven by increase in ocean Si. Pro: Ge/Si suggests LGM increase in Si weathering: increased dust deposition might be another source. Con: The ballast model for organic carbon sinking in ocean interior says that $CaCO_3$ carries 80% of the organic matter to the sea floor, making it difficult to change the OrgC/$CaCO_3$ ratio.

Southern Ocean physical processes or deep ocean temperature. Pro: Deep ocean temperature correlates with pCO_2. Con: Results from Stage 3, and from models, suggests that the termination pCO_2 rise is larger than can be accounted for by deep ocean temperature change alone.

GC61A-07 1035h

Limited Role of Export Production in Glacial-Interglacial CO_2 Cycles?

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Recent *in situ* experiments in the ocean have shown that marine productivity increases when iron availability increases. It has long been hypothesized that this effect may be responsible for part of the 80 ppm drawdown in atmospheric CO_2 at the Last Glacial Maximum (LGM), when atmospheric dust deposition was >2 times larger than it is today. Results from models of varying complexity suggest that this effect is responsible for 8-40 ppm, and for large regional changes in biological export production in the ocean. Here we use observations and a model to assess whether or not the remaining CO_2 drawdown not related to dust increase is also associated to changes in export production. We study two time periods: the LGM where all physical, chemical and biological changes were at their maximum intensity, and Stage 5a-d (80 to 110 kyr ago) where atmospheric dust deposition had not yet started to increase but CO_2 had already gone down by 50 ppm.

We compiled a global dataset of export production using 10 different indicators from over 130 deep-sea cores for the LGM, and from over 30 cores for Stage 5a-d. To investigate the mechanisms, we used a state-of-the-art ocean biogeochemistry model forced by LGM boundary conditions, with and without enhanced atmospheric dust deposition.

The observations highlight distinct regional changes in export production. At the LGM compared to today: export production was reduced south of 50°S and in the eastern North Pacific, but increased in Subantarctic and northwest Pacific. During Stage 5a-d, export production south of 50°S was already reduced to near-glacial levels, but it had not yet increased in the Subantarctic. The model can reproduce the patterns of export production during Stage 5a-d with changes in ocean circulation only. However, to reproduce the LGM patterns, increased iron deposition must be further imposed. The model suggests that increased export production only had an impact on atmospheric CO_2 between Stage 5a-d and the LGM.

We have focused so far on the South Atlantic ocean. Based on observations in that region, our analysis suggests that the first 50 ppm of atmospheric CO_2 drawdown would not be caused by an increase in export production, but would be more consistent with changes in physical or chemical processes.

URL: http://www.bgc-jena.mpg.de/bgc_prentice/projects/green_ocean/index.html

GC61A-08 1050h INVITED

Postglacial Terrestrial Carbon Dynamics and Atmospheric CO2

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Combining PMIP climate model results from the last glacial maximum (LGM) with biome modelling indicates the involvement of both cold, dry climate and physiological effects of low atmospheric CO2 in reducing tree cover on the continents. Further results with the LPJ dynamic vegetation model agree with independent evidence for greatly reduced terrestrial carbon storage at LGM, and suggest that terrestrial carbon storage continued to increase during the Holocene. These results point to predominantly oceanic explanations for preindustrial changes in atmospheric CO2, although land changes after the LGM may have contributed indirectly by reducing the aeolian marine Fe source and (on a longer time scale) by triggering CaCO3 compensation in the ocean.

GC61A-09 1110h

What can Re-growth of the Terrestrial Biosphere and the "Coral Reef Hypothesis" Tell us About the Primary Controls on Atmospheric CO_2 at Glacial Termination?

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Despite the identification of numerous different biogeochemical mechanisms for controlling atmospheric CO_2, we still do not fully understand why CO_2 was some 90 ppm lower during glacials than interglacials. Here, we analyze CO_2 changes since the time of the last glacial maximum in a time-dependent manner with the aid of an atmosphere-ocean-sediment carbon cycle model, focusing on the role of two key changes in the global carbon cycle we know to have taken place the re-growth of the terrestrial biosphere and increased shallow water carbonate deposition. We find that contrary to recent speculations, the land biota does not appear to make a significant contribution to the 20 ppm increase in atmospheric CO_2 observed during the late Holocene. Instead, we demonstrate that the late Holocene rise is consistent with the known history of increased deposition of shallow-water carbonates a revision of the "coral reef hypothesis". By subtracting the combined influence on atmospheric CO_2 of these two key processes from recent high-resolution ice core records, we show that the CO_2 change remaining to be accounted for is mainly restricted to two periods of rapid rise, occurring synchronous with Southern Hemisphere warming. This allows us to place strong constraints on the nature of the remaining processes, and propose that these must involve changes in: sea surface temperatures, "iron fertilization" of the biota, and ocean circulation and sea ice extent.

GC61A-10 1125h INVITED

What Caused the 20 ppm Rise in Atmospheric CO_2 Content Over the Last 8000 Years?

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The CO_2 record in the Taylor Dome Antarctica ice core clearly demonstrates that during the last 8000 years, the CO_2 content of the atmosphere rose from 260 to 280 ppm. Based on shaky ^{13}C results, Indermühle et al conclude that this rise reflects a 195-gigaton C (i.e., huge) decrease in terrestrial biomass. My feeling is instead that it reflects an early past glacial increase in terrestrial biomass. In this talk, I summarize an attempt to determine whether, as required by either scenario, the CO_2 rise was accompanied by an 8 μmol/kg decrease in deep carbonate ion concentration.

GC61A-11 1145h

How Strong is the Organic Pump in the Ocean?

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An average parcel of oceanic deep water contains about 15% more DIC than warm, low-latitude surface waters. A method for separating the deep DIC excess into its solubility, soft tissue, and carbonate components has been described by Volk and Hoffert (1985). The carbonate component is determined by using the alkalinity difference between deep water and average surface water. The soft tissue component is determined by using the phosphate difference from average surface water. The carbonate and organic components are subtracted from the overall DIC difference to determine the strength of the solubility component. According to Volk and Hoffert, the organic or soft tissue pump accounts for more than half of the surface-to-deep DIC difference in the ocean. The carbonate and solubility pumps come in a distant second and third, respectively, in relation to the organic pump.

The three components are separated here using an ocean model. The strength of the solubility pump is determined by running the model to a steady state with its biological processes switched off. The strength of the organic pump is determined with the models solubility and carbonate components switched off. The only agreement found between the model-based technique and that of Volk and Hoffert (1985) is in regard to the strength of the carbonate pump: the alkalinity difference between surface water and deep water turns out to be a fairly good predictor for the surface-to-deep DIC difference in the carbonate-only model. The surface-to-deep phosphate difference, on the other hand, is a poor predictor for the surface-to-deep DIC difference in the organic-only model. The organic pump in the model accounts for only 35% of the overall surface-to-deep DIC difference in the full model and, as such, only slightly exceeds the carbonate contribution at 25%. This is somewhat surprising, as the organisms in the model produce four times more organic C than CaCO3. The organic pump in the ocean is relatively weak because of the way that new deep water is formed in the Southern Ocean and because of the way that this process allows the CO2 from organic particles to cycle back up to the upper ocean via the atmosphere.

GC62A MCC: 102 Saturday 1330h

Carbon Cycle and Climate: Past, Present, and Future II *(joint with A, B, H, OS, PP)*

Presiding: **N Zeng,** University of Maryland**; M Heiman,** Max-Planck-Institut fuer Biogeochemie**; N Gruber,** University of California, Los Angeles

GC62A-01 1330h

Variability of terrestrial CO2 fluxes after volcanic eruptions

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Recent analyses report that terrestrial biospheric processes play a large role in the interannual variability in atmospheric CO2 concentrations, 13C/12C ratios and O2 concentrations. We use a biogeochemical model (CASA) to study the sensitivity of biospheric processes and net biospheric CO2 fluxes at the global scale to observations of interannual variability in climate (solar irradiance, temperature and precipitation), in vegetation amount (FPAR), and in volcanic aerosols during the period 1982 to 1998. The variability in terrestrial carbon fluxes during the two decades is dominated by ENSO cycles and the eruption Mt Pinatubo in 1991. Variability in the CO2 fluxes are mostly driven by changes in FPAR and by increases in diffuse irradiance caused by volcanic aerosols. The year following the Mt. Pinatubo eruption (1992) was marked by low growing season temperatures, low FPAR, increased diffuse irradiance and a reportedly large terrestrial carbon sink at the global scale. Low temperature inhibition of heterotrophic respiration was modest and only stimulation of production by increased diffuse irradiance could offset the influence of lower FPAR and could produce a terrestrial carbon sink for this period.

GC62A-02 1345h

Interannual Variability of CO_2 Sources Estimated Using Multiple Transport Models: Results from TransCom 3

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We estimate CO_2 sources from atmospheric concentration data using Bayesian synthesis inversion. The inversion is performed with 11 different transport models. Using error analyses and pseudodata simulations, an experimental setup has been designed that yields robust estimates of flux variability. We estimate CO_2 sources for 22 regions for the period 1989-2001 using around 80 observed concentration records. We find good agreement between models for the interannual variability of estimated sources, even when 1989-2001 mean regional fluxes may vary considerably between models. The impact on the flux variability estimates from transport model differences seems to be no larger than that due to certain methodological details in the inversions, such as the measurement sites, weights, and regularization approach used. For a given choice of the latter, we discuss the regional interannual variability obtained – certain features appear to correspond well with expected changes in CO_2 fluxes during the 1990s, especially with respect to El Niño, tropical biomass burning, volcanic aerosols, and changes in fossil fuel use.

GC62A-03 1400h INVITED

Daily European CO2 fluxes inferred by inversion of atmospheric transport

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Continuous measurements of atmospheric CO2 over continental areas offer the potential to better understand the carbon fluxes between the terrestrial biosphere and the atmosphere. Up to now, most atmospheric inversions have provided monthly fluxes averaged over large sub continental regions. Refining space and time resolution of European fluxes calculated by inversion of atmospheric transport requires i) continuous CO2 measurements over Europe, ii) a high resolution transport model that can reproduce the variability of CO2 over continents and provide continuous response functions at model resolution, and iii) an updated inverse procedure that can use the increased associated information.

We use here continuous CO2 measurements obtained through AEROCARB EU project (part of CARBOEUROPE cluster) for year 1998 at 10 continental stations to retrieve daily fluxes over Europe at model resolution with LMDZ transport model. LMDZ model is a global transport model with zoom and back-transport capabilities. A zoom was defined over Europe, with 0.4° maximum resolution. Back transport is based on self-adjoint property of atmospheric transport that makes it possible to get model daily response functions at model resolution and at low computing cost.

In this talk, we present the new features of the inverse procedure and we detail the LMDZ back transport. First results obtained for daily European fluxes of the two last months of 1998 are presented and analysed. The question of retrieving fossil emissions from continuous measurements is also developed.

GC62A-04 1420h

Interannual Variation of Carbon Fluxes From 1982 to 2000 Inferred From Atmospheric CO2 Data and Models

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Based on 20 years of NOAA/CMDL's atmospheric CO2 concentration data as well as a global atmospheric transport model, we estimate spatial and interannual patterns of surface CO2 fluxes, by using a Bayesian inversion technique. To increase reliability of temporal features, particular care is exerted towards the selection of data records that are homogeneous in time. Estimates of high-resolution grid-scale fluxes are constrained by a-priori correlations. The transport model is driven by interannual meteorological fields. We make consistent use of unsmoothed measurements.

In agreement with previous studies, we find that the pace of interannual variations of fluxes is predominantly set by El Nino / La Nina. The main exception is the 2-3 year duration of increased sink of atmospheric carbon after the Pinatubo eruption. Land fluxes are much more variable than ocean fluxes. The difference in fluxes between El Nino and La Nina is concentrated to the tropical land regions and is on the order of 2 to 3 PgC/yr. The El Nino / LaNina contrast for the oceans is characterized by reduced outgassing in the Eastern Pacific which is of a similar magnitude as the estimates of Feely et al. (1999). Globally ocean carbon uptake shows a trend similar to the one expected if ocean uptake scales linearly proportional to the anthropogenic atmospheric perturbation. Finally we find weak trends towards increased carbon uptake in the Western tropical Pacific and decreased uptake in the Eastern tropical Pacific.

The longterm mean surface CO2 flux field exhibits a northern hemisphere land sink on the order of 0.9 PgC/yr that is mainly confined to North America. Southern hemisphere land regions are carbon neutral, while the tropical land regions are taking up carbon at a rate of 0.5 PgC/yr. Ocean fluxes show larger uptake in the Northern mid to high latitudes than in the Southern mid latitude regions, in contrast to the estimates by Takahashi et al. (1999) based on in-situ measurements. On a regional basis, results that differ the most from previous estimates are large carbon uptake of 1 to 1.5 PgC/yr by the Southern temperate Pacific ocean region, weak outgassing from the Southern ocean, and a carbon source from Western Europe.

GC62A-05 1435h

A protoype carbon data assimilation system to infer interannual variations in vegetation-atmosphere CO_2 fluxes

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Atmospheric inversion studies have become an important tool for identifying terrestrial sources and sinks of CO_2 at the interannual time scale. We present results of a two-stage assimilation study of satellite radiances (identifying vegetation activity) and atmospheric concentration data into a terrestrial biosphere model. The assimilation optimizes the tunable parameters in the model (some spatially explicit, some global) and we predict the model evolution using these optimized parameters. We fit CO_2 data from 1979-99 and, via the optimized model, identify the processes responsible for the mean terrestrial fluxes and their variability. For example, we note that while the large terrestrial uptake following the Mt. Pinatubo eruption in 1991 is caused by an increase in photosynthesis, the anomalous source during the 1997-1998 El Nino arises from changes in soil respiration. Finally the uncertainties on the parameters, generated as part of the assimilation procedure, allow us to identify those processes which are well constrained by the data as well as assign uncertainties to predictions made using the optimized model.

GC62A-06 1450h

Linking current NBP and NPP estimates with the effect of rising CO2 over three forest biomes

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We have synthesized data on NPP (net primary productivity) and NBP (net biome productivity) over three exemplary forest biomes of the world in the Amazon , in Europe and in Siberia. Both NPP and NBP would be linked unambiguously if the effect of rising CO2 on plant productivity were to be the only underlying process. In reality, thus is not the case since disturbances (fires...) and forest management and N-deposition may also largely control the NBP. We used NBP and NPP measurements over different forest plots, large scale forest biomass inventories, global biosphere models, and atmospheric inversion results, most of these obtained as part of the CARBOEUROPE ensemble of research projects. This analysis of independent estimates of NBP and NPP illustrates the fact that over Europe and Siberia, CO2 fertilisation alone can hardly explain a small fraction (20%) of the current NBP, whereas over the Amazon, and for high productivities, this process is able to account for all the sink obtained in inversions, once the land use induced source is substracted. Large uncertainties in our approach pertain to the inversion-based estimates of NBP as well as to the estimates of NPP from plots in the tropics.

GC62A-07 1525h

Decadal trends in land and ocean carbon exchanges from atmospheric records of CO2 concentration and 13C/12C, 14C/12C, and O2/N2 ratios

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We examine the global atmospheric trends in CO2 concentration, the 14C/12C and 13C/12C ratios of CO2, and the O2/N2 ratio, with the goal of constraining possible decadal variability in CO2 uptake by the oceans and land biota and of constraining possible decadal fluctuations in the isotopic fractionation factors. We show that these combined records are inconsistent with large fluctuations in oceanic CO2 uptake on a decadal time scale but may imply secular shifts in the fractionation factor associated with photosynthetic uptake of CO2. We also examine short-term fluctuations in CO2, 13C/12C, and O2/N2 through the 1990s which confirm earlier suggestions that the variability in

atmospheric CO2 associated with El Nino phenomena is predominately caused by exchanges with land biota. We also present evidence for a global increase in ocean ventilation and associated uptake of O2 by the oceans commencing in 1999.

GC62A-08 1540h

Decadal Changes in Global Ocean Primary Production: Relationships to Climate Change

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An evaluation of decadal changes in global ocean primary production has not previously been possible due to incompatibilities between the CZCS (1978-1986) and the modern SeaWiFS (1997-present). Revision of the historical CZCS record has permitted a quantitative determination of decadal changes from the early 1980's to the present. Results indicate that global ocean annual primary production has declined over the two decadal time segments. Large decreases were observed in the high latitudes. In the northern high latitudes, these reductions in primary production were associated with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans. Three of four low latitude basins indicated decadal increases in annual primary production. These results show global and regional changes in ocean photosynthetic carbon uptake and how they may be related to climatic influences.

GC62A-09 1555h

Ocean carbon transport and atmospheric CO_2

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The oceanic transport of carbon by the large-scale ocean circulation and the associated air-sea exchange of CO_2 are a significant factor controlling the distribution of atmospheric CO_2, from which major inferences are made with regard to global-scale sources and sinks of CO_2. We present here new estimates of pre-industrial and present CO_2 air-sea exchange, their implied ocean carbon transport, and their impact on atmospheric CO_2 on the basis of an ocean inverse modeling method that uses ocean interior observations of dissolved inorganic carbon (DIC) and associated anthropogenic CO_2 estimates. The inversely estimated pre-industrial air-sea fluxes of CO_2 reveal the expected pattern of CO_2 uptake by the oceans in the mid to high latitudes and release back into the atmosphere in the low latitudes. By contrast, the air-sea flux of anthropogenic CO_2 is found to be into the ocean everywhere, totaling about 1.8 Pg C yr^{-1}. The pre-industrial CO_2 flux results imply a net oceanic transport of carbon in pre-industrial times from the high latitudes to the low latitudes and a corresponding transport in the opposite direction in the atmosphere. We find, however, a strong asymmetry between the two hemispheres. This asymmetry is largely caused by the Atlantic Ocean, where CO_2 is taken up at high latitudes and transported across the equator into the southern hemisphere with magnitudes in agreement with estimates derived from direct hydrographic inversions. This Atlantic transport gives rise to a modest cross-equatorial transport of about 0.4 PgC yr^{-1}. Our inversely estimated pre-industrial air-sea CO_2 fluxes nevertheless produce a south pole to north pole gradient of atmospheric CO_2 in pre-industrial times of nearly 1 ppm. Although this south-north interhemispheric gradient is significant, it is too small to negate the need for a large northern hemisphere land carbon sink in order to explain the currently observed atmospheric CO_2 gradients.

GC62A-10 1610h

Modeling the Combined Effects of CO2, Climate and Land Use on the Carbon Stocks of Plants and Soils

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A terrestrial carbon cycle component of the Integrated Science Assessment Model (ISAM) is used to examine the response of plant and soil carbon stocks to historical changes in land cover, land use management, atmospheric CO2 concentration and climate. This geographically-explicit implementation of ISAM simulates the carbon fluxes to and from different compartments of the terrestrial biosphere with 1-by-1 degree spatial resolution (longitude and latitude). Each 1-by-1 degree cell contains thirteen land coverage classifications, which represent both highly managed land uses and less managed biomes. Changes in areas between land cover classifications are driven by land uses that have resulted in, e.g., shifting-agriculture, afforestation, deforestation, and reforestation. Within each grid cell and land-coverage classification, the modeled carbon cycle includes feedback processes such as CO2 fertilization and temperature effects on photosynthesis, and respiration. Plant and soil carbon stocks for land-coverage classifications are also influenced by agriculture and forest management practices including, e.g., soil amendments and tillage. For the historical time period (1765 through 1990), CO2 sources and sinks are derived using the observed temperature change and CO2 concentrations along with surveys of past land cover change and shifts in management practices. After 1990, carbon fluxes are estimated based on the AOGCM based temperature distributions and ISAM based CO2 concentrations. The results are compared to other highly resolved models.

GC62A-11 1625h

Responses of Carbon Uptake to Uncertain Climatic and Economic Parameters in an Integrated Global Systems Model (IGSM)

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Significant uncertainty exists about the magnitude of carbon uptake in the next century. This uncertainty comes from a variety of factors, including economics of future emissions, ocean processes, temperature change, and ecosystem processes. The MIT IGSM contains detailed submodels to address each of these critical factors in the carbon cycle. A previous study showed that oceanic vertical mixing, parameterized by Kv, the coefficent of vertical diffusion, is the dominant uncertain parameter in the ocean component of the IGSM. In this new work we examine the relative contributions of the uncertainty in Kv, economic uncertainty, and climate sensitivity to the final values of carbon uptake by the ocean and the ecosystem. In a case where only climate parameters were allowed to vary and an economic scenario designed to achieve 550 ppm stabilization was used, regression analysis showed that about 96% of the ocean uptake resulted from variation in Kv. When uncertainty in the economic model was addressed, with the assumption of no climate policy, uncertainty in carbon dioxide emissions yielded about 55% of the variation in ocean uptake in 2100. Only about 40% of the variance was due to uncertainty in the coefficient of vertical diffusion. Therefore, the impact of climate sensitivity must be less than 5%. Under a sample policy regime based on extending the Kyoto protocol, emissions became more certain, and the dependence of the uncertainty on Kv increased to about 90%.

GC62A-12 1640h

A Comprehensive GCM-Based Climate and Carbon Cycle Model: Transient Simulations to Year 2100 Using Prescribed Greenhouse Gas Emissions

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We use an interactive global climate and carbon-cycle model to perform simulations of climate change from 1870 AD to 2100 AD forced by anthropogenic emissions of greenhouse gases. The goal of this effort is to produce a simulation tool capable of improved realism in future climate predictions. In particular, we seek to include and better understand feedbacks between the climate system and the carbon cycle. We use the Parallel Climate Model 2 (PCM-2) developed at NCAR as our climate model. The PCM-2 includes a version of NCARs CCM3 for the atmospheric GCM and a version of the POP model for the ocean GCM. The horizontal resolutions for atmosphere and ocean are T42 truncation (about 280 km) and 0.7 degrees (about 75 km), respectively. The ocean carbon model is based on OCMIP protocols, but modified to eliminate the phosphate-restoring restriction. The terrestrial biosphere model is IBIS-2 which simulates biophysical and biogeochemical surface fluxes and includes a dynamic vegetation model. The model is integrated to a pre-industrial equilibrium using a prescribed atmospheric CO2 concentration of 290 ppmv. This equilibrated state serves as the starting point for three transient simulations. The Control Case assumes zero net anthropogenic emissions and is used as a reference for model drift. The Full Interaction case assumes historical greenhouse emissions up to year 2000, then uses SRES A1B emissions up to year 2100. A Carbon Cycle Only Case is the same as the Full Interaction case, except that the greenhouse radiative forcing of climate is held fixed at preindustrial values. We will discuss the models simulation of the twentieth century climate and atmospheric CO2 concentrations, the strength of carbon cycle feedbacks, and compare our simulation results to those of Cox et al. (2000) and Friedlingstein et al. (2001).

GC72A MCC: Hall D Sunday 1330h

Carbon Cycle and Climate: Past, Present, and Future Posters III *(joint with A, B, H, OS, PP)*

Presiding: **N Zeng,** University of Maryland**; M Heiman,** Max-Planck-Institut fuer Biogeochemie**; N Gruber,** University of California, Los Angeles

GC72A-0201 1330h POSTER

Coupling Between Atmospheric $[CO_2]$ and Temperature During the last Millennium

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The Little Ice Age climate deterioration is the most recent cool pulse of a series of recurrent climate fluctuations throughout the Holocene. Within the ongoing discussion on the coupling of CO_2 and temperature, documentation of both parameters on a high temporal resolution is needed. Recent Northern Hemisphere temperature reconstructions based on tree-ring chronologies reveal a higher amplitude for temperature fluctuations during the last millennium than proposed so