Quaternary Science Reviews 137 (2016) 15–32

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Comparative carbon cycle dynamics of the present and last interglacial

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ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form
24 January 2016
Accepted 28 January 2016
Available online xxx

Keywords:
Carbon cycle
Climate
Models
Interglacials
The Holocene
The Eemian
Peatland
Fire
Coral reef

ABSTRACT

Changes in temperature and carbon dioxide during glacial cycles recorded in Antarctic ice cores are tightly coupled. However, this relationship does not hold for interglacials. While climate cooled towards the end of both the last (Eemian) and present (Holocene) interglacials, CO_2 remained stable during the Eemian while rising in the Holocene. We identify and review twelve biogeochemical mechanisms of terrestrial (vegetation dynamics and CO_2 fertilization, land use, wildfire, accumulation of peat, changes in permafrost carbon, subaerial volcanic outgassing) and marine origin (changes in sea surface temperature, carbonate compensation to deglaciation and terrestrial biosphere regrowth, shallow-water carbonate sedimentation, changes in the soft tissue pump, and methane hydrates), which potentially may have contributed to the CO_2 dynamics during interglacials but which remain not well quantified. We use three Earth System Models (ESMs) of intermediate complexity to compare effects of selected mechanisms on the interglacial CO_2 and $\delta^{13}CO_2$ changes, focusing on those with substantial potential impacts: namely carbonate sedimentation in shallow waters, peat growth, and (in the case of the Holocene) human land use. A set of specified carbon cycle forcings could qualitatively explain atmospheric CO_2 dynamics from 8 ka BP to the pre-industrial. However, when applied to Eemian boundary conditions from 126 to 115 ka BP, the same set of forcings led to disagreement with the observed direction of CO_2 changes after 122 ka BP. This failure to simulate late-Eemian CO_2 dynamics could be a result of the imposed forcings such as prescribed $CaCO_3$ accumulation and/or an incorrect response of simulated terrestrial carbon to the surface cooling at the end of the interglacial. These experiments also reveal that key natural processes of interglacial CO_2 dynamics — shallow water $CaCO_3$ accumulation, peat and permafrost carbon dynamics - are not well represented in the current ESMs. Global-scale modeling of these long-term carbon cycle components started only in the last decade, and uncertainty in parameterization of these mechanisms is a main limitation in the successful modeling of interglacial CO_2 dynamics.

1. Introduction

A number of uncertainties complicate future projections of atmospheric CO_2 concentration and climate change (Ciais et al., 2013). In conjunction with the development of mechanistic models of the climate system and carbon cycle, the starting point to addressing these uncertainties is to understand the relationship

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http://dx.doi.org/10.1016/j.quascirev.2016.01.028
0277-3791/

between surface temperatures and atmospheric CO_2 concentrations in the warm intervals of the recent past. The tight coupling between Antarctic temperature and CO_2 during glacial cycles has been known since pioneering studies of the Antarctic ice cores (Barnola et al., 1987; Neftel et al., 1982). Recent studies reveal past CO_2 dynamics during the present (Indermühle et al., 1999; Monnin et al., 2004) and last interglacial periods (Schneider et al., 2013) with much higher precision and accuracy. These analyses demonstrate that during the present interglacial (Holocene), atmospheric CO_2 increased by about 20 ppm from 7 ka BP to before the onset of the industrial era (Fig. 1). In the last interglacial period (Eemian), CO_2 varied around the level of about 270–280 ppm without any significant trend from 126 to 115 ka BP (Fig. 1). Since temperatures in Antarctica decreased towards the end of both periods, the temperature - CO_2 relationship common for the glacial cycles (Petit et al., 1999; van Nes et al., 2015) and, especially, deglaciations (Parrenin et al., 2013) is not valid for these two interglacials.

Here, we address the difference in the interglacial CO_2 dynamics using two approaches. First, we provide a review of proxy data and mechanisms of carbon cycle changes during the Holocene and Eemian. In section 2, we summarize the current state of knowledge with regards to CO_2 variability during interglacials, reviewing the various possible carbon cycle mechanisms that can affect atmospheric CO_2. This overview is followed by a summary of available proxy constraints on these processes. In the second part of the paper, we present model setup (section 3) and results (section 4) from factorial simulations using three Earth System Models of Intermediate Complexity (EMIC). For this model intercomparison, we focus on time periods starting thousands of years after the terminations in order to minimize the memory effects of carbon cycle reorganization during deglaciation. For the Holocene, we chose the period from 8 ka BP, when interglacial climate conditions were well established, to 0.5 ka BP excluding the fossil fuel effect on the carbon cycle. For the Eemian, we analyze the period from 126 to 115 ka BP which corresponds to the Marine Isotopic Stage 5e (Tzedakis et al., 2012). Finally, we summarize how the CO_2 and $\delta^{13}CO_2$ ice core records during both 8–0.5 and 126–115 ka BP periods can be quantified based on the previous research and results of our model intercomparison.

2. An overview of proxy data and mechanisms of interglacial CO_2 change

2.1. Insights from the ice core $\delta^{13}CO_2$ records

Discrimination of the heavy ^{13}C isotope during photosynthesis affects land-atmosphere carbon fluxes and modifies the $^{13}C/^{12}C$ ratio of atmospheric $^{13}CO_2$ (e.g., Lloyd and Farquhar, 1994). An increase (decrease) in organic carbon storage on land leads to higher (lower) $^{13}C/^{12}C$ ratios in the atmosphere. Stable carbon isotope records from the ice cores, expressed as a deviation from the Vienna PeeDee Belemnite (VPDB) reference value in permil (‰), $\delta^{13}CO_2$, could be used to attribute changes in CO_2 to different sources. Indermühle et al. (1999) used newly available $\delta^{13}CO_2$ data at that time to conduct the first attempt to constrain the sources responsible for the growing CO_2 trend in the Holocene. These authors reconstructed the Holocene CO_2 evolution in detail, but had to rely on low temporal resolution measurements of $\delta^{13}CO_2$ with larger

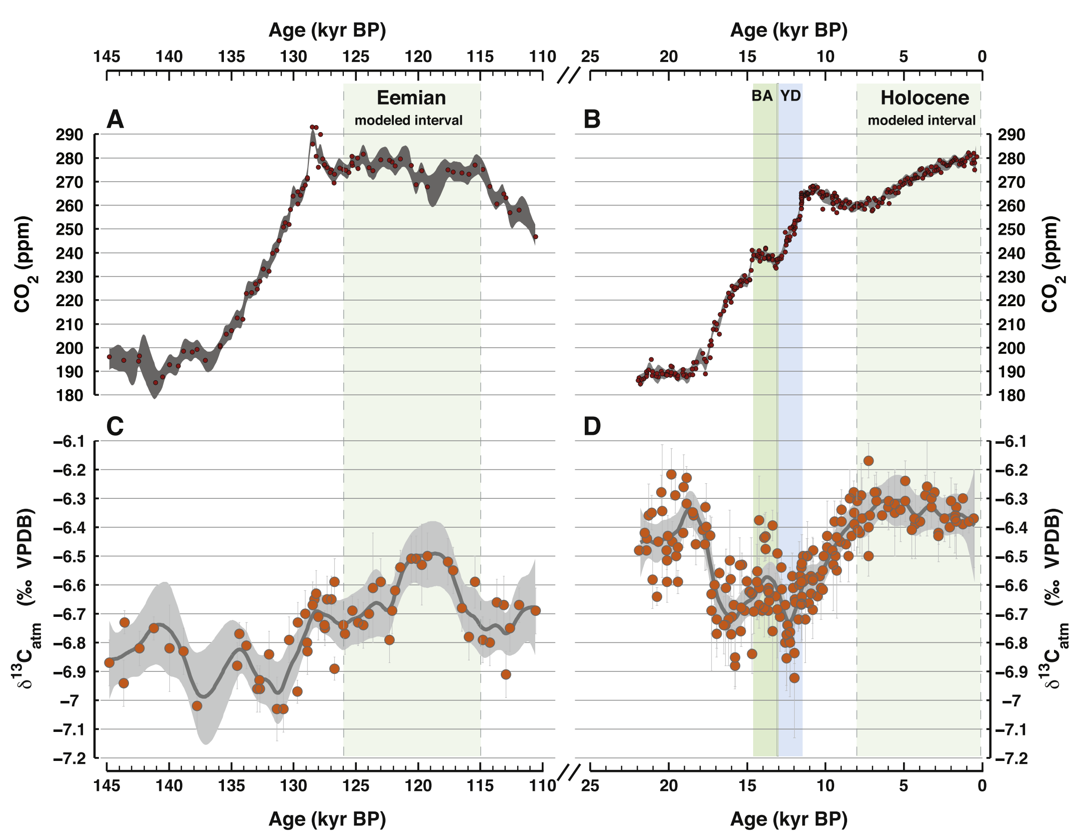

Fig. 1. Atmospheric CO_2 concentration, ppm (A, B) and $\delta^{13}CO_2$, ‰ (C, D) during the present (A, C) and the last (B, D) interglacial as reconstructed from Antarctic ice cores. For the Holocene, CO_2 data are from Monnin et al. (2004) and (Schmitt et al., 2012) plotted on top of a 1σ -error envelope using a Monte-Carlo approach with a cut-off period of 500 years; $\delta^{13}CO_2$ are the data as shown in (Schmitt et al., 2012) along the 1σ-error envelope (cut-off 2000 years). For the Eemian, CO_2 data are from (Lourantou et al., 2010; Schneider et al., 2013) plotted on top of a 1σ-error envelope and cut-off of 800 years, and $\delta^{13}CO_2$ data are from (Schneider et al., 2013) with a cut-off period of 3000 years.