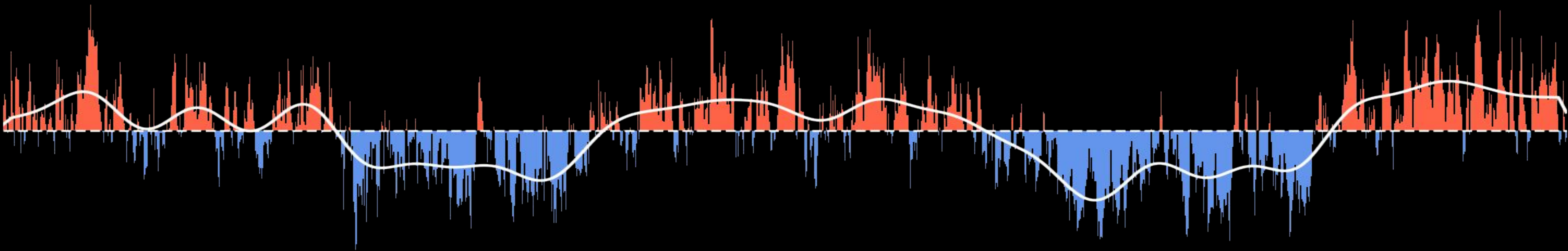
Understanding the Drivers of Atlantic Multidecadal Variability using a Stochastic Model Hierarchy



Glenn Liu[1], Young-Oh Kwon[2], Claude Frankignoul[2], Jian Lu[3]

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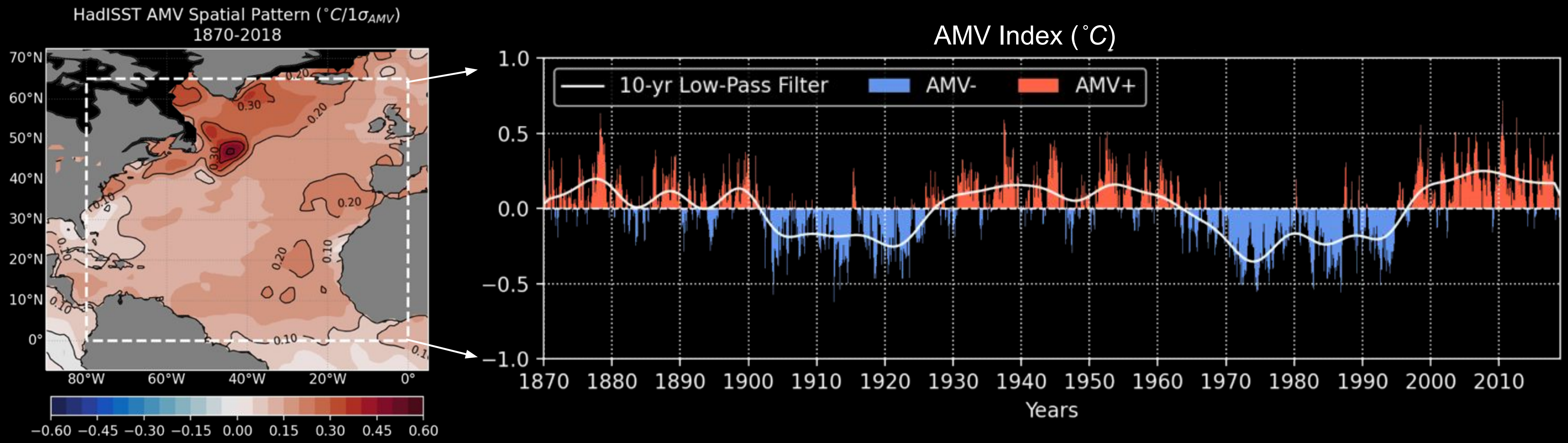
[1]MIT-WHOI Joint Program, [2]Woods Hole Oceanographic Institution, [3]Pacific Northwest National Laboratory

Atlantic Multidecadal Variability (AMV)

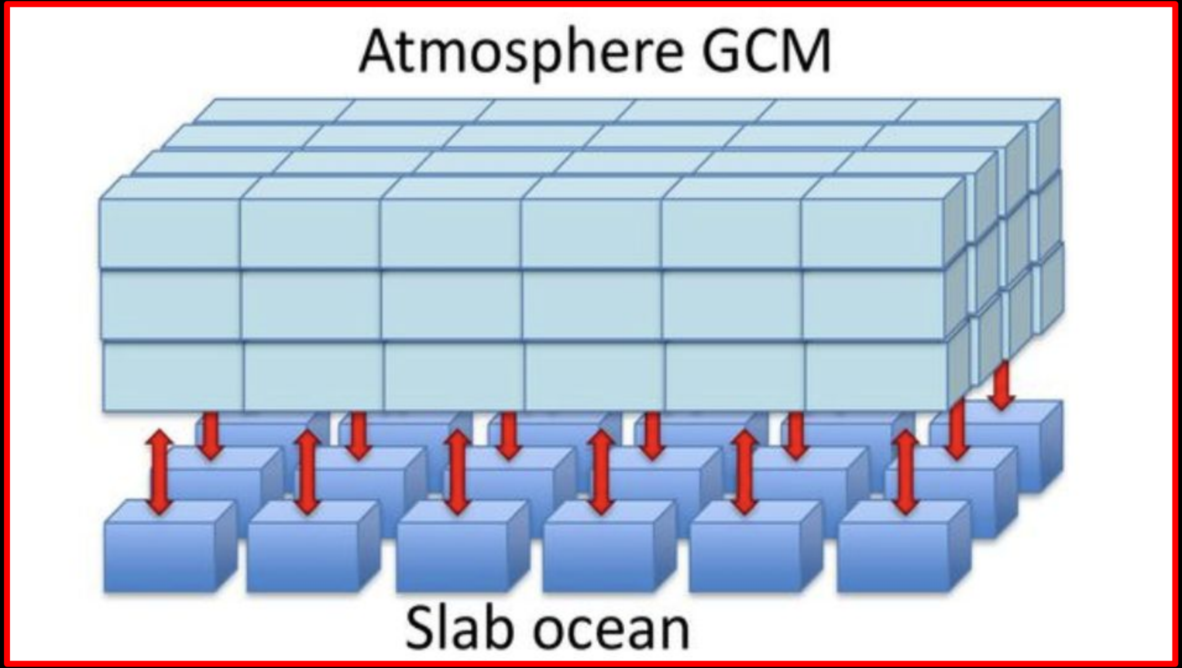


What is the relative importance of oceanic and atmospheric dynamics for AMV?

Ocean
(Atlantic Meridional Overturning Circulation, AMOC)

Atmosphere
(North Atlantic Oscillation, NAO)

Hierarchies with Slab Ocean Models



Source: Dommengat et al. 2012

Slab Ocean Temperature Equation

$$\rho C_p h \frac{dT}{dt} = Q_{net} + Q_{flux}$$

- *No interactive ocean dynamics*
  - Climatological Flux Correction (Q_{flux})
- Fixed thickness h (in time)

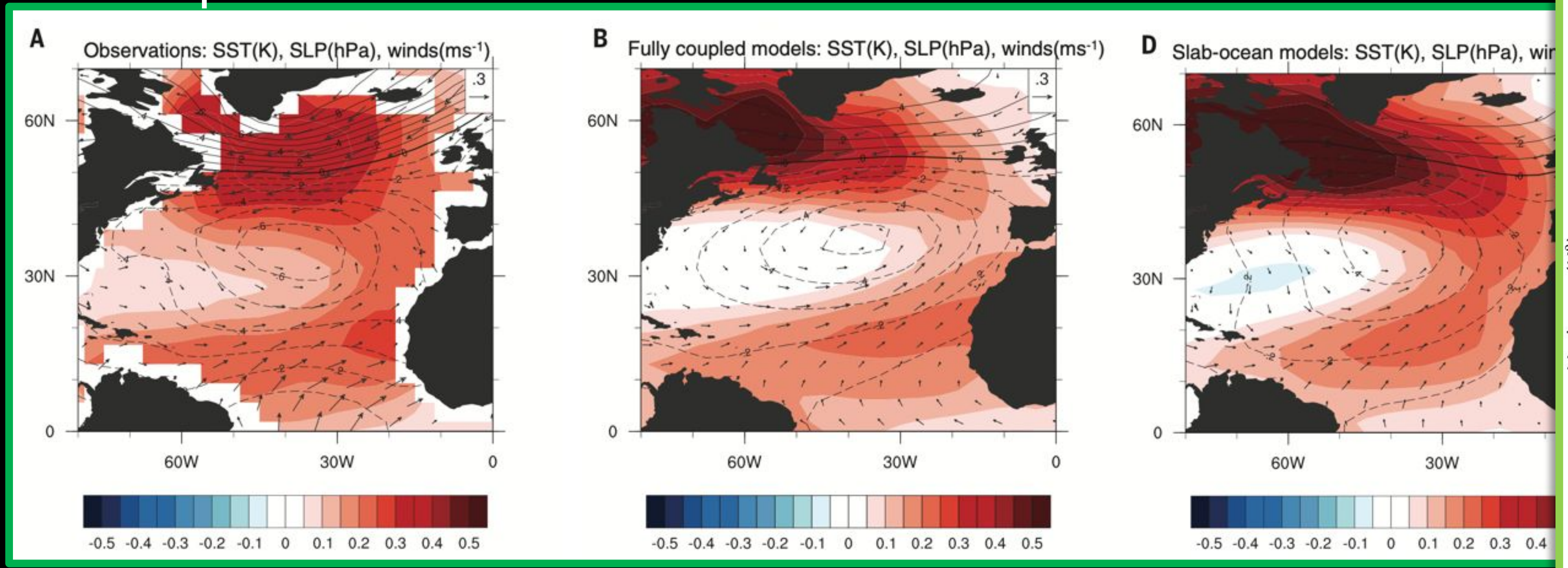
Ocean
(Atlantic Meridional Overturning Circulation, AMOC)

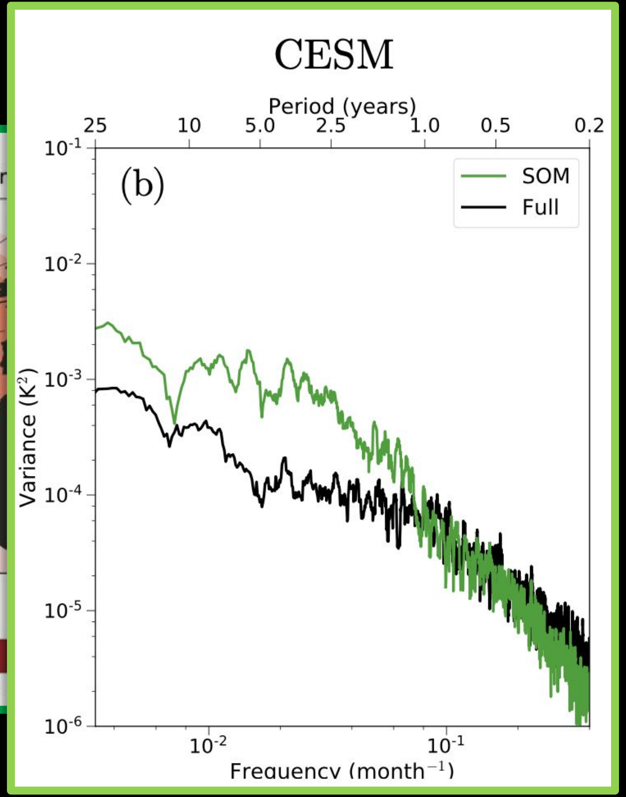
Simplify

Atmosphere
(North Atlantic Oscillation, NAO)

Slab vs. Fully-Coupled Models

AMV Spatial Pattern[1]





Midlatitude North Atlantic SST Power Spectra[3]

- Is ocean circulation necessary to generate AMV?[1]
- Slab has higher SST variance compared to fully-coupled models[2,3]
  - Ocean dynamics damp SST variability, particularly at low frequencies[3]

Need for transparent, process-based understanding of ocean contributions to AMV

[1]Clement et al. 2015, [2]Murphy et al. 2021, [3]Patrizio et al. 2021

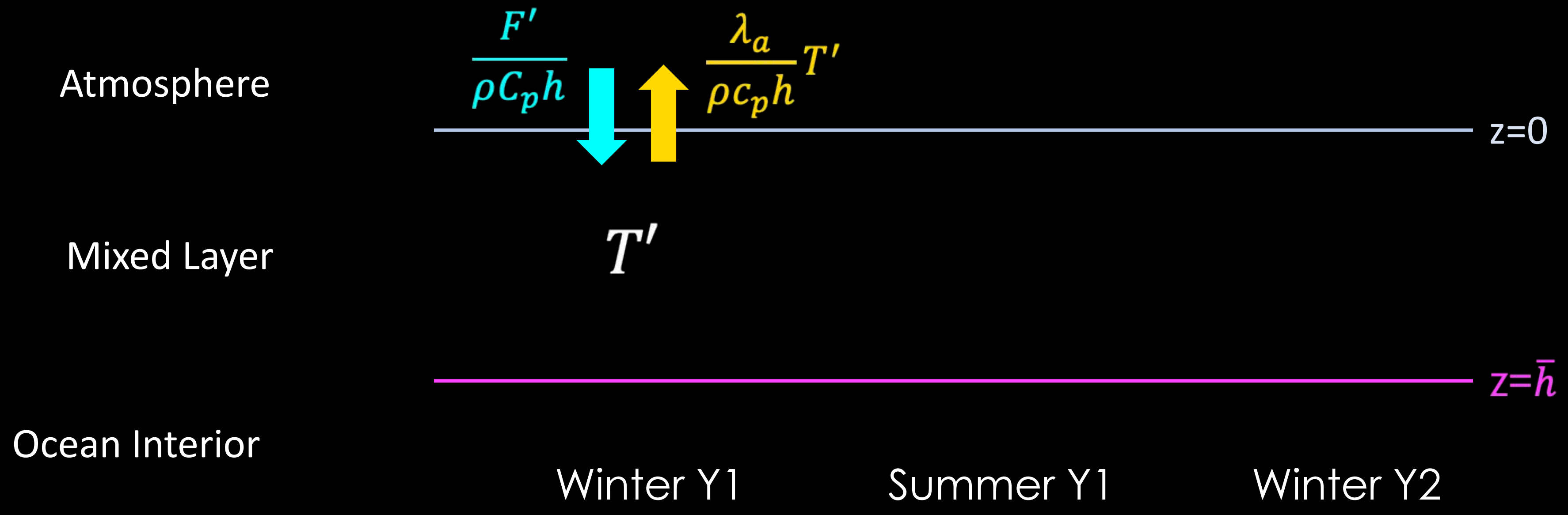
The Stochastic Climate Model

Two-time scale paradigm (Hasselmann 1976)

- Atmospheric heat flux forcing (fast)
- Ocean/Mixed Layer Temps (slow)

stochastic atmospheric forcing; heat flux damping

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T'$$

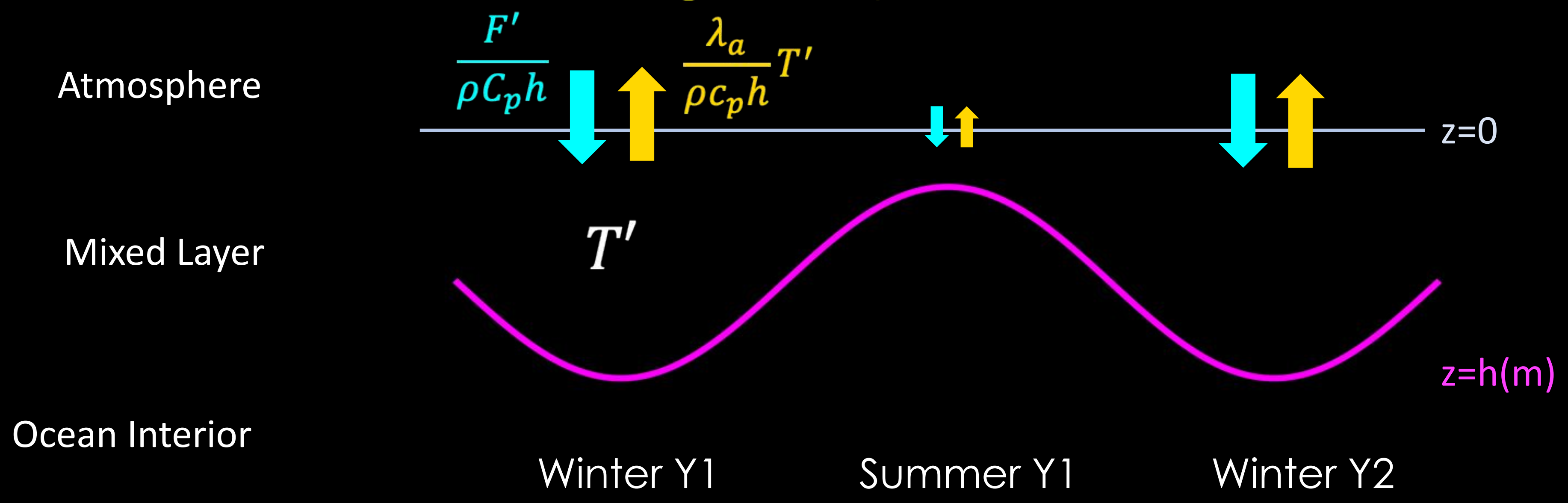


The Stochastic Climate Model

Q1 How does seasonal variation in damping, forcing, and mixed-layer depth impact SST variability?

stochastic atmospheric forcing — heat flux damping

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T'$$

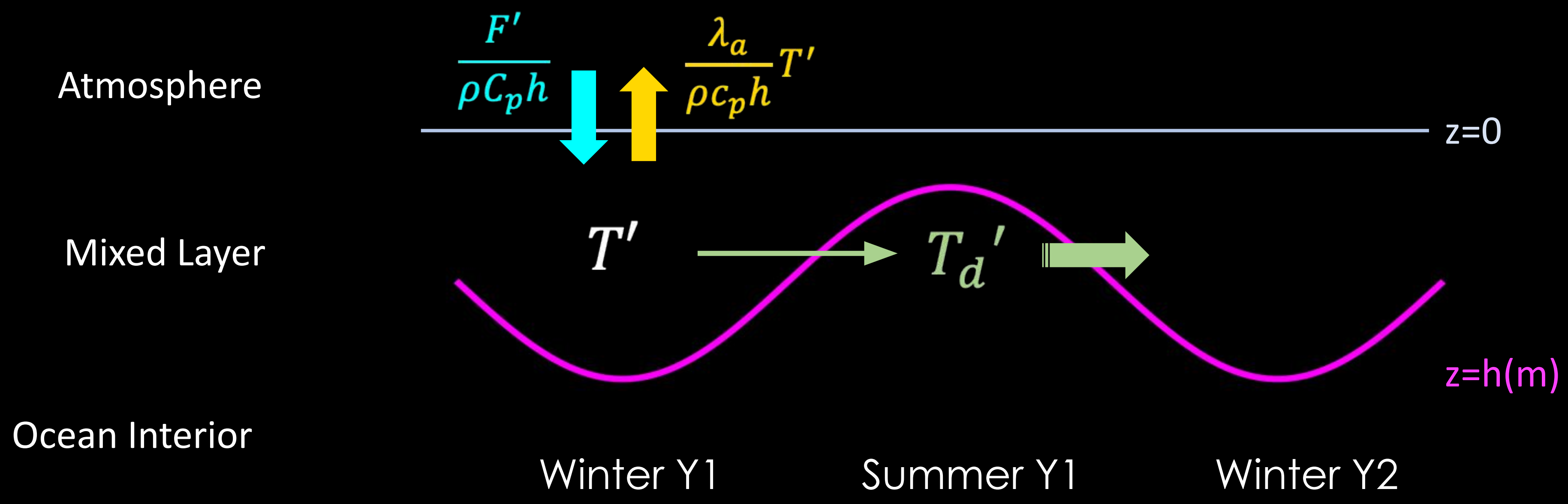


The Entrainment Mechanism

stochastic atmospheric forcing

heat flux damping

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T'$$



The Stochastic Climate Model

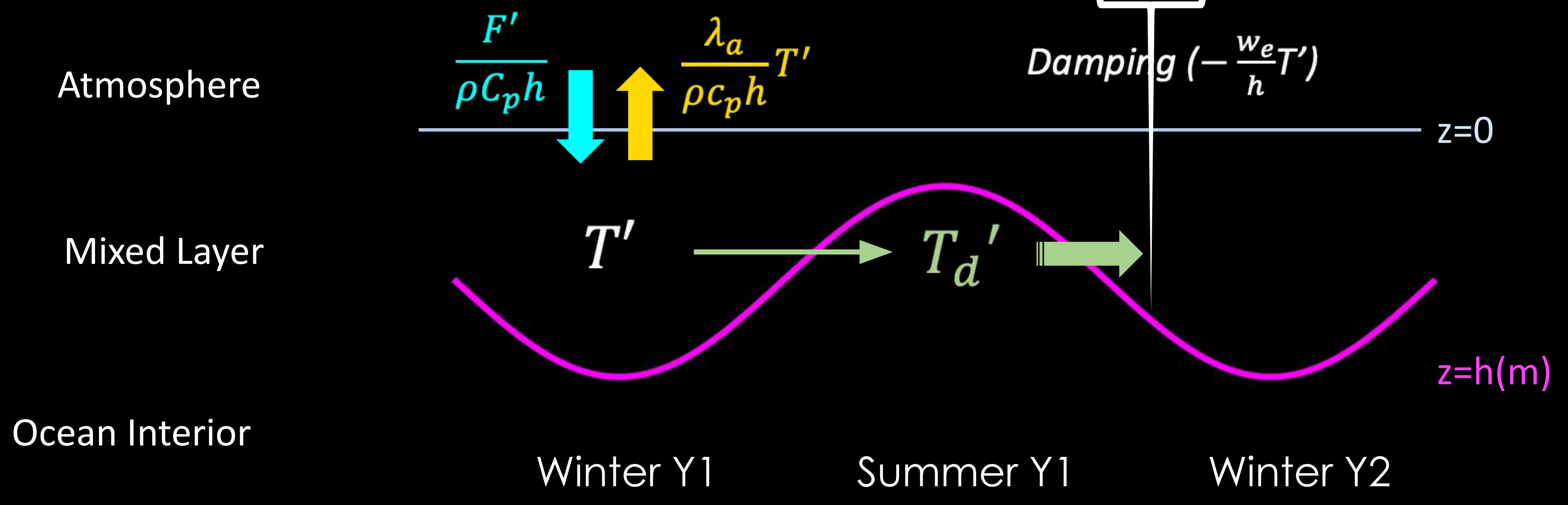
Q2 What is the role of entrainment/re-emergence for SST variability?

stochastic atmospheric forcing — heat flux damping — Entrainment Velocity ($\frac{dh}{dt}$) — SST' below mixed layer

Forcing ($\frac{w_e}{h} T_d'$)

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T' - \frac{1}{h} w_e (T' - T_d')$$

Damping ($-\frac{w_e}{h} T'$)



Estimating Stochastic Model Parameters from CESM1

stochastic atmospheric forcing; heat flux damping; Entrainment Velocity ($\frac{dh}{dt}$); SST' below mixed layer

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T' - \frac{1}{h} w_e (T' - T_d')$$

⇒ 3 Input Parameters

Forcing (F')

EOF Analysis on F' ($= Q'_{net} + \lambda_a T'$)
in CESM for each month

$$F'(x,y,t) = \sum_{n=1}^{k} \alpha(x,y,m,n)\, N_{(0,1)}(n,t)$$

- Temporally Random
- Maintain Spatial Coherence
- Monthly varying amplitude

Heat Flux Feedback (λ_a)

Statistical Approach
(d'Coëtlogon and Frankignoul 2002)

$$\lambda_a = \frac{cov[Q'(t), T'(t-1)]}{cov[T'(t), T'(t-1)]}$$

Mixed Layer-Depth (h)

Seasonal Climatological
Cycle from CESM1-FULL

Estimating Stochastic Model Parameters from CESM1

stochastic atmospheric forcing — heat flux damping — Entrainment Velocity ($\frac{dh}{dt}$) — SST' below mixed layer

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T' - \frac{1}{h} w_e (T' - T_d{}')$$

⇒ 3 Input Parameters

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Heat Flux Feedback (λ_a)

Statistical Approach (d'Coëtlogon and Frankignoul 2002)

$$\lambda_a = \frac{cov[Q'(t), T'(t-1)]}{cov[T'(t), T'(t-1)]}$$

Mixed Layer-Depth (h)

Seasonal Climatological Cycle from CESM1-FULL

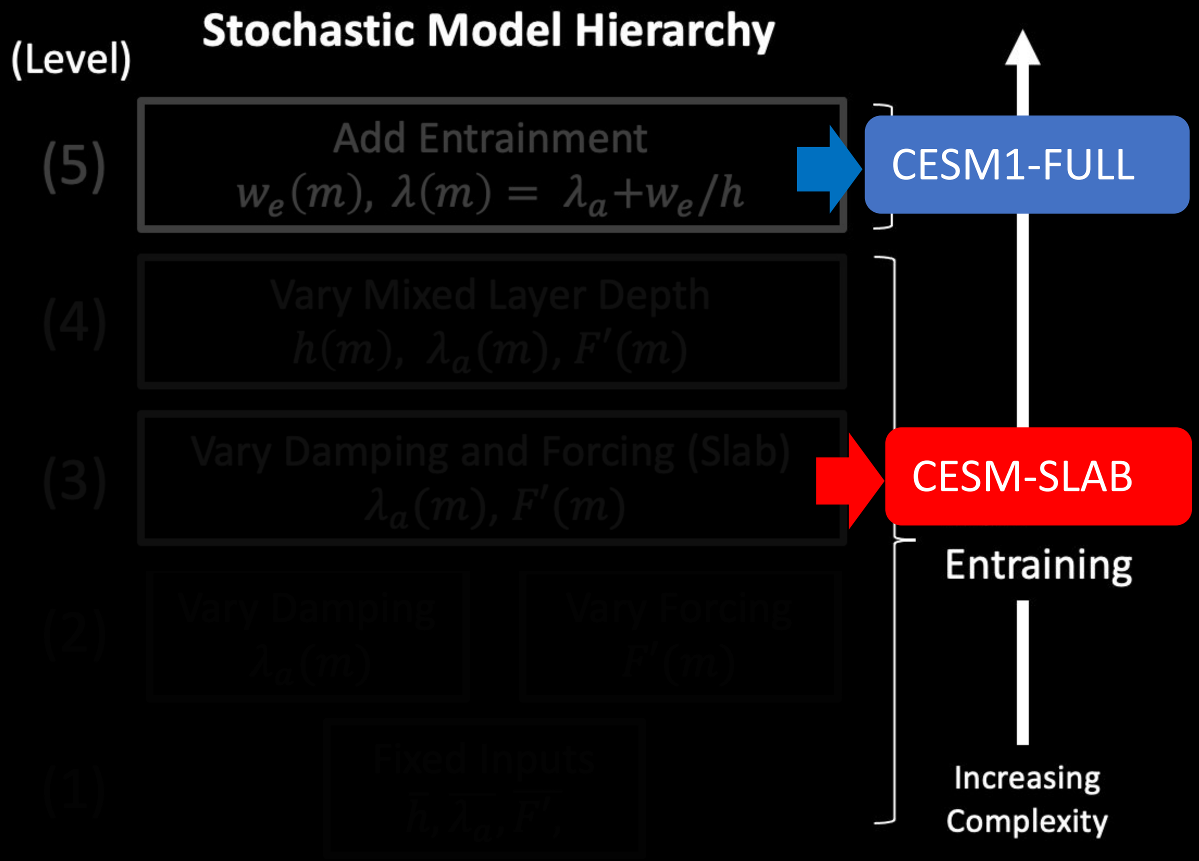
Configuration/Dataset Name	Abbreviation	Years Used	Total Months of Data
Pre-industrial Control	CESM1-FULL	400 - 2200	21,612
Pre-industrial Control (Slab Ocean)	CESM1-SLAB	200 - 1100	10,812

Key Questions

1. How does seasonal variation in the model parameters impact SST variability?

2. What is the role of entrainment in SST variability?

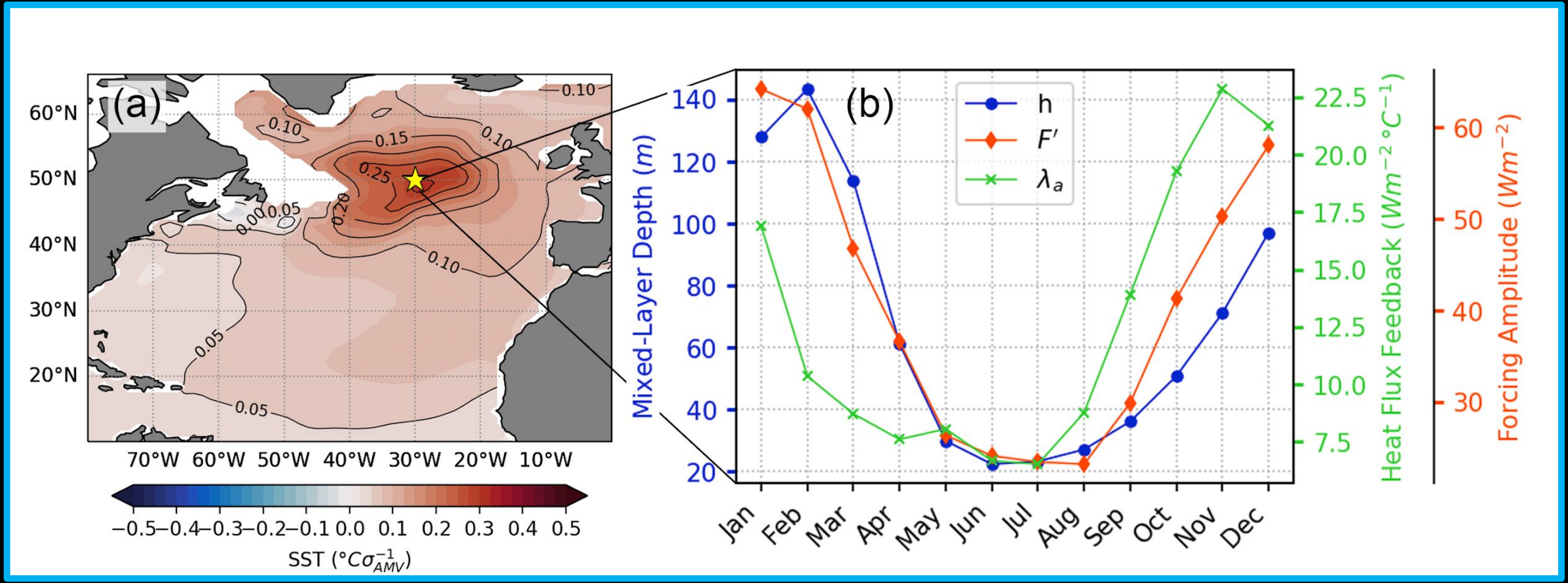
3. Can spatially-coherent, temporally random atmospheric forcing reproduce the AMV Pattern in CESM1?



stochastic atmospheric forcing — heat flux damping — entrainment

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T' - \frac{1}{h} w_e (T' - T_d')$$

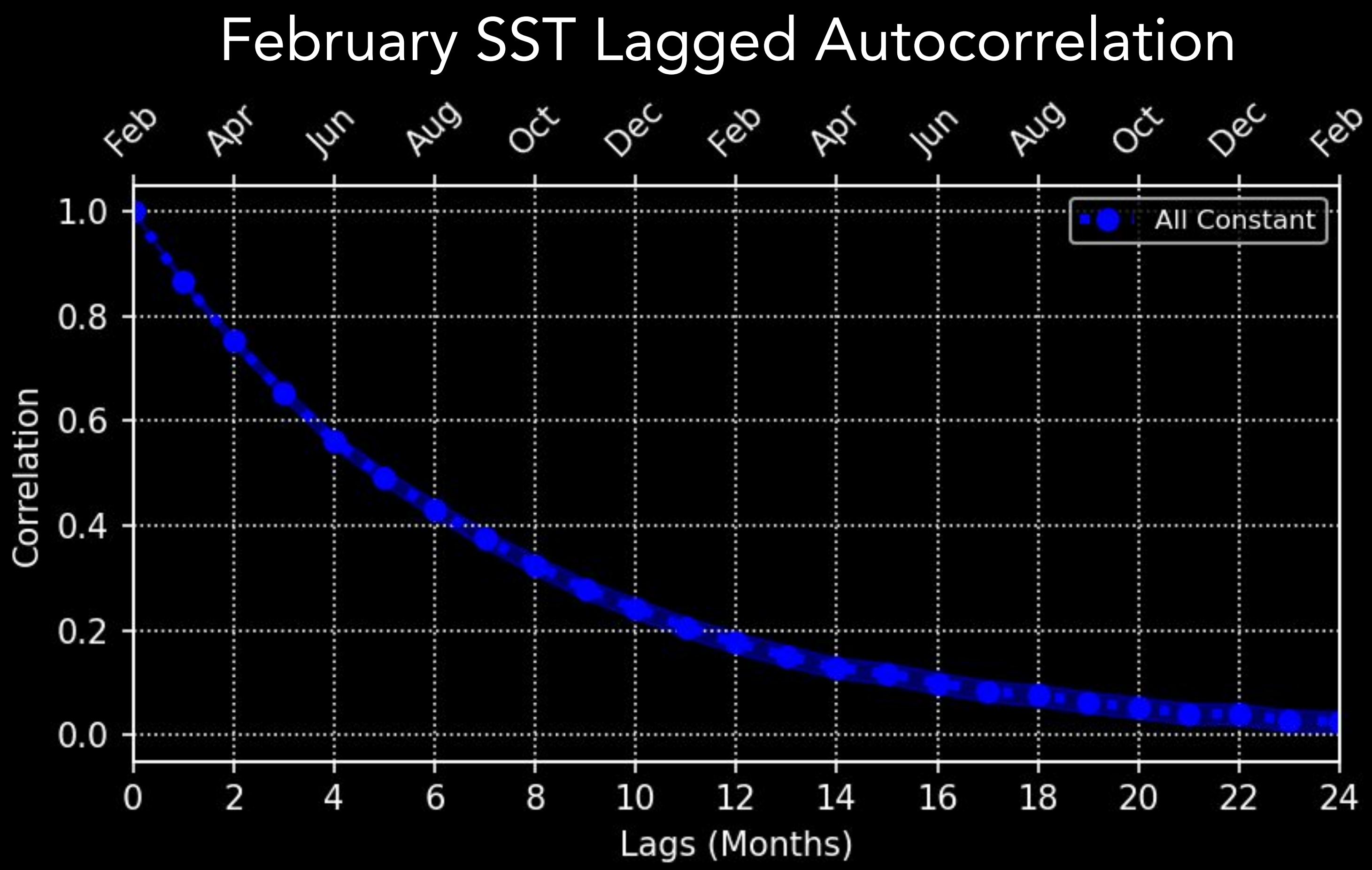
Case Study in the Subpolar Gyre (50˚N, 30˚W)

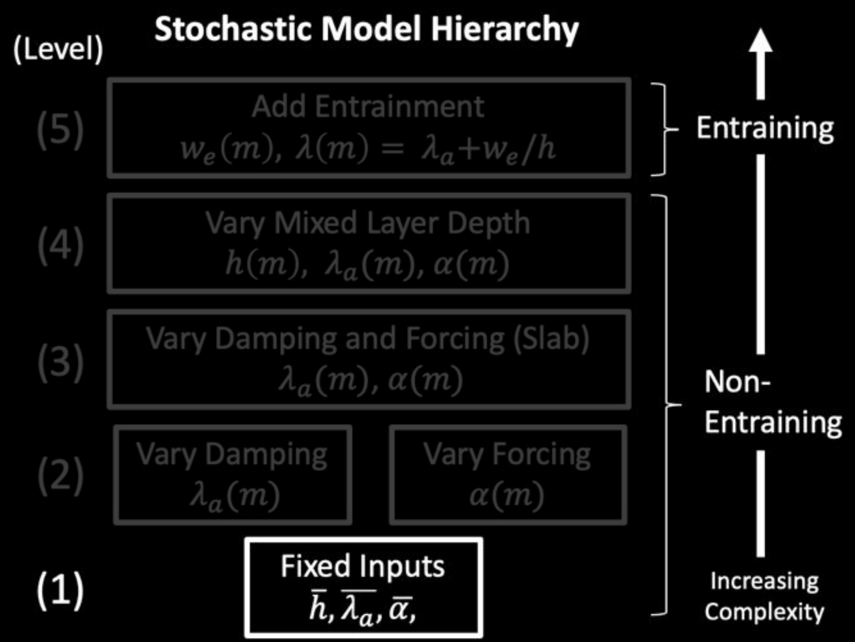


1) Location of maximum AMV loading
2) Away from regions of advection
3) Typical seasonal variation in parameters

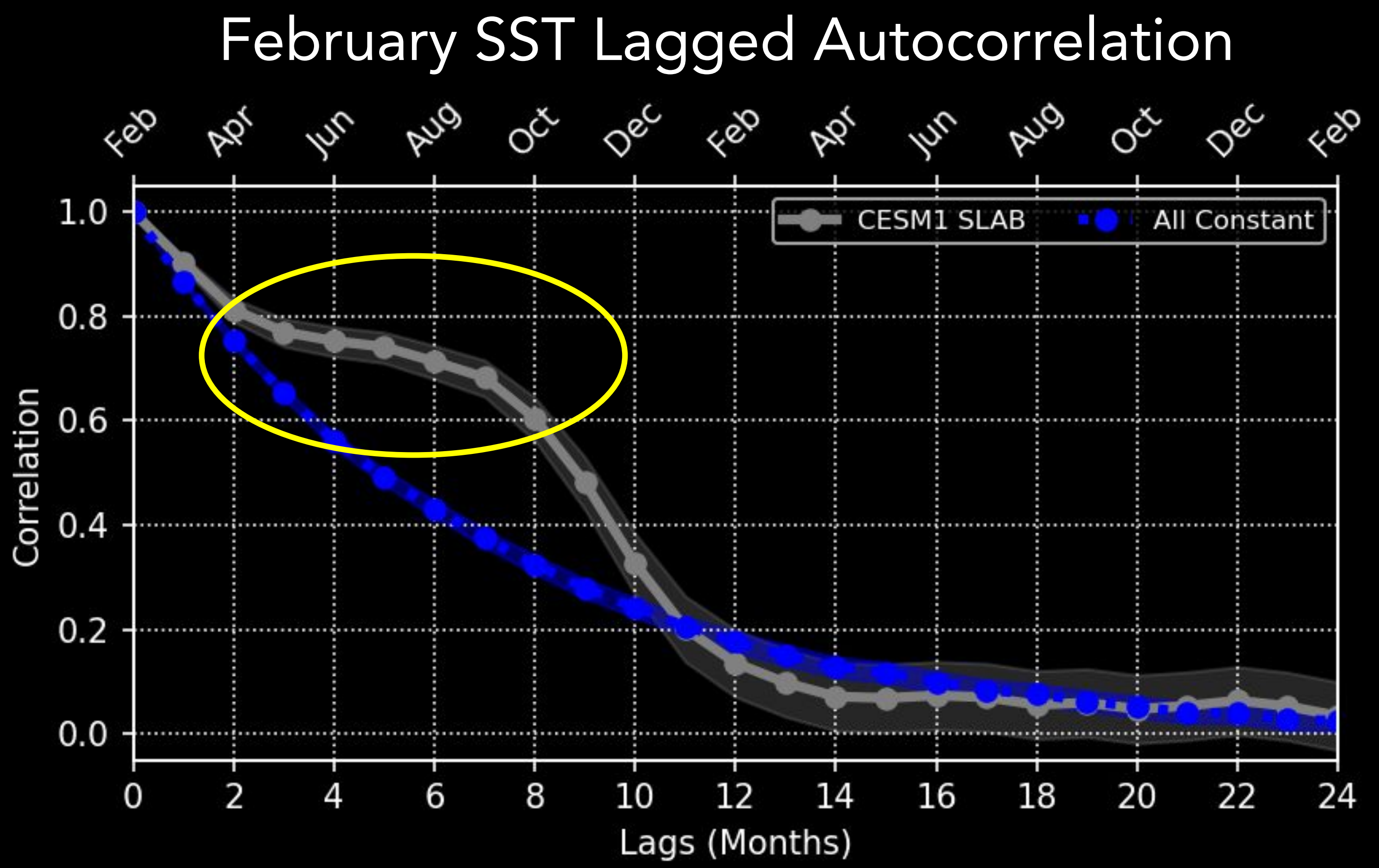
Each stochastic model configuration is integrated for 10,000 years at 50˚N, 30˚W….

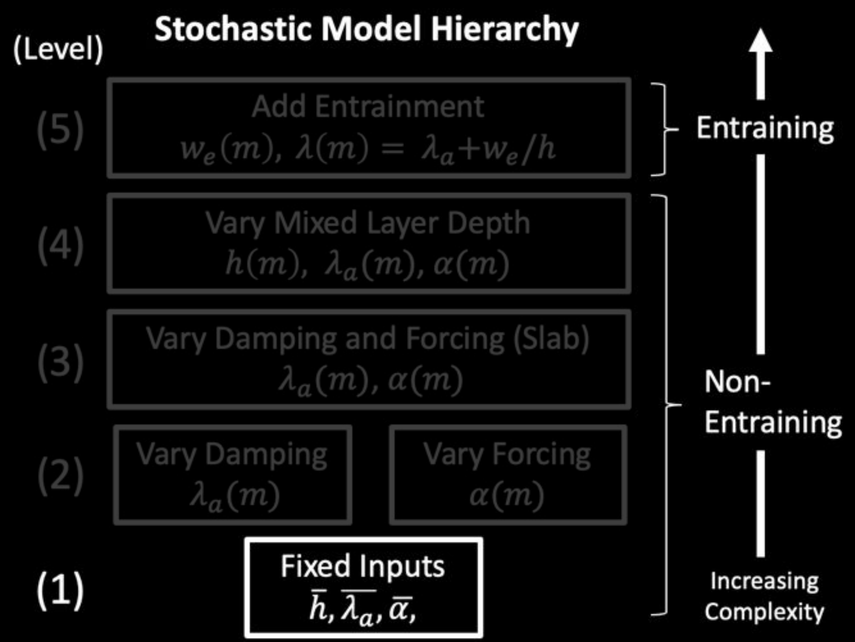
SST Persistence



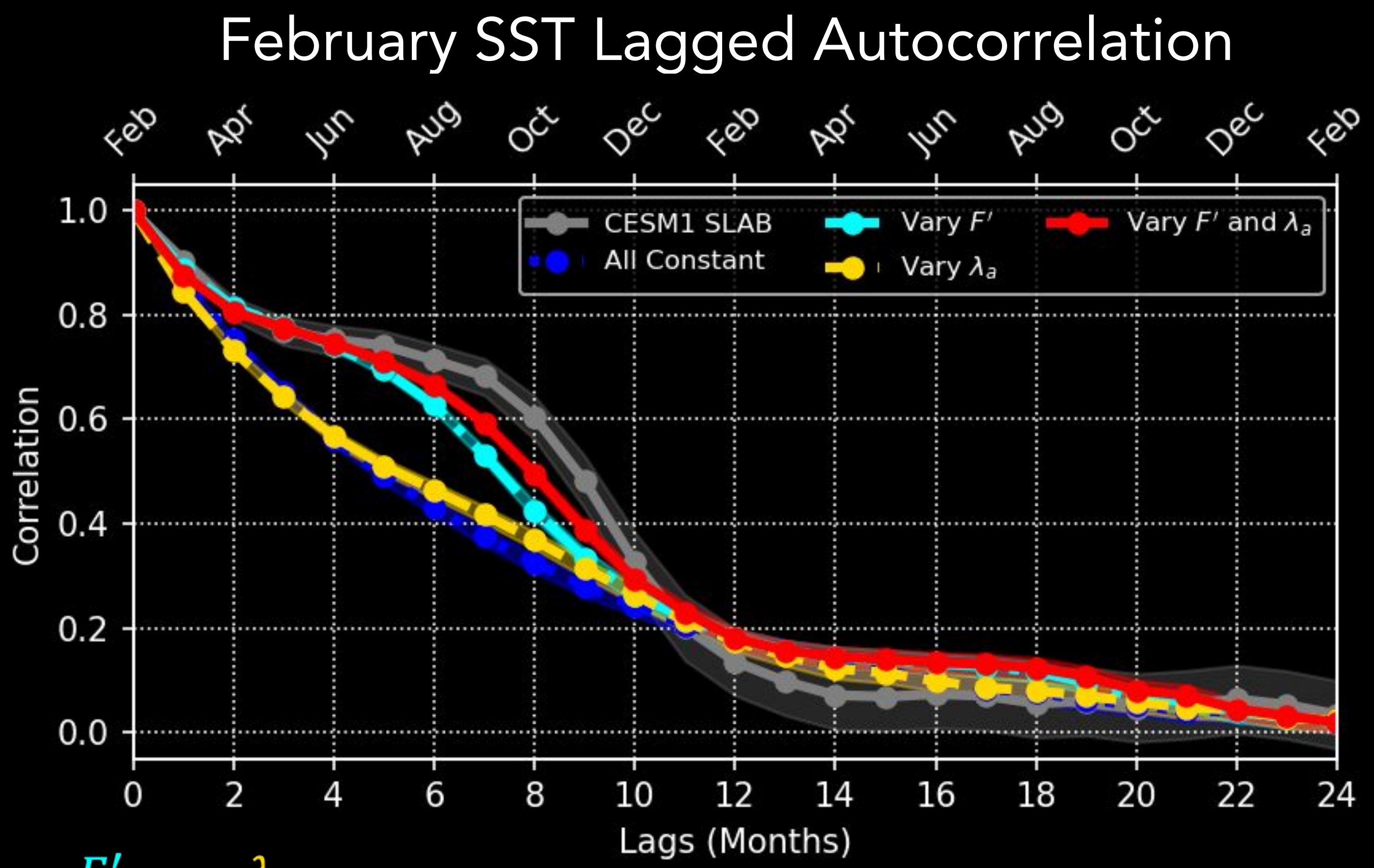


SST Persistence

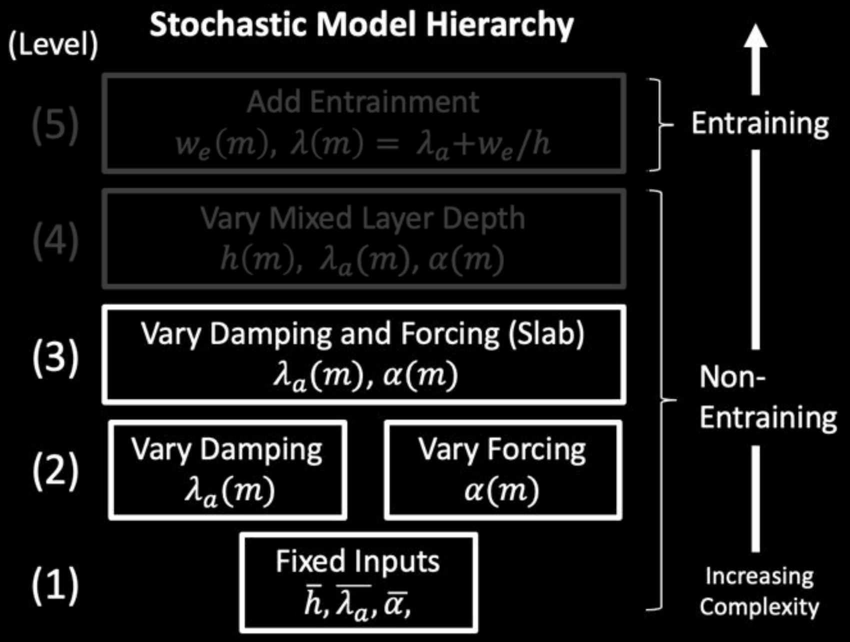




Vary Damping and Forcing



$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p \bar{h}} - \frac{\lambda_a}{\rho C_p \bar{h}} T'$$

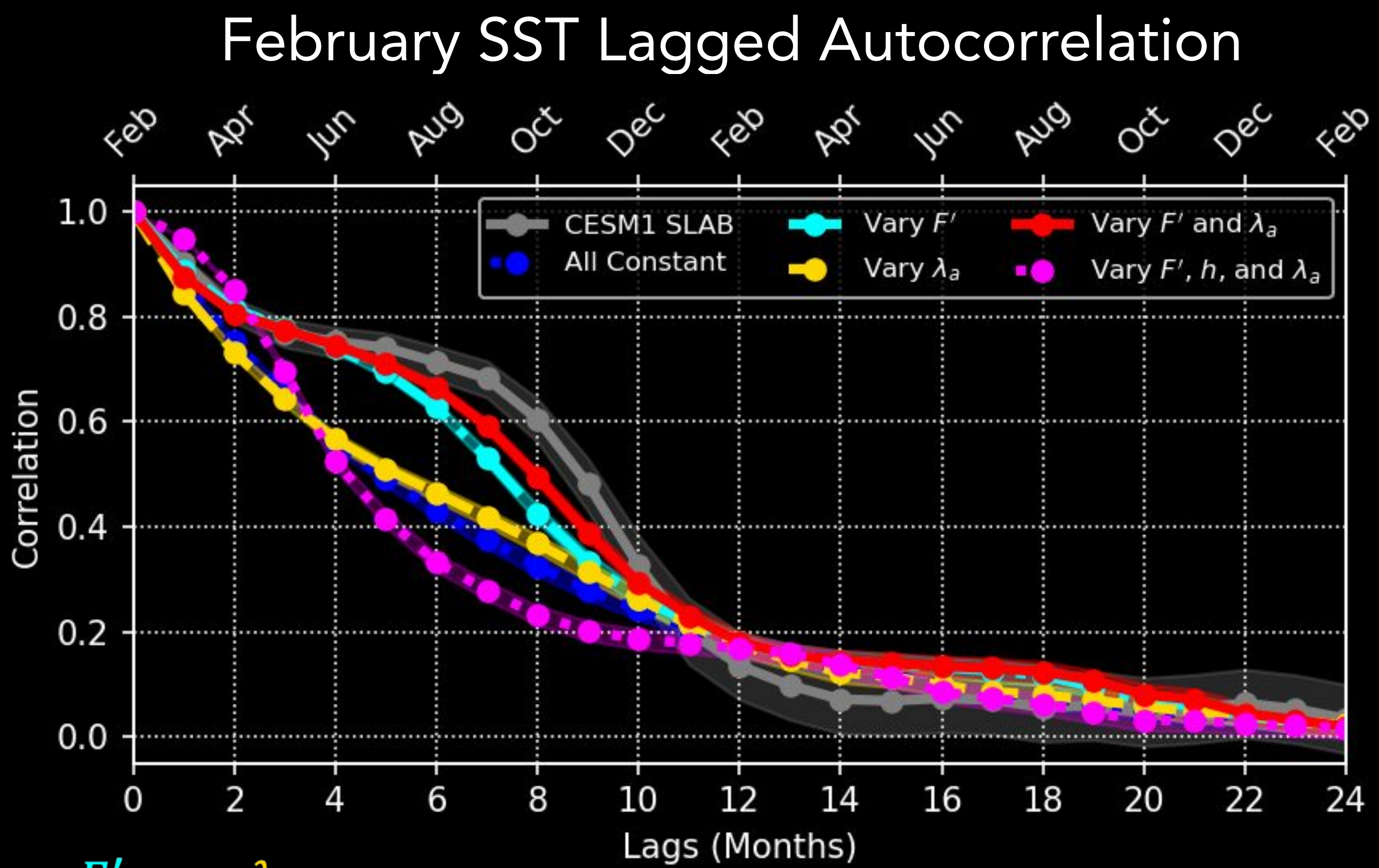


<u>Summer Conditions</u>

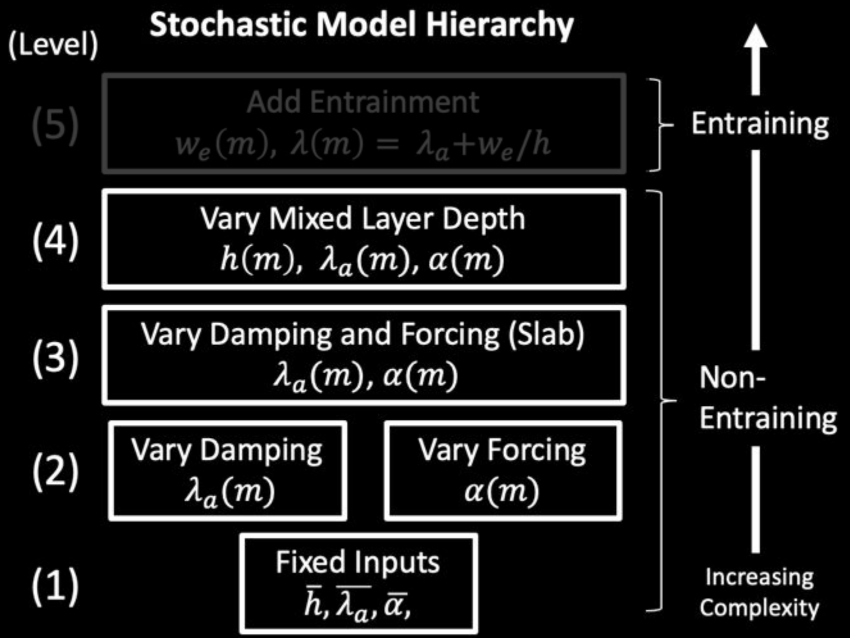
- Weak damping/forcing
- Constant MLD

Unrealistic SST Persistence in Slab-like configurations

Vary MLD



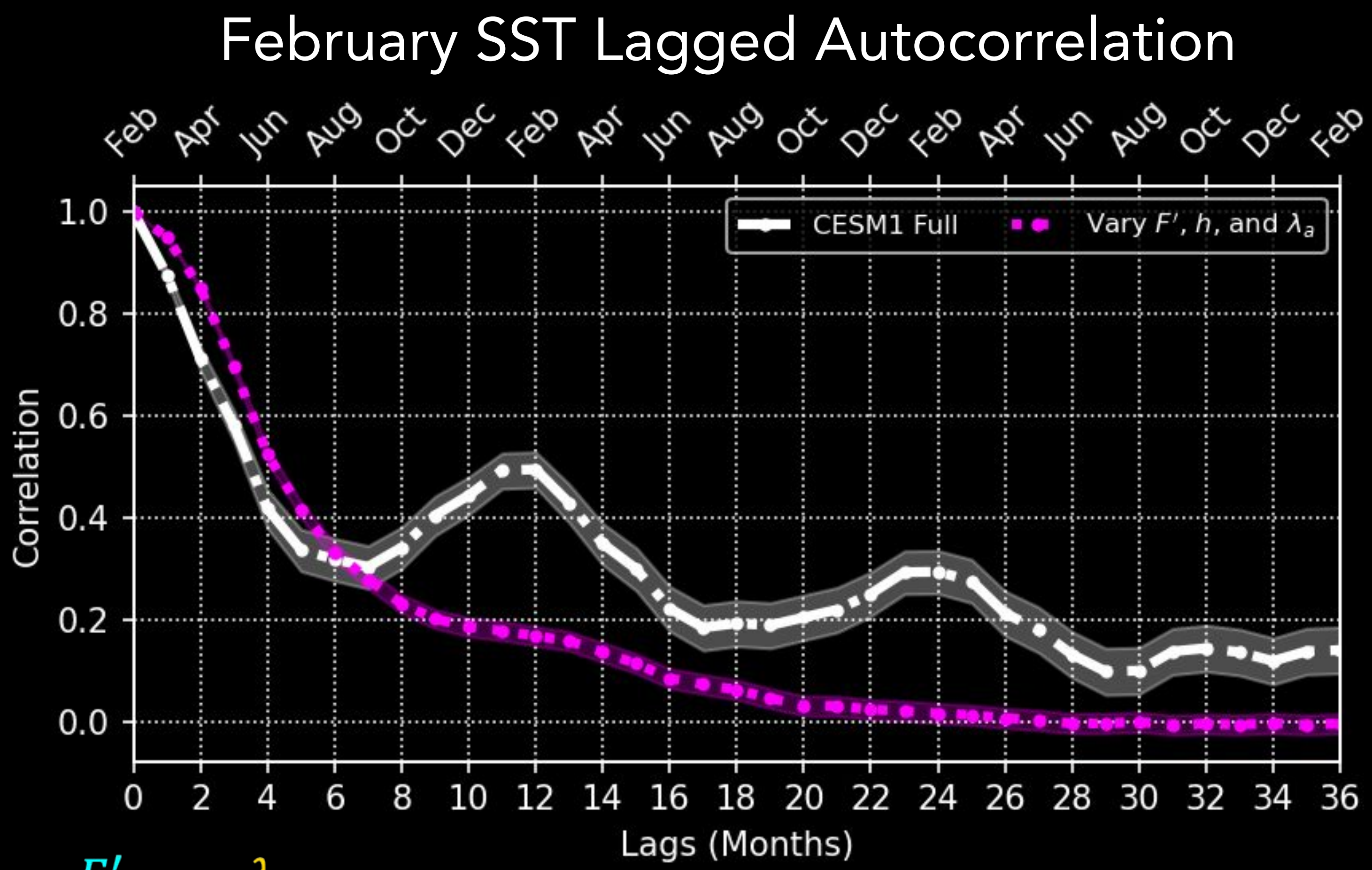
$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T'$$

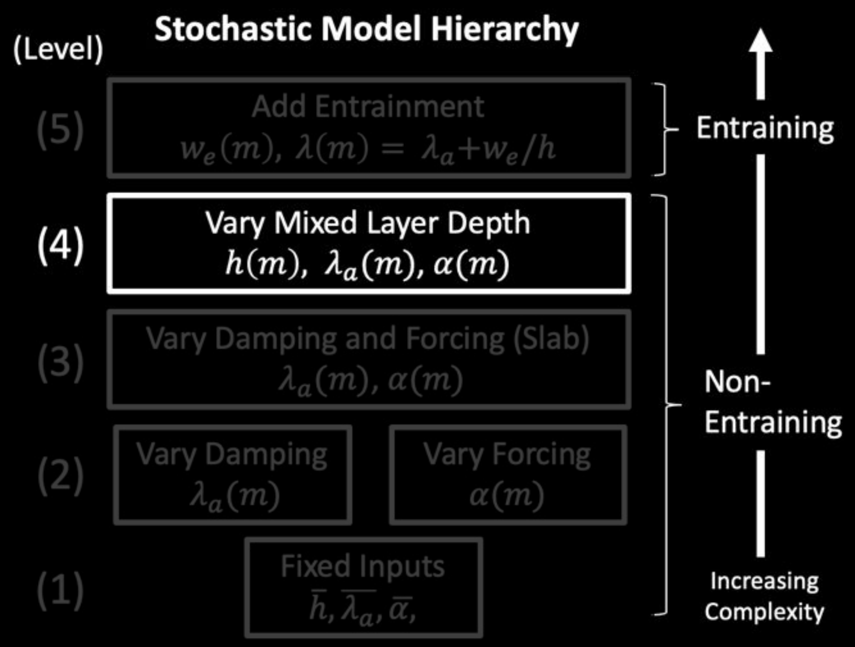


Summer Conditions
- Weak damping/forcing
- Constant MLD

Unrealistic SST Persistence in Slab-like configurations

Adding Entrainment



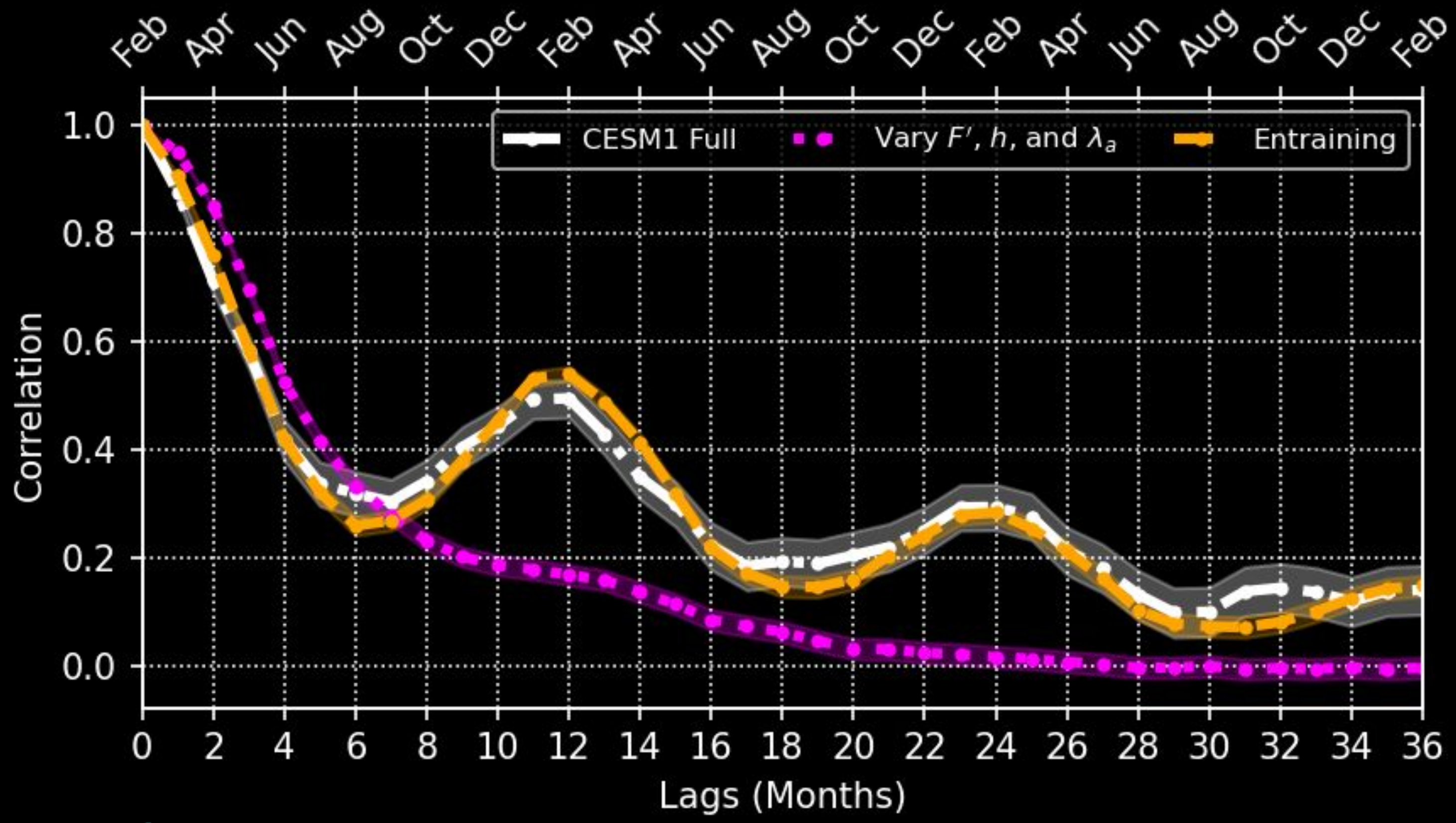


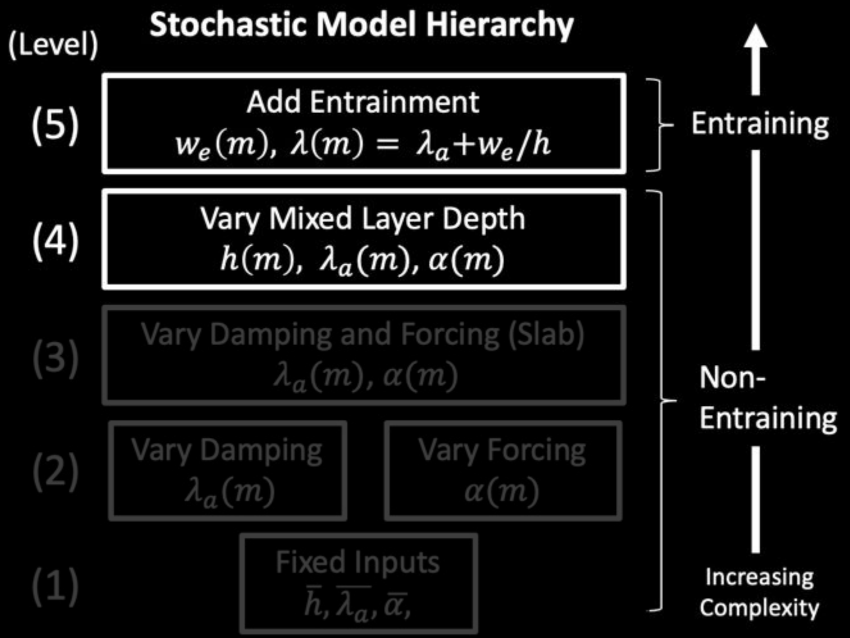
Seasonal MLD variations alone cannot capture SST persistence in CESM-FULL

$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T'$$

Adding Entrainment

February SST Lagged Autocorrelation

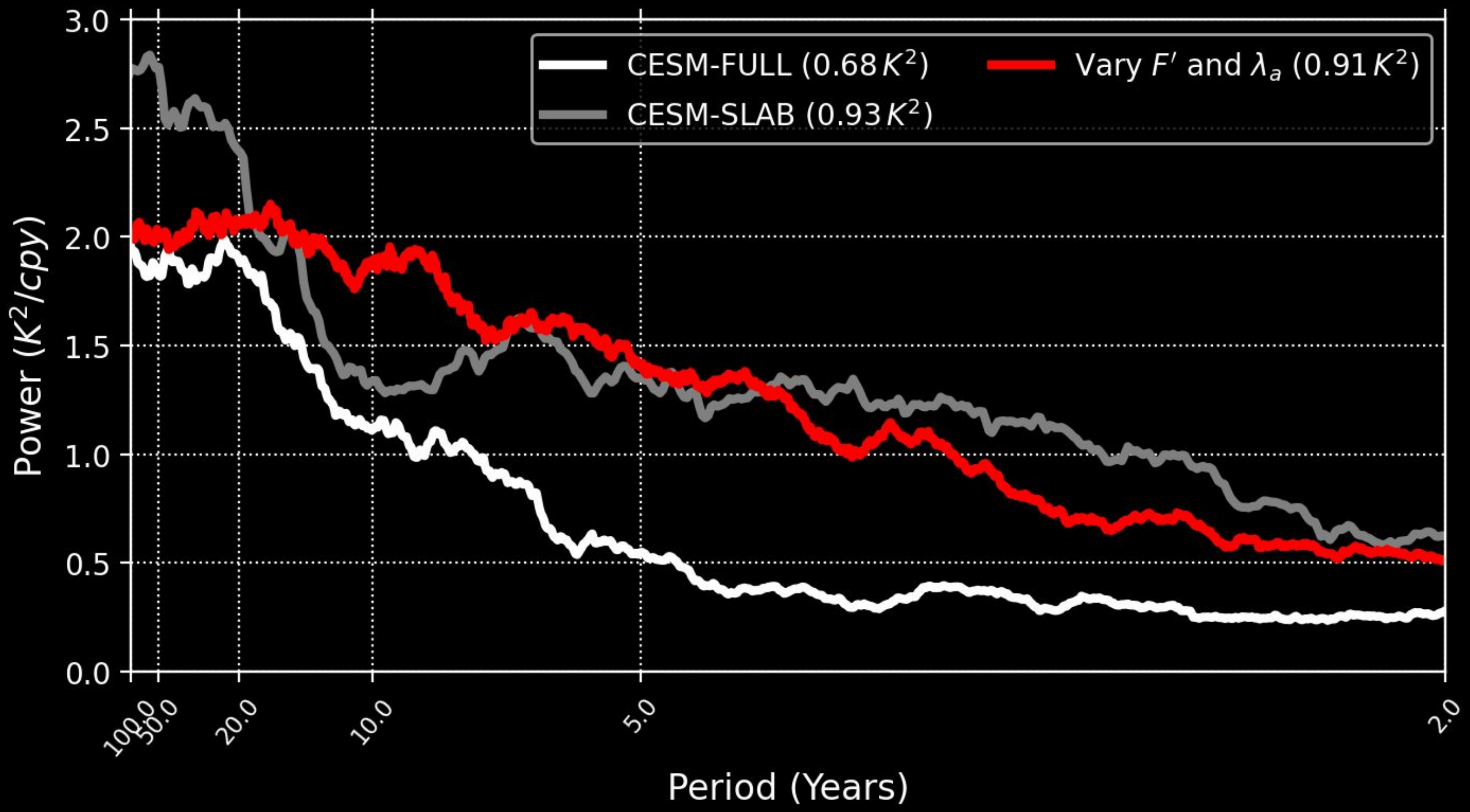




Adding entrainment captures the timing and amplitude of re-emergence in the SPG test point

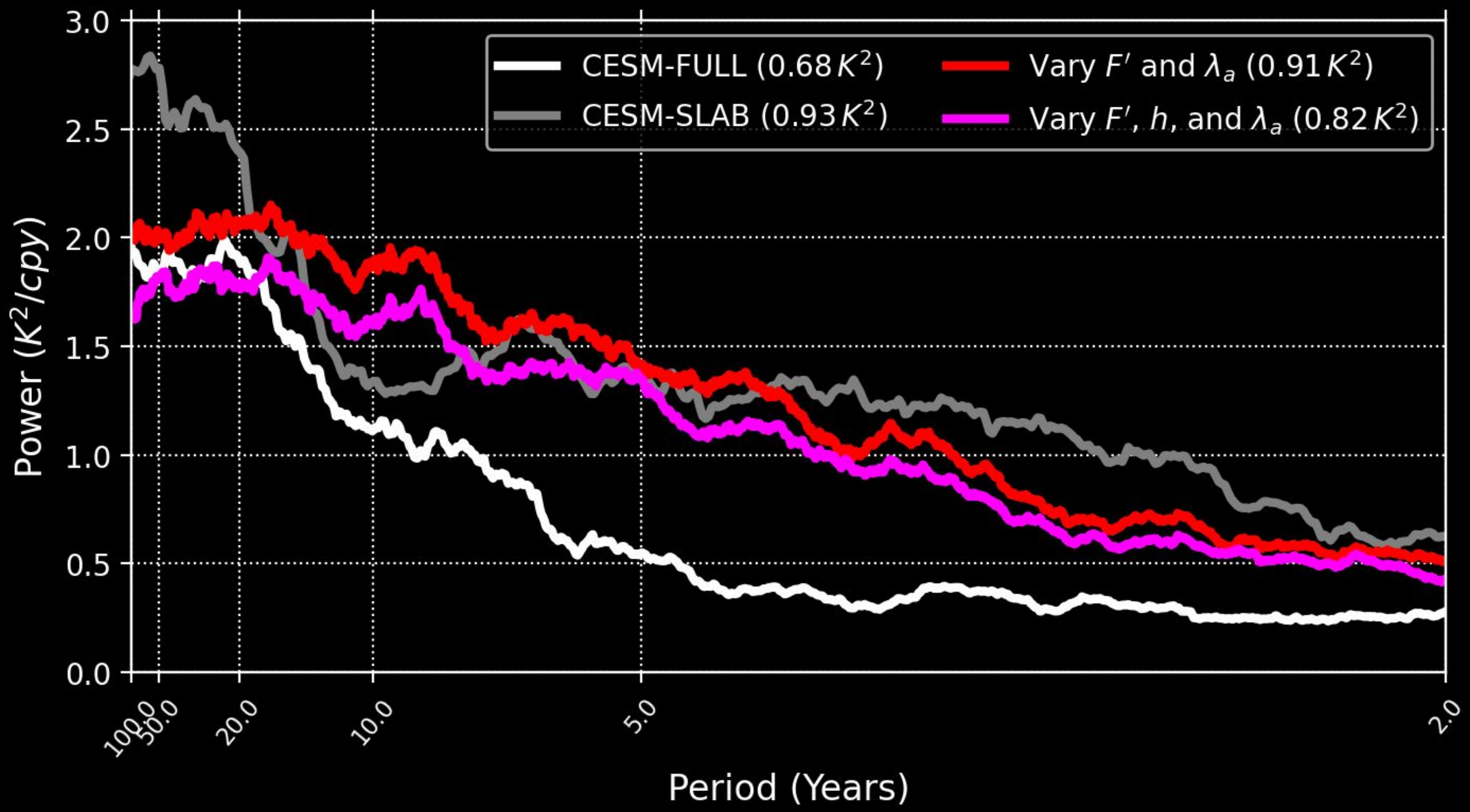
$$\frac{\partial T'}{\partial t} = \frac{F'}{\rho C_p h} - \frac{\lambda_a}{\rho C_p h} T' - \frac{1}{h} w_e (T' - T_d')$$

Interannual-to-Multidecadal Variability



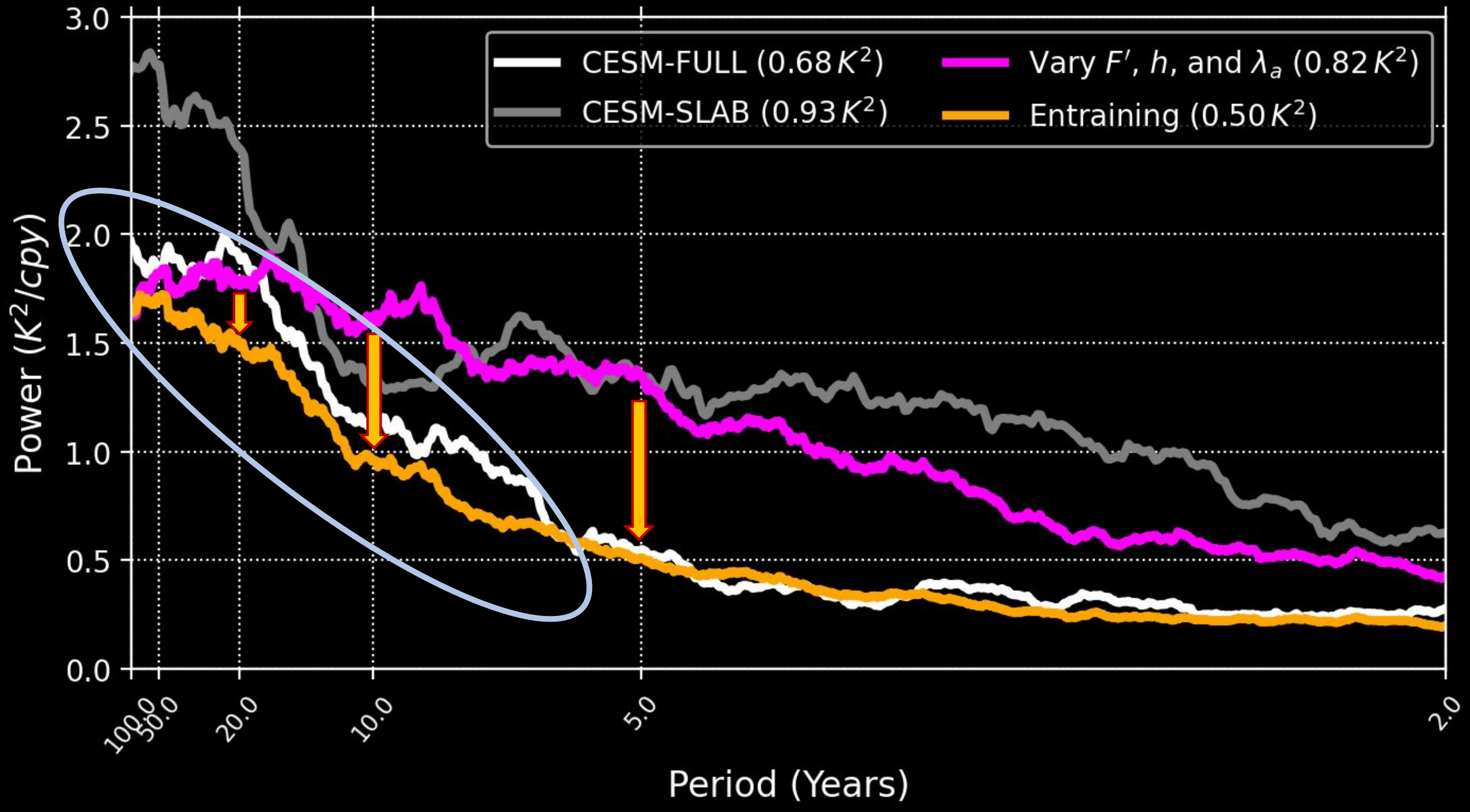
The non-entraining stochastic model and CESM-SLAB have *greater* SST variance than CESM-FULL

Adding MLD Variation



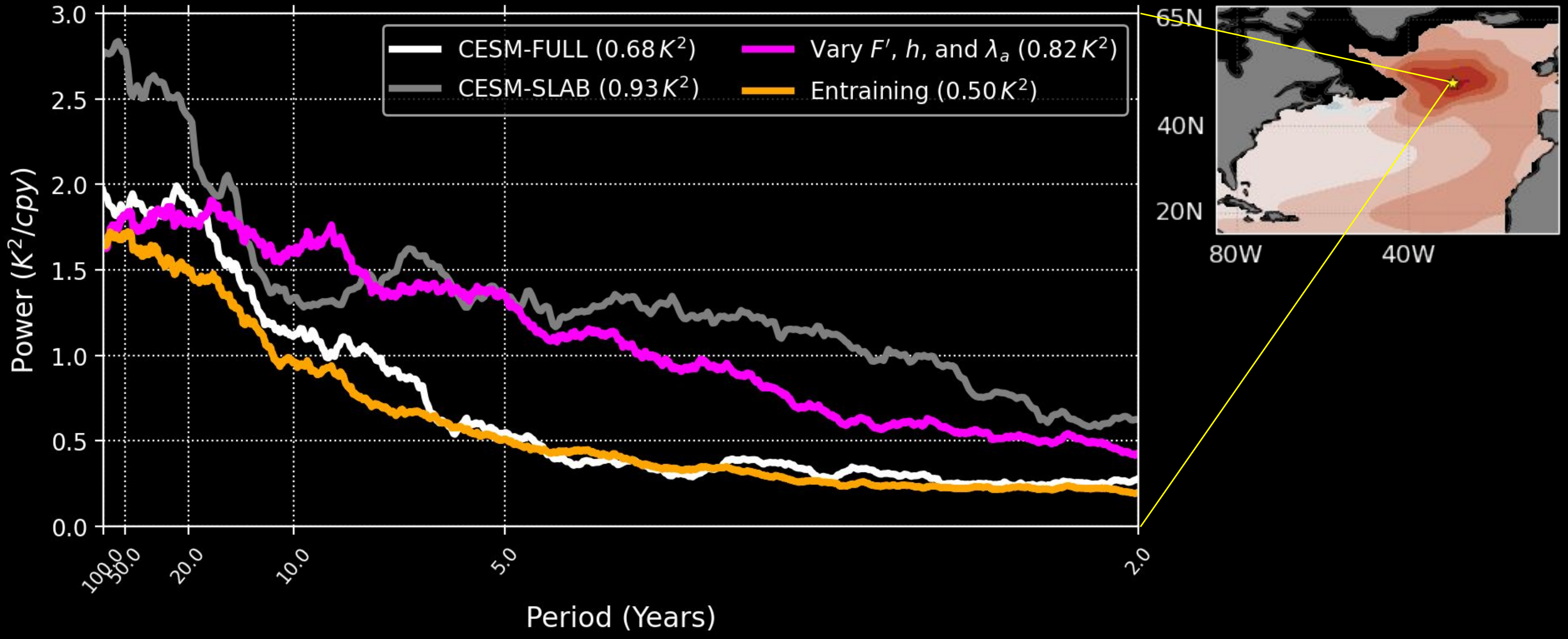
Adding variable MLD damps SST variance, but doesn't alter the spectrum's shape

Adding Entrainment



Entrainment *damps SST variability*, particularly at *interannual-to-decadal timescales*

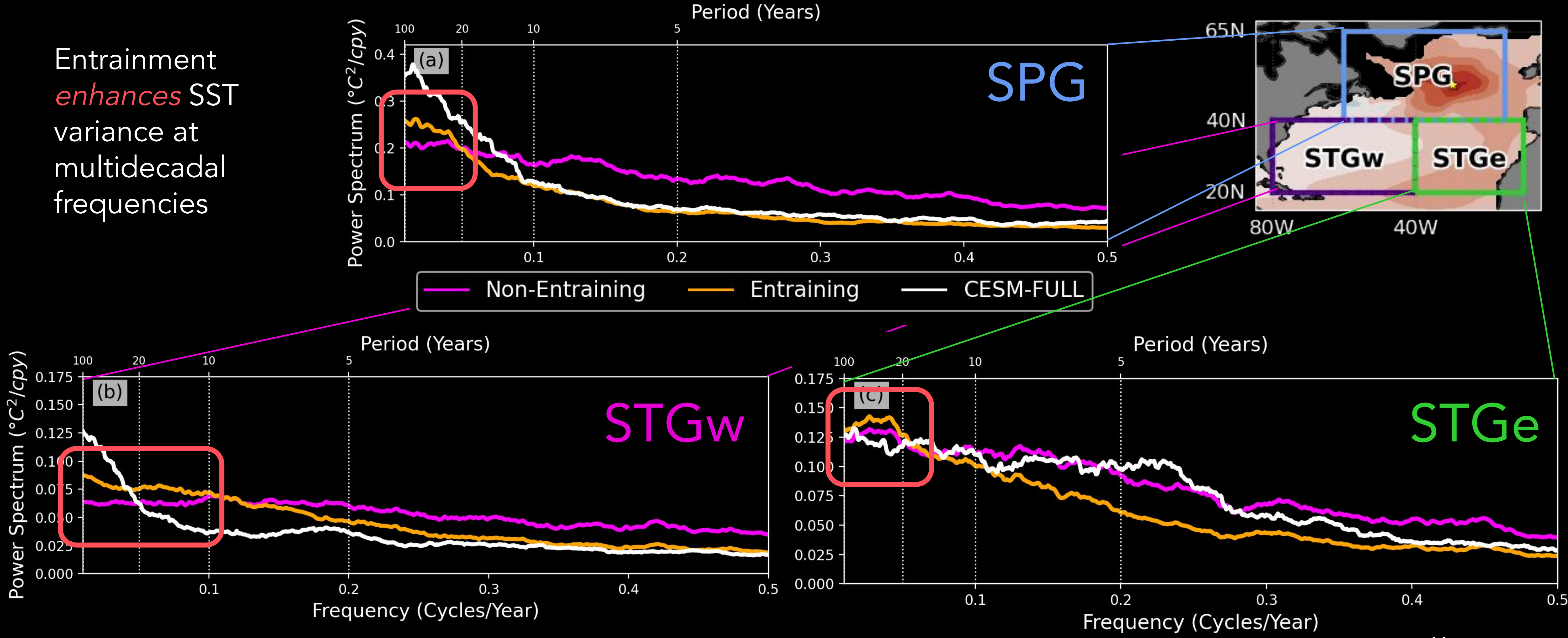
The Role of Entrainment in Other Regions



The Role of Entrainment in Other Regions

SPG: Subpolar Gyre; STGw,e: Subtropical Gyre West, East

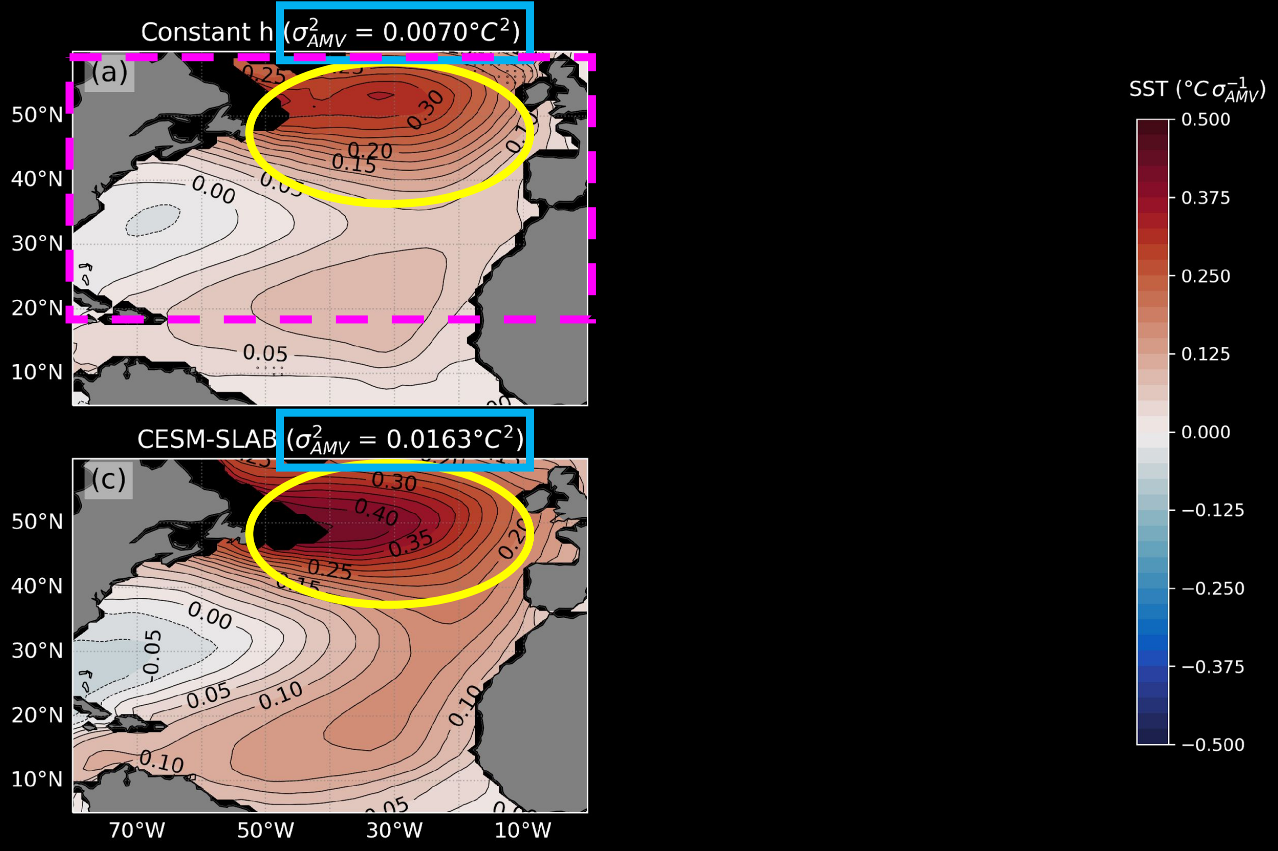
Entrainment *enhances* SST variance at multidecadal frequencies

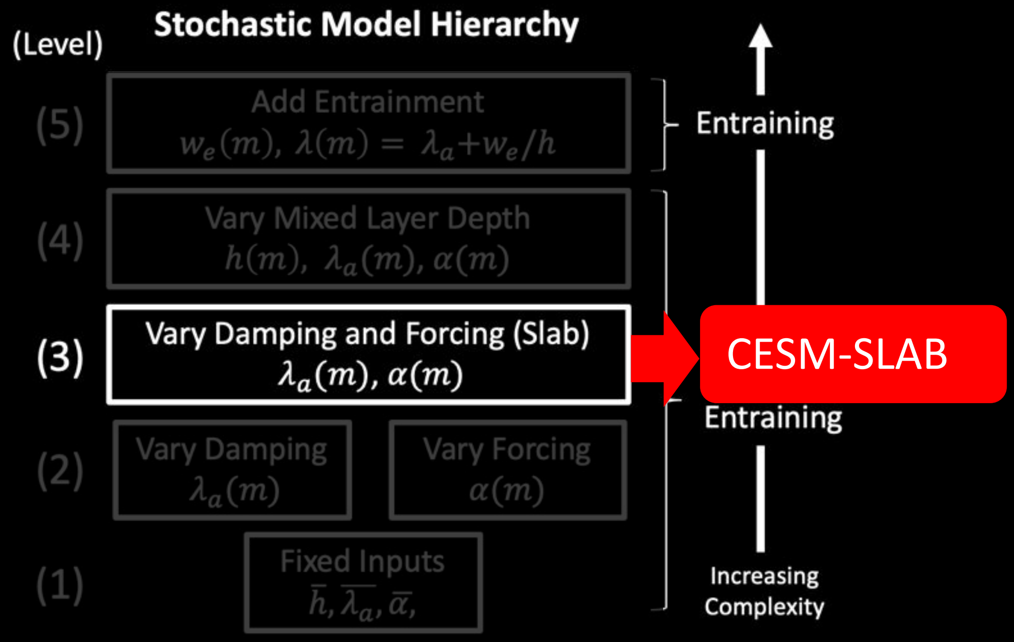


Next Steps: Investigating dynamics behind these regional differences

The AMV Spatial Pattern

Run stochastic model at each point for 10,000 years, then compute the extratropical AMV Pattern (°C σ_{AMV}^{-1})



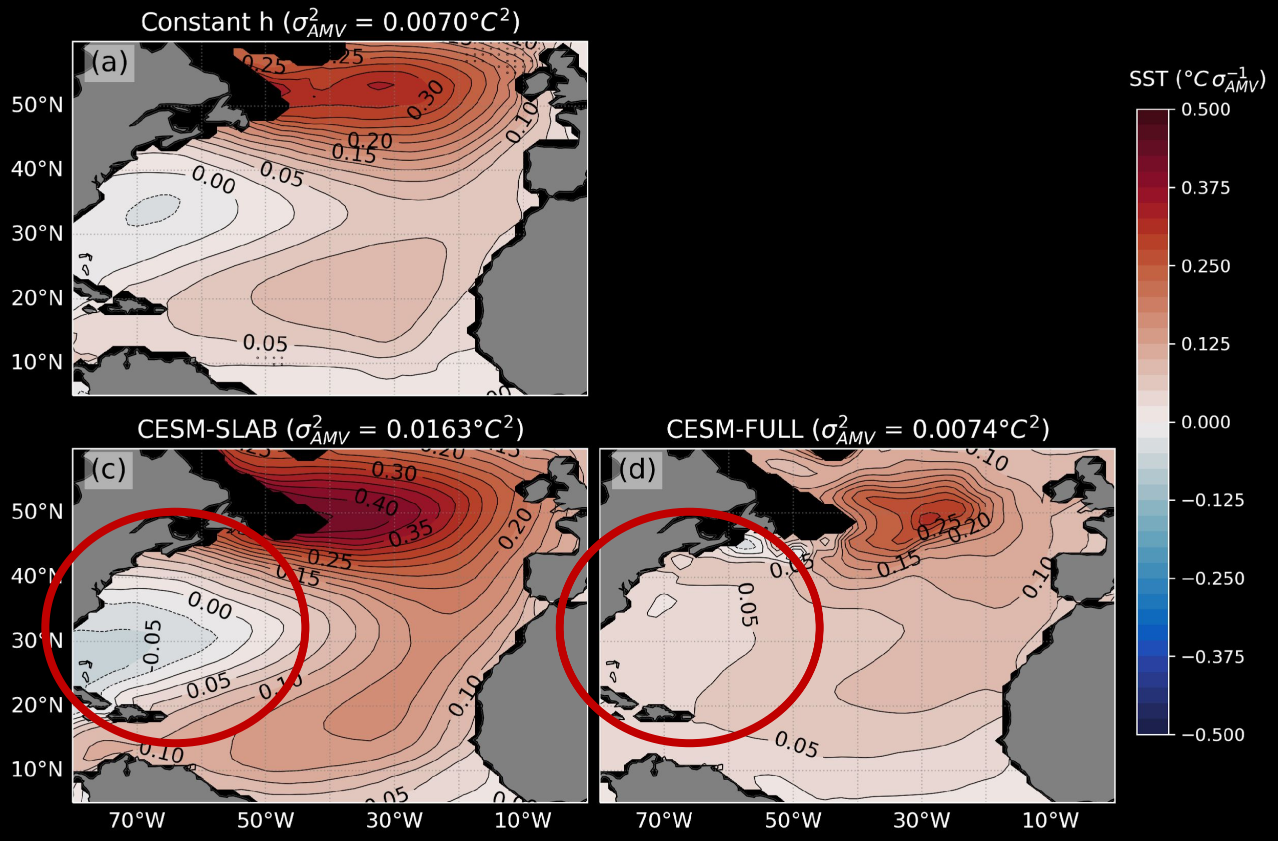


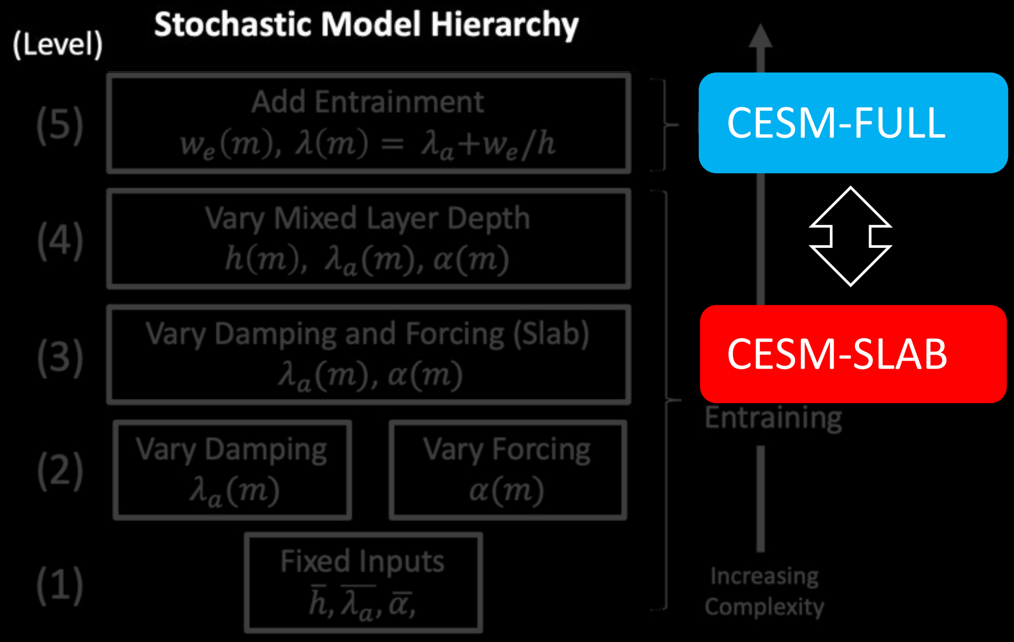
- Stochastic model captures major features of the canonical horseshoe pattern
- The stochastic model underestimates the AMV amplitude

*stippled regions excluded due to insignificant heat flux feedback estimation

The AMV Spatial Pattern

Run stochastic model at each point for 10,000 years, then compute the extratropical AMV Pattern (˚C σ_{AMV}^{-1})



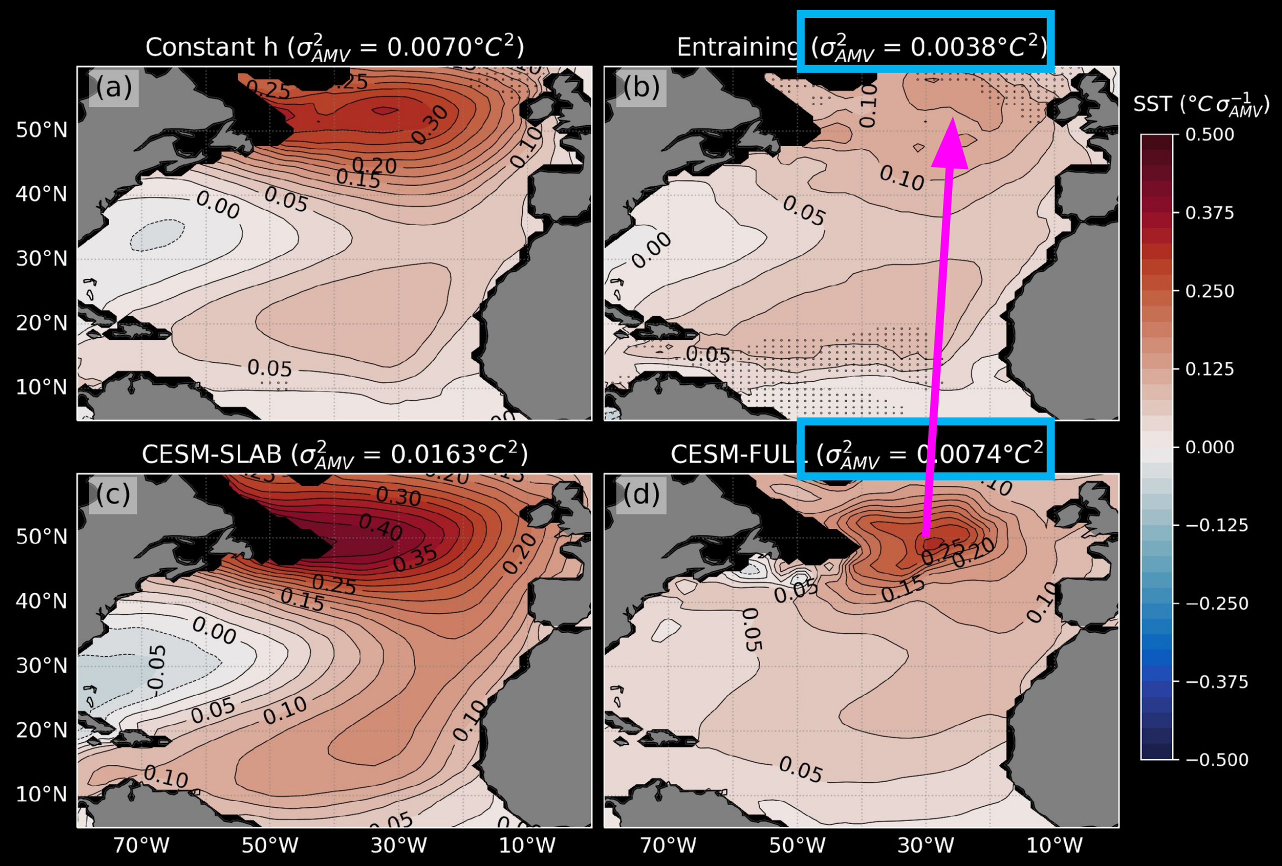


- The SLAB AMV amplitude is larger, and the detail of the pattern differs

*stippled regions excluded due to insignificant heat flux feedback estimation

The AMV Spatial Pattern

Run stochastic model at each point for 10,000 years, then compute the extratropical AMV Pattern (˚C σ_{AMV}^{-1})



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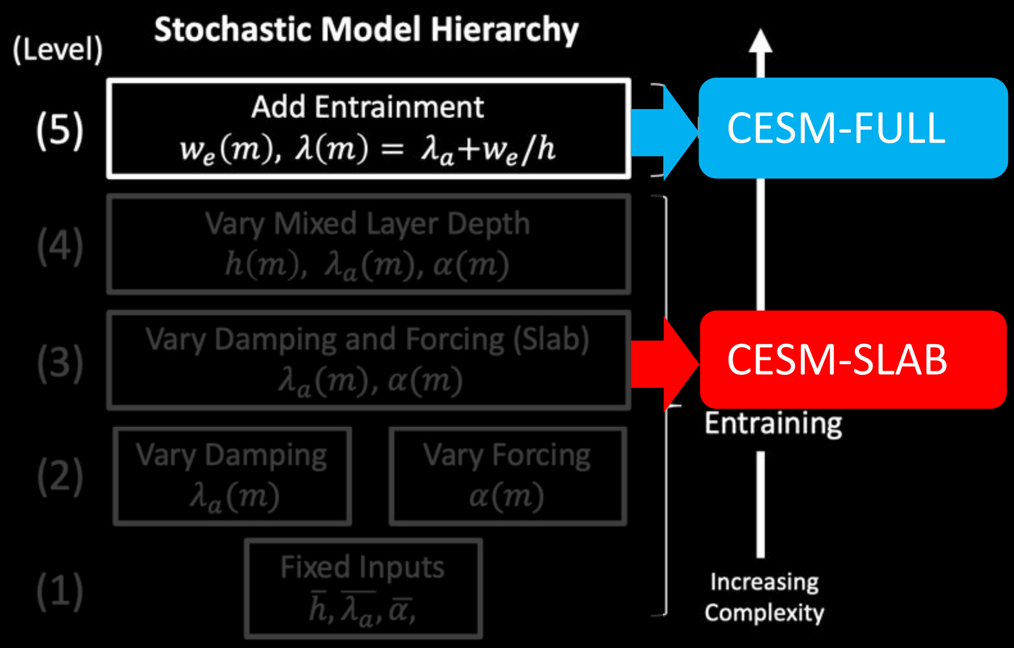
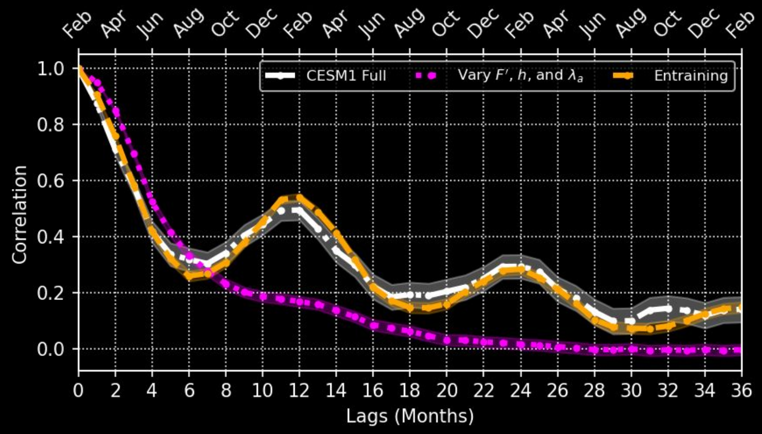


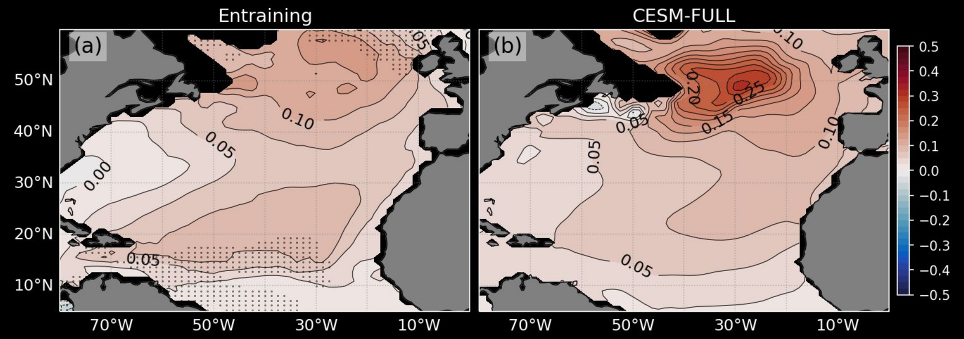
- Including entrainment and seasonal MLD variation *damps SST too much.*
- The SPG maxima is shifted too far to the northeast
- The missing dynamics beyond entrainment are likely needed to reconcile these differences.

Main Takeaways

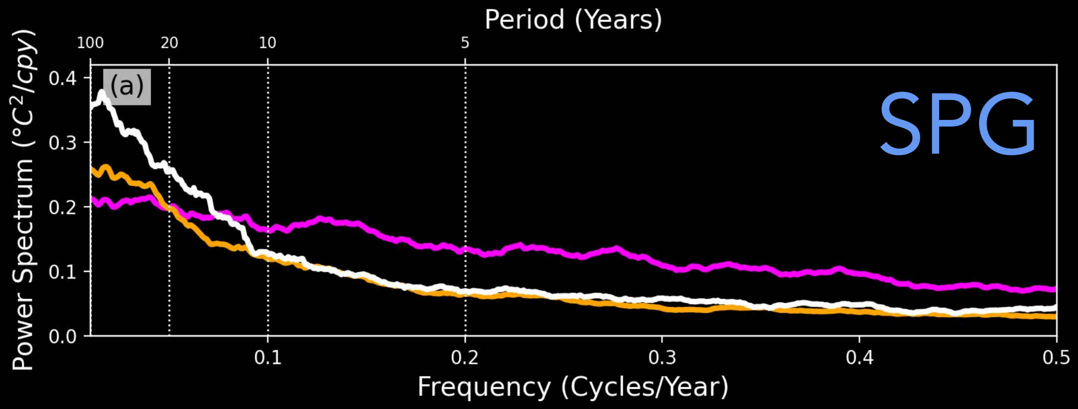


Frequency-dependent effect of entrainment on SST variability:

Interannual □ Multidecadal
(Damping) (Enhancement)



1. Seasonal variation in MLD is important for capturing SST variability and explains unrealistic SST persistence in slab models with fixed MLD



2. Frequency-dependent effect of entrainment on SST variability

3. Spatially coherent, temporally stochastic forcing produces the AMV pattern, but the amplitude is underestimated, leaving a role for the missing dynamics

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Thanks for Listening!

Contact: glennliu@mit.edu