SAND2023-01138O

PACI: *Performance Assessment for Climate Intervention*

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PROJECT MOTIVATION & GOALS

- *"Currently, there are no international agreements imposing any legally binding obligations that are specific to SRM."*
  -Reynolds, 2022: *Solar Radiation Modification: Governance gaps and challenges*)
  - There is a need for an assessment process to understand the impacts of climate intervention strategies against potential future regulations and to support policy decisions
- This project is developing and test a framework for assessing climate intervention scenarios with a focus on Stratospheric Aerosol Injection (SAI)
  - **Objective:** Assessment of **regional** responses, across multiple variables, to a particular set of SAI strategies which incudes a theoretical ranking (global and regional) of those outcomes
- A successful methodology would identify risks of certain scenarios **before** deployment for all affected parties, reducing threats to global and national security

Which tools and proposed frameworks are we using to define or guide our analyses?

1. Leverage existing model archives (GLENS; Tilmes et al., 2018)
2. Adapting an existing assessment framework: Performance Assessment methodology
3. Focusing on Risk-Risk Assessments (e.g., Harrison et al., 2021)
4. Identifying key climate risk parameters using IPCC Matrix of Climate Risks and Sectors of Impacts (IPCC, 2022)
5. Literature reviews of SAI and the events which could impact deployment and need consideration

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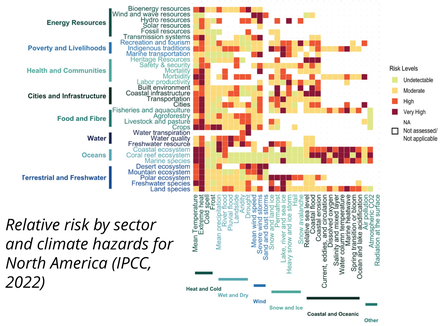
***SAND No.** SAND2023-XXXXXXXXX*

Tailoring Performance Assessment to Climate Intervention

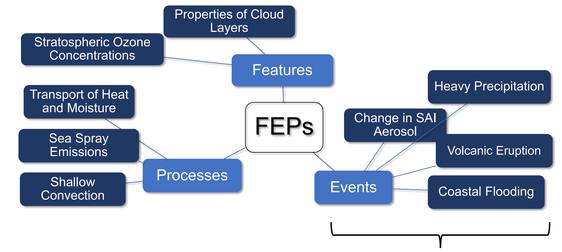
- **The Performance Assessment (PA) methodology (Meacham et al., 2011) can be applied to Climate Intervention to address four primary questions:**
  - **Q1:** What processes and events that might affect the Earth system could occur in the atmosphere through 2100?
  - **Q2:** How likely are the various processes and events that might affect the Earth system to occur in the atmosphere through 2100?
  - **Q3:** What are the consequences of the occurrence of various processes and events that might affect the atmosphere in the Earth system through 2100?
  - **Q4:** How much confidence should be placed in answers to Q1-Q3?
- These questions give rise to a methodology for quantifying the probability distribution of possible response over the next 100 years, and for characterizing the uncertainty in that distribution due to imperfect knowledge about the parameters contained in the models used to predict temperature changes.

The assessment space of impacts across the Earth system is large. Our approach is to identify assessment targets based on current ESM outputs and leverage existing metrics for climate change risk assessments and analyses of SAI simulations.



Relative risk by sector and climate hazards for North America (IPCC, 2022)

Identifying key model output parameters to assess using IPCC Climate Risk Matrix



FEPs informs what scenarios need to be assessed or what's "screened in" to the assessment.

Events that would Disrupt a SAI Deployment and may have Downstream Risks Requiring Further Assessment	
Events	**Description**
Interference by competing SAI programs	Financial requirements may be substantial, but possibility exists (Smith, 2020). Radiative efficacy declines as deployed mass increases beyond some value (Smith, 2020). Covert deployment (rogue actor attempting to geoengineer the world) may be unlikely (Smith and Henley, 2021).
Uncertainty in warming scenarios	Assumptions about Representative Concentration Pathway (RCP) (e.g., 4.5, 6.0, 8.5) as deployment modeling is performed to estimated capability of SAI (Smith, 2020).
Change in aerosol candidates	Due to negative environmental impacts and negative health impacts, an aerosol other than sulfates may be necessary.
Interruption of deployment	Deployment would need to be continuous or cooling effect would cease (Smith and Henly, 2021). **Anthropogenic Interruption -** Supply chain disruptions or slow/stalled technologic development mid-deployment. Interference by competing SAI programs or heterogeneous preferences on the climate outcomes. A failure to converge far prior to the onset of deployment on such consensus targets could compromise the legitimacy of such a program or render deployment impossible (Smith and Henly, 2021). **Natural Interruption -** Interference from large volcanic eruption (e.g., Mount Pinatubo eruption).

Assessing Regional Responses to SAI

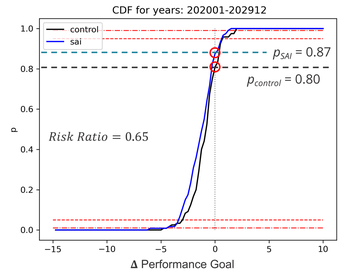
We demonstrate an example assessment, defining the performance goal as well as those for evaluating the scenario against the performance goal, using the Geoengineering Large Ensemble (GLENS) (Tilmes et al., 2018) model archive and building on the Ferraro et al. (2014) methodology. Ferraro et al. (2014) developed a probabilistic method for assessing whether the risk of SAI increases or decreases relative to the risk of climate change. We expand on this by assessing model output metrics beyond mean temperature and mean precipitation, calculating the risk at monthly timescales rather than annual, developing a range of performance goals that include both upper and lower thresholds, and including uncertainty in assessing the risk across multiple ensemble members.

Eq. 1: $PG = \mu + 1\sigma$

Eq. 2: $E_{SAI} = T_{SAI} - T_{PG}$

Eq. 3: $E_{control} = T_{control} - T_{PG}$

Eq. 4: $Risk\ Ratio = \dfrac{p_{SAI} > 0}{p_{control} > 0}$

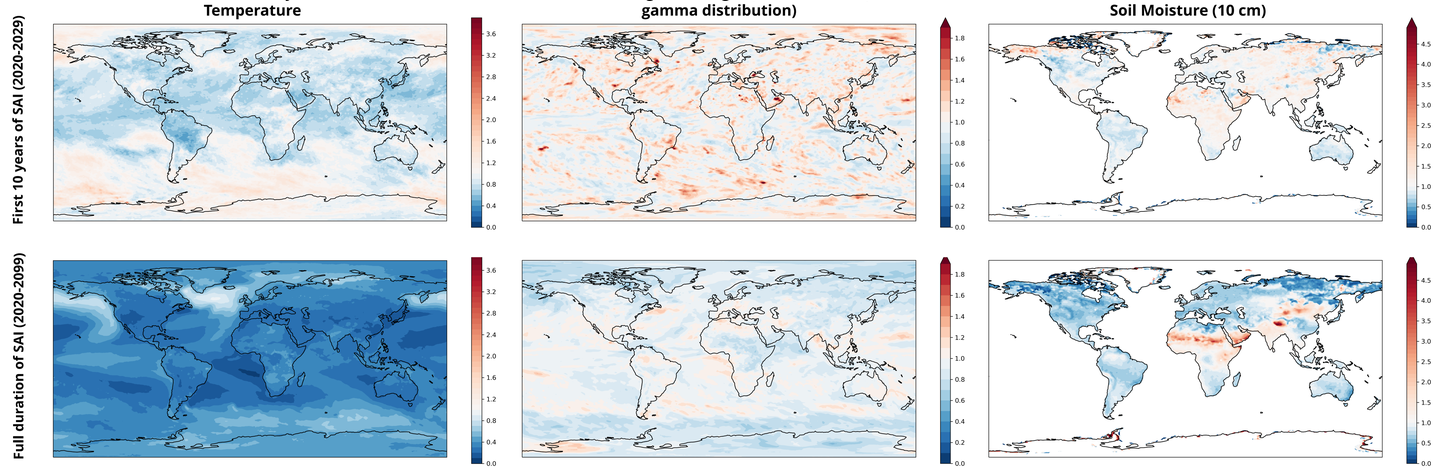


The performance goal (PG; i.e., threshold, regulation) is defined as μ plus 1σ (eq. 1). We use the interannual monthly mean from 2010-2019, pre-SAI deployment to calculate μ and σ. Next, the exceedance (E) is calculated by subtracting the PG from both the control (RCP8.5) and SAI scenarios (eq. 2 and 3). From the CDF of exceedance values for the period of assessment (2020-2030 or 2020-2099), find p at zero for SAI and the control (eq. 4).

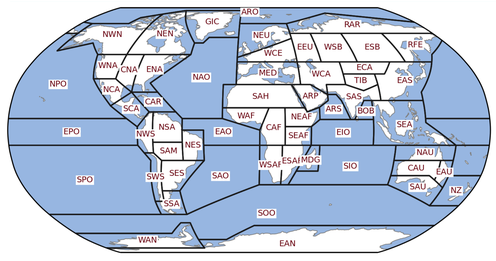
	Performance Goal(s)
Temperature	$\mu + 1\sigma$
Max Temperature	$\mu - 1\sigma$
Monthly Mean Precipitation Rate	$\mu + 1\sigma$ $\mu - 0.5\sigma$
Maximum Precipitation Rate	$\mu + 1\sigma$ $\mu - 0.5\sigma$
Meteorological Drought (SPI, 24 months, gamma)	$\mu + 0.5$ $\mu - 0.5$
Soil Moisture (10 cm)	$\mu - 0.5\sigma$
Solar Flux at the Surface	$\mu - 0.5\sigma$
Surface Runoff	μ

For each metric, the reference period used to define the performance goal is 2015, and μ and σ are calculated from the years 2010-2019.

Risk Ratio [ens no = 1, 2, 3, 21]



- **Risk Ratio > 1.0** means that the **control scenario performs better** against the performance goal
- **Risk Ratio < 1.0** means that the **SAI scenario performs better** against the performance goal



(Iturbide et al. 2022; https://github.com/IPCC-WG1/Atlas)

Short and long term risk ratios over regional land surfaces in response to the GLENS (Tilmes et al. 2018) SAI scenario. Blue cells indicate a RR (plus the uncertainty), that falls below 1.0, and thus SAI performs better against the performance goal.

		N.W.North-America	*South-American-Monsoon*	*N.Europe*	*W.Southern-Africa*	*Russian-Arctic*	*S.Asia*	*S.Australia*
Surface Temperature	***2030***	0.907 (0.323)	0.537 (0.131)	0.838 (0.241)	0.782 (0.243)	0.845 (0.272)	0.746 (0.205)	0.745 (0.300)
	2100	0.387 (0.142)	0.252 (0.067)	0.520 (0.085)	0.248 (0.123)	0.416 (0.126)	0.270 (0.086)	0.313 (0.138)
Max Surface Temperature	***2030***	0.895 (0.269)	0.537 (0.130)	0.849 (0.213)	0.809 (0.211)	0.939 (0.273)	0.811 (0.186)	0.794 (0.191)
	2100	0.393 (0.120)	0.259 (0.058)	0.460 (0.087)	0.286 (0.116)	0.433 (0.114)	0.301 (0.082)	0.255 (0.051)
Precipitation	***2030***	1.006 (0.091)	0.970 (0.081)	1.002 (0.084)	0.986 (0.071)	0.991 (0.090)	1.016 (0.078)	0.966 (0.080)
	2100	0.981 (0.044)	0.944 (0.029)	0.984 (0.039)	0.963 (0.036)	0.933 (0.039)	1.021 (0.036)	0.940 (0.038)
Max Precipitation Rate	***2030***	1.009 (0.156)	1.004 (0.162)	0.998 (0.151)	0.994 (0.171)	1.009 (0.147)	1.043 (0.193)	1.015 (0.155)
	2100	0.811 (0.076)	0.899 (0.072)	0.850 (0.064)	0.959 (0.079)	0.790 (0.057)	0.887 (0.088)	0.874 (0.060)
Meteorological Drought (SPI, 24	***2030***	1.007 (0.254)	0.971 (0.274)	0.980 (0.204)	1.010 (0.289)	1.040 (0.250)	1.033 (0.312)	0.920 (0.213)
	2100	0.822 (0.128)	0.926 (0.105)	0.872 (0.100)	0.986 (0.152)	0.803 (0.097)	0.916 (0.150)	0.902 (0.119)
Soil Moisture (10 cm)	***2030***	1.147 (0.894)	0.815 (0.158)	1.024 (0.317)	0.993 (0.310)	1.063 (1.013)	1.087 (0.346)	0.823 (0.171)
	2100	0.583 (0.284)	0.680 (0.105)	0.737 (0.126)	0.888 (0.157)	0.529 (0.369)	1.221 (0.248)	0.692 (0.118)
FSNS	***2030***	0.976 (0.278)	1.231 (0.215)	1.026 (0.199)	1.074 (0.204)	0.870 (0.261)	1.041 (0.181)	1.144 (0.199)
	2100	1.653 (0.559)	1.559 (0.188)	1.876 (0.447)	1.547 (0.309)	1.403 (0.436)	1.135 (0.159)	2.288 (0.378)

Key Take Aways

- The Risk Ratios assessed here do not clearly identify either the control or SAI scenario as performing better for one region or another.
  - There are clear trade offs, in particular between the performance goals which are either precipitation or temperature-based.
- In some regions, for some metrics, SAI reduces risk of exceeding the performance goals with time, but there is large uncertainty (unsurprisingly) in the Risk Ratio responses related to precipitation.
- Clustering together metrics of interest with a range of performance goals demonstrates a possible path forward for both regional decision-making and regulation, as well as identifying where additional research and higher-resolution modeling may be required to better quantify the risks and trade offs of a scenario.
  - For example, running additional simulations using higher temporal resolution output to capture hydrologic extremes at basin scales as is done in Camilloni et. al. (2022).

REFERENCES & DATA

- **Dataset used:** Stratospheric Aerosol Geoengineering Large Ensemble Project (GLENS), https://doi.org/10.5065/D6JH3JXX
- **SPI calculated using:** Adams, J., 2017. climate_indices, an open source Python library providing reference implementations of commonly used climate indices. https://github.com/monocongo/climate_indices
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