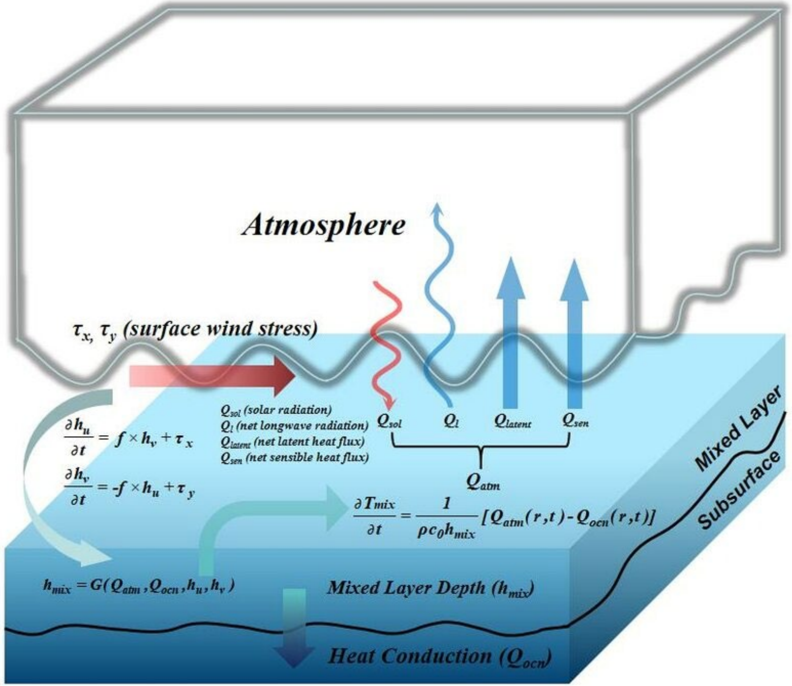
Ocean complexity shapes sea surface temperature variability in a CESM2 model hierarchy

Sarah Larson*, **Kay McMonigal*[1]**, Yuko Okumura, Dillon Amaya, Antonietta Capotondi, Katinka Bellomo, Isla Simpson, Amy Clement

- * NC State University
- [1] Now at University of Alaska Fairbanks
- *Minor revisions with Journal of Climate*

Motivation

- Identifying sources of climate variability is a central question with implications for predictability
- Ocean processes are generally expected to enhance SST persistence
  - Elongation of timescales due to high heat capacity
  - Re emergence of wintertime thermal anomalies
  - Slow ocean dynamical response due to e.g. Rossby waves
- Atmosphere can also enhance persistence
  - Bjerknes feedback
  - Cloud feedbacks

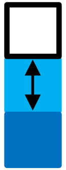


Wang et al., 2022

e.g. Frankignoul & Hasselman 1977; Blade 1997; Barsugli & Battisti 1998; Alexander & Deser 1995; Joh et al 2022; Schneider et al 2002; Deser et al 1999; Seager et al 2001; Kwon & Deser 2007; Newman et al 2016; McCreary 1983; Latif & Barnett 1994; Gu & Philander 1997; Bjerknes 1969; Bellomo et al 2014; Middlemas et al 2019

ktmcmonigal@alaska.edu

Interactive ocean dynamics can alter SST through…



Local ocean processes

Mixing

Entrainment

Time varying mixed layer depth

Ocean dynamical processes

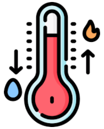
Anomalous heat convergence due to:

Gyre circulation

Overturning circulation

Ekman transports

Waves



Thermodynamically coupled air-sea processes

Bjerknes feedback

Wind-evaporation-SST feedback

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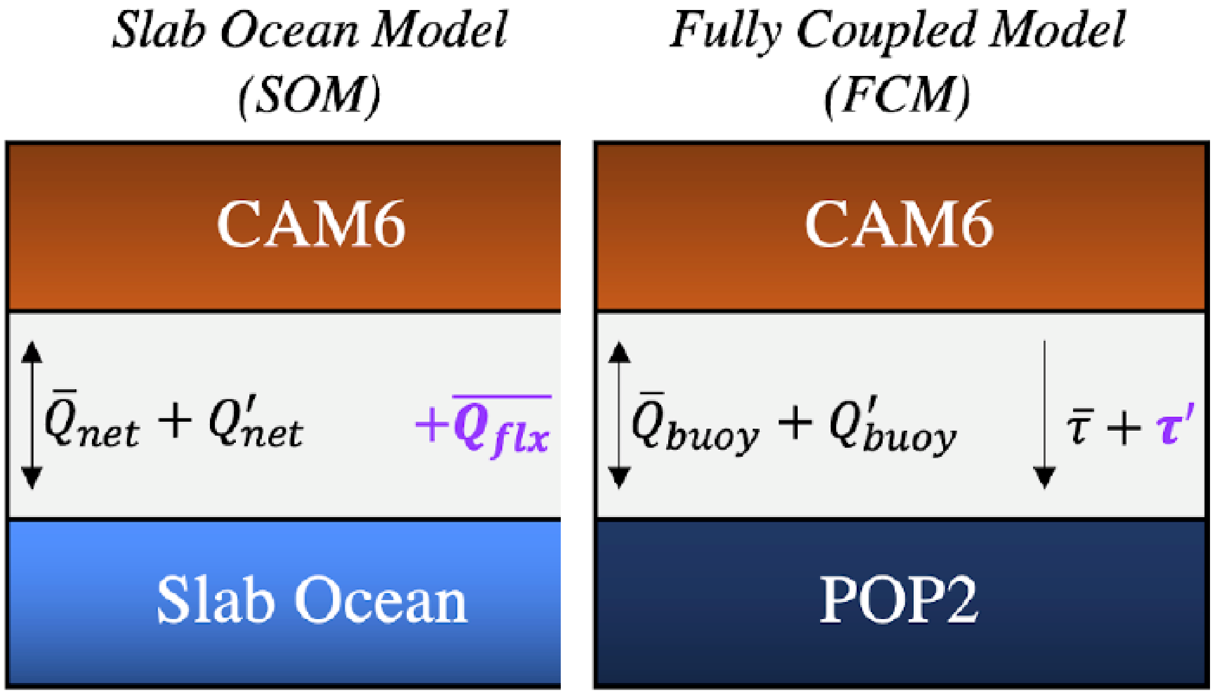
One method is to compare Slab and Fully coupled model



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Slab omits all of the ocean processes

Local ocean processes	Ocean dynamical processes	Thermodynamically coupled air-sea processes
Mixing	Anomalous heat convergence due to:	Bjerknes feedback
Entrainment	Gyre circulation	Wind-evaporation-SST feedback
Time varying mixed layer depth	Overturning circulation	
	Ekman transports	
	Waves	

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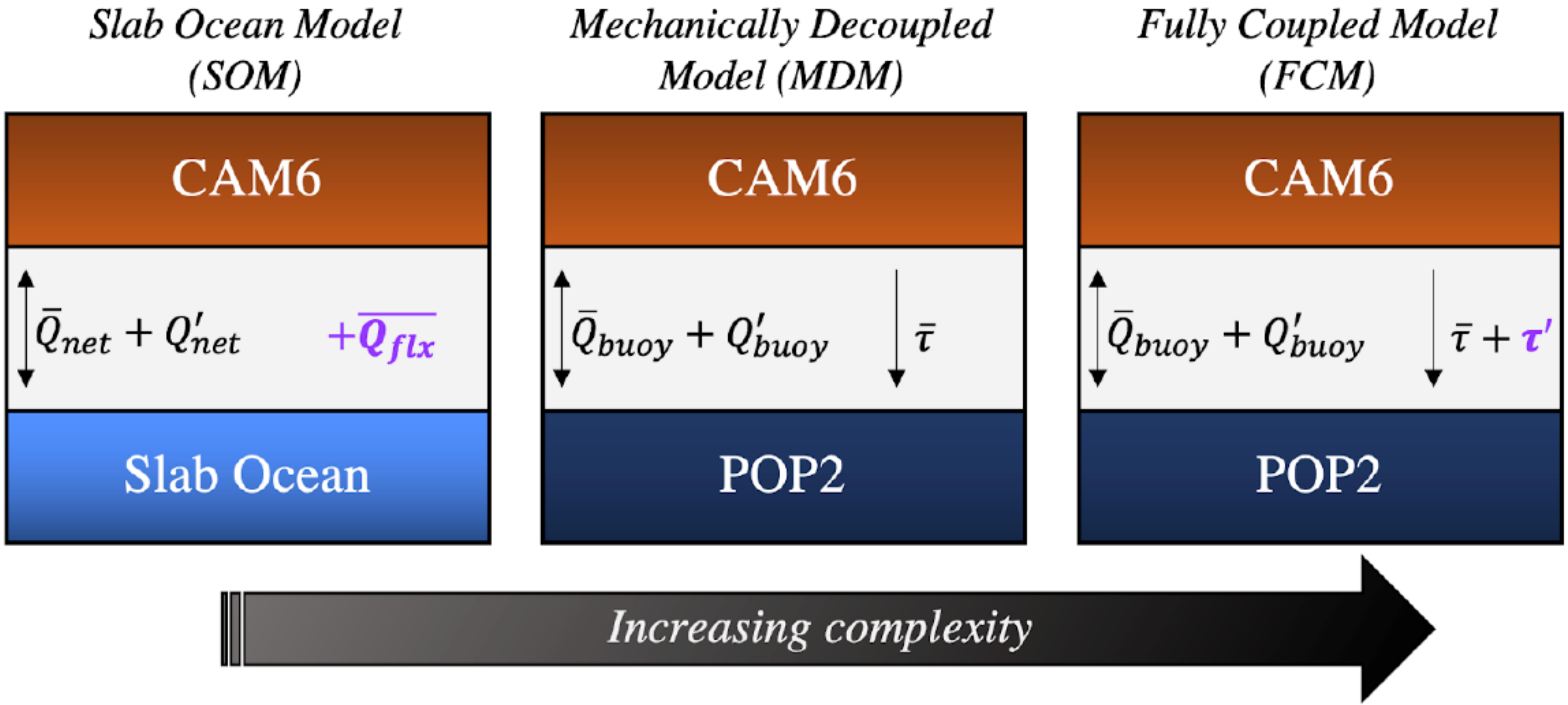
Add MDM as an "in between" hierarchy member



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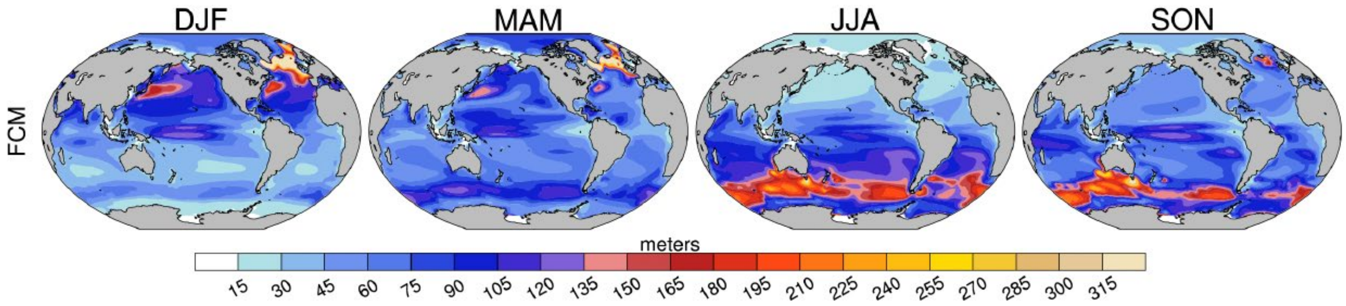
Methodology

- Conducted within CESM2 (1°x1° res) using pre industrial forcing
- MDM is constructed using a 50 year climatology of 6 hourly wind stress forcing on the ocean taken directly from CIME coupler
    - Eliminates any issues due to remapping
    - 50 year spin up followed by 600 years used in analyses
- SOM constructed using 50 years of FCM to estimate mean mixed layer depth and Q_{flx}
    - Run by Dave Bailey at NCAR
    - 10 year spin up, 350 years used for analysis
- MDM -> FCM isolates role of wind stress driven dynamic ocean
- SOM -> MDM isolates role of local ocean processes

ktmcmonigal@alaska.edu

MDM simulates mixed layer depth seasonality



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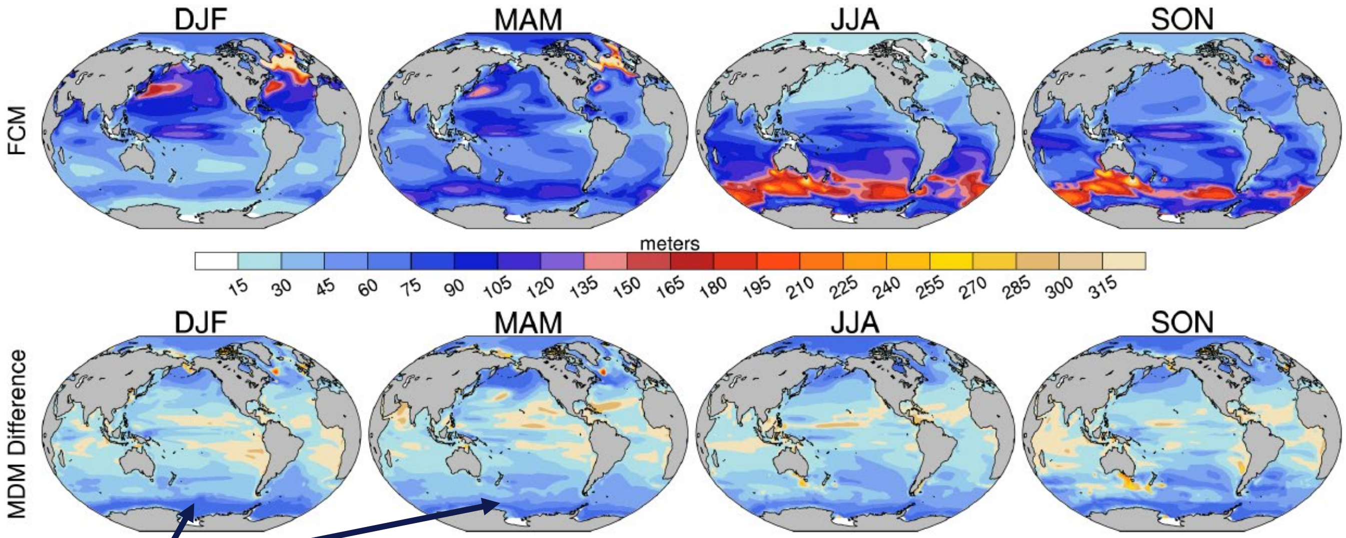
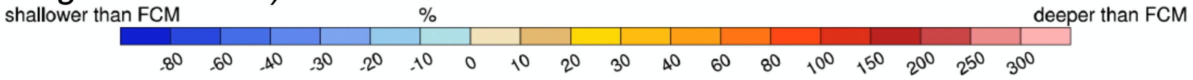


Short term variability in τ important for mean state MLD in regions with high wind variance such as Southern Ocean (e.g. Luongo et al 2024)

In general, MDM is slightly shallower than FCM as there is less wind driven mixing



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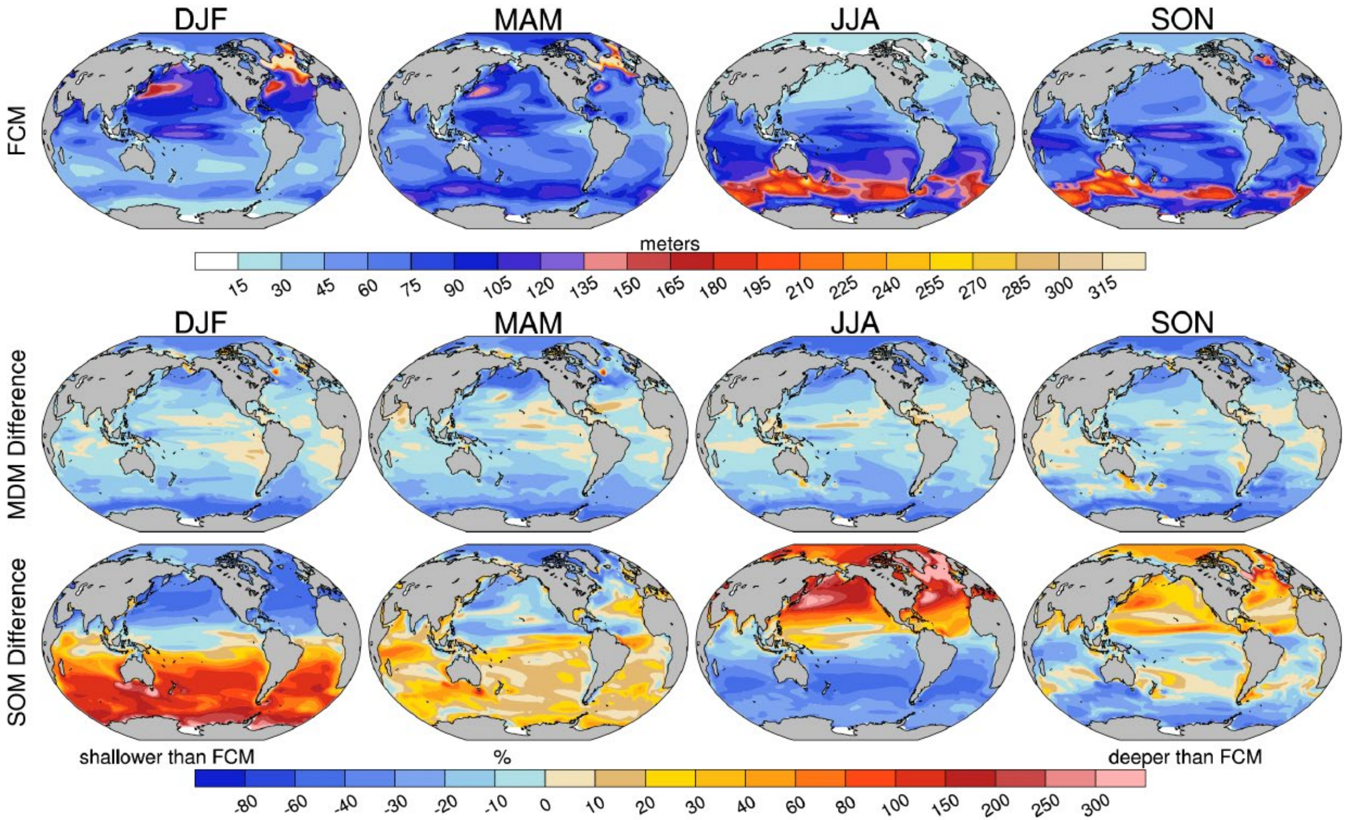
MDM simulates mixed layer depth seasonality



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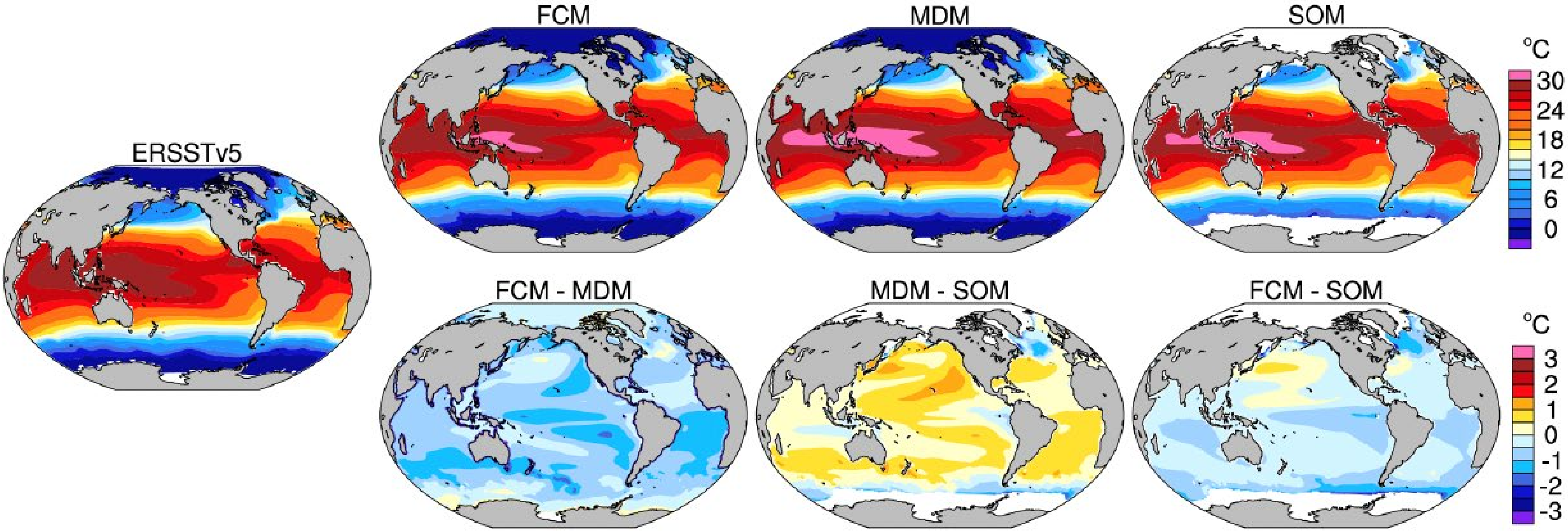
Annual mean SSTs are similar across experiments



In general, MDM is slightly warmer than FCM as the mixed layer depth is shallower

In general, SOM is slightly warmer than FCM likely due to SOM experimental design

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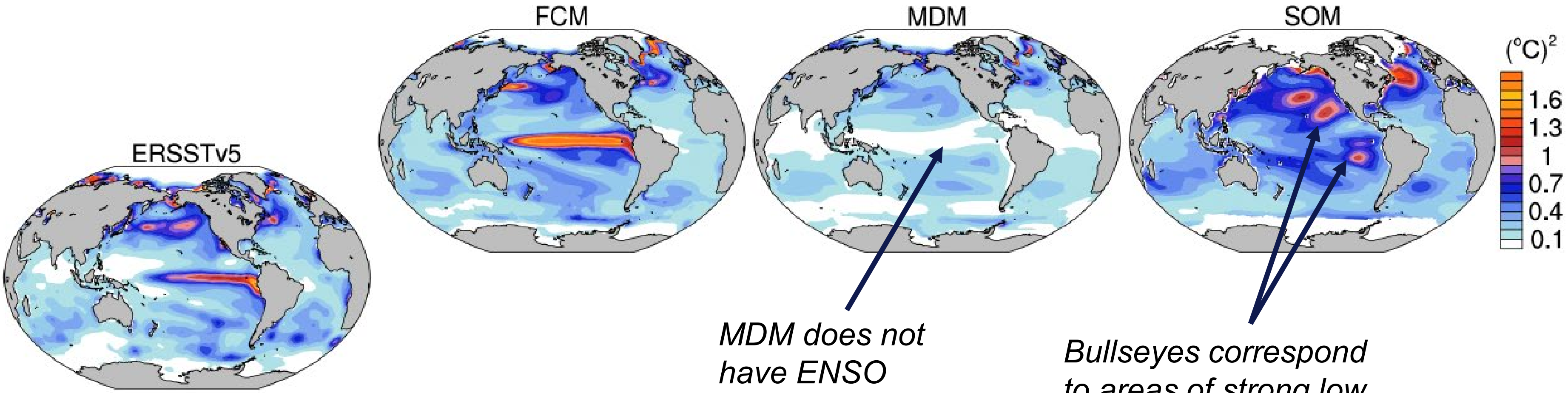
SST variance differences vary regionally



MDM does not have ENSO

Bullseyes correspond to areas of strong low cloud SST feedback – will dig into as part of a NOAA grant

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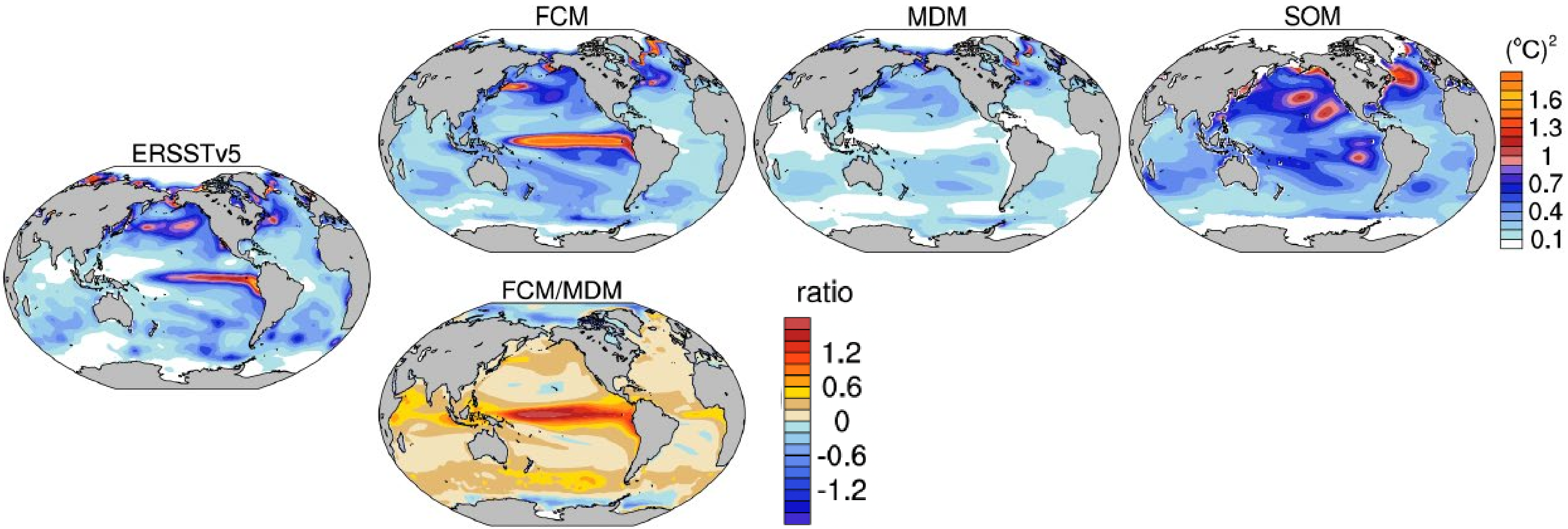
FCM has more variance than MDM -> ocean dynamical processes enhance variance



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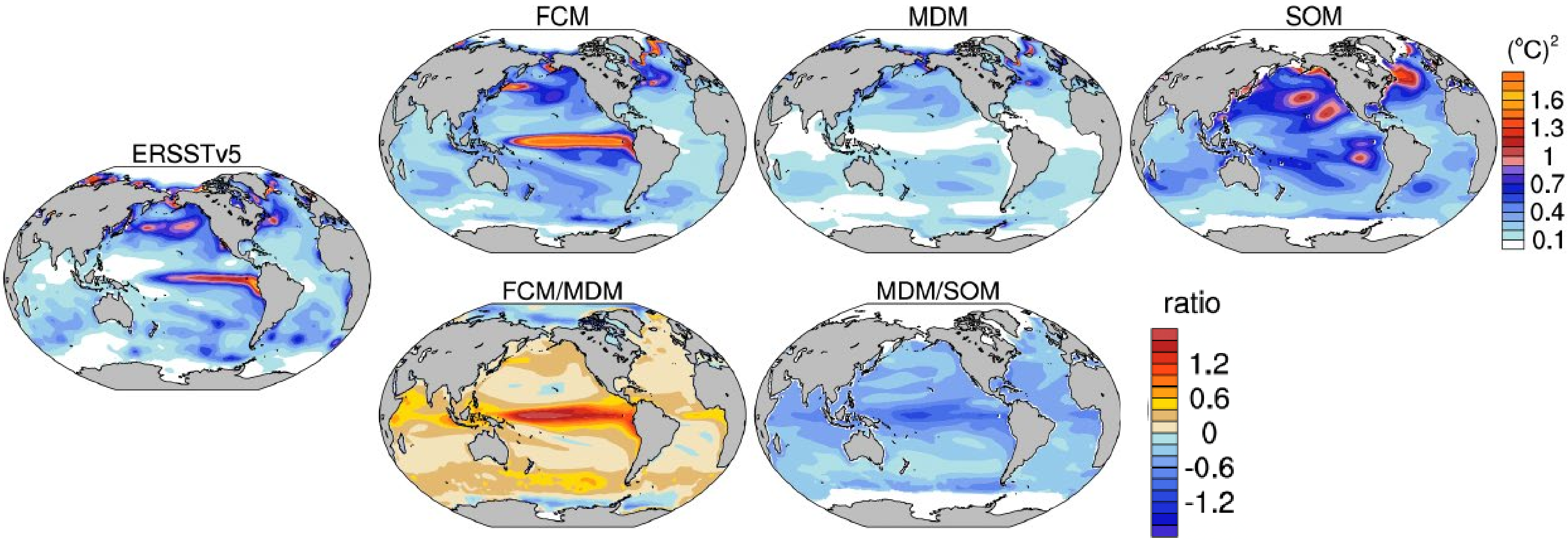
MDM variance is lower than SOM -> local ocean processes damp variance



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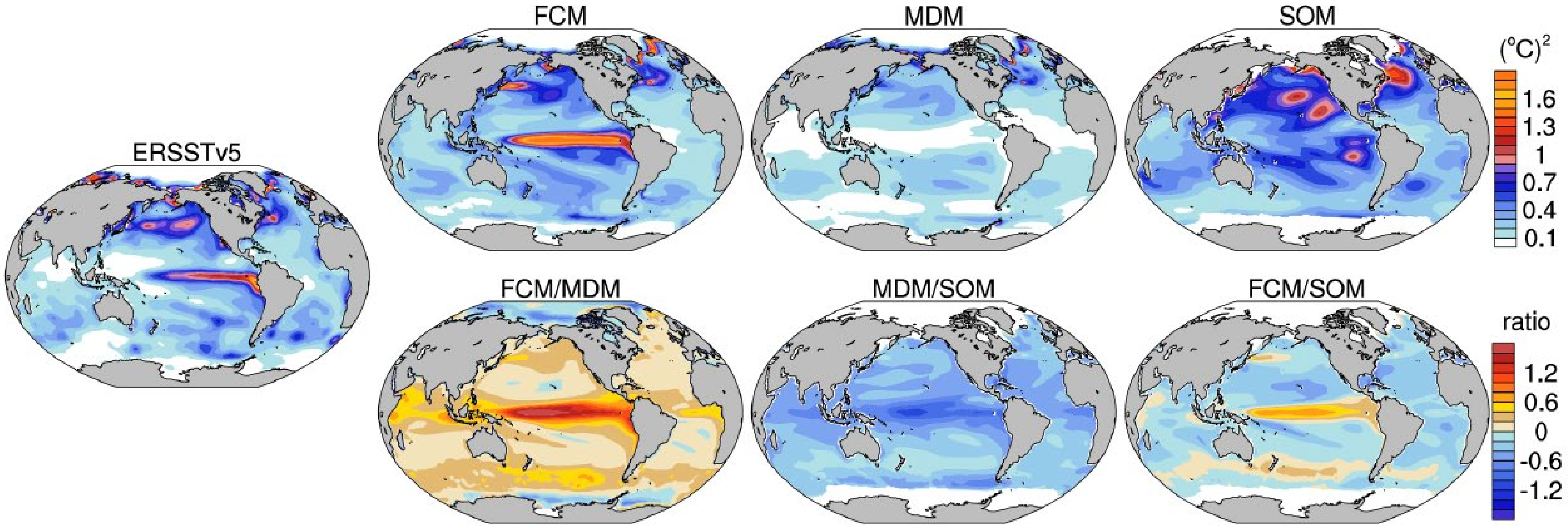
Summed impact of ocean on SST variance is a *tug of war* between damping by local ocean processes and enhancement by ocean dynamical processes



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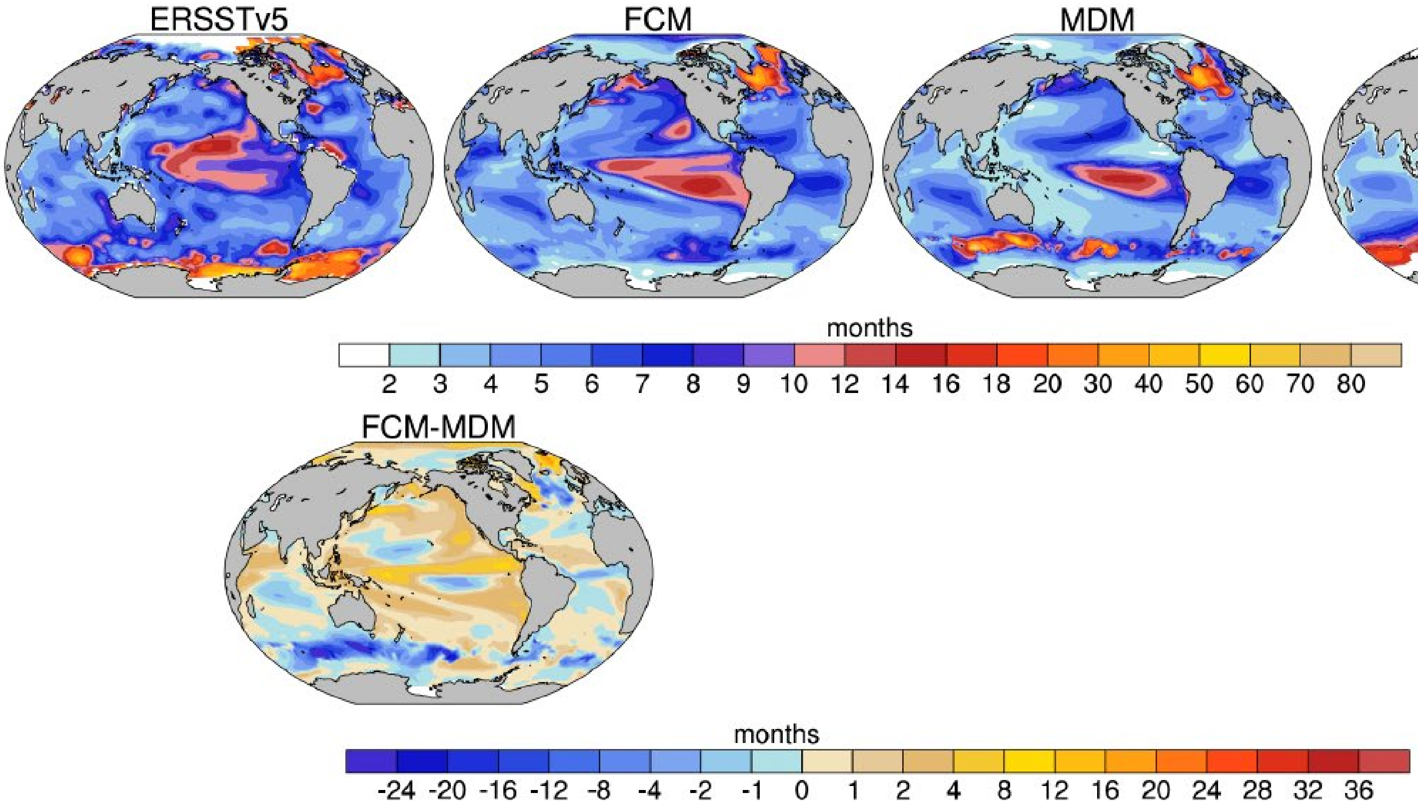
SST persistence enhanced by ocean dynamical processes, reduced by local ocean processes



$$T_2 = 1 + 2\sum_{k=1}^{\infty} \rho_k^2,$$

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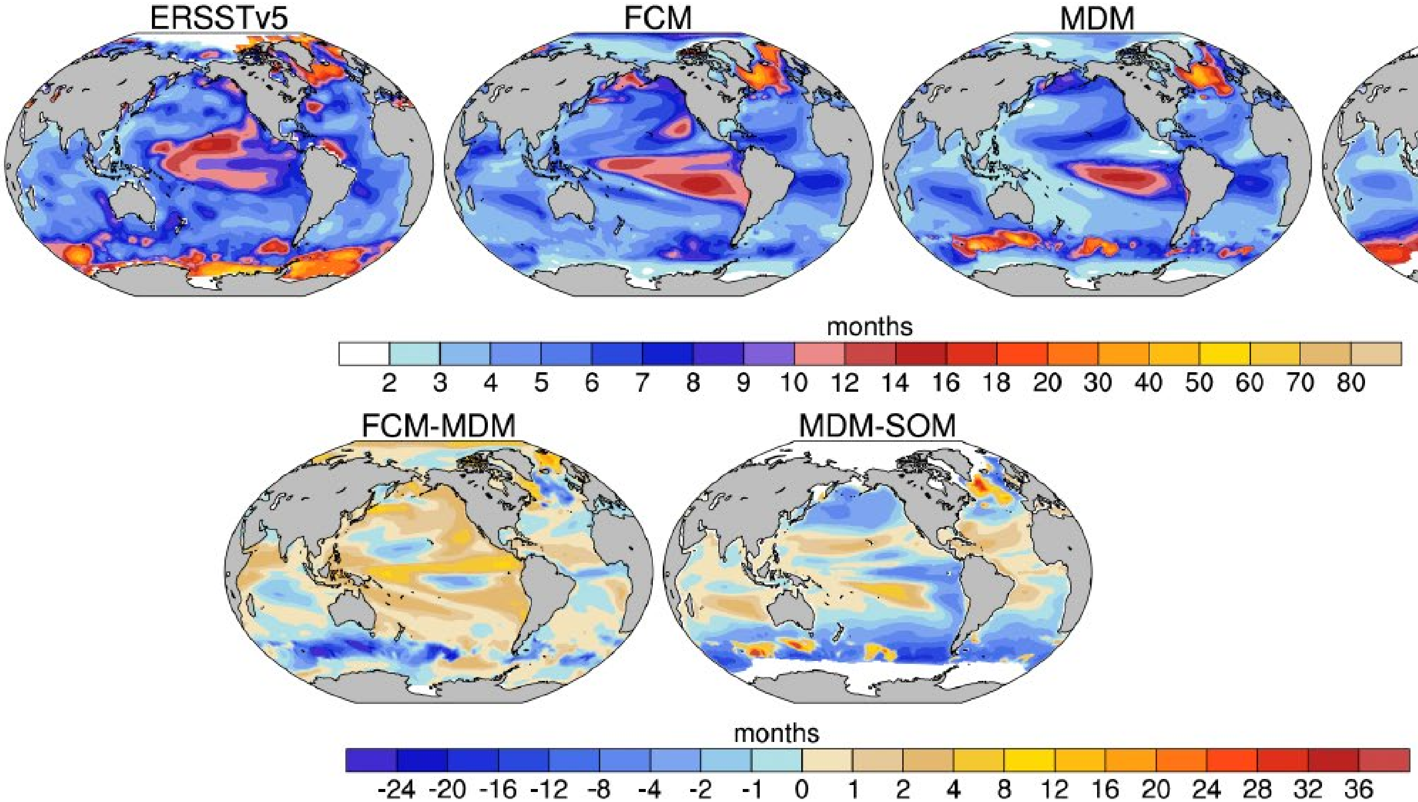

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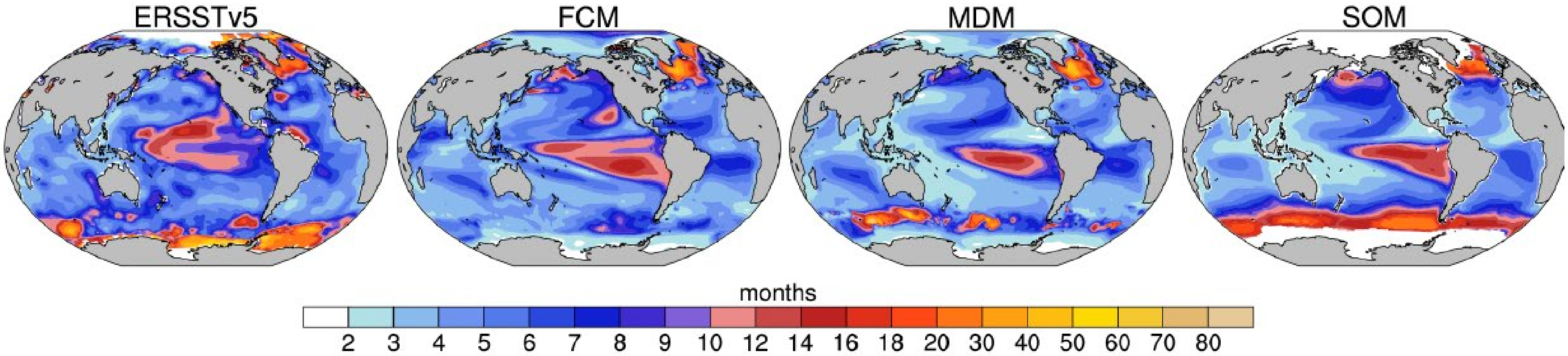
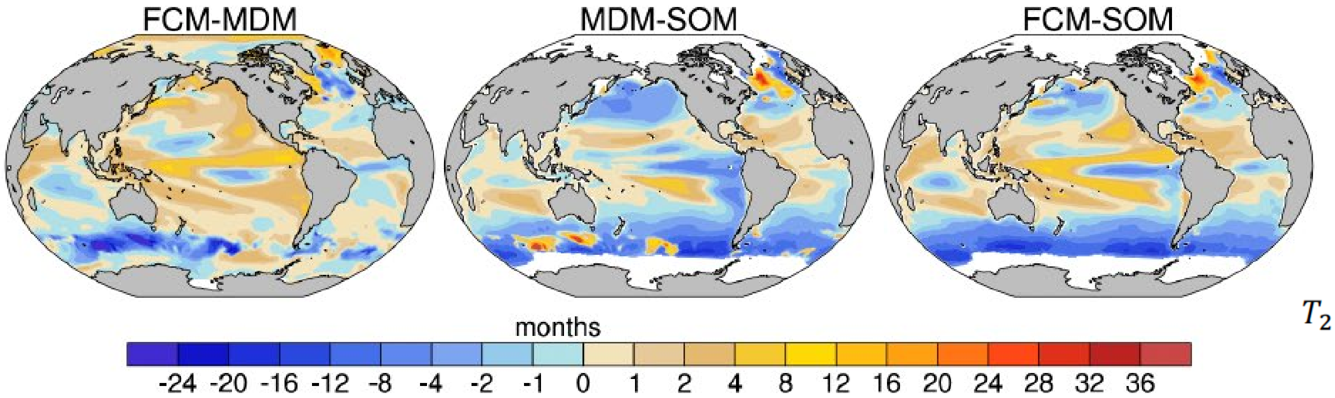




$$T_2 = 1 + 2\sum_{k=1}^{\infty} \rho_k^2,$$

ktmcmonigal@alaska.edu

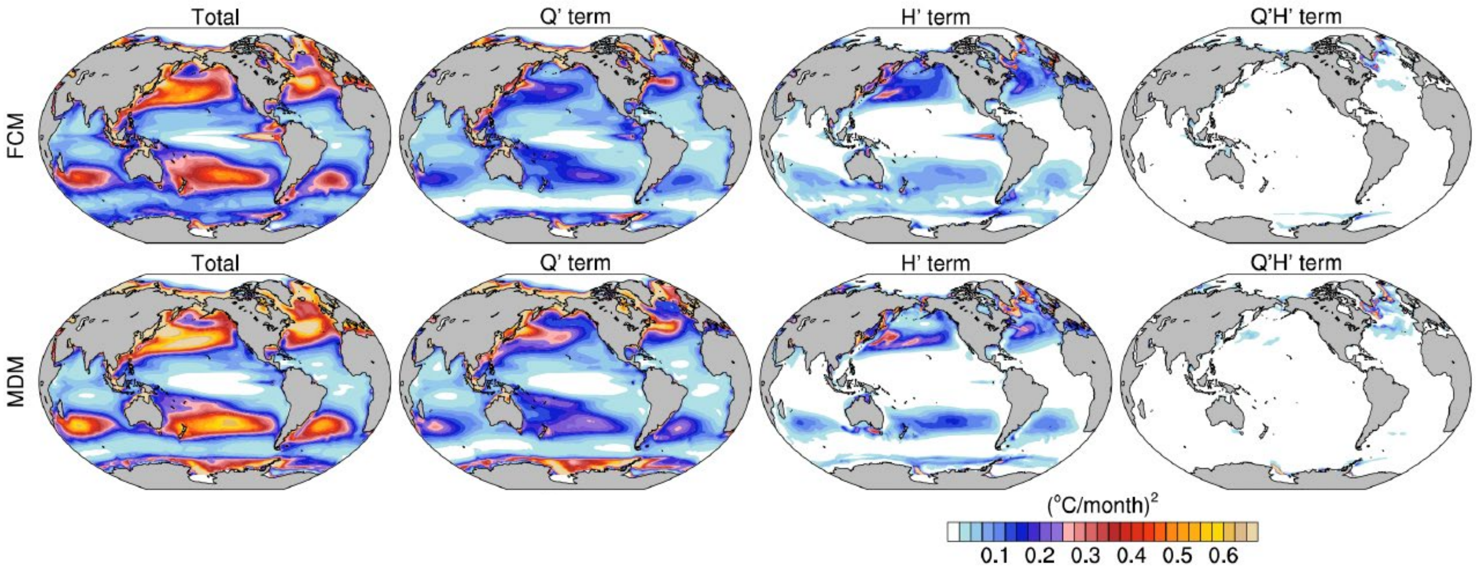
Are differences due to differences in net surface heat flux, MLD, or both?

$$\frac{\partial SST'}{\partial t} \approx \left(\frac{Q_{net}}{\rho c_p H}\right)',$$

$$\left(\frac{Q_{net}}{\rho_0 c_p H}\right)' \approx \frac{Q'_{net}}{\rho_0 c_p \bar{H}} - \frac{\bar{Q}_{net} H'}{\rho_0 c_p \bar{H}^2} - \left(\frac{Q'_{net} H'}{\rho_0 c_p \bar{H}^2} - \frac{\overline{Q'_{net} H'}}{\rho_0 c_p \bar{H}^2}\right)$$

ktmcmonigal@alaska.edu

Compared to FCM, MDM overestimates surface heat flux driven SST variability, because MLD is shallower



$$\frac{\partial SST'}{\partial t} \approx \left(\frac{Q_{net}}{\rho c_p H}\right)',$$

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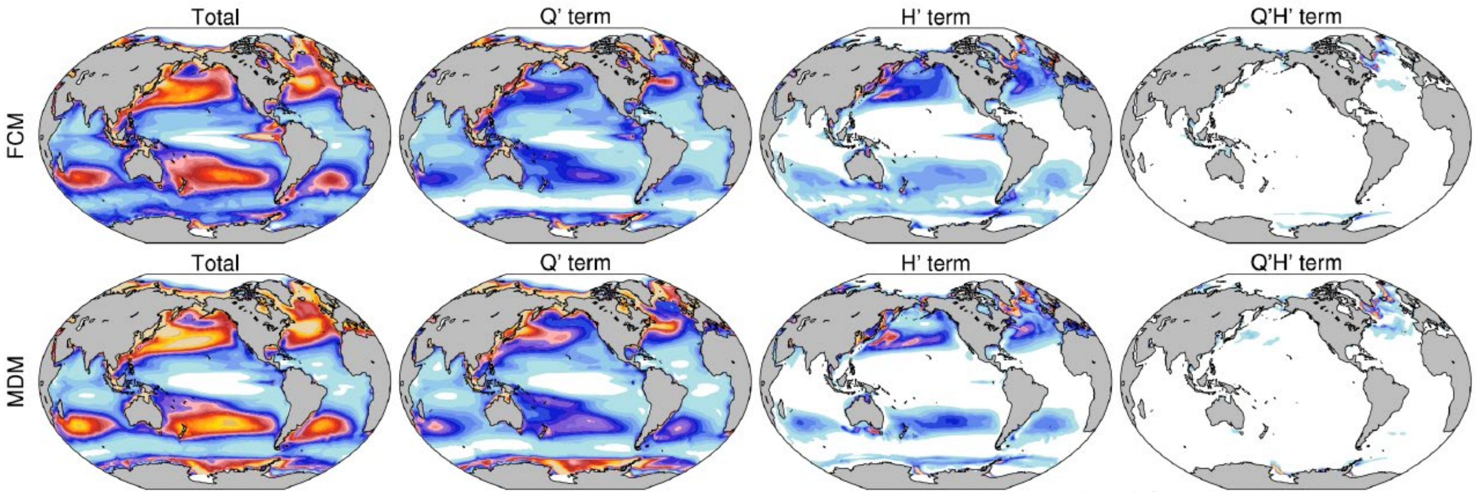
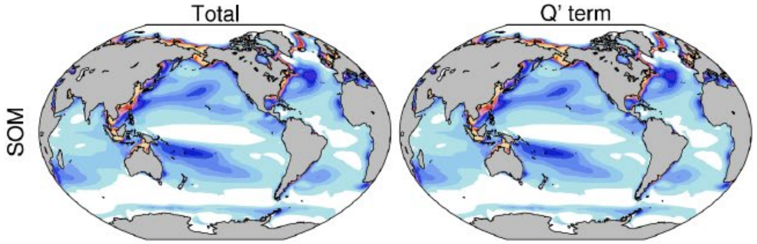
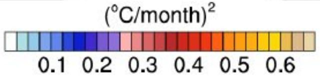
Lower surface heat flux driven SST variance in SOM is primarily due to lack of seasonally varying MLD







Note: overbars represent monthly means

$$\frac{\partial SST'}{\partial t} \approx \left(\frac{Q_{net}}{\rho c_p H}\right)',$$

$$\left(\frac{Q_{net}}{\rho_0 c_p H}\right)' \approx \frac{Q'_{net}}{\rho_0 c_p \bar{H}} - \frac{\bar{Q}_{net} H'}{\rho_0 c_p \bar{H}^2} - \left(\frac{Q'_{net} H'}{\rho_0 c_p \bar{H}^2} - \frac{\overline{Q'_{net} H'}}{\rho_0 c_p \bar{H}^2}\right)$$

ktmcmonigal@alaska.edu

Conclusions

- Net role of the dynamic ocean is regionally dependent, with competing effects from ocean dynamics and ocean damping
- Wind stress driven ocean dynamics (MDM -> FCM) enhance SST variance and persistence
- Ocean damping through local processes (SOM -> MDM) reduces SST variance and reduces persistence
- Reducing ocean complexity changes the magnitude of thermodynamic forcing of SST variability
- MDM data publicly available on Earth System Grid

NCAR UCAR | CISL Computational & Information Systems Lab

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ktmcmonigal@alaska.edu

Considerations for comparing…

FCM and MDM to determine role of ocean dynamics

- MDM mean state SST is warmer, MLD is shallower than FCM. The difference pattern is different than in a similar hierarchy under CESM1, perhaps due to cloud feedbacks
- Larger heat flux driven SST variability in MDM than FCM implies that a comparison of FCM to MDM likely *underestimates* the role of wind stress driven ocean dynamics

FCM and SOM to determine role of ocean damping

- SOM mean state SST is generally warmer than FCM
- SOM has larger SST variance than FCM nearly everywhere, yet has weaker heat flux driven variance
- SOM shows longer persistence than FCM and MDM in many regions
- Comparing SOM to FCM to deduce the role of ocean damping would likely lead to an *underestimate*, since SOM also does not include ocean dynamic processes which enhance variance

ktmcmonigal@alaska.edu