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Significant contribution to climate warming from the permafrost carbon feedback

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Permafrost soils contain an estimated 1,700 Pg of carbon, almost twice the present atmospheric carbon pool[1]. As permafrost soils thaw owing to climate warming, respiration of organic matter within these soils will transfer carbon to the atmosphere, potentially leading to a positive feedback[2]. Models in which the carbon cycle is uncoupled from the atmosphere, together with one-dimensional models, suggest that permafrost soils could release 7–138 Pg carbon by 2100 (refs 3, 4). Here, we use a coupled global climate model to quantify the magnitude of the warming generated by the feedback between permafrost carbon release and climate. According to our simulations, permafrost soils will release between 68 and 508 Pg carbon by 2100. We show that the additional surface warming generated by the feedback between permafrost carbon and climate is independent of the pathway of anthropogenic emissions followed in the twenty-first century. We estimate that this feedback could result in an additional warming of 0.13–1.69 °C by 2300. We further show that the upper bound for the strength of the feedback is reached under the less intensive emissions pathways. We suggest that permafrost carbon release could lead to significant warming, even under less intensive emissions trajectories.

The permafrost carbon feedback (PCF) is estimated using the frozen-ground version of the University of Victoria (UVic) Earth System Climate Model[5] (ESCM) modified using a published method[4] to prescribe carbon into perennially frozen soil layers (see Methods). To estimate a likely range for the strength of the PCF, a suite of sensitivity tests is conducted that explores the estimated range of permafrost carbon density (15.75–26.25 kg m^{-3}; ref. 4) and the likely range of the climate sensitivity to a doubling of the CO_2 concentration (2–4.5 °C; ref 6). The simulated carbon in soils initially underlain by permafrost north of 45° N, contained in both frozen soil layers and the active layer, is 1,026 Pg C averaged over the decade 1990–1999 for our medium estimate of permafrost carbon density. This simulated carbon pool is close to a recent estimate of 1,024 Pg C in the top 3 m of the soils of the permafrost region (this estimate includes both carbon held in permafrost and non-permafrost soils within the northern permafrost region)[1].

As a first step, carbon emissions are diagnosed from simulations of the UVic ESCM driven by specified representative concentration pathways[7] (RCPs). The resulting diagnosed emissions pathways (DEPs), designated by numbers corresponding to the RCP that each DEP is derived from (RCPs 2.6, 4.5, 6.0 and 8.5—Supplementary Fig. S2), are then used to force the UVic ESCM. Emissions pathways are necessary to allow CO_2 to freely evolve in the atmosphere in response to the PCF. The model is integrated under each DEP for combinations of the end points and mid-points of permafrost carbon density and climate sensitivity, in addition to baseline runs for each climate sensitivity with the permafrost carbon density set to zero.

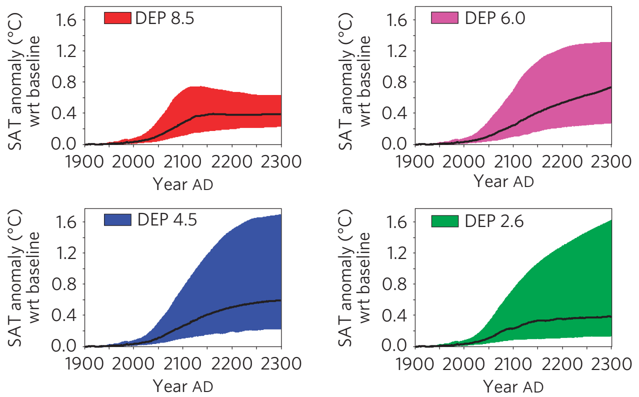

Figure 1 | Global average surface air temperature anomaly with respect to baseline runs with no carbon sequestered in permafrost soil layers. Coloured areas are the likely surface air temperature (SAT) anomaly ranges for each DEP. The median for each DEP is superimposed as a black line. Note that the upper bounds for the two low-emission pathways (DEP 2.6 and 4.5) have the greatest surface air temperature anomaly (but not the greatest total warming).

Figure 1 shows the additional global average warming from the PCF (relative to baseline runs with no permafrost carbon) for each of the DEPs. The additional warming by the end of the twenty-first century is remarkably consistent between the DEPs: 0.23 (0.09–0.73) °C for DEP 2.6, 0.26 (0.11–0.75) °C for DEP 4.5, 0.24 (0.10–0.69) °C for DEP 6.0 and 0.27 (0.11–0.69) °C for DEP 8.5. By the end of the twenty-third century, the additional warming from the PCF has diverged between the DEPs, with the highest upper bounds for the lowest two emission pathways: 0.37 (0.13–1.62) °C for DEP 2.6, 0.59 (0.22–1.69) °C for DEP 4.5, 0.73 (0.28–1.31) °C for DEP 6.0 and 0.39 (0.23–0.63) °C for DEP 8.5. Under the low emissions pathways reductions in carbon emissions limit the amount of carbon liberated from the permafrost. However, the carbon that is transferred to the atmosphere has a higher radiative efficiency than the same unit of carbon released under a high emissions pathway, leading to a strong PCF under low emissions pathways.

By the end of the twenty-first century the net effect of the PCF on the atmosphere is an additional CO_2 concentration (relative to baseline runs with no permafrost carbon) of: 39 (17–99) ppmv for DEP 2.6, 58 (26–132) ppmv for DEP 4.5, 67 (32–148) ppmv for DEP 6.0 and 101 (53–213) ppmv for DEP 8.5. Collectively, soil layers that were formerly permafrost continue to release CO_2 to

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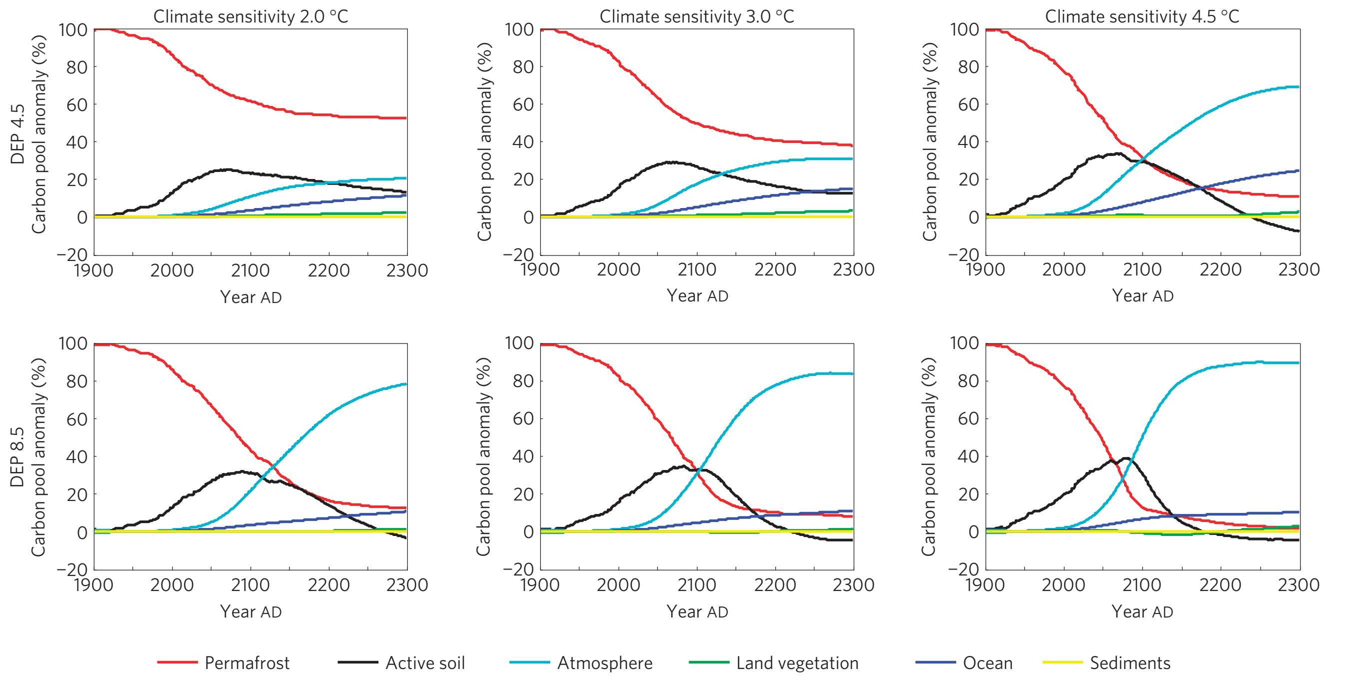

Figure 2 | Changes in the size of each Earth system carbon pool in response to the addition of permafrost carbon to the UVic ESCM. That is, the difference in the size of each carbon pool between simulations with and without permafrost carbon. All values are relative to the initial size of the frozen permafrost carbon pool (and a summation of all of the pools adds up to 100% for each year). Results are given for two emissions pathways (DEPs 4.5 and 8.5) and for three climate sensitivities to a doubling of CO_2 (2.0, 3.0, and 4.5 °C). Soil layers that thaw but are subsequently returned to a permafrost state continue to be administered by the active soil carbon pool, leading to the apparent high rate of transfer of carbon to the active soil carbon pool in the twentieth century.

the atmosphere throughout the twenty-second and twenty-third centuries despite greater than 90% reductions in anthropogenic carbon emissions (from peak values) or, in the case of DEP 2.6, negative anthropogenic emissions (this DEP presumes the development of technology to remove CO_2 from the atmosphere). By the end of the twenty-third century the net effect of the PCF on the atmosphere is an additional CO_2 concentration of: 44 (18–146) ppmv for DEP 2.6, 104 (49–299) ppmv for DEP 4.5, 185 (82–338) ppmv for DEP 6.0 and 279 (196–374) ppmv for DEP 8.5 (see also Supplementary Fig. S5).

Figure 2 shows the effect of the PCF on each of the Earth's carbon pools for DEPs 4.5 and 8.5 under varying climate sensitivities (for DEPs 2.6 and 6.0 see Supplementary Fig. S6). It is clear that the climate sensitivity has a marked effect on the fraction of the permafrost carbon that is transferred to the atmosphere, ranging for DEP 4.5 from 21% under a climate sensitivity of 2.0 °C to 69% under a climate sensitivity of 4.5 °C. The permafrost carbon density has only a small influence on the relative effect of permafrost carbon on the other carbon pools (not shown). Permafrost carbon is initially transferred to the active soil carbon pool as permafrost thaws. The active soil carbon pool grows until the mid-twenty-first century and then declines as soil respiration transfers carbon out of soil faster than it is being transferred in by thawing permafrost. In some model runs the active soil carbon pool becomes smaller than in the baseline run; this is a secondary carbon-cycle feedback driven by additional warming from the PCF. From the atmosphere, carbon is transferred to land vegetation and the ocean carbon pool. The effect of the PCF on land vegetation is in all cases small. The ocean acts as a medium-term sink for permafrost carbon, absorbing 11–25% of the carbon by the end of the twenty-third century under DEP 4.5. The PCF transforms the terrestrial land surface from a sink for carbon to a source of carbon to the atmosphere. This transition occurs in 2053 (2013–2078) for DEP 2.6, 2068 (2026–2104) for DEP 4.5, 2091 (2029–2131) for DEP 6.0 and 2065 (2014–2100) for DEP 8.5 (Supplementary Fig. S7). In the absence of the PCF, such a transition occurs between 2079 and 2198, contingent on climate sensitivity and emissions pathway.

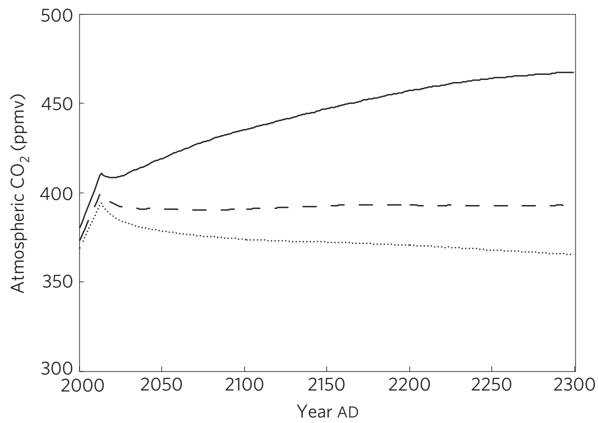

Figure 3 | Evolution of atmospheric CO_2 concentration in response to a cessation of anthropogenic CO_2 and sulphate emissions in the year 2013. The dotted line represents the response for a climate sensitivity (to a doubling of CO_2) of 2.0 °C, the dashed line a climate sensitivity of 3.0 °C and the solid line a climate sensitivity of 4.5 °C.

With the cessation of anthropogenic CO_2 emissions the CO_2 fertilization of plants also ceases, leaving only the oceans as a fast sink for carbon. The strength of this sink is partially determined by the quantity of CO_2 that has been added to the atmosphere. If the rate at which CO_2 is being released from the terrestrial land surface exceeds the rate at which the oceans can take up CO_2, then CO_2 will continue to build up in the atmosphere, further warming the surface and driving a self-sustaining carbon-cycle feedback. In experiments where DEP 8.5 is followed up to a given date when emissions are instantaneously reduced to zero, all simulations with climate sensitivities above 3.0 °C produce a self-sustaining PCF even if emissions are reduced to zero in 2013 (Fig. 3 and Supplementary Fig. S5).

The UVic ESCM simulates a release from all soils of 174 (68–508) Pg C by 2100 as a consequence of the inclusion of the PCF. This release of carbon is larger than that previously estimated using uncoupled ecosystem and one-dimensional models[3,4,8,9]. Each of the models simulates a different assemblage of soil-physical processes, has a different sized initial permafrost carbon pool and is forced with distinct emission pathways. In addition, the cited models are unable to fully account for the subsequent feedback that the release of carbon has on further climate warming. All of these factors conceivably contribute to the inter-model range in the estimated release of carbon from permafrost soils. (See Supplementary Section S7 for a more detailed intercomparison of the cited model studies.)

The method used here to estimate the strength of the PCF is in a number of ways conservative. As a coarse-resolution climate model, the UVic ESCM is able to simulate only permafrost thaw due to active-layer thickening and talik formation. The other two processes that may accelerate permafrost thawing (water erosion and thermokarst development[2]) and the effects of fire are not simulated. At present, the UVic ESCM soil component does not simulate methanogenesis; therefore, all emissions from permafrost are assumed to be in the form of CO_2. The UVic ESCM also has an Arctic amplification that is at the low end of the range simulated by other climate models. As a consequence it produces an estimate of permafrost degradation that is in the low to middle part of the inter-model range[5]. We have chosen not to prescribe permafrost carbon below 3.35 m depth, to accommodate a globally consistent prognostic simulation of permafrost. We have further assumed that the highly recalcitrant fraction of the permafrost carbon will never decay and have not accounted for the heat given off by heterotrophic respiration in soils[10]. A potentially important negative feedback, enhanced plant growth from nutrients released from decaying organic mater, is also not taken into account in the UVic ESCM.

The UVic ESCM simulates a stronger PCF than previous uncoupled modelling efforts to quantify this feedback[3,4,8,9]. However, considering the processes not taken into account by the model, we caution that upward re-evaluation of the strength of the PFC is plausible. Nevertheless the strength and committed nature of the PCF simulated here suggests that it is important to initiate and sustain monitoring of carbon fluxes from permafrost soils and changes in the permafrost itself. Such data will be invaluable for validating and improving model results such as those presented here.

Methods

The UVic ESCM is a coupled model of intermediate complexity[11], which includes a fully coupled representation of oceanic[12] and terrestrial carbon cycles[13]. Here a version of the model incorporating soil freeze thaw processes[5] is augmented to include a representation of sequestered carbon in permafrost soils. The method of transferring sequestered permafrost carbon to the active soil carbon pool presented by ref. 4 is followed, wherein the active carbon pool is administered by the existing soil carbon model component, and a threshold depth (equal to the deepest historical active-layer thickness) separates the active soil and permafrost carbon pools. When the thaw depth of soil exceeds this threshold, the carbon from the newly thawed layers is transferred to the active soil carbon pool and the threshold depth is increased. Permafrost carbon is assumed to have a globally uniform density and extends only down to a depth of 3.35 m. The UVic ESCM soil carbon component has been modified such that soil respiration does not occur in soil layers with a temperature below 0 °C. Soil respiration is calculated independently in each soil layer and carbon from litter-fall is distributed (as a decreasing fraction with depth) into layers with a temperature above a threshold of 1 °C. The model is spun-up under estimated radiative forcing for the year AD 850 and a transient run performed until the year AD 1900 to ensure the threshold depth represents the historical maximum boundary between the active layer and permafrost soils. After AD 1900, permafrost carbon is turned on in the model. The climate sensitivity of the UVic ESCM is varied by altering the outgoing top-of-the-atmosphere long-wave radiation as a function of mean global temperature, following ref. 14.

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Author contributions

A.H.M.D., A.J.W. and C.A.A. formulated the model experiments and wrote the paper. A.H.M.D. performed modifications to the ESCM, conducted experiments and analysed the results.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.H.M.D.

Competing financial interests

The authors declare no competing financial interests.