**SANDIA REPORT**
SAND2024-13005
Printed September 2024

Sandia National Laboratories

# Preliminary Screening of Features, Events, and Processes for an Arctic-Focused Climate Intervention Performance Assessment

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## ABSTRACT

Geoengineering, the deliberate large-scale intervention in Earth's climate system, holds significant potential in the rapidly warming Arctic, where temperatures currently rise at more than twice the global average, accelerating ice sheet and permafrost melt. This contributes to global sea-level rise and releases methane, a potent greenhouse gas. Strategies like solar radiation management (SRM) and carbon dioxide removal (CDR) could mitigate these effects; for instance, SRM techniques aim to reflect a portion of the sun's energy back into space, potentially slowing ice melt and stabilizing permafrost. However, geoengineering in the Arctic faces challenges, including potential unintended consequences on the fragile ecosystem, disruption of local weather patterns, and impacts on indigenous communities. Effective governance requires robust international cooperation, environmental impact assessments, and regulatory frameworks. Despite these challenges, geoengineering's potential benefits make it a critical research area. This report explores application of the Performance Assessment (PA) methodology to Arctic Climate Intervention, providing an initial screening of relevant features, events, and processes (FEPs). At the core of the PA approach is the identification and evaluation of FEPs that could impact the performance of the intervention scheme. Here we provide an initial screening of FEPs to consider in the application of PA to Arctic Climate Intervention.

## ACKNOWLEDGEMENTS

The authors thank Lauren Wheeler for her leadership as the PI of the Performance Assessment for Climate Intervention (PACI) project. The authors would like to acknowledge Erik Webb for his guidance which influenced the selection of Performance Assessment in this project, Benjamin Wagman for his review of the report. The authors would also like to acknowledge the LDRD Office and Earth Science Research Foundation for their support.

This work was funded by the Laboratory Directed Research and Development (LDRD) program at Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by the National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the United States Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis.

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## EXECUTIVE SUMMARY

In order to facilitate decision making on strategies for climate intervention, there is a need to enable decision makers with the information on the climate impacts of greatest importance, as well as the potential impacts of each decision across different sectors. We have previously considered one possible framework for assisting decision makers focused on climate intervention by adapting an existing assessment framework: Performance Assessment (PA) methodology, a risk assessment framework pioneered by the Nuclear Waste Disposal community. At the core of the PA approach for waste repositories is the identification and evaluation of relevant features, events, and processes (FEPs) that could impact the repository's performance. Here we consider the application of PA to Arctic Climate Intervention (ACI) and provide an initial screening of features, events, and processes (FEPs) to be included in a potential PA model (i.e., those that could impact the performance of the intervention scheme).

Here we have considered a hypothetical, currently-undefined PA for Arctic Climate Intervention with no performance goals defined. We have assumed that such a PA would be performed using analysis tools similar to current climate models that would yield outputs relevant to climate changes, such as global temperatures. Although a complete FEPs analysis was not completed, we outline the necessary steps to complete the analysis.

In this analysis, 227 FEPs were initially identified, but when duplicates were eliminated, a total of 188 independent FEPs were identified. The 188 FEPs consisted of 103 features, 11 events, and 74 processes identified. A total of 94 FEPs were identified as Atmospheric, 40 as Oceanic, 55 as Land, and 23 as Other (16 FEPs were categorized in two or more categories).

For this preliminary FEPs database, the analysis focused on the 94 Atmospheric FEPs due to time constraints. Each of the Atmospheric FEPs is described in some detail, including its characteristics, potential mechanisms of action, and the context in which it might occur. To complete this analysis, a similar discussion of each of the Oceanic, Land, and Other FEPs should be done.

## ACRONYMS AND TERMS

| Acronym/Term | Definition |
|---|---|
| AA | Arctic amplification |
| AIE | aerosol indirect effect |
| AOD | aerosol optical depth |
| CDR | carbon dioxide removal |
| CI | climate intervention |
| FEPs | features, events, and processes |
| GCM | general circulation model |
| IR | infrared |
| ITCZ | inter-tropical convergence zone |
| MCB | marine cloud brightening |
| PA | performance assessment |
| SAI | stratospheric aerosol injection |
| SRM | solar radiation management |
| SSP | shared socioeconomic pathway |
| WIPP | Waste Isolation Pilot Plant |
| | |
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| $H_2SO_4$ | sulfuric acid |
| $(NH_4)_2SO_4$ | ammonium sulfate |
| $OH^-$ | hydroxyl |
| $SO_2$ | sulfur dioxide |
| | |
| $W/m^2$ | watts per square meter |

# 1. INTRODUCTION

Geoengineering, the deliberate large-scale intervention in the Earth's climate system to counteract climate change, holds significant potential, particularly in the Arctic region. The Arctic is experiencing rapid warming, with temperatures rising at more than twice the global average [1, 2], leading to the accelerated melting of ice sheets and permafrost [2-4]. This not only contributes to global sea-level rise but also releases vast amounts of methane, a potent greenhouse gas, from thawing permafrost [4]. Geoengineering strategies, such as solar radiation management (SRM) and carbon dioxide removal (CDR), could be employed to mitigate these effects [5-7]. SRM techniques, like stratospheric aerosol injection, aim to reflect a portion of the sun's energy back into space, thereby cooling the planet. In the Arctic, this could slow ice melt and stabilize permafrost, potentially averting some of the most catastrophic feedback loops associated with climate change [2-5, 8, 9].

However, the implementation of geoengineering in the Arctic is fraught with challenges and uncertainties. The region's unique and fragile ecosystem could be disproportionately affected by unintended consequences of such interventions. For instance, altering the albedo (reflectivity) of ice and snow through SRM could disrupt local weather patterns and marine ecosystems, impacting indigenous communities and wildlife [2, 6, 10, 11]. Additionally, the governance of geoengineering efforts poses significant ethical and political dilemmas, as the Arctic is an international space with multiple stakeholders. Robust international cooperation, comprehensive environmental impact assessments, and stringent regulatory frameworks would be essential to ensure that geoengineering efforts do not cause more harm than good [12, 13]. Despite these challenges, the potential benefits of geoengineering in mitigating Arctic climate change make it a critical area of research and discussion in the quest to combat global warming.

Policy makers need information to be able to make decisions regarding how to address climate change and given tools to facilitate making their decision(s). In order to facilitate decision making on strategies for climate intervention, there is a need to enable decision makers with the information on the climate impacts of greatest importance, as well as the potential impacts of each decision across different sectors. We have previously considered one possible framework for assisting decision makers focused on climate intervention by adapting an existing assessment framework [14]: Performance Assessment (PA) methodology, a risk assessment framework pioneered by the Nuclear Waste Disposal community [15] (Figure 1). Here we consider the application of PA to Arctic Climate Intervention and provide an initial screening of features, events, and processes (FEPs) to be included in a potential PA model.

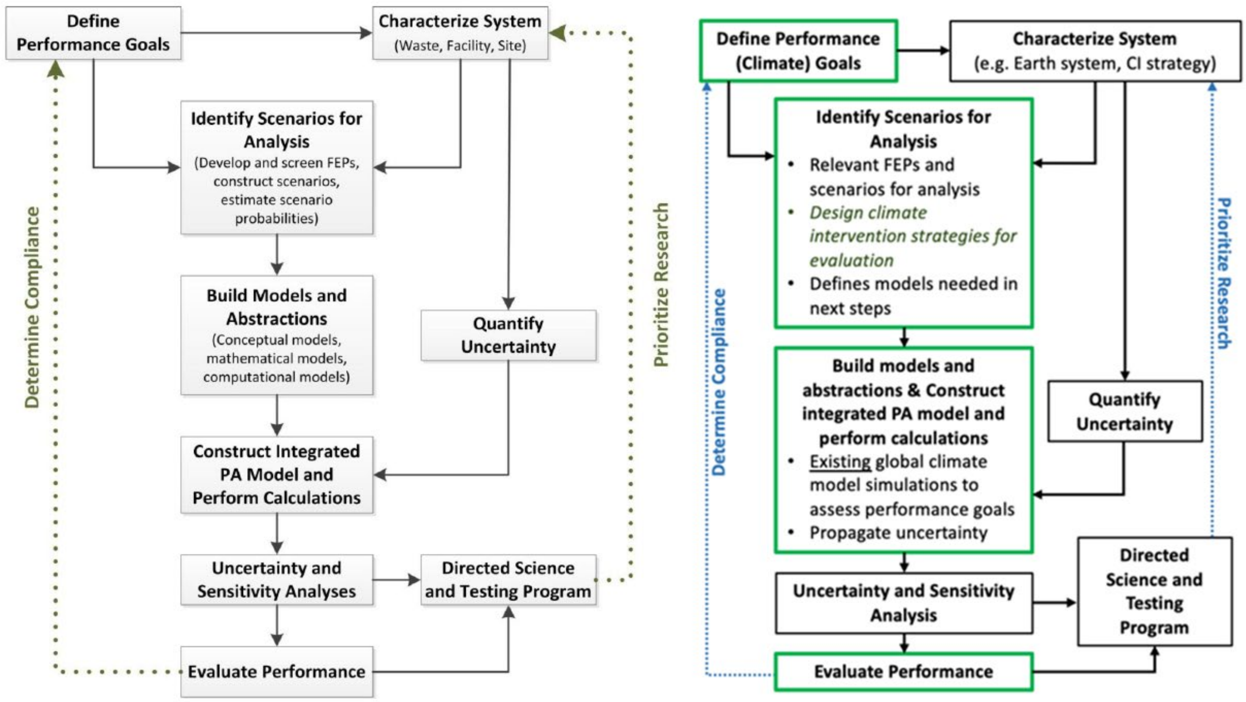


**Figure 1. (Left) PA methodology for nuclear waste disposal (reproduced from [15]). (Right) PA methodology as outlined in [15] modified for climate intervention. Areas where a PA framework focused on climate intervention may modify or differ from the PA framework applied to nuclear waste management are outlined in green.**

# 2. PA APPROACH

The performance assessment (PA) approach is a systematic and comprehensive method used to evaluate the long-term safety and effectiveness of geological repositories for the disposal of radioactive waste, such as the Waste Isolation Pilot Plant (WIPP) in New Mexico and the proposed Yucca Mountain repository in Nevada [15]. This approach involves a detailed analysis of the repository system's ability to contain and isolate radioactive waste over extended periods, often spanning thousands to millions of years. The primary purpose of PA is as a tool that provides, for a given set of identified system FEPs, estimates of risks to human health and the environment [16].

At the core of the PA approach is the identification and evaluation of relevant FEPs that could impact the repository's performance [17]. Features refer to the physical and chemical characteristics of the repository and its surrounding environment, such as geological formations, hydrology, and geochemistry. Events are discrete occurrences that could affect the repository, including natural phenomena like earthquakes, volcanic activity, and human activities such as drilling or mining. Processes encompass ongoing natural and engineered mechanisms, such as corrosion of waste containers, groundwater flow, and radionuclide transport.

To assess the impact and probability of these FEPs, the PA approach employs a combination of deterministic and probabilistic methods [18]. Deterministic analysis involves creating detailed models of the repository system and simulating its behavior under specific scenarios. This helps to understand the potential consequences of individual FEPs. Probabilistic analysis, on the other hand, quantifies the likelihood of various FEPs occurring and their combined effects on the repository's performance. By integrating these methods, the PA approach can provide a comprehensive risk assessment that accounts for both the severity and probability of different FEPs.

The results of the PA are used to inform decision-making and regulatory compliance [18]. For instance, the WIPP PA demonstrates that the repository could safely contain transuranic waste for 10,000 years, leading to its certification by the Environmental Protection Agency (EPA) [19]. Similarly, the Yucca Mountain PA aimed to show compliance with regulatory standards for high-level radioactive waste disposal [15]. By rigorously evaluating the potential risks and uncertainties associated with geological repositories, the PA approach ensures that these facilities can be designed and operated to protect public health and the environment over the long term.

The FEPs screening process is a critical component of the PA approach for evaluating the long-term safety of geological repositories for radioactive waste. This process systematically identifies, categorizes, and evaluates the various factors that could influence the repository's performance over time [17]. The primary objective of FEPs screening is to ensure that all relevant factors are considered and that those with significant potential impacts are thoroughly analyzed in the PA. The screening process typically involves several key steps:

1. **Identification of FEPs**: The first step in the FEPs screening process is to compile a comprehensive list of potential features, events, and processes that could affect the repository. This involves reviewing scientific literature, historical data, expert judgment, and regulatory requirements. The list includes natural phenomena (e.g., earthquakes, volcanic activity), human activities (e.g., drilling, mining), and intrinsic properties of the repository system (e.g., geological formations, hydrological conditions, waste characteristics).
2. **Categorization and Description**: Once identified, FEPs are categorized based on their nature and potential impact on the repository. Categories might include geological,

hydrological, biological, chemical, and human-induced factors. Each FEP is then described in detail, including its characteristics, potential mechanisms of action, and the context in which it might occur.

3. **Screening Criteria Development**: To evaluate the relevance and significance of each FEP, specific screening criteria are established. These criteria typically consider factors such as the likelihood of occurrence, the magnitude of potential impact, the timescale over which the FEP might act, and the degree of uncertainty associated with the FEP. Regulatory guidelines and safety standards also play a crucial role in defining these criteria.
4. **Evaluation and Screening**: Each FEP is systematically evaluated against the screening criteria. This involves qualitative and quantitative assessments to determine whether a FEP should be included in the detailed PA. FEPs that are deemed highly unlikely to occur or have negligible impact on the repository's performance may be screened out. Conversely, FEPs with significant potential impacts or higher probabilities of occurrence are retained for further analysis.
5. **Documentation and Justification**: The results of the screening process are thoroughly documented, including the rationale for including or excluding each FEP. This documentation provides transparency and traceability, ensuring that the screening decisions are well-justified and can be reviewed by stakeholders, regulators, and independent experts.
6. **Integration into PA Models**: FEPs that pass the screening process are integrated into the PA models. These models simulate the behavior of the repository system under various scenarios, incorporating the effects of the retained FEPs. The models help to predict the long-term performance of the repository and assess its compliance with safety standards.

The FEPs screening process is iterative and may be revisited as new information becomes available or as part of periodic reviews of the PA. By systematically identifying and evaluating the factors that could influence the repository's performance, the FEPs screening process ensures that the PA provides a comprehensive and robust assessment of the repository's long-term safety.

# 3. APPLICATION OF PA TO ARCTIC CLIMATE INTERVENTION

Screening FEPs for Arctic Climate Intervention involves a meticulous and systematic approach to ensure that all relevant factors are considered and that those with significant potential impacts are thoroughly analyzed. Here we have considered a hypothetical, currently undefined PA for Arctic Climate Intervention with no performance goals defined. We have assumed that such a PA would be performed using analysis tools similar to current climate models that would yield outputs relevant to climate changes, such as global temperatures. Although a complete FEPs analysis was not completed, we outline the necessary steps to complete the analysis.

The first step in an Arctic PA FEPs analysis is to compile a comprehensive list of *potential* FEPs that could influence the outcomes of Arctic Climate Intervention strategies. This involves a review of current literature examining existing scientific research, historical data, and case studies related to Arctic climate dynamics and geoengineering techniques. The FEPs list developed here was derived based on a list of references generated for an FY23 literature survey of research done on Arctic Climate Intervention. Although this approach likely resulted in the identification of most of the relevant, impactful FEPs, a more thorough review of Arctic climate research should be undertaken to complete the FEPs analysis.

The reference list was split into two lists with each of the authors charged with identifying Arctic-related FEPs and documenting the source of at least the first mention of each FEP. In many cases, FEPs were identified in multiple references, but this was not done comprehensively, so the table of FEPs (Table 1) should not be considered inclusive of all FEP-reference pairs. All FEPs identified through the literature search, no matter how borderline-relevant to Arctic climate change, were kept in the process up to this point. Each FEP was identified as a feature (F), event (E), or process (P).

The two lists generated by the two authors were combined, removing duplicates. The remaining FEPs were then categorized based on four broad categories (or combination of categories). Categories included:

- **Atmospheric:** These FEPs are primarily associated with the atmosphere (above the surface) and include examples such as changes in albedo, cloud formation, and atmospheric circulation patterns.
- **Oceanic**: These FEPs are primarily associated with the oceans and include examples such as changes in ocean circulation patterns, chemistry, sea ice formation, and sea level.
- **Land**: These FEPs are primarily associated with land or subsurface and include examples such as changes in permafrost, snow cover, biodiversity, and surface temperature.
- **Other**: These FEPs are not included in the other three categories and include examples such as political, social, and economic factors.

In this analysis, 227 FEPs were initially identified, but when duplicates were eliminated, a total of 188 independent FEPs were identified. The 188 FEPs consisted of 103 features, 11 events, and 74 processes identified. A total of 94 FEPs were identified as Atmospheric, 40 as Oceanic, 55 as Land, and 23 as Other (16 FEPs were categorized in two or more categories). When numbering the independent FEPs, only one prefix is specified. An "A" prefix is given to any FEP identified under the Atmospheric category (93 cases). Then 27 FEPs were specified as Oceanic ("O" prefix), 44 as Land ("L" prefix), and 23 as Other ("X" prefix).

For this preliminary FEPs database, the analysis focused on the 94 Atmospheric FEPs due to time constraints. In some cases, the Atmospheric FEPs were grouped into subcategories based on whether they were closely related and could easily be discussed together. For example, 14 Atmospheric FEPs were subcategorized under "Cloud Effects" and discussed together.

Each of the Atmospheric FEPs is described below in some detail, including its characteristics, potential mechanisms of action, and the context in which it might occur. To complete this analysis, a similar discussion of each of the Oceanic, Land, and Other FEPs should be done.

Typically, specific screening criteria are established to evaluate the relevance and significance of each FEP. FEPs that are deemed highly unlikely to occur or have negligible impact may be screened out, while those with significant potential impacts or higher probabilities of occurrence are retained for further analysis. In this analysis, no performance criteria have been defined (either by regulation or internally), so no formal FEPs screening could be performed. The performance criteria would be used to judge whether a given FEP was quantitatively relevant. Additionally, without a specified probability for whether a FEP would be "likely" to occur, no formal screening could be done.

Instead, informal, tentative screening decisions were made based on whether a FEP would likely be relevant to Arctic Climate Intervention. Because the initial FEPs identification process was used to identify FEPs relevant to Arctic Climate Intervention, and no quantitative analyses were performed to screen out FEPs, nearly all of the 188 independent FEPs were screened in. Two FEPs were screened as "Undetermined" based on high uncertainty for whether it would occur (A83, Leakage of Artificial Carbon Dioxide Reservoirs; further analysis is needed) or dependence on whether a specific intervention strategy is employed (A84, Sea Spray Engineering). One FEP (A85, Hurricane Strength) was screened-out as, even though it was borderline-relevant for climate modeling, it would almost certainly not be relevant to Arctic climate due to the limited influence of hurricanes on polar climate.

**Table 1. Summary of Steps Taken and Steps Remaining in FEPs Analysis**

| FEP Category | FEPs Identification from Ref | FEPs Screening In/Out | Number of FEPs Identified | FEPs Descriptions |
|---|---|---|---|---|
| Atmospheric | Y | Y | 94 | Y |
| Oceanic | Y | N | 40 | N |
| Land | Y | N | 55 | N |
| Other | Y | N | 23 | N |

# 4. PRELIMINARY SCREENING OF ATMOSPHERIC FEPS

The following screening of FEPs for Arctic Climate Intervention resulted from the analysis of available literature focused on Arctic climate and climate modeling. It was a "conservative" assessment, meaning that, when it was unclear whether a FEP should be screened-in, it was screened-in. This approach was used given that no performance criteria have been prescribed. The screening has been limited to only Atmospheric FEPs due to time constraints. In some cases, FEPs have been grouped together when it aids discussion. Atmospheric FEPs are numbered A1-A94 and are each given a designation of F (feature), E (event), or P (process) following the name of the FEP. Key references are provided for each FEP or group of FEPs. The attached spreadsheet contains a more extensive list of relevant references for each FEP.

## Stratospheric Aerosol Injection: Timing

***(A1) FEP Title: Start Date for Intervention [E]***
***(A2) FEP Title: Planned Injection Stopping Point [E]***
***(A3) FEP Title: Abrupt Termination in Deployment [E]***
***(A4) FEP Title: Planned Gradual Phase-out [E]***
***(A5) FEP Title: Interruption in Deployment [E]***
***(A6) FEP Title: Seasonality of Injections [E]***

### FEP Definition

Assumptions about the timing of stratospheric aerosol injection (SAI) events play an important role in determining potential climate outcomes. The assumption for the initiation date for SAI events (FEP A1) in the model will impact model results, as it will determine the initial temperature conditions. SAI events are likely to be carried out over extended periods of time and are typically modeled as such. While the duration of the SAI may be defined by a planned stopping point (FEP A2), other assumptions for the termination of SAI may also be assumed for the purposes of analyzing potential future scenarios, including an abrupt termination of deployment (FEP A3) (i.e., a planned long-term SAI scenario is cut short due to outside influences) or a planned gradual reduction in SAI (FEP A4) in which the frequency and/or magnitude of SAI is reduced over time. Also, potentially impactful to the effectiveness of SAI is an interruption in deployment (FEP A5) in which a planned SAI scenario is abruptly terminated but then resumed. There is evidence that the seasonality of injections (FEP A6) (i.e., rather than a continuous year-round injection, injections are only performed in certain times of the year), may also be an influential factor in climate outcomes; injections in the summer have a much higher impact than injection in the winter.

### Screening Decision: Screened-In

### Screening Argument

FEPs A1-A6 are screened in due their high likelihood for impacting model results of climate outcomes. Although each of these six FEPs would not be implemented simultaneously (e.g., an abrupt termination of SAI—FEP A3—is not compatible with a planned gradual phase-out of SAI—FEP A4), for the purposes of the FEPs screening here, screening in should be done if the FEPs are considered as part of a modeling scenario. In the references below, modeling results have shown impacts of these FEPs on final results.

### References

Baur et al., (2023). [20]
Lee et al., (2021). [1]
MacMartin et al., (2022). [21]

## Stratospheric Aerosol Injection: Injection Region

### *(A7) FEP Title: Aerosol Injection Latitude [F]*
### *(A8) FEP Title: Aerosol Injection Hemisphere [F]*
### *(A9) FEP Title: Aerosol Injection Altitude [F]*

### FEP Definition

Assumptions about the location of SAI events impact potential global climate outcomes. The impact of injection latitude (FEP A7) has been shown to be substantial in multiple models. The implementation of SAI only in the subpolar regions has been proposed to focus the effects on reducing the loss of ice and permafrost near the poles. The injection region has also shown to be impactful in that injection effects tend to remain in the northern/southern hemisphere (FEP A8) in which they originate; the choice of northern vs. southern (or both) hemisphere for injection is impactful to model results. Additionally, the altitude at which SAI events take place (FEP A9) influences the impact (and costs) of this technology; there are cooling effects and cost tradeoffs in injecting at higher altitudes. The references below contain information on the impacts of these FEPs on final modeling results.

### Screening Decision: Screened-In

### Screening Argument

FEPs A7-A9 are screened in due their high likelihood for impacting model results of climate outcomes. For global models, each of these FEPs has been shown to be impactful to climate results. Especially for the case of FEP A7, there are substantial impacts on Arctic cooling.

### References

Caldeira and Wood (2008). [5]
Carnegie Climate Governance Initiative (2022). [6]
Smith et al., (2022). [22]
Sun et al., (2020). [23]

## Stratospheric Aerosol Injection: Injection Amount

### *(A10) FEP Title: Aerosol Injection Rate [P]*
### *(A11) FEP Title: Amount of Prescribed Cooling [F]*

### FEP Definition

Assumptions about the amount of aerosol injected in SAI are impactful to the modeling results. Injection rates (FEP A10) may be prescribed as constant or variable with time. In some models, assumptions have been made about changing injection rates based on feedback from the system (i.e., extent of cooling) in which the amount of cooling is prescribed (FEP A11) and injection rates varied accordingly. These are generally referred to as "forcing scenarios" and are a widely accepted technique for potential future uses of SAI.

### Screening Decision: Screened-In

### Screening Argument

FEPs A10 and A11 are screened in due to their high likelihood for impacting model results of climate outcomes. Clearly, the amount of aerosol injected into the atmosphere will have an impact on the cooling effects realized in global models and these FEPs focus on the injection rate over time. In the references below, modeling results have shown impacts of these FEPs on final results.

### References

Caldeira and Wood (2008). [5]
Kravitz et al., (2011). [24]
Lee et al., (2023). [2]
MacMartin et al., (2022). [21]
Richter et al., (2022). [25]
Tilmes, et al., (2018). [26]

## *(A12) FEP Title: Radiative Forcing Overshoot [P]*

### FEP Definition

Radiative forcing overshoot (FEP A12) is proposed as a pathway in which radiative forcing (i.e., solar irradiance minus longwave cooling) results in an overshoot of the long-term equilibrium level of heat uptake in the system; in other words, even though a system may be "designed" to have a specific level of long-term, acceptable level of heat uptake, the system can overshoot that acceptable level in the short term before approaching the acceptable level. This process occurs as a result of radiative forcings imposed on the model, so it may not be considered an "independent" FEP that would require implementation of a new, specific process model. However, it is an accepted process that should be shown to occur in global climate model. For that reason, we include it here as a separate process. Because it is tied to the radiative forcing that arrives via the atmosphere, it is included as an atmospheric FEP; however, radiative uptake via the ocean plays an important role in the ultimate effect on heating and cooling in the global climate model.

### Screening Decision: Screened-In

### Screening Argument

FEP A12 is screened in due to the number of existing studies showing that, rather than heat uptake making a direct, asymptotic approach to the long-term equilibration level, an overshoot first occurs before the heat uptake consequently lowering to the equilibrium level. The reference below describes the process of radiative forcing overshoot.

### References

Johansson et al., (2011). [27]

### *(A13) FEP Title: SAI Deployment Logistics [F]*

#### FEP Definition

Assumptions of SAI deployment logistics (FEP A13) are important to the impacts of SAI cooling as they set limits on the availability of SAI in the atmosphere. The logistics considered here include the availability of suitable aircraft, airports, aerosol material, etc. to be able to carry out SAI at a prescribed level. However, the details of these logistics are likely not necessary for inclusion in a model directly, but rather indirectly through the assumptions made elsewhere in the model; for example, injection altitude (FEP A7) or aerosol injection rate (FEP A10). So, while the number of airplanes needed to accomplish the task would be important for calculating estimated costs of running SAI, it would not be a necessary input into global climate models when other input parameters (e.g., injection rate) are used directly as model inputs.

#### Screening Decision: Screened-Out

#### Screening Argument

FEP A13 is screened out due to presumed redundancy with the implementation of other FEPs. Without a need for the granularity of individual logistical parameters, there is not a need to keep this FEP as part of a global model.

#### References

Smith et al., (2022). [22]

### *(A14) FEP Title: SAI Technological Advances [P]*

#### FEP Definition

Potential technological advances in SAI (FEP A14) could improve the effectiveness of SAI as well as impact the rate at which it is implemented on local or global scales. The technological development could be due to enhanced understanding of aerosol materials, aerosol transport, etc. or improvement in the availability of suitable aircraft used in injection events or something else not yet conceived. One potential implementation strategy for this FEP is to make assumptions on how the future rate of technological advancement could impact key parameters considered in other FEPs (e.g., injection rate, injection latitude). In that case, a "multiplier" parameter (perhaps with an associated uncertainty) could be applied to currently available data to be used as model inputs. Another approach could be to consider the currently available data to represent a lower bound or "conservative" approach to the effectiveness or timing of SAI implementation (i.e., without specifically implementing a model or parameterization for this FEP, we could assume that SAI would be more effective and implemented sooner in the future than how it is assumed in the model).

#### Screening Decision: Screened-In

#### Screening Argument

FEP A14 is screened in as a process that could be implemented (perhaps via parameterization of processes under separate FEPs) to take credit for future technological advancements due to ongoing research prior to and during the early stages of SAI implementation. Because these advancements could directly impact assumptions about key input parameters (and associated uncertainty), they should be considered in the context of model development for climate models. References below discuss the potential impacts of technological advancements on climate impacts.

### References

Lockley et al., (2022). [28]

## Stratospheric Aerosol Injection: Aerosol Characteristics

## *(A15) FEP Title: Aerosol Material [F]*
## *(A16) FEP Title: Aerosol Properties [F]*
## *(A17) FEP Title: Aerosol Size Distribution [F]*

### FEP Definition

Assumptions about the characteristics of aerosols used in SAI play an important role in calculations assessing potential climate outcomes. Although most models typically use sulfur dioxide ($SO_2$) as the assumed aerosol precursor material (FEP A15), other materials have also been considered and a choice in material as research expands in this area; use of a mixture of materials is also possible, if not likely. Any material chosen as an aerosol for SAI will be chosen based on its radiative and optical properties (FEP A16) which will determine, to a large extent, the effectiveness of SAI. Aerosol particle size, and the distribution of those sizes in a representative sample (FEP A17), also plays a role in the effectiveness of SAI; there may be an advantage to varying particle size distribution with time as well. The size distribution is linked to the microphysical processes of nucleation and growth of aerosols (FEP A18).

### Screening Decision: Screened-In

### Screening Argument

FEPs A15-A17 are screened in as they define the impact of aerosols in climate calculations. Identification of the aerosol material(s) (FEP A15) is linked directly with the aerosol properties (FEP A16). References below discuss the importance and impacts of aerosol materials, their properties, and size distribution.

### References

Dykema et al., (2016). [29]
Grisé et al., (2021). [30]
Kravitz et al., (2011). [24]
Lockley et al., (2022). [28]
National Academies of Sciences, Engineering, and Medicine (2021). [31]

## *(A18) FEP Title: Aerosol Microphysical Processes [P]*

### FEP Definition

Microphysical processes for aerosols (FEP A18) include processes that typically occur on a scale smaller than a climate model grid cell, such as nucleation, condensation, and coagulation, that determine aerosol size distribution (FEP A17). If the processes occur on a smaller scale than a grid cell, then they may be included indirectly via the size distribution without the processes being simulated directly in the climate model or via a simplified process called parameterization. A simplified process may combine processes to result in a net effect that can be implemented in the larger model.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A18 is screened in as microphysical processes leading to the nucleation and growth of aerosol particles are key to SAI. Although the microphysical processes may not be implemented as individual process models in the global-scale climate simulations, their impacts can be realized via parameterization or via chosen aerosol size distributions (FEP A17). References below discuss the potential impacts of aerosol microphysical processes on climate impacts.

#### References

Gruber et al., (2019). [32]
National Academies of Sciences, Engineering, and Medicine (2021). [31]
Taylor et al., (2022). [33]

### *(A19) FEP Title: Stratospheric Aerosol Optical Depth [F]*

#### FEP Definition

One of the key properties of stratospheric aerosols in SAI is the aerosol optical depth (AOD) (FEP A19), or the optical "thickness" of an aerosol layer as aerosol particles block sunlight. One of the principal purposes of SAI is increased AOD. The usefulness of AOD in climate models may not be as a direct input, but as something that has contributions from various processes and features (e.g., aerosol microphysical processes, dust, pollution) and can be considered a feature of the model that is subsequently measured.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A19 is screened in as an important feature to describe the culmination of various features and processes to provide an overall measure of the attenuation of direct sunlight realized in the model. References below discuss AOD as a feature of climate models.

#### References

National Academies of Sciences, Engineering, and Medicine (2021). [31]

### *(A20) FEP Title: Background Aerosol Distribution [F]*

#### FEP Definition

Background aerosol concentration (FEP A20) provides a starting point for developing aerosol levels during a climate simulation and can be prescribed as a distribution across the globe. Assumptions about current and future aerosol distributions prior to the implementation of SAI can be used in global climate models to provide the baseline level of various species such as dust and carbon species. Background aerosol concentrations will impact particle growth.

### Screening Decision: Screened-In

### Screening Argument

FEP A20 is screened in as initial conditions in the model would likely include some assumptions about baseline levels of various aerosol species. References below discuss the use of background aerosol assumptions.

### References

Lockley et al., (2022). [28]
Visioni et al., (2023). [34]

## *(A21) FEP Title: Oxidation of Sulfur Dioxide [P]*

### FEP Definition

The oxidation of sulfur dioxide ($SO_2$) to sulfuric acid ($H_2SO_4$) in the gaseous phase is a chemical reaction used in some SAI models. It is assumed to take place in the stratosphere via reactions with the hydroxyl ($OH^-$) radical. The result is $H_2SO_4$ aerosols. Alternatively, ammonium sulfate ($(NH_4)_2SO_4$) can be prescribed in a model as it has similar optical properties to $H_2SO_4$.

### Screening Decision: Screened-In

### Screening Argument

FEP A21 is screened in as it is a reaction to convert the injected $SO_2$ into aerosol, a key component of SAI. References below describe the use of this reaction in SAI for climate models.

### References

Jackson et al., (2015). [35]
National Academies of Sciences, Engineering, and Medicine (2021). [31]

## *(A22) FEP Title: Dry and Wet Deposition [P]*

### FEP Definition

Dry and wet deposition of sulfate aerosols (FEP A22) are processes that remove aerosols from the atmosphere subsequent to injection. They have been used in some climate models implementing SAI as part of the "life cycle" of aerosols. Dry deposition may occur due to impaction (small particles hitting larger particles) or gravitational sedimentation (settling of particles due to gravity). Wet deposition may occur due to precipitation (FEP A38).

### Screening Decision: Screened-In

### Screening Argument

FEP A22 is screened in as processes for sulfate aerosol removal. References below discuss the dry and wet deposition processes in the context of SAI modeling.

#### References

Emerson et al., (2020). [36]
Kravitz et al., (2014). [37]
National Academies of Sciences, Engineering, and Medicine (2021). [31]
Robock et al., (2008). [38]

### *(A23) FEP Title: Twomey Effect (Aerosol Indirect Effect) [P]*

#### FEP Definition

The Twomey effect or aerosol indirect effect (AIE) (FEP A23) describes the impacts of aerosols on cloud albedo. This effect can be exploited, e.g., by conducting aerosol injection to increase marine cloud albedo (FEP A32) ("marine cloud brightening"). By spreading water content over smaller droplets, an increase in reflectivity is realized. This effect is utilized in marine cloud brightening (MCB). The aerosol indirect effect may not be a process that is implemented in all models directly but may be included in a net-effect process that accounts for related processes such as turbulence-driven entrainment (FEP A55) and drop growth (FEP A42).

#### Screening Decision: Screened-In

#### Screening Argument

FEP A23 is screened in for its impact on reflectivity, particularly if marine cloud brightening is modeled. References below describe the effect.

#### References

National Academies of Sciences, Engineering, and Medicine (2021). [31]
Twomey, S. (1974). [39]
Twomey, S. (1977). [40]

### *(A24) FEP Title: Background Emissions Scenarios [P]*

#### FEP Definition

Background emissions scenarios (FEP A24) are defined by sets of assumptions about future baseline changes (i.e., those not related to an intervention scenario) in emissions. Given the uncertainty in future global emissions, various scenarios have been proposed and implemented in global climate models. One example is SSP2-45 (SSP indicates a "shared socioeconomic pathway"), which assumes a 4.5 $W/m^2$ radiative forcing in the year 2100. Other proposed scenarios assume higher or lower forcing values over the same time period.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A24 is screened in as impactful to assumptions that need to be made for the amount of intervention necessary to combat future climate change, as well as the effectiveness of intervention scenarios. Given the uncertainty in future global emissions, multiple potential background emissions scenarios may be considered. References below describe the use of these scenarios.

### References

IPCC (2023). [41]
Davy and Outten (2020). [42]

## Atmospheric Composition

### *(A25) FEP Title: Air Pollution [P]*
### *(A26) FEP Title: Ozone Level [F]*
### *(A27) FEP Title: Atmospheric Carbon Dioxide Level [P]*
### *(A28) FEP Title: Greenhouse Gas Concentration [F]*
### *(A29) FEP Title: Atmospheric Humidity Distribution [F]*
### *(A30) FEP Title: Atmospheric Sulfur Level [F]*

### FEP Definition

Assumptions about the composition of the atmosphere prior to the implementation of climate intervention strategies play an important role in the effectiveness of the strategies during implementation. Gas-phase atmospheric composition can currently be measured experimentally by ground-based networks for some atmospheric components. However, as with background emissions scenarios (FEP A24), there are substantial uncertainties in the future local and global compositions of the atmosphere with respect to key atmospheric components such as: pollution (FEP A25), ozone (FEP A26), carbon dioxide ($CO_2$) (FEP A27), greenhouse gases (FEP A28), water/humidity (FEP A29), and sulfur (e.g., $SO_2$ or $H_2SO_4$) (FEP A30). Each of these components has a potential impact on the effectiveness of a climate intervention strategy and should be tracked throughout the duration of the climate model simulation.

### Screening Decision: Screened-In

### Screening Argument

FEPs A25-A30 are screened in as important contributors to the overall atmospheric composition; additionally, each component potentially plays a role in the evolution of the climate model due to taking part in other processes included in the climate model. References below discuss these atmospheric components and their potential impacts.

### References

Carnegie Climate Governance Initiative (2022). [6]
Gruber et al., (2019). [32]
National Academies of Sciences, Engineering, and Medicine (2021). [31]
MacMartin et al., (2022). [21]
McCormack et al., (2016). [43]

## Albedo

### *(A31) FEP Title: Marine Cloud Albedo [F]*
### *(A32) FEP Title: Clear-Sky Albedo [F]*
### *(A33) FEP Title: Top-of-Atmosphere Albedo [F]*
### *(A34) FEP Title: Cloud Albedo [F]*
### *(A35) FEP Title: Planetary Albedo [F]*

#### FEP Definition

The albedo (or reflectivity) of the various atmosphere-land components of the Earth system are key features of any model investigating climate intervention (CI) strategies. Typically, CI strategies seek to increase albedo to reduce the amount of incoming sunlight reaching the Earth's surface. Important components of the overall albedo include marine cloud albedo (FEP A32) due to the reflection of clouds over the oceans; clear-sky albedo (FEP A33) for cloud-free days; top-of-atmosphere albedo (FEP A34) measured at the top of the atmosphere layer; cloud albedo (FEP A35) due to reflection of terrestrial clouds; and planetary albedo (FEP A36), defined as the overall reflectivity of the Earth. Albedo due to reflection from land (FEP L1), snow (FEP L19), and ice (FEPs O23 and O25) are covered below.

#### Screening Decision: Screened-In

#### Screening Argument

FEPs A32-A36 are screened in as the albedo/reflectivity is a key feature related to various climate intervention strategies. As features, they do not necessarily represent inputs into process models, but are rather measures of the outputs of other process models.

#### References

McCormack et al., (2016). [43]
Kravitz et al., (2014). [37]
Latham et al., (2014). [44]
Lee et al., (2023). [2]
Nalam et al., (2018). [45]
Song et al., (2022). [46]

## Water in Air

### *(A36) FEP Title: Hydrological Cycle [P]*
### *(A37) FEP Title: Water Vapor [F]*
### *(A38) FEP Title: Storm Tracks [F]*
### *(A39) FEP Title: Acid Rain [P]*

#### FEP Definition

Atmospheric water content is an important component of climate models, particularly for SAI where aerosol lifetimes are impacted by water content. At the same time, geoengineering efforts such as SAI also impact the hydrological cycle (FEP A36); i.e., precipitation and evaporation. Local and global precipitation and evaporation effects would occur due to geoengineering interventions designed to induce temperature changes. The extent of these effects will play a role in overall climate outcomes for individual and global ecosystems (FEP A88), including human health concerns (FEP X13). Important components when considering water in air include water vapor content (FEP A37), storm tracks (FEP A38), and acid rain (FEP A39). Water vapor feedback plays a role in polar amplification. Storm tracks impact where precipitation occurs and tend to transport moisture toward the poles; storm tracks themselves can also be influenced by the extent of Arctic ice. Although there is not expected to be a large impact on ocean pH due to acid rain (e.g., from sulfur via SAI), there is a potential for acid rain in local climates that currently do not experience it.

#### Screening Decision: Screened-In

#### Screening Argument

FEPs A36-39 are screened in based on the high impact of atmospheric water content on climate outcomes, including via feedback with other processes. Although acid rain may not be impactful to all areas, if pristine areas are included in the model, the effects of acid rain (FEP A39) should be included. References below discuss atmospheric water content impacts on climate models.

#### References

Bala et al., (2008). [47]
Nalam et al., (2018). [45]
Visioni et al., (2020). [48]

### Atmosphere Dynamics

***(A40) FEP Title: Atmospheric Circulation [P]***
***(A41) FEP Title: Aerosol Transport [P]***
***(A42) FEP Title: Ozone Transport [P]***
***(A43) FEP Title: Jet Streams [F]***
***(A44) FEP Title: Upper Troposphere Zonal Winds [F]***
***(A45) FEP Title: Stratosphere Zonal Winds [F]***
***(A46) FEP Title: Stratospheric Circulation [P]***
***(A47) FEP Title: Stratospheric Transport [P]***
***(A48) FEP Title: Inter-tropical Convergence Zone [F]***
***(A49) FEP Title: Plume Dynamics [P]***
***(A50) FEP Title: Boundary Layer Mixing [P]***
***(A51) FEP Title: Turbulence in the Lower Atmosphere [P]***
***(A52) FEP Title: Turbulence-Driven Entrainment [P]***
***(A53) FEP Title: Motion of Warmer Air Masses [F]***

#### FEP Definition

We use the general term "atmosphere dynamics" here to refer to the myriad processes and features related to the movement of air in the atmosphere that are impactful to climate projections and are included in climate models. Here, 14 FEPs are grouped together as they represent the interplays of processes and features occurring in the various levels of atmosphere and particularly impacting air flow that impacts global temperatures and aerosol mobility (and thus effectiveness).

Atmospheric circulation (FEP A40) is a process associated with the feature of atmospheric dynamics as it accounts for the overall movement of air and heat across the globe. It is necessarily a key component of a climate model. Aerosol transport (FEP A41), a key component of SAI, tracks the movement of aerosol through and between atmospheric layers. Ozone transport (FEP A42) is impacted by stratospheric heating (potentially due to volcanic activity or SAI) and is influential in global temperature changes (ozone loss is also associated with the use of SAI, so the local concentration of ozone near aerosol injections would be impacted). The jet streams (FEP A43), strong wind currents in the upper atmosphere, are impacted by the warming of the stratosphere due to the use of SAI.

Upper troposphere zonal winds (FEP A44) have been shown to be increased in models using SAI in the Northern Hemisphere, while stratosphere zonal winds (FEP A45) were shown to be decreased. Stratospheric circulation (FEP A46) consists in the upwelling of air from the tropics toward the poles and is influenced by large-scale atmospheric waves; disruption of stratospheric circulation (perhaps by stratospheric warming) can be impactful to local weather events, as well as the stratospheric transport (FEP A47) of aerosols or other atmospheric components. In particular, the Inter-Tropical Convergence Zone (FEP A48), an observable band of clouds that appears near the equator due to a convergence of tropical and northeast trade winds, can also be impacted by geoengineering efforts and possibly lead to changes in tropical precipitation.

Plume dynamics (FEP A49) refers to the movement of the aerosol plume in the part of the stratosphere immediately behind aircraft implementing SAI; it is a localized effect but can impact the aerosol size distribution (FEP A17). Boundary layer mixing (FEP 50) refers to turbulence driven (FEP A51), vertical mixing that can result in the changing of air component concentrations in the lower troposphere and potentially the trapping of air (FEP A52) at the interface between the cloud zone and free atmosphere above it. The motion of warmer air masses (FEP A53), generally upward, can be impacted by heating due to SAI in the stratosphere and also impact water vapor levels.

### Screening Decision: Screened-In

### Screening Argument

FEPs A40-53 are screened in due to impacts on the movement of heat throughout the atmosphere as well as the transport of aerosols. Some of these FEPs may be too fine-grained for global-scale models depending on desired output resolution. However, atmosphere dynamics remain a key component of any climate model.

### References

Caldeira and Wood (2008). [5]
Lin and McElroy (2010). [49]
National Academies of Sciences, Engineering, and Medicine (2021). [31]
Nalam et al., (2018). [45]
Visioni et al., (2021). [50]

## Solar Properties

### *(A54) FEP Title: Insolation (Light Availability) [F]*
### *(A55) FEP Title: Solar Irradiance (Incoming Solar Radiation) [P]*
### *(A56) FEP Title: Radiation Absorption [P]*

#### FEP Definition

Light availability or insolation (FEP A54) is the amount of light making it to the Earth's surface from the sun. In simplest terms, light availability is the difference between solar irradiance arriving at the top of the atmosphere (a relatively constant measure of incoming solar radiation, FEP A55) and attenuation due to radiation absorption (FEP A56), reflection, or scattering. Light availability impacts crop yield (FEP L27), phytoplankton growth (FEP O6), plant biodiversity (FEP L29), etc. Solar absorption is used here as a general term that could include absorption from "natural" phenomena or human-induced phenomena associated with SRM. Solar radiation reduction has been shown to impact Arctic temperatures, as well as the location of the Inter-tropical Convergence Zone (ITCZ).

#### Screening Decision: Screened-In

#### Screening Argument

FEPs A54-56 are screened in as they account for the incoming solar radiation, the amount that radiation is reduced (via various phenomena), and ultimately the availability of light at the Earth's surface (i.e., insolation) to impact the evolution of other FEPs. References below discuss the topic of incoming solar radiation.

#### References

Desch et al., (2017). [8]
Kravitz et al., (2014). [37]
Kravitz et al., (2016). [51]
McCormack et al., (2016). [43]

### *(A57) FEP Title: Stratospheric Heating [P]*

#### FEP Definition

Stratospheric heating is a general term for increased temperature in the stratosphere due to various phenomena including volcanic activity (which can inject ash into the stratosphere) or SAI (in which aerosols are injected into the stratosphere, resulting in heating due to the absorption of near-infrared (near-IR) solar radiation and the IR emanating from the Earth). Stratospheric heating may occur due to a collection of potential processes described elsewhere in this document (e.g., FEP L40 (volcanic activity) and the FEPs associated with SAI, A1-A17). This heating consequently impacts air temperature, movement in the stratosphere, and ozone concentration.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A57 is screened in as processes associated with stratospheric heating have been shown to impact global temperatures and directly impact other atmospheric processes in Earth system models.

### References

Duffey et al. (2023). [4]
Lee et al. (2021). [1]
Visioni et al. (2023). [34]

## Cloud Features and Processes

### *(A58) FEP Title: Cloud Formation Processes [P]*
### *(A59) FEP Title: Cirrus Clouds [P]*
### *(A60) FEP Title: Shortwave and Longwave Radiation [P]*
### *(A61) FEP Title: Mixed-Phase Clouds [F]*
### *(A62) FEP Title: Cloud Vertical and Horizontal Extent [F]*
### *(A63) FEP Title: Cloud Evaporation [P]*
### *(A64) FEP Title: Cloud "Lifetime" Effect [P]*
### *(A65) FEP Title: Cloud Water Content [F]*
### *(A66) FEP Title: Cloud Feedback [P]*
### *(A67) FEP Title: Cloud Opacity [F]*
### *(A68) FEP Title: Cloud Microphysical Parameters [F]*
### *(A69) FEP Title: Cloud Altitude [F]*
### *(A70) FEP Title: Ice Fall Velocity [F]*
### *(A71) FEP Title: Cloud Updraft Velocity [P]*

### FEP Definition

Fourteen FEPs associated with clouds are discussed here. Clouds are omnipresent and their presence impacts the Earth's energy balance, thus influencing the Earth's cooling and climate outcomes. The processes associated with the formation of clouds (FEP A58), including cirrus clouds (FEP A59), are important processes as they coalesce water vapor from the atmosphere. Cirrus clouds, which form from ice crystals (not water droplets) at high altitudes and low temperatures, have a net warming effect on the Earth's atmosphere (they reflect less incoming shortwave radiation than absorb longwave radiation below them, FEP A60) such that cirrus cloud thinning has been proposed as a cooling mechanism. Vertical ice fall velocity (FEP A70) has shown to be an important parameter in cirrus cloud formation.

The presence of mixed-phase clouds (which include water vapor, ice particles, and supercooled liquid water droplets) (FEP A61) has been shown to be impactful to climate sensitivity, particularly the supercooled liquid portion. They also impact the extent to which temperature inversions (FEP A79) occur. Additionally, the lateral and vertical extent of cloud cover (impacted by aerosol size, FEP A17) (FEP A62) influences the amount of heating or cooling in the atmosphere.

Cloud evaporation (FEP A63) is another process impacting the amount of water in clouds, and thus reflectivity—this process is intertwined with humidity (FEP A29) and turbulence-driven entrainment (FEP A52). These processes are impactful to marine cloud brightening. While they may occur on a scale smaller than a grid cell (FEP A91), the processes may be parameterized to reflect an overall effect even if the microphysics are not explicitly modeled. The extent of cloud cover can represent the "cloud lifetime effect", a secondary effect to the primary Twomey effect (FEP A23) due to the presence of aerosols in the atmosphere (i.e., cloud-aerosol interactions). The cloud water content (FEP A65) is thus a key feature to track in the model.

Cloud feedback (FEP A66) is a general term to describe the process of the changing relative amounts of cloud types due to climate change effects, which then impact additional climate change, including atmospheric temperature. Net cloud feedback has been shown to be a substantial factor in polar warming amplification—this has been attributed to increased downward longwave radiation toward the Earth's surface. Various cloud properties, including opacity (FEP A67, which depends on cloud density and optical depth), cloud microphysical properties (FEP A68; such as the size, shape, and concentration of ice crystals), cloud altitude (FEP A69), and updraft velocity (FEP A71; localized, upward air speed) are influential in the relative impact of the cloud feedback. Again, these are examples of microphysical processes and features that may not be modeled directly on the scale of global models but are nonetheless important to include in a model via parameterization.

#### Screening Decision: Screened-In

#### Screening Argument

FEPs A57-A71 are screened in due their impact on cloud properties which have been shown to be substantially impactful to climate change modeling. References below discuss the various cloud related FEPs.

#### References

Ahola et al., (2022). [52]
Pithan et al., (2014). [53]
Quaas et al., (2008). [54]
Tan et al., (2016). [55]
Taylor et al., (2013). [56]

## Meridional Processes

### *(A72) FEP Title: Meridional Heat Flux [P]*
### *(A73) FEP Title: Meridional Atmospheric Moisture Transport [P]*

#### FEP Definition

Meridional processes occur across lines of latitude; for processes impacting the Arctic, we are concerned with processes that act toward the North pole. Meridional heat flux (FEP A72) involves increased temperature moving from the Tropics toward the Arctic. Meridional atmospheric moisture transport (FEP A73) has been proposed as a substantial factor in Arctic ice melt and thus Arctic amplification (AA), the greater rate of warming observed in the Arctic compared to the overall global rate.

These two FEPs are not physical processes themselves, but the observed cumulative result of multiple underlying processes covered elsewhere in this document. As a result, we define these two FEPs as "features" here, which should be consistent with the results of simulations using a global model.

#### Screening Decision: Screened-In

#### Screening Argument

FEPs A72 and A73 are screened in as these prominent features are widely observed and accepted as occurring, so they should also be observed in a global model. The processes that lead to these features have particular impact on Arctic climate.

### References

Parkes et al., (2012). [57]
Graversen et al., (2016). [58]

## Atmosphere Properties

### *(A74) FEP Title: Air Temperature [F]*
### *(A75) FEP Title: Specific Humidity [F]*
### *(A76) FEP Title: Atmospheric Pressure [F]*
### *(A77) FEP Title: Surface Pressure [F]*
### *(A78) FEP Title: Global Temperature [F]*

#### FEP Definition

Key atmospheric properties that are impacted by various global and local processes include air temperature (FEP A74), specific humidity (FEP A75), atmospheric pressure (FEP A76), and surface pressure (FEP A77), and global temperature (FEP A78). These are defined here as features of the model to be tracked during simulation for the reasons of passing important variable values among process models, as well as comparing against expected trends. In the case of global temperature, it is a key output of the model, as well as likely to be closely tied to performance goals.

#### Screening Decision: Screened-In

#### Screening Argument

FEPs A74-A78 are screened in due to their importance as features among various process models that make up the global simulation model.

#### References

National Academies of Sciences, Engineering, and Medicine (2021). [31]
Richter et al., (2022). [25]

### *(A79) FEP Title: Near-Surface Air Temperature Inversion [P]*

#### FEP Definition

Temperature inversion (or thermal inversion) occurs in a layer of the atmosphere in which temperature increases with altitude, an atypical temperature trend. A layer of warm air traps cooler air below it. A climate model has shown that Arctic amplification (AA) is more intense when there is a near-surface air temperature inversion (FEP A79). The increased warming is due to the warming of the cool layer, which results in enhanced radiation in a downward direction and less cooling toward space.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A79 is screened in as an important factor in arctic amplification.

#### References

Bintanja et al., (2011). [59]

### *(A80) FEP Title: Planck Feedback [P]*

#### FEP Definition

Planck feedback is a term given to the change in the process by which the warming Earth cools naturally as it gives off radiation. The uncertainty in this feedback is relatively minor but it is substantial enough to impact calculations in Earth system models.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A80 is screened in due to the impact on the overall energy balance calculations performed in Earth system models.

#### References

Cronin and Dutta, (2023). [60]
Pithan and Mauritsen, (2014). [61]

### *(A81) FEP Title: Lapse Rate Feedback [P]*

#### FEP Definition

The lapse rate feedback is a process that results in a changing vertical temperature profile from the Earth's surface skyward depending upon the incoming radiative forcing. Positive or negative feedbacks are possible. Climate models show an impact of lapse rate on AA; however, the extent of this impact is dependent upon the assumptions of radiative forcing.

#### Screening Decision: Screened-In

#### Screening Argument

FEP A81 is screened in on the basis of impact on AA, an impactful process on climate change in the Arctic.

#### References

Stuecker et al., (2018). [62]
Henry and Merlis, (2020). [63]

### *(A82) FEP Title: Atmosphere-Soil Coupling in Winter (Soil Cooling) [F]*

#### FEP Definition

Soil cooling may result due to a greater degree of atmosphere-soil coupling (FEP A82) in winter. This can result from cases of higher snow density (and thus lower snow depth), for example when there is increased herbivore grazing. The greater atmosphere-soil coupling can result in increased permafrost melting (FEP L24) which increases the greenhouse gas concentrations (FEP A28) and global temperatures (FEP A78).

**Screening Decision: Screened-In**

**Screening Argument**

FEP A82 is screened in due to the impact on other processes and potential for resulting in increased global temperatures.

**References**

Qiao et al., (2023). [64]
Matthes et al., (2017). [65]

## *(A83) FEP Title: Disruption of Weather Patterns [P]*

**FEP Definition**

Arctic weather patterns (FEP A83) are known to be impacted by changes in sea-ice melting (sea-level rise) (FEP O15), snow levels, and the polar vortex. The implementation of SRM methods (e.g., SAI) will undoubtedly impact weather patterns in the Arctic, which will simultaneously alter weather patterns in more populated areas as well. The interplay between weather patterns (including extreme weather events) and AA is studied in global models.

**Screening Decision: Screened-In**

**Screening Argument**

FEP A83 is screened in as an observable feature of models (not as a separate, individual process) that comes as a result of other processes.

**References**

Francis et al., (2017). [66]

## *(A84) FEP Title: Leakage of Artificial Carbon Dioxide Reservoirs [P]*

**FEP Definition**

CDR is a term to represent the many proposed processes for directly removing $CO_2$ from the atmosphere. One aspect of CDR is the sequestration of $CO_2$ (on the order of gigatons) in underground reservoirs. A potential inadvertent release scenario of $CO_2$ from such a reservoir (FEP A84) could have severely detrimental results in terms of greenhouse gas effects on global warming (FEP A28).

**Screening Decision: Undetermined**

**Screening Argument**

While the potential impact of a large release of $CO_2$ into the atmosphere is large, the screening of FEP A84 will depend on the scope of the model and whether high impact/low likelihood events should be included. The screening decision would benefit from an assessment of the probability of such an event occurring.

### References

GAO (2011). [7]
Lockley et al., (2022). [28]

## *(A85) FEP Title: Sea Spray Geoengineering [P]*

### FEP Definition

Sea spray geoengineering (FEP A85) (or salt aerosol injection) consists of using sea spray to introduce cloud condensation nuclei in ocean clouds, resulting in aerosol-cloud interactions (FEP A64). These interactions are proposed to result in MCB that ultimately uses the radiative factors of the aerosol-cloud interactions to increase cooling of the Earth via the increased albedo of the clouds.

### Screening Decision: Undetermined

### Screening Argument

FEP A85 may be screened into models if sea spray geoengineering (i.e., salt aerosol injection or MCB) is part of the intended intervention strategy.

### References

Kravitz et al., (2013). [67]
Pringle et al., (2012). [68]

## *(A86) FEP Title: Hurricane Strength [P]*

### FEP Definition

It has been proposed that MCB can lead to weakening of hurricanes based on sea surface temperatures and a link between high intensity hurricanes and increased temperatures. Hurricanes may be a direct result of climate change, but do not have direct feedback on climate change, particularly in the Arctic.

### Screening Decision: Screened-Out

### Screening Argument

FEP A86 is screened out based on low impact of hurricanes on Arctic climate.

### References

Latham et al., (2014). [44]

## *(A87) FEP Title: Methane Release from Melting Permafrost [P]*

### FEP Definition

Arctic permafrost contains trapped stores of methane ($CH_4$) that can be released to the accessible environment when permafrost melting (FEP L24) occurs. Methane is a more powerful greenhouse gas than $CO_2$ and thus increased levels of methane in the atmosphere will lead to increased global temperatures.

### Screening Decision: Screened-In

### Screening Argument

FEP A87 is screened in based on the substantial impact of methane release on global temperatures.

### References

Field et al., (2018). [9]
Latham et al., (2014). [44]

## Ecosystem Effects

## *(A88) FEP Title: Natural Ecosystems [F]*
## *(A89) FEP Title: Ecosystem Damage / Loss [P]*

### FEP Definition

Both land-based and ocean-based natural ecosystems (FEP A88) depend on stable atmospheric climates, so this FEP is considered a combination Atmosphere/Land/Ocean FEP. The damage or loss of ecosystems (FEP A88) due to climate change in the Arctic is likely without the implementation of any intervention strategy. Marine ecosystems are dependent upon plankton which get nutrients from glacier sediments; reduced glacier extent (FEP L22) due to thaw can thus impact these ecosystems. Additionally, Arctic land-based ecosystems depend on plant biodiversity (FEP L29), the presence of large herbivores (FEP L36), etc., all of which are potentially impacted by permafrost thaw (FEP L24).

### Screening Decision: Screened-In

### Screening Argument

FEPs A88 and A89 are screened in as an important Arctic feature and process, both of which are directly impacted by climate change in the Arctic. They are closely tied to other Arctic FEPs.

### References

Macias-Fauria et al., (2020). [69]
National Academies of Sciences, Engineering, and Medicine (2021). [31]
United Nations Environment Programme (2023). [70]

## *(A90) FEP Title: Regional Climate [F]*

### FEP Definition

While there has been a focus on reducing rising global temperatures, the consequences of various climate intervention strategies will have uneven impacts on regional climates (FEP A90). For example, some regions may have increased rainfall while others will have reduced rainfall. Some modeling work has shown monsoon seasons to be substantially impacted, which then impacts the amount of food produced in that region, introducing new risks on a local scale. The intensity and frequency of extreme weather events are also subject to change for specific regions over others.

### Screening Decision: Screened-In

### Screening Argument

FEP A90 is screened in to ensure that regional impacts on climate are considered alongside global climate outcomes.

### References

Da-Allada et al., (2020). [71]
Nalam, A. et al., (2018). [45]

## *(A91) FEP Title: GCM Grid Resolution [F]*

### FEP Definition

General Circulation Models (GCMs) are numerical models that include various process models representing physical processes. Due to numerical limitations, the lateral spatial resolution (FEP A91) of computational cells may be about 100 x 100 km, while vertically there may be only 20-30 layers. With greater resolution comes greater ability to distinguish the impacts of physical processes on smaller scales, but at increased computational expense. Many physical processes important to global (or Arctic) climate occur on a scale smaller than a single grid cell; therefore, it is necessary to parameterize processes such that the effects of these processes are properly translated to the global model. A resolution that is too coarse will potentially miss important aspects of the evolution of global climate outcomes.

### Screening Decision: Screened-In

### Screening Argument

FEP A91 is screened in as a key feature of GCMs that should be selected with caution to ensure sufficient capture of physical processes.

### References

Iles et al., (2020). [72]

# Polar Atmosphere

## *(A92) FEP Title: Polar Temperature [F]*
## *(A93) FEP Title: Total Ice Concentration [P]*
## *(A94) FEP Title: Ice Processes [P]*

### FEP Definition

Aspects of the polar atmosphere that are important to climate change in the Arctic include polar temperature (FEP A92), total ice concentration (FEP A93), and ice processes (FEP A94). Polar temperature (i.e., polar warming or cooling) is impacted by the ice-albedo feedback via radiative heating (FEP O25) and Arctic amplification (FEP X4). Modeling has used total ice concentration (including cloud ice, snow, and graupel) as an indicator for cloud ice number concentration; below a certain level, the cloud ice concentration is decreased. Processes related to ice nucleation are important to the cloud formation; modeling suggests marine cloud brightening in the Arctic is impactful to local radiative effects, but not necessarily to the global radiation budget.

### Screening Decision: Screened-In

### Screening Argument

FEPs A92-A94 are screened in based on impact to cloud formation in the Arctic.

### References

Field et al., (2018). [9]
Kravitz et al., (2014). [37]
Parkes et al., (2012). [57]
Rantanen et al., (2022). [73]
Taylor et al., (2022). [33]

# 5. UNSCREENED FEPS

In addition to the Atmospheric FEPs screened above, the process used here has identified FEPs associated with Land, Ocean, and "Other" (FEPs that are not associated directly with the other three categories) categories. In some cases, more than one category was specified. The full list of categories for each FEP is found in the Excel workbook attached to this report. One category was specified for each FEP in order to establish a prefix for the associated FEP number. The "L" prefix is assigned to Land FEPs, "O" prefix for Ocean FEPs, and "X" prefix for Other FEPs. The L, O, and X FEPs have not yet undergone even the preliminary screening process that the Atmospheric ("A") FEPs have undergone. Tables of the names for the L, O, and X FEPs are included below. In some cases, the FEPs have been grouped together when appropriate. The literature references associated with these FEPs are also included in the Excel spreadsheet.

**Table 2. Land-focused FEPs Identified by the Current Analysis**

| FEP Number | FEP Category (Atmosphere, Ocean, Land, Other) | FEP Group | FEP Name |
|---|---|---|---|
| L1 | Land | Surface Properties | Surface Albedo (Urban vs. Desert vs. Crop) |
| L2 | Ocean, Land | | Surface Type |
| L3 | Land | | Land Surface Temperature |
| L4 | Land | | Mean Annual Ground Temperature |
| L5 | Land | | Soil Thermal Properties |
| L6 | Land | | Soil Insulation |
| L7 | Land | | Soil Temperature Regime |
| L8 | Land | | Soil Hydrology |
| L9 | Land | | Soil Moisture Levels |
| L10 | Land | | Soil Depth Down to Bedrock |
| L11 | Land | Surface Dynamics | Terrestrial Carbon Cycle |
| L12 | Land | | Surface Water Availability |
| L13 | Land | | Flooding |
| L14 | Land | | Vertical Heat Conduction |
| L15 | Land | | Ice Sheet Melting (Greenland) |
| L16 | Land | Snow Properties | Snow Accumulation |
| L17 | Land | | Snow Density |
| L18 | Land | | Insulation Efficiency of Snow |
| L19 | Land | Snow Dynamics | Snow Albedo Feedback |
| L20 | Land | | Snow Compaction Rate |
| L21 | Land | Glaciers | Permanent Glaciers |
| L22 | Ocean | | Glacial Melting |
| L23 | Ocean, Land | | Glaciation |
| L24 | Land | Permafrost | Permafrost Thaw |
| L25 | Land | | Permafrost Temperature |
| L26 | Land | | Permafrost Area |
| L27 | Land | Land Ecosystems / Plants | Agriculture |
| L28 | Land | | Evapotranspiration |
| L29 | Land | | Plant Biodiversity |
| L30 | Land | | Moss Cover |
| L31 | Land | | Moss Turnover Rate |
| L32 | Land | | Shrub and Tree Cover |
| L33 | Land | | Vascular Vegetation Coverage |
| L34 | Land | | Vegetation Characteristics |
| L35 | Land | | Photosynthesis |
| L36 | Land | Land Ecosystems / Animals | Population Density of Large Herbivores |
| L37 | Land | | Winter Grazing |
| L38 | Land | | Grazing "Intensity" |
| L39 | Land | | Fauna Dynamics |
| L40 | Land | | Volcanic Eruption |
| L41 | Land | | Wildfires |
| L42 | Land | | Biotic Interactions |
| L43 | Land | | Carbon Sequestration |
| L44 | Land | | Waterlogging |

## Table 3. Ocean-focused FEPs Identified by the Current Analysis

| FEP Number | FEP Category (Atmosphere, Ocean, Land, Other) | FEP Group | FEP Name |
|---|---|---|---|
| O1 | Ocean, Land | Ocean and Land Ecosystems | Loss of Biodiversity |
| O2 | Ocean, Land | | Ecosystem Adaptability / Change |
| O3 | Ocean, Land | | Animal Species Distributions / Migration Patterns / Breeding |
| O4 | Ocean | | Bio-Geochemical Interactions |
| O5 | Ocean | Ocean Ecosystems | Phytoplankton Levels |
| O6 | Ocean | | Phytoplankton Nutrient Uptake |
| O7 | Ocean | | Phytoplankton-Bacterial Dynamics |
| O8 | Ocean | | Ocean iron enrichment |
| O9 | Ocean | | Marine Ecological Nutrient Patterns |
| O10 | Ocean | Warm Water | Floating Sunscreen |
| O11 | Ocean | | Coral Reefs |
| O12 | Ocean | Ocean Dynamics | Ocean Circulation Patterns |
| O13 | Ocean | | Ocean-Atmosphere Dynamics |
| O14 | Ocean | | Ocean Upwelling / Downwelling |
| O15 | Ocean | | Sea-Level Rise |
| O16 | Ocean | | Ocean Currents |
| O17 | Ocean | Ocean Chemistry | Ocean Chemistry |
| O18 | Ocean | | Ocean Carbon Cycle |
| O19 | Ocean | | Sea-Surface Temperature |
| O20 | Ocean | | Lagged ocean response |
| O21 | Ocean | Sea Ice Properties | Sea Ice Coverage |
| O22 | Ocean | | Sea Ice Extent |
| O23 | Ocean | | Ice Albedo |
| O24 | Ocean | Sea Ice Dynamics | Sea ice Dynamics |
| O25 | Ocean | | Sea Ice Albedo Feedback |
| O26 | Ocean | | Arctic Sea Ice-Loss |
| O27 | Ocean | | Sea Ice Variability |

## Table 4. "Other" FEPs Identified by the Current Analysis

| FEP Number | FEP Category (Atmosphere, Ocean, Land, Other) | FEP Group | FEP Name |
|---|---|---|---|
| X1 | Other | Other - Technical | Targets |
| X2 | Other | | Cooling Rate |
| X3 | Other | | Termination Effect |
| X4 | Other | | Polar Amplification |
| X5 | Other | | Risk of Extreme Events |
| X6 | Other | | Rate of Decarbonization |
| X7 | Other | | Ecosystem Management Practices |
| X8 | Other | | Counter-Geoengineering |
| X9 | Other | | Multiple, Simultaneous Uncoordinated Efforts |
| X10 | Other | | Anthropogenic Effects |
| X11 | Other | Other - Non-Technical | Moral Hazard |
| X12 | Other | | Social Factors |
| X13 | Other | | Human Health |
| X14 | Other | | Food and Water Contamination |
| X15 | Other | | Political Factors |
| X16 | Other | | Economic Factors |
| X17 | Other | | Moral Permissibility of Intentionally Manipulating the Climate |
| X18 | Other | | Food and Water Scarcity |
| X19 | Other | | Governance |
| X20 | Other | | Local Land Use |
| X21 | Other | | International Cooperation and Coordination |
| X22 | Other | | Cooperative Monitoring |
| X23 | Other | | Feedback from Societal Responses to SG |

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# APPENDIX A. DESCRIPTION OF ATTACHED EXCEL WORKBOOK

The attached Excel workbook contains two worksheets, “FEPsTable” and “RefsTable”. The FEPsTable worksheet contains a table of the FEPs identified in this process, including FEPs categories, screening decisions (where available), and associated literature references. The literature references are identified by number and the reference numbers are correlated to full references in the RefsTable tab. Note that the reference numbers in the workbook do not match the numbering of references in this document.

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