Ocean heat uptake slows 21st century surface warming driven by extratropical cloud feedbacks

William Frey
Elizabeth Maroon, Angeline Pendergrass, Jennifer Kay

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Reducing Radiation Biases

Absorbed Shortwave Radiation Bias: Model minus Observations

Control: CESM Large Ensemble
Experiment: Decreased radiation biases via modified cloud phase partitioning

See Kay et al (2016), J Clim for details
Extratropical cloud radiative feedbacks increase climate sensitivity

Control:
CESM Large Ensemble

Experiment:
Decreased radiation biases via modified cloud phase partitioning

Frey and Kay (In Review)
Climate Sensitivity correlated with transient warming

![Graph showing the correlation between Equilibrium Climate Sensitivity and Transient Warming](image)

- **CMIP5 Models (Forster et al., 2013)**
- **CESM CAM5 (Large Ensemble)**
Climate Sensitivity correlated with transient warming

Does the large (1.5K) increase in ECS imply a large difference in 21st Century Warming?

![Graph showing correlation between Equilibrium Climate Sensitivity and Transient Warming](image)

- CMIP5 Models (Forster et al., 2013)
- CESM CAM5 (Large Ensemble)
Little Change in 21st Century Warming

Late 21st Century Warming

Experiment: 4.78 K
Large Ensemble Max: 4.72 K
Large Ensemble Mean: 4.50 +/- 0.03 K
Large Ensemble Min: 4.38 K

Frey et al., in prep
Little Change in 21st Century Warming

Experiment

Experiment - Large Ensemble

Frey et al., in prep
Increased Shortwave Cloud Feedback
Increased *Extratropical* Shortwave Cloud Feedback

Frey et al., in prep

Experiment
CESM LE Members

*Frey et al., in prep*
Ocean takes up heat in the Extratropics
Ocean takes up heat in the Extratropics

Experiment

CESM Large Ensemble

△ Surface Heat Flux Anomaly

Frey et al., in prep
Southern Ocean
Mean state circulation takes up heat

Ocean Heat Content Anomaly

Frey et al., in prep
Southern Ocean
Mean state circulation takes up heat

Frey et al., in prep

Ocean Heat Content Anomaly

\[ \Delta \text{Ocean Heat Content Anomaly Experiment – Large Ensemble} \]
North Atlantic AMOC

Experiment Pre-Industrial AMOC (Sverdrups)
North Atlantic
Slowdown of the AMOC takes up heat

Late 21st Century Experiment:
Colors: Ocean Heat Content Anomaly
Contours: AMOC Anomaly (Sverdrups)

Frey et al., in prep
North Atlantic
Slowdown of the AMOC takes up heat

Late 21st Century Experiment:
Colors: Ocean Heat Content Anomaly
Contours: AMOC Anomaly (Sverdrups)

Late 21st Century Experiment – CESM LE:
Colors: Δ Ocean Heat Content Anomaly
Contours: Δ AMOC Anomaly (Sverdrups)

Frey et al., in prep
Conclusions

Modified extratropical cloud radiative feedbacks increase equilibrium climate sensitivity by 1.5 K, but have a small impact on 21st century warming.
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Energy input by extratropical cloud radiative feedbacks is taken up by the ocean and moved to depth, slowing transient surface warming.
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Energy input by extratropical cloud radiative feedbacks is taken up by the ocean and moved to depth, slowing transient surface warming.

Equilibrium warming cannot be used to infer transient warming when it is driven by extratropical feedbacks.
Radiative Feedbacks

Frey et al., in prep
Ocean takes up heat in the Extratropics
Stores heat further equatorward

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Ocean takes up heat in the Extratropics
Stores heat further equatorward

Experiment - CESM Large Ensemble

\(\Delta\) Surface Heat Flux Anomaly

\(\Delta\) Ocean Heat Content Anomaly

Frey et al., in prep