Parametric Uncertainty in Prediction of AMOC weakening by an earth system model

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Submited to Earth System Dynamics

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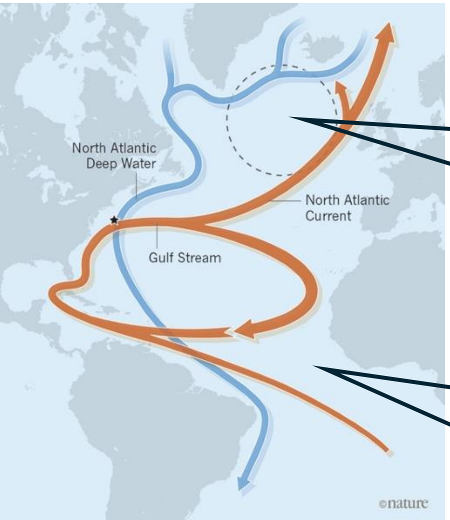
No Direct Observation of AMOC Climate Tipping

Climate Tipping

- Sudden and irreversible changes in the Earth system which are feared to be caused by anthropogenic global warming
  - AMOC weakening

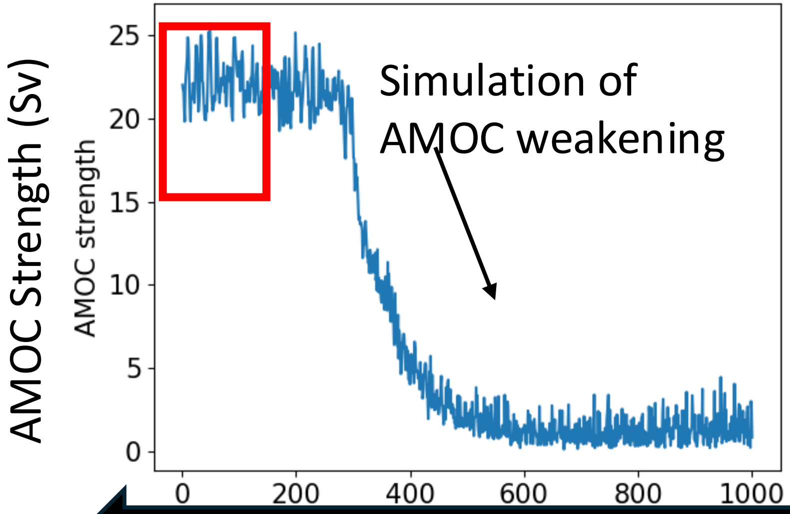


Freshwater input to this area is significant to AMOC

AMOC maintains the EU climate transporting heats from the lower latitude

AMOC Observation

Temporal Deficit

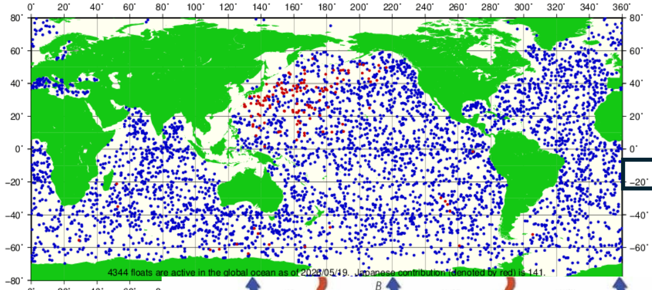


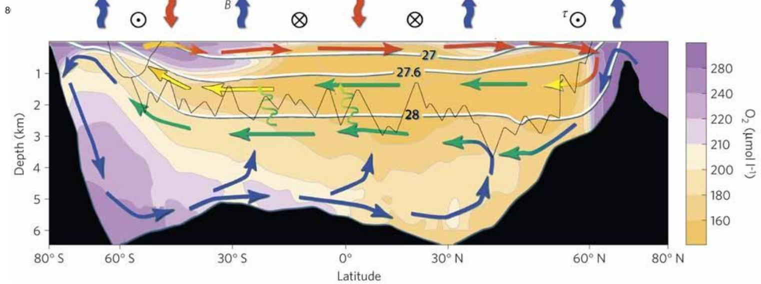
Simulation of AMOC weakening

1000 years

No Tipping Observation

Spatial Deficit





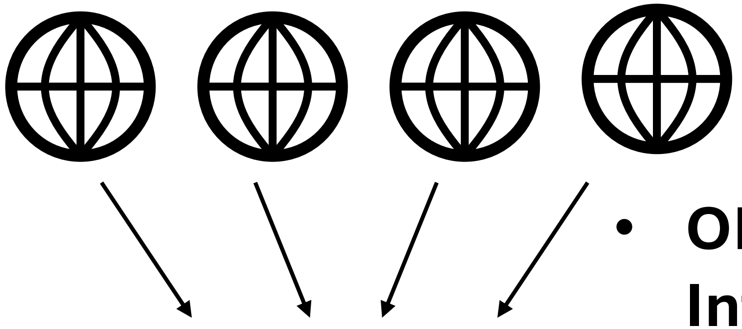
No Direct AMOC observation

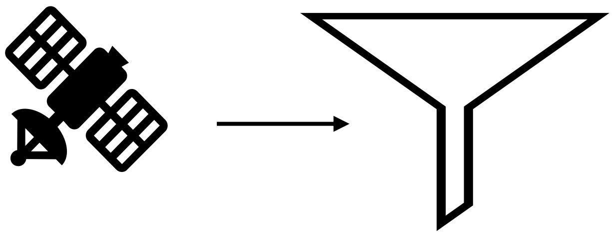
Inference

Prediction/Risk assessment of AMOC Climate Tipping

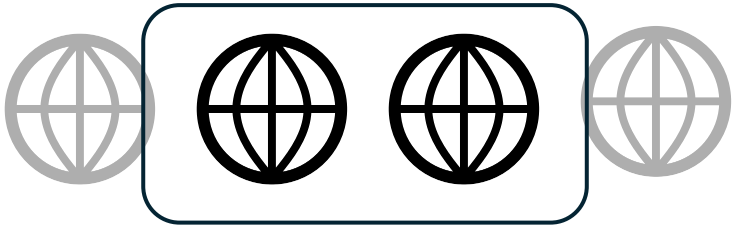
Model-based Assessment

- **AMOC tipping in ESM**
  Some EMICs (Borner et al., 2026,)
  Even a full-scale ESM, CESM (van Westen et al., 2024)



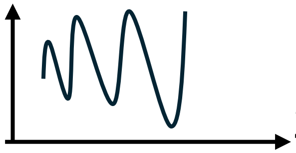


- **Observation Integration**
  Emergent Constraint
  e.g.) AMOC satisfying thermal wind relationship
  Bonan et al., 2025



Indicator-based Assessment

- **Statistical Early warning signal**



Boulton et al., 2014

- **Physics-based Early warning indicator** (van Westen et al., 2024)

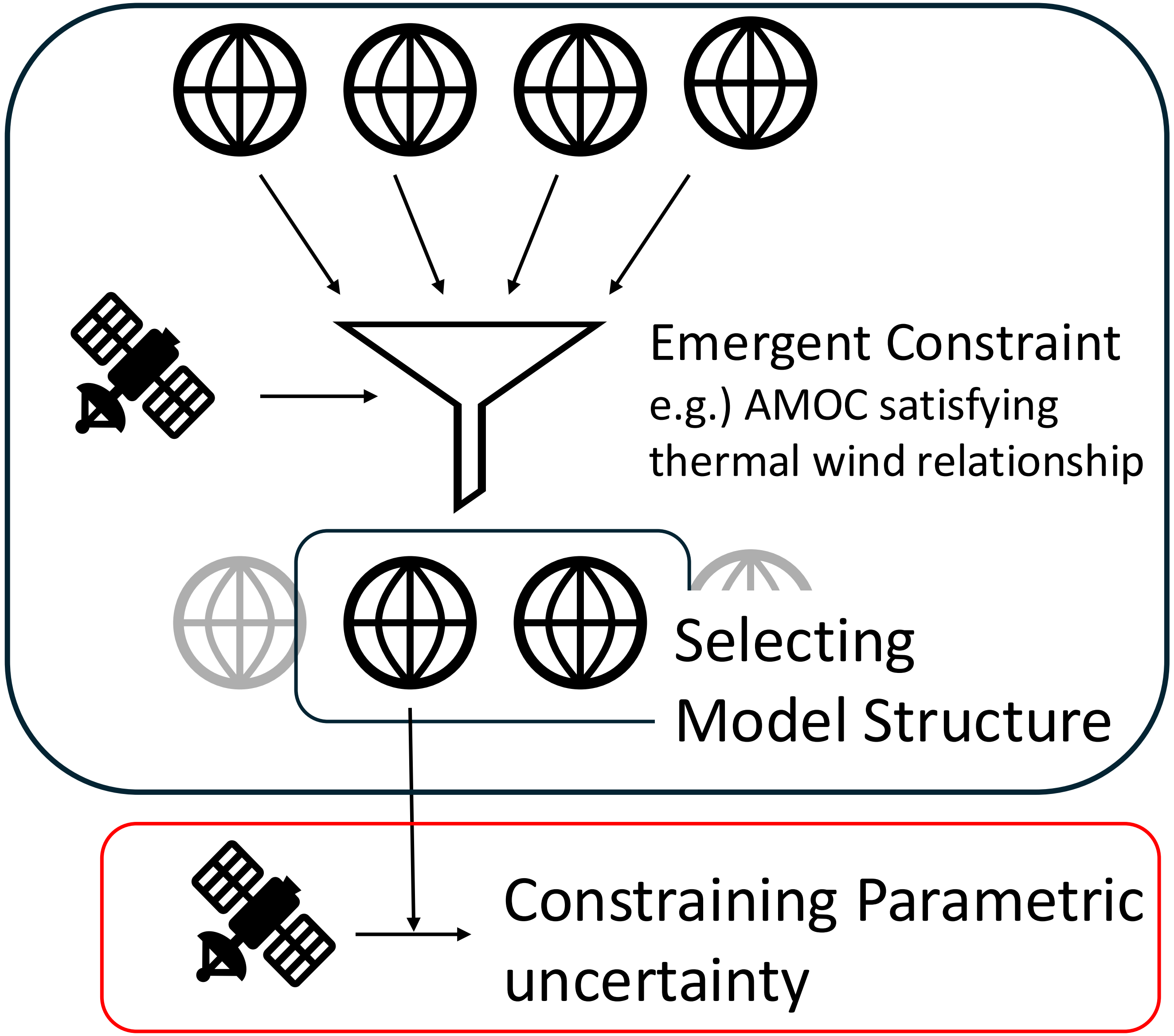
The ways to use observation to improve model-based assessment

Observation Integration

- **Emergent Constraint**
  - Evaluating model structure (which is invariant under slight modification in parameters)

- **Parametric Uncertainty Quantification**
  - Even with an accurate structure, parameter which is uncertain plays a significant role to determine model

Our Focus



Research Question

How should we integrate Earth system model and observation to reduce parametric uncertainty and future climate projection uncertainty, especially projection uncertainty of AMOC climate tipping?

This study

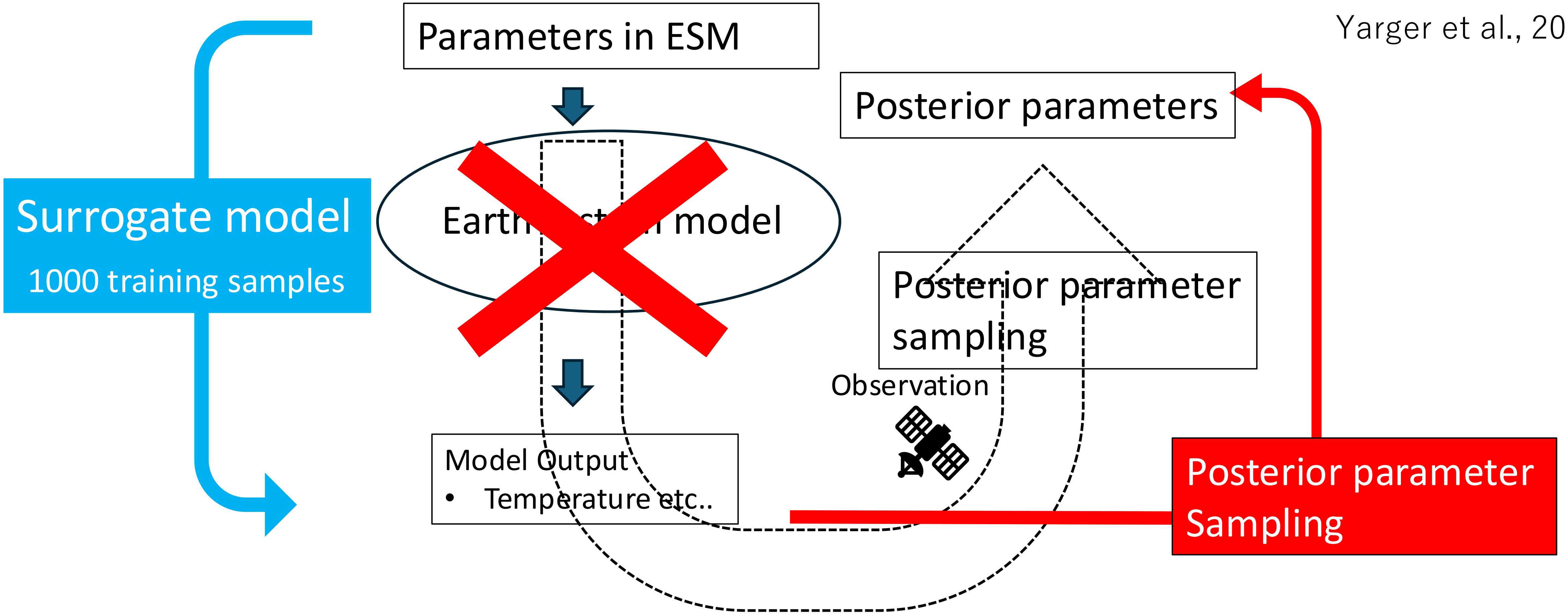
Observing System Simulation experiments.

1. Parametric Uncertianty Quantification
2. Simulation accuracy in the observation period
3. Quantify future climate projection uncertainty and its evaluation

Surrogate-model uncertainty quantification

Surrogate model

Machine Learning model which maps parameters to the ESM outputs instantaneously once it is trained.



Experimental setting (LOVECLIM, Goosse et al., 2010)

Observing System Simulation Experiments : Use simulation data with a true parameter as a synthetic true data, and the observation comes from the synthetic true data.

4 Observation variable

Ocean：Sea surface salinity (SSS) & sea surface temperature (SST)

Atmos：Relative humidity (Q) & pressure (GEOPG)

4 Observation Error 1%, 2%, 5%, 10%

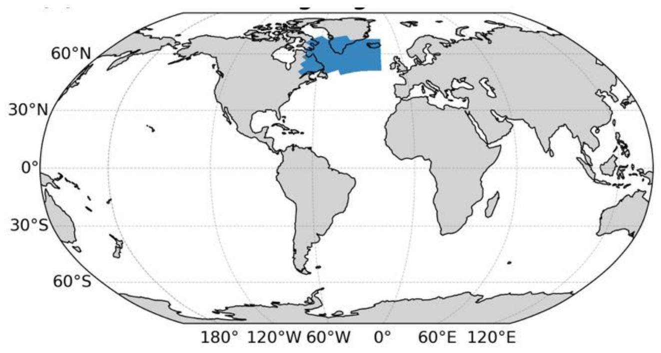
50-year averaged climatology

25 Parameters including...

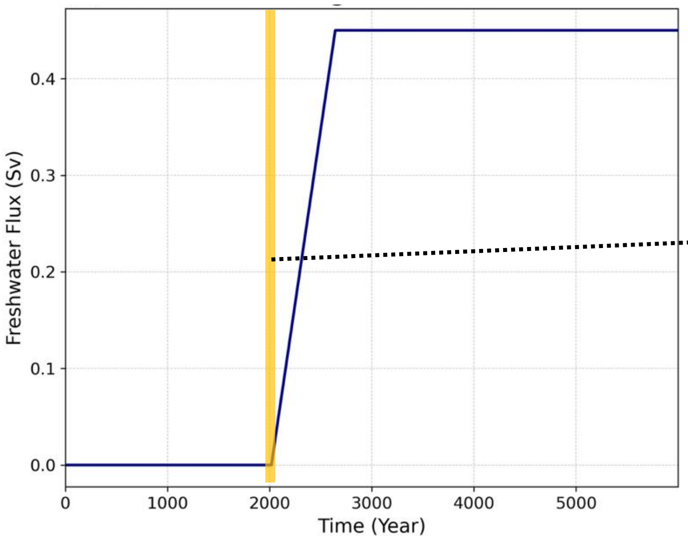
- Albedo
- Diffusion coefficient
- Coupling between Atmos and Ocean etc....

Scenario of Freshwater forcing

Region



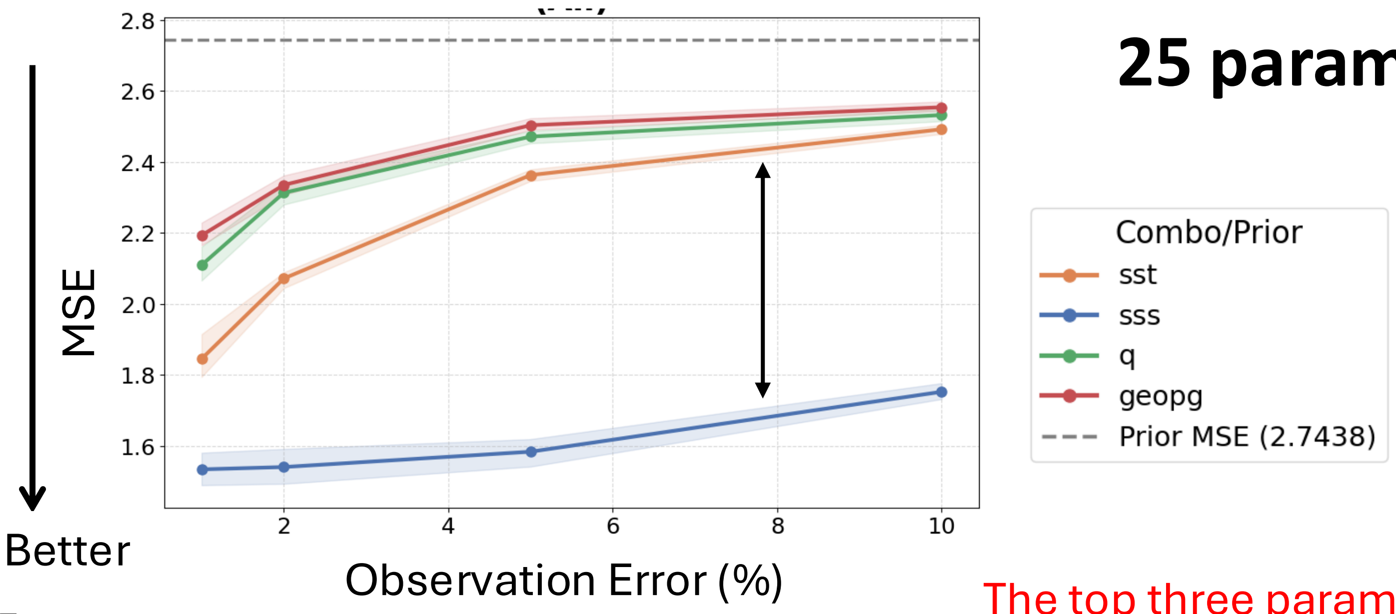
Scenario



Kim et al., 2022

1950 – 2000(before freshwater forcing starts) is used as observation period.

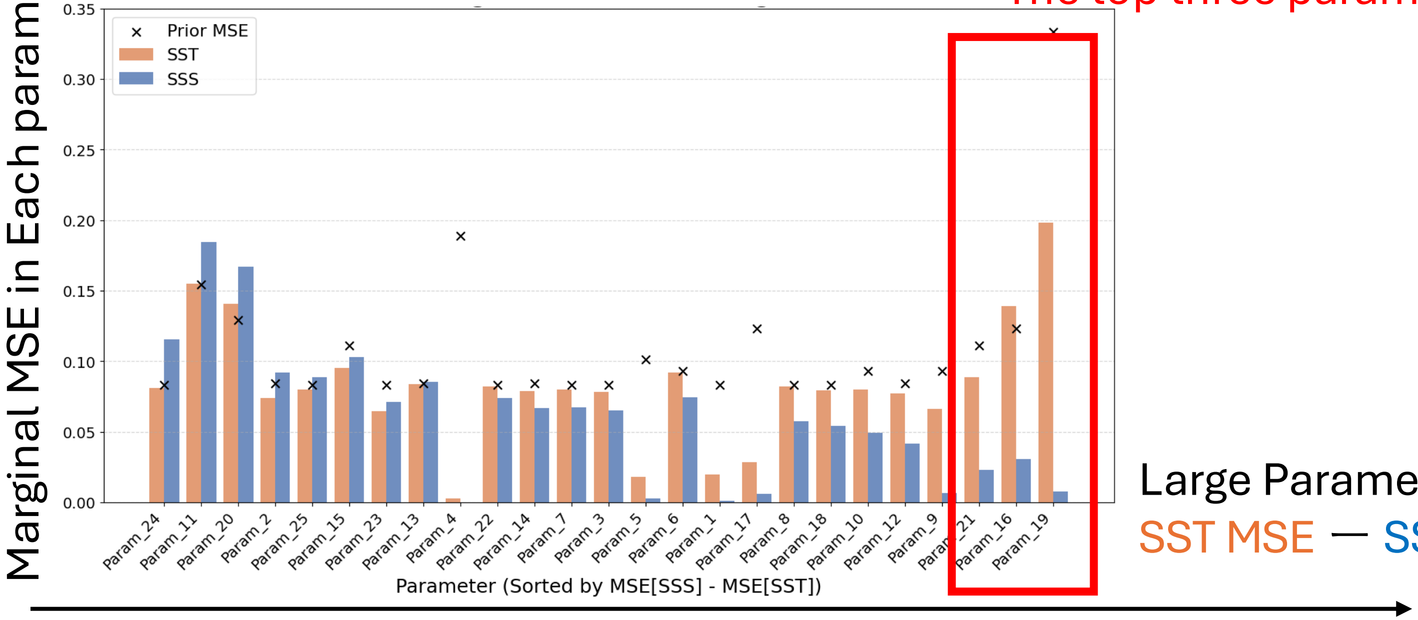
*Imitate fwf rate of CMIP6 output (2017-2100)



25 parameter posterior uncertainty

- 25 parameter uncertainty is calculated on different observation settings
  - MSE is reduced in all the observation settings.

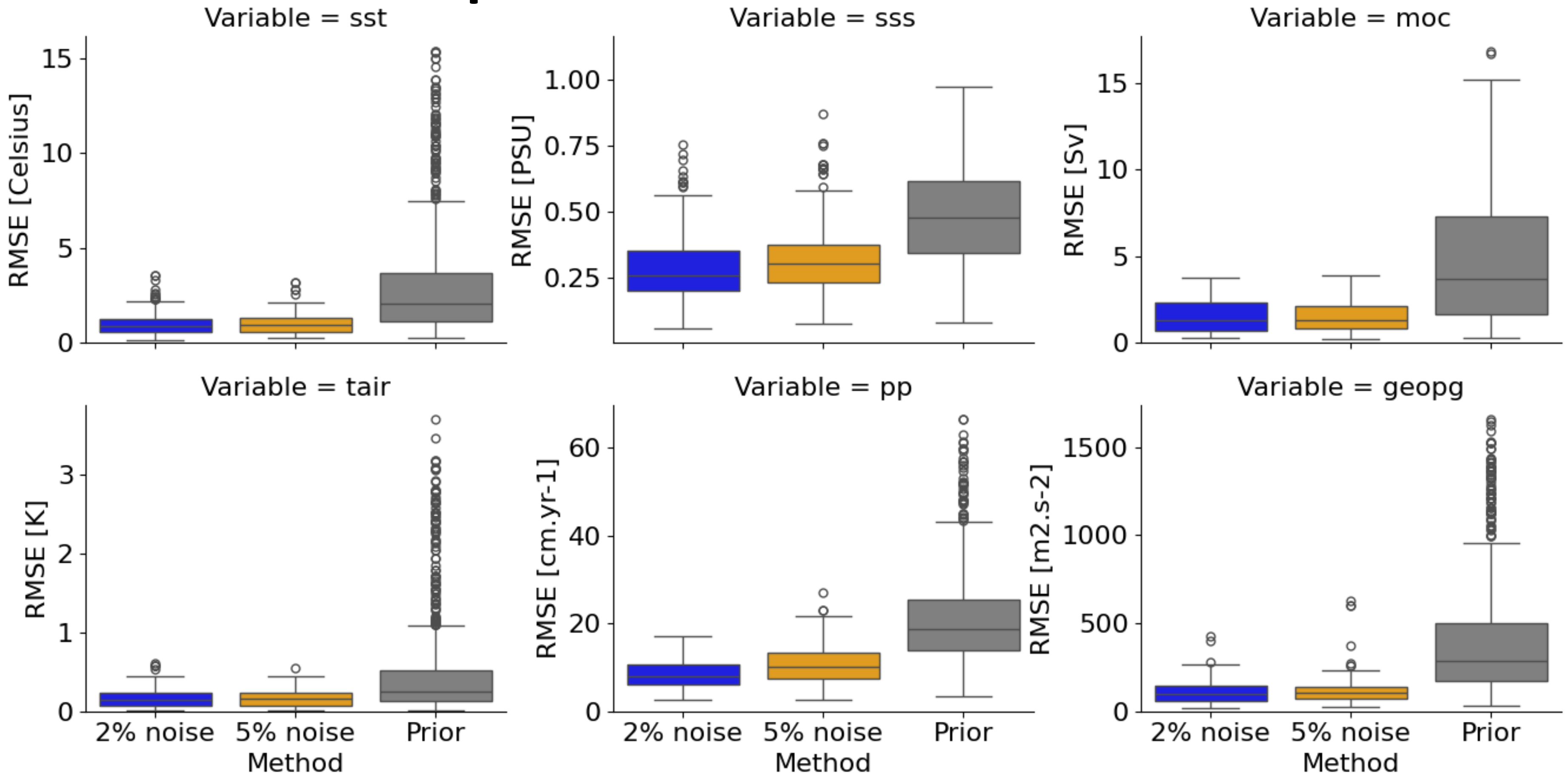
The top three parameter uncertainty is dominant !



- Parameter 16, 19 and 21 dominate the parameter MSE.
- These parameters related to freshwater flux in the North Atlantic Ocean

Large Parameter MSE Difference
SST MSE — SSS MSE

How does the posterior simulation fit the synthetic true data in the observation period?



- RMSEs of multiple predicted variables

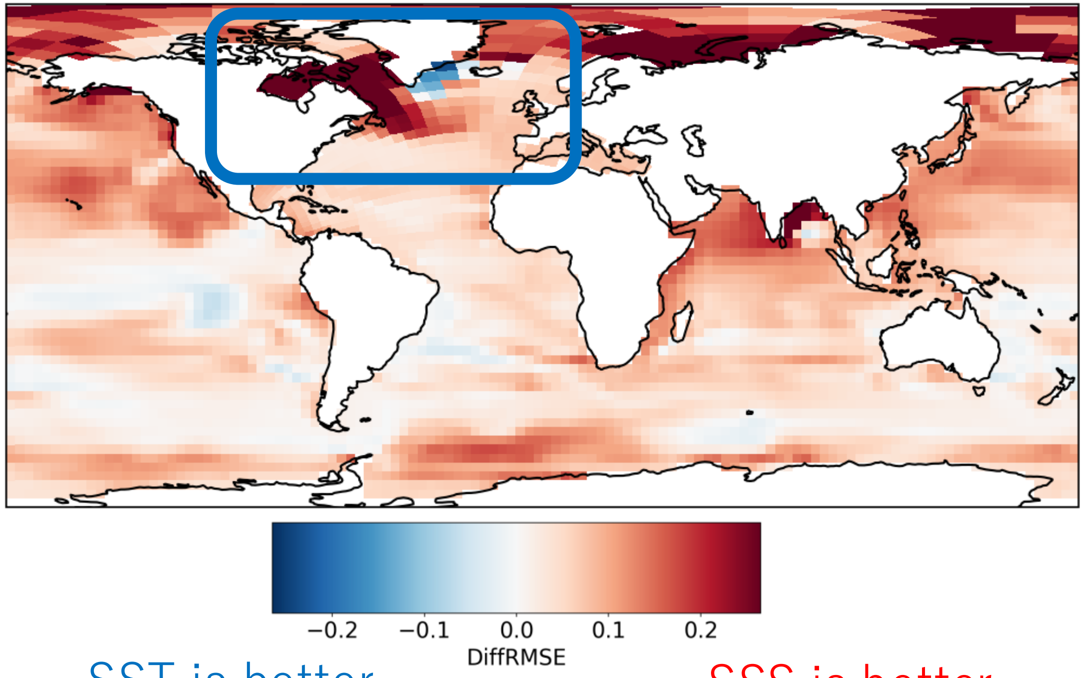
- Observation setting
  - Sea Surface Temperature
  - Spatial distribution of 50-year mean

- No observation
- 2 % Noise
- 5 % Noise

- The observation also helps improving historical reproduction accuracy.

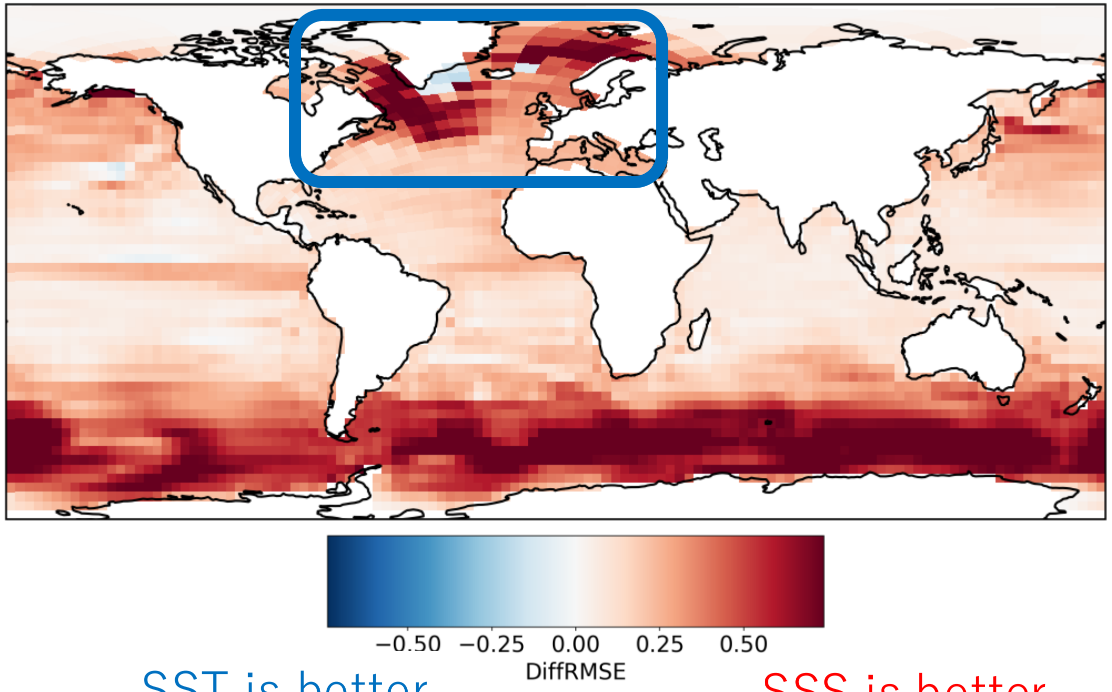
The Difference in performance of reproduction between the cases with SSS observation and SST observation.

$\Delta RMSE$ in SSS mean climatology (1950-2000)



SST is better SSS is better

$\Delta RMSE$ in SST mean climatology (1950-2000)

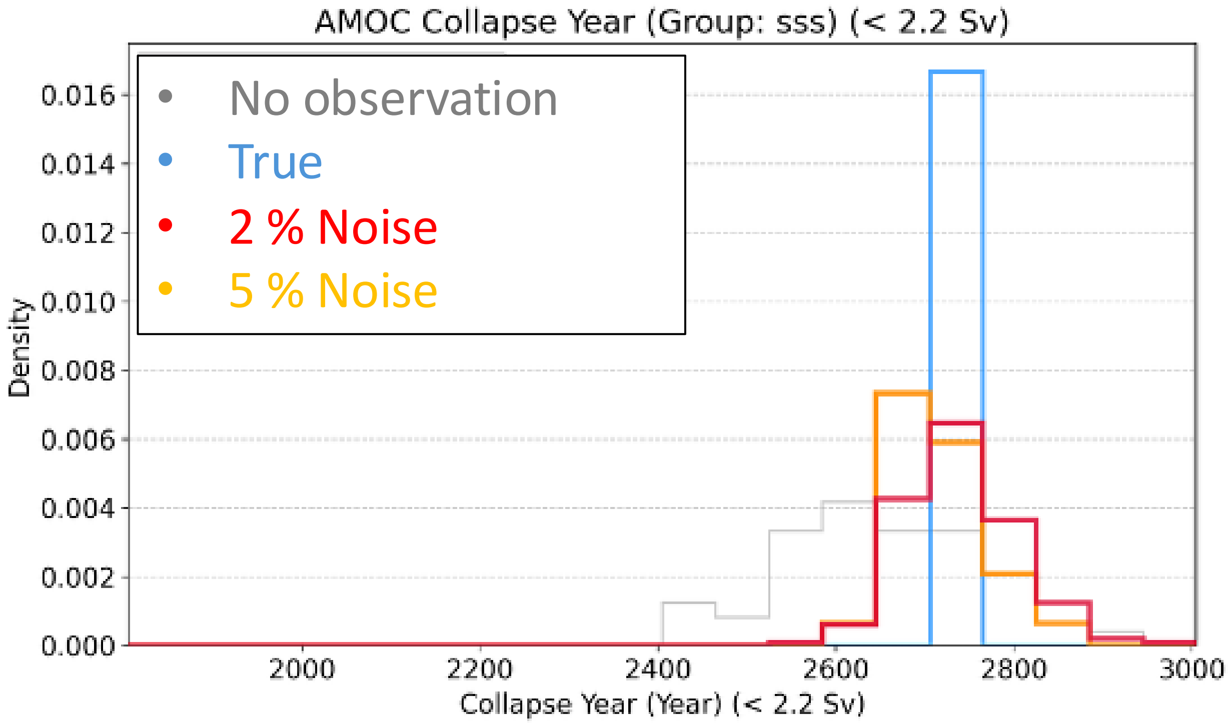


SST is better SSS is better

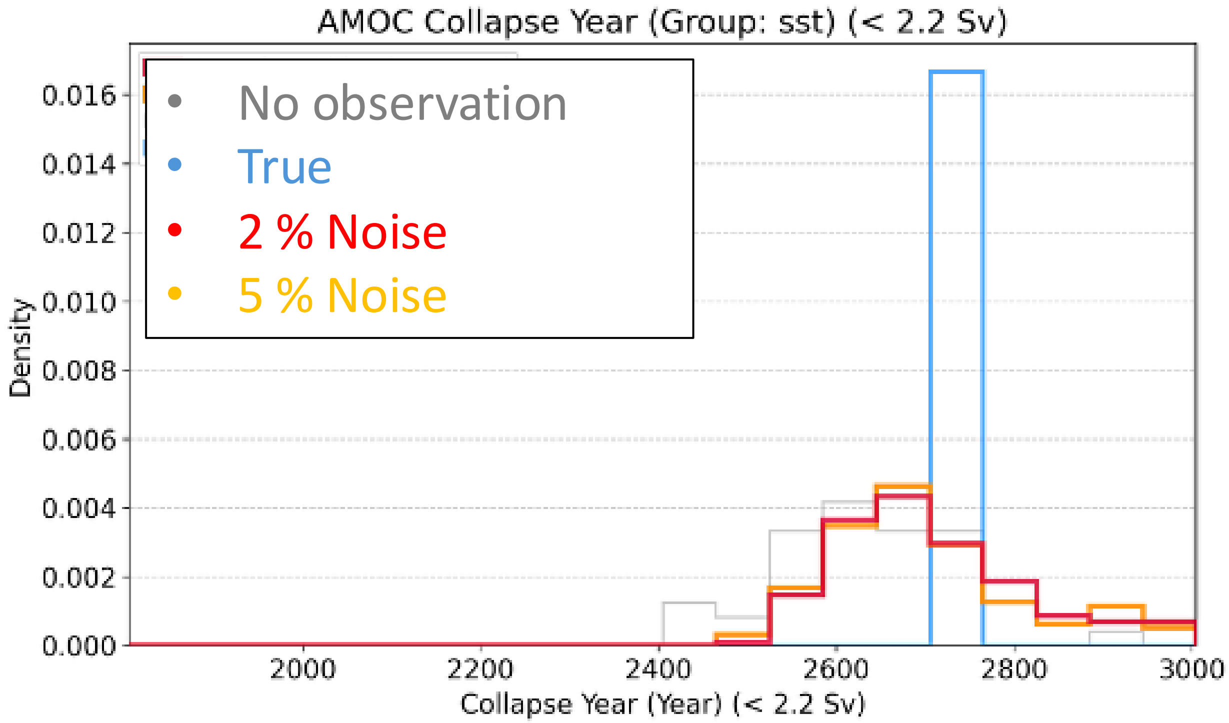
- Excessive parameter uncertainty with SST observation leads to excessive uncertainty in North Atlantic Climatology

Tipping Timing dependency on Observation setting

Observation: SSS



Observation: SST

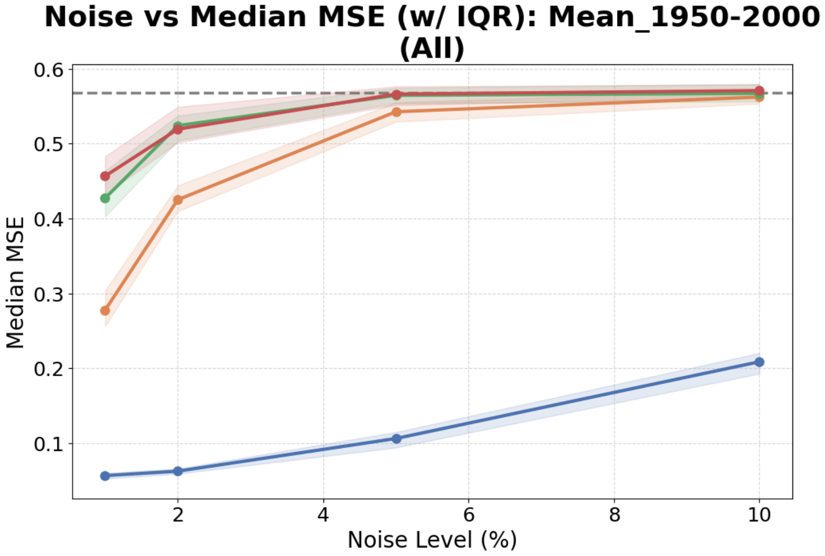


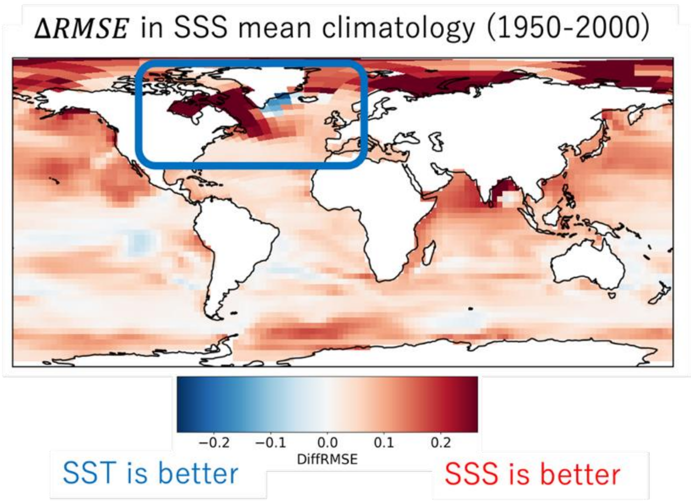
- When SST (also with Q and Geopg) is used as observation, The uncertainty reduction in AMOC tipping timing is quite limited even though parameter uncertainty is reduced.

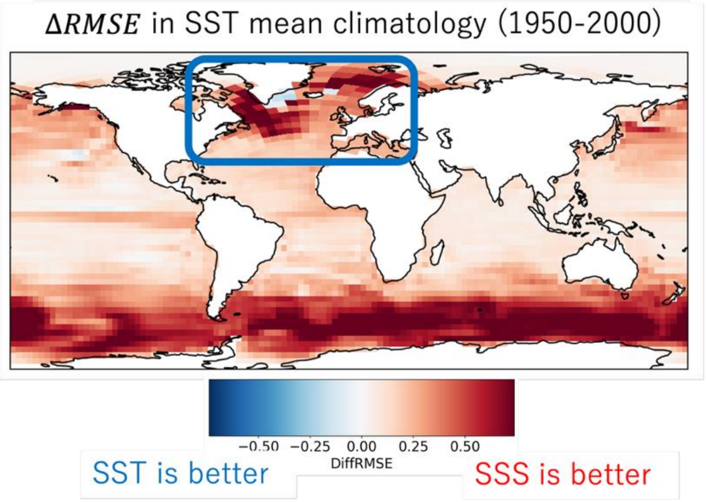
Summary

Current: Uncertainty in NA SSS and SST depending on the observation variable setting

Parameter uncertainty In NA Freshwater flux



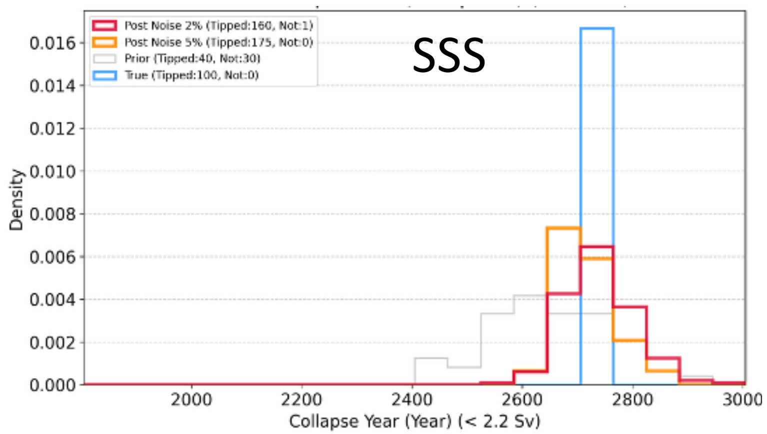


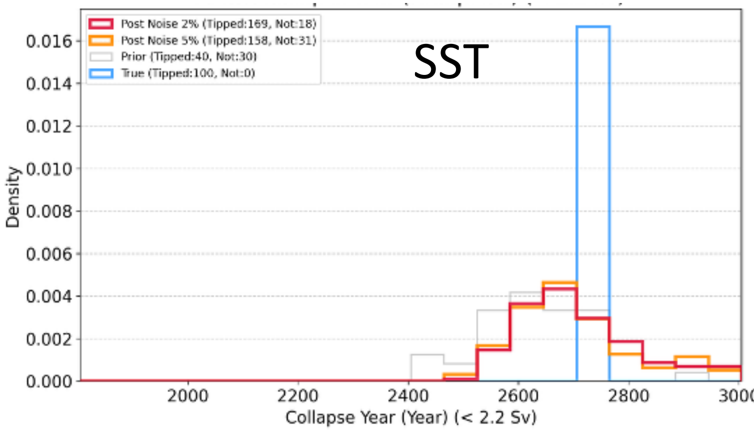


*NA: North Atlantic Ocean

25 Parameters uncertainty Quantification with Surrogate model

Future: AMOC tipping timing uncertainty

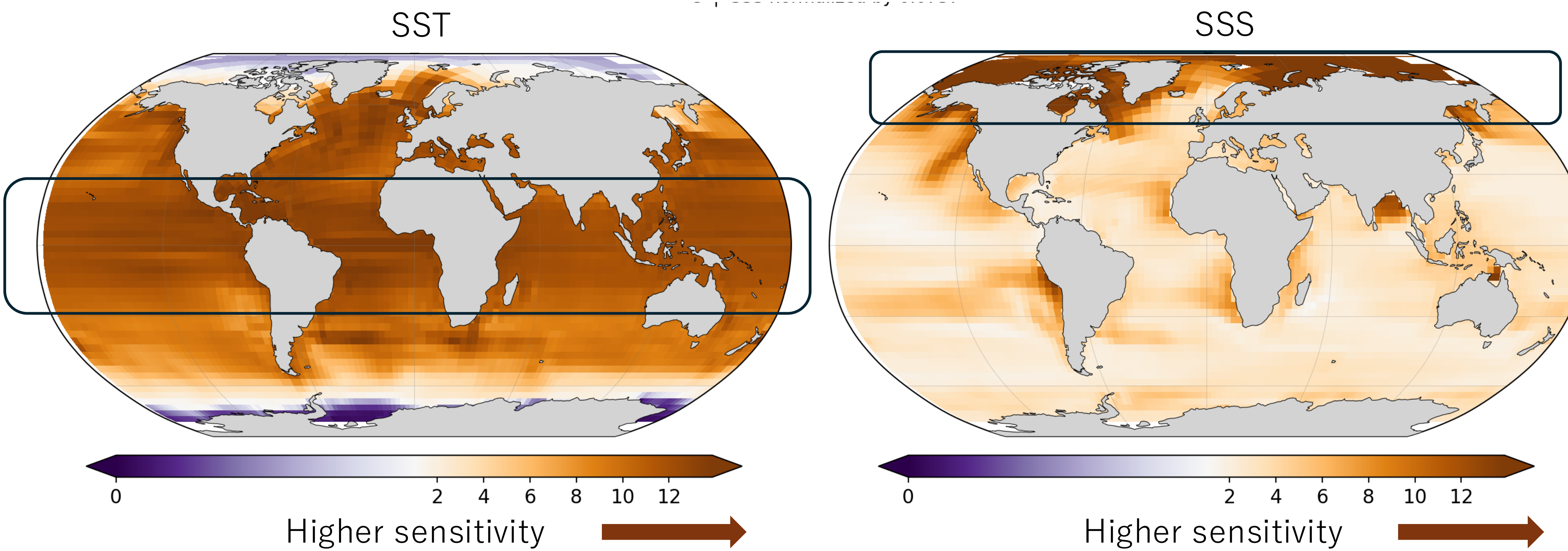




Discussion

- Interpretation: Why SSS works better than other observation variables?

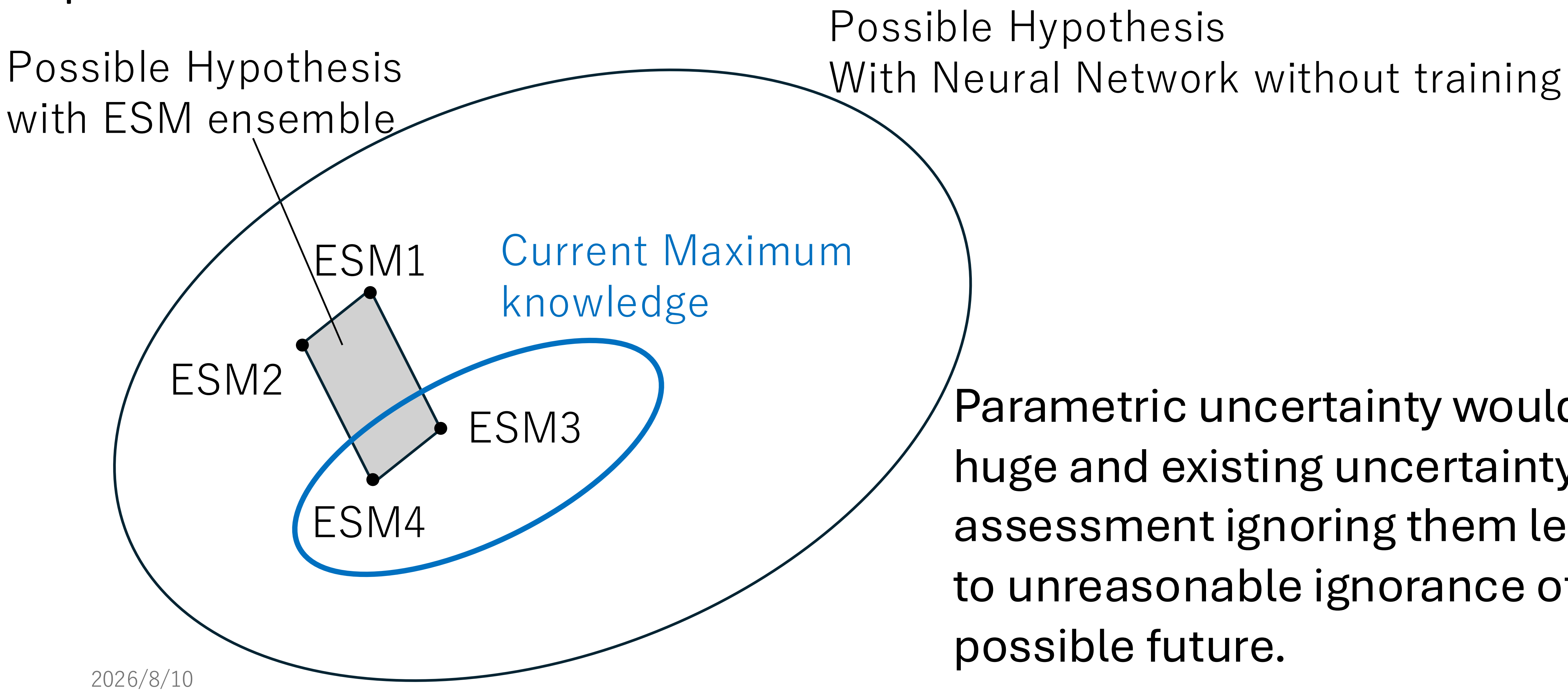
Sensitivity to the 25 parameters relative to the annual variability



- Signal-to-noise ratio in SSS to the North Atlantic(NA) is locally high and error reduction in the NA region contributes to improvement in AMOC prediction Consistent with Boulton et al., 2014, Smolders et al. 2025 van Westen et al., 2024

Discussion

- How is the existing knowledge about Climate projection uncertainty is updated?



Parametric uncertainty would be huge and existing uncertainty assessment ignoring them leads to unreasonable ignorance of possible future.

Conclusion

- We assessed predictability of future AMOC rapid weakening using Earth System Model.
- We quantified 25 parameter uncertainty and assessed its effects on simulation accuracy in the observation period and future prediction using OSSE framework
- We found that SSS in the North Atlantic region is sensitive to the parameter and that leads to the superior performance of SSS compared with other observation variables.