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Carbon cycle dynamics during episodes of rapid climate change

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Abstract

Past climate records reveal many instances of rapid climate change that are often coincident with fast changes in atmospheric greenhouse gas concentrations, suggesting links and positive feedbacks between the carbon cycle and the physical climate system. The carbon reservoirs that might have played an important role during these past episodes of rapid change include near-surface soil and peatland carbon, permafrost, carbon stored in vegetation, methane hydrates in deep-sea sediments, volcanism, and carbon stored in parts of the ocean that are easily ventilated through changes in circulation. To determine whether similar changes might lie in store in our future, we must gain a better understanding of the physics, biogeochemistry, dynamics, and feedbacks involved in such events. Specifically, we need to ascertain the main natural sources of atmospheric carbon dioxide and methane linked to rapid climate events in the paleoclimate record, and understand the mechanisms, triggers, thresholds, and feedbacks that were involved. Our review contributes to this focus issue by synthesizing results from nine studies covering a broad range of past time episodes. Studies are categorized into (a) episodes of massive carbon release millions of years ago; (b) the transition from the last glacial to the current interglacial 19 000–11 000 years ago; and (c) the current era. We conclude with a discussion on major remaining research challenges and implications for future projections and risk assessment.

1. Introduction

State-of-the-art climate models predict a relatively steady increase in temperature for the coming centuries. There is growing evidence, however, that these models might be too stable (Lenton *et al* 2008, 2019, Valdes 2011, Fischer *et al* 2018, Steffen *et al* 2018). For example, there were many episodes of rapid climate change in the Earth's climate history that were coincident with fast changes in atmospheric greenhouse gas concentrations, evidence for strong positive feedbacks between the carbon cycle and climate. These feedbacks were ultimately triggered by relatively slow changes in boundary conditions, such as changes in orbital parameters and solar insolation. Based on today's knowledge about past climate variability, we can identify a list of fast-release carbon reservoirs that have the potential to influence future climate projections. These include the ocean, permafrost, peat, hydrates, and vegetation (figure 1).

Present day increases in greenhouse gases and associated global climate change are occurring at much faster rates than during any of these past episodes (Marcott *et al* 2014, Zeebe *et al* 2016), and the climate system is far from being in equilibrium with current atmospheric carbon dioxide concentrations. We therefore urgently need to understand the mechanisms and triggers for natural carbon release and uptake that have influenced climates in the past, and are not necessarily well represented in current models, in order to refine potential trajectories of future change. These processes and resulting feedbacks may amplify the current and future atmospheric greenhouse gas increase by adding natural carbon emissions to anthropogenic emissions (Cox *et al* 2000), potentially yielding climate forcing at the top end of the Intergovernmental Panel on Climate Change (IPCC) scenarios, even at more moderate anthropogenic emission levels. Further, paleoecological records indicate that the capacity of

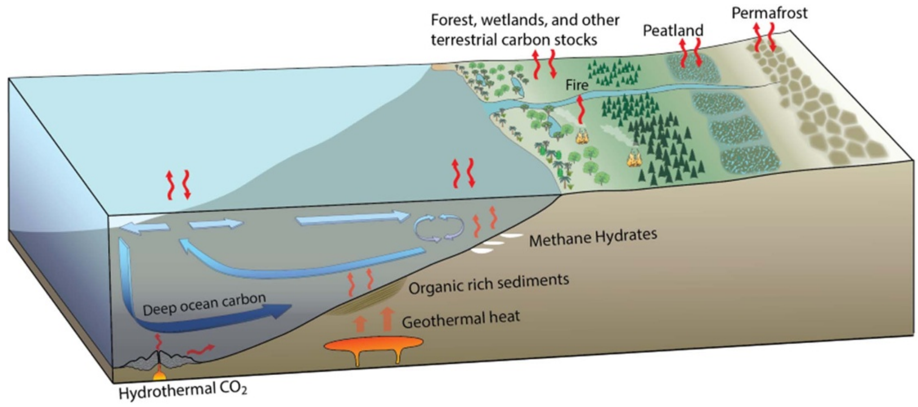

Figure 1. Schematic diagram illustrating carbon reservoirs that may be involved in abrupt changes in atmospheric CO_2 on various geological time scales and are important aspects of predicting future change. Paleoceanographic data and models suggest potential for rapid release of carbon from deep ocean reservoirs due to changes in ocean circulation or biogeochemistry. Volcanic intrusions heating of carbon rich sediments may play a role in deep time events like the Paleocene–Eocene Thermal Maximum. Recent work hypothesizes that release of carbon from geological sources like midocean ridges or subaerial volcanoes may happen on shorter time scales than typically appreciated. Terrestrial systems also have significant potential as both abrupt source and sinks of atmospheric CO_2, with permafrost and peatland carbon dynamics receiving a great deal of attention. Changes in temperate and tropical carbon dynamics as well as wildfire in both high and low latitude systems also have potential to play a role in fast carbon changes.

ecosystems to take up carbon changes under rapid climate change; quantifying the capacity for carbon uptake under warmer climates is also critically important. This focus issue uses the lens of Earth history to explore the potential for rapid carbon cycle feedbacks in a series of papers spanning the oceans, the cryosphere and terrestrial ecosystems.

2. Carbon–climate feedbacks through time

Throughout Earth history, warming episodes generally occurred on faster timescales than cooling episodes (Kvale *et al* 2018, this issue). This asymmetry can be seen on millennial timescales (e.g. hyperthermals or glacial–interglacial cycles) and centennial timescales (e.g. Dansgaard/Oeschger Oscillations during the last glacial). This points to effective positive feedbacks in the system during episodes of warming, which can be physical (e.g. it takes longer to build an ice sheet than to melt it) or biogeochemical (e.g. it takes longer to accumulate carbon in permafrost than to release it). Several instances of rapid warming events discussed in this issue are outlined below (figure 2).

2.1. Going millions of years back in time: negative carbon isotope excursions and hyperthermals

Episodes of massive carbon release to the ocean–atmosphere system and associated global warming punctuate the geological record, and are often recorded by negative carbon isotope excursions (nCIEs) in sedimentary deposits—see article by Vervoot *et al* (2019) in this issue. The most studied of these hyperthermal events is the Paleocene–Eocene Thermal Maximum (PETM), which occurred 56 million years ago (Zeebe and Lourens 2019). The PETM is associated with widespread ocean acidification (Penman *et al* 2014, Gutjahr *et al* 2017), extensive dissolution of deep-sea carbonates (Zachos *et al* 2005) and one of the largest known extinctions of deep-sea species (Thomas 1990, McInerney and Wing 2011). While the magnitude of warming during the PETM has been relatively well constrained (4 °C–5 °C, Dunkley Jones *et al* 2013), the source, magnitude and speed of carbon release into the atmosphere is still debated. Potential sources include volcanism that coincided with the initial opening of the Norwegian–Greenland Sea (North Atlantic Igneous Province, Story *et al* 2007, Gutjahr *et al* 2017); methane hydrates in deep-sea sediments (Dickens *et al* 1995); and thawing of permafrost (DeConto *et al* 2012).

Quantifying the characteristics of carbon release during events like the PETM is important for several reasons. A reliable estimate of the magnitude of carbon release, in conjunction with estimates of temperature change, will help constrain the planet's climate sensitivity under warmer boundary conditions and therefore refine future projections of temperature rise. Constraining the speed of change will give new insights into the resilience of ecosystems and the operation of buffering Earth system feedbacks. Determining the sources of carbon will help us to quantify the risk of potential future carbon releases from fast-release reservoirs, such as methane hydrates or permafrost.

Unfortunately it is not straightforward to constrain these parameters. An nCIE can theoretically constrain the magnitude of carbon released, but only if the source of carbon, and therefore its isotopic signature, is known. The amount of warming can theoretically inform on the magnitude of emissions, but

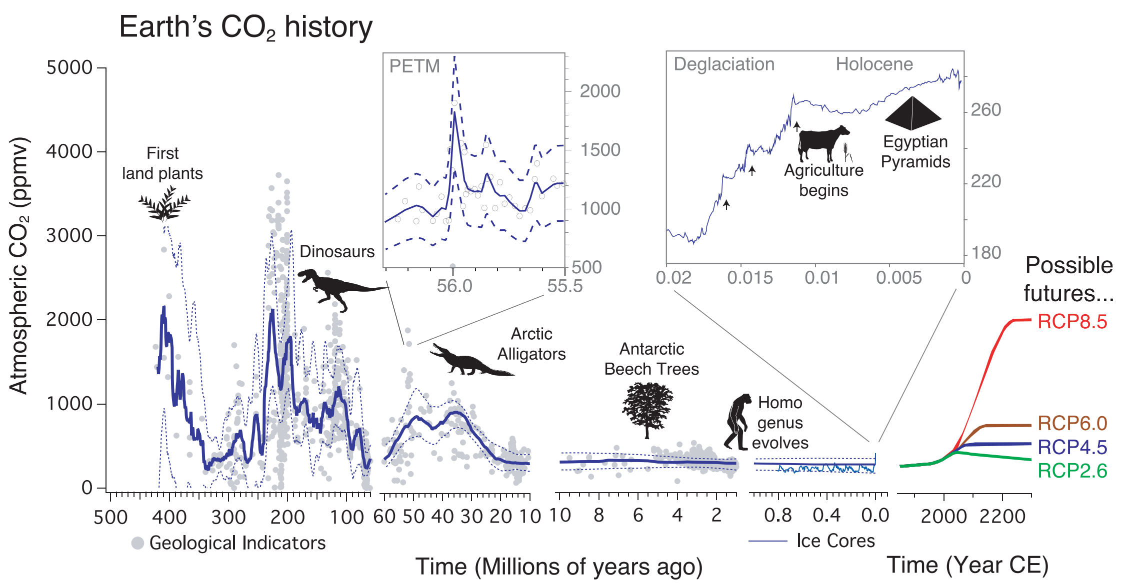

Figure 2. The geological record of CO_2 change. Inset panels show time intervals of notable carbon cycle dynamics, as discussed in this issue: the Paleocene–Eocene Thermal Maximum (PETM), the deglaciation at the end of the last ice age (including abrupt CO_2 jumps indicated by small arrows), and the Holocene—the time of relatively stable CO_2 and climate in which human agriculture and settlement began. Prior to 1 million years ago CO_2 data come from various geological reconstructions, as compiled by Foster *et al* (2017); from 0.8 million years ago forward, data come from Antarctic ice cores, as compiled by Bereiter *et al* (2015); PETM data are from Gutjahr *et al* (2017) and Penman *et al* (2014), with calculation following Rae *et al* (2021)—note that absolute CO_2 values at this time carry significant uncertainty (as denoted by the dotted lines), but relative changes are relatively robust. Possible future CO_2 changes, based on Representative Concentration Pathways 2.6, 4.5, 6.0, and 8.5 from IPCC AR5, are also shown (Meinshausen *et al* 2011). Although RCP 8.5 is now considered an unlikely scenario (Hausfather and Peters 2020), it does illustrate the range of potential impacts of future energy choices. While the CO_2 levels that may be reached in the coming century are not geologically unprecedented, they are entirely unfamiliar to our genus, and were associated with strikingly different biota and climate, as indicated by the inset images. It is also notable that even the most rapid rises in CO_2 in the geological record—during the PETM and last deglaciation—are at least an order of magnitude slower than the rate of anthropogenic CO_2 rise (see Penman and Zachos, this issue).

only if the climate sensitivity is known. The climate sensitivity could be constrained, but only if the CO_2 concentrations and temperature are known, and if Earth's albedo can be estimated. The problem is underconstrained.

The articles by Vervoort *et al* (2019) and Penman and Zachos (2018) in this issue represent major advances in constraining the carbon release during nCIEs. Using efficient Earth system models (ESMs), these studies simulate a wide range of possible nCIE scenarios. A striking result from both studies is the importance of constraining the temporal evolution—and thus the rate—of the nCIE onset. For the same total amount of carbon released, the impacts are reduced if the emissions are smaller and sustained over longer timescales (Meissner and Bralower 2017, Penman and Zachos 2018, Vervoort *et al* 2019), due to the operation of several negative feedbacks which act to remove carbon from the atmosphere or to replenish carbonate ions in the ocean. This underlines the importance of accurate age models and the time-varying nature of carbon isotope excursions—rather than magnitude alone—in constraining carbon release. Further constraints can also be gained from other carbon cycle proxies, with Penman and Zachos (2018) showing how pH reconstructions using boron isotopes, and consideration of carbonate preservation, may be combined with carbon isotopes and Earth system modeling to narrow down plausible PETM scenarios. This and other studies now suggest that PETM carbon release rates were an order of magnitude smaller than present day anthropogenic emissions (Zeebe *et al* 2016, Gutjahr *et al* 2017, Penman and Zachos 2018), highlighting the potential impact of the current, more rapid increase in greenhouse gas concentrations on the future evolution of the Earth system.

2.2. Transitioning out of the last ice age: carbon dioxide, nitrous oxide and methane

A more recent example of positive climate–carbon cycle feedbacks is the last deglaciation (19–11 000 years before present), when the planet transitioned from full glacial conditions to the current interglacial, the Holocene. During this transition, large Northern Hemispheric ice sheets disintegrated, leading to a global sea-level rise of ∼134 m (Lambeck *et al* 2014). Changes in biogeochemical cycles on land and in the ocean caused a net release of greenhouse gases into the atmosphere, resulting in a rise of ∼90 parts per million (ppm) in carbon dioxide (CO_2), ∼300 parts per billion (ppb) in methane (CH_4) and ∼60 ppb in nitrous oxide (N_2O) (Köhler *et al* 2017). Most of the CO_2 must have originated from the ocean (Kohfeld and Ridgwell 2009), as land acted overall as a carbon sink when vegetation recolonized formerly glaciated regions and warmer temperatures enhanced biological productivity (Sigman and Boyle 2000, Menviel *et al* 2017, Jeltsch-Thömmes *et al* 2019). Permafrost thaw during the deglaciation may also have led to carbon release (Meyer *et al* 2019, this issue).

Ice core data show that the CO_2 rise during the last deglaciation was not monotonic (Monnin *et al* 2001, Marcott *et al* 2014), but instead punctuated by three episodes of accelerated change, with increases of ∼10–12 ppm in one or two centuries (figure 2, inset panel). The first, at ∼16.3 thousand years before present (ka BP), occurred at a time of cold conditions in the northern hemisphere and may be coincident with a major iceberg discharge to the North Atlantic (Heinrich event 1, Marcott *et al* 2014, Rhodes *et al* 2015). The second and third are associated with abrupt warming in Greenland (Marcott *et al* 2014)—at the onset of the Bølling warm period (at ∼14.8 ka BP) and again at the end of the Younger Dryas (at ∼11.6 ka BP). Although these changes are small in comparison to the current anthropogenic transient, they do suggest the existence of fast mechanisms in the carbon cycle. A number of explanations have been proposed for each of these episodes, including oceanic mechanisms, such as CO_2 release due to sea surface warming, rapid shifts in ocean circulation bringing carbon-enriched deep water to the surface, or fast changes in the ocean biological pump (Meissner 2007, Kohfeld and Ridgwell 2009, Menviel *et al* 2018), but also changes in terrestrial carbon storage, for example by shelf flooding (Montenegro *et al* 2006, Köhler *et al* 2014), permafrost thaw (Meyer *et al* 2019, this issue), high latitude warming, and tropical drying due to shifting rain belts. Such events are also present during full glacial conditions, for example between 40 and 30 ka BP (Bauska *et al* 2018, 2021) and early interglacial conditions (Nehrbass-Ahles *et al* 2020).

Lund *et al* (2019, this issue) show evidence based on carbon isotopes in oceanic surface and deep waters that the initial rise in CO_2 during the deglaciation lags behind significant changes in the deep ocean and the overturning circulation in the Atlantic. While not addressing the most rapid changes during this first episode of CO_2 increase directly, their analysis clearly shows that changes in ocean circulation (thought to be very important in the sequence of events that causes glacial to interglacial CO_2 change) are leading atmospheric changes—with a timing that is consistent with models that simulate the impact of circulation change on ocean biogeochemistry. Other recent data (Rae *et al* 2018, Li *et al* 2020) and model results (Menviel *et al* 2018) also suggest that ocean circulation changes lead to the first atmospheric CO_2 increase at ∼16.3 ka BP. Joos *et al* (2019, this issue) are successful in simulating changes in concentrations of another greenhouse gas, nitrous oxide (N_2O), during the third episode, the Younger Dryas, with an ESM. Their analysis points to a century-scale lag between changes in ocean circulation and the resulting changes in atmospheric N_2O. Finally, Stott *et al* (2019, this issue) examine the role of geological carbon in glacial–interglacial CO_2 cycles (Huybers and Langmuir 2009). They present evidence that liquid and hydrated carbon present in the deep ocean, ultimately derived from geological sources, may be important. However, it remains questionable whether geological sourced carbon significantly influenced basin-scale water mass features and thus atmospheric CO_2 (Chen *et al* 2020).

The possibility that permafrost carbon contributed to some of these events is of concern given that the Arctic will likely warm more than other parts of the globe in the near future. Permafrost contributions to the deglacial CO_2 increase are examined further in this issue by Meyer *et al* (2019), who use biomarker data and compound specific radiocarbon dating in a series of marine sediment cores, identifying an important role for meltwater flooding and coastal erosion in destabilizing permafrost carbon. Combining this result with previous carbon cycle modeling (Winterfeld *et al* 2018), they suggest that permafrost carbon contributed substantially to the CO_2 pulses at the onset of the Bølling and the end of the Younger Dryas, the second and third episodes of accelerated CO_2 increase. An issue with hypotheses that involve terrestrial carbon sources for these events is that the atmospheric carbon isotope record ($\delta^{13}CO_2$) does not show much change at these times, and is therefore not consistent with land carbon input without some other compensating processes being involved (Bauska *et al* 2016).

The methane release to the atmosphere during the deglacial was likely derived mostly from wetlands (Diyonisius *et al* 2020); these are important components of the terrestrial carbon cycle both in terms of methane (CH_4) release, and also in terms of their natural capacity for carbon burial in anoxic soils and carbon release due to warming or hydrological changes. This is shown by Peteet *et al* (2020, this issue) in a paleoecological study of a tidal marsh adjacent to New York City; the results also highlight the diminishing capacity of this marsh to sequester carbon due to urban encroachment and habitat loss, invasive species and eutrophication. This paper makes the link between the geological record and management approaches to maintain ecosystem function with respect to mitigating the risk of fast carbon releases in today's world.

2.3. The current era: the Holocene

Atmospheric concentrations of greenhouse gases and temperatures have been relatively stable during the Holocene (figure 2, inset panel). This recent era is therefore not well suited to study large scale dynamic climate–carbon interactions. It can, however, provide an understanding of the size and accumulation rates of some fast-release reservoirs, such as peats, wetlands and permafrost.

Large datasets of Holocene peat core data have been assembled over the past several decades, with a strong focus on boreal to subarctic bogs and fens (Gorham 1991, MacDonald *et al* 2006, Beilman *et al* 2009, Loisel *et al* 2014, Packalen *et al* 2014). It has long been accepted that wetlands bury carbon and sequester the vast majority of it, with the exception of very small slow carbon release (Clymo 1984). Analyses of Holocene records indicate strong controls by climate in terms of rates of carbon burial (e.g. van Bellen *et al* 2011), with important implications for impacts of climate warming on the peatland carbon pool. More recently, the total size of the peatland carbon pool has been revised significantly upwards, with a recent estimate that includes middle-latitude peatlands in addition to the vast boreal and sub-arctic bogs and fens, exceeding 1000 Gt (Nichols and Peteet 2019). Further, other studies are showing the importance of other wetland types outside of the boreal/sub-arctic bog and fen categories, including tropical peatlands (Dargie *et al* 2017), and freshwater swamps and marshes in the temperate zone (Bao *et al* 2011).

Peteet *et al* (2020, this issue) and Piilo *et al* (2019, this issue) address these emerging questions on the development of the wetland carbon pool and its sensitivity to rapid change. Peteet *et al* (2020) focus on the Late Holocene record from mid-latitude tidal marsh where rates of carbon burial exceed those of bogs or fens by an order of magnitude under certain conditions. Further, this study documents significant impacts of climate changes associated with the Medieval Climate Anomaly (∼800–1300 Common Era (CE)) and the Little Ice Age (1450–1850 CE) on rates of carbon burial in this marsh system, providing key data on the sensitivity of this land–atmosphere carbon flux. Piilo *et al* (2019) report on a series of peat cores spanning the boreal—tundra ecotone in Northeastern Canada with an emphasis on very recent changes, and suggest the possibility that warming climates are enhancing rates of carbon uptake in these regions.

These papers and others are piecing together a picture of burial of significant quantities of carbon in wetlands of all types. Holocene paleoecological records demonstrate the sensitivity of peatlands to changes in climate, hydrology and vegetation type; changes in any of those parameters can rapidly reduce or enhance the capacity of uptake (e.g. Holmquist *et al* 2016), as well as increase the potential for methane release (Jones and Yu 2010). Thus the studies by Piilo *et al* (2019) and Peteet *et al* (2020) reinforce the idea that wetlands are a 'handle with care' ecosystem in the sense that a large carbon pool has accumulated slowly, and may continue to accumulate even under warmer climates, but this pool is vulnerable to rapid release, mainly due to direct human impacts. Despite this, wetlands have been severely degraded; in some locations, the majority of wetland area has been converted to other land uses over recent centuries or even decades (Ausseuil *et al* 2015, Byun *et al* 2018), resulting in significant carbon losses. Thus, the Holocene paleoecological record provides a strong rationale for wetland conservation from the perspective of mitigating risk of a rapid and very large carbon release.

2.4. The future: risk of significant greenhouse gas—climate feedbacks

Risk is usually defined as likelihood multiplied by impact. The IPCC reports have been focussing primarily on likelihood. This entails the danger that events that are unlikely but have high impact, and are therefore high risk, might be underestimated or ignored (Sutton 2018). Some carbon–climate feedbacks fall under this category. While the impact of a potential positive carbon–climate feedback is relatively easy to assess, as long as the size of the reservoir is known, we need to understand past instances of carbon release and their underlying mechanisms to be able to quantify the likelihood.

For past climates that were as warm as today or slightly warmer, such as the last interglacial (LIG, ∼129–116 000 years ago) or Marine Isotope Stage (MIS)11.3 (∼410–400 ka) there is little to no evidence for carbon–climate feedbacks large enough to substantially change predictions of future global temperature (Fischer *et al* 2018). For climates under comparable CO_2 concentrations to today or with concentrations expected in the near future, such as the Mid Pliocene Warm Period (300–450 ppm, 3.3–3 million years ago), the lack of high resolution proxy records, and in particular the lack of ice core records, which provide atmospheric concentrations and isotopes, make it more difficult to detect potential episodes of large carbon–climate feedbacks. The hyperthermals during the Paleocene (see section 2.1) show some evidence of significant positive feedbacks between the carbon cycle and climate, but the background climate was very different, and it is therefore difficult to extrapolate the likelihood of such events to present and future climate scenarios.

It is also important to note that potential fast changes in the carbon cycle might not only lead to unexpected changes in future radiative forcing. These changes highlight the sensitivity of biogeochemical systems to change rapidly in ways that could have important implications for the future. For example, much recent work has highlighted the role of shifts in tropical rainfall belts during abrupt climate changes during the LIG, the last ice age and deglaciation. Though these are associated with relatively small changes in greenhouse gases, as discussed above, they likely were associated with large changes in hydroclimate and vegetation that, if they occurred today, would be of considerable importance to society.

Climate models used to simulate future projections are complex representations of the physical climate system. However, many of the components important for determining the stability of fast-release carbon reservoirs are still missing in these models. Recently, the climate modeling community has been including more biogeochemical processes into these models, leading to the development of so-called ESMs, which aim to provide a more holistic representation of the Earth. These models can then be tested against past episodes of rapid warming and greenhouse gas rises. The geological record and paleoenvironmental archives therefore provide opportunities to quantify the sensitivity of key biogeochemical processes to climate shifts; the series of papers in this focus issue include both modeling and proxy-based studies, further developing the ideas needed to better parametrize ESMs to fully capture climate–carbon cycle feedbacks.

3. Conclusion

The papers in this focus issue address the major fast-release carbon reservoirs, including near-surface soil and peatland carbon, permafrost, carbon stored in vegetation, and carbon stored in parts of the ocean that are easily ventilated through changes in circulation. These papers complement recent and ongoing research quantifying fluxes from the oceans and the terrestrial realm, and also help to frame next steps in terms of research most needed to reduce uncertainties. Reducing uncertainties related to the magnitude and stability of these fast-release reservoirs will help quantifying the risk of unexpected rapid climate change and rapid changes in carbon cycle dynamics in the near future.

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References

Ausseil A-G E, Jamali H, Clarkson B R and Golubiewski N E 2015 Soil carbon stocks in wetlands of New Zealand and impact of land conversion since European settlement *Wetlands Ecol. Manage.* **23** 947–61

Bao K, Zhao H, Xing W, Lu X, McLaughlin N B and Wang G 2011 Carbon accumulation in temperate wetlands of Sanjiang plain, Northeast China *Soil Sci. Soc. Am. J.* **75** 2386

Bauska T K, Baggenstos D, Brook E J, Mix A C, Marcott S A, Petrenko V V, Schaefer H, Severinghaus J P and Lee J E 2016 Carbon dioxide isotopes during the deglaciation *Proc. Natl Acad. Sci.* **113** 3465–70

Bauska T K, Brook E J, Marcott S A, Baggenstos D, Shackleton S, Severinghaus J P and Petrenko V V 2018 Controls on millennial-scale atmospheric CO_2 variability during the last glacial period *Geophys. Res. Lett.* **45** 7731–40

Bauska T K, Marcott S A and Brook E J 2021 Abrupt changes in the global carbon cycle during the last glacial period *Nat. Geosci.* **14** 91–6

Beilman D W, MacDonald G M, Smith L C and Reimer P J 2009 Carbon accumulation in peatlands of West Siberia over the last 2000 years *Glob. Biogeochem. Cycles* **23** GB1012

Bereiter B, Eggleston S, Schmitt J, Nehrbass-Ahles C, Stocker T F, Fischer H, Kipfstuhl S and Chappellaz J 2015 Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present *Geophys. Res. Lett.* **42** 542–9

Byun E, Finkelstein S A, Cowling S A and Badiou P 2018 Potential carbon loss associated with post-settlement wetland conversion in southern Ontario, Canada *Carbon Balance Manage.* **13** 6

Chen T *et al* 2020 Persistently well-ventilated intermediate-depth ocean through the last deglaciation *Nat. Geosci.* **13** 733–8

Clymo R S 1984 The limits to peat bog growth *Phil. Trans. R. Soc.* B **303** 605–54

Cox P, Betts R, Jones C, Spall S A and Totterdell I J 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model *Nature* **408** 184–7

Dargie G, Lewis S, Lawson I, Mitchard E T A, Page S E, Bocko Y E and Ifo S A 2017 Age, extent and carbon storage of the central Congo Basin peatland complex *Nature* **542** 86–90

DeConto R, Galeotti S, Pagani M, Tracy D, Schaefer K, Zhang T, Pollard D and Beerling D J 2012 Past extreme warming events linked to massive carbon release from thawing permafrost *Nature* **484** 87–91

Dickens G R, O'Neil J R, Rea D K and Owen R M 1995 Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene *Paleoceanography* **10** 965–71

Dunkley Jones T, Lunt D J, Schmidt D N, Ridgwell A, Sluijs A, Valdes P J and Maslin M 2013 Climate model and proxy data constraints on ocean warming across the Paleocene–Eocene Thermal Maximum *Earth Sci. Rev.* **125** 123–45

Dyonisius M N *et al* 2020 Old carbon reservoirs were not important in the deglacial methane budget *Science* **367** 907–10

Fischer H *et al* 2018 Palaeoclimate constraints on the impact of 2 °C anthropogenic warming and beyond *Nat. Geosci.* **11** 474–85

Foster G L, Royer D L and Lunt D J 2017 Future climate forcing potentially without precedent in the last 420 million years *Nat. Commun.* **8** 14845

Gorham E 1991 Northern peatlands: role in the carbon cycle and probable responses to climatic warming *Ecol. Appl.* **1** 182–95

Gutjahr M, Ridgwell A, Sexton P, Anagnostou E, Pearson P N, Pälike H, Norris R D, Thomas E and Foster G L 2017 Very large release of mostly volcanic carbon during the Palaeocene–Eocene Thermal Maximum *Nature* **548** 573–7

Hausfather Z and Peters G P 2020 Emissions—the 'business as usual' story is misleading *Nature* **577** 618–20

Holmquist J R, Booth R K and MacDonald G M 2016 Boreal peatland water table depth and carbon accumulation during the Holocene thermal maximum, Roman Warm Period, and Medieval Climate Anomaly *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **444** 15–27

Huybers P and Langmuir C 2009 Feedback between deglaciation, volcanism, and atmospheric CO_2 *Earth Planet. Sci. Lett.* **286** 479–91

Jeltsch-Thömmes A, Battaglia G, Cartapanis O, Jaccard S L and Joos F 2019 Low terrestrial carbon storage at the Last Glacial Maximum: constraints from multi-proxy data *Clim. Past* **15** 849–79

Jones M C and Yu Z C 2010 Rapid deglacial and early Holocene expansion of peatlands in Alaska *Proc. Natl Acad. Sci. USA* **107** 7347–52

Joos F, Battaglia G, Fischer H, Jeltsch-Thömmes A and Schmitt J 2019 Marine N_2O emissions during a Younger Dryas-like event: the role of meridional overturning, tropical

thermocline ventilation, and biological productivity *Environ. Res. Lett.* **14** 075007
Kohfeld K and Ridgwell A 2009 Glacial–interglacial variability in atmospheric CO_2 *Surface Ocean-Lower Atmosphere Processes* Geophysical Monograph Series vol 187, ed C le Quere and E S Salzman (Washington, DC: AGU) pp 251–86
Köhler P, Knorr G and Bard E 2014 Permafrost thawing as a possible source of abrupt carbon release at the onset of the Bølling/Allerød *Nat. Commun.* **5** 5520
Köhler P, Nehrbass-Ahles C, Schmitt J, Stocker T F and Fischer H 2017 A 156 kyr smoothed history of the atmospheric greenhouse gases CO_2, CH_4, and N_2O and their radiative forcing *Earth Syst. Sci. Data* **9** 363–87
Kvale K F, Turner K E, Keller D P and Meissner K J 2018 Asymmetric dynamical ocean responses in warming icehouse and cooling greenhouse climates *Environ. Res. Lett.* **3** 125011
Lambeck K, Rouby H, Purcell A, Sun Y and Sambridge M 2014 Sea level and ice volume since the glacial maximum *Proc. Natl Acad. Sci.* **111** 15296–303
Lenton T M *et al* 2019 Climate tipping points—too risky to bet against: the growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions *Nat. Comment* **575** 592–5
Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the Earth's climate system *Proc. Natl Acad. Sci.* **105** 1786–93
Li T *et al* 2020 Rapid shifts in circulation and biogeochemistry of the Southern Ocean during deglacial carbon cycle events *Sci. Adv.* **6** eabb3807
Loisel J *et al* 2014 A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation *Holocene* **24** 1028–42
Lund D, Hertzberg J and Lacerra M 2019 Carbon isotope minima in the South Atlantic during the last deglaciation: evaluating the influence of air-sea gas exchange *Environ. Res. Lett.* **14** 055004
MacDonald G M, Beilman D W, Kremenetski K V, Sheng Y W, Smith L C and Velichko A A 2006 Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations *Science* **314** 285–8
Marcott S *et al* 2014 Centennial-scale changes in the global carbon cycle during the last deglaciation *Nature* **514** 616–9
McInerney F A and Wing S L 2011 The Paleocene–Eocene Thermal Maximum: a perturbation of carbon cycle, climate, and biosphere with implications for the future *Annu. Rev. Earth Planet. Sci.* **39** 489–516
Meinshausen M *et al* 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 *Clim. Change* **109** 213
Meissner K J 2007 Younger Dryas: a data to model comparison to constrain the strength of the overturning circulation *Geophys. Res. Lett.* **34** L21705
Meissner K J and Bralower T 2017 Volcanism caused ancient global warming *Nature* **548** 531–3
Menviel L, Spence P, Yu J, Chamberlain M A, Matear R J, Meissner K J and England M H 2018 Southern Hemisphere westerlies as a driver of the early deglacial atmospheric CO_2 rise *Nat. Commun.* **9** 2503
Menviel L, Yu J, Joos F, Mouchet A, Meissner K J and England M H 2017 Poorly ventilated deep ocean at the Last Glacial Maximum inferred from carbon isotopes: a data-model comparison study *Paleoceanography* **32** 2–17
Meyer V D, Hefter J, Köhler P, Tiedemann R, Gersonde R, Wacker L and Mollenhauer G 2019 Permafrost-carbon mobilization in Beringia caused by deglacial meltwater runoff, sea-level rise and warming *Environ. Res. Lett.* **14** 085003
Monnin E *et al* 2001 Atmospheric CO_2 concentrations over the last glacial termination *Science* **291** 112–4
Montenegro A, Eby M, Kaplan J O, Meissner K J and Weaver A J 2006 Carbon storage on exposed continental shelves during the glacial-interglacial transition *Geophys. Res. Lett.* **33** L08703
Nehrbass-Ahles C *et al* 2020 Abrupt CO_2 release to the atmosphere under glacial and early interglacial climate conditions *Science* **369** 1000–5
Nichols J E and Peteet D M 2019 Rapid expansion of northern peatlands and doubled estimate of carbon storage *Nat. Geosci.* **12** 917–21
Packalen M S, Finkelstein S A and McLaughlin J W 2014 Carbon storage and potential methane production in the Hudson Bay Lowlands since mid-Holocene peat initiation *Nat. Commun.* **5** 4078
Penman D E, Hönisch B, Zeebe R E, Thomas E and Zachos J C 2014 Rapid and sustained surface ocean acidification during the Paleocene–Eocene Thermal Maximum *Paleoceanography* **29** 357–69
Penman D E and Zachos J C 2018 New constraints on massive carbon release and recovery processes during the Paleocene–Eocene Thermal Maximum *Environ. Res. Lett.* **13** 10
Peteet D, Nichols J, Pederson D, Kenna T, Chang C, Newton B and Vincent S 2020 Climate and anthropogenic controls on blue carbon sequestration in Hudson River Tidal Marsh, Piermont, New York *Environ. Res. Lett.* **15** 065001
Piilo S R, Zhang H, Garneau M, Gallego-Sala A, Amesbury M J and Väliranta M M 2019 Recent peat and carbon accumulation following the Little Ice Age in northwestern Québec, Canada *Environ. Res. Lett.* **14** 075002
Rae J W B, Burke A, Adkins J F, Greenop R, Chen T, Cole C, Littley E F M, Nita D C and Robinson L F 2018 CO_2 storage and release in the deep Southern Ocean on millennial to centennial timescales *Nature* **562** 569–73
Rae J W B, Zhang Y G, Liu X, Foster G L and Stoll H M 2021 Atmospheric CO_2 over the last 66 million years from marine archives *Annu. Rev. Earth Planet. Sci.* accepted
Rhodes R H, Brook E J, Chiang J C H, Blunier T, Maselli O J, McConnell J R, Romanini D and Severinghaus J P 2015 Enhanced tropical methane production in response to iceberg discharge in the North Atlantic *Science* **348** 1016–9
Sigman D and Boyle E 2000 Glacial/interglacial variations in atmospheric carbon dioxide *Nature* **407** 859–69
Steffen W *et al* 2018 Trajectories of the Earth System in the Anthropocene *Proc. Natl Acad. Sci.* **115** 8252–9
Storey M, Duncan R A and Swisher C C 2007 Paleocene–Eocene thermal maximum and the opening of the northeast Atlantic *Science* **31** 587–9
Stott L D, Harazin K M and Quintana Krupinski N B 2019 Hydrothermal carbon release to the ocean and atmosphere from the eastern equatorial Pacific during the last glacial termination *Environ. Res. Lett.* **14** 025007
Sutton R W 2018 ESD Ideas: a simple proposal to improve the contribution of IPCC WGI to the assessment and communication of climate change risks *Earth Syst. Dyn.* **9** 1155–8
Thomas E 1990 Late Cretaceous–early Eocene mass extinctions in the deep sea *Global Catastrophes in Earth History* Special Paper No. 247 ed V L Sharpton and P D Ward (Boulder, CO: Geological Society of America) pp 481–96
Valdes P 2011 Built for stability *Nat. Geosci.* **4** 414–6
van Bellen S, Garneau M and Booth R K 2011 Holocene carbon accumulation rates from three ombrotrophic peatlands in boreal Quebec, Canada: impact of climate-driven ecohydrological change *Holocene* **21** 1217–31
Vervoort P, Adloff M, Greene S E and Kirtland Turner S 2019 Negative carbon isotope excursions: an interpretive framework *Environ. Res. Lett.* **14** 085014

Winterfeld M *et al* 2018 Deglacial mobilization of pre-aged terrestrial carbon from degrading permafrost *Nat. Commun.* **9** 3666

Zachos J C *et al* 2005 Rapid acidification of the ocean during the Paleocene–Eocene thermal maximum *Science* **308** 1611–5

Zeebe R E and Lourens L J 2019 Solar System chaos and the Paleocene–Eocene boundary age constrained by geology and astronomy *Science* **365** 926–9

Zeebe R, Ridgwell A and Zachos J 2016 Anthropogenic carbon release rate unprecedented during the past 66 million years *Nat. Geosci.* **9** 325–9