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PALEOCLIMATIC CHANGES IN THE GLOBAL CARBON CYCLE

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1 Summary

Within RESPIC (young scientist Research group for Earth climate System reconstructions on Polar Ice Cores) new $\delta^{13}CO_2$ and aerosol paleorecords derived from the EPICA (European Project for Ice Coring in Antarctica) ice core currently drilled in Dronning Maud Land (DML), Antarctica, are reconstructed. For this purpose novel analytical methods and modeling approaches are developed. The expected high accuracy data in conjunction with our model approach allows to pinpoint major drivers of the global carbon cycle on glacial/ interglacial timescales. First results showed high interannual and decadal variability in sea salt and marine biogenic aerosol during the Holocene, in part related to the Antarctic Circumpolar Wave. Carbon cycle modeling studies on biospheric changes from 30,000 yrs before present (BP) to the preindustrial era, point to a substantial reorganization of the terrestrial biosphere superimposed on long-term variations in ocean/atmosphere carbon fluxes.

2 Aim of the research in the framework of DEKLIM

The overarching goal of RESPIC is the quantitative understanding of paleoatmospheric changes over the last glacial cycle and here especially the coupling of paleoclimate and the global carbon cycle. To this end new high-resolution atmospheric paleorecords derived from the EPICA DML ice core are derived which set the boundary conditions of temporal changes in the global carbon cycle. Those records will comprise isotopic measurements on $\delta^{13}CO_2$ - an urgently lacking constraint on marine and biospheric carbon fluxes - and multivariate chemical aerosol records providing information on aeolian nutrient input into the Southern Ocean as well as on marine biogenic aerosol species, hence potential information on temporal changes in the biological productivity of the Southern Ocean ecosystem. While the first of these tasks requires the development of a novel sublimation extraction technique and establishing a high-precision isotope analysis for very small air samples, the latter task relies heavily on state-of-the-art time series analysis and the understanding of atmospheric circulation in the past. Quantitative interpretation to pinpoint the major drivers of changes in atmospheric CO_2 is assured by the development of a new multiboxmodel of the global carbon cycle. Model applications require also the assimilation of proxydata from other paleoarchives. With these interdisciplinary objectives RESPIC represents an important contribution to the research topics of DEKLIM such as the influence of climate variations on global nutrient cycles, the paleoclimatic and paleoatmospheric variability and the understanding of the physical processes which link the two as well as the synthesis of models and paleoclimatic data.

3 Recent and completed activities

During the last field season (where HF had the duty of field leader and chief scientist) ice core drilling in DML was very successful and proceeded another 1100 m down to a depth of 1550 m covering the time period until approximately 55,000 yrs BP. The core drilled in 2002/2003 was completely retrograded to Germany and will be available for the joint core

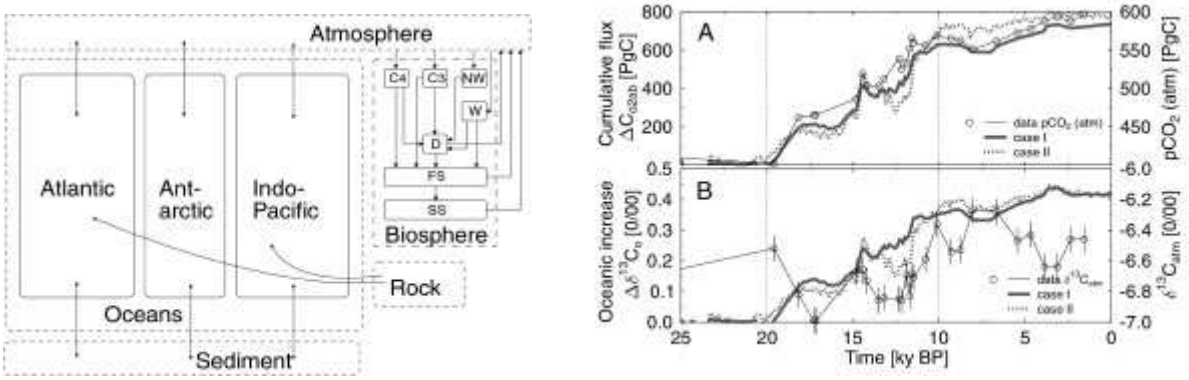

Figure 1. Left: Setup of BICYCLE. Right: Cumulative carbon fluxes from atmosphere/biosphere to the ocean from simulations of the terrestrial biosphere only. A: total carbon. B: isotopic $\delta^{13}C$ signal. Simulations of case I (enhanced pCO_2 fertilization) and case II (enhanced temperature sensitivity).

processing of the EPICA community this year. Last years core, covering the time interval from 7500 BP to the present, was completely processed in 2002. Among others, this processing provided seasonally resolved aerosol records using a contamination free continuous melt water flow analysis (CFA) for selected ion concentrations. In parallel an automated melt water sampling was established providing about 7000 discrete samples for ion chromatography (IC) analysis in annual resolution shared by different European labs. IC analysis provides concentrations on sea salt (Na^+, Cl^-), mineral dust (Ca^{2+}, K^+), biogenic aerosol species (SO_4^{2-}, methanesulfonate (MSA), NH_4^+), volcanic deposition (F^-, SO_4^{2-}) and reactive nitrogen (NO_3^-). Up to now samples for the time period from 170 AD to the present and from 4600-7200 BP have been evaluated at the Alfred-Wegener-Institute (AWI). After completion of the CFA records, they will be the basis for precise stratigraphic dating of the core at least for the Holocene, where seasonal cycles in the chemical species can be clearly resolved. This has been already accomplished for the last 2000 years. Further preliminary dating was performed by counting annual cycles in the solid state conductivity record which is available for the full core down to 1550 m. In the course of the core processing samples have been taken every 12th meter (equivalent to a temporal resolution of 300 yrs) for carbon isotopic analyses within RESPIC. In addition to the EPICA deep ice core studies our chemical investigations on shallow ice cores from DML have been extended. In a cooperation with the CNRS, Grenoble, sulfate isotope ratios are determined to quantify the stratospheric influence on sulfate fluxes onto DML.

The development of a sublimation extraction system for air entrapped in bubble and clathrate ice has proceeded. Quantitative sublimation extraction of CO_2 from 10 g of ice is sufficient for $\delta^{13}CO_2$ measurements using our new gas chromatography isotope ratio mass spectrometry (GC-irmMS) method and 20-40 times less than required for conventional methods. First $\delta^{13}CO_2$ measurements showed that further refinements are necessary. Based on $\delta^{13}CH_4$ measurements performed with this method an accuracy for $\delta^{13}CO_2$ of 0.05 ‰ is feasible.

For the interpretation of ice core data on atmospheric $\delta^{13}C$ and CO_2 the simple ocean-atmosphere-biosphere box model BICYCLE (Fig. 1) has been developed (Köhler et al., 2003). The model includes mass balance equations for the carbon stocks of the biospheric compartments, for dissolved inorganic carbon, total alkalinity, phosphate (chosen as the limiting nutrient) and oxygen in 10 oceanic reservoirs (five surface, two intermediate, three deep), for atmospheric CO_2 in the atmosphere, and the ^{13}C and ^{14}C isotopic characteristics in all of them. The globally averaged terrestrial biosphere is divided into seven compartments representing C3 and C4 ground vegetation, trees, and soil carbon with different turnover times. Most importantly, our model parametrizes the physiological response of photosynthesis

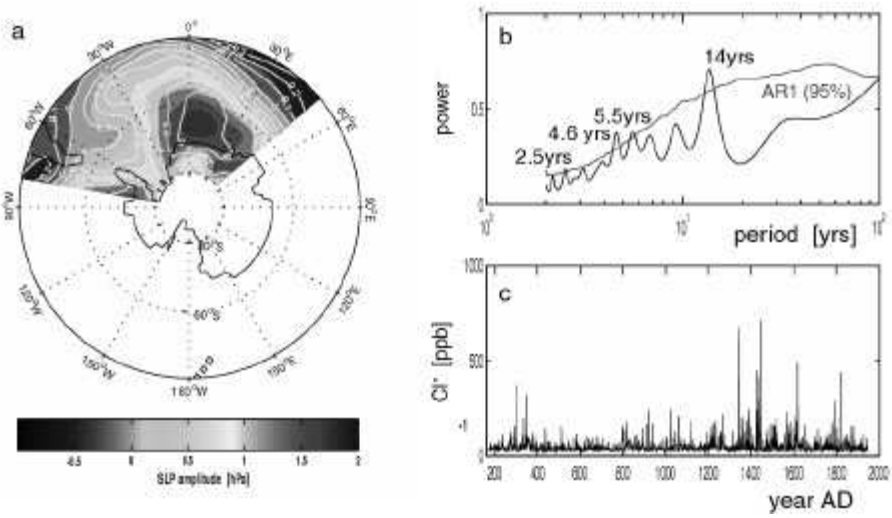

Figure 2. ACW signal as archived in sea salt records from DML: a) correlation/regression analysis of Na^+ concentrations and sea level pressure data for the spring season; b) spectral analysis of the Cl^- data for the period 176-1950 AD as shown in c).

and respiration on changing atmospheric CO_2 levels and temperature. We also take into account the consumption of atmospheric CO_2 and the transfer of bicarbonate to the ocean due to continental weathering as well as deep-sea sediment/ocean exchange and carbonate accumulation in coral reefs and on banks and shelves in the coastal zone.

4 Principal results

4.1 Southern Ocean atmosphere variability

Special emphasis has been put on the evaluation of the interannual and decadal variability in Southern Ocean atmosphere dynamics as reflected in sea salt aerosol export onto DML. Using spatial correlation of chemical ice core data and meteorological reanalysis data (Fig. 2a) it was possible to show, that sea salt export is modulated by the Antarctic Circumpolar Wave (ACW). Sea level pressure anomalies induced by the ACW create a blocking high pressure ridge north-northeast of the EPICA drill site, leading to diversion of circumpolar cyclones into the interior of DML and hence to increased sea salt concentration. This interannual variability exhibits a pronounced periodicity of 4-5 yrs as related to the circumpolar progression of the ACW over the last 40 yrs. Spectral analysis on the sea salt records derived from the deep DML ice core shows that this cycle (Fig. 2b) has been also prevalent over the last 2000 years as well as during the time interval 4600-7200 yrs BP (Fischer et al., 2003b).

Further efforts have been made in quantifying spatial and temporal effects on aerosol deposition in the study area (Göktas et al., 2003). The postdepositional loss of acidic aerosol tracers such as HCl and HNO_3 from the snow pack has been quantified. In addition marine biogenic MSA shows an increasing loss with lower snow accumulation obliterating its interannual variability (Weller et al., 2003). Nevertheless MSA exhibits pronounced changes on decadal time scales, which together with variations in biogenic sulfate can be related to either atmospheric transport and/or variations in source strength. Furthermore, we were able to derive an independent volcano chronology over the last 2000 years using our stratigraphic dating, considerably increasing the dating accuracy of volcanoes in the penultimate millennium where historic documentation is increasingly sparse and uncertain (Traufetter et al., 2003).

4.2 Quantification of changes in the global carbon cycle

In a first step we ran our model in a “biosphere only” mode, driven by atmospheric CO_2 and $\delta^{13}C$ as well as temperature, sea level and land surface changes from the Last Glacial

Maximum (LGM) to the Holocene to determine which forcing factors are appropriate to explain observed changes in the biosphere (Köhler and Fischer, 2003). Former forcing strengths of this type of model on recent climate changes were too large to explain glacial/interglacial variations. In our model the terrestrial carbon stock at the LGM consists of about 1600 PgC, 600 PgC less than in preindustrial times, which agrees very well with other estimates of the changes in biomass from the LGM to the Holocene. During the transition the oceanic release of carbon is in phase with the atmospheric pCO_2 record, but four times larger than the pCO_2 increase due to the build-up of the terrestrial stocks.

5 Main conclusions

Evaluation of continuous aerosol records shows that the seasonal and interannual variability in snow chemistry and Southern Ocean atmosphere dynamics is well archived in DML ice during the Holocene. For the first time it could be shown, that the ACW is not only a prominent phenomenon of the last decades but was persistent throughout most of the Holocene. The partial loss of MSA and other acidic aerosol species from the snow pack compromises their quantitative interpretation, however, MSA exhibits still a pronounced decadal variability, which may be related to climatic changes.

Calculated changes in the isotopic signature of oceanic $\delta^{13}C$ correspond well with data and suggest not only a dominant role of the biosphere during the stable climate conditions such as LGM and the Holocene (Fischer et al., 2003a), but also a relevant influence on $\delta^{13}C(atm)$ during the transition. Further insight is expected from coupled ocean/biosphere/atmosphere model runs as well as new high-precision records of $\delta^{13}C$ to be measured within RESPIC.

6 Planned activities

The RESPIC project will continue as described in the proposal. The EPICA drilling in DML will proceed in austral summer 2003/04 to 2400 m (app. 160,000 yrs BP). The core processing of the DML core will take place in the summer following the respective field season. First results will be presented on the ESF Conference “Polar regions and Quaternary climate” to be held in October in San Feliu, Spain, where HF is member of the organizing committee as well as solicited speaker. In 2005 the second ESF conference of this series will be held. In 2004 the PAGES meeting will be held in Bejing, where HF has also been invited as speaker. Intensified collaboration is envisaged with the carbon modeling group at Uni Bern, where PK will spend a few months as exchange scientist in 2004.

7 Cooperation within DEKLIM and with other programs

D. Wolf-Gladrow, AWI; G. Lohmann, Uni Bremen; H. von Storch, GKSS; Antje Schwalb, Uni Braunschweig; M. Wahlen, Scripps Institution of Oceanography, UCSD; EPICA: A consortium of institutions from 11 European countries.

8 Policy relevance and application

Reliable projections of future changes in the global carbon cycle and climate requires an inside knowledge of the processes which govern such changes. Paleoclimatic reconstructions represent the test bed for such modeling approaches and give clues about the processes involved in global change. However, changes in the global carbon cycle over glacial/interglacial timescales have so far eluded a quantitative explanation. Accordingly, RESPIC is expected to make an important contribution to the validation of carbon cycle modeling and the understanding of the coupling between climate and the atmosphere.

The development of high-precision mass spectrometric techniques for very small gas samples may result in industrial applications of this new techniques. In addition, this new technique opens the door to a multitude of geoscientific and atmospheric studies where most often sample sizes are strongly limited.

RESPIC related publications

Fischer, H., Wahlen, M., and Smith, J., 2003a, Reconstruction of glacial/interglacial changes in the global carbon cycle from CO_2 and $\delta^{13}CO_2$ in Antarctic ice cores, Memoirs of the National Institute for Polar Research, in press.

Fischer, H., Göktas, F., Oerter, H., Weller, R., and Miller, H., 2003b, Prevalence of the Antarctic Circumpolar Wave over the last two millennia in Dronning Maud Land ice, submitted to Nature.

Göktas, F., Fischer, H., Oerter, H, Weller, R. Sommer, S., and Miller, H., 2003, A glacio-chemical characterisation of the new EPICA deep drilling site on Amundsenisen, Dronning Maud Land, Antarctica. Annals of Glaciology, 35, 347-354.

Köhler, P., and Fischer, H., 2003, Simulating changes in the terrestrial biosphere over glacial/interglacial timescales, submitted to Global Biogeochemical Cycles.

Köhler, P., Fischer, H., Zeebe, R.E., and Wolf-Gladrow, D.A., 2003, A coupled ocean-atmosphere-biosphere box model to investigate glacial/interglacial dynamics of the global carbon cycle, in preparation.

Traufetter, F., Oerter, H., Fischer, H., Weller, R., Graf, W., and Miller, H., 2003, Spatio-temporal variability in volcanic sulphate deposition over the past 2 kyr in ice cores from Amundsenisen, Dronning Maud Land, Antarctica, submitted to Journal of Glaciology.

Weller, R., Traufetter, F., Fischer, H., Oerter, H., and Miller H., 2003, Post depositional losses of methane sulfonate, nitrate, and chloride at the EPICA deep-drilling site in Dronning Maud Land, Antarctica, in preparation.