Carbon storage on exposed continental shelves during the glacial-interglacial transition

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Received 13 December 2005; revised 20 February 2006; accepted 24 February 2006; published 18 April 2006.

[1] We present analyses of new and previously published estimates of total (vegetation plus soil) carbon storage on exposed continental shelves during the LGM. Carbon stock estimates from environmental reconstructions vary from 113 to 202 Pg C. Estimates from vegetation models range from 112 to 323 Pg C. After standardization of exposed shelf area by a topographic model the range of best estimates for reconstructions and models converge to 182–266 Pg C. Up to ~10000 years before present, the time dependent estimate of the amount of inundated carbon is in good qualitative agreement with the increase in the atmospheric carbon reservoir. Given its relative size compared to the change in terrestrial carbon storage and the potential link between inundated carbon and atmospheric CO_2 increase, the carbon stock of the LGM exposed shelves cannot be ignored and merits more detailed attention from modelling and reconstruction efforts.

Citation: Montenegro, A., M. Eby, J. O. Kaplan, K. J. Meissner, and A. J. Weaver (2006), Carbon storage on exposed continental shelves during the glacial-interglacial transition, *Geophys. Res. Lett.*, *33*, L08703, doi:10.1029/2005GL025480.

1. Introduction

[2] The change in the terrestrial carbon reservoir from the Last Glacial Maximum (LGM) to the preindustrial period has been the subject of a series of studies (see *Köhler and Fischer* [2004] and *Zeng* [2003] for recent reviews). While there are significant differences between estimated values, the overall consensus is that carbon storage on land has increased since the LGM (but see *Zeng* [2003] for a contrary view based on the burial of carbon by glaciers during the Pleistocene). In general, changes in terrestrial carbon storage based on vegetation models and vegetation reconstructions are larger than estimates from ocean core δ^{13}C data.

[3] A number of time series of atmospheric CO_2 concentration based on ice core records indicate a rise in atmospheric CO_2 from ~180 ppm (parts per million) at the LGM to ~280 ppm during preindustrial times. The vegetation and soil carbon present on exposed portions of the continental shelves during the LGM could have acted as a source for continental and/or atmospheric carbon stocks as sea level rose and inundated these areas during the glacial-interglacial transition. Uncertainties about the rate of sea level rise, isostatic rebound and therefore the size of exposed areas complicate the reconstruction of the total amount of carbon present on the LGM shelves [*Faure et al.*, 1996].

[4] Here we present a series of LGM shelf carbon stock estimates obtained from the literature and from new modelling experiments. The ICE-5G topography model [*Peltier*, 2004] is used to standardize results and minimize uncertainties associated with shelf area differences between estimates. Results from a simulation spanning the glacial-interglacial transition are used to analyze the temporal change in the amount of carbon stored on the shelf.

2. Data and Methods

2.1. Data

[5] We compile carbon storage values on the exposed shelf from three LGM vegetation reconstructions based on proxy data and from the output of four paleovegetation models. The reconstructions are based on fossil pollen alone [*Crowley*, 1995, hereinafter referred to as CRW] and a combination of fossil pollen, sedimentological and zoological proxies [*Faure et al.*, 1996, hereinafter referred to as FAR] and [it *Adams and Faure*, 1998, hereinafter referred to as A&F].

[6] Vegetation model results come from: the High Resolution Biosphere Model (HRBM) forced by output from the ECHAM2 atmosphere general circulation model [*Esser and Lautenschlager*, 1994], the Vegetation-Global-Atmosphere-Soil (VEGAS) model forced by the NCAR Community Climate Model [*Zeng*, 2003], the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) forced by the Hadley Center Unified Model [*Kaplan et al.*, 2002] and the University of Victoria Earth System Climate Model (UVic ESCM) [*Weaver et al.*, 2001; *Meissner et al.*, 2003]. In the first three vegetation models, terrestrial carbon storage is determined by the external forcing of climate on the vegetation, i.e., offline coupling. In the UVic ESCM, vegetation cover is a fully interactive component of the climate model, vegetation and the terrestrial carbon cycle both respond to changing climate and feed back upon the climate itself. The LGM atmospheric CO_2 concentration in the LPJ-DGVM simulation is 185 ppm, the other three models use 200 ppm.

2.2. Shelf Area

[7] The estimated amount of shelf carbon depends strongly on the size of the exposed shelf. Due to differences in grid size, the total shelf area exposed during the LGM varies between the vegetation models (the models used in this study are global simulations operating on coarse resolution grids and were not designed to reproduce the ice free shelf areas adequately). Vegetation models and proxy

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0094-8276/06/2005GL025480$05.00

Table 1. LGM Surface Area in 10^{12} m^{2a}

Source	ifTA	ifSA	SA	ifSA/ifTA	ifSA/SA	Reference
				Models		
HRBM	115	12.1	16.8	.12	.72	*Esser and Lautenschlager* [1994]
VEGAS	-	18.0	-	-	-	*Zeng* [2003]
LPJ-DGMV	125	7.2	8.0	.06	.91	present study
UVic ESCM	137	15.6	21.0	.11	.74	present study
				Reconstrucions		
CRW	132	15.7	26.9	.12	.75	CRW
FAR	-	-	19.1	-	-	FAR
A&F	131	15.9	27.1	.12	.59	A&F
				Topography		
ICE-5G	134	17.3	24.5	.13	.71	*Peltier* [2004]

[a]ifTA, ice free continents; ifSA, ice free exposed shelf; SA, total area of exposed shelf.

reconstructions tend to underestimate the exposed ice free shelf area when compared to a topographic model (Table 1). In order to make the simulations and reconstructions consistent, we calculate a mean concentration of terrestrial carbon on the exposed shelf for each simulation and reconstruction and multiply this value with a standardized area of exposed shelf. This standardized area is computed with the ICE-5G topography model [*Peltier*, 2004] (Table 1, last line). The total amount of stored carbon obtained with this standardized area for each study is shown in Table 2, last column.

2.3. Mean Carbon Concentration on Shelves

[8] FAR provide an estimate of the amount of carbon inundated by the oceanic transgression based on the area of the LGM exposed shelf and a continental carbon concentration of 10.65 kg/m^2. According to FAR, this value should be representative of the period between the LGM and 9 kyr BP, and incorporates the expected increase in carbon density associated with the glacial-interglacial transition. In order to maintain consistency with the other studies, the FAR shelf carbon storage (SCa, Table 2) is not calculated using the 10.65 kg/m^2, instead, the FAR mean LGM continental carbon concentration is adopted. For the CRW and A&F reconstructions, terrestrial carbon storage is calculated based on the average of the biome-specific carbon concentrations given by CRW's Table 3.

[9] Vegetation models compute the carbon storage in each grid cell on the shelves and the mean value can be directly calculated. All the mean carbon concentrations are listed in Table 2.

2.4. Time Series

[10] The rate of inundation of the continental shelves and estimates of carbon density on these areas are used to generate time series of the amount of carbon "lost" to flooding on the exposed shelves (Figure 1). The ice free shelf area values come from a glacial-interglacial transition simulation with the ICE-4G topography and ice sheet model [*Peltier*, 1993] with 1000 years temporal resolution. Three different time series are obtained by multiplying the ICE-4G ice free shelf area with two constant carbon concentrations (15 and 20 kgC/m^2) and the time varying shelf carbon concentration given by the LPJ-DGMV results, respectively. Atmospheric CO_2 concentrations come from a combination of high-resolution Antarctic ice core data from Taylor Dome for the Holocene and Byrd Station for the late Pleistocene [*Kaplan et al.*, 2002].

[11] The adopted carbon shelf concentrations (15 and 20 kg/m^2) are slightly higher than the range of LGM estimates (see Table 2) to take into account the expected increase in terrestrial carbon density associated with warmer and wetter climate and higher atmospheric CO_2 concentrations. ICE-4G is used instead of the more recent ICE-5G because ICE-5G output was not available for the complete period between LGM and the present. Values estimated from these same mean shelf carbon concentrations and the total ICE-5G ice free area have been added to the figure for comparison.

3. Results and Discussion

[12] Modelled and reconstructed estimates of LGM shelf carbon storage (Table 2) range from 112 to 323 Pg of carbon (Pg C). As noted above, this wide dispersion stems in great part from differences in total shelf areas and standardization by the ICE-5G shelf reduces the scatter in storage values (IG5 SCa, Table 2). The lower limit in this case comes from the FAR reconstruction (144 Pg C), and is a consequence of the use of mean continental carbon density instead of shelf specific carbon density. On the other hand, the HRBM shelf carbon concentration (26 km/m^2) is much higher than the estimates from other models and reconstructions (10.6 to 15.5 km/m^2) a fact reflected in a global bias toward high terrestrial carbon storage for this simulation.

[13] For the reconstructions, estimates of shelf carbon storage based on the ICE-5G topography are 7–9% larger

Table 2. Vegetation and Soil Carbon Storage Values (Columns 2 and 3 and 7) in Pg C and Concentrations (Columns 5 and 6) in kg/m^{-2a}

Source	TCa	SCa	SCa/TCa	[TCa]	[SCa]	IG5 SCa
			Models			
HRBM	1870	323	.17	16.3	26.7	457
VEGAS	2180	254	.12	-	14.1	242
LPJ-DGMV	1655	112	.06	13.4	15.5	266
UVic ESCM	1548	200	.13	11.3	12.8	220
			Reconstrucions			
CRW	1381	202	.15	10.5	12.9	220
FAR	968	113	.15	5.9	-	144
A&M	1091	169	.15	8.4	10.6	182

[a]TCa, total continental carbon; SCa, carbon on exposed shelf; [TCa], continental carbon concentration; [SCa], exposed shelf carbon concentration; IG5 SCa, storage on shelf, based on ICE-5G ice free shelf area. Different from the other estimates, FAR total and shelf carbon densities refer to the total instead of ice free areas.

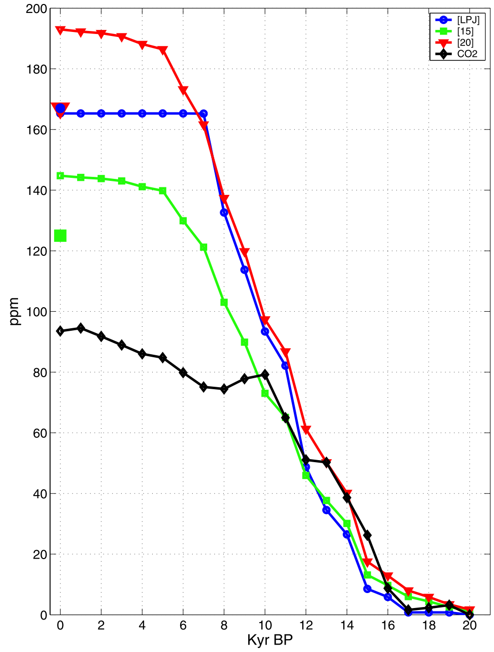

Figure 1. Inundated carbon expressed in atmospheric ppm since the LGM. Values are based on area of ice free shelf inundated every 1000 years multiplied by shelf carbon concentrations from: blue, LPJ-DGMV, green, 15 kg of carbon per m^2; red, 20 kg of carbon per m^2. Black is the atmospheric CO_2 concentration from ice cores [*Kaplan et al.*, 2002]. Isolated symbols mark the amount of carbon present of the total ICE-5G inundated shelf based on concentrations of 15 kg m^2, green square; 20 kg m^2, red triangle; 19.3 kg m^2 (time mean concentration of the inundated area in the LPG-DGMV model), blue circle.

than the original values. In the case of the vegetation models, the change in shelf carbon (differences between the SCa and IG5 SCa columns in Table 2) after normalization range from −5% to 138%. Excluding the FAR and HRBM results, the overall "area corrected" estimates of the vegetation models range from 220–266 Pg C and are slightly higher than the reconstruction range of 182–220 Pg C.

[14] Estimates of the increase in the total terrestrial carbon reservoir between LGM and present day range between 270 and 1106 Pg C [*Köhler and Fischer*, 2004]. Based on the results of the present study, the carbon stored on exposed shelves at the glacial maximum represents between 17% and 99% of the total estimated terrestrial carbon increase from LGM to the present.

[15] In terms of atmospheric CO_2, these amounts of flooded shelf carbon translate to concentrations between 88–128 ppm. The observed increase in CO_2 concentration during the same period is ∼100 ppm.

[16] The temporal evolution of the amount of carbon being inundated at the shelf is expressed in Figure 1 in terms of ppm of atmospheric CO_2. Up to about 10,000 years before present, there is a good qualitative agreement between the inundated carbon and atmospheric CO_2 curves. The similarities between the actual quantities could be an indication of a relationship between atmospheric CO_2 increase and terrestrial carbon flooded on continental shelves. The actual fate of the submerged carbon depends on biogeochemical processes occurring in the water column and sediments of the shelf and open ocean as well as in the atmosphere. Estimating the partition of the submerged carbon stock due to these mechanisms is not within the scope of the present study. The potential link between shelf carbon and atmospheric CO_2 must the tested by further analyses that take into account complete terrestrial, atmospheric and oceanic carbon stocks.

4. Conclusions

[17] In this study we compile estimates of the amount of carbon stored on exposed continental shelves during the last glacial maximum. Simulated values from vegetation models converge to around 240 Pg C (219–266 Pg C), whereas reconstructions yield slightly lower values (182–220 Pg C) when the same area of exposed shelf is used. These values represent between 17% and 99% of the estimated total change in terrestrial carbon between the last glacial maximum and today. Time series of inundated carbon on the shelves compare well with the increase of atmospheric CO_2 at the end of Pleistocene. Given its relative size compared to the change in terrestrial carbon storage and the potential link between inundated carbon and atmospheric CO_2 increase, we believe that the size and fate of carbon stocks on the LGM exposed shelves cannot be ignored and merits more detailed attention from both modelling and reconstruction perspectives.

[18] **Acknowledgments.** The authors are grateful for funding received from both NSERC and CFCAS. We would also like to thank Ed Wiebe for his technical support.

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