Stratospheric aerosol injection to stabilize Northern Hemisphere terrestrial permafrost under the ARISE-SAI-1.5 scenario

Ariel Lena Morrison[1], Elizabeth A. Barnes[1], and James Wilson Hurrell[1]

[1]Colorado State University

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A. L. Morrison[1], E. A. Barnes[1], and J. W. Hurrell[1]

[1]Department of Atmospheric Sciences, Colorado State University, Fort Collins, CO, USA

Key Points:

- Stratospheric aerosol injection is unlikely to fully stabilize permafrost extent by 2069 despite maintaining permafrost temperature
- Stratospheric aerosol injection could prevent nearly all talik formation compared to SSP2-4.5
- Near-zero net changes in carbon stocks are projected in total permafrost and permafrost peat regions after stratospheric aerosol injection

Corresponding author: A. L. Morrison, ariel.morrison@colostate.edu

Abstract

Permafrost, or ground that is continuously frozen for at least two years, contains vast stores of organic soil carbon. Stratospheric aerosol injection (SAI) may prevent tipping points that lead to widespread permafrost thaw and carbon release by cooling surface and soil temperatures, but it is unclear if or when permafrost could stabilize after SAI deployment. Here we use output from the ARISE-SAI-1.5 simulations to assess how permafrost may respond to a specific SAI strategy that maintains global mean surface temperature to 1.5°C above pre-industrial levels. Permafrost responses under SAI are compared to responses under the control SSP2-4.5 emissions scenario. We show that the rate of boreal permafrost thaw slows under SAI but does not fully stop, likely due to deep permafrost thaw processes that are resistant to surface temperatures changes. In both the ARISE-SAI-1.5 and SSP2-4.5 simulations, permafrost completely thaws and disappears along the southern edge of the permafrost area by 2069, indicating that some complete thaw may be inevitable even if SAI successfully stabilizes global mean surface temperatures. SAI does prevent a potential tipping point (talik formation) in roughly 1 million km^2 of permafrost, most of which is located in permafrost peatlands. Thus, a more aggressive SAI strategy than that of ARISE-SAI-1.5 is likely required to prevent all future projected permafrost thaw.

Plain Language Summary

Permafrost is ground that stays frozen for at least two years. Permafrost thaw is a global concern because of how much soil carbon it stores, which can be released into the atmosphere as carbon dioxide and methane if permafrost thaws. One proposed method that could prevent permafrost thaw is to cool the Earth by injecting reflective particles into the stratosphere, which would block a small percentage of incoming sunlight and stabilize Earth's temperature to 1.5°C above pre-industrial temperatures. We use climate projections from an Earth system model to assess how permafrost might respond to a proposed scenario for stabilizing Earth's temperature. We find that the total amount of permafrost still decreases even in a scenario where the Earth's temperature has stabilized, but pockets of unfrozen soil within and above permafrost are less likely to form, which reduces the possibility of rapid and widespread permafrost thaw. A climate intervention strategy that starts sooner or aims to cool the Earth more may be required

in order to fully prevent future permafrost thaw and associated carbon dioxide and methane emissions.

1 Introduction

We are not on track to meet the Paris Climate Agreement goal of limiting warming to below 2°C (Pihl et al., 2019). Rising global temperatures increases the likelihood of reaching tipping points in the climate system, or positive feedbacks that accelerate warming (Armstrong McKay et al., 2022; Lenton, 2012). While CO_2 removal and reduced dependence on fossil fuels are preferred ways to prevent possible critical climate conditions that lead to tipping points, the speed and intensity of ongoing climate changes might necessitate direct climate intervention. Stratospheric aerosol injection (SAI) is a hypothetical solar radiation management (SRM) strategy (Keith, 2000) that would increase Earth's albedo and stabilize or reduce surface temperatures by injecting highly reflective particles into the stratosphere (Rasch et al., 2008). If deployed, SAI could potentially mitigate some climate change impacts (e.g., Chen et al., 2020; Dagon & Schrag, 2017), although the full range of possible impacts has not yet been established. One region of particular concern is the Arctic, which is currently warming several times faster than the global average (Rantanen et al., 2022) and has many potential positive feedbacks, such as permafrost thaw.

Permafrost is ground that is continually below 0°C for at least two years. Permafrost thaw is a regional and global concern because of the carbon stores in permafrost soils: it is estimated that the northern circumpolar permafrost zone contains ∼1,460-1,600 Pg carbon (Hugelius et al., 2014; Schuur et al., 2015), or twice as much carbon as is in the atmosphere (Schuur et al., 2018). Permafrost peatlands contain ∼12% of the total soil organic carbon stored in northern boreal permafrost (Hugelius et al., 2020), and the carbon released from peatlands can be released as CO_2 or CH_4 (Swindles et al., 2015; Voigt et al., 2019). This carbon loss can occur on the scale of years-to-decades, although it may take centuries for peatlands to regain pre-thaw carbon stores (Fewster et al., 2022; Heffernan et al., 2020; Jones et al., 2016; Manies et al., 2021). Some of the loss could be offset by increased productivity and peat accumulation in warmer conditions (Heffernan et al., 2020; Swindles et al., 2015; Treat et al., 2021). Under moderate warming scenarios, permafrost peatland area is projected to decrease by 75-90% by the 2060s (Fewster et al., 2022; Könönen et al., 2023), and may soon reach a tipping point that leads to rapid and widespread thaw.

Talik, or perennially unfrozen soil within or above permafrost, may be a precursor to both widespread permafrost thaw (Schuur et al., 2008) and permafrost soils transitioning from a carbon sink to a carbon source (Connon et al., 2018; Devoie et al., 2019; Farquharson et al., 2022; Parazoo et al., 2018). Permafrost tipping points are difficult to quantify and generally refer to the onset of widespread permafrost thaw (Lenton, 2012), so talik formation, as a precursor to widespread thaw, may be considered a quantifiable indication of an imminent permafrost tipping point. Therefore, it is important to understand when and where talik may form in the future.

Previous work has shown that different climate intervention strategies could slow the rate and extent of permafrost thaw (Chen et al., 2023; H. Lee et al., 2019; W. Lee et al., 2023; Liu et al., 2023) and reduce carbon emissions from permafrost soils (Chen et al., 2020, 2023; W. Lee et al., 2023; Liu et al., 2023), but these studies did not separate permafrost response by land type or assess specific forms of permafrost degradation such as talik formation. The goal of this study is to assess whether a specific SAI strategy might stabilize existing Northern Hemisphere terrestrial permafrost and prevent future critical climate conditions such as talik formation that could lead to widespread accelerated thaw and carbon release.

2 Data and Methods

2.1 ARISE-SAI-1.5 simulations

The Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (ARISE-SAI) project is a set of Earth system simulations that was designed to assess the potential risks and benefits of a specific SRM protocol (Richter et al., 2022). The ARISE-SAI simulations were run with the Community Earth System Model version 2 (CESM2; Danabasoglu et al. (2020)) on a 0.9 x 1.25° horizontal resolution grid with the Whole Atmosphere Community Climate Model version 6 (WACCM6; Gettelman et al. (2019)) as the atmospheric component and the Community Land Model version 5 (CLM5; Lawrence et al. (2019)) as the land component. While CESM2 does not specifically include a permafrost model, its land model component has updated snow density, soil biogeochemistry, and soil hydrology to more accurately simulate permafrost dynamics compared with previous versions of CLM (Lawrence et al., 2019). The soil column in CLM5 has 25 layers of variable thickness that extend

to nearly 50 m depth. Only the top 20 layers, down to 8.6 m, can be soil; the remaining five layers are bedrock. The bedrock depth in CLM5, however, is spatially variable and ranges from 8.6 m at its deepest to < 1 m at its shallowest (Lawrence et al., 2018, 2019). The only hydrologically and biogeochemically active layers of the soil column are the layers above the bedrock.

We use the 10-member ensemble of ARISE-SAI-1.5 simulations, in which sulfur dioxide (SO_2) is injected into the stratosphere at ~21.5 km altitude at 15° and 30°N/S along 180°E. The initial aerosol injection is in 2035, and the simulation runs for 35 years until 2069. Every year, a feedback-control algorithm (MacMartin et al., 2014; Kravitz et al., 2017) in ARISE-SAI-1.5 adjusts how much aerosol is injected from each of the four locations in an effort to meet three climate objectives: maintain global mean temperature increase at 1.5°C above pre-industrial levels, maintain the north-south surface temperature gradient, and maintain the Equator-to-pole surface temperature gradient, all under the Shared Socioeconomic Pathway 2 (SSP2)-4.5 emissions scenario (Riahi et al., 2017). In order to assess climate outcomes in a potential SAI vs non-SAI world, we compare the climate outcomes in ARISE-SAI-1.5 with a 10-member ensemble of SSP2-4.5 reference (or control) simulations also run from 2015–2069.

2.2 Permafrost data

Permafrost exists in CLM5 where there is an active layer, or ground that seasonally thaws and re-freezes. Since we are interested in the biogeochemically active permafrost (i.e., permafrost that can release carbon when it thaws), we restrict permafrost to only the grid cells where the maximum annual active layer thickness (ALTMAX) is shallower than the bedrock depth. That is, ALTMAX must be < 8.6 m. A shallower active layer means that the near-surface soil remains frozen, while a deeper active layer indicates that the region is warmer and the underlying permafrost is likely more degraded and less responsive to surface changes in temperature or precipitation. To our knowledge, this is the first study that uses a variable depth limit for ALTMAX and permafrost based on a variable bedrock depth. We use ALTMAX to find annual permafrost extent, and the annual mean active layer depth (ALT) in calculations for permafrost volume and temperature. Permafrost volume in each grid cell is calculated as the depth of soil between the bottom of the active layer and the top of the bedrock in each cell, multiplied by each grid cell's area. Permafrost temperature is a weighted average of the soil temperature

between the bottom of the active layer and the top of the bedrock in each grid cell, where the thickness of each soil layer is the weight.

While talik is not often assessed in climate models due to their relatively coarse horizontal and vertical resolution, Parazoo et al. (2018) provide a framework for finding talik in CESM2 and we use their definition here. The timing of talik formation is the first year when the monthly mean soil temperature (TSOI) in any subsurface layer down to the bedrock exceeds -0.5°C for the entire calendar year (January–December; based on the freeze-thaw threshold from Parazoo et al. (2018)). The soil layer must consistently remain above -0.5°C for at least two years. Talik formation is restricted to permafrost regions.

Finally, we use changes in total ecosystem carbon (ΔECOC; units gC m^{-2}) to assess changes in total carbon stocks in the boreal permafrost area over time. ΔECOC accounts for changes in vegetation, leaf and root litter, and soil carbon (Lawrence et al., 2019). ΔECOC allows us to see the yearly balance between increasing land carbon through plant growth, and decreasing land carbon through emissions from decomposition in thawing permafrost. ΔECOC is calculated for each year relative to 2035 values in SSP2-4.5 and ARISE-SAI-1.5. It is only assessed in the grid cells that contain permafrost each year, so each year the area for which ECOC is calculated may be different. Therefore, we report ΔECOC in units of gC m^{-2} instead of reporting the ΔECOC in total gC for the entire permafrost area.

2.3 Land type

We show some permafrost changes in the context of land type, specifically peatlands. 'Peatland' in CESM2 refers to soils with high organic matter content, and its areal coverage is derived from a combination of geologic surveys and global databases (Lawrence et al., 2018; Tarnocai et al., 2011; Wells et al., 2010). Peatland cover is a prescribed characteristic of the land model.

3 Results

3.1 Permafrost and related fields

We begin by comparing the time series of terrestrial permafrost extent north of 50°N in the SSP2-4.5 (control) and ARISE-SAI-1.5 simulations (Fig. 1a). In the control sim-

ulations (red dashed line), the ensemble mean permafrost extent steadily declines at an average rate of 0.08 million km^2 year^{-1}. In the ARISE-SAI-1.5 simulations, the ensemble mean permafrost extent (blue solid line) declines at a rate of 0.04 million km^2 year^{-1} from 2035–2045. The rate of thaw starts to slow down over time, but does not completely stabilize. For the last 10 years of the simulation, 2060–2069, permafrost extent under SAI declines at a rate of 0.02 million km^2 year^{-1}. Along with smaller permafrost extent, there is also less permafrost by volume from 2015–2069 in SSP2-4.5 (Fig. 1b). Unlike the decline in extent, however, permafrost volume does not shrink at a constant rate, and actually remains at roughly 33.5 km^3 for the last decade of the simulation. Under SAI (blue solid line), the ensemble mean permafrost volume only decreases by 0.6 km^3 from 2035–2069, and half of that volume loss occurs before 2042. For both simulations there is a lot more interannual variability in volume than in extent. The annual mean SSP2-4.5 temperature increases by ∼1°C from 2015-2069, but stays near -4°C for the last decade (Fig. 1c). The ARISE-SAI-1.5 ensemble mean temperature gets slightly colder over the simulation, and is 1.2°C colder than the SSP2-4.5 ensemble mean temperature by 2069.

While the total permafrost extent continues to decline under both simulations (Fig. 1a), changes to the active layer depth (Fig. 2) indicate that SAI does have a noticeable influence on permafrost. As expected, ALTMAX is deepest ($>$ 3 m) at the lowest latitude of permafrost extent, where permafrost is warmest and most degraded, during 2035–2044 in SSP2-4.5 (Fig. 2a) and ARISE-SAI-1.5 (Fig. 2b). By 2060–2069, ALTMAX is still $>$ 3 m along much of the permafrost area margin, but is generally deeper in SSP2-4.5 (Fig. 2c) compared with ARISE-SAI-1.5 (Fig. 2d). SAI's effect on the active layer is most apparent when looking at the differences in ALTMAX between 2035–2044 and 2060–2069 in the two simulations (Fig. 2e, 2f). ALTMAX increases by up to 30 cm in most of Canada and northern Russia in SSP2-4.5, but also decreases by 5–25 cm in parts of southern Russia (Fig. 2e).

Even though total permafrost extent does not fully stabilize or recover by 2069 under SAI (Fig. 1a), active layer depth remains stable in most of the permafrost region in ARISE-SAI-1.5 (white cells in Fig. 2f). Furthermore, there are some places where new permafrost forms between 2035–2044 and 2060–2069 (green cells in Fig. 2f). New permafrost may form either because soil in a previously thawed grid cell permanently freezes, or because the ALTMAX in that grid cell becomes shallower than the bedrock depth. The black cells denote the presence of an active layer in the SSP2-4.5 or ARISE-SAI-

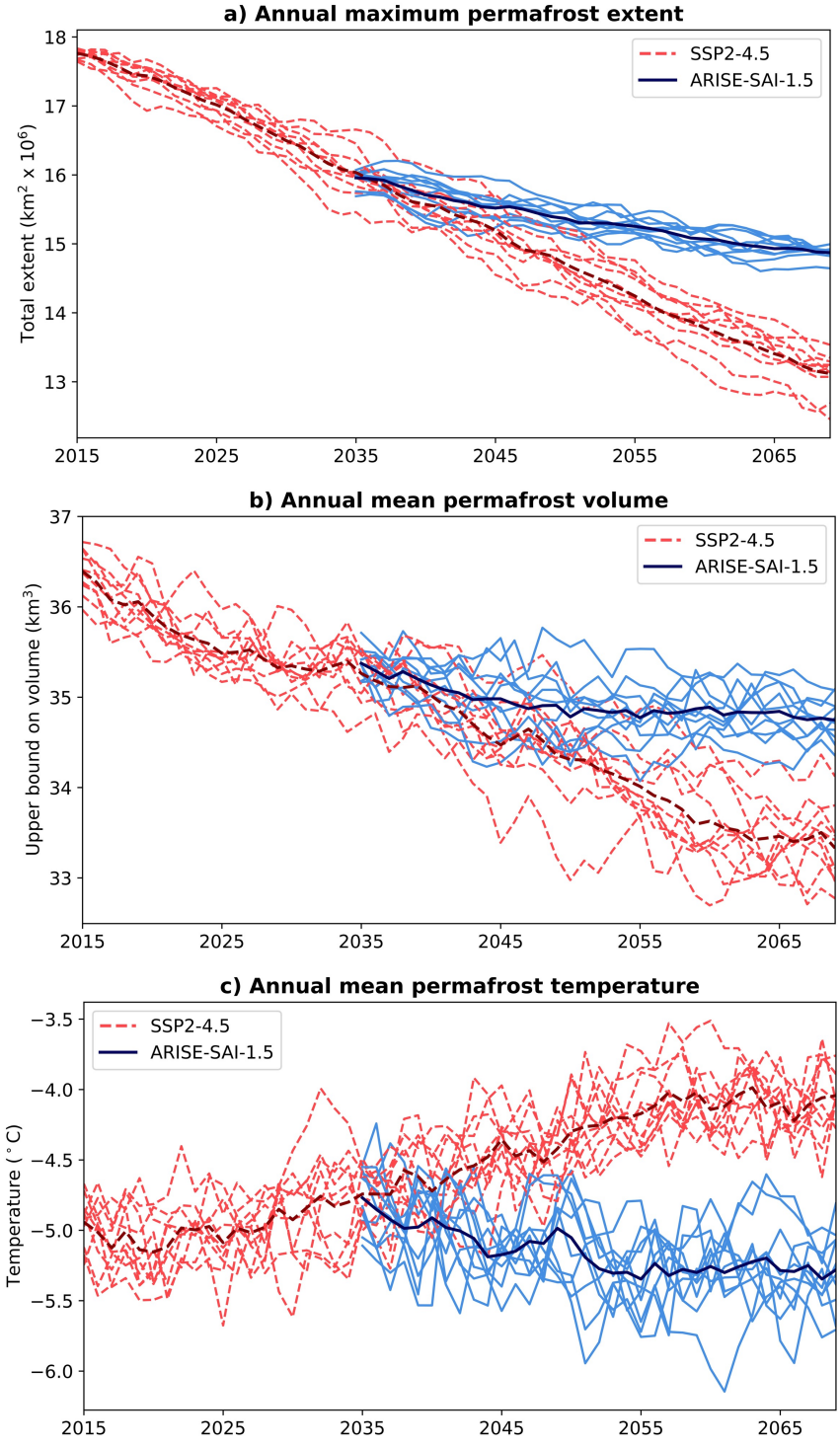

Figure 1. Time series of annual a) maximum permafrost extent, b) mean permafrost volume, and c) mean permafrost temperature for the SSP2-4.5 (red dashed line) and ARISE-SAI-1.5 (blue solid line) simulations. All time series are over land north of 50°N. Thin lines are individual ensemble members; thick lines are the ensemble means.

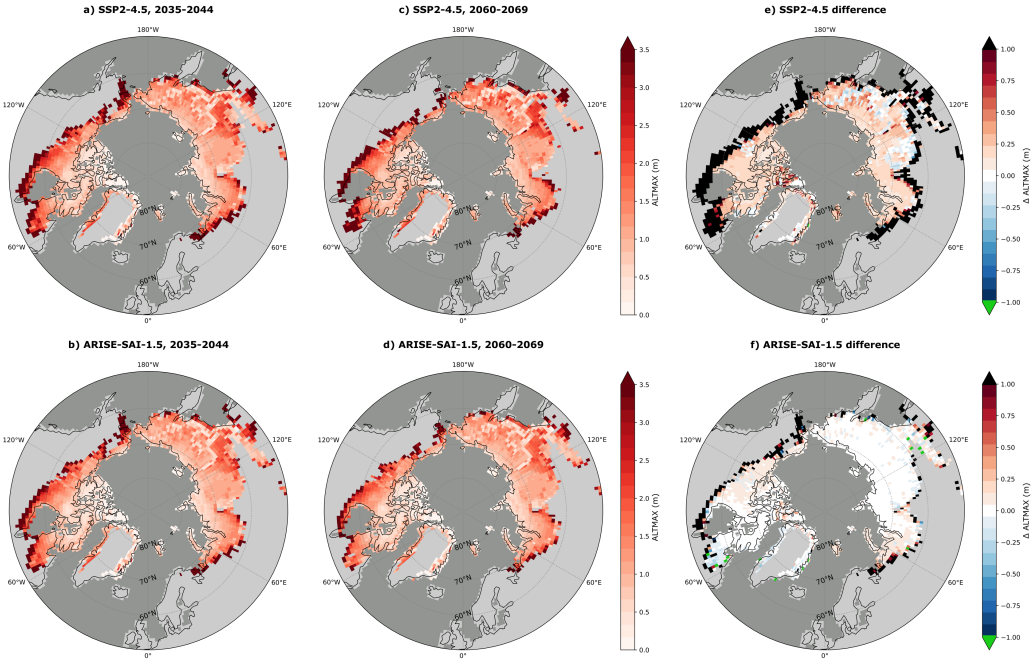

Figure 2. Annual maximum active layer depth (ALTMAX) in the ensemble mean a) SSP2-4.5 and b) ARISE-SAI-1.5 simulations from 2035–2044 and c) SSP2-4.5 and d) ARISE-SAI-1.5 simulations from 2060–2069. Difference in ALTMAX in the ensemble mean e) SSP2-4.5 and f) ARISE-SAI-1.5 simulations, 2060–2069 minus 2035–2044. Black cells are where permafrost exists in 2035–2044 but has thawed by 2060–2069. Green cells are where permafrost has frozen by 2060–2069 but did not exist in 2035–2044.

1.5 ensemble mean from 2035–2044 but not from 2060–2069. That is, the black cells along the southernmost margin of the permafrost region are where permafrost exists at the beginning of the simulations but then thaws and disappears by the end, or where ALTMAX becomes deeper than the bedrock depth.

3.2 Critical climate conditions for permafrost

Just as SAI prevents the annual maximum active layer depth from getting deeper in much of the permafrost region (Fig. 2f), it also delays or prevents most projected talik formation. Color shading in Figure 3a and 3b indicates the first year that talik forms in each simulation ensemble mean, and the green line denotes cells that contain >10% peatland in CESM2. SSP2-4.5 projects widespread talik formation across northern Canada and Alaska, starting in the lower latitudes in 2015 and moving poleward through 2069

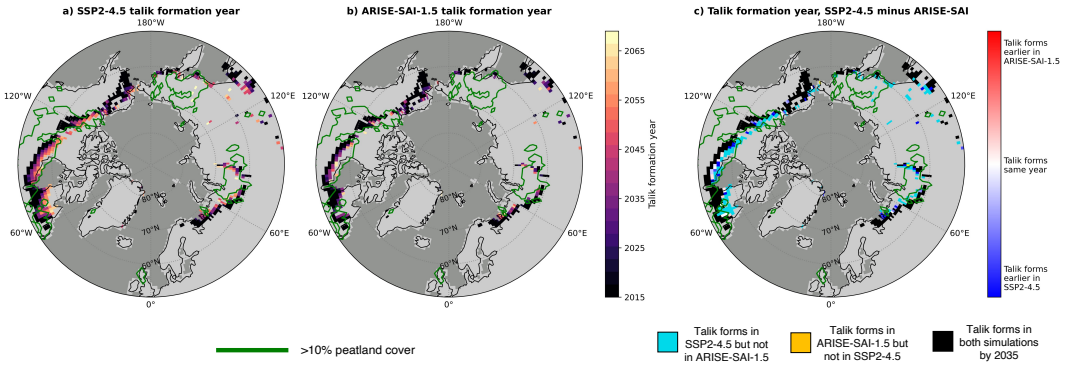

Figure 3. First year of projected talik formation in a) SSP2-4.5 and b) ARISE-SAI-1.5 ensemble mean simulations. Green line indicates where land is >10% peatland in CESM2 based on organic matter content. c) Difference in year of projected talik formation, SSP2-4.5 minus ARISE-SAI-1.5 ensemble means. Dark blue cells are where talik forms earlier in SSP2-4.5 than in ARISE-SAI-1.5, red cells are where talik forms earlier in ARISE-SAI-1.5 than in SSP2-4.5, cyan cells are where talik forms in SSP2-4.5 by 2069 but does *not* form in ARISE-SAI-1.5, yellow cells are where talik forms in ARISE-SAI-1.5 by 2069 but does *not* form in SSP2-4.5, and black cells are where talik has formed in both simulations by 2035.

(Fig. 3a). Less talik forms in ARISE-SAI-1.5 (Fig. 3b), and much of the talik that is projected to exist in this simulation has already formed by 2035 (black cells in Fig. 3a, 3b), or by the beginning of SAI deployment. Note that the cells with the most permafrost thaw (black cells in Fig. 2e, 2f) had already formed talik when SAI started in 2035. SAI prevents talik formation in 1.1 million km^2 of permafrost compared with SSP2-4.5 (cyan cells in Fig. 3c; Fig. 4) and delays talik formation by up to 20 years in 0.3 million km^2 of permafrost (dark blue cells in Fig. 3c). Roughly 64% of the talik formation that is either delayed or prevented by SAI is in peatland (green line in Fig. 3). The area of permafrost that contains talik in SSP2-4.5 rises at a fairly constant rate, increasing by 168% in the ensemble mean from 2015–2069, and by 68% from 2035–2069. From 2035–2069, the area containing talik in the ARISE-SAI-1.5 ensemble mean increases by only 18% (Fig. 4).

Much of the talik formation prevented by SAI is in peatlands, but how much total permafrost peatland thaw could SAI prevent in this scenario? In CESM2, the largest peatland cover poleward of 50°N is found in Canada along the coast of Hudson Bay (Fig.

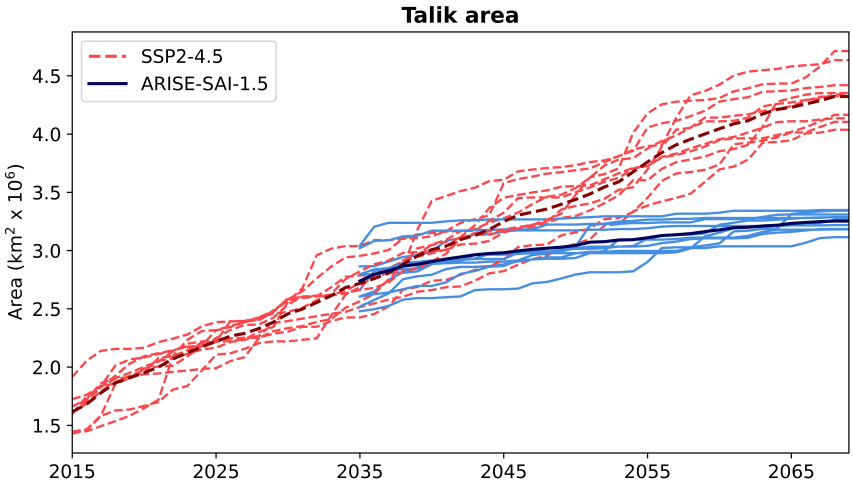

Figure 4. Total area of grid cells that contain talik in the SSP2-4.5 (red dashed line) and ARISE-SAI-1.5 (blue solid line) simulations. Thin lines are individual ensemble members; thick lines are the ensemble means.

5a). Figure 5b shows the time series of the percentage of permafrost peatland remaining relative to 2035 values in SSP2-4.5 (red dashed lines) and ARISE-SAI-1.5 (blue solid lines). Permafrost peatland is only considered in grid cells with >10% peatland cover (see green line in Fig. 3). Permafrost peatland area declines in both simulations, but decreases at a nearly linear rate in SSP2-4.5 compared with a more gradual decline in ARISE-SAI-1.5. By 2045, significantly more permafrost peatland remains in ARISE-SAI-1.5 compared with SSP2-4.5 ($p < 0.05$). By 2069, ~70% of total permafrost peatland remains in the SSP2-4.5 ensemble mean, compared with ~92% remaining in the ARISE-SAI-1.5 ensemble mean.

Identifying SAI's influence on permafrost is not only important for understanding the physical changes to permafrost but also for the downstream effects of permafrost thaw, which includes changes to carbon stocks. Figure 6 shows changes in total ecosystem carbon (ΔECOC) per unit area from 2035–2069 from the entire permafrost region (Fig. 6a) and from only permafrost peatland (Fig. 6b). Again, permafrost peatland is only considered in grid cells with >10% peatland cover. As discussed in section 2.2, ΔECOC is given in per unit area to account for the difference in permafrost area between the simulations and the year-to-year differences in permafrost area within each simulation. Un-

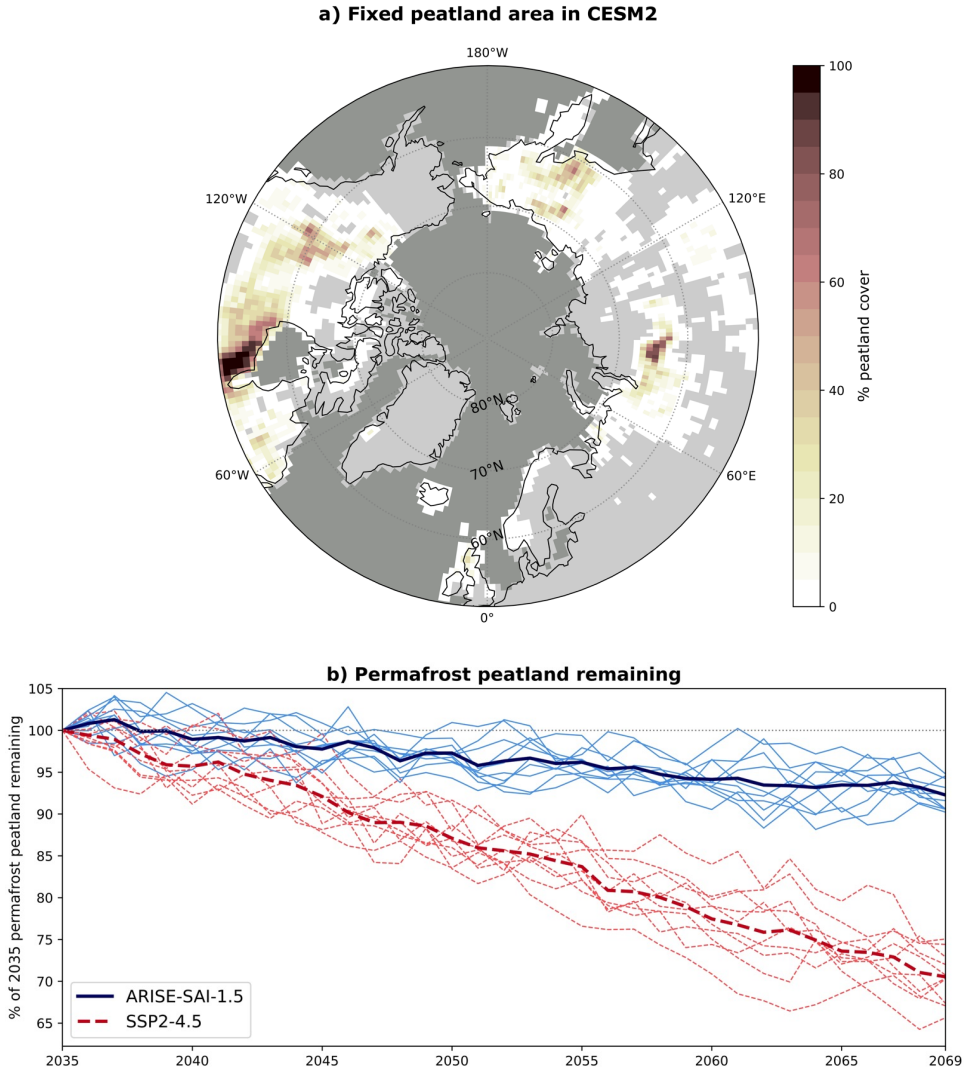

Figure 5. a) Prescribed peatland cover in CESM2 based on soil organic matter content. Peatland cover is a fixed constant in CESM2. b) Percent of 2035 annual mean permafrost soil in grid cells with >10% peatland cover in SSP2-4.5 (red dashed line) and ARISE-SAI-1.5 (blue solid line) simulations. Thin lines are individual ensemble members; thick lines are the ensemble means.

der SSP2-4.5, land carbon stocks in the total permafrost and permafrost peatland regions increase, while permafrost carbon under SAI remains nearly constant (Fig. 6a).

Why does ΔECOC increase in SSP2-4.5 but stay close to zero in ARISE-SAI-1.5? As the Arctic warms under SSP2-4.5, CO_2 concentrations increase, and the environment becomes more conducive to plant growth which adds more carbon back into the system via photosynthesis and increased root litter. Permafrost thaw still leads to enhanced microbial activity in the thawed soil and more carbon release through respiration and decomposition, but enhanced vegetation puts more carbon into the permafrost environment than microbial activity removes. Until 2045, the permafrost carbon sinks and sources in ARISE-SAI-1.5 are well-balanced, leading to a near-zero ΔECOC. As surface temperatures stabilize under SAI and the rate of permafrost thaw begins to slow down, however, plant growth in response to increasing CO_2 concentrations begins to outweigh the loss of carbon through respiration and decomposition. As a result, ΔECOC under SAI becomes slightly positive over time.

4 Discussion

One key result of our study is that total permafrost extent still declines (Fig. 1a) and some permafrost thaws completely (Fig. 2f) under the ARISE-SAI-1.5 scenario. The permafrost that completely thaws in both simulations is at the lowest latitude of permafrost extent and is vulnerable to thaw because it is greater than 3 m underground at the start of the stratospheric aerosol deployment in 2035 (Fig. 2a, 2b). Permafrost under a deep active layer is warmer than near-surface permafrost, and therefore more likely to imminently thaw. Deeper permafrost is also resistant to changes in surface temperatures and precipitation. The low latitude permafrost that thaws in SSP2-4.5 but does not thaw in ARISE-SAI-1.5, mostly located in southern Russia, is under a shallower active layer and may respond faster to surface temperature changes. Furthermore, most of the 'vulnerable' permafrost that thaws in both simulations already contained talik by the time SAI was deployed (Fig. 3b). That is, most of the degraded permafrost had already reached a critical condition for rapid thaw (i.e., a tipping point) that SAI could not prevent in the ARISE-SAI-1.5 simulations. Shallow talik can potentially re-freeze in the winter if temperatures are cold enough and there is sparse snow cover (Farquharson et al., 2022; Fewster et al., 2022). SAI is successful at preventing permafrost tipping points in the permafrost that can be preserved – that is, thaw and talik formation are still pre-

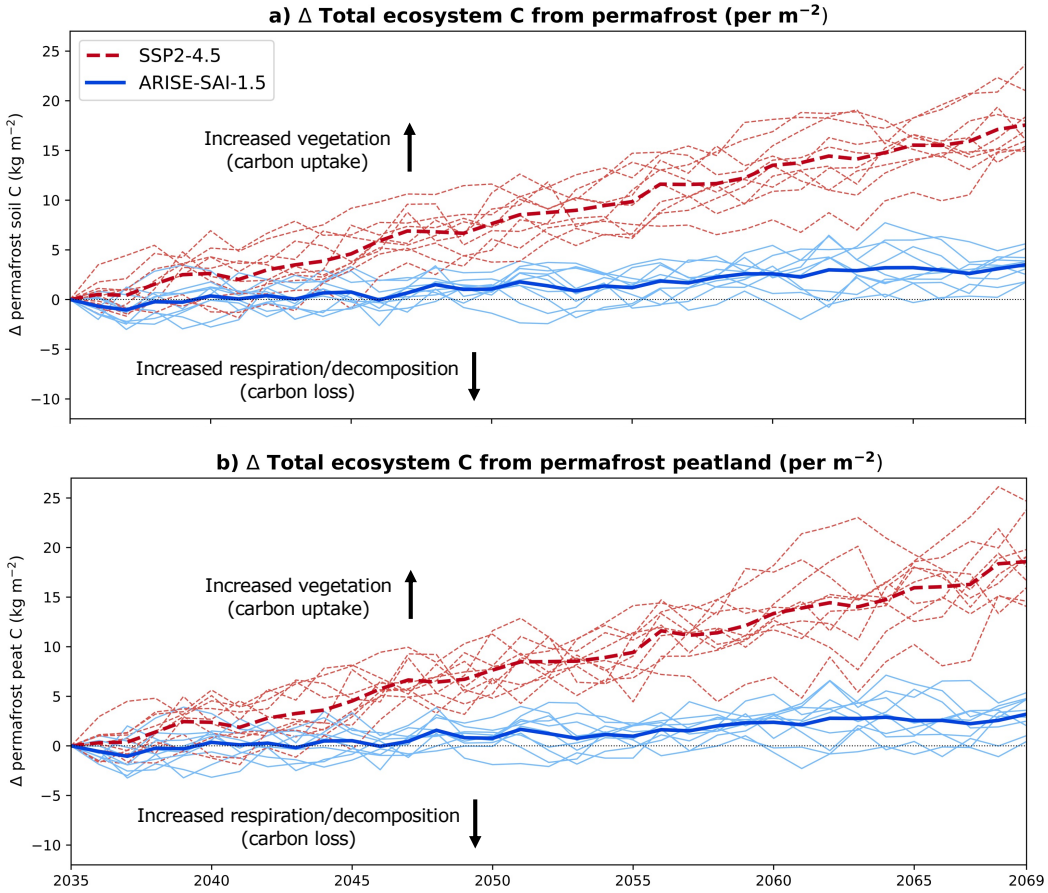

Figure 6. Change in annual mean total ecosystem carbon (ΔECOC) per unit area in a) total permafrost and b) permafrost grid cells that are >10% peatland from 2035–2069 in the SSP2-4.5 (red dashed lines) and ARISE-SAI-1.5 (blue solid lines) simulations. Thin lines are individual ensemble members; thick lines are the ensemble means. Positive (negative) ΔECOC indicates that increased vegetation carbon offsets (is outweighed by) increased soil carbon loss through respiration and decomposition.

vented in the cold shallow permafrost that is responsive to the temperature changes that SAI produces. Another tipping point potentially avoided by SAI is the irreversible loss of carbon from peatlands. For example, carbon stocks on coastal Hudson Bay are likely irrecoverable if released into the atmosphere (Noon et al., 2022), and ARISE-SAI-1.5 preserves more than 90% of the permafrost in this region (Fig. 5b).

Despite steadily thawing permafrost (Fig. 1, Fig. 2) and talik formation across an increasing area (Fig. 3a, Fig. 4), the permafrost region in SSP2-4.5 continues to be a carbon sink through 2069 (Fig. 6). Under most plausible climate trajectories, permafrost soils are projected to switch from a carbon sink to a carbon source as continued warming thaws permafrost and increases the depth of soil available for microbial activity (e.g., Koven et al., 2015; McGuire et al., 2018; Parazoo et al., 2018; Schuur et al., 2008). Talik formation can also trigger a transition from carbon sink to source. The timing of the sink-to-source transition is regionally variable, but in many areas occurs after 2070, or after the end of the simulations assessed in this study (Parazoo et al., 2018). From 2035–2069, the positive ΔECOC under SSP2-4.5 captures projected increases in soil carbon associated with enhanced vegetation productivity and increased plant litter. It also indicates that permafrost does not thaw enough under SSP2-4.5 from 2035–2069 to offset ecosystem carbon gains from vegetation changes. Increased plant cover, especially shrubs, has also been correlated with reduced summer permafrost thaw by reducing the amount of sunlight that reaches the ground surface (Blok et al., 2010). Warmer temperatures could also lengthen the growing season, giving plants more time to sequester carbon. These vegetation changes may make the permafrost region a stronger (short term) carbon sink in SSP2-4.5 than under ARISE-SAI-1.5.

Over the same time period in ARISE-SAI-1.5 there is only a small increase in ΔECOC (Fig. 6). The small increase indicates that the balance between net ecosystem carbon loss and net ecosystem carbon gain is slightly tipped in favor of net carbon gain, but not as much as it is in SSP2-4.5. Even without warmer temperatures, the tundra may become more productive under SAI as CO_2-driven plant growth responds to increasing CO_2 concentrations. As in SSP2-4.5, increased plant cover could reduce potential summer permafrost thaw, but the shading influence may be reduced because aerosols are already blocking some incoming sunlight. In both a potential SAI and non-SAI world there is an upper bound on how hospitable the permafrost region can be to new vegetation because of sunlight, nutrient, and temperature limitations (Mekonnen et al., 2021; Riley et al.,

2021; Zhang et al., 2022). Eventually carbon uptake may stagnate and no longer offset carbon losses from increased warming and permafrost thaw. Those timescales, however, are outside the current scope of these simulations. In the short term, permafrost soils under SSP2-4.5 sequester more carbon than permafrost soils under SAI.

There are a few caveats to our study that should be kept in mind. For instance, some permafrost processes are not fully represented in the current generation of Earth system models. Processes such as thaw-induced slumps or thermokarst production occur at resolutions too fine to be captured in the CESM2 model, both of which can rapidly release carbon that the model may not capture. Processes related to talik formation are also difficult to implement. Taliks often form beneath lakes or rivers that are not resolved in most Earth system models. As a result, our projections may underestimate how much talik forms in both the SSP2-4.5 and ARISE-SAI-1.5 simulations. We also define talik solely by temperature from Parazoo et al. (2018), but do not account for small-scale soil hydrology characteristics that affect talik formation (Treat et al., 2022). Our findings do agree with studies that observed degraded permafrost and talik at sites in Alaska (Farquharson et al., 2022) and the Northwest Territories (Connon et al., 2018) before 2020, in regions where talik is projected to form before 2020 in SSP2-4.5 (Fig. 3a).

Our results generally agree with previous studies that find that different SAI protocols can reduce permafrost thaw and permafrost temperature relative to a non-SAI world (Chen et al., 2020, 2023; H. Lee et al., 2019; W. Lee et al., 2023). While preserving some low latitude permafrost through ARISE-SAI-1.5 may be impossible, it remains to be seen whether climate intervention strategies with more aggressive temperature targets (e.g., to limit warming to 0.5°C or 1°C) or earlier deployment may be sufficient to better prevent permafrost thaw. SAI with region-specific goals has been shown to increase permafrost area (W. Lee et al., 2023). It is important to note, however, that different SAI strategies may come with their own suite of potential side effects (Tang & Kemp, 2021).

5 Conclusions

We assessed the possible influence of SAI on Northern Hemisphere terrestrial permafrost, with a particular interest in whether the SAI as deployed in the ARISE-SAI-1.5 simulations could prevent tipping points that lead to accelerated permafrost thaw. Using a variable bedrock depth to restrict permafrost only to the land model's soil lay-

ers restricts our analysis only to potentially biogeochemically active permafrost. While permafrost extent continues to decline under SAI, this is due to deeper permafrost disappearing along the southern margin of the permafrost region. Talik had already formed within this vulnerable region when SAI was deployed in the model, potentially tipping these permafrost cells into a critical climate condition where the entire soil column thaws down to the bedrock. Outside of this deeper permafrost, the active layer stabilizes in ARISE-SAI-1.5, and even new permafrost forms in parts of southern Russia. Most of the talik formation projected to occur in the SSP2-4.5 simulations is delayed or prevented entirely by SAI. Preventing permafrost thaw also leads to a small increase in total ecosystem carbon, likely due to enhanced productivity, but this carbon increase is smaller under SAI than under SSP2-4.5 conditions. Our results suggest that while SAI - as simulated by ARISE-SAI-1.5 - may be effective in stabilizing active layer depth and preventing talik formation outside of the most vulnerable permafrost regions, more aggressive SAI strategies with lower temperature targets may be required to stop ongoing and future permafrost thaw or significantly reduce the carbon released from thawing permafrost soils.

6 Open Research

All Python code and processed data for this analysis are available at `https://github.com/eabarnes1010/actm-sai-csu/tree/main/research/arise_arctic_climate`. At the time of publication this will be converted to a permanent repository on Zenodo. The unprocessed monthly mean ARISE-SAI-1.5 and SSP2-4.5 data that support this study are publicly available from Richter (2022) and Mills et al. (2022), respectively.

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