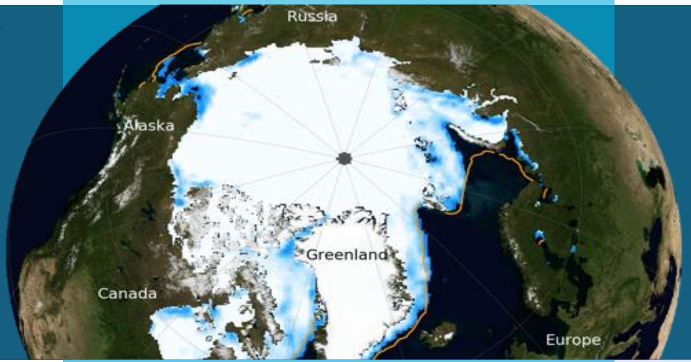
# Global Sensitivity Analysis Using the Ultra-Low Resolution Energy Exascale Earth System Model (E3SM)

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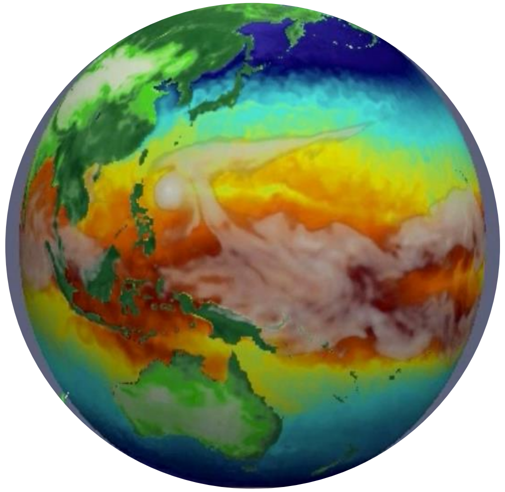
# Outline

- Background and motivation
- Methodology
- Model tuning and spin-up
- Evaluation of the ultra-low resolution (ULR) E3SM
- Global sensitivity analysis results
- Summary



## The focus of this talk is the following paper:

- Paper is **under review** for publication in the *Journal of Advances in Modeling Earth Systems (JAMES)*.
- Pre-print **available** at https://www.essoar.org/doi/10.1002/essoar.10508267.2

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## Abstract

For decades, the Arctic has been warming at least twice as fast as the rest of the globe. As a first step towards quantifying parametric uncertainty in Arctic feedbacks, we perform a variance-based global sensitivity analysis (GSA) using a fully-coupled, ultra-low resolution (ULR) configuration of version 1 of the Department of Energy's Energy Exascale Earth System Model (E3SMv1). The study randomly draws 139 realizations of ten model parameters spanning three E3SMv1 components (sea ice, atmosphere and ocean), which are used to generate 75 year long projections of future climate using a fixed pre-industrial forcing. We quantify the sensitivity of six Arctic-focused quantities of interest (QOIs) to these parameters using main effect, total effect and Sobol sensitivity indices computed with a Gaussian process emulator. A sensitivity index-based ranking of model parameters shows that the atmospheric parameters in the CLUBB (Cloud Layers Unified by Binormals) scheme have significant impact on sea ice status and the larger Arctic climate. We also use the Gaussian process emulator to predict the response of varying each variable when the impact of other parameters are averaged out. These results allow one to assess the non-linearity of a parameter's impact on a QOI and investigate the presence of local minima encountered during the spin-up tuning process. Our study confirms the necessity of performing global analyses involving fully-coupled climate models, and motivates follow-on investigations in which the ULR model is compared rigorously to higher resolution configurations to confirm its viability as a lower-cost surrogate in fully-coupled climate uncertainty analyses.

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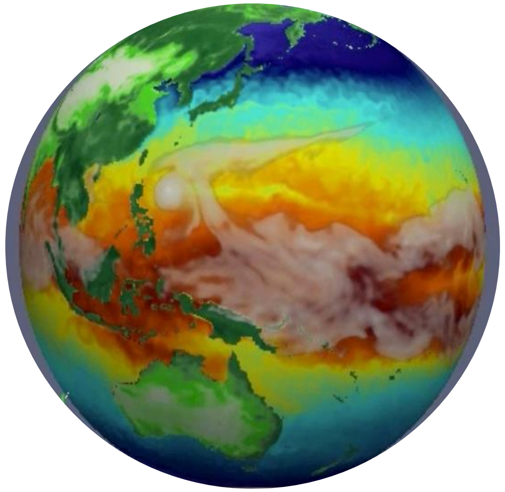
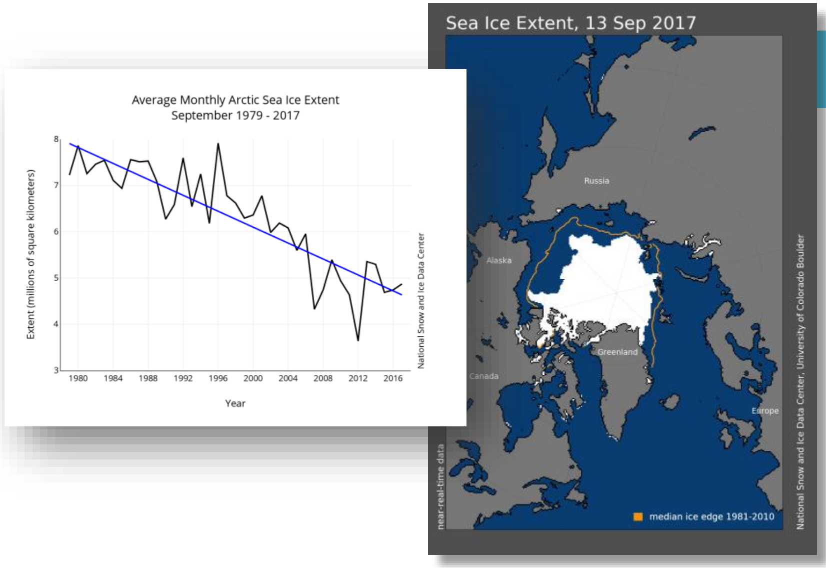
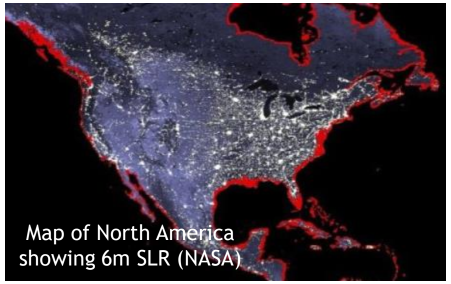


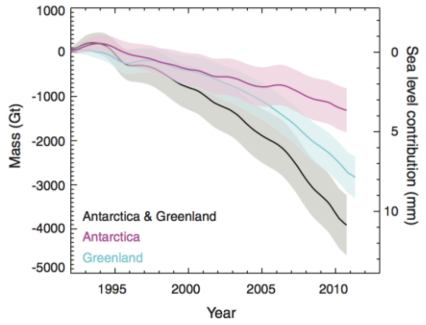
# Background and motivation

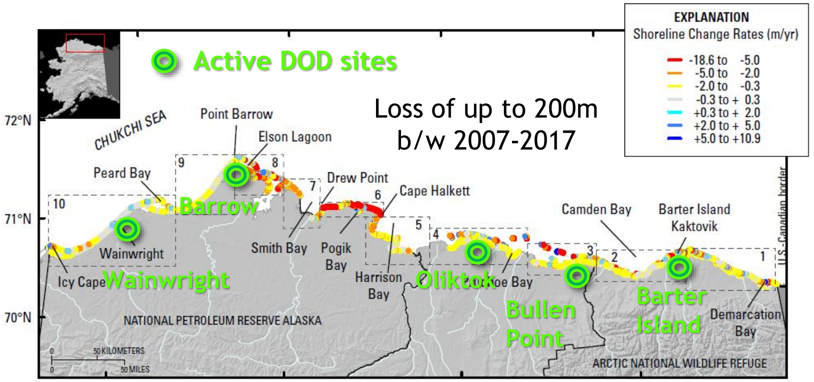
**Arctic systems are strongly coupled and rapidly changing!**

- Arctic is **warming** at twice the rate of the rest of the globe[1]
- Abrupt changes related to **sea ice loss**, **land ice melt** and **permafrost thaw** have the potential to cause significant **global climate impacts**[2]
  - ➢ September **sea ice extent** has declined **13.1% per decade** from 1979-2020 relative to 1979-2010 average[1]
  - ➢ **Global mean sea-level** is rising at the rate of **3.2 mm/year** and this rate is increasing due to **melting** of **polar ice sheets**
  - ➢ **Arctic permafrost** erosion rates have **accelerated**, leading to threats to coastal communities, coastal infrastructure and global carbon balance
- Changes can potentially lead to **tipping events** with significant global impacts[2]
- Research to **advance predictability** and **bound uncertainty** of Earth system models are **crucial** to inform **planning** and **decision-making**




Gibbs & Richmond, 2015

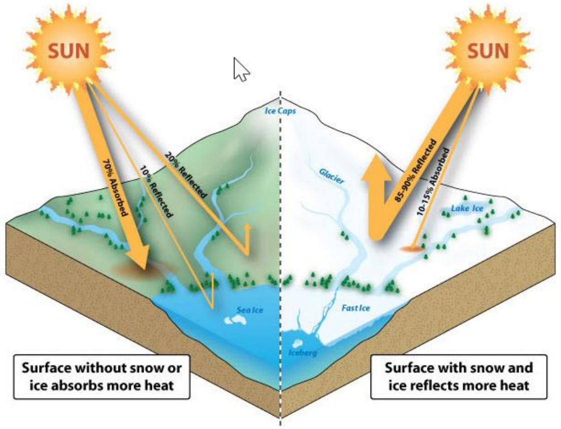
[1] NOAA Arctic Report Card 2020.
[2] "Climate tipping points – too risky to bet against", Lenton *et al*. Nature 2019.

# Background and motivation

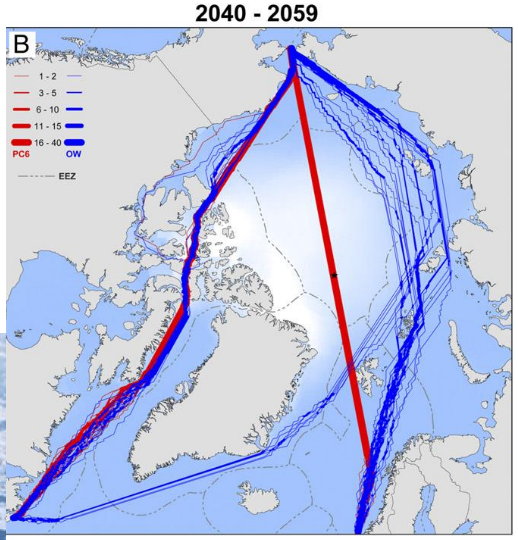
**Goal:** characterize important factors influencing **interannual variability** and **Arctic sea ice loss** in the coupled Earth system

## Why sea ice?

- Sea ice plays an important role in **modulating Earth's climate**
  - ➢ Reflects solar radiation
  - ➢ Influences ocean circulation
- Sea ice loss **impacts other parts** of the Earth system[1]
  - ➢ Impacts to mid-latitude weather, potentially increases in winter storms and drought
  - ➢ Disruption of Atlantic ocean circulation
  - ➢ Increased coastal erosion
- Loss of sea ice is expected to **encourage maritime** and **commercial activity**, potentially contributing to geopolitical conflict[2]
  - ➢ Potential for new trans-Atlantic shipping routes




https://oceanbites.org/sea-ice-and-albedo-should-we-be-worried/


Smith & Stephenson 2013

[1] Cohen *et al.*, 2018; Cvijanovic *et al.*, 2018. Sévellec *et al.*, 2017.
[2] Smith & Stephenson, 2013; "Climate Change and Security in the Arctic", Center for Climate & Security Report, Jan. 2021.

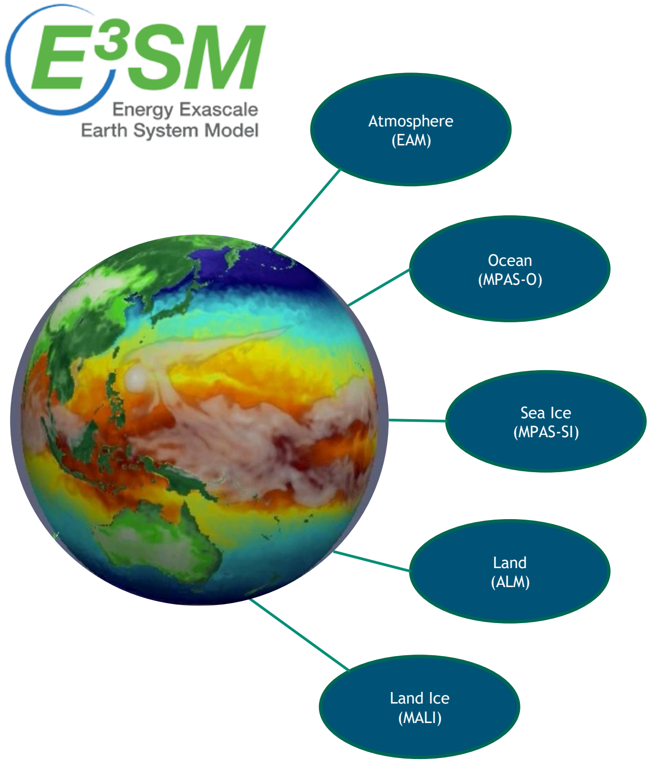
# Objective and Approach

## Objective:

- Gain understanding of **Arctic system dynamics** including feedbacks between Arctic physical systems using **sea ice** as an **exemplar**

## Approach:

- Perform **global sensitivity analysis (GSA)** using the **fully-coupled ultra-low resolution (ULR)** configuration of the Energy Exascale Earth System Model (E3SM)
  - Investigate **uncertainty** and **stability** in E3SM simulations
  - **Analyze trends** and investigate **internal variability** in E3SM simulations of sea ice extent




## Energy Exascale Earth System Model (E3SM):

- U.S. DOE flagship **open-source**[1] coupled Earth system model
- **Collaboration** between 8 national labs and 12 academic institutions
- Development driven by **DOE Office of Science mission interests**: energy and water issues looking out 40 years
- Our study utilized version 1 of the E3SM, denoted by **E3SMv1**, with **pre-industrial control** (1850) forcing at the **ULR** configuration

[1] www.e3sm.org; https://github.com/E3SM-Project/E3SM.

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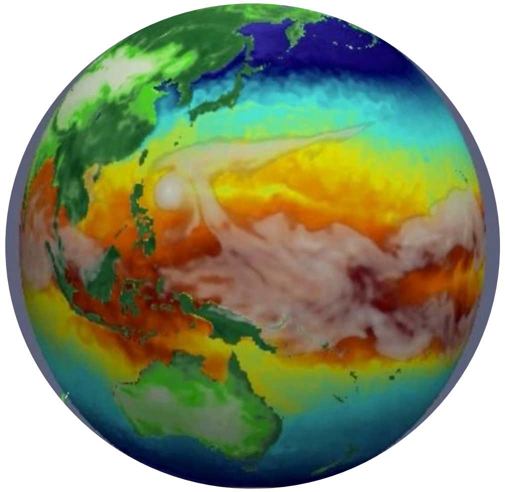


# Methodology

**Global Sensitivity Analysis (GSA):** find which **parameters** have **largest impact** on model's QOIs

- Initial step in **quantifying uncertainty** in model parameterizations and measuring their impact on QOIs
- **Pros:** considers parameter sensitivity over **entire domain**, IDs **cross-component parameter interactions**
- **Cons:** computationally **expensive**!
- **Sobol sensitivity analysis:** quantifies global sensitivity of a QOI $(f)$ as the fraction of the variance due to each parameter $(z_i)$

ANOVA Expansion of QOI: $$f(z) = \hat{f}_0 + \sum_{i=1}^{d} \hat{f}_i(z_i) + \sum_{i,j=1}^{d} \hat{f}_{i,j}(z_i, z_j) + \sum_{i,j,k=1}^{d} \hat{f}_{i,j,k}(z_i, z_j, z_k) + \ \dots = \sum_{\boldsymbol{u} \subseteq D} \hat{f}_{\boldsymbol{u}}(z_{\boldsymbol{u}})$$

Variance of QOI: $$\mathbb{V}[f] = \sum_{\boldsymbol{u} \subseteq D} \mathbb{V}[\hat{f}_{\boldsymbol{u}}]$$

Main effect indices: $$S_i^M = \frac{\mathbb{V}[\hat{f}_{\boldsymbol{e}_i}]}{\mathbb{V}[f]}$$

Measure effect of individual parameters acting alone

Total effect indices: $$S_i^T = \frac{\sum_{\boldsymbol{u} \subseteq J} \mathbb{V}[\hat{f}_{\boldsymbol{u}}]}{\mathbb{V}[f]}$$

Sobol indices: $$S_{\boldsymbol{u}} = \frac{\mathbb{V}[\hat{f}_{\boldsymbol{u}}]}{\mathbb{V}[f]}$$

Measure contribution of each parameter and parameter interactions to the variance of QOI

# Parameters

| Component | Notation | Parameter | Units | Min | Max | Description |
|---|---|---|---|---|---|---|
| Sea Ice (MPAS-SeaIce) | $z_1$ | ksno | W/(mK) | 0.2 | 0.6 | Snow conductivity |
| | $z_2$ | lambda_pond | 1/s | 1.15e-8 | 1.15e-4 | Drainage timescale of ponds |
| | $z_3$ | dragio | – | 0.2e-3 | 160e-3 | Neutral ocean-ice drag |
| Atmosphere[1] (EAM) | $z_4$ | clubb_c1 | – | 1.0 | 5.0 | Const assoc. w/ dissipation of variance $w'^2$ |
| | $z_5$ | clubb_c8 | – | 2.0 | 8.0 | Const assoc. w/ Newtonian damping of $w'^3$ |
| | $z_6$ | gamma_coeff | – | 0.1 | 0.5 | Const of width of PDF in $w$ coord |
| | $z_7$ | cldfrc_dp1 | – | 0.02 | 0.1 | Deep convection cloud fraction parameter |
| Ocean (MPAS-O) | $z_8$ | standardgm_tracer_kappa | $m^2/s$ | 600 | 1800 | Bolus coefficient of GM parameterization of eddy transport |
| | $z_9$ | cvmix_kpp_criticalbulkrichardson_number | – | 0.2 | 1.0 | Bulk Richardson number used in KPP vertical mixing scheme |

[1] CLUBB (Cloud Layers Unified by Binormals): cloud physics parameterization in EAM.

- **Nine parameters** span **three E3SM components** (sea ice, atmosphere, ocean)
- Parameters and parameter ranges were guided by **past analyses** [Urrego-Blanco *et al.*, 2016; Urrego-Blanco *et al.* 2019; Reckinger *et al.*, 2015; Asay-Davis *et al.*, 2018; Qian *et al.*, 2018; Rasch *et al.*, 2019]

# Quantities of Interest (QOIs)

| QOI | Units | Description | Component |
|---|---|---|---|
| SIE | $km^2$ | Total Arctic sea ice extent | Sea ice |
| SIV | $km^3$ | Total Arctic sea ice volume | Sea ice |
| SST | °C | Sea surface temperature averaged over 60-90° N | Ocean |
| TS | °C | Surface air temperature averaged over 60-90° N | Atmosphere |
| FLNS | $W/m^2$ | Net longwave flux at surface over 60-90° N | Atmosphere |
| CLDLOW | – | Low cloud coverage below 700 hPa averaged over 60-90° N | Atmosphere |

- **Six QOIs** span **three E3SM components** (sea ice, ocean and atmosphere)
- QOIs are **Arctic-focused**, motivated by literature [Urrego-Blanco *et al.*, 2016; Urrego-Blanco *et al.*, 2019]
- QOIs are computed by **averaging annually** and **seasonally** over **last 25 years** of each 75-year simulation

# GSA workflow with fully-coupled E3SM

*N=202 75-year E3SM runs, **M=139** of which **succeeded** (~69%)*

*See talk by J. Jakeman, MS47, Wed AM*

[1] Flexible and efficient open-source tool for high-dimensional approximation and UQ: https://github.com/sandialabs/pyapprox

***Step 0a.*** Obtain **initial condition** by **spin-up** of ULR E3SMv1 to physical equilibrium

***Step 0b.*** **Generate** using DAKOTA $N$ **randomly perturbed parameter sets** as E3SM inputs

***Step 1.*** Create **E3SM namelist files** for $N$ tuning realizations of **perturbed parameter sets** for different model components

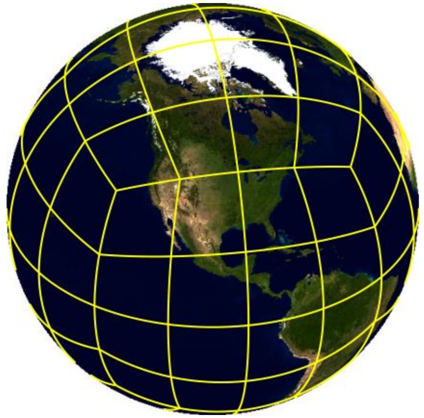
***Step 2.*** **Launch** $N$ E3SM runs, **branching** off equilibrated E3SM initial condition

***Step 3.*** **Post-process** the $M \leq N$ successful perturbed simulation results to **extract Quantities of Interest (QoIs)**

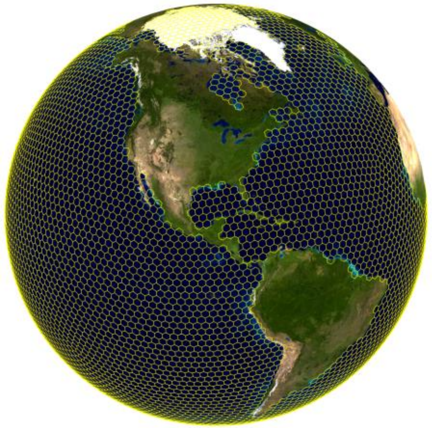
***Step 4.*** Perform **Global Sensitivity Analysis** by providing $M$ QOI-parameter pairs to **PyApprox**

https://dakota.sandia.gov

*Sensitivity indices for each QOI were computed using a **Gaussian process** (GP) emulator using **PyApprox**[1]*



*Above*: ULR atmosphere grid ($\approx 7.5°$)
*Below*: ULR ocean/sea ice grid (240km or $\approx 2.2°$)



The **ULR configuration** enables sufficient ensemble generation for **full GSA** with the **fully-coupled E3SM!**

- ULR E3SM configuration is $\approx \mathbf{100} \times$ **less expensive** to run than the "standard" 1° resolution E3SM
  - Using the ULR E3SM, our study took $\approx \mathbf{1.00 \times 10^6}$ **CPU hours**[1] on Sandia's Skybridge HPC cluster
  - The same study using the standard 1° resolution E3SM would require $\approx \mathbf{1.14 \times 10^8}$ **CPU hours**

[1] Equivalent to 24 sypd on 6 Skybridge nodes.

# Previous related work

## Sensitivity analysis of individual Earth system components:

- "Uncertainty quantification and global sensitivity analysis of the Los Alamos sea ice model", Urrego-Blanco *et al.*, *JGR Oceans*, 2016.
  - ➢ Sobol sensitivity analysis of 1° resolution LANL CICE model on 39 sea ice parameters
- "Parametric sensitivity and uncertainty quantification in the version 1 of E3SM atmosphere model based on short perturbed parameter ensemble simulations", Qian *et al.*, *JGR Atmospheres*, 2018.
  - ➢ Used short (3-day) simulations of 1° resolution EAM to study sensitivity w.r.t. 18 atmosphere parameters
- "Antarctic ice shelf-ocean interactions in high-resolution, global simulations using the E3SM Part 2: Sensitivity studies and model tuning", Asay-Davis *et al.*, *Ocean Sciences Meeting*, *AGU*, 2018.
  - ➢ Used ≈30km (≈ 1°) resolution in Southern Ocean and Antarctic continental shelf to perform local sensitivity analysis of 12 land ice + ocean parameters using the Greens' function method (GFM).

## Sensitivity analysis of Earth system models for polar quantities of interest:

- "Emergent relationships among sea ice, longwave radiation, and the Beaufort high circulation exposed through parameter uncertainty analysis", Urrego-Blanco *et al.*, *JGR Oceans*, 2019.
  - ➢ Used 1° resolution E3SMv0 with MOAT method, 5 parameters and 24 ensemble members

Our work **builds** on this research by performing the **first Global Sensitivity Analysis** with a **fully-coupled E3SMv1**

# Previous related work

*See talk by N. Urban, MS15, Tues PM*

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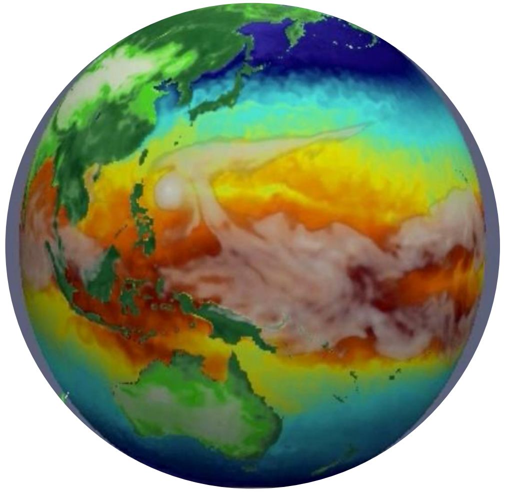


# Model tuning and spin-up

**Objective:** before initializing perturbed runs, run the model until an **equilibrium**, **Earth-like state** is achieved using pre-industrial (1850) control (piControl) forcing in which we have

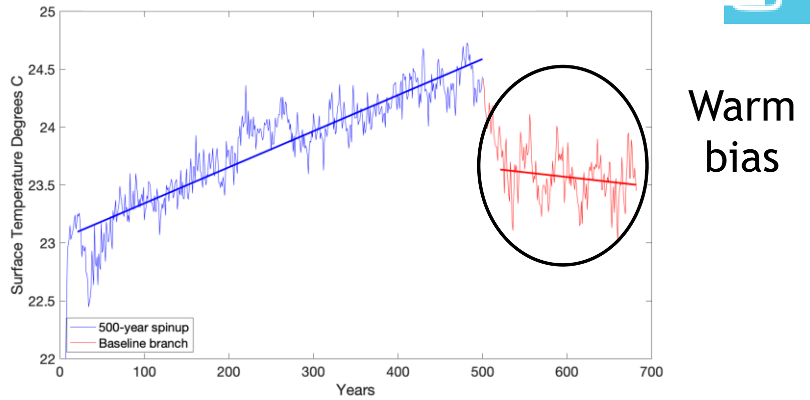
- Constant global average mean **surface air temperature**, (a)
- Near-zero long-term average net **top-of-atmosphere (TOA) energy flux**, (b)
- Stable yearly **sea ice coverage**, (c)

**Spin-up approach:**

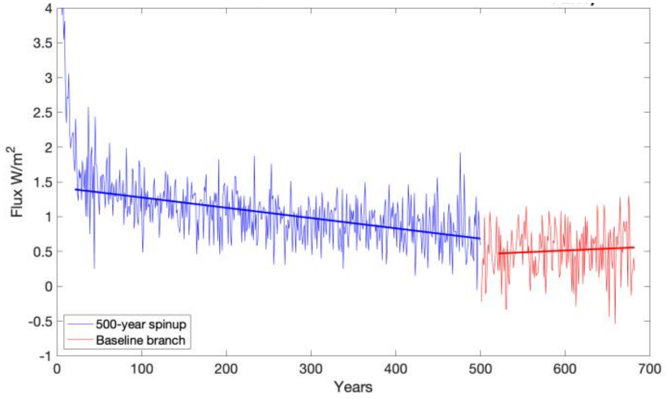
- 500 year run with pre-industrial control forcing, **default parameter values**
- 180 year run branched from 500 year initial run, with **parameter values from Golaz *et al*. 2018**
- **Year 675** of the branch run was used as **IC** for GSA runs

*Right figures*: bold lines indicate linear trends in years 26-500 and 526-800. Trends are much closer to 0 for branch run (slope = $-0.00082$, $0.0005$, $0.0012$ for surface temperature, TOA flux, Arctic sea ice, respectively)

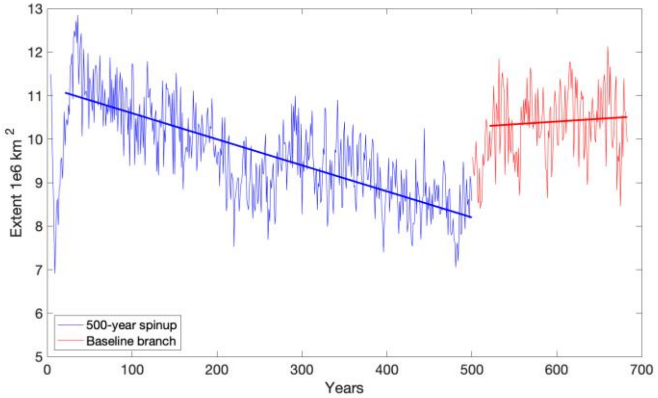
(a) Global Yearly Average Surface Temperature




(b) Global Yearly Average Net Flux at Atmosphere




(c) Global Yearly Average Sea Ice Extent



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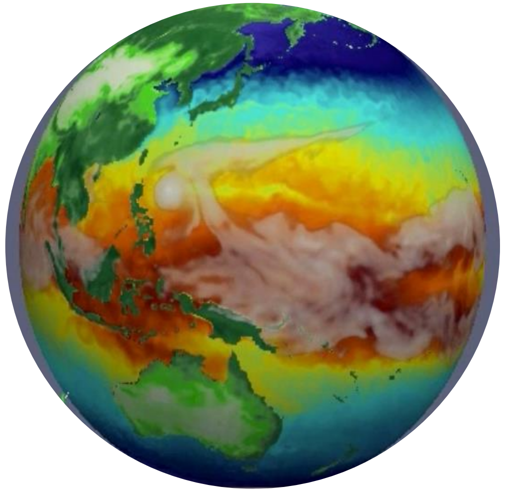


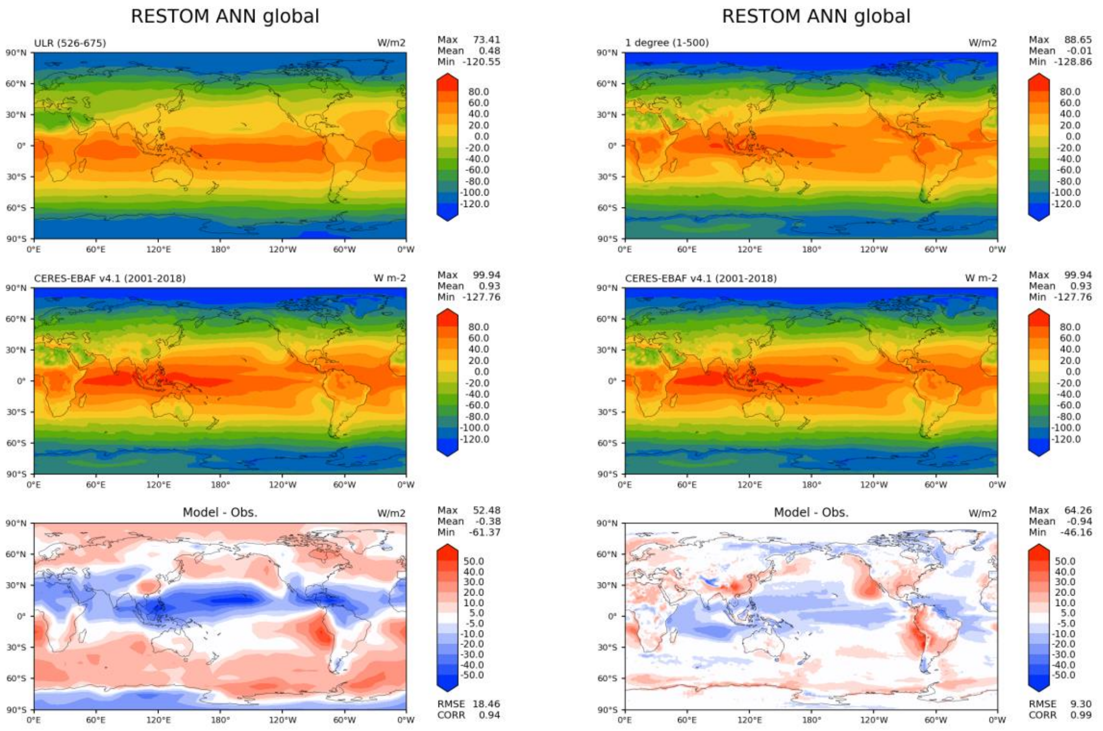
# How good is the ULR E3SM?

- ULR configuration of the E3SM has not been **scientifically validated**; it was designed primarily for **rapid turn-around testing**
- Years 526-675 of the ULR simulation were compared to **observational data** from CERES-EBAF Ed4.1 [Loeb *et al*. 2018] and ERA-Interim reanalysis [Dee *et al*., 2011], and **1° resolution E3SM** simulation data

Model

CERES-EBAF Ed4.1

Diff.




(a) ULR E3SM

(b) 1° E3SM

*Left figures*: TOA flux (W/m$^2$) for (a) years 526-675 of branched ULR spin-up simulation and (b) years 1-500 of the 1° piControl, compared with CERES-EBAF Ed4.1 data

*Although ULR simulation does not capture small-scale/regional features seen in 1° resolution simulation, **large-scale patterns are similar**.*

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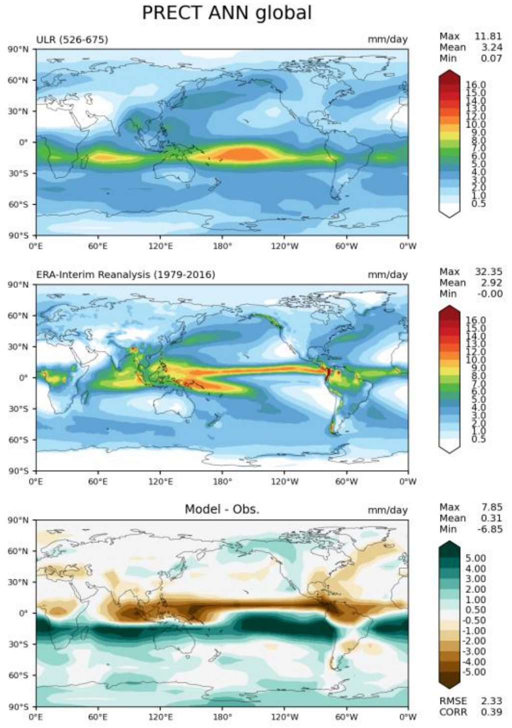
Model

ERA-Interim

Diff.

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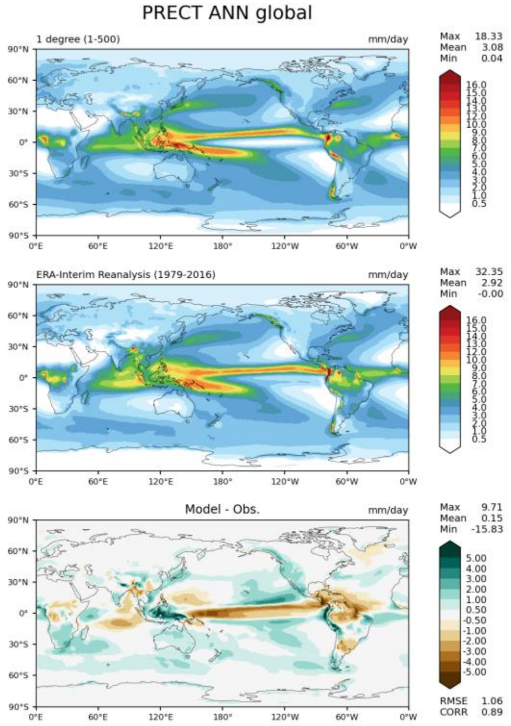


(b) 1° E3SM

*Left figures*: Total precipitation (mm/day) for (a) years 526-675 of branched ULR spin-up simulation and (b) years 1-500 of the 1° piControl, compared with ERA-Interim data

*Although ULR simulation does not capture small-scale/regional features seen in 1° resolution simulation, **large-scale patterns are similar**.*

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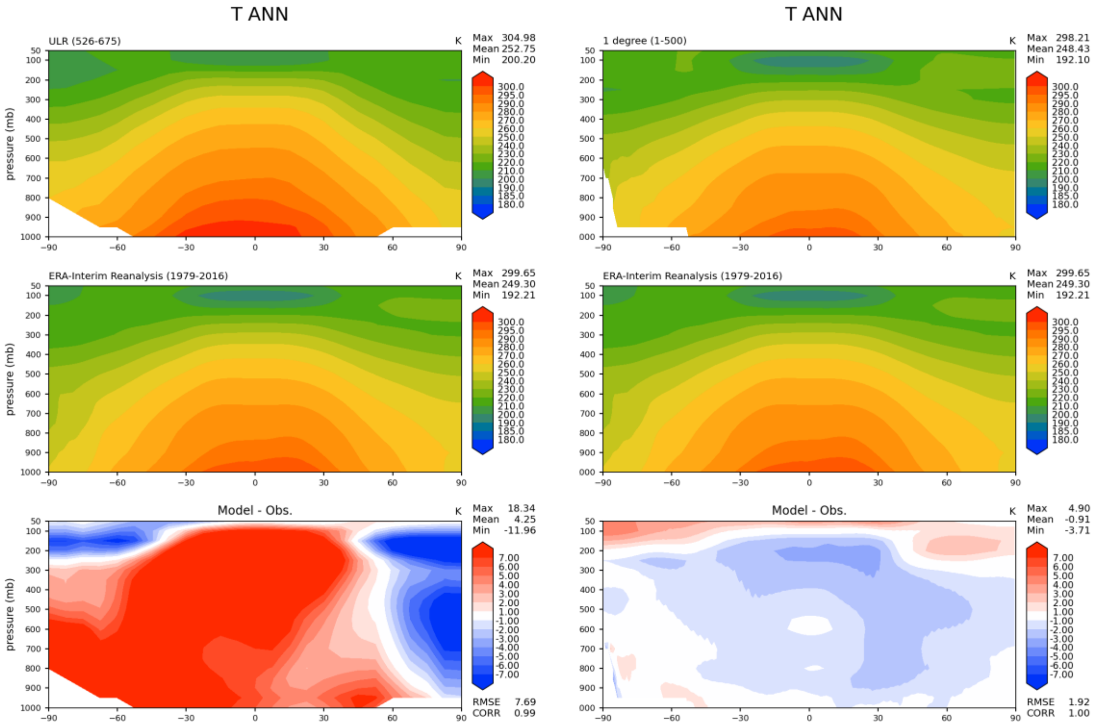


(a) ULR E3SM

(b) 1° E3SM

*Left figures*: Zonal temperature (°C) for (a) years 526-675 of branched ULR spin-up simulation and (b) years 1-500 of the 1° piControl, compared with ERA-Interim data, to demonstrate vertical variation in atmosphere

*Temperature field shows most divergence from observations (**warm bias of ~8°C**)*

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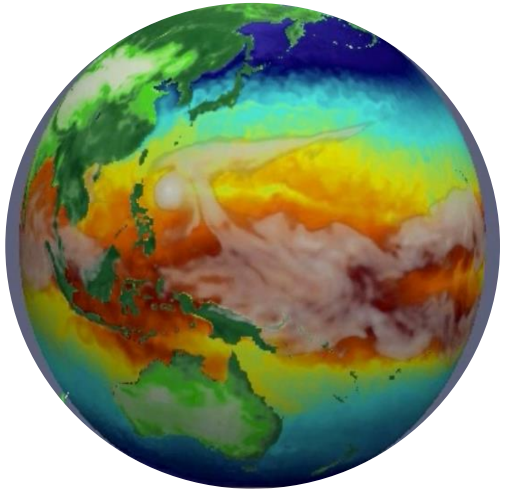
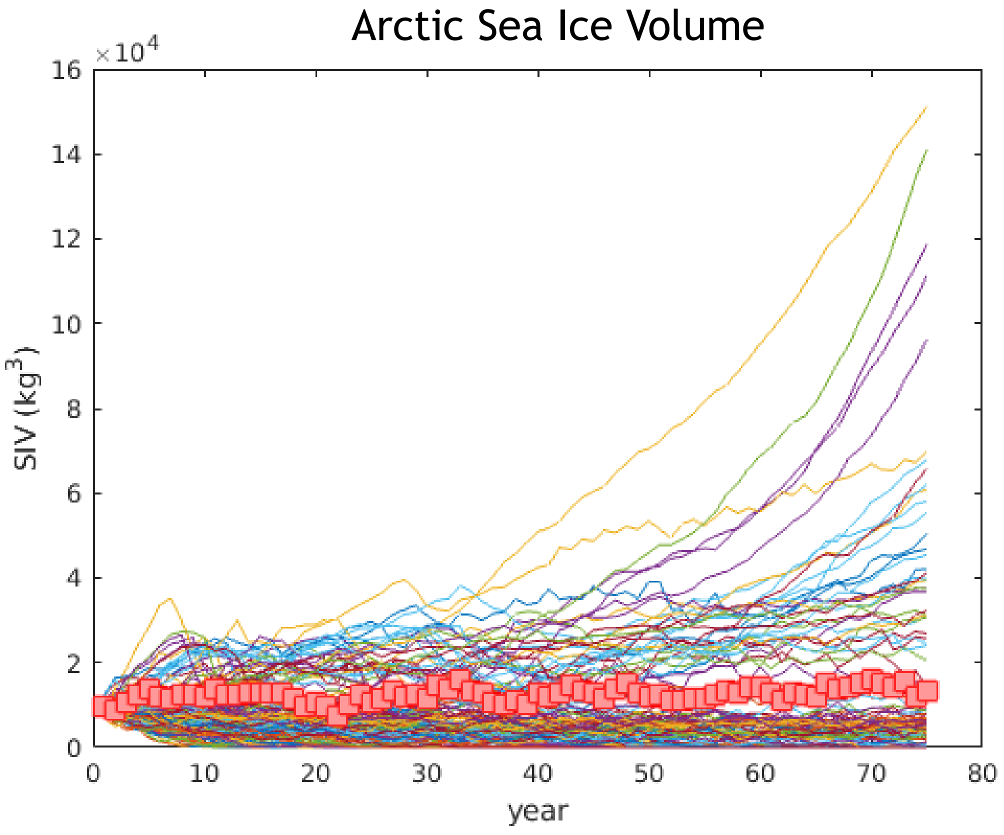
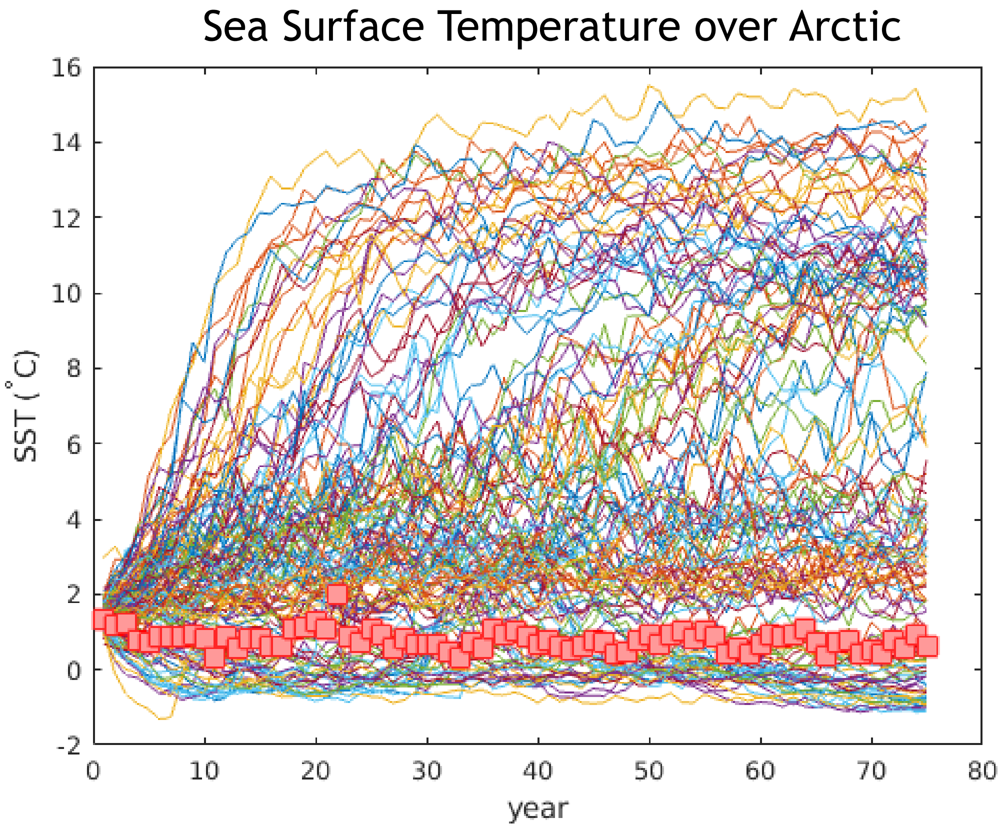


# Ensemble trajectories



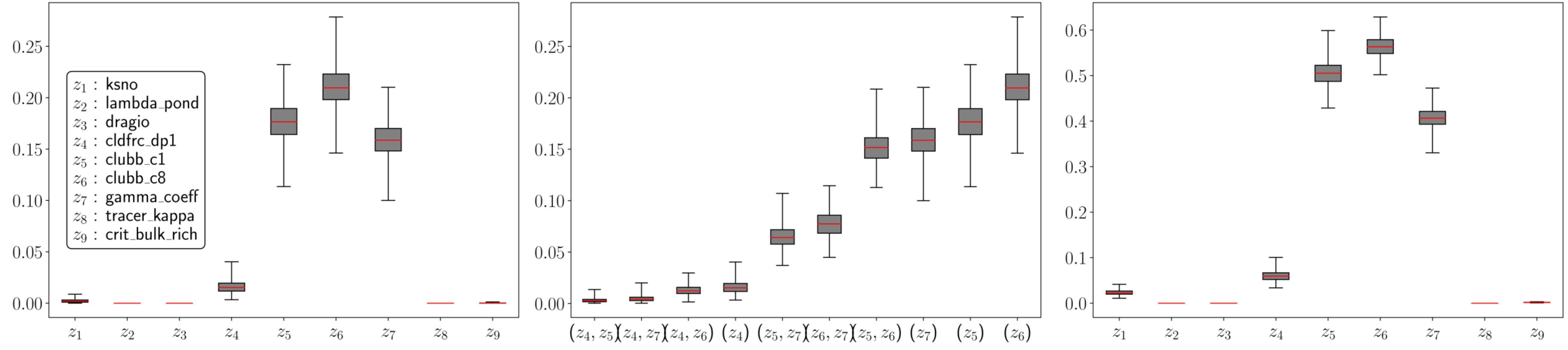

- Most perturbed runs have reached **equilibrium** by **year 40**
- Runs exhibit a great deal of **variability**:
  - Several runs result in complete loss of Arctic sea ice
  - Several runs exhibit apparent exponential growth in sea ice

*Figures above*: "Spaghetti plot" of two QOIs for our 139 successful ULR runs. Red markers indicate baseline run (no parameter perturbation)

# GSA results: sensitivity indices

[1] Measure effect of individual parameters acting alone
[2] Measure variance that remains after learning values of every variable except $z_i$
[3] Measure contribution of interaction between parameter subset $\boldsymbol{u}$ on the variance of a QOI

Main Effects[1] | Sobol Indices[2] | Total Effects[3]




Sea ice params | Atmosphere params | Ocean params

- Figure above shows **sensitivity indices** for **Sea Ice Volume QOI** in **spring**

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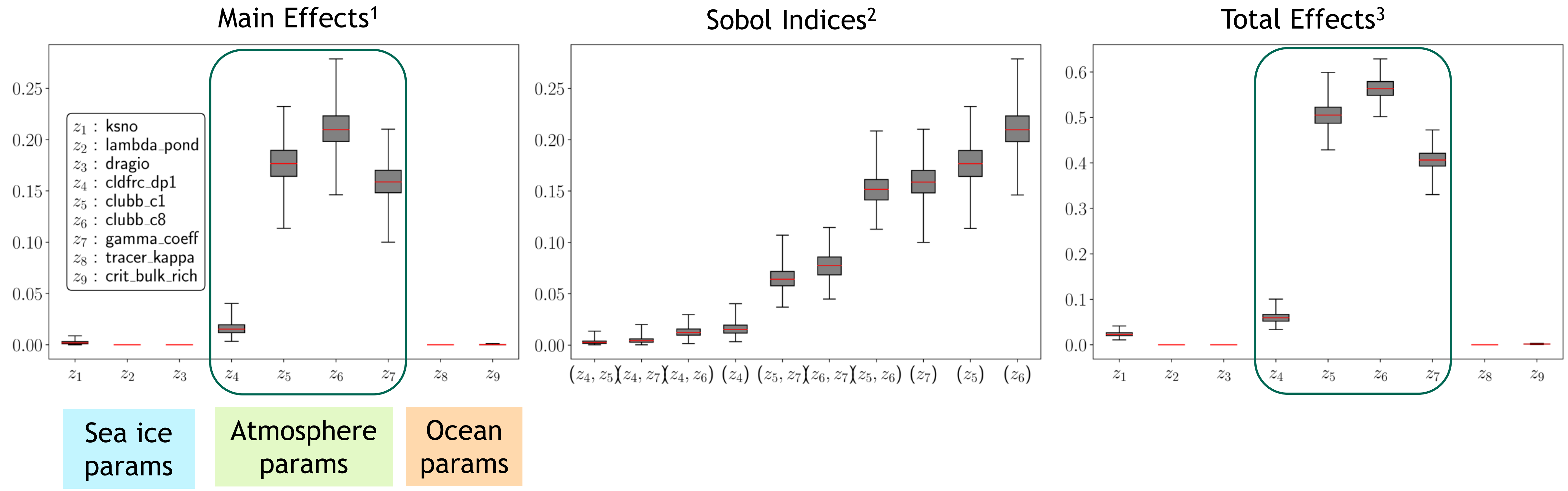


- Figure above shows **sensitivity indices** for **Sea Ice Volume QOI** in **spring**
- Atmospheric **parameters related to cloud parameterizations** (CLUBB) are **most important** for all QOIs; $z_6$ (clubb_c8) has largest total effects

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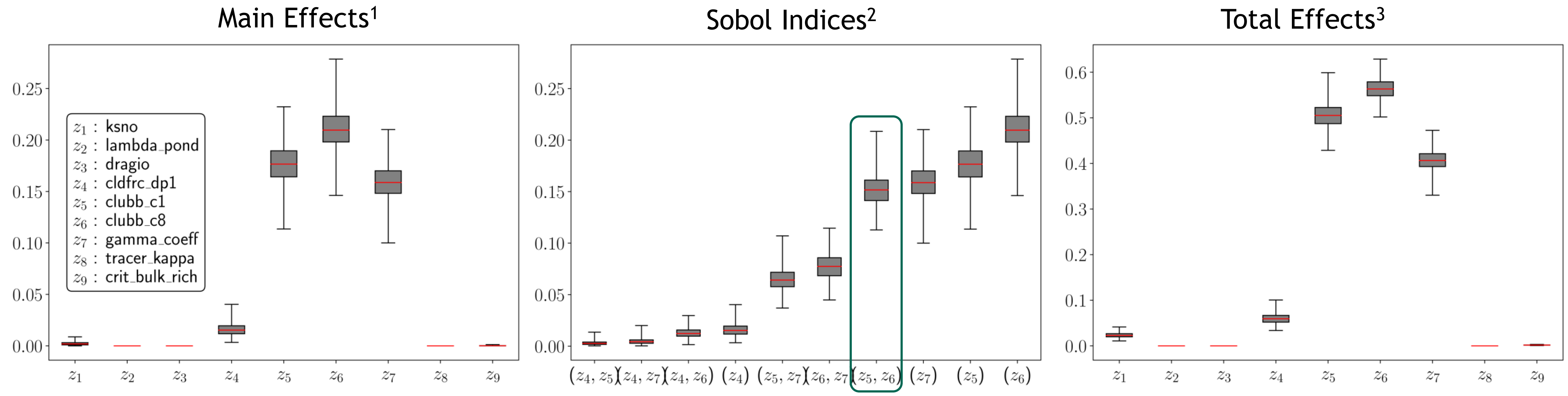


Sea ice params

Atmosphere params

Ocean params

*$z_5$ (clubb_c1) and $z_6$ (clubb_c8) combined effects are stronger than total effects for 5 insensitive parameters*

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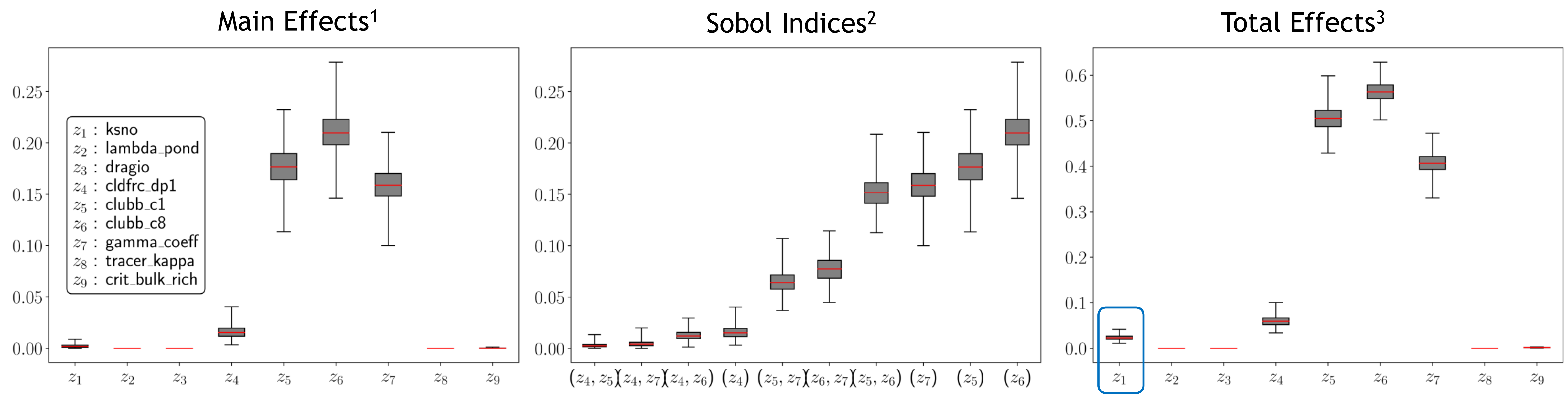


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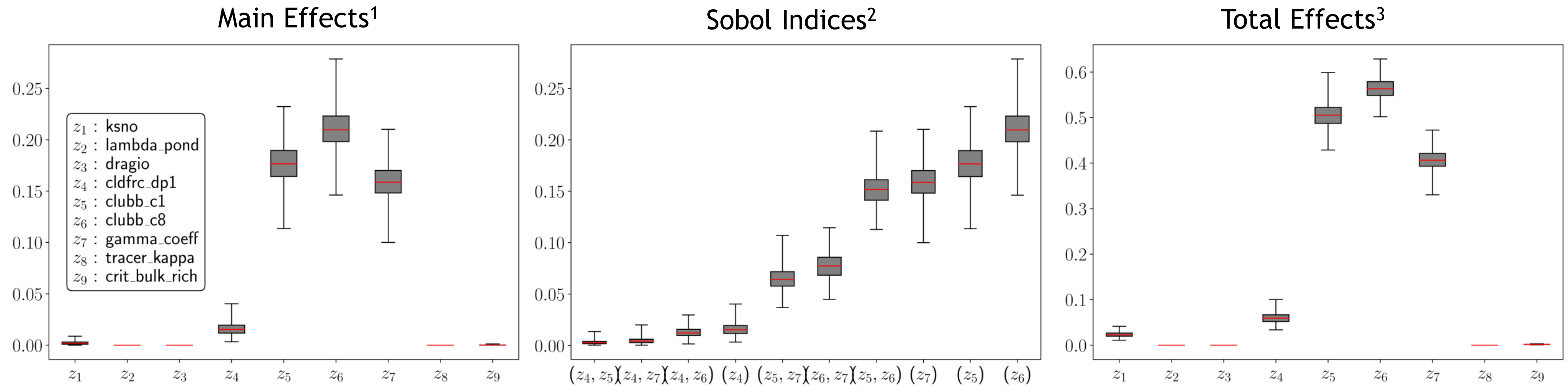


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- Analysis also reveals **significant parameter interactions** between atmosphere parameters
- Non-zero total effect indices associated with **sea ice parameters** are seen for several QOIs
- Effects of **ocean parameters** and their interactions with each other/other parameters are **negligible**

Results are **qualitatively similar** to MOAT fully-coupled E3SMv0 study in [Urrego-Blanco *et al.*, 2019]

# GSA results: sensitivity indices

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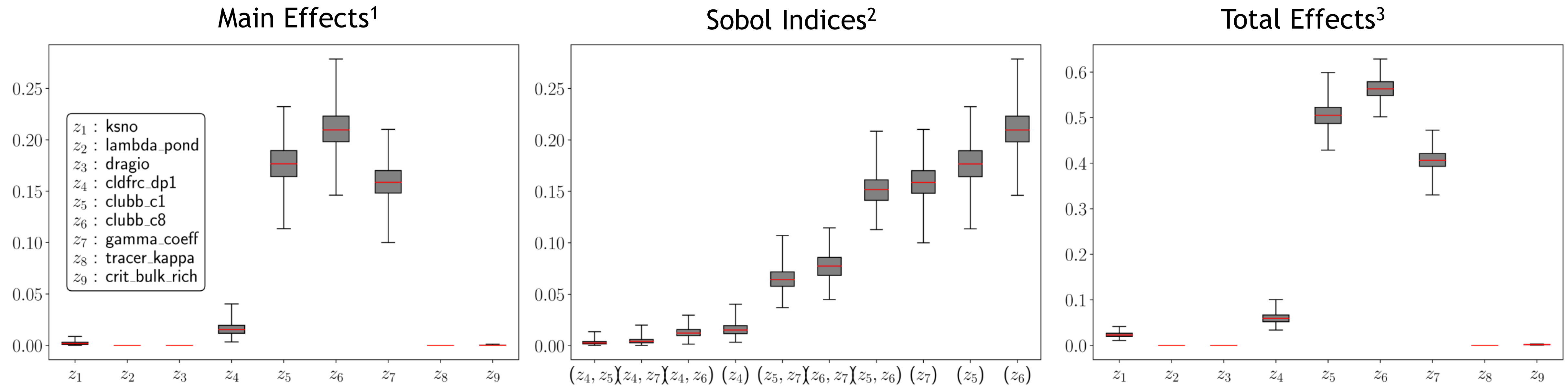


Sea ice params | Atmosphere params | Ocean params

*$z_5$ (clubb_c1) and $z_6$ (clubb_c8) combined effects are stronger than total effects for 5 insensitive parameters*

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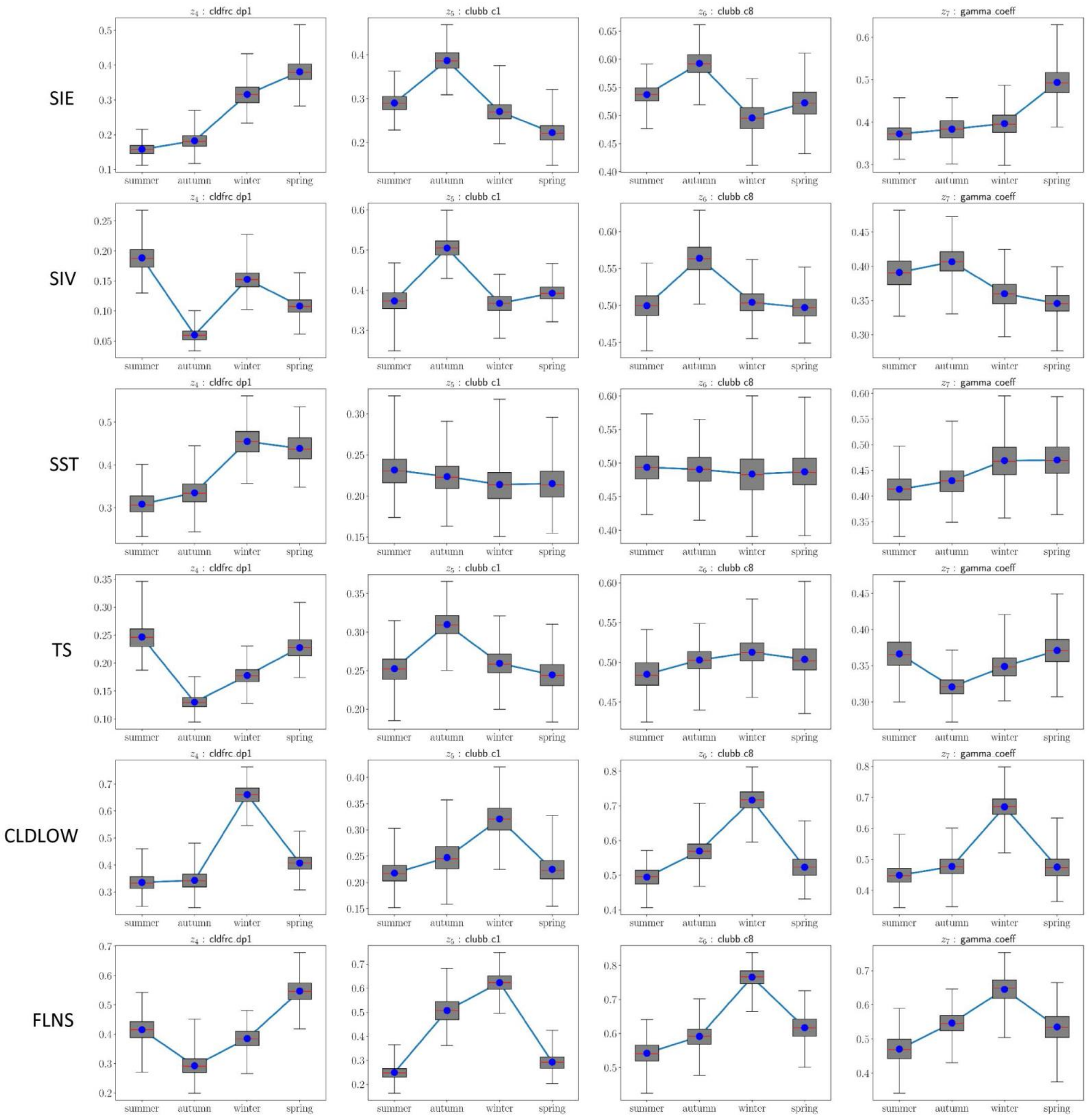
- Non-zero total effect indices associated with **sea ice parameters** are seen for several QOIs
- Effects of **ocean parameters** and their interactions with each other/other parameters are **negligible**

Although **atmospheric parameters** are most influential, they influence **sea ice** and **ocean QOIs** → analysis requires ***fully-coupled*** E3SM

# GSA results: total effects indices – atmosphere parameters




***Conclusions drawn from atmosphere parameters' total effects indices can be related to physical processes.***

- SIE[1] QOI shows **strong response** to $z_6$ (clubb_c8) in fall
  - Increasing $z_6$ (clubb_c8) **brightens clouds**, resulting in Earth surface **cooling** [Larson, 2020]
  - Suggests that **cloud brightening** has potential to control **degree** to which **sea ice is lost** towards the end of the melting season
- Sensitivities in SIE & SIV[2] have strong **cyclical trends**
  - For $z_4$ (cldfrc_dp1) and $z_7$ (gamma_coeff), SIE[1] and SIV[2] **trend differently** – could reflect difference between **young, seasonal ice** and relatively stable **multi-year ice**
- Sensitivity of CLDLOW[3] to clubb_c1 ($z_5$) in fall is **not as strong** as sensitivity of FLNS[4]
  - Results suggest while clubb_c1 ($z_5$) influences **cloud type**, it may not strongly influence the fraction of **general low cloud cover**

⋮

[1] Sea Ice Extent. [2] Sea Ice Volume. [3] Low Cloud Overage below 700 hPa over Arctic. [4] Net longwave flux at surface over Arctic.

# GSA results: marginalized main effects

- Sensitivity analysis results can be used to calculate **normalized posterior mean of the main effect functions marginalized over one parameter at a time**, $\pm 2$ standard deviations:

$$\mathbb{V}^*[Y]^{-\frac{1}{2}}(\mathbb{E}^*\left[\mathbb{E}[Y|z_i]\right] - \mathbb{E}^*[\mathbb{E}[Y]] \pm 2\mathbb{V}^*[Y]^{-\frac{1}{2}}\mathbb{V}^*[\mathbb{E}[Y|z_i]]^{1/2}$$

* : expectation over posterior distribution of GP

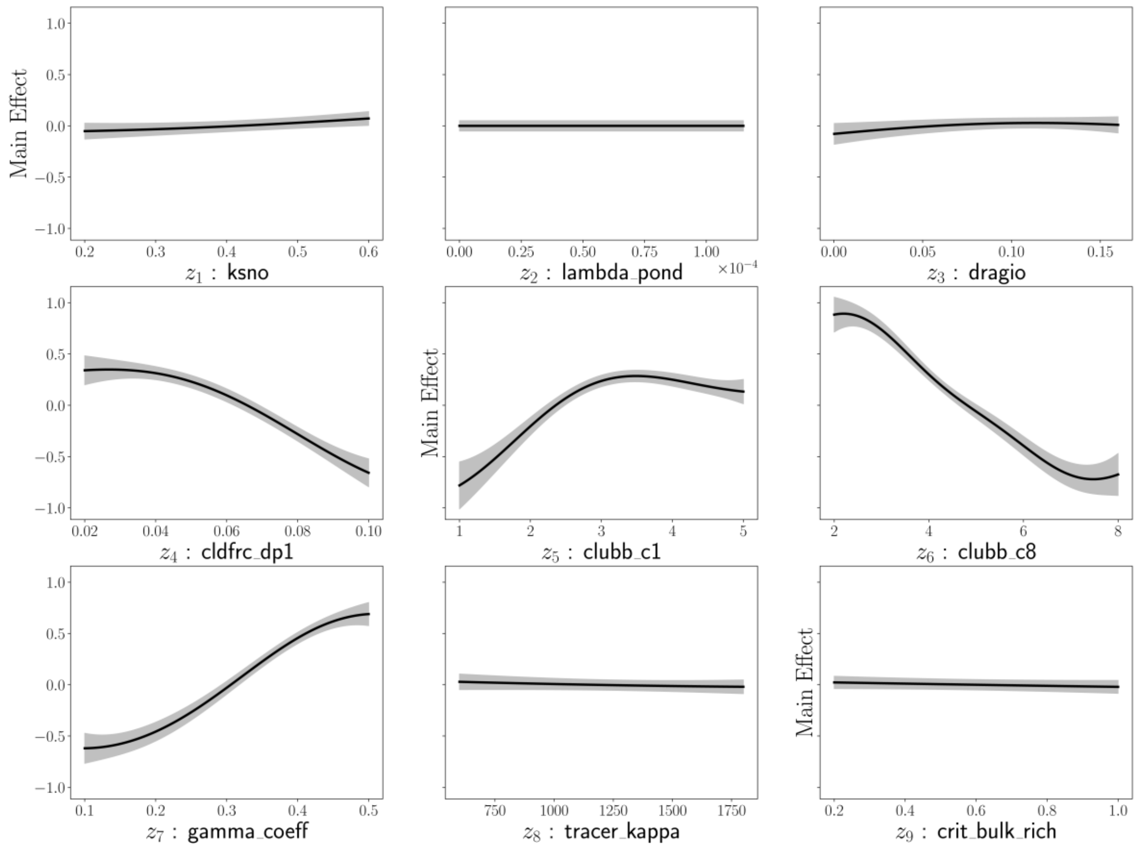



*Figure:* marginalized main effects for surface temperature (TS) QOI. 95% CIs shown in gray.

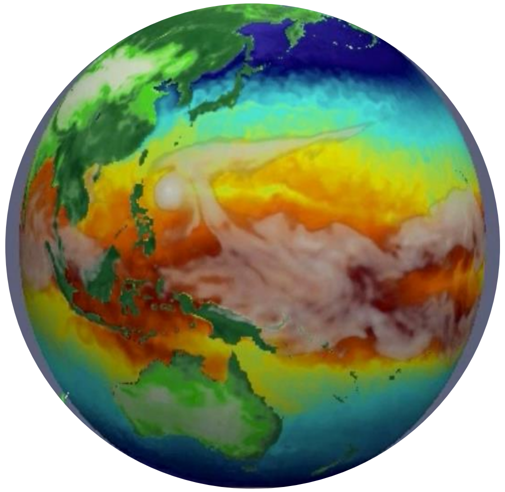
Results can help **validate** ULR E3SM and **guide model spin-ups**.

- Decreasing $z_5$/ $z_7$ and/or increasing $z_4$/ $z_6$ will **bring down** surface temperature
- Increasing $z_6$ (clubb_c8) is known to lead to **cloud brightening** and **cooling** the Earth's surface
- Low values of $z_5$ (clubb_c1) favor **insolation-reducing stratiform clouds** ⇒ **cooling**
- **Curvature** in $z_1$ (ksno) and $z_3$ (dragio[1]) **match trends** in [Urrego-Blanco *et al.*, 2016]
- Results are **consistent** with **manual tuning** trends observed

[1] Neutral ocean-ice drag

# Outline

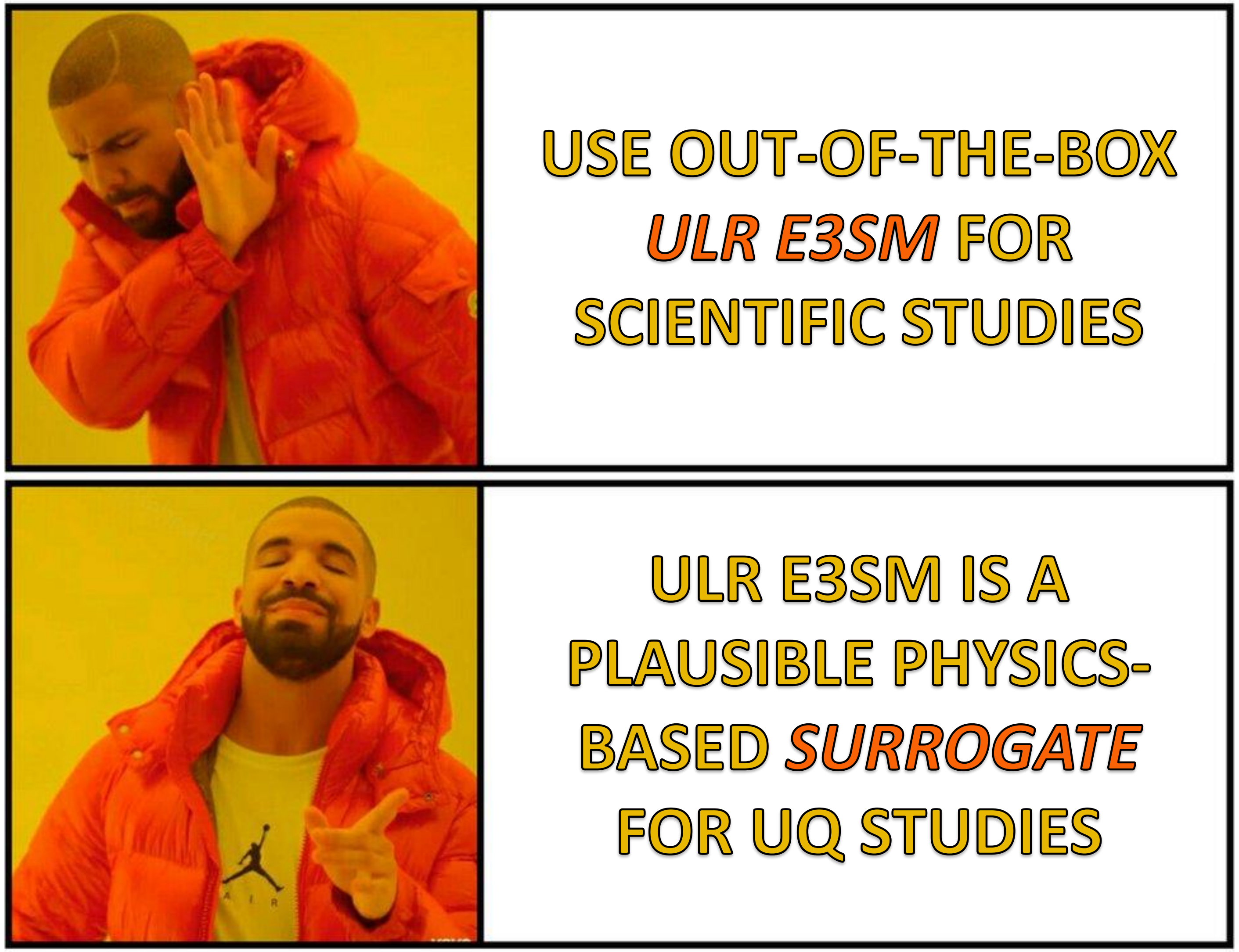
- Background and motivation
- Methodology
- Model tuning and spin-up
- Evaluation of the ultra-low resolution (ULR) E3SM
- Global sensitivity analysis results
- **Summary**



# Summary

- We performed a **GSA** involving **9 parameters** and **6 QOIs** spanning **3 climate components** (atmosphere, ocean, sea ice) using the **ULR configuration** of the **fully-coupled E3SMv1**
  - **First** GSA using E3SMv1
  - A study of this scope is currently **intractable** using higher-resolution scientifically-validated configurations (e.g., 1° E3SM)
- A **spin-up** of the ULR E3SMv1 was performed to achieve an **equilibrium climate**
- ULR E3SM reproduced **large-scale patterns** in TOA radiation, precipitation, zonal mean temperature and zonal mean wind compared to observational data (CERES-EBAF, ERA-Interim) and the 1° E3SM
- **Main effect**, **total effect** and **Sobol indices** were calculated using a fast **Gaussian Process (GP) emulator** from 139 75-year runs of ULR E3SMv1 using the PyApprox software
- QOI-QOI and parameter-parameter interactions using sensitivity indices were able to **reconcile** relationships with several **well-known Arctic feedbacks**
- The **atmospheric parameters** related to cloud physics (CLUBB model in EAM) and their interactions had the largest impact on the Arctic climate state
  - Parameters were shown to affect **QOIs** from **3 different climate components**
- **Marginalized main effects functions** demonstrated that trends uncovered by this study are consistent with **manual spin-up** of ULR E3SMv1 and **physical processes** underlying the CLUBB parameterization

# Summary



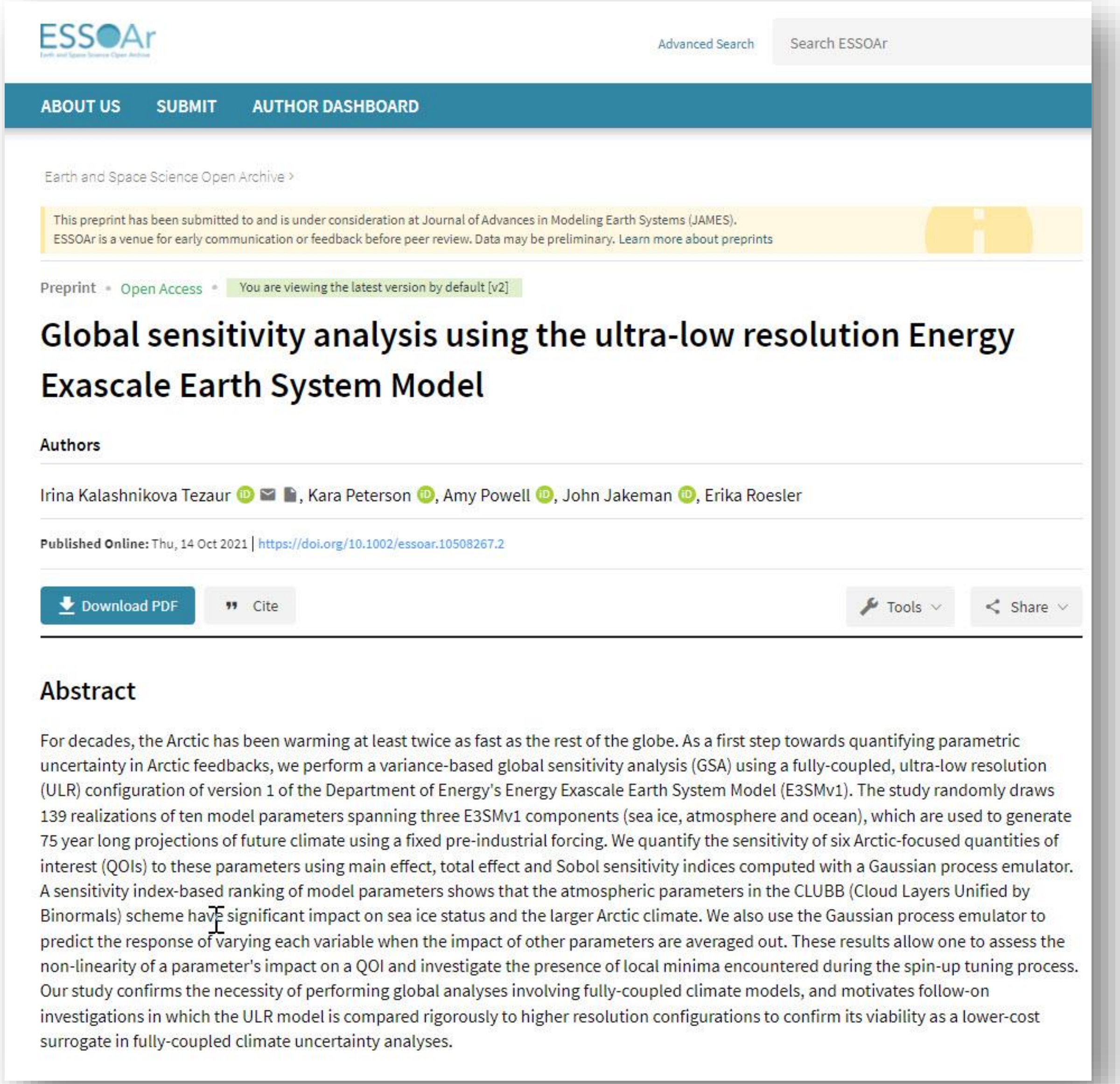

## Significance of this work:

- Our study can serve as a **baseline** for and **guide** future studies with higher-resolution models, if/when it is **tractable** to repeat our GSA using higher-resolution E3SM
- Results can be used to show **number of samples** needed to get even moderate **accuracy** in a sensitivity analysis with variety of parameters → useful for predicting **computational budget** for future GSAs

## Future work:

- Augment present study with higher-fidelity ensemble data (e.g., medium-low resolution 2.7° E3SM), towards a **multi-fidelity GSA**

# References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Global sensitivity analysis using the ultra-low resolution Energy Exascale Earth System Model

Authors

Irina Kalashnikova Tezaur, Kara Peterson, Amy Powell, John Jakeman, Erika Roesler

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Abstract

For decades, the Arctic has been warming at least twice as fast as the rest of the globe. As a first step towards quantifying parametric uncertainty in Arctic feedbacks, we perform a variance-based global sensitivity analysis (GSA) using a fully-coupled, ultra-low resolution (ULR) configuration of version 1 of the Department of Energy's Energy Exascale Earth System Model (E3SMv1). The study randomly draws 139 realizations of ten model parameters spanning three E3SMv1 components (sea ice, atmosphere and ocean), which are used to generate 75 year long projections of future climate using a fixed pre-industrial forcing. We quantify the sensitivity of six Arctic-focused quantities of interest (QOIs) to these parameters using main effect, total effect and Sobol sensitivity indices computed with a Gaussian process emulator. A sensitivity index-based ranking of model parameters shows that the atmospheric parameters in the CLUBB (Cloud Layers Unified by Binormals) scheme have significant impact on sea ice status and the larger Arctic climate. We also use the Gaussian process emulator to predict the response of varying each variable when the impact of other parameters are averaged out. These results allow one to assess the non-linearity of a parameter's impact on a QOI and investigate the presence of local minima encountered during the spin-up tuning process. Our study confirms the necessity of performing global analyses involving fully-coupled climate models, and motivates follow-on investigations in which the ULR model is compared rigorously to higher resolution configurations to confirm its viability as a lower-cost surrogate in fully-coupled climate uncertainty analyses.

**Pre-print available at:**

https://www.essoar.org/doi/10.1002/essoar.10508267.2 (paper is under review for publication in *JAMES*)

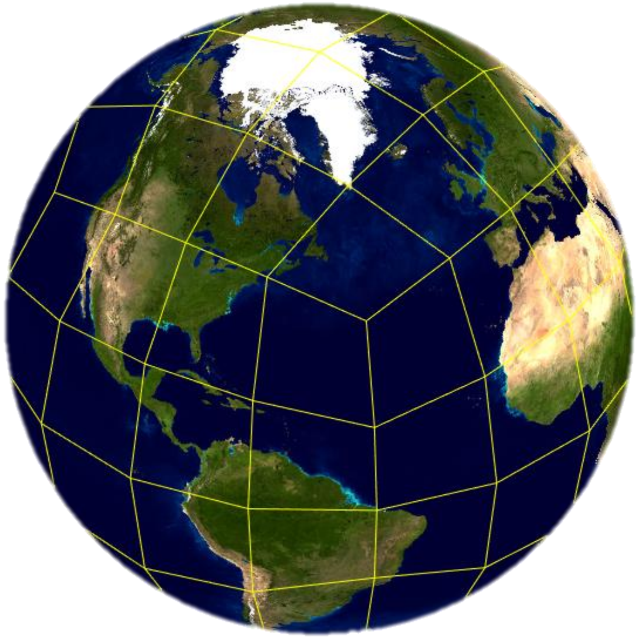
## Other references:


- K. Peterson, A. Powell, **I. Tezaur**, E. Roesler, J. Nichol, M. Peterson, W. Davis, D. Stracuzzi, D. Bull. "Arctic Tipping Points Triggering Global Change LDRD Final Report", *Sand No. 2020-9932*. Sandia National Laboratories, Albuquerque, NM (2020) [and references therein].
- Code: https://github.com/karapeterson/E3SM
- Data: https://github.com/karapeterson/E3SM_ULR_GSA_Data

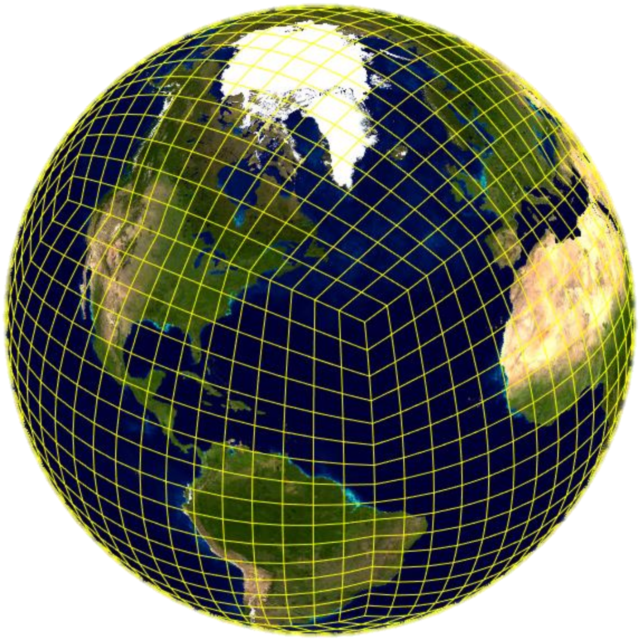

***Thank you for your attention!***

Start of Back-Up Slides

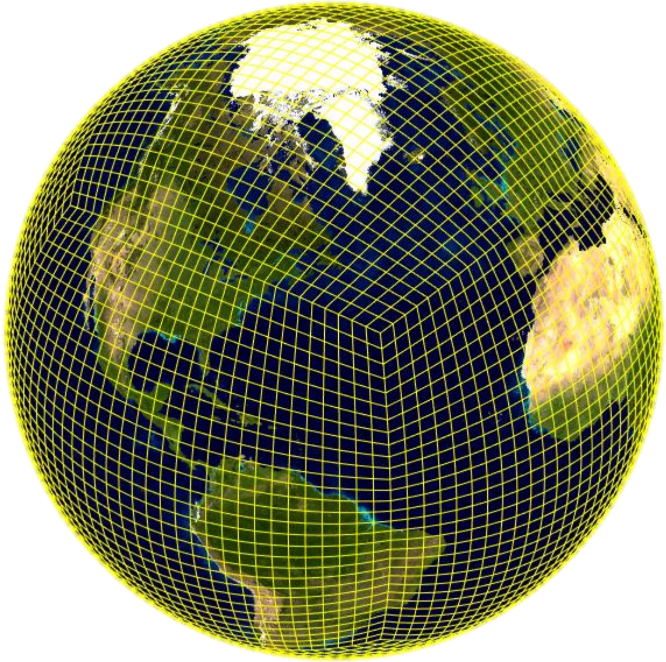
# E3SM atmosphere grids



Ultra-low resolution (ULR) atmosphere grid (≈ 7.5°)



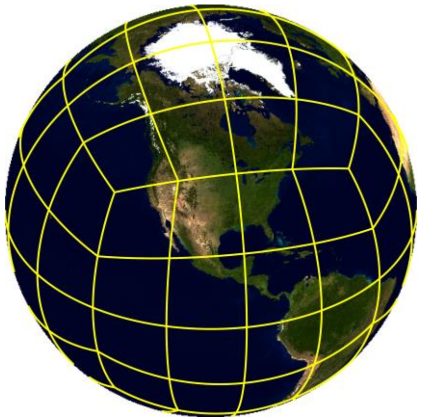
Medium-low resolution (MLR) atmosphere grid (≈ 2.7°)



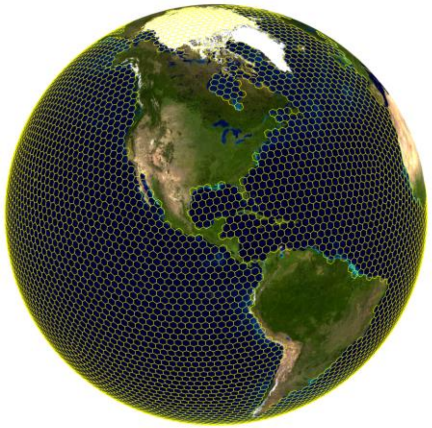
Standard resolution atmosphere grid (≈ 1°)

# GSA workflow with fully-coupled E3SM

- Perform **spin-up** of **ultra-low resolution (ULR) model** to reach equilibrium conditions of global climate state
- Select $P = 9$ **parameters** and **parameter ranges** from the sea ice, ocean and atmosphere components of the E3SM that play a significant role in model response based on previous literature
- Select $K = 6$ **QOIs**, including sea ice extent and surface air temperature averaged over the Arctic
- Use DAKOTA toolkit[1] to $N$ **generate samples** from the parameter distributions
- Run 75-year simulations for each sample using the **ULR version of E3SM** with **pre-industrial control forcing**
  - ➢ For our study, $N = 202$ perturbed runs were attempted, which led to $M = 139$ successful 75-year runs



*Above:* ULR atmosphere grid ($\approx 7.5°$)
*Below:* ULR ocean/sea ice grid (240km or $\approx 2.2°$)



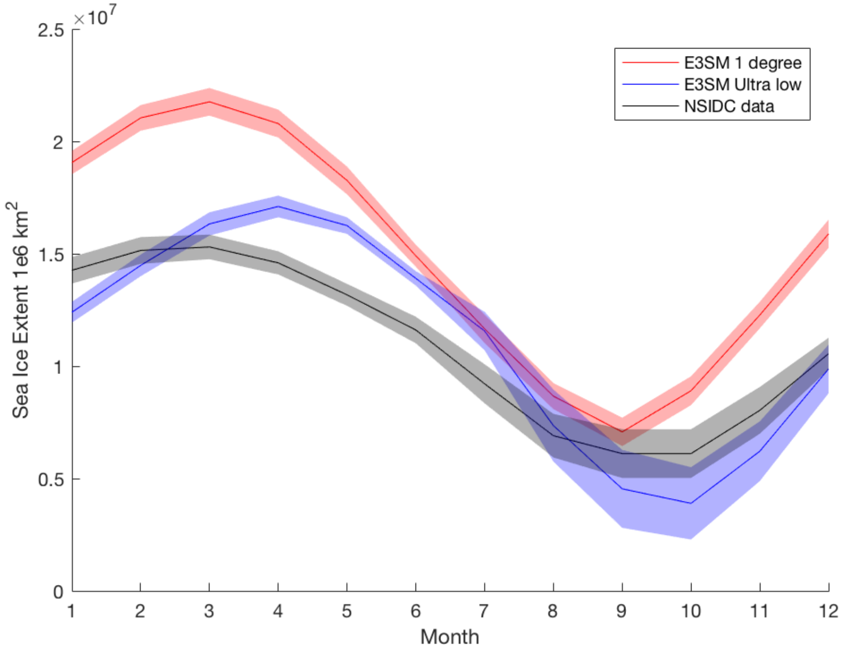
The **ULR configuration** enables sufficient ensemble generation for **full GSA** with the **fully-coupled E3SM!**

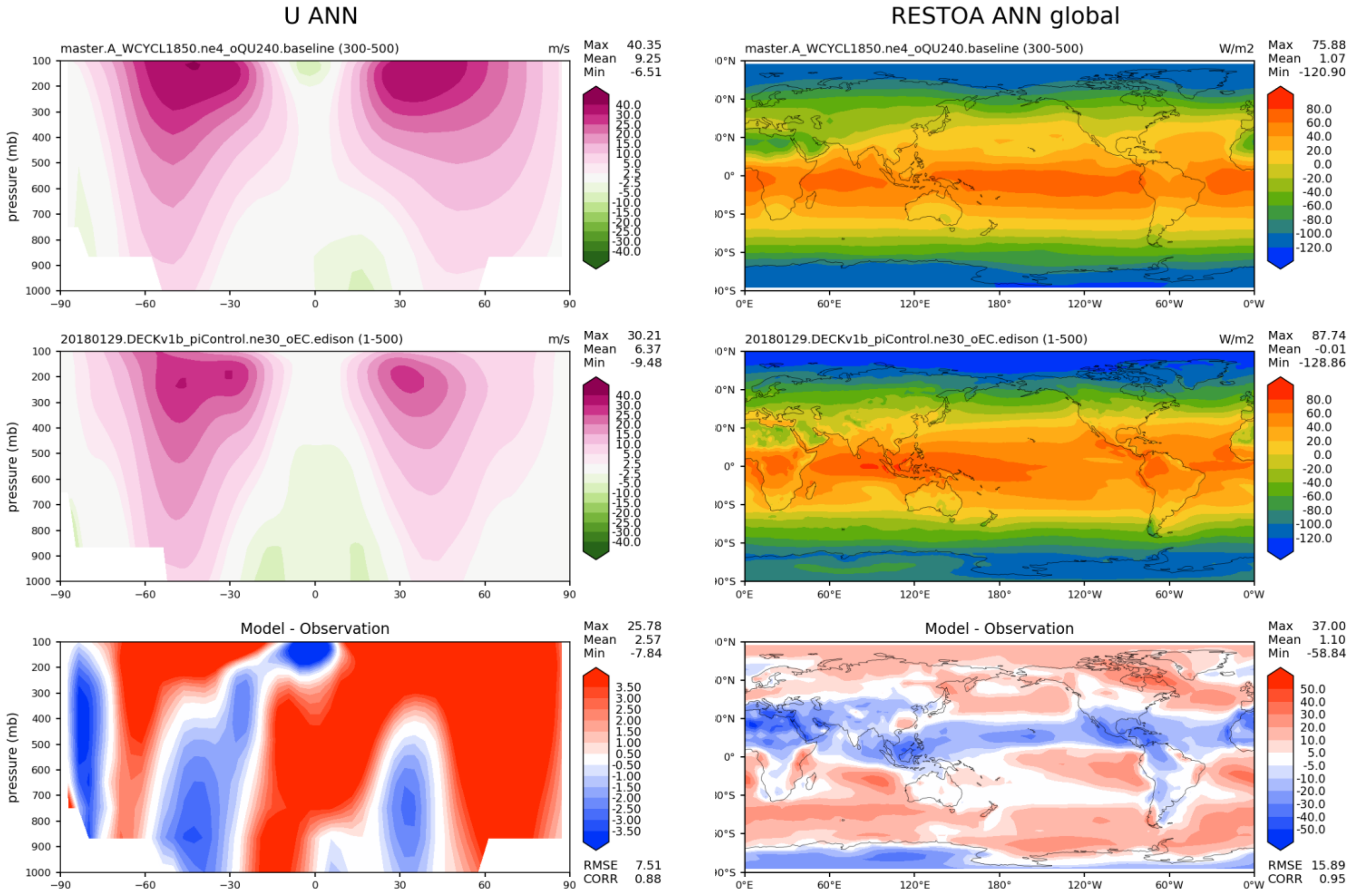
[1] https://dakota.sandia.gov

- ULR E3SM configuration is $\approx 100 \times$ less expensive to run than the "standard" 1° resolution E3SM
  - ➢ Using the ULR E3SM, our study took $\approx 1.00 \times 10^6$ CPU hours on Sandia's Skybridge HPC cluster
  - ➢ The same study using the standard 1° resolution E3SM would require $\approx 1.14 \times 10^8$ CPU hours

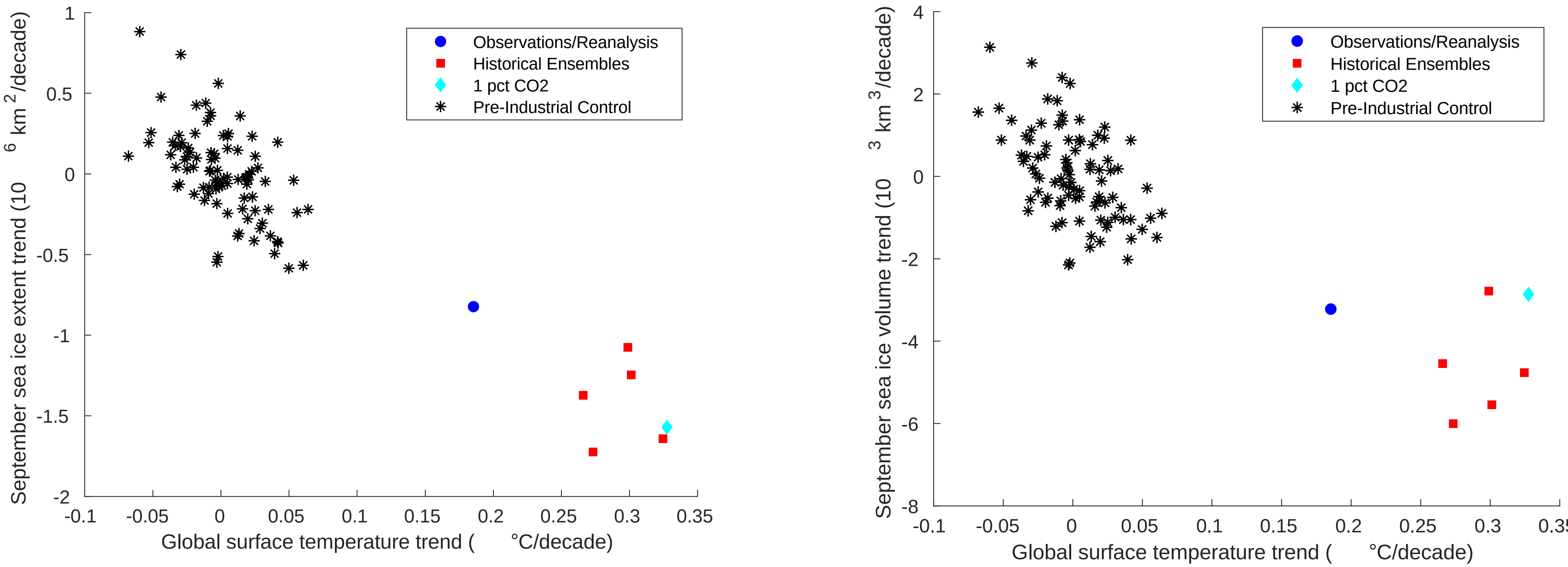
# E3SM Ultralow Resolution Simulations

- At these resolutions we cannot resolve some processes
- Can we resolve large scale dynamics we are interested in?



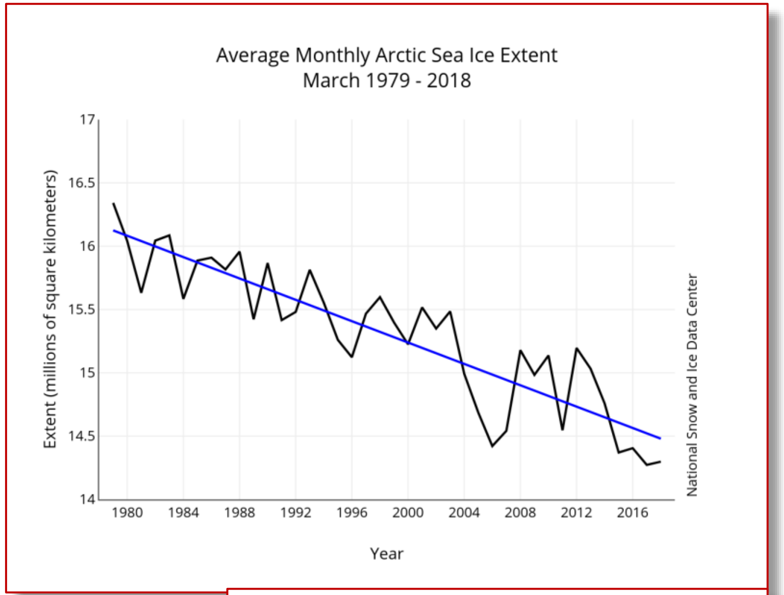
# Arctic sea ice decadal trends

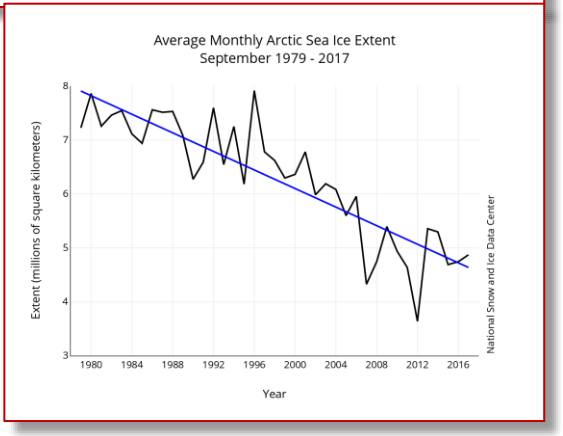



Global surface temperature versus sea ice extent (left) and sea ice volume (right) trends. Historical ensemble trends are computed for the years 1979-2014 and overlapping 35-year pseudo-ensembles are created from the pre-industrial control simulation for the computed trends.

# Factors controlling sea ice decline

- To predict when we will see an Ice-Free Arctic need to understand
  - Long-term decline due to external forcing ($C0_2$)
  - Superimposed year-to-year and decade-to-decade variability
- No consensus on
  - How much internal variability has influenced decline
  - Most important factors influencing internal variability
  - Recent papers have looked at
- Two recent papers looked at this:
  - Ding et al., Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations, Nature Geoscience 2019.
  - Screen and Deser, Pacific Ocean Variability Influences the Time of Emergence of Seasonally Ice-Free Arctic Ocean, GRL 2019.



# QOI-QOI correlation coefficients

**Winter**

| | SIE | SIV | SST | TS | CLDLOW | FLNS |
|---|---|---|---|---|---|---|
| SIE | 1.0 | 0.77 | −0.90 | −0.98 | 0.44 | −0.039 |
| SIV | | 1.0 | −0.57 | −0.86 | −0.0545 | 0.38 |
| SST | | | 1.0 | 0.87 | −0.67 | 0.28 |
| TS | | | | 1.0 | −0.30 | −0.096 |
| CLDLOW | | | | | 1.0 | −0.77 |
| FLNS | | | | | | 1.0 |

**Summer**

| | SIE | SIV | SST | TS | CLDLOW | FLNS |
|---|---|---|---|---|---|---|
| SIE | 1.0 | 0.85 | −0.90 | −0.92 | 0.89 | −0.87 |
| SIV | | 1.0 | −0.66 | −0.73 | 0.66 | −0.59 |
| SST | | | 1.0 | 0.99 | −1.0 | 0.97 |
| TS | | | | 1.0 | −0.99 | 0.95 |
| CLDLOW | | | | | 1.0 | −0.98 |
| FLNS | | | | | | 1.0 |

## Relationships between QOIs are generally consistent with expectations:

- Positive correlations between SIE[1] & SIV[2], SST[3] & TS[4]
- Negative correlations between SIE/SIV & SST/TS
- Negative correlation between CLDLOW[5] & FLNS[6], especially in warmer seasons: a lot of low cloud cover ⇒ less net longwave radiation flux at the surface
- Negative correlation between CLDLOW and SST/TS across all 4 seasons
  - In winter, cloud coverage expected to increase surface temperature → not observed in our data, may be due to biases from runs without sea ice coverage
- Lack of correlation between SIE & FLNS and SIV & CLDLOW in winter is contrary to results obtained using higher resolutions of E3SM [Urrego-Blanco *et al.*, 2019]

[1] Sea Ice Extent. [2] Sea Ice Volume. [3] Sea Surface Temperature averaged over 60-90° N. [4] Air Temperature averaged over 60-90° N. [5] Low Cloud Overage below 700 hPa averaged over 60-90° N. [6] Net longwave flux at surface over 60-90° N.

# GSA results: sensitivity indices – atmosphere parameters

## Effects associated with the 4 atmosphere parameters [Larson, 2020]:

- $z_4$ **(cldfrc_dp1):** CLUBB parameter which controls cumulus cloud-formation convective regimes in E3SM
- $z_5$ **(clubb_c1):** CLUBB parameter which controls the balance of cumulus versus stratocumulus clouds
  - Large positive values favor cumulus clouds, while small or negative values are associated with stratocumulus clouds
  - Stratocumulus clouds are believed to have planet-wide surface cooling effect, and Arctic cooling effects over most of the year [Eastman & Warren, 2010]
- $z_6$ **(clubb_c8):** CLUBB parameter developed to achieve radiative balance in atmospheric models
  - Increasing clubb_c8 brightens clouds, resulting in Earth surface cooling (brighter clouds reflect more incoming solar radiation)
- $z_7$ **(gamma_coeff):** tunable parameter in CLUBB shallow convection parameterization scheme that can brighten/dim clouds

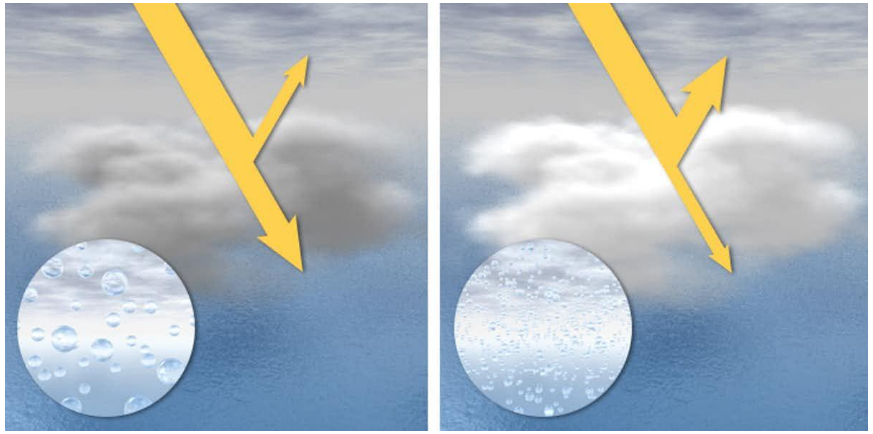
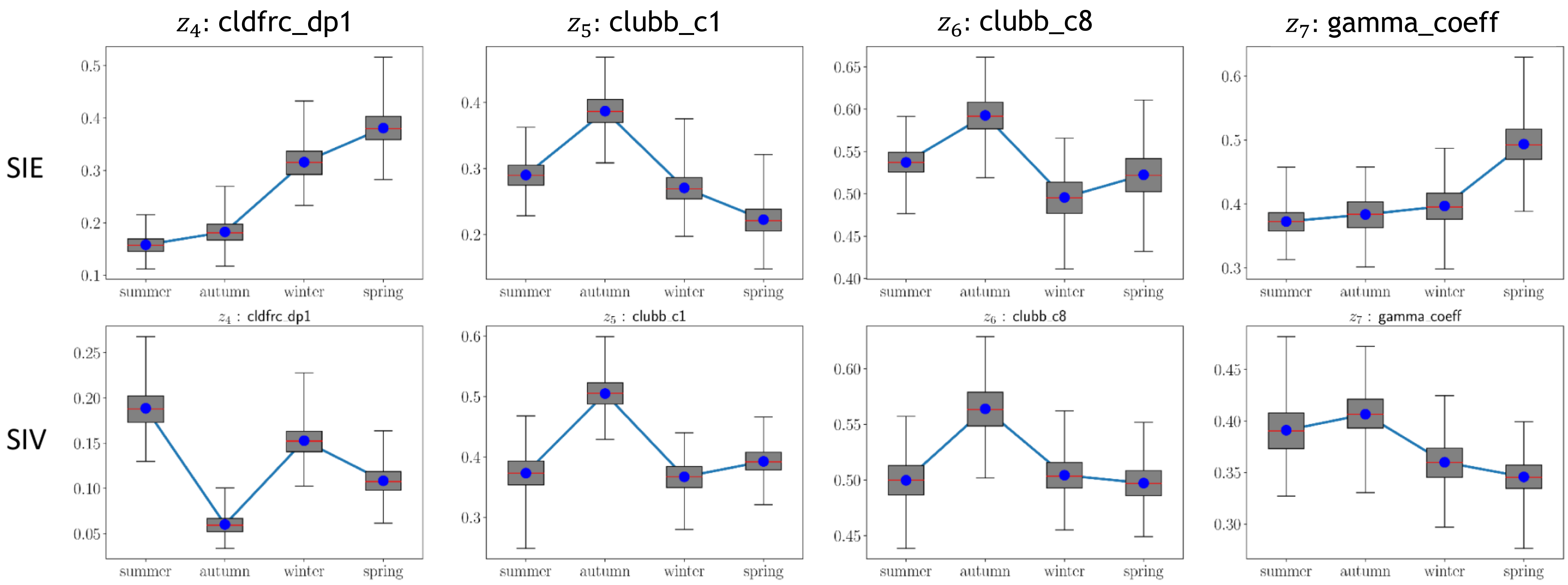


*Figure*: cloud brightening produced micro-droplets that reflect more sunlight
http://earthobservatory.nasa.gov/Features/Aerosols/page4.php

# GSA results: total effects indices – atmosphere parameters




***Atmosphere parameters influence sea ice QOIs***

*Figure*: box shows 25-75% CIs for mean total effects. Blue dot indicates mean.

- For $z_4$ (cldfrc_dp1) and $z_7$ (gamma_coeff), SIE[1] and SIV[2] **trend differently**
  - ➢ Could reflect difference between relatively stable **multi-year ice** (measured by SIV) and **young, seasonal ice** (measured by SIE)
- SIE QOI shows **strong response** to $z_6$ (clubb_c8) in autumn
  - ➢ Increasing $z_6$ (clubb_c8) **brightens clouds**, resulting in Earth surface **cooling** [Larson, 2020]
  - ➢ Suggests that **cloud brightening** has potential to control **degree** to which **sea ice is lost** towards the end of the melting season

[1] Sea Ice Extent. [2] Sea Ice Volume.

# GSA results: total effects indices – atmosphere parameters

CLDLOW

FLNS

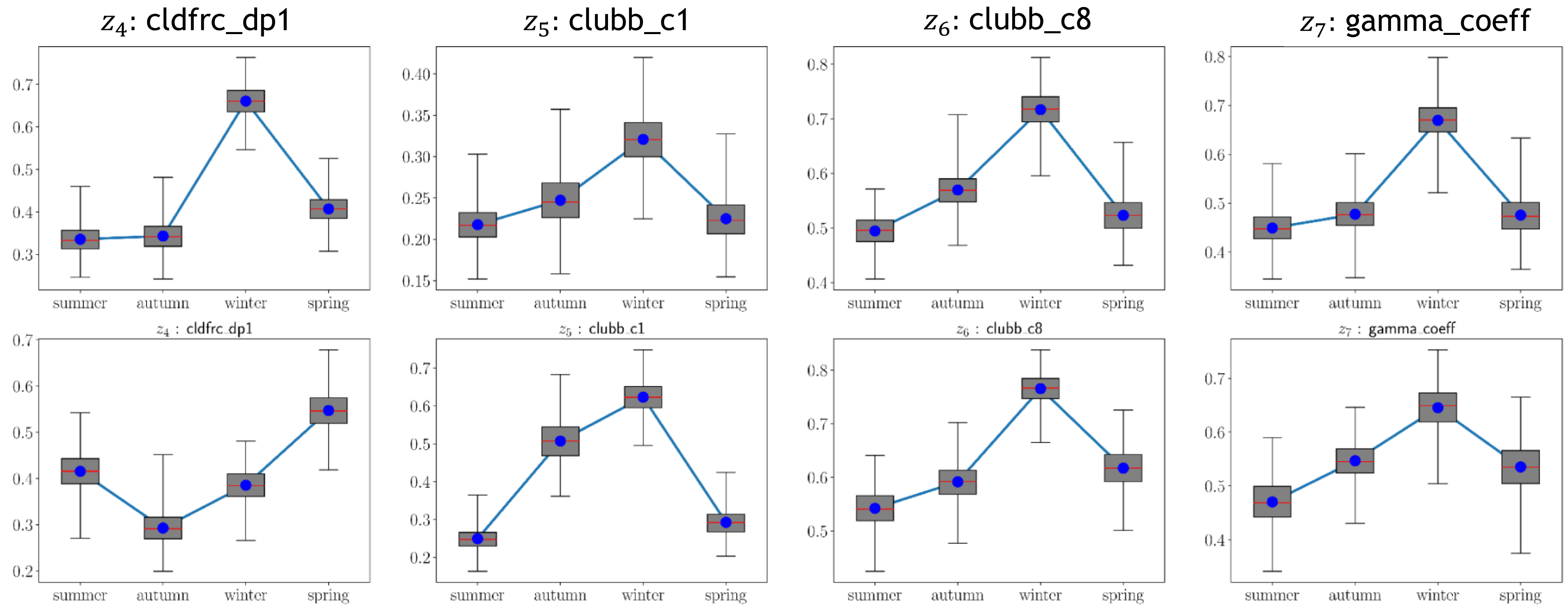



*Figure*: box shows 25-75% CIs for mean total effects. Blue dot indicates mean.

- CLDLOW[1] and FLNS[2] **trend similarly** for all but $z_4$ (cldfrc_dp1) parameter
- Sensitivity of CLDLOW to clubb_c1 ($z_5$) in autumn is **not as strong** as sensitivity of FLNS
  - clubb_c1 ($z_5$) parameter controls **balance** of **cumulus vs. stratocumulus clouds** [Larson, 2020]
  - Results suggest while clubb_c1 ($z_5$) influences **cloud type**, it may not strongly influence the fraction of **general low cloud cover**

[1] Low Cloud Overage below 700 hPa averaged over 60-90° N. [2] Net longwave flux at surface over 60-90° N.

# References

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