DFG - Research Unit

Understanding Cenozoic Climate Cooling: The Role of the Hydrological Cycle, the Carbon Cycle, and Vegetation Changes

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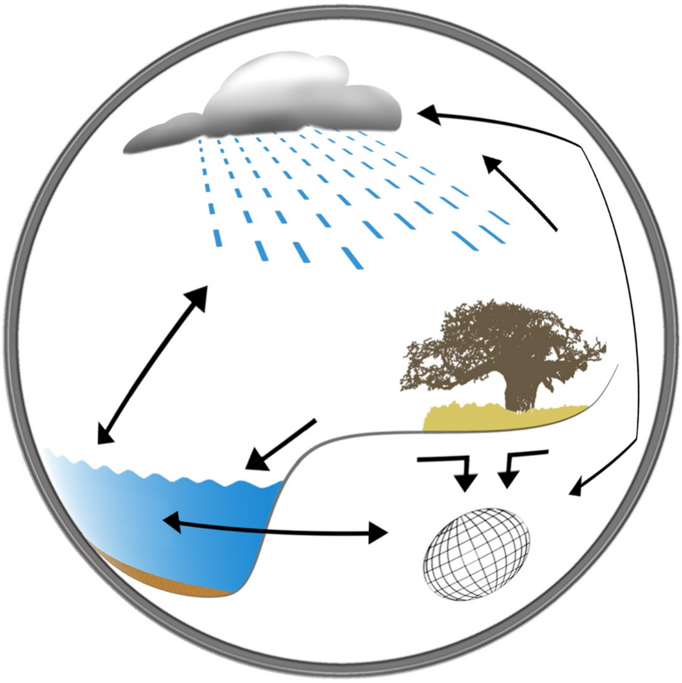

Introduction

The Eocene-Oligocene climate transition and the Mid Miocene cooling are two major steps in the Cenozoic climate evolution (Fig 0-1: Zachos et al. 2001). The drastic increase in the oxygen-isotopic composition measured in deep-sea benthic foraminifer shells describes a combination of Antarctic ice growth and global cooling at 34 Ma and 14 Ma, respectively, which is also indicated by the occurrence of Southern Ocean ice-rafted detritus and eustatic sealevel change (Miller et al. 1987, Kennett and Barker 1990, Billups and Schrag 2002). Ocean circulation and atmospheric *p*CO2 variations are often cited as potential catalysts of these cooling events (DeConto and Pollard 2003). Large-scale reorganizations of ocean circulation driven by atmospheric circulation changes and/or tectonic reorganizations of gateway regions may have altered poleward heat and moisture transport, resulting in Antarctic ice growth and global cooling (Kennett 1977, Zachos et al. 2001). Ocean circulation hypotheses are supported by $\delta^{13}C$ proxy evidence (e.g. Wright and Miller 1996, Billups 2002) and the timing of tectonic events at critical ocean pathways like the Drake Passage, the Tasmanian Seaway, and the Indonesian Throughflow (Cane and Molnar 2001, Lawver and Gahagan 2003).

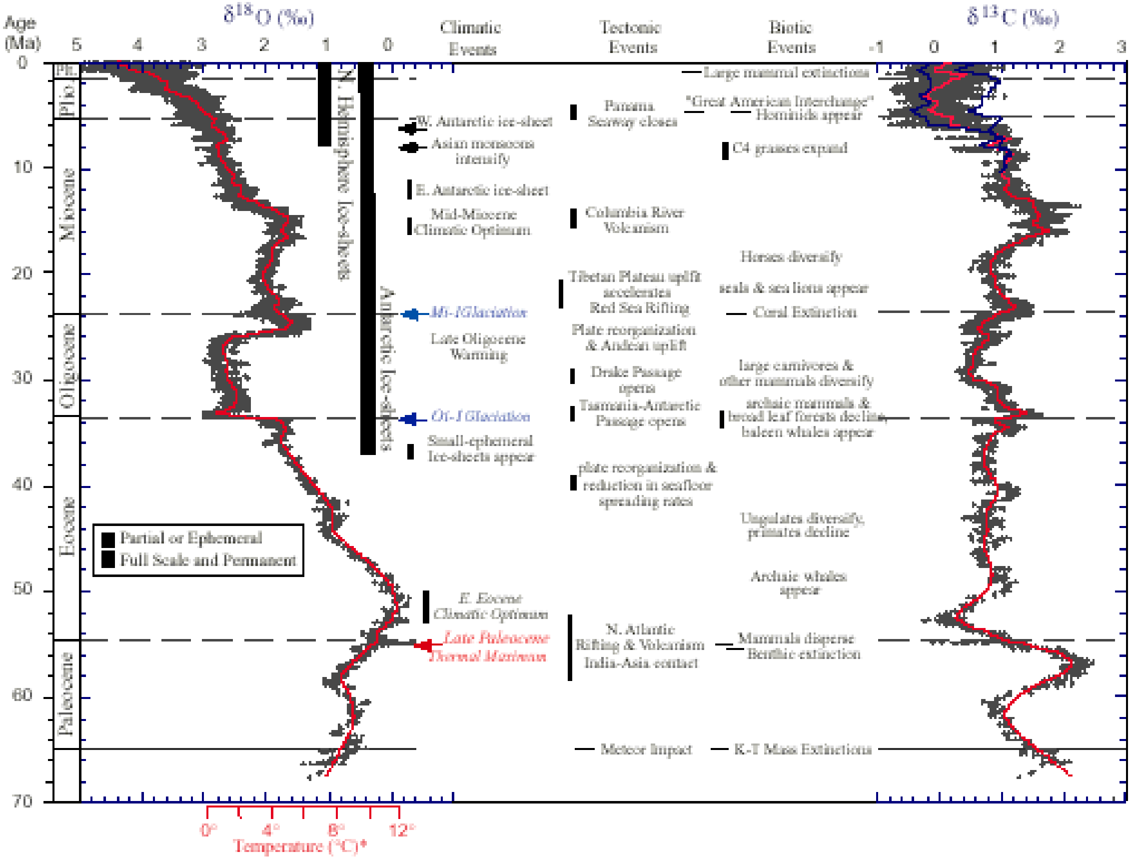

Fig. 0-1. Global deep-sea stable oxygen and carbon isotope records as compiled from over 40 DSDP and ODP cores (Zachos et al. 2001).

Alternatively, atmospheric pCO_2 drawdown, through organic carbon sequestration on the mid-latitude continental margins (Derry and France-Lanord 1996) or enhanced silicate weathering rates (Raymo 1994), may have driven Antarctic ice-sheet expansion and cooling. Support for this hypothesis, at least for the Mid Miocene cooling, comes from thick, organic carbon-rich sedimentary sequences around the Pacific Rim indicating an enhanced carbon burial during that time (Vincent and Berger 1985). However, a complication of the hypothesis is revealed by paleo-pCO_2 estimates, which indicate that atmospheric pCO_2 levels declined significantly around the Eocene to Oligocene climate transition, but not at the Mid Miocene cooling event, where the pCO_2 remained at about the same level (Fig.0-2; Pagani et al. 1999, Pearson and Palmer 2000). Furthermore, while at the Eocene-Oligocene climate transition a corresponding $\delta^{13}C$ increase of about 1‰ supports the role of the carbon burial as a main driver of pCO_2 drawdown and hence cooling, a $\delta^{13}C$ decrease of about the same magnitude at the Mid Miocene cooling event reveals a potential contradiction to this hypothesis. These observations indicate that factors others than those related to global carbon cycling may contribute to these major Cenozoic climate transitions.

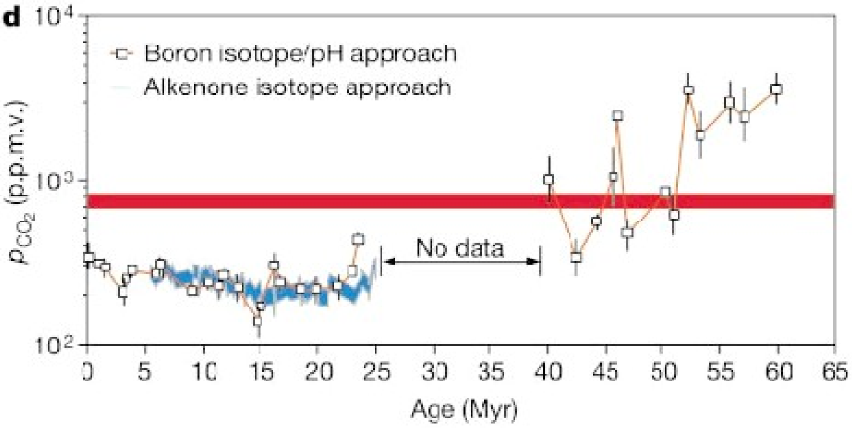

Fig. 0-2. Proxy estimates of atmospheric pCO_2 for the Cenozoic based on the boron isotope / pH approach (Pearson and Palmer 2000) and the alkenone isotope approach (Pagani et al. 1999).

To date, little is known about the role of continental vegetation for climate change during the Cenozoic. Although paleontological and palynological data give evidence for drastic changes in vegetation and therefore climate during the Cenozoic (e.g., Cerling et al. 1997, Morley 1999, Bredenkamp et al. 2002), it is a question whether the vegetation is just responding to changes in the hydrological cycle or playing an active role as a modifier of major Cenozoic climate transitions or whether it amplifies or even drives climate changes. Forests growing under moist and warm conditions underwent great changes at the Eocene/ Oligocene glaciation. Tropical rain forests virtually disappeared poleward of the northern and southern high pressure zones. Grassy vegetation began to develop under dry conditions during the Eocene, and grasslands became more and more widespread in the Oligocene. During the Mid-Miocene Climatic Optimum, moist warm forests expanded poleward of the subtropical high pressure zones for a short period. Following the global climatic deterioration after the Mid-Miocene Climatic Optimum, tropical rain forests withdrew again to the equatorial zone. Grasslands and deserts expanded through much of the lower mid-latitudes (Morley 1999, Bredenkamp et al. 2002). C_4 grasslands became widespread during the interval from about 8 to 5 Ma (Cerling et al. 1997, Freeman and Colarusso 2001) which potentially reflects a substantial decrease in the partial pressure of atmospheric carbon dioxide to levels that favored C_4 over C_3 photosynthesis, or a change of regional aridity and seasonal precipitation. Finally, a drastic change in vegetation is related to the onset of permafrost in the circum-arctic realm and the freezing of wetlands, which is dated to originate somewhere in the late Pliocene, but might have started already in the mid Miocene (Romanovskii et al. 2004). Therefore, during the Miocene most of the climatically arranged vegetation belts ranging from rain forests along the equator to polar deserts at high latitudes developed.

Sensitivity experiments with atmospheric general circulation models demonstrate that the late Miocene vegetation contributes to a warming of particularly the high latitudes (Dutton and Barron 1997, Micheels et al. submitted). Moreover, those experiments indicate that the Late Miocene vegetation significantly enhances the hydrological cycle with increased precipitation rates over continental areas which is related with higher runoff into the oceans (Micheels et al. submitted). Therefore, vegetation contributes to a weaker-than-present meridional temperature gradient in the Miocene. Other authors have suggested that atmospheric heat transport may play an important role in resolving this low gradient paradox (Schmidt and Mysak 1996; Hay et al. 1997). It is plausible to expect a warmer atmosphere to transport more latent heat poleward, helping to reduce meridional temperature gradients. Moreover, the exponential increase of saturation vapor pressure with temperature suggests that the feedback could become increasingly powerful as temperature rises (Caballero and Langen 2005). Other possible mechanisms involve the atmospheric stationary wave response due to changing paleogeography and sea level. Keppler et al. (2006) showed that methane emissions from terrestrial plants under aerobic conditions may play an important role in the global methane budget. This previously unknown source would have serious implications for Miocene methane budget due to the increased vegetation cover compared to present day. Kepler et al. (2006) also measured a very strong temperature sensitivity of the plant methane emission rates which may have further increased the plant methane emissions of the Miocene.

To evaluate the processes and feedbacks involved in the Cenozoic cooling, a Research Unit on the role of the hydrological cycle, the carbon cycle, and vegetation for climate change during the Cenozoic is proposed. In a joint effort of data-based paleoenvironmental reconstructions and modeling experiments within six working packages, detailed information will be provided regarding the magnitude and phasing of vegetation changes, carbon cycling, Antarctic ice growth, and high-latitude oceanic/atmospheric cooling. In a first proposal period, it is suggested to concentrate on the Mid Miocene cooling event and the Late Miocene extension of grasslands and the development of modern ocean circulation. In a second proposal period, also climate changes around the Eocene / Oligocene climate transition will be studied. Special attention will be paid to the validation of model experiments with terrestrial and marine sediment data. Emphasis is given to the role of the thermohaline circulation, the hydrological cycle, the cryosphere, the vegetation, and the dominant pattern of atmospheric chemistry and circulation. The model experiments will allow to evaluate the sensitivity of the system to climate conditions very different from the modern. The intended work will improve the knowledge of the feedback processes between the different climate subsystems which is an important step to understand future climate change and its prediction.

Major Objectives

Major objectives of the proposed Research Unit will be:

- to examine Cenozoic vegetation changes by compilation of existing data sets and own reconstructions for low as well as for high latitudes from terrestrial and marine sediments
- to study the effect of changed paleogeography and morphology on the hydrological cycle, continental weathering, and vegetation cover
- to identify feedbacks and synergisms in the atmosphere-ocean-vegetation system through model experiments under different Cenozoic boundary conditions
- to study atmospheric circulation changes under different boundary conditions, e.g. the North Atlantic Oscillation in the absence of a Greenland Ice Sheet and altered paleogeography or monsoon changes resulting from the closing of the Tethys seaway and the uplift of the Tibetan Plateau
- to validate the modeled changes in the hydrological cycle and vegetation by comparison to paleovegetation maps using geostatistical methods
- to evaluate the effect of vegetation extremes on the ocean circulation, especially for the North Atlantic Deep Water formation
- to study changes in the terrestrial and oceanic carbon cycle related to Cenozoic climate cooling in a combined paleoenvironmental reconstruction - climate modeling approach
- to identify the controlling factors of C_3/C_4 vegetation changes and to quantify the consequences for carbon fractionation and the geographical distribution of carbon pools

- to estimate the change in the distribution of potential wetlands and their methane (CH_4) emissions on the Cenozoic climate

Workpackages

To address the objectives given above, partners from five institutes will form a consortium and contribute to six working packages to ensure maximum gains from the different activities and expertise provided to the project. The consortium will intimately merge data measurements, climate modeling, and analyses. The close link between modeling work and paleodata time-series reconstruction will be fostered through the analysis of the temporal and spatial temperature and precipitation patterns which are robust in the model experiments and in the paleodata records. The workpackages are:

WP 1 Changes in global climate and vegetation patterns during Cenozoic cooling as derived from proxy-data

Volker Mosbrugger

Vegetation and climate for the selected time intervals are reconstructed, the spatial heterogenity of climate parameters and transfer functions are evaluated. In addition the project provides the needed data base for the quantitative validation of terrestrial modeling results (vegetation and climate).

WP 2 Southern African climate changes during C4 plant evolution and expansion

Enno Schefuß, Lydie Dupont

Based on terrigenous plant lipid biomarkers and their molecular carbon and hydrogen isotopic signatures, and on the analysis of pollen in marine sediments of the equatorial and South Atlantic, this project will provide data for identifying the controlling factors of C_3/C_4 vegetation changes and to quantify the consequences for Cenozoic carbon fractionation and the geographical distribution of carbon pools.

WP 3 Vegetation and climate during the Cenozoic global cooling: AGCM sensitivity experiments and their validation

Arne Micheels

Using the tools climate and vegetation modelling, the work package analyses the climate and vegetation sensitivity on palaeogeographic, palaeorographic and palaeovegetation changes, and on variations of the orbital parameters for a warm climate situation. Special emphasis is set on the influence of high-latitude forests/wetlands on the hydrological cycle and on the atmospheric circulation. The work package compiles boundary conditions and provides them also to WP4, 5 and 6. The reliability of the model experiments is tested against proxy data.

WP 4 Cenozoic climate, thermohaline circulation and the marine carbon cycle

Torsten Bickert, Martin Butzin

Sensitivity experiments with an ocean general circulation model (OGCM) contribute to explain the climatic effect of the ocean circulation for the selected time intervals. The work package also analyses the coupled marine and terrestrial carbon cycle. The model results will be validated with proxy data of marine sediments (in cooperation with the projects 1 and 2 for terrestrial proxy data).

WP 5 Global climate simulations, vegetation, and feedback analysis

Gerrit Lohmann, Johann Jungclaus, Claudia Kubatzki

The work package performs realistic long-term simulations with a highly complex coupled atmosphere-ocean-vegetation general circulation model (AOVGCM). Cooperation with projects 3 and 4 will allow systematic feedback analysis of the climate system components. The reliability of the model results will be validated with terrestrial and marine proxy data.

WP 6 Global atmospheric chemistry simulations and wetlands

Martin Schultz, Gerrit Lohmann

The global distribution of potential wetlands and their methane (CH_4) emissions at the present-day and during the Cenozoic climate will be estimated. Budgets are based on general circulation model simulations including a dynamic vegetation model (WP3 and 5). Simple algorithms for determining wetland area based on paleo-topography and soil moisture, and estimates of CH_4 emissions based on ecosystem carbon turnover in wet soils will be applied. The main focus is the estimation of the sinks of methane and other atmospheric compounds applying a recent-developed atmospheric chemistry module. Interactions with the climate dynamics are evaluated in this workpackage.

Infrastructure and collaboration

The Research Unit will be coordinated by Prof. Gerrit Lohmann and Dr. Torsten Bickert, University of Bremen. In the Research Unit several co-operations exists between specialists of modeling and paleoclimate reconstruction. The joint work has network-character. Visits, workshops and common publications are planned. The proposed Research Unit is a chance to use the synergies of integrating different disciplines.

The proposed Research Unit will closely cooperate with other national and international research groups, in particular with NECLIME (Neogene Climate Evolution in Eurasia), IODP (Integrated Ocean Drilling Program), and RCOM (Research Center Ocean Margins, University of Bremen). There are excellent contacts to other paleobotanists (e.g. Johanna Kovar-Eder, Jean-Pierre Suc, Torsten Utescher, Gary Upchurch, etc.) who focus on climate and vegetation reconstructions of Cenozoic time intervals, as well as to mammal palaeontologists (e.g. Mikael Fortelius, Jan Van Dam), which contribute to climate and vegetation reconstructions, and to stratigraphers (Werner Piller, Matthias Harzhauser, etc.).