A Critical Role for Seasonality in Forcing, Feedback, and Climate System Response over the Midlatitude Oceans

Daniel Vimont[1], Sagar Rathod[1], Jack Zweifel[1], Salil Mahajan[2] and David Henderson[1]

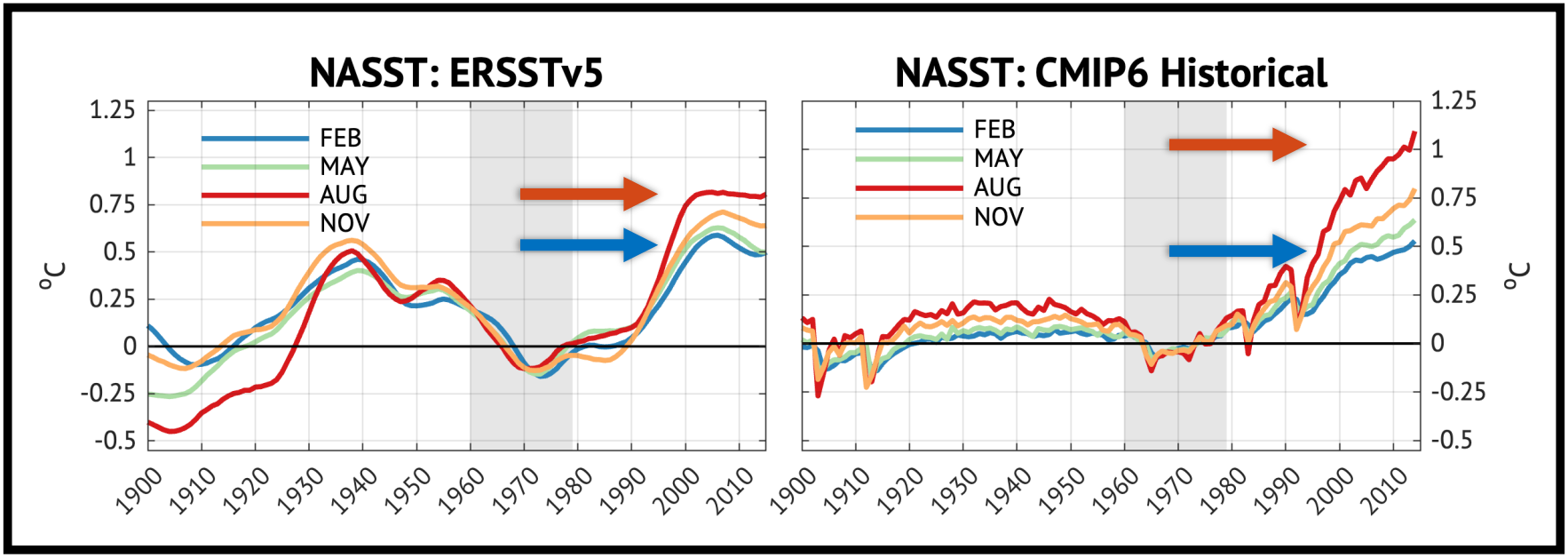
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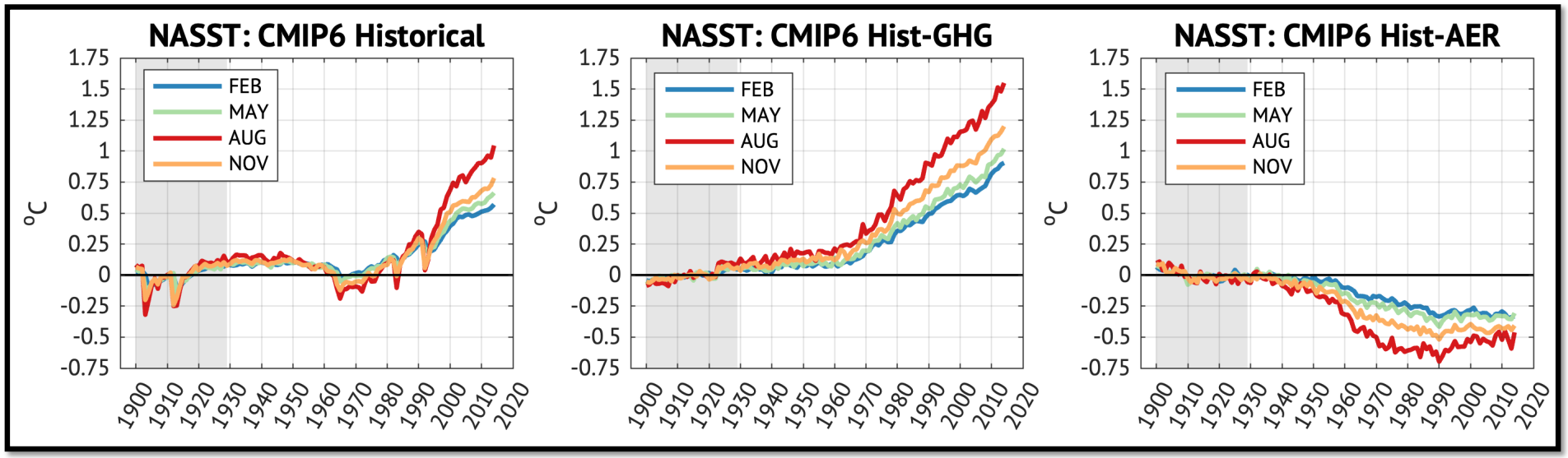
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Since 1970, North Atlantic SST has warmed 50% – 100% faster during late **SUMMER** than late **WINTER**



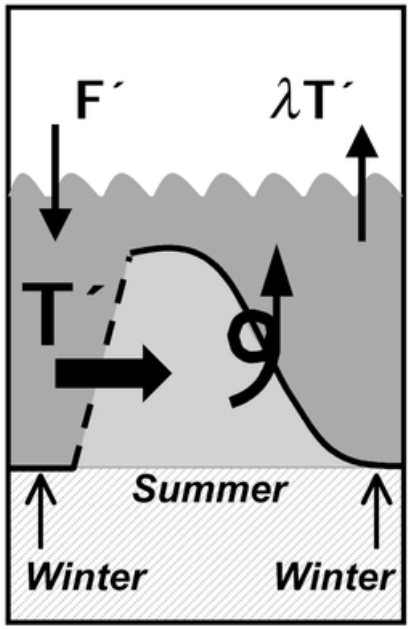
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CMIP6 Single Forcing Simulations: All forcings generate a stronger response in **SUMMER** than in **WINTER**



Overview:

Research Question: What processes are responsible for the seasonal response to forcing? (FOCUS: Sulfate Aerosol Forcing)



Framework: Entraining Mixed Layer Model (Deser et al. 2003):

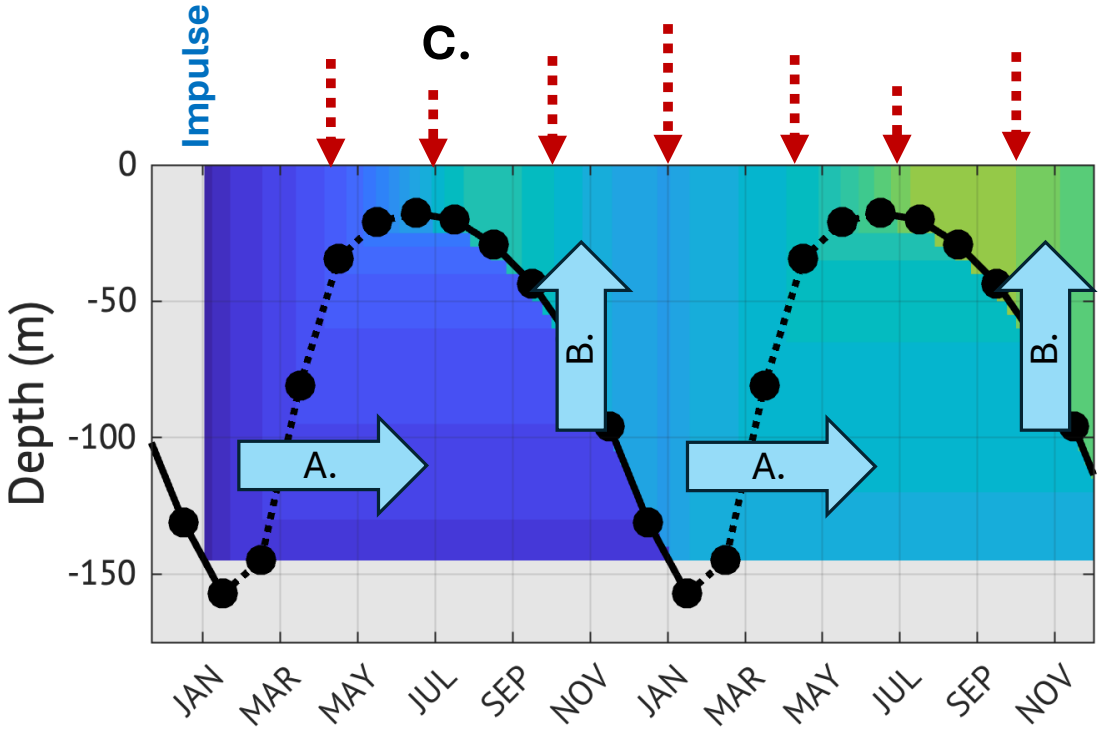
$$\underset{(i)}{\frac{d\left(\rho c H(t)\right)}{dt}} = \underset{(ii)}{F(t)} - \underset{(iii)}{\lambda(t)T}$$

Seasonality in SST arises from:

(i) Seasonal entraining mixed layer dynamics
(ii) Seasonality of forcing
(iii) Seasonality in air-sea feedbacks (LHFLX and LWFLX)

(i) Effect of Seasonal Mixed Layer Depth

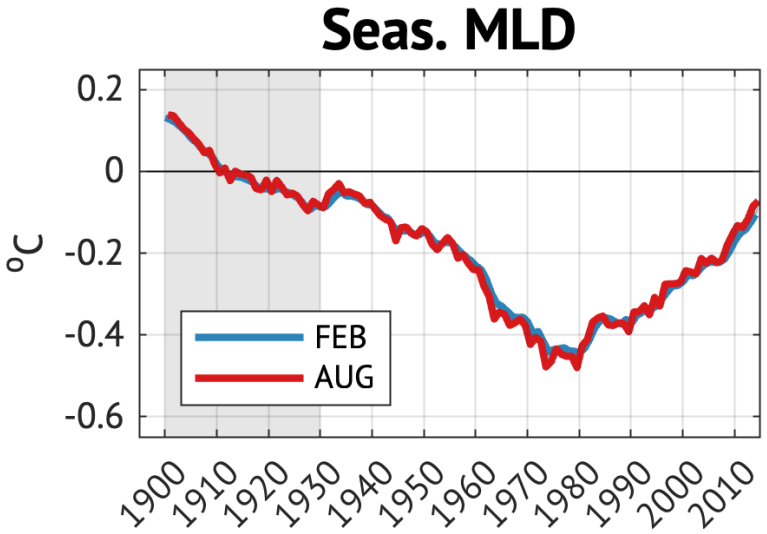
Seasonal ML Example: Impulse forcing at time of max MLD



A. **ML Shoaling:** Heat content anomalies sequestered at depth, insulated from surface
B. **ML Deepening:** Heat content anomalies re-entrained to surface
C. **Surface damping:** Seasonal fluxes damp surface heat content anomalies

(i) Effect of Seasonal Mixed Layer Depth

Model simulation: Seasonal MLD, annual averaged forcing and feedback parameter



$$\frac{d\left(\rho c H(t)\right)}{dt} = F(t) - \lambda(t)T$$

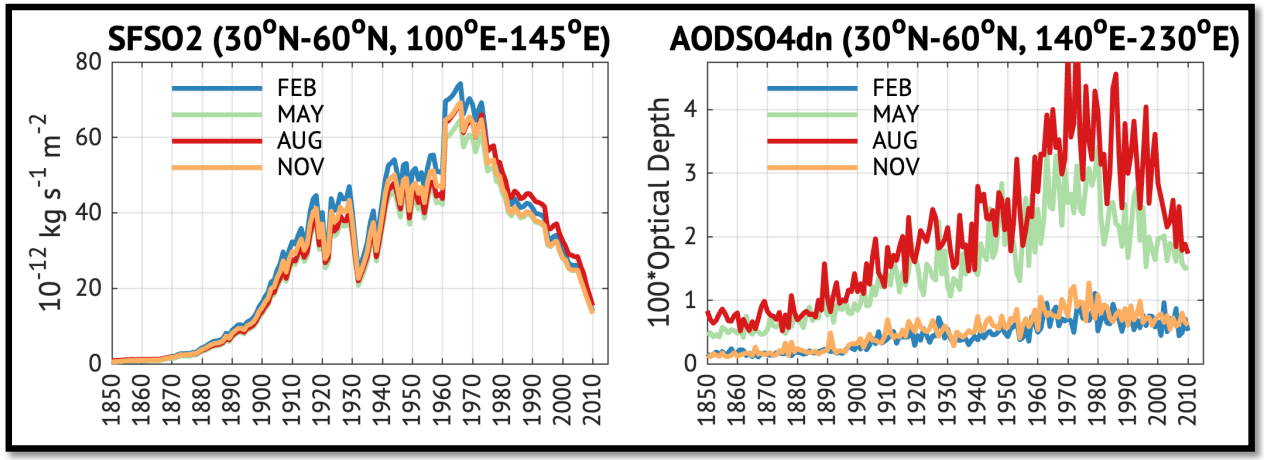
(i) *(ii)* *(iii)*

Seasonality in SST arises from:

- *(i)* ~~**Seasonal entraining mixed layer dynamics**~~
- *(ii)* Seasonality in air-sea feedbacks (LHFLX and LWFLX)
- *(iii)* Seasonality of forcing

(ii) Seasonality of SO_4 amount over NATL

Sulfate Aerosols:



U.S. SO_2 Emissions:
NO SEASONALITY

NATL SO_4 Amount:
LARGE SEASONALITY

WHY?

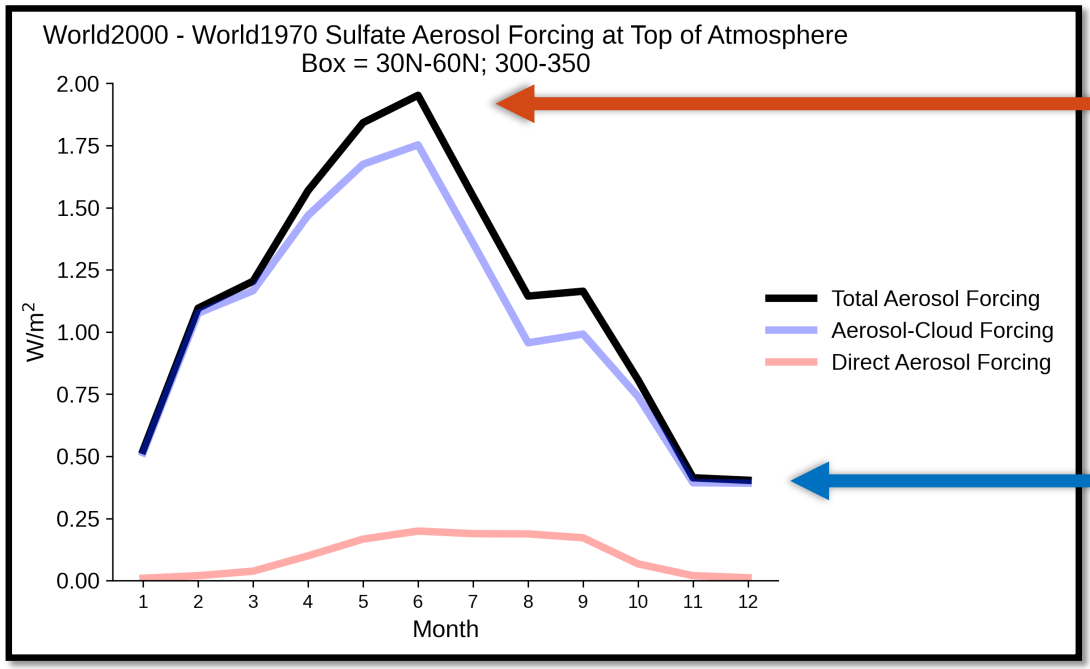
Interstitial SO_4 production is determined by OH concentration, which has large seasonality. Summer production of SO_4 over the US is transported over the North Atlantic

Rathod et al. (2025)

(ii) Seasonality of SO_4 forcing over NATL

CESM2 Direct Simulation: Direct and Indirect (Twomey) Forcing

CESM2: SO_2 set to 2000 or 1970 levels, all other emissions at 2000 levels



Surface Forcing from anthropogenic sulfate:

Strong seasonality, with

SUMMER forcing ~ 2 W m^{-2}

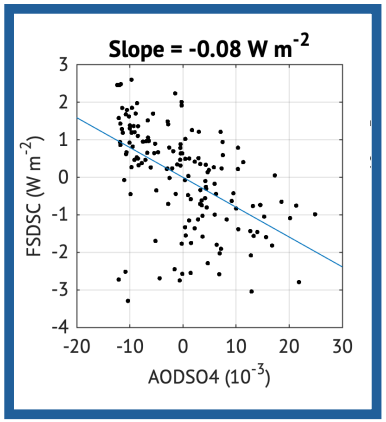
WINTER forcing ~0.4 W m^{-2}

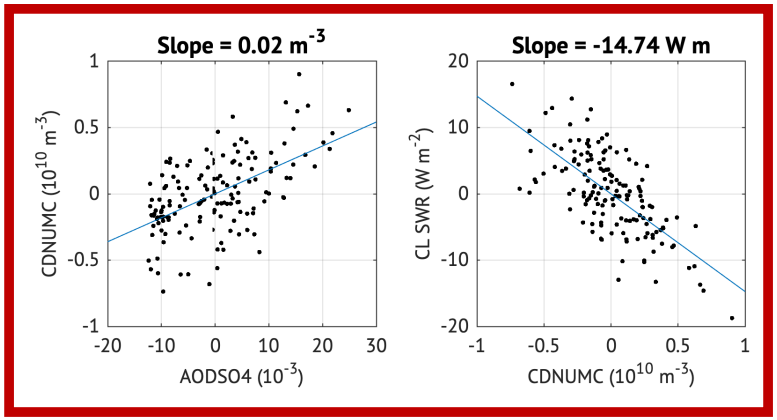
Indirect effect is about 10 times the direct effect

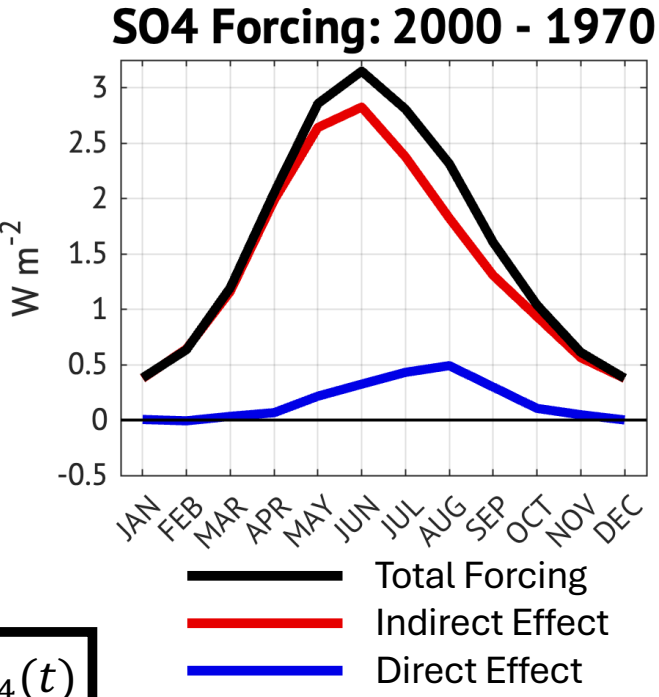
(Ghan et al. 2012, Ghan 2013, Rathod et al. 2025)

(ii) Seasonality of SO_4 forcing over NATL

CESM2 SO4 Forcing: Estimate from historical simulation







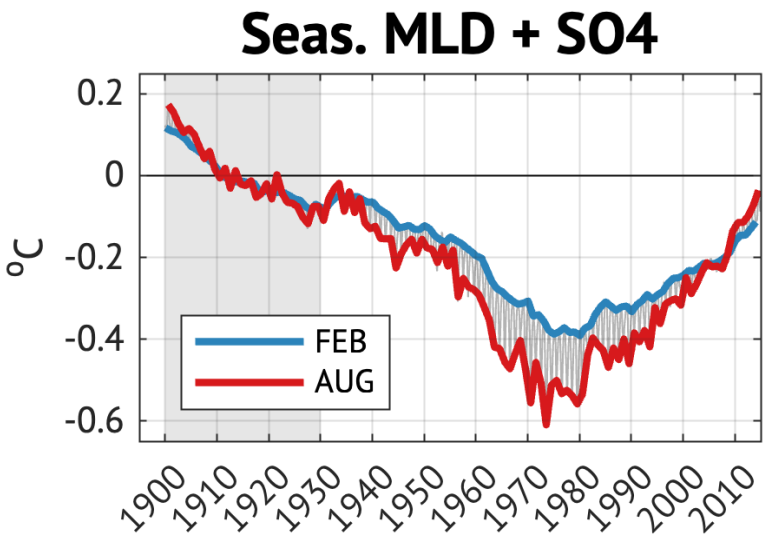
$$R_{direct} = \frac{\partial F_{SW}}{\partial SO_4} \cdot \Delta SO_4$$

$$R_{indirect} = \frac{\partial N_C}{\partial SO_4} \cdot \frac{\partial F_{SW}}{\partial N_C} \cdot \Delta SO_4$$

$$R_{total}(t) = [(1 - \mathrm{CLDTOT}) \cdot R_{direct} + \mathrm{CLDLOW} \cdot R_{indirect}] \cdot \Delta SO_4(t)$$

(ii) Effect of Seasonal MLD + SO4 Forcing

Model simulation: Seasonal MLD, annual averaged forcing and feedback parameter



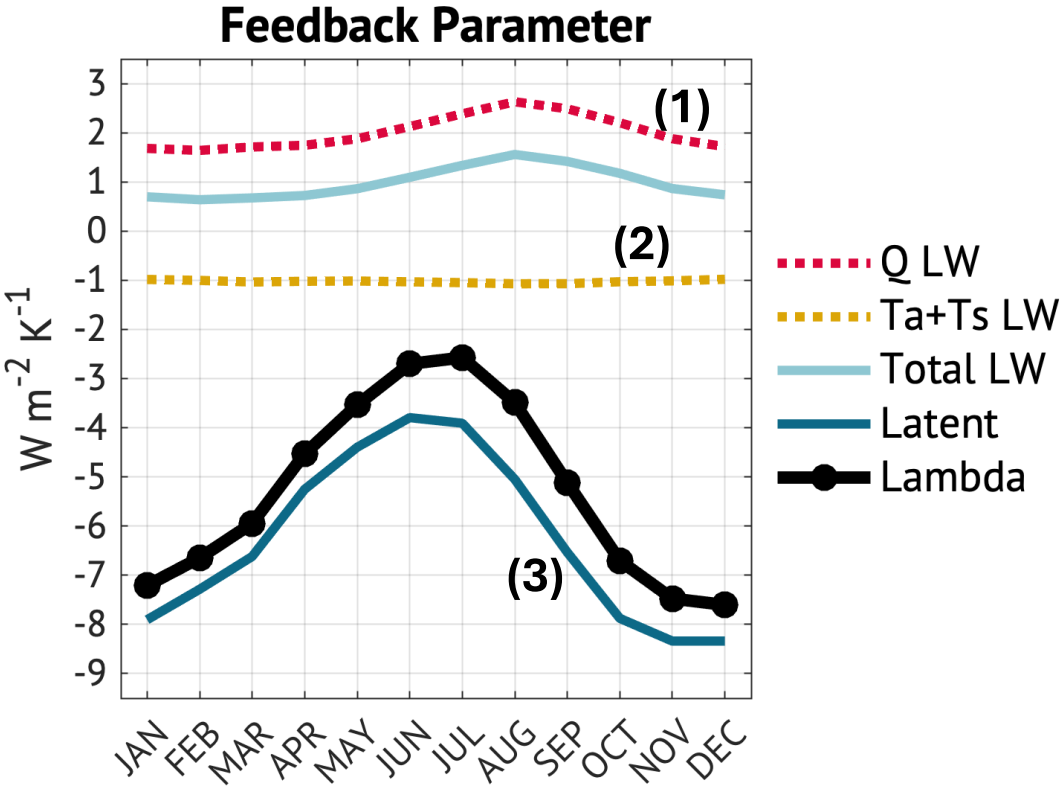
$$\frac{d\left(\rho c H(t)\right)}{dt} = F(t) - \lambda(t)T$$

(i) *(ii)* *(iii)*

Seasonality in SST arises from:

- *(i)* ~~Seasonal entraining mixed layer dynamics~~
- *(ii)* Seasonality in air-sea feedbacks (LHFLX and LWFLX)
- *(iii)* **Seasonality of forcing ✓**

(iii) Seasonality of Surface Flux Feedbacks



(1) Water Vapor Feedback*:
Maximum in Summer

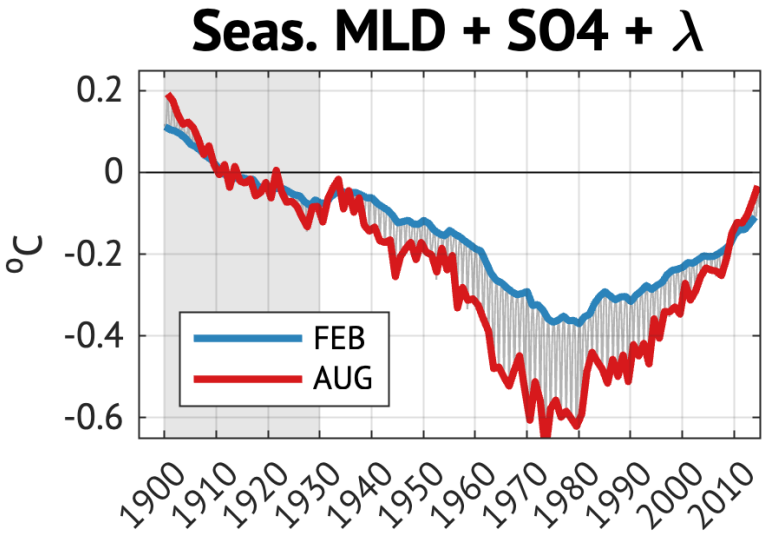
(2) Ta (+), TS (-):
Approx. Stefan Boltzman, little seasonal sensitivity

Based on ERA5 kernel estimates (Huang and Huang, 2023)

(3) Latent Heat Flux:
Strong seasonality due to seasonal wind speed variations

(iii) Effect of Seasonal MLD + Forcing + Feedback

Model simulation: Seasonal MLD, annual averaged forcing and feedback parameter



$$\underset{(i)}{\frac{d\left(\rho c H(t)\right)}{dt}} = \underset{(ii)}{F(t)} - \underset{(iii)}{\lambda(t)T}$$

Seasonality in SST arises from:

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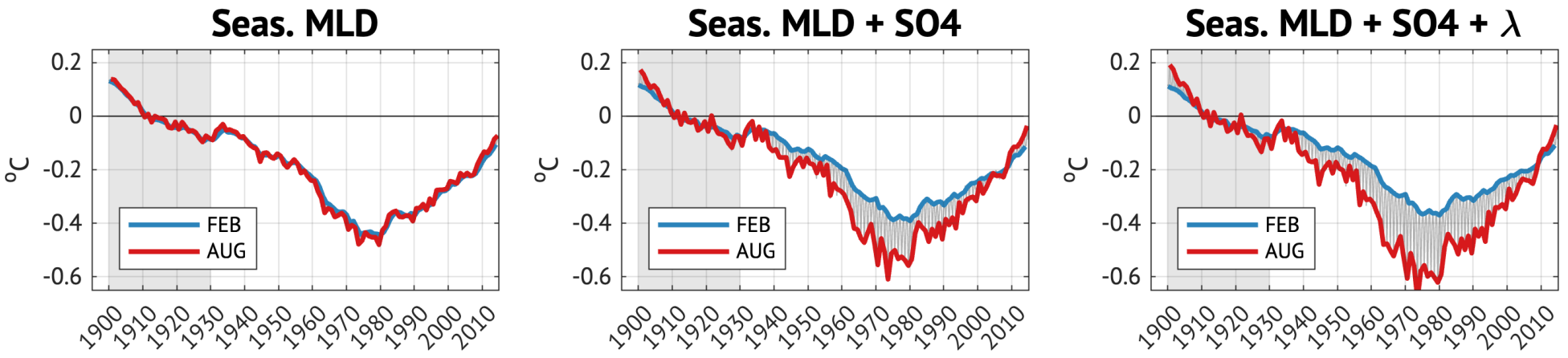
(ii) **Seasonality in air-sea feedbacks (LHFLX and LWFLX) ✓**

(iii) **Seasonality of forcing ✓**

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Key Result: Seasonal response of the mid-latitude oceans to forcing is largely due to seasonality in the forcing and feedbacks.

→ BUT! Seasonal Mixed Layer Dynamics are critical for a winter response to seasonal sulfate aerosol forcing!



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