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High Latitude Impacts on Deglacial CO_2: Southern Ocean Westerly Winds and Northern Hemisphere Permafrost Thawing

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With 2 Figures

Climate in the high latitudes changed massively during the last deglaciation. Temperature rose due to the polar amplification more than twice as much as in the global mean leading predominately to the shrinking of various parts of the cryosphere: decline of northern hemispheric (NH) land ice sheets and permafrost thawing, and a reduction in sea ice extent in both hemispheres. It is thus a rather natural choice to also analyse how changes in these polar regions might influence the global carbon cycle and atmospheric CO_2. Here we use carbon cycle models to analyse two examples of the impact of high latitude climate change on deglacial CO_2: (*i*) changes in the position of the westerly winds in the Southern Ocean during the Last Glacial Maximum (LGM) (based on Völker and Köhler 2013); (*ii*) Northern Hemisphere permafrost thawing at the onset of the Bølling/Allerød (B/A) around 14.6 ka ago (based on Köhler et al. 2014).

1. Southern Ocean Westerly Winds

The synchronicity of changes in atmospheric CO_2 and Antarctic temperature found in ice cores (e.g. Parrenin et al. 2013) has led to hypotheses which suggest Southern Ocean processes as causes for a dominant part of the observed deglacial rise in atmospheric CO_2. Toggweiler et al. (2006) e.g. proposed that changes in the Southern Hemispheric (SH) belt of westerly winds are the cause for a dominant part of the observed deglacial CO_2 rise. The reasoning of Toggweiler et al. (2006) is that nowadays Southern Hemispheric westerly winds lead to the upwelling of carbon-rich waters *via* a northward Ekman transport. If this westerly-induced upwelling is reduced (either by a northward shift or a reducing of the strength of the westerlies), less carbon-rich water is brought to the surface. As a consequence, net oceanic carbon uptake would drag CO_2 from the atmosphere to the surface of the Southern Ocean, where it would finally be transported to the abyss with deep waters formed around Antarctica. Toggweiler et al. (2006) argued about latitudinal shifts in the wind belt (equatorward during colder climates) while they performed simulation scenarios in which the strength, not the position of the SH westerly winds, was modified under the assumption that the effect of both on atmospheric CO_2 might be similar. In Völker and Köhler (2013) we provided a sensitivity test of the westerly wind hypothesis in which various shortcomings of the original study or its successors (Menviel et al. 2008, Tschumi et al. 2008, d'Orgeville et al. 2010, Lee et al. 2011) are overcome: We used a (*i*) full ocean general circulation model (the MITgcm) (*ii*) including a fully prognostic sea ice model and applied (*iii*) LGM background conditions using (*iv*) a realistic bathymetry. In doing so, the potential role of the different carbon pumps on atmospheric CO_2 can be elucidated. In detail, we shifted the Southern Ocean westerly winds both southward and northward by up to 10°.

We find (Fig. 1) that a southward (northward) shift in the westerly winds leads to an intensification (weakening) of no more than 10 % of the Atlantic meridional overturning circulation (AMOC). This response of the ocean physics to shifting winds agrees with other studies starting from preindustrial background climate, but the responsible processes are different. In our setup, changes in AMOC seemed to be more pulled by upwelling in the south than pushed by buoyancy changes and subsequent downwelling in the north, opposite to what previous studies with different background climate are suggesting. The net effects of the changes in ocean circulation lead to a rise in atmospheric pCO_2 of less than 10 µatm for both northward and southward shift in the winds. For northward shifted winds the zone of upwelling of carbon- and nutrient-rich waters in the Southern Ocean is expanded, leading to more CO_2 outgassing to the atmosphere but also to an enhanced biological pump in the subpolar region. For southward shifted winds the upwelling region contracts around Antarctica, leading to less nutrient export northward and thus a weakening of the biological pump. These model results do not support the idea that shifts in the westerly wind belt play a dominant role in coupling atmospheric CO_2 rise and Antarctic temperature during deglaciation suggested by the ice core data.

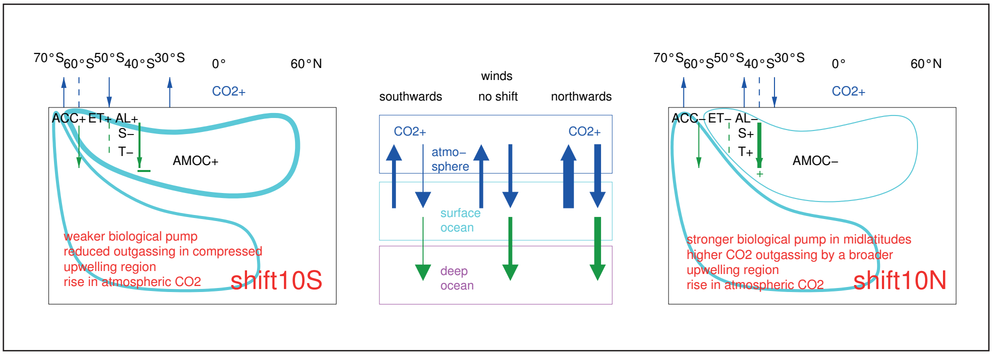

Fig. 1 Conceptual view of how changes in the SH winds influence the ocean circulation and the carbon cycle (after Völker and Köhler 2013). Impact of Southern Ocean westerly winds shifted (*left*) 10°S, and (*right*) 10°N as function of latitude. (*Middle*) Condensed changes in the carbon cycle comparing the LGM simulations. Strength of the biological pump (*green*) and of the gas exchange (*blue*) depict how carbon varies between atmosphere, surface, and deep ocean. ACC: Antarctic Circumpolar Current, ET: Ekman transport, and AL: Agulhas leakage.

According to our results, the impact of changes in the SH westerlies on ocean circulation and on atmospheric CO_2 during the deglaciation might have been as follows: Independent estimates (Kohfeld et al. 2013) suggest that the SH westerly wind belt was probably shifted to the north by no more than 5° in the LGM. In the atmospheric forcing of our LGM simulation the maximum in zonal wind stress was already shifted north by 4°. We, therefore, argue that starting from our LGM reference simulation, a southward shift of the westerly winds by 5° is the closest analogue to what might have happened in the past during termination I. These changes in the SH winds probably evolved slowly over the whole deglaciation, not abrupt in a short time window of a few centuries. It might thus explain only a small part of less than 10 % of the deglacial AMOC enhancement and a rise in atmospheric CO_2 by 7 µatm. Thus, it becomes clear that SH westerly wind belt variation was not the dominant process which tightly couples atmospheric CO_2 and high-latitude SH temperature during terminations or even over whole glacial cycles.

2. Northern Hemisphere Permafrost Thawing

One of the most abrupt and yet unexplained past rises in atmospheric CO_2 (10 ppmv in two centuries in the EPICA Dome C [EDC] ice core) occurred in quasi-synchrony with abrupt northern hemispheric warming into the Bølling/Allerød, about 14.6 ka ago. In Köhler et al. (2014) we used a U/Th-dated record of atmospheric $\Delta^{14}C$ from Tahiti corals to provide an independent and precise age control for this CO_2 rise. We also used model simulations to show that the release of old (nearly ^{14}C-free) carbon can explain these changes in CO_2 and $\Delta^{14}C$. The $\Delta^{14}C$ record provides an independent constraint on the amount of carbon released (125 PgC). We suggest, in line with observations of atmospheric CH_4 and terrigenous biomarkers, that thawing permafrost in high northern latitudes could have been the source of carbon, possibly with contribution from flooding of the Siberian continental shelf during meltwater pulse 1A. Our findings highlight the potential of the permafrost carbon reservoir to modulate abrupt climate changes *via* greenhouse-gas feedbacks. These calculations and conclusions were challenged by the new CO_2 data (Marcott et al. 2014) from the West Antarctic Ice Sheet Divide Ice Core (WDC), which have a higher temporal resolution. We therefore revised our carbon release experiments (Fig. 2) in order to meet these new WDC CO_2 data. We furthermore used a new age distribution during gas enclosure in ice which includes the most recent understanding of firn densification. We then can align EDC and WDC CO_2 data and propose a peak amplitude in atmospheric CO_2 of about 15 ppmv around 14.6 ka BP corresponding to a C pulse of 85 PgC released in 200 years (0.425 PgC per year). This is 68 % of the initial suggested strength of the C pulse of 125 PgC, that then led to a peak amplitude in true atmospheric CO_2 of 22 ppmv. CO_2 data from other ice cores suggest that the amplitude in atmospheric CO_2 was in-between both these scenarios. The revised scenario proposes a carbon release that is still large enough to explain the atmospheric $\Delta^{14}C$ anomaly of –(50 – 60) ‰ in 200 – 250 years derived from Tahiti corals. However, in the revised scenario the released carbon needs to be essentially free of ^{14}C, while in the previously suggested scenario there was still the possibility that the released carbon still contained some ^{14}C and had a difference in the $\Delta^{14}C$ signature to the atmosphere $\Delta(\Delta^{14}C)$ of –700 ‰. The previous scenario, therefore, contained a larger possibility that the released carbon might eventually been released from the deep ocean. The revised interpretation proposed here strengthens the idea that the carbon was released from permafrost thawing, since this had more likely a nearly ^{14}C-free signature than any other known source. We therefore conclude, that the new WDC CO_2 data are not in conflict with our permafrost thawing hypothesis, but indicate only that the magnitude of the released carbon might have been smaller than initially suggested.

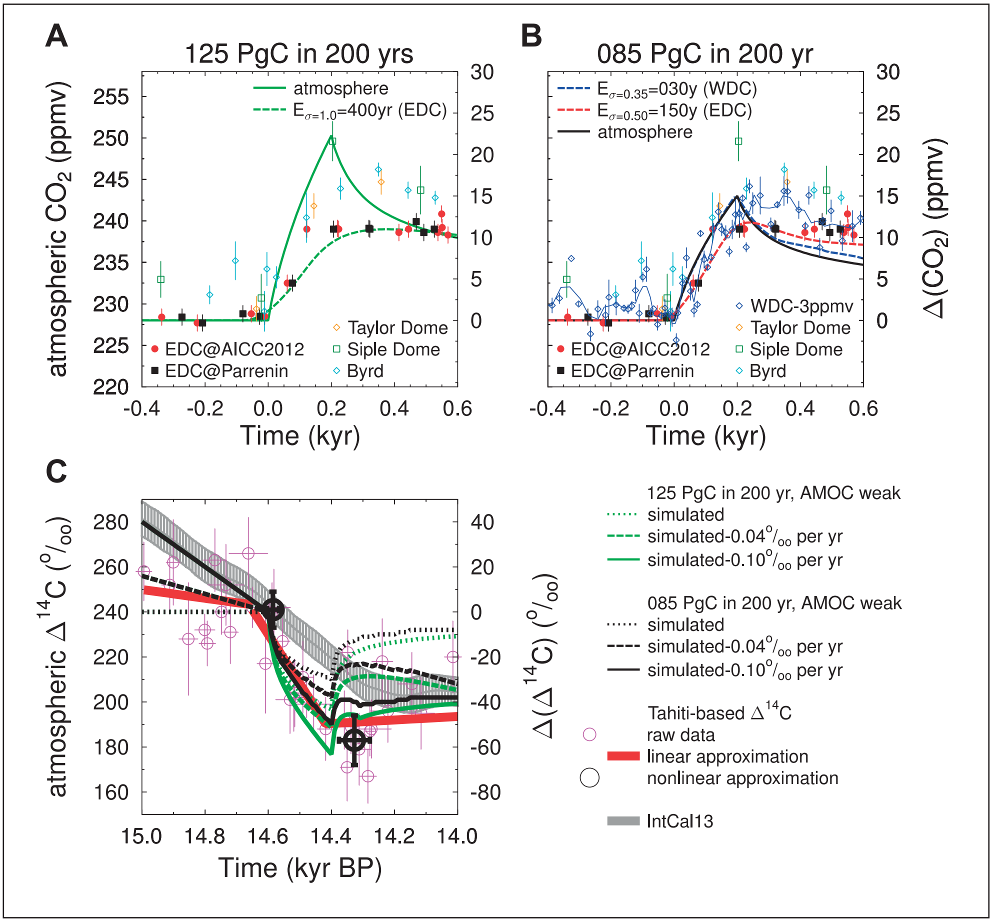

Fig. 2 Simulated atmospheric CO_2 and $\Delta^{14}C$ anomalies around 14.6 ka BP following the idea of NH permafrost thawing (Köhler et al. 2014). True atmospheric CO_2 as simulated by either a carbon release of (*A*) 125 PgC or (*B*) 85 PgC. Signal filtered with the log-normal function with a mean width E of (*A*) 400 years to mimic gas enclosure in EDC or by (*B*) 30 and 150 years to mimic gas enclosure in WDC or EDC, respectively, following the newly proposed age distribution characteristics of the OSU firn densification model (Mitchell et al. 2013, Marcott et al. 2014). Shape of the log-normal filter function is determined by the parameter σ given in the subscript to E with σ = 1.0 being the previous standard choice leading to a long-tailed filter function, while new evidences point to a more narrow age distribution, thus to σ<1.0 (*A*): Ice core CO_2 data (±1SD) from EDC (Schmitt et al. 2012, Monnin et al. 2001, Lourantou et al. 2010) on two different chronologies (Parrenin et al. 2013, Veres et al. 2013) AICC2012 and Parrenin, Taylor Dome on revised age model (Smith et al. 1999, Ahn et al. 2004), Siple Dome (Ahn et al. 2004), Byrd on age model GICC05 (Neftel et al. 1988, Pedro et al. 2012). (*B*): Additionally to CO_2 data in (*A*) the new WDC CO_2 data (Marcott et al. 2014) are plotted as individual data points and as 3-point-running mean (*blue line*), both shifted by −3 ppmv. All CO_2 time series in (*A*, *B*) are shifted to have the beginning of the abrupt CO_2 rise at t = 0 ka. (*C*): Impacts of both scenarios of a carbon release event around 14.6 ka BP on atmospheric $\Delta^{14}C$, including transient background anomalies and compared with the Tahiti-based $\Delta^{14}C$ signal (start and stop of $\Delta^{14}C$ anomaly given by bold black circles, mean±1SD) derived in Köhler et al. (2014) from the data published in Durand et al. (2013) (magenta circles, mean±1SD) and how this disagrees with the IntCal13 stack (Reimer et al. 2013).

References

Ahn, J., Wahlen, M., Deck, B. L., Brook, E. J., Mayewski, P. A., Taylor, K. C., and White, J. W. C.: A record of atmospheric CO_2 during the last 40,000 years from the Siple Dome, Antarctica ice core. J. Geophys. Res. *109*, D13 305; doi:10.1029/2003JD004415 (2004)

Durand, N., Deschamps, P., Bard, E., Hamelin, B., Camoin, G., Thomas, A. L., Henderson, G. M., Yokoyama, Y., and Matsuzaki, H.: Comparison of ^{14}C and U-Th ages in corals from IODP #310 cores offshore Tahiti. Radiocarbon *55*, 1947–1974; doi:10.2458/azu_js_rc.v55i2.16134 (2013)

d'Orgeville, M., Sijp, W. P., England, M. H., and Meissner, K. J.: On the control of glacial-interglacial atmospheric CO_2 variations by the Southern Hemisphere westerlies. Geophys. Res. Lett. *37*, L21703; doi:10.1029/2010GL045261 (2010)

Köhler, P., Knorr, G., and Bard, E.: Permafrost thawing as a possible source of abrupt carbon release at the onset of the Bølling/Allerød. Nature Comm. *5*, 5520; doi:10.1038/ncomms6520 (2014)

Kohfeld, K. E., Graham, R. M., Boer, A. M. de, Sime, L. C., Wolff, E. W., Le Quéré, C., and Bopp, L.: Southern Hemisphere westerly wind changes during the Last Glacial Maximum: paleo-data synthesis. Quat. Sci. Rev. *68*, 76–95; doi:10.1016/j.quascirev.2013.01.017 (2013)

Lee, S.-Y., Chiang, J. C. H., Matsumoto, K., and Tokos, K. S.: Southern Ocean wind response to North Atlantic cooling and the rise in atmospheric CO_2: Modeling perspective and paleoceanographic implications. Paleoceanography *26*, PA1214; doi:10.1029/2010PA002004 (2011)

Lourantou, A., Lavrič, J. V., Köhler, P., Barnola, J.-M., Paillard, D., Michel, E., Raynaud, D., and Chappellaz, J.: Constraint of the CO_2 rise by new atmospheric carbon isotopic measurements during the last deglaciation. Global Biogeochem. Cycles *24*, GB2015; doi: 10.1029/2009GB003545 (2010)

Marcott, S. A., Bauska, T. K., Buizert, C., Steig, E. J., Rosen, J. L., Cuffey, K. M., Fudge, T. J., Severinghaus, J. P., Ahn, J., Kalk, M. L., McConnell, J. R., Sowers, T., Taylor, K. C., White, J. W. C., and Brook, E. J.: Centennial scale changes in the global carbon cycle during the last deglaciation. Nature *514*, 616–619; doi:10.1038/nature13799 (2014)

Menviel, L., Timmermann, A., Mouchet, A., and Timm, O.: Climate and marine carbon cycle response to changes in the strength of the southern hemispheric westerlies. Paleoceanography *23*, PA4201; doi:10.1029/2008PA001604 (2008)

Mitchell, L., Brook, E., Lee, J. E., Buizert, C., and Sowers, T.: Constraints on the late Holocene anthropogenic contribution to the atmospheric methane budget. Science *342*, 964–966; doi:10.1126/science.1238920 (2013)

Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J.-M.: Atmospheric CO_2 concentrations over the last glacial termination. Science *291*, 112–114; doi:10.1126/science.291.5501.112 (2001)

Neftel, A., Oeschger, H., Staffelbach, T., and Stauffer, B.: CO_2 record in the Byrd ice core 50,000-5,000 years BP. Nature *331*, 609–611 (1988)

Parrenin, F., Masson-Delmotte, V., Köhler, P., Raynaud, D., Paillard, D., Schwander, J., Barbante, C., Landais, A., Wegner, A., and Jouzel, J.: Synchronous change in atmospheric CO_2 and Antarctic temperature during the last deglacial warming. Science *339*, 1060–1063; doi:10.1126/science.1226368 (2013)

Pedro, J. B., Rasmussen, S. O., and van Ommen, T. D.: Tightened constraints on the time-lag between Antarctic temperature and CO_2 during the last deglaciation. Clim. Past *8*, 1213–1221; doi:10.5194/cp-8-1213-2012 (2012)

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidison, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht, J.: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon *55*, 1869–1887; doi:10.2458/azu_js_rc.55.16947 (2013)

Schmitt, J., Schneider, R., Elsig, J., Leuenberger, D., Lourantou, A., Chappellaz, J., Köhler, P., Joos, F., Stocker, T. F., Leuenberger, M., and Fischer, H.: Carbon isotope constraints on the deglacial CO_2 rise from ice cores. Science *336*, 711–714; doi:10.1126/science.1217161 (2012)

Smith, H. J., Fischer, H., Wahlen, M., Mastroianni, D., and Deck, B.: Dual modes of the carbon cycle since the Last Glacial Maximum. Nature *400*, 248–250 (1999)

Toggweiler, J. R., Russell, J. L., and Carson, S. R.: Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages. Paleoceanography *21*, PA2005; doi:10.1029/2005PA001154 (2006)

Tschumi, T., Joos, F., and Parekh, P.: How important are Southern Hemisphere wind changes for low glacial carbon dioxide? A model study. Paleoceanography *23*, PA4208; doi:10.1029/2008PA001592 (2008)

Veres, D., Bazin, L., Landais, A., Toyé Mahamadou Kele, H., Lemieux-Dudon, B., Parrenin, F., Martinerie, P., Blayo, E., Blunier, T., Capron, E., Chappellaz, J., Rasmussen, S. O., Severi, M., Svensson, A., Vinther, B., and Wolff, E. W.: The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years. Clim. Past *9*, 1733 – 1748; doi: 10.5194/cp-9-1733-2013 (2013)

Völker, C., and Köhler, P.: Responses of ocean circulation and carbon cycle to changes in the position of the Southern Hemisphere westerlies at Last Glacial Maximum. Paleoceanography *28*, 726 – 739; doi:10.1002/2013PA002556 (2013)

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