Natural variability can mask forced permafrost response to stratospheric aerosol injection in the ARISE-SAI-1.5 simulations

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Abstract

Stratospheric aerosol injection (SAI has been proposed as a potential method for mitigating risks and impacts associated with anthropogenic climate change. One such risk is widespread permafrost thaw and associated carbon release. While permafrost has been shown to stabilize under different SAI scenarios, natural variability may lead to a wide range of projected climate futures under SAI. Here we use the 10-member ensemble from the ARISE-SAI-1.5 simulations to assess the spread in projected active layer depth and permafrost temperature across boreal permafrost soils and specifically in four peatland and Yedoma regions. The forced response in active layer depth and permafrost temperature quickly diverge between an SAI and non-SAI world, but individual ensemble members overlap for several years following SAI deployment. Projected permafrost variability may mask the forced response to SAI and make it difficult to detect if and when SAI is stabilizing permafrost in any single realization. We find that it may take more than a decade of SAI deployment to detect the effects of SAI on permafrost temperature and almost 30 years to detect its effects on active layer depth. Not only does natural variability make it more difficult to detect SAI’s influence, it could also affect the likelihood of reaching a permafrost tipping point. In some realizations, SAI fails to prevent a tipping point that is also reached in a non-SAI world. Our results underscore the importance of accounting for natural variability in assessments of SAI’s potential influence on the climate system.
a) Canada peatland
b) Alaska Yedoma
c) Tibet Yedoma
d) Siberia Yedoma
e) Entire permafrost area

a) Maximum active layer depth trends, SSP2-4.5 (2025-2034)

b) Maximum active layer depth trends, ARISE-SAI-1.5 (2035-2044)
a) Canada peatland
b) Alaska Yedoma
c) Tibet Yedoma
d) Siberia Yedoma
e) Entire permafrost area

a) Permafrost temperature trends, SSP2-4.5 (2025-2034)

Ensemble 03  Ensemble 10  EM

b) Permafrost temperature trends, ARISE-SAI-1.5 (2035-2044)
### Timing of talik, SSP2-4.5 minus ARISE-SAI

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<th>Talik Forms Same Year</th>
<th>Talik Forms Earlier in ARISE-SAI-1.5</th>
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- **Talik Forms in SSP2-4.5 but not in ARISE-SAI-1.5**
- **Talik Forms in ARISE-SAI-1.5 but not in SSP2-4.5**
- **Talik Forms in both simulations by 2035**
Annual maximum active layer depth trends, ARISE-SAI-1.5 (2035-2044)
Permafrost soil temperature trends, ARISE-SAI-1.5 (2035-2044)

Temperature trend (°C per decade)
Natural variability can mask forced permafrost response to stratospheric aerosol injection in the ARISE-SAI-1.5 simulations

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Key Points:

• Projected natural variability in permafrost fields in peatland and Yedoma regions can mask forced response to SAI
• Effect of SAI on active layer and soil temperature is only detectable after more than a decade of aerosol deployment
• Natural variability affects likelihood of reaching permafrost tipping points despite surface cooling effect of SAI

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Abstract

Stratospheric aerosol injection (SAI) has been proposed as a potential method for mitigating risks and impacts associated with anthropogenic climate change. One such risk is widespread permafrost thaw and associated carbon release. While permafrost has been shown to stabilize under different SAI scenarios, natural variability may lead to a wide range of projected climate futures under SAI. Here we use the 10-member ensemble from the ARISE-SAI-1.5 simulations to assess the spread in projected active layer depth and permafrost temperature across boreal permafrost soils and specifically in four peatland and Yedoma regions. The forced response in active layer depth and permafrost temperature quickly diverge between an SAI and non-SAI world, but individual ensemble members overlap for several years following SAI deployment. Projected permafrost variability may mask the forced response to SAI and make it difficult to detect if and when SAI is stabilizing permafrost in any single realization. We find that it may take more than a decade of SAI deployment to detect the effects of SAI on permafrost temperature and almost 30 years to detect its effects on active layer depth. Not only does natural variability make it more difficult to detect SAI’s influence, it could also affect the likelihood of reaching a permafrost tipping point. In some realizations, SAI fails to prevent a tipping point that is also reached in a non-SAI world. Our results underscore the importance of accounting for natural variability in assessments of SAI’s potential influence on the climate system.

Plain Language Summary

Injecting highly reflective particles into the upper atmosphere, or stratospheric aerosol injection (SAI), is a proposed climate intervention method for deliberately stabilizing or cooling the Earth’s temperature and preventing undesirable impacts of human-caused climate change, such as thawing permafrost. Permafrost can potentially release stored carbon into the atmosphere as carbon dioxide and methane that contributes to the greenhouse effect. Climate model simulations show that SAI could stabilize permafrost and prevent it from thawing, but that natural fluctuations in the Earth’s climate may cause a wide range of outcomes for future permafrost thaw depth and soil temperature. We show that, due to these natural climate fluctuations, it may take 10–30 years of SAI to clearly see its influence on permafrost thaw depth and temperature. Certain conditions that lead to runaway thaw and soil carbon release (i.e., tipping points) may also occur.
even if SAI successfully stabilizes the Earth’s globally averaged temperature. When weigh-
ing possible outcomes of proposed climate intervention strategies, it is important to con-
sider the effects of natural climate fluctuations in assessing the pros and cons of differ-
ent strategies.
1 Introduction

Despite efforts to reduce greenhouse gas emissions and meet the climate goals of the 2015 Paris Agreement, humanity is not on track to limit warming to 1.5°C above pre-industrial temperatures (Matthews & Wynes, 2022; Pihl et al., 2019). Climate intervention, or deliberate manipulation of the Earth’s climate, is gaining traction as a possible method for mitigating increasing temperatures as a result of anthropogenic activity. Stratospheric aerosol injection (SAI) is a form of solar climate intervention that aims to reduce incoming sunlight by injecting highly reflective sulfur dioxide (SO$_2$) particles into the stratosphere. The National Academies of Sciences, Engineering, and Medicine (NASEM) recommended the formation of an international transdisciplinary research program to improve our understanding of the feasibility and consequences of solar climate intervention strategies (NASEM, 2021) in light of observed impacts already attributable to the current degree of warming (Gulev et al., 2021). These observed impacts are not evenly distributed across the globe: the Arctic is warming several times faster than the global average (Rantanen et al., 2022), leading to concern that this warming may lead to tipping points that cause further runaway warming. Exceeding 1.5°C of warming may trigger certain cryospheric tipping conditions (Armstrong McKay et al., 2022; Lenton, 2012), adding urgency to evaluating the global and regional impacts of different SAI methods.

While most proposed SAI methods do not specifically target the poles, different potential SAI strategies may be effective at stabilizing Arctic Ocean surface temperatures (Richter et al., 2022), maintaining Arctic sea ice extent near present-day values (Hueholt et al., 2023; Jones et al., 2018; Kravitz et al., 2019), and, importantly for cryospheric tipping points, slow the rate of boreal permafrost thaw (Chen et al., 2020, 2023; H. Lee et al., 2019; W. Lee et al., 2023; Liu et al., 2023). The thawing of permafrost, or ground that is consistently frozen for at least two consecutive years, is a particular area of concern because of the carbon stored in permafrost soils. Recent estimates put the total carbon storage of boreal permafrost soils at 1,460-1,600 PgC (Hugelius et al., 2014; Schuur et al., 2015, 2018), or roughly twice the carbon stored in the atmosphere (Schuur et al., 2008). The type of permafrost soils affects the distribution of carbon. Peatlands contain a high density of organic material, but overall account for about 12% of permafrost carbon (Hugelius et al., 2020). Yedoma, or Pleistocene-age ice-rich permafrost that can be more than 40 m thick (Miner et al., 2022; Strauss et al., 2021; Tarnocai et al., 2009), is...
not made of carbon-rich soils but is so deep that the total carbon inventory of Yedoma
is estimated to be ∼20-30% of the total boreal permafrost carbon stores (Schuur et al.,
2018; Strauss et al., 2013, 2017). As permafrost temperatures increase and permafrost
soils thaw, this stored carbon can be released into the atmosphere as CO₂ or CH₄.

Certain permafrost tipping conditions may be reached if permafrost thaws abruptly,
releasing large amounts of this stored carbon, or setting off a positive feedback within
the soil that accelerates the rate of thaw. While permafrost tipping points can be dif-
ficult to quantify and the likelihood of reaching them is uncertain (Lenton, 2012), par-
ticular conditions within permafrost soil make it more likely to reach tipping conditions.
The formation of talik, a layer of thawed soil within permafrost, can accelerate in-ground
respiration that in turn can lead to more permafrost thaw and soil carbon release (Devoie
et al., 2019; Parazoo et al., 2018). Taliks can also exist between permafrost and the base
of the active layer, or the ground layer that thaws and freezes each year. These taliks
grow by thawing the underlying permafrost (Connon et al., 2018), and since talik for-
mation can initiate a positive feedback of thawing and soil respiration, it may be con-
sidered a permafrost tipping condition.

SAI has been proposed as a strategy to prevent climate tipping points, but there
is uncertainty about how effective it might be and when we could detect its effects. It
is especially uncertain given the range of scenarios in which SAI could be deployed, from
stabilizing surface temperatures to rapidly cooling the planet (MacMartin et al., 2022).
The response to solar climate intervention strategies can vary greatly in fields such as
temperature and precipitation due to regional differences and natural variability within
the climate system (Barnes et al., 2022; Dagon & Schrag, 2017; Labe et al., 2023; Ricke
et al., 2010). Over short timescales, natural variability can mask a system’s response to
external forcings such as anthropogenic warming caused by greenhouse gas emissions (e.g.,
Deser et al., 2014), or anthropogenic cooling caused by SAI. This masking could hinder
efforts to determine what, if any, effect SAI has on a system in the short term. In a re-
region as sensitive to temperature shifts as the Arctic, natural variability may lead to per-
mafrost thaw or talik formation even if SAI successfully stabilizes global mean surface
temperatures, thereby masking the forced response to SAI. Natural variability could also
accelerate how quickly SAI halts permafrost thaw, essentially helping the forced response
in preserving permafrost.
Large-scale solar climate intervention currently only exists in the realm of climate models that provide a range of possible future outcomes as a result of SAI deployment (e.g., Kravitz et al., 2011; Richter et al., 2022; Tilmes et al., 2018). Each possible outcome is represented by a single member of an "ensemble" of simulations. The ensemble mean defines the forced response to SAI deployment. Our future will be a combination of the forced response and the influence of natural variability, so the real world can be thought of as a single ensemble member. No studies have yet assessed the effect of SAI on permafrost in the context of internal variability, nor has there been work on how internal variability may affect the likelihood of reaching permafrost tipping conditions with or without SAI. Using output from every ensemble member of an SAI deployment simulation, here we seek to answer three main questions:

1. What is the range of certain boreal permafrost responses to SAI due to natural variability, especially in regions with high organic soil matter content?
2. Given a possible range of permafrost responses to SAI due to natural variability, how long might it take to detect the effect of SAI on permafrost in a single climate realization?
3. Could internal variability still push boreal permafrost into tipping conditions even if SAI successfully stabilizes global mean surface temperatures?

2 Materials and Methods

2.1 Climate intervention and control simulations

To explore the role of natural variability in the permafrost response to SAI, we use output from two parallel 10-member climate simulations. Both simulations were run with the fully-coupled Community Earth System Model version 2 (CESM2; Danabasoglu et al. (2020)) at a ~1° 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. (2018, 2019)) as the land component. CLM5 has 25 soil levels down to almost 50 m, with soil level thickness ranging from 0.4 cm to 8.5 m. Up to the first 20 layers are soil and at least the bottom five layers are bedrock. Bedrock depth is variable (Lawrence et al., 2018), but is no deeper than 8.6 m. The vertical resolution of the soil layers increased from previous versions of the land model in order to more accurately simulate hydrological and permafrost...
processes (Lawrence et al., 2019). The non-SAI control simulation uses the Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5; Riahi et al. (2017)) emissions scenario with five members run from 2015–2069 and five members run from 2015–2100.

The parallel simulation in which SAI is deployed is the Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection 1.5 experiment (ARISE-SAI-1.5; Richter et al. (2022)), which runs from 2035–2069 and also utilizes the SSP2-4.5 emissions scenario. In the experiment, sulfur dioxide aerosols are injected into the stratosphere at \(\sim 21.5 \text{ km} \) from 15°/30°N/S at 180°E starting in 2035. A feedback-control algorithm (Kravitz et al., 2017; MacMartin et al., 2014) within the simulations adjusts the volume and altitude of aerosols deployed from each location in order to meet three climate targets: to maintain global mean surface temperatures close to 1.5°C above pre-industrial levels, to maintain the north–south surface temperature gradient, and to maintain the equator-to-pole surface temperature gradient (Richter et al., 2022).

### 2.2 Permafrost data and tipping points

In CESM2, permafrost exists where there is an active layer. The depth of the active layer can be 0 m if the entire subsurface column is permafrost. A grid cell contains permafrost if the annual maximum active layer depth is shallower than the depth of the bedrock in that cell, which means that the active layer does not extend all the way to the bedrock and that some of the soil column is permafrost. To assess possible permafrost outcomes under SAI, we focus on changes to the annual mean active layer depth (ALT), the maximum annual active layer depth (ALTMAX), and annual mean soil temperature down to the bedrock in grid cells with permafrost (TSOI). We focus on ALT and ALTMAX because they are proxies for permafrost extent. A deeper active layer means the underlying permafrost is warmer and more degraded, and therefore is closer to thawing conditions. A deeper active layer also means more soil is exposed to microbial activity that releases stored carbon into the atmosphere through decomposition and respiration. We focus on TSOI because temperature directly informs us whether the upper soil levels are thawed. Most permafrost soil carbon is stored in the upper 3 m (Tarnocai et al., 2009), so thawing can potentially release much of the stored carbon. Increasing TSOI may also inform us whether permafrost is warming and degrading even if the active layer depth has not yet changed. There is an established relationship between mean annual
Figure 1. Regions selected to assess regional variability in permafrost fields. The boxed regions are 1) Canada peatland, 2) Alaska Yedoma, 3) Siberia Yedoma, and 4) Tibetan Plateau Yedoma.

air temperature and mean annual ground temperature (Burke et al., 2020), so the surface cooling effects of SAI may also influence in-ground temperature.

Permafrost thaw in regions with relatively high organic soil matter content is of concern because of how much carbon can potentially be released into the atmosphere, so we assess the variability in future ALTMAX and TSOI in four sub-regions across the permafrost area. Each region, outlined in Figure 1, has observed high organic soil matter content: three of the four regions (Alaska, Siberia, and the Tibetan Plateau) have high concentrations of observed Yedoma permafrost (Strauss et al., 2021) and the fourth (Canada) is extensively covered by peatlands (Tarnocai et al., 2011; Wells et al., 2010). Since all permafrost soils can release stored carbon, we also look at variability across the entire boreal permafrost region.

Finally, we consider the formation of talik, or perennially unfrozen soil within or above permafrost, to be a quantifiable precursor to a potential permafrost tipping point. Following the definition used by Parazoo et al. (2018) for talik in an Earth system model, the first year of talik formation is the first year when the monthly mean temperature of
any subsurface layer in a permafrost grid cell exceeds -0.5°C and remains above -0.5°C for at least two consecutive years. The cutoff of -0.5°C is similar to the -0.3°C temperature cutoff used by Farquharson et al. (2022) for assessing talik formation in a high-resolution numerical model (Jafarov et al., 2012).

2.3 Logistic regression model

To determine when the influence of SAI on permafrost-related fields might be detectable, we trained two logistic regression models to predict the probability that a map of annual mean active layer depth or permafrost temperature is from the ARISE-SAI-1.5 or SSP2-4.5 simulation. The maps are restricted to the boreal permafrost region from 50-84°N, which are flattened into arrays of 10656 units, or 37 latitude by 288 longitude points. The arrays are normalized to a mean of 0 and a standard deviation of 1 across all grid points. For each variable, the model receives these flattened and normalized arrays as input vectors. The output layer of the logistic regression models produce values that, when passed through the sigmoid activation function, can be interpreted as the probability that the map comes from either the ARISE-SAI-1.5 or SSP2-4.5 simulation. More information about the models’ architecture is in the Supplemental Information (Tables S1, S2). Each model is trained on seven ensemble members, validated on two, and tested on one. The models are trained on the full 35-year experiment (2035–2069).

To better understand which permafrost regions are most helpful for the logistic regression models to make their predictions, we also perform feature contribution analysis. Feature contribution is a method to improve interpretability of the logistic regression models by identifying which regions contributed to the prediction that a map came from either the ARISE-SAI-1.5 or SSP2-4.5 simulations. Contribution maps are created by multiplying the model weights by the annual mean input values for either ALT or TSOI at every grid point. Positive (negative) contributions are regions that drive the model toward predicting a map is from the ARISE-SAI-1.5 (SSP2-4.5) simulations. The more positive or negative the contribution of a particular point or region, the more ‘important’ that point or region is for driving the logistic regression model prediction toward either the ARISE-SAI-1.5 or SSP2-4.5 simulations.
3 Results

3.1 Natural variability in permafrost fields

We begin by evaluating projected natural and regional variability in the active layer and in soil temperature. Figure 2 shows time series of the annual maximum active layer depth (ALTMAX) in the four selected regions (Fig. 2a-d) and across the entire permafrost region (Fig. 2e) in the SSP2-4.5 (red dashed lines) and ARISE-SAI-1.5 (blue solid lines) simulations. We include a map of the ensemble mean ALTMAX in 2034 from the SSP2-4.5 simulation as reference for the spatial pattern of ALTMAX in the year before SAI deployment (center map, Fig. 2). There is a lot of regional variability between all five panels (note the panel scale differences), with the deepest ALTMAX in both simulations in Canada peatland (Fig. 2a) and the shallowest in Siberia Yedoma (Fig. 2d). The ensemble means of the two simulations (thick lines) diverge soon after SAI deployment in 2035, with the SSP2-4.5 ensemble mean ALTMAX getting deeper in response to increasing surface temperatures and the ARISE-SAI-1.5 ensemble mean either stabilizing or getting shallower in response to stabilizing surface temperatures. By 2045, the ensemble mean ALTMAX in SSP2-4.5 is 6–61 cm deeper than in ARISE-SAI-1.5 in all five regions, and 21–201 cm deeper in SSP2-4.5 than in ARISE-SAI-1.5 by the end of the simulations in 2069.

The individual ALTMAX ensemble members (thin lines) continue to overlap between the two simulations for several years after SAI deployment, indicating that internal variability may mask the forced response of permafrost to SAI and make it hard to distinguish one climate realization from another when it comes to an SAI vs non-SAI world. For example, the different realizations in the Alaska Yedoma region (Fig. 2b) exhibit a wide range of ALTMAX following SAI: there are some ensemble members in ARISE-SAI-1.5 where ALTMAX is deeper than in almost all the ensemble members in SSP2-4.5, and the ALTMAX time series never completely diverge between the two simulations. Only in Siberia Yedoma (Fig. 2d) and the entire permafrost region (Fig. 2e) do all the ARISE-SAI-1.5 realizations fully diverge from all the SSP2-4.5 realizations by 2069. While the overall trend in the simulations’ ensemble mean ALTMAX is clear, the interannual and internal variability inherent in the different ensemble members makes it difficult to discern the ALTMAX trends in the years immediately preceding and following SAI deployment in any single realization.
Figure 2. Time series of annual maximum active layer depth in SSP2-4.5 (red dashed lines) and ARISE-SAI-1.5 (blue solid lines) within a) Canada peatland, b) Alaska Yedoma, c) Siberia Yedoma, d) Tibet Yedoma, and e) the entire permafrost region. The regions in a-d are identified in Figure 1. Thin lines are individual ensemble members; thick lines are the ensemble means. The central map is the ensemble mean annual maximum active layer depth in SSP2-4.5 in 2034.
ALTMAX trends pre- and post-SAI deployment are highly variable by region and by ensemble member. In the decade preceding SAI deployment (2025–2034; Fig. 3a) the ALTMAX trend in ensemble member #3 is positive across Canada but almost entirely negative across Siberia, while in ensemble member #10 the trends are positive in far eastern and western Russia. Regionally the active layer can get deeper or shallower (trends for all ensemble members are in Fig. S1 in the Supplemental Information), despite a generally positive ALTMAX trend in the forced response (see the ensemble mean, or EM), especially along the lowest latitude of the permafrost region.

ALTMAX trends are also highly variable in the decade following SAI deployment (2035–2044; Fig. 3b). The active layer gets deeper in far eastern and western Russia in ensemble member #3, but otherwise exhibits similar ALTMAX trends as the previous decade (Fig. 3a). In contrast to ensemble member #3, ensemble member #10 shows decreasing ALTMAX trends across the entire permafrost region, with the largest trends in eastern Canada and near the Hudson Bay. While not all ensemble members have differing trends pre- and post-deployment (Figs. S1, S2), ensemble members #3 and #10 are examples of how natural variability could lead to SAI being perceived as ‘successful’ at preventing permafrost thaw (i.e., a positive ALTMAX trend into a negative trend) or as ‘failing’ to prevent permafrost thaw (i.e., a negative or neutral ALTMAX trend into a positive trend). Compared to trends in individual ensemble members, the ensemble mean ALTMAX trends are relatively small, except for along the margins of the permafrost region.

As for ALTMAX (Fig. 2), the annual mean time series of the permafrost temperature (TSOI) in the four regions with high organic soil matter content (Fig. 4a-d) and across the entire permafrost region (Fig. 4e) exhibit large regional and natural variability. As expected, the warmest permafrost temperatures are at the lowest latitude of the permafrost extent, and get colder with increasing latitude (center map, Fig. 4). While the ensemble mean annual mean TSOI (thick lines) increases in all regions from 2015–2069 in SSP2-4.5 (red dashed lines), permafrost reaches the warmest temperatures in Canada peatland (Fig. 4a). TSOI either stabilizes or decreases in all regions in ARISE-SAI-1.5 (blue solid lines), but there is a large range in projected temperature. In a single year, TSOI can span several degrees between individual ensemble members. Similar to ALTMAX, the TSOI time series in ARISE-SAI-1.5 and SSP2-4.5 only fully diverge in Siberia Yedoma (Fig. 4d) and when averaged over the entire permafrost region (Fig. 4e). Oth-
Figure 3. Decadal trends in maximum active layer depth in ensemble members #8 and #9 and the 10-member ensemble mean (EM) in a) SSP2-4.5 from 2025–2034, or the decade immediately preceding SAI deployment, and b) ARISE-SAI-1.5 from 2035–2044, or the decade immediately following SAI deployment. Trends are calculated using least squares regression. Purple (orange) means the active layer gets deeper (shallower).
Figure 4. As in Figure 2 except for the annual mean permafrost soil temperature.

erwise it is difficult to distinguish the temperature time series between simulations, es-

cially in Alaska Yedoma (Fig. 4b).

Given the large spread in TSOI between ensemble members (Fig. 4), it is perhaps

unsurprising that there is also a large spread in pre- and post-SAI deployment decadal

temperature trends (Figs. 5, S3, S4). Most ensemble members, including #3 and #10,

show warming trends of > 0.3°C decade$^{-1}$ in the decade leading up to SAI deployment

(Fig. 5a, S3), but temperature trends are highly regionally variable. Most of Canada strongly

warms in ensemble member #3 from 2025–2034 (Fig. 5a), and continues to warm in 2035–

2044 post-SAI deployment (Fig. 5b). In ensemble member #10, however, temperature
trends go from warming to a strong cooling trend across the entire permafrost region,
indicating that SAI may be perceived as ‘successful’ at preventing the permafrost soil

temperature from increasing. Along with variability in 2035–2044 temperature trends

between ensemble members (Fig. S4), there is a lot of spatial heterogeneity in most en-
semble members’ TSOI trends, resulting in a near-zero ensemble mean trend across the entire permafrost region.

3.2 Detecting permafrost response to stratospheric aerosol injection

Given the large spread in permafrost fields driven by internal climate variability in both the SSP2-4.5 and ARISE-SAI-1.5 simulations, we next move to trying to quantify how long it might take to tell if or when SAI is influencing permafrost. To do this, we use logistic regression models that learn the patterns of active layer depth and soil-to-bedrock temperature that occur in an SAI and non-SAI world. How long does it take the models to confidently predict which simulation a map of annual mean ALT or TSOI comes from? For ALT, the model correctly predicts which maps belong to which simulation starting in 2060 (Fig. 6a). That is, it takes almost 30 years of SAI deployment for the model to be confident and accurate in its prediction that a map of annual mean

Figure 5. As in Figure 3 except for the annual mean permafrost soil temperature.
active layer depth comes from an SAI or non-SA1 world. Model confidence is nearly 100% for the SSP2-4.5 predictions (red line) by 2050, but only reaches 100% confidence for the ARISE-SAI-1.5 predictions (blue line) at the end of the simulations. It takes fewer years of SAI deployment for the model to identify the correct simulations for maps of annual mean TSOI (Fig. 6b). The model achieves perfect accuracy for both simulations starting in 2051, and reaches near-100% confidence in its predictions for both the SSP2-4.5 and ARISE-SAI-1.5 maps in 2066.

Certain regional patterns of ALT and TSOI help the logistic regression models achieve perfect accuracy in their predictions, and we use contribution maps to identify these patterns. For ALT predictions, the areas that provide the largest contribution are found along the lowest latitude of the permafrost region (Fig. 7a). The contributions to the model prediction in southern Alaska and southeastern Russia are positive, meaning that the ALT information here contributed to the logistic regression model predicting that the map came from the ARISE-SAI-1.5 simulation. Otherwise, with the exception of small negative contributions around the Tibet Yedoma region, ALT in the rest of the permafrost region has a negligible contribution to the model prediction.

Temperature contributions to the logistic regression model predictions are far more heterogeneous than ALT contributions and come from the entire permafrost region (Fig. 7b). The largest positive contributions, or the regions that make a map more likely to be from the ARISE-SAI-1.5 simulations, are also in the same regions with positive ALT contributions (Fig. 7a). Regions that push the prediction towards the SSP2-4.5 simulations (largest negative contributions) are concentrated near the Tibet Yedoma region. Most of Canada, except for grid cells along the southern margin of permafrost, also contributes to the logistic regression model predicting that a map of TSOI comes from SSP2-4.5.

### 3.3 Permafrost tipping points reached through natural variability

Since there is a large range of outcomes for active layer thickness and soil temperature in SAI and non-SA1 worlds, there may also be a large range of outcomes for a key climatic concern from permafrost thaw - namely, the formation of talik that could lead to widespread, accelerated, and irreversible thaw and carbon release. The difference in the timing of talik formation, or the first year that permafrost reaches a potential tip-
Figure 6. Logistic regression model confidence for the single testing member (bold line) and the training and validation members (thin lines) of the SSP2-4.5 (red) and ARISE-SAI-1.5 (blue) simulations for annual mean maps of a) active layer depth and b) soil temperature down to the bedrock in grid cells with permafrost.
Figure 7. Contribution maps (input × weights) for the ARISE-SAI-1.5 testing ensemble member averaged over 2035–2069 for a) active layer depth and b) permafrost temperature logistic regression model predictions.
Figure 8. Difference in the timing of projected talik formation in each ensemble member, SSP2-4.5 minus ARISE-SAI-1.5. Cyan cells are where talik forms in an SSP2-4.5 ensemble member by 2069 but never forms in the corresponding ARISE-SAI-1.5 ensemble member. Yellow cells are where talik forms in an ARISE-SAI-1.5 ensemble member by 2069 but never forms in the corresponding SSP2-4.5 ensemble member. Black cells are where talik exists by 2035 in the ensemble member for both simulations. The final map is the difference in the timing of projected talik formation in the 10-member ensemble mean (EM).
Figure 9. Probability that talik formation is prevented in all ten ARISE-SAI-1.5 ensemble members compared to corresponding SSP2-4.5 ensemble members.
Regional and natural variability in permafrost lead to a range of outcomes in projected talik formation. Some regions are clearly more susceptible to reaching a permafrost tipping point even under SAI, due to the influence of natural variability (darker colored cells in Fig. 9), while some regions appear to be robustly resistant to reaching tipping conditions - i.e., ARISE-SAI-1.5 completely prevents talik formation relative to SSP2-4.5 (yellow cells in Fig. 9), not just delays it. Outside of the degraded permafrost cells where talik already exists by 2035 (black cells; Fig. 8, Fig. 9), talik formation is prevented most often in north-central Canada, and least often prevented in parts of Russia. Importantly, talik formation is prevented under the ARISE-SAI-1.5 scenario in at least one ensemble member in every grid cell where talik did not already exist by 2035. That is, outside of the black grid cells in Figure 9, the likelihood that SAI prevents talik formation in at least one ensemble member compared to the corresponding SSP2-4.5 ensemble member is at least 10%. There are a few scattered cells where the likelihood of talik prevention is 100%, but these cells are not clustered together in any particular region.

4 Discussion and Conclusions

Overall our results show that natural climate variability leads to a range of projected outcomes for ALTMAX and TSOI with and without SAI. In four regions with high organic soil matter content, natural variability in both ALTMAX and TSOI makes it difficult to distinguish between individual ensemble members in the ARISE-SAI-1.5 and SSP2-4.5 simulations for several years after SAI deployment. The overlap between the simulations suggests that it may take many years of aerosol deployment before SAI has a noticeable effect on permafrost Yedoma and peatland. The ensemble means of the two simulations do diverge within a few years of SAI deployment. These results support previous work that SAI prevents permafrost thaw in the forced response (H. Lee et al., 2019; W. Lee et al., 2023), though to our knowledge this is the first work to assess the extent to which natural variability may mask the forced permafrost response to SAI.

There is also a range in the projected timing of talik formation, although natural variability could push boreal permafrost into tipping conditions even under SAI, but this is highly regionally dependent. All ensemble members are in agreement that the southern margin of permafrost already contains talik by 2035, and therefore permafrost along the southern margin has reached a tipping point regardless of any SAI influence. That is, the southernmost permafrost is very likely to be lost no matter what impact SAI has.
on the rest of the permafrost region under ARISE-SAI-1.5. Most of the Alaska Yedoma region already contains talik by 2035 (Fig. 9) and therefore may be on the verge of widespread thaw. The pre-SAI talik may explain why ALTMAX appears to stabilize and become shallower over time in the Alaska Yedoma region (Fig. 2b): the deepest ALTMAX is over the warmest and most degraded permafrost and once the warm permafrost thaws, the remaining permafrost is more stable and exists under a shallower active layer. All members are also in agreement that SAI as deployed by ARISE-SAI-1.5 prevents the majority of pan-Arctic talik formation outside of the southern margin.

Why is the SAI influence detectable earlier on soil temperature than on active layer depth? It may be because temperature responds faster to increasing surface temperatures in SSP2-4.5 than the active layer does. Since permafrost temperature remains below freezing, but does get warmer in SSP2-4.5 (Fig. 2), the soil may not be thawing quickly enough to increase the active layer depth. Permafrost temperature may be changing rapidly enough in the SSP2-4.5 simulations to distinguish a map of TSOI between the two simulations earlier than a map of ALT. TSOI is also changing everywhere, which is why contributions to the TSOI predictions come from the entire permafrost region (Fig. 7b). Once permafrost thaws and the active layer deepens, it is difficult to refreeze permafrost and reduce the active layer depth. This is particularly difficult if talik has formed between the permafrost and base of the active layer (Connon et al., 2018). Once the permafrost is completely thawed, there is no more ALT in the SSP2-4.5 simulations. The logistic regression model uses the pattern of ALT loss to differentiate between the ARISE-SAI-1.5 and SSP2-4.5 simulations, which is why the ALT prediction contributions are only from the permafrost margins (Fig. 7a): if a map of ALT has an active layer on the southern permafrost margin, then it belongs to the ARISE-SAI-1.5 simulation.

Although our results come from a single idealized SAI scenario that is simulated by one Earth system model, models are the best available tools for assessing possible impacts of SAI. Models are the only way to study climate projections, and using ensembles of different climate realizations also gives us insight into how natural variability may affect climate outcomes. Different processes can be easier or harder to simulate in models, however. Permafrost is difficult to simulate because it is affected by subgrid-scale processes that are not yet represented in the current generation of climate models. We do not specifically identify subaerial talik (formed below a lake), which is a common location for talik to be found in observations (Devoie et al., 2019), and therefore may be
underestimating the extent of talik formation in CESM2. It is important to note that
talik formation is a precursor to widespread permafrost thaw in observations (Connon
et al., 2018; Deviose et al., 2019), but the 35-year simulation may be too short to deter-
mine if a permafrost tipping point actually occurs. Permafrost outcomes may be very
different under an SAI scenario that reduces global mean surface temperature instead
of stabilizing it at 1.5°C, such as those considered by MacMartin et al. (2022).

Our results indicate that SAI as simulated by the ARISE-SAI-1.5 scenario gener-
ally preserves permafrost and stabilizes both ALTMAX and TSOI at near-2035 levels,
though it may take one to three decades of SAI deployment to robustly detect its influ-
ence on both permafrost fields. Natural variability may lead to a climate future where
ALTMAX or TSOI increase in the decade following SAI deployment, contrary to the forced
response. Interpreting the effects of SAI on permafrost only from the forced response (i.e.,
the ensemble means) may lead to a possibly erroneous conclusion that SAI could quickly
preserve permafrost and associated tipping points. Assessing the forced response is crit-
ical for improving our understanding of how SAI may affect different aspects of the cli-
mate system, but there is no guarantee that our future climate will resemble the out-
come of the ensemble mean. This study highlights the importance of accounting for nat-
ural variability when assessing the potential impact of SAI on the climate system, es-
pecially if SAI is deployed in an effort to prevent climate tipping points.

5 Open Research

The code for this analysis are available at https://github.com/eabarnes1010/
actm-sai-csu/tree/main/research/arise_arctic_climate. At publication this will
be converted to a permanent repository on Zenodo. The unprocessed monthly mean CESM2
ARISE-SAI-1.5 and SSP2-4.5 data that support this study are publicly available from
Richter (2022) and Mills et al. (2022).

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Figure 1.
Figure 2.
a) Canada peatland

b) Alaska Yedoma

c) Tibet Yedoma

d) Siberia Yedoma

e) Entire permafrost area

Annual maximum active layer depth, SSP2-4.5 (2034)
a) Maximum active layer depth trends, SSP2-4.5 (2025-2034)

b) Maximum active layer depth trends, ARISE-RAI-1.5 (2035-2044)
Figure 4.
Annual mean permafrost soil temperature, SSP2-4.5 (2034)

- a) Canada peatland
- b) Alaska Yedoma
- c) Tibet Yedoma
- d) Siberia Yedoma
- e) Entire permafrost area
Figure 5.
Figure 6.
Figure 7.
Figure 8.
Talik forms in SSP2-4.5 but not in ARISE-SAI-1.5

Talik forms in ARISE-SAI-1.5 but not in SSP2-4.5

Talik forms in both simulations by 2035
Figure 9.
Natural variability can mask forced permafrost response to stratospheric aerosol injection in the ARISE-SAI-1.5 simulations

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Key Points:

• Projected natural variability in permafrost fields in peatland and Yedoma regions can mask forced response to SAI
• Effect of SAI on active layer and soil temperature is only detectable after more than a decade of aerosol deployment
• Natural variability affects likelihood of reaching permafrost tipping points despite surface cooling effect of SAI

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Abstract

Stratospheric aerosol injection (SAI) has been proposed as a potential method for mitigating risks and impacts associated with anthropogenic climate change. One such risk is widespread permafrost thaw and associated carbon release. While permafrost has been shown to stabilize under different SAI scenarios, natural variability may lead to a wide range of projected climate futures under SAI. Here we use the 10-member ensemble from the ARISE-SAI-1.5 simulations to assess the spread in projected active layer depth and permafrost temperature across boreal permafrost soils and specifically in four peatland and Yedoma regions. The forced response in active layer depth and permafrost temperature quickly diverge between an SAI and non-SAI world, but individual ensemble members overlap for several years following SAI deployment. Projected permafrost variability may mask the forced response to SAI and make it difficult to detect if and when SAI is stabilizing permafrost in any single realization. We find that it may take more than a decade of SAI deployment to detect the effects of SAI on permafrost temperature and almost 30 years to detect its effects on active layer depth. Not only does natural variability make it more difficult to detect SAI’s influence, it could also affect the likelihood of reaching a permafrost tipping point. In some realizations, SAI fails to prevent a tipping point that is also reached in a non-SAI world. Our results underscore the importance of accounting for natural variability in assessments of SAI’s potential influence on the climate system.

Plain Language Summary

Injecting highly reflective particles into the upper atmosphere, or stratospheric aerosol injection (SAI), is a proposed climate intervention method for deliberately stabilizing or cooling the Earth’s temperature and preventing undesirable impacts of human-caused climate change, such as thawing permafrost. Permafrost can potentially release stored carbon into the atmosphere as carbon dioxide and methane that contributes to the greenhouse effect. Climate model simulations show that SAI could stabilize permafrost and prevent it from thawing, but that natural fluctuations in the Earth’s climate may cause a wide range of outcomes for future permafrost thaw depth and soil temperature. We show that, due to these natural climate fluctuations, it may take 10–30 years of SAI to clearly see its influence on permafrost thaw depth and temperature. Certain conditions that lead to runaway thaw and soil carbon release (i.e., tipping points) may also occur.
even if SAI successfully stabilizes the Earth’s globally averaged temperature. When weighing possible outcomes of proposed climate intervention strategies, it is important to consider the effects of natural climate fluctuations in assessing the pros and cons of different strategies.
1 Introduction

Despite efforts to reduce greenhouse gas emissions and meet the climate goals of the 2015 Paris Agreement, humanity is not on track to limit warming to 1.5°C above pre-industrial temperatures (Matthews & Wynes, 2022; Pihl et al., 2019). Climate intervention, or deliberate manipulation of the Earth’s climate, is gaining traction as a possible method for mitigating increasing temperatures as a result of anthropogenic activity. Stratospheric aerosol injection (SAI) is a form of solar climate intervention that aims to reduce incoming sunlight by injecting highly reflective sulfur dioxide (SO$_2$) particles into the stratosphere. The National Academies of Sciences, Engineering, and Medicine (NASEM) recommended the formation of an international transdisciplinary research program to improve our understanding of the feasibility and consequences of solar climate intervention strategies (NASEM, 2021) in light of observed impacts already attributable to the current degree of warming (Gulev et al., 2021). These observed impacts are not evenly distributed across the globe: the Arctic is warming several times faster than the global average (Rantanen et al., 2022), leading to concern that this warming may lead to tipping conditions that cause further runaway warming. Exceeding 1.5°C of warming may trigger certain cryospheric tipping conditions (Armstrong McKay et al., 2022; Lenton, 2012), adding urgency to evaluating the global and regional impacts of different SAI methods.

While most proposed SAI methods do not specifically target the poles, different potential SAI strategies may be effective at stabilizing Arctic Ocean surface temperatures (Richter et al., 2022), maintaining Arctic sea ice extent near present-day values (Hueholt et al., 2023; Jones et al., 2018; Kravitz et al., 2019), and, importantly for cryospheric tipping points, slow the rate of boreal permafrost thaw (Chen et al., 2020, 2023; H. Lee et al., 2019; W. Lee et al., 2023; Liu et al., 2023). The thawing of permafrost, or ground that is consistently frozen for at least two consecutive years, is a particular area of concern because of the carbon stored in permafrost soils. Recent estimates put the total carbon storage of boreal permafrost soils at 1,460-1,600 PgC (Hugelius et al., 2014; Schuur et al., 2015, 2018), or roughly twice the carbon stored in the atmosphere (Schuur et al., 2008). The type of permafrost soils affects the distribution of carbon. Peatlands contain a high density of organic material, but overall account for about 12% of permafrost carbon (Hugelius et al., 2020). Yedoma, or Pleistocene-age ice-rich permafrost that can be more than 40 m thick (Miner et al., 2022; Strauss et al., 2021; Tarnocai et al., 2009), is
not made of carbon-rich soils but is so deep that the total carbon inventory of Yedoma
is estimated to be \( \sim 20-30\% \) of the total boreal permafrost carbon stores (Schuur et al.,
2018; Strauss et al., 2013, 2017). As permafrost temperatures increase and permafrost
soils thaw, this stored carbon can be released into the atmosphere as CO\(_2\) or CH\(_4\).

Certain permafrost tipping conditions may be reached if permafrost thaws abruptly,
releasing large amounts of this stored carbon, or setting off a positive feedback within
the soil that accelerates the rate of thaw. While permafrost tipping points can be dif-
ficult to quantify and the likelihood of reaching them is uncertain (Lenton, 2012), par-
ticular conditions within permafrost soil make it more likely to reach tipping conditions.
The formation of talik, a layer of thawed soil within permafrost, can accelerate in-ground
respiration that in turn can lead to more permafrost thaw and soil carbon release (Devoie
et al., 2019; Parazoo et al., 2018). Taliks can also exist between permafrost and the base
of the active layer, or the ground layer that thaws and freezes each year. These taliks
grow by thawing the underlying permafrost (Connon et al., 2018), and since talik for-
mation can initiate a positive feedback of thawing and soil respiration, it may be con-
sidered a permafrost tipping condition.

SAI has been proposed as a strategy to prevent climate tipping points, but there
is uncertainty about how effective it might be and when we could detect its effects. It
is especially uncertain given the range of scenarios in which SAI could be deployed, from
stabilizing surface temperatures to rapidly cooling the planet (MacMartin et al., 2022).
The response to solar climate intervention strategies can vary greatly in fields such as
temperature and precipitation due to regional differences and natural variability within
the climate system (Barnes et al., 2022; Dagon & Schrag, 2017; Labe et al., 2023; Ricke
et al., 2010). Over short timescales, natural variability can mask a system’s response to
external forcings such as anthropogenic warming caused by greenhouse gas emissions (e.g.,
Deser et al., 2014), or anthropogenic cooling caused by SAI. This masking could hinder
efforts to determine what, if any, effect SAI has on a system in the short term. In a re-

gion as sensitive to temperature shifts as the Arctic, natural variability may lead to per-
mafrost thaw or talik formation even if SAI successfully stabilizes global mean surface


temperatures, thereby masking the forced response to SAI. Natural variability could also
accelerate how quickly SAI halts permafrost thaw, essentially helping the forced response
in preserving permafrost.
Large-scale solar climate intervention currently only exists in the realm of climate models that provide a range of possible future outcomes as a result of SAI deployment (e.g., Kravitz et al., 2011; Richter et al., 2022; Tilmes et al., 2018). Each possible outcome is represented by a single member of an "ensemble" of simulations. The ensemble mean defines the forced response to SAI deployment. Our future will be a combination of the forced response and the influence of natural variability, so the real world can be thought of as a single ensemble member. No studies have yet assessed the effect of SAI on permafrost in the context of internal variability, nor has there been work on how internal variability may affect the likelihood of reaching permafrost tipping conditions with or without SAI. Using output from every ensemble member of an SAI deployment simulation, here we seek to answer three main questions:

1. What is the range of certain boreal permafrost responses to SAI due to natural variability, especially in regions with high organic soil matter content?
2. Given a possible range of permafrost responses to SAI due to natural variability, how long might it take to detect the effect of SAI on permafrost in a single climate realization?
3. Could internal variability still push boreal permafrost into tipping conditions even if SAI successfully stabilizes global mean surface temperatures?

2 Materials and Methods

2.1 Climate intervention and control simulations

To explore the role of natural variability in the permafrost response to SAI, we use output from two parallel 10-member climate simulations. Both simulations were run with the fully-coupled Community Earth System Model version 2 (CESM2; Danabasoglu et al. (2020)) at a ∼ 1° 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. (2018, 2019)) as the land component. CLM5 has 25 soil levels down to almost 50 m, with soil level thickness ranging from 0.4 cm to 8.5 m. Up to the first 20 layers are soil and at least the bottom five layers are bedrock. Bedrock depth is variable (Lawrence et al., 2018), but is no deeper than 8.6 m. The vertical resolution of the soil layers increased from previous versions of the land model in order to more accurately simulate hydrological and permafrost
processes (Lawrence et al., 2019). The non-SAI control simulation uses the Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5; Riahi et al. (2017)) emissions scenario with five members run from 2015–2069 and five members run from 2015–2100.

The parallel simulation in which SAI is deployed is the Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection 1.5 experiment (ARISE-SAI-1.5; Richter et al. (2022)), which runs from 2035–2069 and also utilizes the SSP2-4.5 emissions scenario. In the experiment, sulfur dioxide aerosols are injected into the stratosphere at \(\sim 21.5 \text{ km}\) from 15°/30°N/S at 180°E starting in 2035. A feedback-control algorithm (Kravitz et al., 2017; MacMartin et al., 2014) within the simulations adjusts the volume and altitude of aerosols deployed from each location in order to meet three climate targets: to maintain global mean surface temperatures close to 1.5°C above pre-industrial levels, to maintain the north–south surface temperature gradient, and to maintain the equator-to-pole surface temperature gradient (Richter et al., 2022).

2.2 Permafrost data and tipping points

In CESM2, permafrost exists where there is an active layer. The depth of the active layer can be 0 m if the entire subsurface column is permafrost. A grid cell contains permafrost if the annual maximum active layer depth is shallower than the depth of the bedrock in that cell, which means that the active layer does not extend all the way to the bedrock and that some of the soil column is permafrost. To assess possible permafrost outcomes under SAI, we focus on changes to the annual mean active layer depth (ALT), the maximum annual active layer depth (ALTMAX), and annual mean soil temperature down to the bedrock in grid cells with permafrost (TSOI). We focus on ALT and ALTMAX because they are proxies for permafrost extent. A deeper active layer means the underlying permafrost is warmer and more degraded, and therefore is closer to thawing conditions. A deeper active layer also means more soil is exposed to microbial activity that releases stored carbon into the atmosphere through decomposition and respiration. We focus on TSOI because temperature directly informs us whether the upper soil levels are thawed. Most permafrost soil carbon is stored in the upper 3 m (Tarnocai et al., 2009), so thawing can potentially release much of the stored carbon. Increasing TSOI may also inform us whether permafrost is warming and degrading even if the active layer depth has not yet changed. There is an established relationship between mean annual
Figure 1. Regions selected to assess regional variability in permafrost fields. The boxed regions are 1) Canada peatland, 2) Alaska Yedoma, 3) Siberia Yedoma, and 4) Tibetan Plateau Yedoma.

Permafrost thaw in regions with relatively high organic soil matter content is of concern because of how much carbon can potentially be released into the atmosphere, so we assess the variability in future ALTMAX and TSOI in four sub-regions across the permafrost area. Each region, outlined in Figure 1, has observed high organic soil matter content: three of the four regions (Alaska, Siberia, and the Tibetan Plateau) have high concentrations of observed Yedoma permafrost (Strauss et al., 2021) and the fourth (Canada) is extensively covered by peatlands (Tarnocai et al., 2011; Wells et al., 2010).

Since all permafrost soils can release stored carbon, we also look at variability across the entire boreal permafrost region.

Finally, we consider the formation of talik, or perennially unfrozen soil within or above permafrost, to be a quantifiable precursor to a potential permafrost tipping point. Following the definition used by Parazoo et al. (2018) for talik in an Earth system model, the first year of talik formation is the first year when the monthly mean temperature of
any subsurface layer in a permafrost grid cell exceeds -0.5°C and remains above -0.5°C for at least two consecutive years. The cutoff of -0.5°C is similar to the -0.3°C temperature cutoff used by Farquharson et al. (2022) for assessing talik formation in a high-resolution numerical model (Jafarov et al., 2012).

### 2.3 Logistic regression model

To determine when the influence of SAI on permafrost-related fields might be detectable, we trained two logistic regression models to predict the probability that a map of annual mean active layer depth or permafrost temperature is from the ARISE-SAI-1.5 or SSP2-4.5 simulation. The maps are restricted to the boreal permafrost region from 50-84°N, which are flattened into arrays of 10656 units, or 37 latitude by 288 longitude points. The arrays are normalized to a mean of 0 and a standard deviation of 1 across all grid points. For each variable, the model receives these flattened and normalized arrays as input vectors. The output layer of the logistic regression models produce values that, when passed through the sigmoid activation function, can be interpreted as the probability that the map comes from either the ARISE-SAI-1.5 or SSP2-4.5 simulation. More information about the models’ architecture is in the Supplemental Information (Tables S1, S2). Each model is trained on seven ensemble members, validated on two, and tested on one. The models are trained on the full 35-year experiment (2035–2069).

To better understand which permafrost regions are most helpful for the logistic regression models to make their predictions, we also perform feature contribution analysis. Feature contribution is a method to improve interpretability of the logistic regression models by identifying which regions contributed to the prediction that a map came from either the ARISE-SAI-1.5 or SSP2-4.5 simulations. Contribution maps are created by multiplying the model weights by the annual mean input values for either ALT or TSOI at every grid point. Positive (negative) contributions are regions that drive the model toward predicting a map is from the ARISE-SAI-1.5 (SSP2-4.5) simulations. The more positive or negative the contribution of a particular point or region, the more ‘important’ that point or region is for driving the logistic regression model prediction toward either the ARISE-SAI-1.5 or SSP2-4.5 simulations.
3 Results

3.1 Natural variability in permafrost fields

We begin by evaluating projected natural and regional variability in the active layer and in soil temperature. Figure 2 shows time series of the annual maximum active layer depth (ALTMAX) in the four selected regions (Fig. 2a-d) and across the entire permafrost region (Fig. 2e) in the SSP2-4.5 (red dashed lines) and ARISE-SAI-1.5 (blue solid lines) simulations. We include a map of the ensemble mean ALTMAX in 2034 from the SSP2-4.5 simulation as reference for the spatial pattern of ALTMAX in the year before SAI deployment (center map, Fig. 2). There is a lot of regional variability between all five panels (note the panel scale differences), with the deepest ALTMAX in both simulations in Canada peatland (Fig. 2a) and the shallowest in Siberia Yedoma (Fig. 2d). The ensemble means of the two simulations (thick lines) diverge soon after SAI deployment in 2035, with the SSP2-4.5 ensemble mean ALTMAX getting deeper in response to increasing surface temperatures and the ARISE-SAI-1.5 ensemble mean either stabilizing or getting shallower in response to stabilizing surface temperatures. By 2045, the ensemble mean ALTMAX in SSP2-4.5 is 6–61 cm deeper than in ARISE-SAI-1.5 in all five regions, and 21–201 cm deeper in SSP2-4.5 than in ARISE-SAI-1.5 by the end of the simulations in 2069.

The individual ALTMAX ensemble members (thin lines) continue to overlap between the two simulations for several years after SAI deployment, indicating that internal variability may mask the forced response of permafrost to SAI and make it hard to distinguish one climate realization from another when it comes to an SAI vs non-SAI world. For example, the different realizations in the Alaska Yedoma region (Fig. 2b) exhibit a wide range of ALTMAX following SAI: there are some ensemble members in ARISE-SAI-1.5 where ALTMAX is deeper than in almost all the ensemble members in SSP2-4.5, and the ALTMAX time series never completely diverge between the two simulations. Only in Siberia Yedoma (Fig. 2d) and the entire permafrost region (Fig. 2e) do all the ARISE-SAI-1.5 realizations fully diverge from all the SSP2-4.5 realizations by 2069. While the overall trend in the simulations’ ensemble mean ALTMAX is clear, the interannual and internal variability inherent in the different ensemble members makes it difficult to discern the ALTMAX trends in the years immediately preceding and following SAI deployment in any single realization.
Figure 2. Time series of annual maximum active layer depth in SSP2-4.5 (red dashed lines) and ARISE-SAI-1.5 (blue solid lines) within a) Canada peatland, b) Alaska Yedoma, c) Siberia Yedoma, d) Tibet Yedoma, and e) the entire permafrost region. The regions in a-d are identified in Figure 1. Thin lines are individual ensemble members; thick lines are the ensemble means. The central map is the ensemble mean annual maximum active layer depth in SSP2-4.5 in 2034.
ALTMAX trends pre- and post-SAI deployment are highly variable by region and
by ensemble member. In the decade preceding SAI deployment (2025–2034; Fig. 3a) the
ALTMAX trend in ensemble member #3 is positive across Canada but almost entirely
negative across Siberia, while in ensemble member #10 the trends are positive in far east-
ern and western Russia. Regionally the active layer can get deeper or shallower (trends
for all ensemble members are in Fig. S1 in the Supplemental Information), despite a gen-
erally positive ALTMAX trend in the forced response (see the ensemble mean, or EM),
especially along the lowest latitude of the permafrost region.

ALTMAX trends are also highly variable in the decade following SAI deployment
(2035–2044; Fig. 3b). The active layer gets deeper in far eastern and western Russia
in ensemble member #3, but otherwise exhibits similar ALTMAX trends as the previ-
ous decade (Fig. 3a). In contrast to ensemble member #3, ensemble member #10 shows
decreasing ALTMAX trends across the entire permafrost region, with the largest trends
in eastern Canada and near the Hudson Bay. While not all ensemble members have dif-
f ering trends pre- and post-deployment (Figs. S1, S2), ensemble members #3 and #10
are examples of how natural variability could lead to SAI being perceived as ‘success-
ful’ at preventing permafrost thaw (i.e., a positive ALTMAX trend into a negative trend)
or as ’failing’ to prevent permafrost thaw (i.e., a negative or neutral ALTMAX trend into
a positive trend). Compared to trends in individual ensemble members, the ensemble
mean ALTMAX trends are relatively small, except for along the margins of the permafrost
region.

As for ALTMAX (Fig. 2), the annual mean time series of the permafrost temper-
ature (TSOI) in the four regions with high organic soil matter content (Fig. 4a-d) and
across the entire permafrost region (Fig. 4e) exhibit large regional and natural variabil-
ity. As expected, the warmest permafrost temperatures are at the lowest latitude of the
permafrost extent, and get colder with increasing latitude (center map, Fig. 4). While
the ensemble mean annual mean TSOI (thick lines) increases in all regions from 2015–
2069 in SSP2-4.5 (red dashed lines), permafrost reaches the warmest temperatures in Canada
peatland (Fig. 4a). TSOI either stabilizes or decreases in all regions in ARISE-SAI-1.5
(blue solid lines), but there is a large range in projected temperature. In a single year,
TSOI can span several degrees between individual ensemble members. Similar to ALT-
MAX, the TSOI time series in ARISE-SAI-1.5 and SSP2-4.5 only fully diverge in Siberia
Yedoma (Fig. 4d) and when averaged over the entire permafrost region (Fig. 4e). Oth-
Figure 3. Decadal trends in maximum active layer depth in ensemble members #8 and #9 and the 10-member ensemble mean (EM) in a) SSP2-4.5 from 2025–2034, or the decade immediately preceding SAI deployment, and b) ARISE-SAI-1.5 from 2035–2044, or the decade immediately following SAI deployment. Trends are calculated using least squares regression. Purple (orange) means the active layer gets deeper (shallower).
Figure 4. As in Figure 2 except for the annual mean permafrost soil temperature.

erwise it is difficult to distinguish the temperature time series between simulations, es-

cially in Alaska Yedoma (Fig. 4b).

Given the large spread in TSOI between ensemble members (Fig. 4), it is perhaps

unsurprising that there is also a large spread in pre- and post-SAI deployment decadal

temperature trends (Figs. 5, S3, S4). Most ensemble members, including #3 and #10,

show warming trends of > 0.3°C decade\(^{-1}\) in the decade leading up to SAI deployment

(Fig. 5a, S3), but temperature trends are highly regionally variable. Most of Canada strongly

warms in ensemble member #3 from 2025–2034 (Fig. 5a), and continues to warm in 2035–

2044 post-SAI deployment (Fig. 5b). In ensemble member #10, however, temperature
trends go from warming to a strong cooling trend across the entire permafrost region,
indicating that SAI may be perceived as ‘successful’ at preventing the permafrost soil
temperature from increasing. Along with variability in 2035–2044 temperature trends
between ensemble members (Fig. S4), there is a lot of spatial heterogeneity in most en-
Assemble members’ TSOI trends, resulting in a near-zero ensemble mean trend across the entire permafrost region.

3.2 Detecting permafrost response to stratospheric aerosol injection

Given the large spread in permafrost fields driven by internal climate variability in both the SSP2-4.5 and ARISE-SAI-1.5 simulations, we next move to trying to quantify how long it might take to tell if or when SAI is influencing permafrost. To do this, we use logistic regression models that learn the patterns of active layer depth and soil-to-bedrock temperature that occur in an SAI and non-SAI world. How long does it take the models to confidently predict which simulation a map of annual mean ALT or TSOI comes from? For ALT, the model correctly predicts which maps belong to which simulation starting in 2060 (Fig. 6a). That is, it takes almost 30 years of SAI deployment for the model to be confident and accurate in its prediction that a map of annual mean

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**Figure 5.** As in Figure 3 except for the annual mean permafrost soil temperature.
active layer depth comes from an SAI or non-SAI world. Model confidence is nearly 100% for the SSP2-4.5 predictions (red line) by 2050, but only reaches 100% confidence for the ARISE-SAI-1.5 predictions (blue line) at the end of the simulations. It takes fewer years of SAI deployment for the model to identify the correct simulations for maps of annual mean TSOI (Fig. 6b). The model achieves perfect accuracy for both simulations starting in 2051, and reaches near-100% confidence in its predictions for both the SSP2-4.5 and ARISE-SAI-1.5 maps in 2066.

Certain regional patterns of ALT and TSOI help the logistic regression models achieve perfect accuracy in their predictions, and we use contribution maps to identify these patterns. For ALT predictions, the areas that provide the largest contribution are found along the lowest latitude of the permafrost region (Fig. 7a). The contributions to the model prediction in southern Alaska and southeastern Russia are positive, meaning that the ALT information here contributed to the logistic regression model predicting that the map came from the ARISE-SAI-1.5 simulation. Otherwise, with the exception of small negative contributions around the Tibet Yedoma region, ALT in the rest of the permafrost region has a negligible contribution to the model prediction.

Temperature contributions to the logistic regression model predictions are far more heterogeneous than ALT contributions and come from the entire permafrost region (Fig. 7b). The largest positive contributions, or the regions that make a map more likely to be from the ARISE-SAI-1.5 simulations, are also in the same regions with positive ALT contributions (Fig. 7a). Regions that push the prediction towards the SSP2-4.5 simulations (largest negative contributions) are concentrated near the Tibet Yedoma region. Most of Canada, except for grid cells along the southern margin of permafrost, also contributes to the logistic regression model predicting that a map of TSOI comes from SSP2-4.5.

### 3.3 Permafrost tipping points reached through natural variability

Since there is a large range of outcomes for active layer thickness and soil temperature in SAI and non-SAI worlds, there may also be a large range of outcomes for a key climatic concern from permafrost thaw - namely, the formation of talik that could lead to widespread, accelerated, and irreversible thaw and carbon release. The difference in the timing of talik formation, or the first year that permafrost reaches a potential tip-
Figure 6. Logistic regression model confidence for the single testing member (bold line) and the training and validation members (thin lines) of the SSP2-4.5 (red) and ARISE-SAI-1.5 (blue) simulations for annual mean maps of a) active layer depth and b) soil temperature down to the bedrock in grid cells with permafrost.
Figure 7. Contribution maps (input × weights) for the ARISE-SAI-1.5 testing ensemble member averaged over 2035–2069 for (a) active layer depth and (b) permafrost temperature logistic regression model predictions.
Talik forms in SSP2-4.5 but not in ARISE-SAI-1.5. Talik forms in ARISE-SAI-1.5 but not in SSP2-4.5. Talik forms in both simulations by 2035.

Figure 8. Difference in the timing of projected talik formation in each ensemble member, SSP2-4.5 minus ARISE-SAI-1.5. Cyan cells are where talik forms in an SSP2-4.5 ensemble member by 2069 but never forms in the corresponding ARISE-SAI-1.5 ensemble member. Yellow cells are where talik forms in an ARISE-SAI-1.5 ensemble member by 2069 but never forms in the corresponding SSP2-4.5 ensemble member. Black cells are where talik exists by 2035 in the ensemble member for both simulations. The final map is the difference in the timing of projected talik formation in the 10-member ensemble mean (EM).
Figure 9. Probability that talik formation is prevented in all ten ARISE-SAI-1.5 ensemble members compared to corresponding SSP2-4.5 ensemble members.
Regional and natural variability in permafrost lead to a range of outcomes in projected talik formation. Some regions are clearly more susceptible to reaching a permafrost tipping point even under SAI, due to the influence of natural variability (darker colored cells in Fig. 9), while some regions appear to be robustly resistant to reaching tipping conditions - i.e., ARISE-SAI-1.5 completely prevents talik formation relative to SSP2-4.5 (yellow cells in Fig. 9), not just delays it. Outside of the degraded permafrost cells where talik already exists by 2035 (black cells; Fig. 8, Fig. 9), talik formation is prevented most often in north-central Canada, and least often prevented in parts of Russia. Importantly, talik formation is prevented under the ARISE-SAI-1.5 scenario in at least one ensemble member in every grid cell where talik did not already exist by 2035. That is, outside of the black grid cells in Figure 9, the likelihood that SAI prevents talik formation in at least one ensemble member compared to the corresponding SSP2-4.5 ensemble member is at least 10%. There are a few scattered cells where the likelihood of talik prevention is 100%, but these cells are not clustered together in any particular region.

4 Discussion and Conclusions

Overall our results show that natural climate variability leads to a range of projected outcomes for ALTMAX and TSOI with and without SAI. In four regions with high organic soil matter content, natural variability in both ALTMAX and TSOI makes it difficult to distinguish between individual ensemble members in the ARISE-SAI-1.5 and SSP2-4.5 simulations for several years after SAI deployment. The overlap between the simulations suggests that it may take many years of aerosol deployment before SAI has a noticeable effect on permafrost Yedoma and peatland. The ensemble means of the two simulations do diverge within a few years of SAI deployment. These results support previous work that SAI prevents permafrost thaw in the forced response (H. Lee et al., 2019; W. Lee et al., 2023), though to our knowledge this is the first work to assess the extent to which natural variability may mask the forced permafrost response to SAI.

There is also a range in the projected timing of talik formation, although natural variability could push boreal permafrost into tipping conditions even under SAI, but this is highly regionally dependent. All ensemble members are in agreement that the southern margin of permafrost already contains talik by 2035, and therefore permafrost along the southern margin has reached a tipping point regardless of any SAI influence. That is, the southernmost permafrost is very likely to be lost no matter what impact SAI has.
on the rest of the permafrost region under ARISE-SAI-1.5. Most of the Alaska Yedoma
region already contains talik by 2035 (Fig. 9) and therefore may be on the verge of widespread
thaw. The pre-SAI talik may explain why ALTMAX appears to stabilize and become
shallower over time in the Alaska Yedoma region (Fig. 2b): the deepest ALTMAX is over
the warmest and most degraded permafrost and once the warm permafrost thaws, the
remaining permafrost is more stable and exists under a shallower active layer. All mem-
bers are also in agreement that SAI as deployed by ARISE-SAI-1.5 prevents the major-
ity of pan-Arctic talik formation outside of the southern margin.

Why is the SAI influence detectable earlier on soil temperature than on active layer
depth? It may be because temperature responds faster to increasing surface tempera-
tures in SSP2-4.5 than the active layer does. Since permafrost temperature remains be-
low freezing, but does get warmer in SSP2-4.5 (Fig. 2), the soil may not be thawing quickly
enough to increase the active layer depth. Permafrost temperature may be changing rapidly
enough in the SSP2-4.5 simulations to distinguish a map of TSOI between the two sim-
ulations earlier than a map of ALT. TSOI is also changing everywhere, which is why con-
tributions to the TSOI predictions come from the entire permafrost region (Fig. 7b). Once
permafrost thaws and the active layer deepens, it is difficult to refreeze permafrost and
reduce the active layer depth. This is particularly difficult if talik has formed between
the permafrost and base of the active layer (Connon et al., 2018). Once the permafrost
is completely thawed, there is no more ALT in the SSP2-4.5 simulations. The logistic
regression model uses the pattern of ALT loss to differentiate between the ARISE-SAI-
1.5 and SSP2-4.5 simulations, which is why the ALT prediction contributions are only
from the permafrost margins (Fig. 7a): if a map of ALT has an active layer on the south-
ern permafrost margin, then it belongs to the ARISE-SAI-1.5 simulation.

Although our results come from a single idealized SAI scenario that is simulated
by one Earth system model, models are the best available tools for assessing possible im-
pacts of SAI. Models are the only way to study climate projections, and using ensem-
bles of different climate realizations also gives us insight into how natural variability may
affect climate outcomes. Different processes can be easier or harder to simulate in mod-
els, however. Permafrost is difficult to simulate because it is affected by subgrid-scale
processes that are not yet represented in the current generation of climate models. We
do not specifically identify subaerial talik (formed below a lake), which is a common lo-
cation for talik to be found in observations (Devoie et al., 2019), and therefore may be
underestimating the extent of talik formation in CESM2. It is important to note that
talik formation is a precursor to widespread permafrost thaw in observations (Connon
et al., 2018; Devoie et al., 2019), but the 35-year simulation may be too short to deter-
mine if a permafrost tipping point actually occurs. Permafrost outcomes may be very
different under an SAI scenario that reduces global mean surface temperature instead
of stabilizing it at 1.5°C, such as those considered by MacMartin et al. (2022).

Our results indicate that SAI as simulated by the ARISE-SAI-1.5 scenario gener-
ally preserves permafrost and stabilizes both ALTMAX and TSOI at near-2035 levels,
though it may take one to three decades of SAI deployment to robustly detect its influ-
ence on both permafrost fields. Natural variability may lead to a climate future where
ALTMAX or TSOI increase in the decade following SAI deployment, contrary to the forced
response. Interpreting the effects of SAI on permafrost only from the forced response (i.e.,
the ensemble means) may lead to a possibly erroneous conclusion that SAI could quickly
preserve permafrost and associated tipping points. Assessing the forced response is crit-
ical for improving our understanding of how SAI may affect different aspects of the cli-
mate system, but there is no guarantee that our future climate will resemble the out-
come of the ensemble mean. This study highlights the importance of accounting for nat-
ural variability when assessing the potential impact of SAI on the climate system, es-
pecially if SAI is deployed in an effort to prevent climate tipping points.

5 Open Research

The code for this analysis are available at https://github.com/eabarnes1010/
actm-sai-csu/tree/main/research/arise_arctic_climate. At publication this will
be converted to a permanent repository on Zenodo. The unprocessed monthly mean CESM2
ARISE-SAI-1.5 and SSP2-4.5 data that support this study are publicly available from
Richter (2022) and Mills et al. (2022).

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Supporting Information for "Natural variability masks forced permafrost response to stratospheric aerosol injection in the ARISE-SAI-1.5 simulations"

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Introduction

Text S1.

The Supplemental Information provides more information about the logistic regression models’ architecture (Tables 1, 2), and decadal trends in the maximum active layer depth (Figs. S1, 2) and integrated top 3 m soil temperature (Figs. S3, 4) for all 10 ensemble members and the ensemble mean of the SSP2-4.5 and ARISE-SAI-1.5 simulations.

References

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Table S1. Active layer depth (ALT) logistic regression model parameters

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Table S2. Soil temperature down to the bedrock in permafrost cells (TSOI) logistic regression model parameters

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Figure S1. Decadal trends in maximum active layer depth (ALTMAX) in all 10 ensemble members and the 10-member ensemble mean (EM) in SSP2-4.5 from 2025–2034, or the decade immediately preceding SAI deployment. Trends are calculated using least squares regression. Purple (orange) means the active layer gets deeper (shallower).
Figure S2. Decadal trends in maximum active layer depth (ALTMAX) in all 10 ensemble members and the 10-member ensemble mean (EM) in ARISE-SAI-1.5 from 2035–2044, or the decade immediately following SAI deployment. Trends are calculated using least squares regression. Purple (orange) means the active layer gets deeper (shallower).
Figure S3. Decadal trends in permafrost temperature (TSOI) in all 10 ensemble members and the 10-member ensemble mean (EM) in SSP2-4.5 from 2025–2034, or the decade immediately preceding SAI deployment. Trends are calculated using least squares regression.
Figure S4. Decadal trends in permafrost temperature (TSOI) in all 10 ensemble members and the 10-member ensemble mean (EM) in ARISE-SAI-1.5 from 2035–2044, or the decade immediately following SAI deployment. Trends are calculated using least squares regression.