

Towards the time dependent modeling of sediment core data on a global basis

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Abstract. The procedure for the simulation of a time dependent sediment stratigraphy for 4 different sediment species with a global biogeochemical ocean general circulation model is presented. In this feasibility study, a sediment column for the last 131 kyr was accumulated through use of a variable ocean velocity field (mixed from preindustrial and glacial ocean time slices in a kinematic approach). The biogenic components of sediment are entirely a model product. Artificial sediment cores were “recovered” from the simulated stratigraphy. The approach is the foundation for a systematic comparison of paleoclimate simulations with the sediment record. Through use of adjoint model codes the direct 4-dimensional data assimilation of paleoclimate observations will become possible in the long range.

Introduction

Global coupled atmosphere-ocean climate models can reproduce the modern climate reasonably well (for example [Roeckner *et al.*, 1999]). Use of these models in forecast mode in order to estimate the climatic change due to anthropogenic greenhouse gas emissions requires an additional capability: the models must reproduce rates of climate change correctly. A straightforward method for a test of the models’ sensitivity are paleoclimate experiments which are validated with paleoclimate data from terrestrial records and marine sediment cores. This feasibility study investigates, whether it is in practice possible to generate globally a time dependent marine sediment stratigraphy by use of a BOGCM (biogeochemical ocean general circulation model) over the last climatic cycle (from the Eemian around 130 kyr B.P. until today, kyr B.P. = 10^3 years before present), which is well documented by sediment and ice core data. The BOGCM uses a time dependent velocity field. At each model grid point, it predicts the sediment composition and accumulation rates. After the simulation, artificial sediment cores are “recovered” from the accumulated model sediment material.

Model description

Here, the HAMOCC BOGCM (HAMOCC = Hamburg Oceanic Carbon Cycle) [Maier-Reimer, 1993] is employed in its annually averaged version ([Heinze *et al.*, 1999]; [Heinze and Maier-Reimer, 1999]) with modifications as described in [Heinze *et al.*, in preparation]. The model includes the three reservoirs atmosphere, water column (11 layers), and bioturbated sediment (10 layers) with a horizontal resolution of $3.5^\circ \times 3.5^\circ$. The processes ocean/atmosphere gas exchange, biological export production (organic carbon, CaCO_3 , opal),

particle flux, redissolution, remineralisation and deposition onto the ocean floor, sediment pore water transport and chemistry, bioturbation, and sediment accumulation are represented through basic parameterisations. Tracers, which are predicted in space and time by the model are, in the atmosphere, CO_2 and O_2 , in the water column and the sediment pore waters, TCO_2 , TAlk, PO_4^{3-} , Si(OH)_4 , O_2 , DOC (water column only), and finally the solid sediment species CaCO_3 , opal, organic carbon, and clay. For biological particle export production, Michaelis-Menten nutrient uptake kinetics are used. Opal and organic carbon production are predicted on the basis of the corresponding nutrient concentrations in surface waters. CaCO_3 export production is computed proportionally to the local ratio of opal to organic carbon production and set to zero if the latter ratio exceeds a threshold value of 0.7 (on a molar Si:C basis). Instead of defining vertical redistribution profiles for biogenic matter in the water column, a revised particle flux scheme is applied allowing to separate particle redissolution kinetics and settling velocities and to predict local concentrations of particulate matter for all particle types within the water column. Close to full equilibration of the model, prescribed input rates of nutrients and carbon as well as alkalinity from continents are balanced by burial within the sediment. Compared to [Heinze *et al.*, 1999], a more realistic global opal accumulation rate of $5.5 \text{ teramoles Si yr}^{-1}$ could be achieved in the actual model for full equilibration. During a time dependent model run, transient global disequilibria between continental input and output by burial can occur. The pattern of the biogenic sediment accumulation and the local accumulation rates are prognostic variables. A homogeneous deposition rate of inert material (clay, weathering product of continental crust) of $1 \text{ g m}^{-2} \text{ yr}^{-1}$ is prescribed. Porewater diffusion and chemistry are treated simultaneously by use of an implicit numerical scheme using depth dependent porosities. The water column tracers are advected and mixed by use of physical input fields (velocities, hydrography, and seaice cover) from the dynamical LSG OGCM (LSG = Large Scale Geostrophic) (Maier-Reimer *et al.*, 1993). Here, two different velocity fields are used from the work of Winguth *et al.* (1999): one for the modern (or preindustrial) late Holocene ocean and another one for the Last Glacial Maximum (LGM, 21 kyr B.P.). The BOGCM is initialised with constant dissolved tracer concentrations in the water column as well as the sediment pore waters and inert clay sediment throughout. Besides biogenic export production rates and water column tracer distributions, the model then builds up its own biogenic sediment components and pore water distributions. The loss of material due to sediment accumulation is compensated through an influx of matter at the model surface layer. The model is computationally efficient (2000 years in 1 CPU hour on one processor of a Cray C-916 system).

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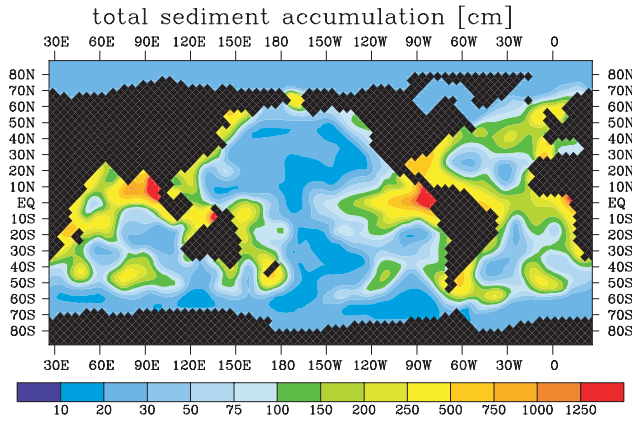


Figure 1. Thickness of sediment column which was accumulated by the model over the entire integration period of 131,000 years from the Eemian until today.

Experiment description

At present, no continuous temporally varying oceanic velocity field over the last climatic cycle is available. Therefore, such a preliminary variable velocity field was generated by mixing the preindustrial and LGM time slice computations in different proportions. This “kinematic” approach (the velocity fields are combined and averaged regardless of dynamical considerations) yields a time dependent flow field which has a good chance of at least giving appropriate results in the vicinity of the extreme climatic conditions (warm phases, glacial high times). It should be stressed, that the study presented here does not aim at a proper reconstruction of the last climatic cycle, but rather at an example for what will be possible once time dependent velocity fields from fully dynamical computations will become available. The model experiment was started in the Eemian at 131 kyr B.P. As initial conditions, the modern

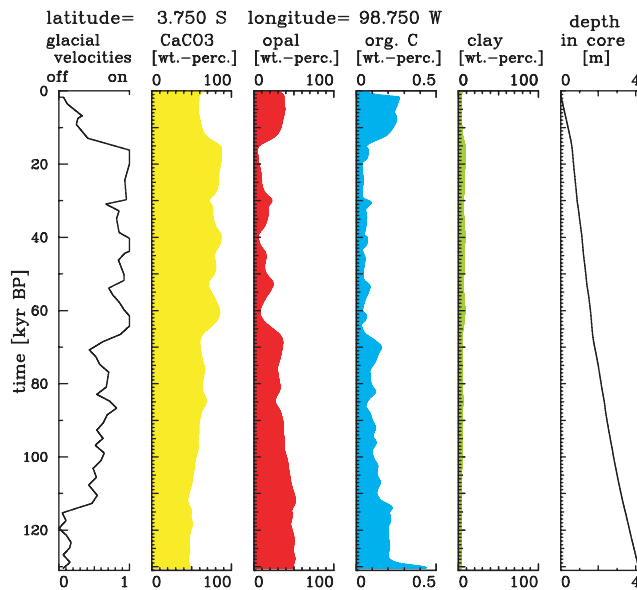


Figure 2. Example for a sediment core which was “recovered” from the artificially produced sediment column shown in Figure 1. The core is located in the central equatorial Pacific.

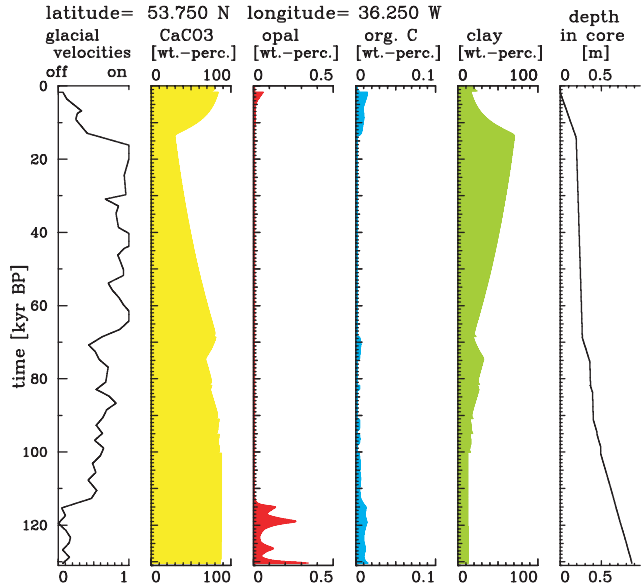


Figure 3. Example for a North Atlantic core, which was taken from the simulated sediment stratigraphy. The core location is within the deep western boundary current flowing southward along the east American continental margin. Sediment data are given vs. time.

velocity field and the corresponding biogeochemical distributions were taken with fully equilibrated sediment. The mixing of the two velocity fields was carried out by calibration with the Vostok ice core atmospheric $p\text{CO}_2$ time series from [Barnola *et al.*, 1999]. For $p\text{CO}_2$ values ≥ 280 ppm only the preindustrial field and for those < 194.5 ppm only the glacial field was applied. In between these threshold values, the two fields were averaged proportionally to the corresponding $p\text{CO}_2$ value. The experiment was annually

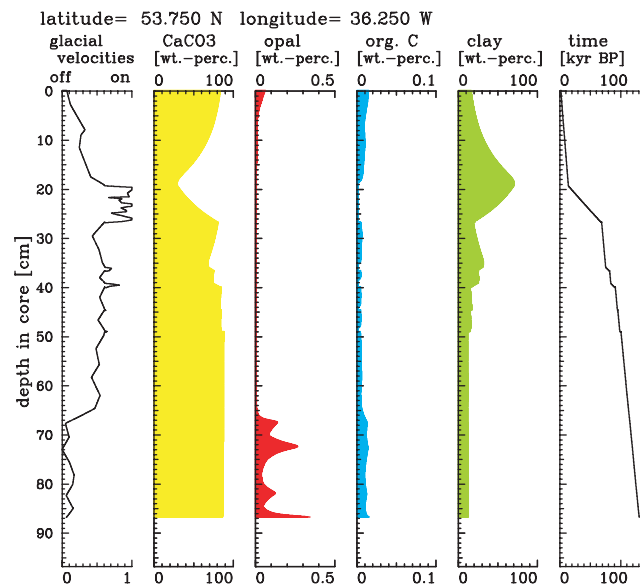


Figure 4. Data for the North Atlantic core as shown in Figure 3, but this time drawn vs. depth in core. On the rightmost panel the age model for the simulated core is given.

stepped forward in time from 131 kyr B.P. until 0 kyr B.P. At each time step and each grid point, the composition of the sediment being accumulated (weight percentages of CaCO₃, opal, organic carbon, and clay) and the sediment accumulation rates were archived on files. The final data base with continuous sediment stratigraphy over the last 131 kyr at 3452 wet gridpoints amounts to 27 Gbytes which are stored in a tape silo.

Results and discussion

The integrated total sediment column which was accumulated by the model over the entire integration period reflects primarily upwelling regions (e.g. in the eastern equatorial Pacific) and regions of high CaCO₃ preservation (e.g. Atlantic and western equatorial Pacific) (Figure 1). From this sediment with a formal vertical time resolution of 1 year (blurred by the bioturbation which was modelled in the BOGCM), sediment cores were “recovered” through extracting the sediment composition, depth in core, and time information from the data base (“drilling” into the database). As a first example, such an artificial sediment core from 3.75° S and 98.75° W in the central equatorial Pacific (Figure 2) clearly shows the increase of CaCO₃ preservation during glacial conditions as documented by the experimental analysis of [Farrell and Prell, 1989]. The core contains also sizable amounts of opal sediment. Decreased opal weight percentages during the glacial were deduced from observations in the eastern equatorial Pacific [Lyle et al., 1988]. In contrast to the Pacific site, an artificial sediment core taken in the western North Atlantic (Figure 3) in the region of the southward flowing deep western boundary current (53.75° N, 36.25° W) shows a more variable sediment accumulation (as indicated by “depth in core” in the rightmost vertical panel in Figures 2 and 3). The Atlantic core reveals the strong increase of CaCO₃ corrosion towards the last glacial maximum which is well documented by sediment core data from the real world (e.g. [Balsam, 1983]). In opposite to the Pacific Ocean core, the example from the western North Atlantic shows almost vanishing opal weight percentages. The simulation renders automatically an age model for each synthetically produced sediment column, which is shown for the Atlantic core in the rightmost vertical panel (“time”) of Figure 4. Strong increases in the time gradient with depth indicate temporal intervals of low sediment accumulation rates (especially around glacial high times 28-20 kyr B.P.). Model results can be compared directly with the observed sediment core data given versus depth in core. Though not even an age model for the observed core would be needed for comparison, at least selected age determinations of the observed data would be desirable in practice.

Summary and perspective

Though details of the simulation in quantitative terms need to be improved, the feasibility study shows: (1) It is possible to generate long sediment core data time series with a BOGCM. (2) The data amount generated by the simulation can be administrated and artificial sediment cores can be taken from the simulated record for comparison with observed records. (3) Direct comparison of model results with sediment core observations (even in cases where no continuous age model for the observations is available) is possible, because the model generates automatically age

models for each predicted core. (4) The model allows for “negative accumulation” (e.g., if sediment redissolution exceeds deposition) and therefore is able to model gaps in the stratigraphy (hiatus events). (5) The procedure can easily be extended to further paleoclimate tracers such as $\delta^{13}\text{C}$ of CaCO₃ and Pa/Th ratios.

In this study, the time for the sediment dating is set when the sediment leaves the bioturbated zone (at 10 cm depth below the water/sediment interface). It would be advisable, however, to set the model sediment clock to the actual time represented by the model time step when the modelled particles are deposited onto the sediment. For such a transfer of time information throughout the bioturbated zone, an additional time variable would be required for every solid sediment species. Improvements of the sediment model would include such a “time transport model” and also refinements of diagenetic processes (such as the addition of anaerobic chemistry). At this stage, the need for a compilation of a comprehensive, readily synchronisable global sediment core data base (observations) becomes obvious, which should ideally include detailed age information and should be automatically synchronisable for different stratigraphic reference curves such as time scale given in [Martinson et al., 1987]. On the basis of such a data collection, forthcoming coupled ocean atmosphere biogeochemistry GCM runs for the last climatic cycle could be validated. A long-term goal would be to use coupled atmosphere ocean biogeochemistry general circulation models in inverse mode, e.g. through application of the adjoint method. Time dependent sediment core data from observations could then be directly assimilated into the model system and step by step enable an optimal simulation of the past and future global climate evolution.

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References

- Balsam, W. L., Carbonate dissolution on the Muir Seamount (Western North Atlantic): Interglacial/glacial changes, *Journal of Sedimentary Petrology*, 53, 719-731, 1983.
- Barnola, J.M., D. Raynaud, C. Lorius, and N.I. Barkov, Historical CO₂ record from the Vostok ice core. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., 1999.
- Farrell, J. W., and W. L. Prell, Climatic change and CaCO₃ preservation: An 800,000 year bathymetric reconstruction from the central equatorial Pacific Ocean, *Paleoceanography*, 4, 447-466, 1989.
- Heinze, C., A. Hupe, E. Maier-Reimer, N. Dittert, and O. Rague-Neau, Sensitivity of the marine biospheric Si cycle for biogeochemical parameter variations. Part I. Control run and observations, in preparation, 41 pp.
- Heinze, C., and E. Maier-Reimer, The Hamburg Oceanic Carbon Cycle Circulation Model Version “HAMOCC2s” for long time integrations, Deutsches Klimarechenzentrum, *Technical Report No. 20*, 71 pp., 1999.
- Heinze, C., E. Maier-Reimer, A. M. E. Winguth, and D. Archer, A global oceanic sediment model for longterm climate studies. *Global Biogeochemical Cycles*, 13, 221-250, 1999.
- Maier-Reimer, E., 1993, Geochemical cycles in an ocean general circulation model. Preindustrial Tracer Distributions, *Global Biogeochemical Cycles*, 7, 645-677, 1993.

- Martinson, D. G., N. G. Pisias, J. D. Hays, J. Imbrie, T. C. Moore, Jr., and N. J. Shackleton, Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy, *Quaternary Research*, 27, 1-29, 1987.
- Lyle, M., D. W. Murray, B. P. Finney, J. Dymond, J. M. Robbins, and K. Brooksforce, The record of late Pleistocene biogenic sedimentation in the eastern tropical Pacific Ocean, *Paleoceanography*, 3, 39-59, 1988.
- Roeckner, E., L. Bengtsson, J. Feichter, J. Lelieveld and H. Rodhe, Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle, *Journal of Climate*, 12, 3004-3032, 1999.
- Winguth, A. M. E., D. Archer, J.-C. Duplessy, E. Maier-Reimer, and U. Mikolajewicz, Sensitivity of paleonutrient tracer distributions and deep sea circulation to glacial boundary conditions, *Paleoceanography*, 14, 304-323, 1999.

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