ChatGPT

Permafrost: Definition and Distribution

Permafrost is **perennially frozen ground** (soil, sediment, or rock) that remains at or below 0 °C for at least two consecutive years [1]. It underlies ~22% of the Northern Hemisphere land area [1] (about 15 million km^2, ~24% of exposed high-latitude land [2]). Permafrost occurs in Arctic and sub-Arctic regions (tundra, boreal forest, polar deserts) and in high-altitude mountainous zones. Importantly, frozen ground extends offshore as **subsea permafrost** beneath Arctic continental shelves.

Permafrost Carbon Stocks

Permafrost soils lock up **huge organic carbon pools** built up over millennia. The best estimate for *northern circumpolar* permafrost carbon is on the order of **1,460–1,600 Pg C** (billion tonnes of carbon) [3]. About 65–70% of this (~1,035±150 Pg C) lies in the top 3 m of soil [3] [4]. Yedoma deposits and other deep permafrost hold an additional hundreds of PgC [5]. Subsea permafrost can contain an extra ~500–2,800 Pg C [4]. (For comparison, the atmosphere contains ~850 Pg C [6].) In sum, permafrost regions contain on the order of 1,500 Pg C or more – roughly **twice** the carbon currently in the atmosphere [6].

Thaw and Carbon Release

Figure: A Siberian permafrost thermokarst slump (source: Annett Bartsch). Thawing ground ice causes surface collapse and erosion. Such disturbances expose large volumes of ancient, organic-rich soil to microbial decomposition [7].

As permafrost thaws, the previously-frozen organic matter becomes available to microbes. **Aerobic decomposition** (when soils are drained) converts carbon into CO_2, while **anaerobic decomposition** (in water-logged conditions) produces CH_4 (methane) along with CO_2 [6] [8]. In other words, warming “wakes up” soil microbes from hibernation, and they metabolize the old organic carbon, emitting greenhouse gases (primarily CO_2 by mass) into the atmosphere [6]. Local hydrology and **thermokarst** processes can amplify this: excess ground ice melt leads to land subsidence and formation of thaw slumps, ponds, and lakes, which drive rapid, localized carbon release [7] [9]. For example, melt of ground ice produces **thaw slumps and gullies** that increase ground heat flux and expose deep soil layers [7] (see image).

These emissions create a **positive climate feedback**: warming → permafrost thaw → more CO_2/CH_4 → further warming. Current estimates suggest permafrost carbon release adds a non-negligible warming signal. Models project that permafrost feedback could add on the order of **0.05–0.7 °C** of global warming by 2100 (depending on emission scenario) [10]. Methane, though smaller in mass, contributes disproportionately to forcing – it may account for roughly **40–70%** of the permafrost-related radiative forcing this century [11] [12]. (However, even in this feedback, human fossil emissions remain dominant.)

Thresholds and Tipping Points

No abrupt global "tipping point" is seen in state-of-knowledge: permafrost thaw generally increases **gradually** with rising temperature [13] [14]. For every 1 °C of global warming, models estimate roughly a 25% loss of near-surface permafrost volume [14]. Nonetheless, **critical thresholds exist**: even a few degrees of warming could eliminate large areas of permafrost. Studies suggest limiting warming to 1.5 °C would preserve much of today's permafrost, whereas 2 °C or more could *"shrink permafrost-covered land by over 40%"* [15]. For example, one analysis finds ~4 Mkm² of permafrost lost per °C, so that 2 °C warming would remove ~6–7 Mkm² (~40% of current area) [15]. By 5 °C, virtually all permafrost (except small remnants) would thaw [16]. Importantly, once thawed, the carbon loss is effectively **irreversible on human timescales** [17] [8]: refreezing is slow, so carbon continues to be emitted even if temperatures later stabilize. Locally, abrupt changes (thawslides, thermokarst lakes) can occur quickly when warm spells or disturbances exceed ground-ice stability, but models show no global "tipping" at a sharp threshold [13] [14].

Quantitative Parameters for Modeling

- **Permafrost carbon stock:** ~1,500 Pg C in northern permafrost soils [3] (roughly 1,035±150 PgC in top 3 m [4]). (For model initialization, assign ~1000–1500 GtC globally.)
- **Active-layer deepening:** Roughly *25% loss* of near-surface permafrost volume per 1 °C warming [14]. Equivalently, about **4×10^6 km²** of permafrost lost per 1 °C [18]. (Active layer thickness trends vary regionally; some studies project <30% increase in depth by 2100 under moderate warming.)
- **Emission rates:** Model studies project **0.5–2 Pg C/yr** (CO_2+CH_4) release from permafrost thaw by 2100 under high warming [19]. For calibration, note current Arctic observations suggest net emissions of ~0.3–0.6 Pg C/yr to the atmosphere [20] [21]. (Methane is ~10–20% of carbon flux by mass in some scenarios, but ~30–50× more potent per molecule.)
- **Radiative forcing constants:** A common CO_2 forcing formula is used:

$$\Delta F_{CO_2} = 5.35\ \ln\!\big(C/C_0\big)\ [\mathrm{W/m^2}],$$

  where C_0 is a reference concentration [22]. (Doubling CO_2 from pre-industrial levels gives ≈+3.7 W/m² [23].) For CH_4, Myhre et al. (1998) give

$$\Delta F_{CH_4} = 0.036\,(\sqrt{M} - \sqrt{M_0}),$$

  with M the CH_4 concentration. These yield the instantaneous radiative forcing; one may then apply a climate sensitivity (typically ≈0.8 K per W/m², so ~3 K per CO_2 doubling).
- **Temperature-dependence (decay constants):** Microbial decomposition is often parameterized with an Arrhenius or Q_{10} approach. A typical assumption is $\mathbf{Q_{10} \approx 2}$, meaning decomposition rates double for each +10 °C increase in temperature. (Exact values can vary; some lab studies find Q_{10}=2–3 for Arctic soils.) The corresponding activation energy (E_a) is on the order of 0.6–0.7 eV. These values enter rate equations for soil carbon turnover.

Data and Model Resources

- **Circumpolar permafrost maps:** NSIDC's *Circum-Arctic Map of Permafrost and Ground-Ice* (GGD318, v2) provides permafrost extent and ice-content classes [1]. A high-resolution vector or gridded dataset is available from NSIDC.
- **Active-layer and ground temperature:** The Global Terrestrial Network for Permafrost (GTN-P) archive compiles field data (CALM sites, borehole temperatures). NSIDC hosts metadata for ~100 active-layer sites and 300+ boreholes [24]. The Circumpolar Active Layer Monitoring (CALM) database and GTN-P website (at arcticportal.org) are key sources.
- **Remote-sensing products:** ESA's Climate Change Initiative (CCI) Permafrost project produces satellite-derived Essential Climate Variables (e.g. frozen-ground extent, land-surface temperature) and active-layer thickness models [25] [1]. Other datasets include NASA/NOAA Arctic portal summaries of permafrost change (e.g. *Arctic Report Card* essays) [6].
- **Carbon inventories:** Scholarly compilations (e.g. *Hugelius et al. 2014*, *Schuur et al. 2015*) and updates are the basis for permafrost carbon budgets [3]. The Global Terrestrial Network and projects like the Northern Circumpolar Soil Carbon Database (NCSCD) provide spatial SOC maps.
- **Climate scenarios:** Use IPCC AR6/CMIP6 forcing pathways (SSP2-4.5, SSP5-8.5, etc.) for temperature trajectories. Radiative forcing formulas and greenhouse gas lifetimes (from IPCC reports or NOAA AGGI) allow conversion of C emissions to CO_2-equivalent forcing.
- **Repositories:** GTN-P (active-layer data), NSIDC (frozen ground products), NOAA (Arctic data portal), and academic databases (e.g. NASA's ORNL DAAC). Many permafrost models and data tools (e.g. PFLOTRAN-based models, Community Land Model – CLM, and Python libraries like *Cryosphere* tools) are on GitHub or Arctic research centers.

Sources: Up-to-date reviews and reports (Schuur *et al.* (2015, 2022) [26] [8], IPCC AR6 chapters, NOAA/NSIDC summaries [3] [4], and peer-reviewed studies [15] [22]) were used to extract the above values and relations.

---

[1] Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2 | National Snow and Ice Data Center
https://nsidc.org/data/ggd318/versions/2

[2] [15] [16] [18] Warming limit of 1.5C would 'save' huge expanses of permafrost, study says - Carbon Brief
https://www.carbonbrief.org/warming-limit-one-point-five-would-save-huge-expanses-permafrost/

[3] [5] [6] [20] [21] Permafrost and the Global Carbon Cycle - NOAA Arctic
https://arctic.noaa.gov/report-card/report-card-2019/permafrost-and-the-global-carbon-cycle/

[4] [7] [8] [10] [12] [14] Global Tipping Points | 1.2.2.4 Permafrost
https://report-2023.global-tipping-points.org/section1/1-earth-system-tipping-points/1-2-tipping-points-in-the-cryosphere/1-2-2-current-state-of-knowledge-on-cryosphere-tipping-points/1-2-2-4-permafrost/

[9] [13] Max-Planck-Institute for Meteorology: Permafrost Thaw: Gradual Change or Climate Tipping Point?
https://mpimet.mpg.de/en/communication/news/permafrost-thaw-gradual-change-or-climate-tipping-point

[11] [19] [26] Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic
https://epic.awi.de/57387/1/Schuur_2022.pdf

[17] Review of permafrost science in IPCC's AR6 WG1 - Woodwell Climate
https://www.woodwellclimate.org/review-of-permafrost-science-in-ipccs-ar6-wg1/

[22] (PDF) New estimtes of raditive forcing due to well mixed greenhouse gases
https://www.researchgate.net/publication/238498266_New_estimtes_of_raditive_forcing_due_to_well_mixed_greenhouse_gases

[23] Radiative forcing - Wikipedia
https://en.wikipedia.org/wiki/Radiative_forcing

[24] Global Terrestrial Network for Permafrost (GTN-P), Version 1 | National Snow and Ice Data Center
https://nsidc.org/data/ggd633/versions/1

[25] Dataset - Arctic Permafrost Geospatial Centre
https://apgc.awi.de/dataset/