Comparison of Climate and Carbon Cycle Dynamics During Late Quaternary Interglacials

Thomas Kleinen, Elena Bezrukova, Victor Brovkin, Hubertus Fischer, Steffi Hildebrandt, Stefanie Müller, Matthias Prange, Rima Rachmayani, Jochen Schmitt, Robert Schneider, Michael Schulz and Pavel Tarasov

Abstract Within the project COIN we investigated climate and carbon cycle changes during late Quaternary interglacials using ice core and terrestrial archives, as well as earth system models. The Holocene carbon cycle dynamics can be explained both in models and data by natural forcings, where the increase in CO_2 is due to oceanic carbon release, while the land is a carbon sink. Climate changes during MIS 11.3 were mainly driven by insolation changes, showing substantial differences within the interglacial. Terrestrial reconstructions and model results agree, though data coverage leaves room for improvement. The carbon cycle dynamics during MIS 11.3 can generally be explained by the same forcing mechanisms as for the Holocene, while model and data disagree during MIS 5.5, showing an increasing CO_2 trend in the model though reconstructions are constant.

Keywords Interglacial · Carbon cycle · $\delta^{13}CO_2$ · Holocene · MIS 11.3 · MIS 5.5 · Ice core data · Terrestrial data · Earth system model · CO_2

T. Kleinen (✉) · V. Brovkin
Max Planck Institute for Meteorology, Hamburg, Germany
e-mail: thomas.kleinen@mpimet.mpg.de

E. Bezrukova
A.P. Vinogradov Institute of Geochemistry SB RAS, Irkutsk, Russia

H. Fischer · J. Schmitt · R. Schneider
Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

S. Hildebrandt · S. Müller · P. Tarasov
Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

M. Prange · R. Rachmayani · M. Schulz
MARUM—Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Bremen, Germany

M. Schulz and A. Paul (eds.), *Integrated Analysis of Interglacial Climate Dynamics (INTERDYNAMIC)*, SpringerBriefs in Earth System Sciences,
DOI 10.1007/978-3-319-00693-2_2

1 Introduction

The successful simulation of past climate changes is an important indicator of the ability of climate models to forecast future climate changes. While the climate of the Holocene has been relatively well investigated with global climate models, previous interglacials received much less attention.

Within this project, we provided quantitative reconstructions of several interglacials using ice core and terrestrial archives on the one hand and a hierarchy of Earth System models on the other hand. While components such as peat accumulation and $CaCO_3$ sedimentation, which are necessary to explain the ice core data, were previously missing from carbon cycle models, the ice core community only recently succeeded in measuring carbon isotopic data, which provides important constraints on the mechanisms of the CO_2 changes observed.

2 Materials and Methods

2.1 CLIMBER2-LPJ

CLIMBER2-LPJ (Kleinen et al. 2010) is a coupled climate carbon cycle model consisting of the earth system model of intermediate complexity (EMIC) CLIMBER2 coupled to the dynamic global vegetation model (DGVM) LPJ, extended by a model of peat accumulation and decay (Kleinen et al. 2012).

2.2 Community Climate System Model Version 3 (CCSM3)

The National Center for Atmospheric Research (NCAR) CCSM3 is a state-of-the-art coupled climate model (Yeager et al. 2006). The resolution of the atmosphere is T31 (3.75° transform grid), while the ocean model has a horizontal resolution of 3° with a finer resolution around the equator.

2.3 Ice Core Measurements of Atmospheric $\delta^{13}CO_2$

The carbon isotopic composition of atmospheric CO_2 provides important benchmark data to test hypotheses on past changes in the global carbon cycle. Previous $\delta^{13}CO_2$ measurements were limited in resolution and precision, requiring large ice samples. We employed a novel sublimation extraction technique (Schmitt et al. 2011), cutting down sample size to 30 g of ice, while improving precision by a factor of up to 2–0.06 ‰. This has been applied to ice core samples from the

EPICA Dome C and Talos Dome ice cores, Antarctica, over the time interval 1 thousand years (ka) before present (BP)–25 ka BP and 105–155 ka BP (Schneider et al. 2013).

2.4 Palaeodata Assemblage

We reviewed a total of 162 publications affiliated with MIS 11.3 climate (Kleinen et al. 2014) and a set of 234 records for MIS 5.5. However, this extensive search revealed that the majority of the publications provide only qualitative, discontinuous and/or poorly dated information about the past climate. Therefore we focused on more recently published continuous records of interglacial climate and vegetation with well constrained chronologies, most suitable for a robust data-model comparison (e.g., Kleinen et al. 2011).

3 Key Findings

3.1 Trends in Interglacial Carbon Cycle Dynamics

During Termination I, atmospheric CO_2 rose as the ocean released carbon to the atmosphere (Schmitt et al. 2012). The $\delta^{13}CO_2$ measurements over Termination II point at the same processes being responsible for the CO_2 increase as in Termination I, however, with different phasing and magnitude (Schneider et al. 2013). After an initial CO_2 peak, CO_2 decreases during most interglacials, while the Holocene and MIS 11.3 reveal CO_2 increases by about 20 and 10 ppmv, respectively. Ruddiman (2003) interprets the rising CO_2 during the Holocene as the onset of the Anthropocene. However, simulations with CLIMBER2-LPJ suggest that the ocean mostly operates as a source of CO_2 to the atmosphere during interglacials (Kleinen et al. 2010). Carbonate compensation and the excessive accumulation of $CaCO_3$ in coral reefs lead to a slow CO_2 release to the atmosphere (Kleinen et al. 2010). The role of land carbon is more complex. During the Holocene, the land mainly serves as a sink of carbon since soil and peat storages on land are slowly growing (Kleinen et al. 2012). Reconstructed $\delta^{13}CO_2$ data from ice cores (Elsig et al. 2009; Schmitt et al. 2012; Schneider et al. 2013) suggests a continuous increase in the terrestrial carbon storage from 12 to 6 ka BP and a mostly neutral role of the land from 6 to 2 ka (Fig. 1a, b), invalidating the early Anthropocene hypothesis. The CLIMBER2-LPJ simulation for MIS 11.3 using the same forcing setup as for the Holocene shows CO_2 dynamics close to observations (Fig. 1d). Our new ice core measurements also show constant CO_2 concentrations over most of MIS 5.5. However, the CLIMBER2-LPJ results are in disagreement with CO_2 reconstructions (Fig. 1c), suggesting that the model still misses some important

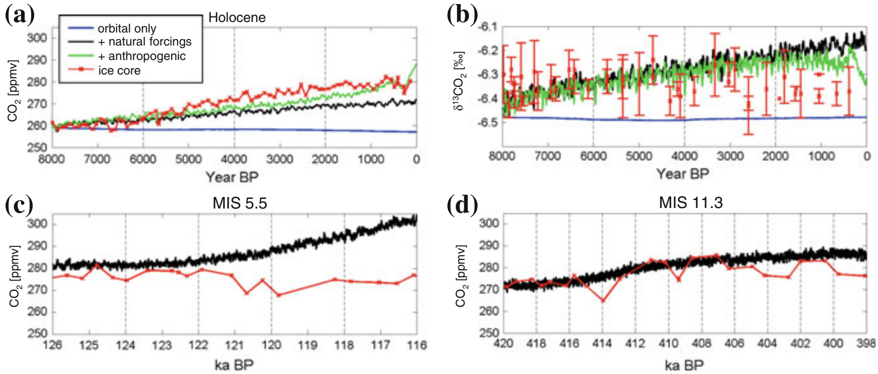

Fig. 1 CO_2 development during interglacials. **a** Holocene CO_2, **b** Holocene $\delta^{13}CO_2$, **c** MIS 5.5 CO_2, **d** MIS 11.3 CO_2. Ice core measurements (*red*, *crosses*), orbital forcing only (*blue*), plus natural forcings (*peat and corals*, *black*), plus anthropogenic landuse emissions (*green*). Ice core data as in Elsig et al. (2009), Schneider et al. (2013) and Petit et al. (1999) for Holocene, MIS 5.5, and MIS 11.3, respectively

process. We conclude that the difference between land and ocean biogeochemical processes during interglacials can drive atmospheric CO_2 either upward or downward, depending on the strength of warming controlled by orbital forcing and the history of carbon changes during the preceding terminations.

3.2 *Climate and Vegetation Changes*

Climate responds to numerous forcings. During interglacials, ice sheet changes are negligible, leading to a strong influence of insolation and greenhouse gas changes on climate. During the early Holocene, the CO_2 concentration ($\sim$265 ppm) was somewhat lower than preindustrial (280 ppm), but summer insolation in the high northern latitudes was substantially higher. This led to a strong summer warming and major changes in vegetation, a northerly advance of the northern tree line. Changes in tree cover for CLIMBER2-LPJ and 8 ka BP are shown in Fig. 2a. These tree cover changes compare favourably with reconstructions of woody cover from terrestrial records as shown in Fig. 2b. Since we performed transient integrations of the climate model and used tree cover reconstructions at high temporal resolution, we could show that the changes in tree cover occurred at similar times in model and reconstructions, though locally deviations of up to 1,000 years occurred (Kleinen et al. 2011).

For MIS 11.3 (Kleinen et al. 2014), we performed transient experiments with CLIMBER2-LPJ and time slice experiments with CCSM3, which were used to drive the LPJ DGVM. Climate changes are surprisingly similar for the two models, though CCSM3 reacts somewhat more strongly to insolation changes. Model results show large variations for MIS 11.3 climate, with European summer

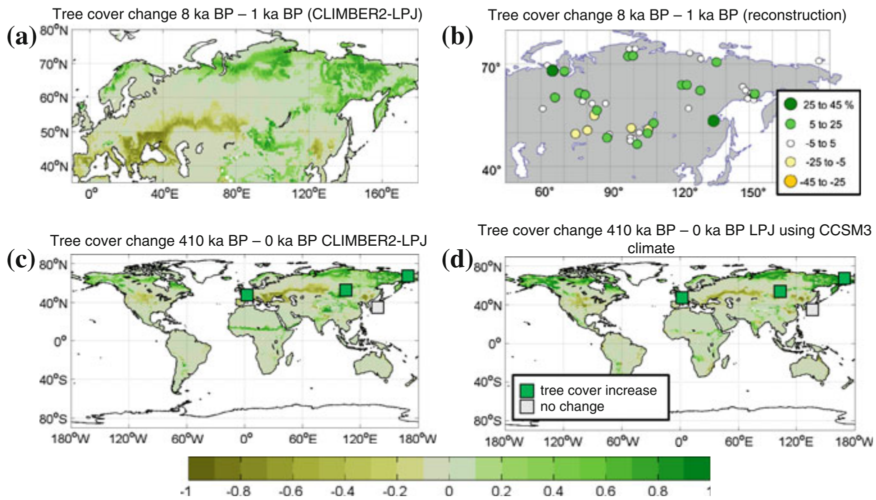

Fig. 2 Modeled and reconstructed tree cover change during the Holocene and MIS 11.3. **a** 8–1 ka BP, CLIMBER2-LPJ; **b** 8–1 ka BP, reconstruction (after Kleinen et al. 2011); **c** 410–0 ka BP, CLIMBER2-LPJ; **d** 410–0 ka BP, LPJ using CCSM3 climate. Reconstructed tree cover changes for MIS 11.3 are shown as *squares* in **c** and **d** (after Kleinen et al. 2014)

temperatures, for example, ranging from 2 °C colder to 3 °C warmer than preindustrial. For vegetation changes, shown in Fig. 2c, d for 410 ka BP, the results from the two models once more agree well, showing a northward shift of the taiga-tundra boundary in the high northern latitudes. Reconstructions from terrestrial records (Kleinen et al. 2014) show a similar magnitude of climate change, but the coverage by well-dated high-resolution records is very limited, preventing a model-data comparison for more than a few points.

References

Elsig J, Schmitt J, Leuenberger D, Schneider R, Eyer M, Leuenberger M, Joos F, Fischer H, Stocker TF (2009) Stable isotope constraints on Holocene carbon cycle changes from an Antarctic ice core. Nature 461:507–510

Kleinen T, Brovkin V, von Bloh W, Archer D, Munhoven G (2010) Holocene carbon cycle dynamics. Geophys Res Lett 37:L02705. doi:10.1029/2009GL041391

Kleinen T, Tarasov P, Brovkin V, Andreev A, Stebich M (2011) Comparison of modeled and reconstructed changes in forest cover through the past 8000 years: Eurasian perspective. Holocene 21(5):723–734

Kleinen T, Brovkin V, Schuldt RJ (2012) A dynamic model of wetland extent and peat accumulation: results for the Holocene. Biogeosciences 9:235–248

Kleinen T, Hildebrandt S, Prange M, Rachmayani R, Müller S, Bezrukova E, Brovkin V, Tarasov P (2014) The climate and vegetation of marine isotope stage 11—model results and proxy-based reconstructions at global and regional scale. Quatern Int. doi:10.1016/j.quaint.2013.12.028

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Benders M, Chappellaz J, Davis M, Delayque G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pépin L, Ritz C, Saltzman E, Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399:429–436

Ruddiman WF (2003) The anthropogenic Greenhouse Era began thousands of years ago. Clim Change 61:261–293

Schmitt J, Schneider R, Fischer H (2011) A sublimation technique for high-precision $\delta^{13}C$ on CO_2 and CO_2 mixing ratio from air trapped in deep ice cores. Atmos Meas Tech 4:1445–1461

Schmitt J, Schneider R, Elsig J, Leuenberger D, Lourantou A, Chappellaz J, Köhler P, Joos F, Stocker TF, Leuenberger M, Fischer H (2012) Carbon isotope constraints on the deglacial CO_2 rise from ice cores. Science 336:711–714

Schneider R, Schmitt J, Köhler P, Joos F, Fischer H (2013) A reconstruction of atmospheric carbon dioxide and its stable carbon isotopic composition from the penultimate glacial maximum to the glacial inception. Clim Past 9:2507–2523

Yeager SG, Shields CA, Large WG, Hack JJ (2006) The low-resolution CCSM3. J Clim 19:2545–2566