Frequently Asked Questions

FAQ 6.1 | Could Rapid Release of Methane and Carbon Dioxide from Thawing Permafrost or Ocean Warming Substantially Increase Warming?

Permafrost is permanently frozen ground, mainly found in the high latitudes of the Arctic. Permafrost, including the sub-sea permafrost on the shallow shelves of the Arctic Ocean, contains old organic carbon deposits. Some are relicts from the last glaciation, and hold at least twice the amount of carbon currently present in the atmosphere as carbon dioxide (CO_2). Should a sizeable fraction of this carbon be released as methane and CO_2, it would increase atmospheric concentrations, which would lead to higher atmospheric temperatures. That in turn would cause yet more methane and CO_2 to be released, creating a positive feedback, which would further amplify global warming.
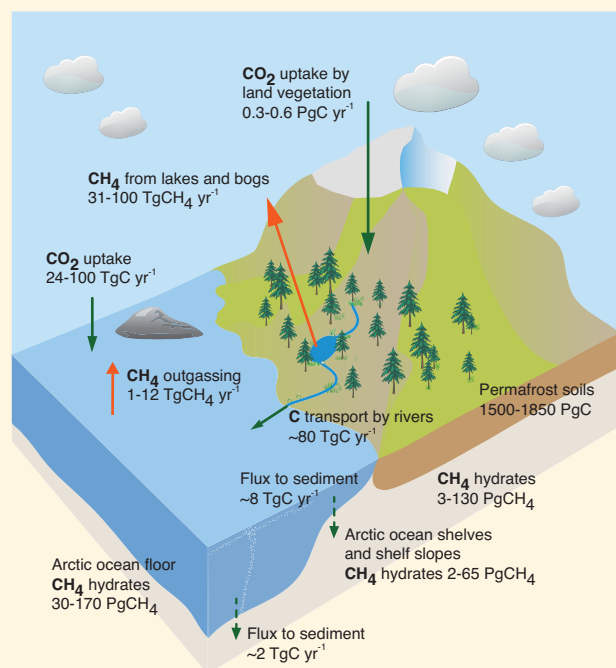
The Arctic domain presently represents a net sink of CO_2—sequestering around 0.4 ± 0.4 PgC yr^{-1} in growing vegetation representing about 10% of the current global land sink. It is also a modest source of methane (CH_4): between 15 and 50 Tg(CH_4) yr^{-1} are emitted mostly from seasonally unfrozen wetlands corresponding to about 10% of the global wetland methane source. There is no clear evidence yet that thawing contributes significantly to the current global budgets of these two greenhouse gases. However, under sustained Arctic warming, modelling studies and expert judgments indicate with medium agreement that a potential combined release totalling up to 350 PgC as CO_2 equivalent could occur by the year 2100.

Permafrost soils on land, and in ocean shelves, contain large pools of organic carbon, which must be thawed and decomposed by microbes before it can be released—mostly as CO_2. Where oxygen is limited, as in waterlogged soils, some microbes also produce methane.

On land, permafrost is overlain by a surface 'active layer', which thaws during summer and forms part of the tundra ecosystem. If spring and summer temperatures become warmer on average, the active layer will thicken, making more organic carbon available for microbial decomposition. However, warmer summers would also result in greater uptake of carbon dioxide by Arctic vegetation through photosynthesis. That means the net Arctic carbon balance is a delicate one between enhanced uptake and enhanced release of carbon.

Hydrological conditions during the summer thaw are also important. The melting of bodies of excess ground ice may create standing water conditions in pools and lakes, where lack of oxygen will induce methane production. The complexity of Arctic landscapes under climate warming means we have *low confidence* in which of these different processes might dominate on a regional scale. Heat diffusion and permafrost melt-

FAQ 6.1, Figure 1 | A simplified graph of current major carbon pools and flows in the Arctic domain, including permafrost on land, continental shelves and ocean. (Adapted from McGuire et al., 2009; and Tarnocai et al., 2009.) TgC = 10^{12} gC, and PgC = 10^{15} gC.

ing takes time—in fact, the deeper Arctic permafrost can be seen as a relict of the last glaciation, which is still slowly eroding—so any significant loss of permafrost soil carbon will happen over long time scales.

Given enough oxygen, decomposition of organic matter in soil is accompanied by the release of heat by microbes (similar to compost), which, during summer, might stimulate further permafrost thaw. Depending on carbon and ice content of the permafrost, and the hydrological regime, this mechanism could, under warming, trigger relatively fast local permafrost degradation. *(continued on next page)*

6

FAQ 6.1 (continued)

Modelling studies of permafrost dynamics and greenhouse gas emissions indicate a relatively slow positive feedback, on time scales of hundreds of years. Until the year 2100, up to 250 PgC could be released as CO_2, and up to 5 Pg as CH_4. Given methane's stronger greenhouse warming potential, that corresponds to a further 100 PgC of equivalent CO_2 released until the year 2100. These amounts are similar in magnitude to other biogeochemical feedbacks, for example, the additional CO_2 released by the global warming of terrestrial soils. However, current models do not include the full complexity of Arctic processes that occur when permafrost thaws, such as the formation of lakes and ponds.

Methane hydrates are another form of frozen carbon, occurring in deep permafrost soils, ocean shelves, shelf slopes and deeper ocean bottom sediments. They consist of methane and water molecule clusters, which are only stable in a specific window of low temperatures and high pressures. On land and in the ocean, most of these hydrates originate from marine or terrestrial biogenic carbon, decomposed in the absence of oxygen and trapped in an aquatic environment under suitable temperature–pressure conditions.

Any warming of permafrost soils, ocean waters and sediments and/or changes in pressure could destabilise those hydrates, releasing their CH_4 to the ocean. During larger, more sporadic releases, a fraction of that CH_4 might also be outgassed to the atmosphere. There is a large pool of these hydrates: in the Arctic alone, the amount of CH_4 stored as hydrates could be more than 10 times greater than the CH_4 presently in the global atmosphere.

Like permafrost thawing, liberating hydrates on land is a slow process, taking decades to centuries. The deeper ocean regions and bottom sediments will take still longer—between centuries and millennia to warm enough to destabilise the hydrates within them. Furthermore, methane released in deeper waters has to reach the surface and atmosphere before it can become climatically active, but most is expected to be consumed by microorganisms before it gets there. Only the CH_4 from hydrates in shallow shelves, such as in the Arctic Ocean north of Eastern Siberia, may actually reach the atmosphere to have a climate impact.

Several recent studies have documented locally significant CH_4 emissions over the Arctic Siberian shelf and from Siberian lakes. How much of this CH_4 originates from decomposing organic carbon or from destabilizing hydrates is not known. There is also no evidence available to determine whether these sources have been stimulated by recent regional warming, or whether they have always existed—it may be possible that these CH_4 seepages have been present since the last deglaciation. In any event, these sources make a very small contribution to the global CH_4 budget—less than 5%. This is also confirmed by atmospheric methane concentration observations, which do not show any substantial increases over the Arctic.

However modelling studies and expert judgment indicate that CH_4 and CO_2 emissions will increase under Arctic warming, and that they will provide a positive climate feedback. Over centuries, this feedback will be moderate: of a magnitude similar to other climate–terrestrial ecosystem feedbacks. Over millennia and longer, however, CO_2 and CH_4 releases from permafrost and shelves/shelf slopes are much more important, because of the large carbon and methane hydrate pools involved.

where $\Omega_A = [Ca^{+2}][CO_3^{2-}]/K_{sp}$, where K_{sp} is the solubility product for the metastable form of $CaCO_3$ known as aragonite; a value of $\Omega_A < 1$ thus indicates aragonite undersaturation). This aragonite undersaturation in surface waters is reached before the end of the 21st century in the Southern Ocean as highlighted in AR4, but occurs sooner and is more intense in the Arctic (Steinacher et al., 2009). Ten percent of Arctic surface waters are projected to become undersaturated when atmospheric CO_2 reaches 428 ppm (by 2025 under all IPCC SRES scenarios). That proportion increases to 50% when atmospheric CO_2 reaches 534 ppm (Steinacher et al., 2009). By 2100 under the A2 scenario, much of the Arctic surface is projected to become undersaturated with respect to calcite (Feely et al., 2009). Surface waters would then be corrosive to all $CaCO_3$ minerals. These general trends are confirmed by the latest projections from the CMIP5 Earth System models (Figure 6.28 and 6.29). Between 1986–2005 and 2081–2100, decrease in global-mean surface pH is 0.065 (0.06 to 0.07) for RCP2.6, 0.145 (0.14 to 0.15) for RCP4.5, 0.203 (0.20 to 0.21) for RCP6.0 and 0.31 (0.30 to 0.32) for RCP8.5 (range from CMIP5 models spread).

Surface $CaCO_3$ saturation also varies seasonally, particularly in the high latitudes, where observed saturation is higher in summer and lower in winter (Feely et al., 1988; Merico et al., 2006; Findlay et al.,