The Role of Thermodynamic Phase Shifts in the Extratropical Cloud Optical Depth Feedback

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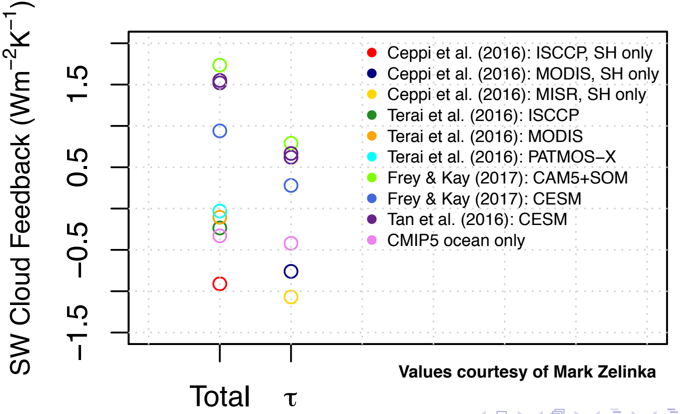
Motivation

There is a large spread in the extratropical shortwave (SW) cloud feedback and the SW cloud optical depth (τ) feedback.



Motivation

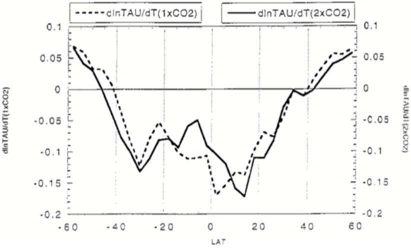
- Unknowns:
  - What is the sign of the extratropical SW τ feedback?
  - What physical processes are most important for it?
- $\tau = f(r_{eff}, \text{water content}, \Delta z)$

Process	Comment
r_{eff}: Thermodynamic phase shifts	Applies only to cold clouds (below freezing); liquid clouds increase at the expense of ice clouds upon warming; WBF process & ice nucleation are relevant; explains τ increases with temperature; Mitchell et al. (1989), Tsushima et al. (2006), McCoy et al. (2015), Ceppi et al. (2016), Tan et al. (2016), Frey & Kay (2017)
Water content: adiabatic water content	Adiabatic water content increases proportionally to the derivative of the moist adiabat with respect to temperature; explains τ increases with temperature; Betts & Harshvardhan (1987), Tselioudis et al. (1992), Gordon & Klein (2014)
Δz: cloud physical thickness	Due to e.g. convective activity (increase τ), boundary layer decoupling (decrease τ); Tselioudis et al. (1998), Gordon & Klein (2014)

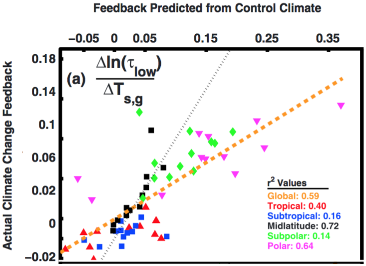
Question

What is the relative importance of thermodynamic phase shifts to $\underbrace{\text{variations in } \tau \text{ with temperature}}_{\frac{d \ln \tau}{dT}}$?

Previous studies have shown that τ variations with temperature ($\frac{d\ln\tau}{dT}$) in the current climate are qualitatively similar to those seen under climate warming $\Rightarrow$ "time-scale invariance" of $\frac{d\ln\tau}{dT}$.



Tselioudis et al. (1998), J. Clim.



Gordon & Klein (2014), JGR

Note:

$\frac{d\ln\tau}{dT} > 0 \Rightarrow$ negative optical depth feedback

$\frac{d\ln\tau}{dT} < 0 \Rightarrow$ positive optical depth feedback

Method

Using MODIS level 3, 1° by 1°, daily dataset:

$$\overline{\ln \tau(T)} = k_i(T)\overline{\ln \tau_i(T)} + k_l(T)\overline{\ln \tau_l(T)}, \tag{1}$$

$$\begin{aligned}\overline{\ln \tau(T)} &= k_i(T)\overline{\ln \tau_i(T)} + (1 - k_i(T))\overline{\ln \tau_l(T)} \\ &= k_i(T)\left(\overline{\ln \tau_i(T)} - \overline{\ln \tau_l(T)}\right) + \overline{\ln \tau_l(T)}\end{aligned} \tag{2}$$

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Dataset & Results

- Using MODIS/Aqua level 3, 1° by 1° gridded daily dataset, Dec. 1, 2012 to Nov. 30, 2016
- T refers to daytime cloud top temperature
- Considered all clouds (not just restricted to low clouds)
- Used mean gridcell values, but only those with σ_T <5 K criterion to reduce high/low cloud overlap
- Required grid cells to contain both liquid and ice clouds
- Regressions performed in 15°C-wide bins
- F-test to evaluate statistical significance (>95%) of regressions

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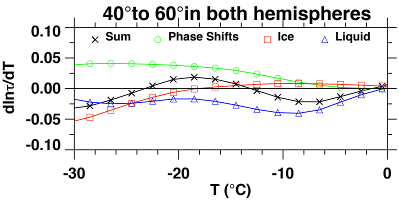
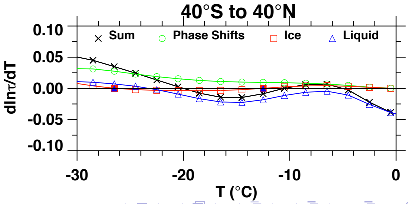
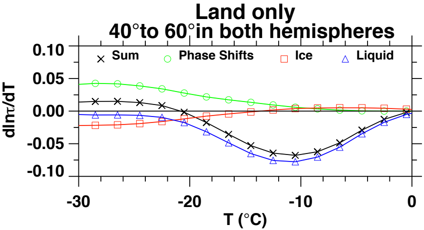
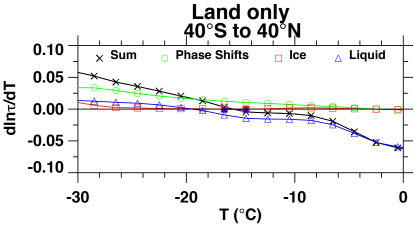
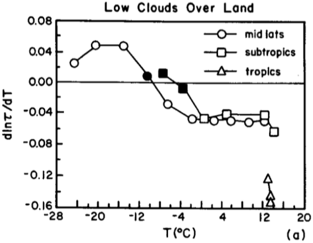




Results: land only







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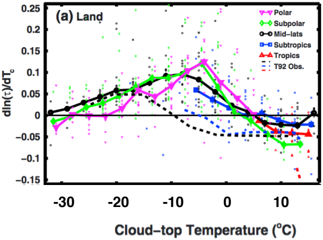
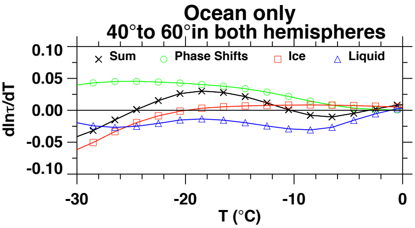
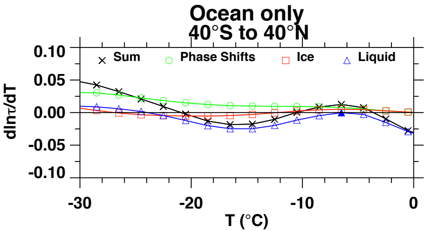
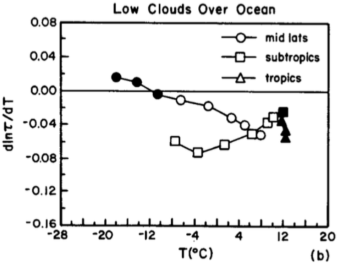


Gordon & Klein (2014), JGR

Results: ocean only







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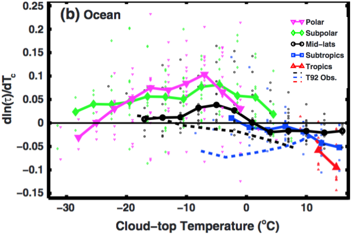


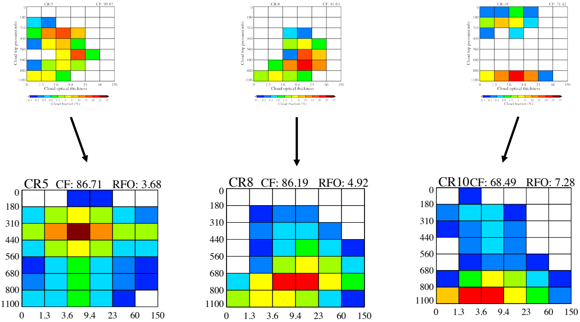
Gordon & Klein (2014), JGR

Question

To what extent do dynamical processes influence $\frac{d \ln \tau}{dT}$?

MODIS Cloud Regimes

- Apply k-means clustering algorithm on MODIS CTP-τ histograms (daily, 1° by 1°, level 3, Dec. 1, 2002 to Nov. 30, 2014) to group histograms into similar "weather states" by assigning each histogram to the nearest centroid in terms of its Euclidean distance.
- The cloud regimes are the mean centroids after convergence.



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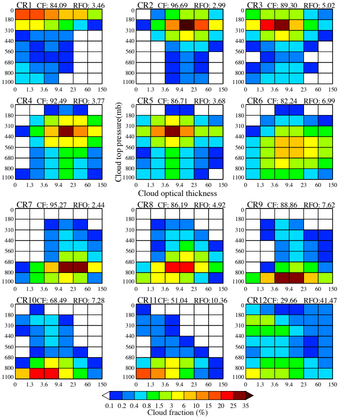
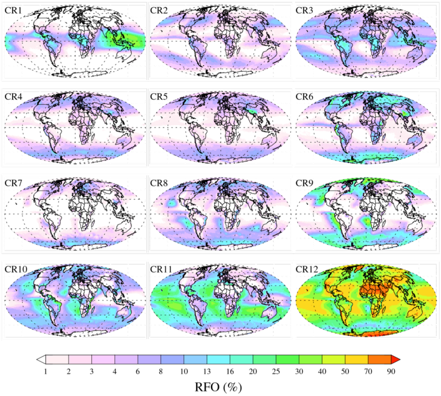
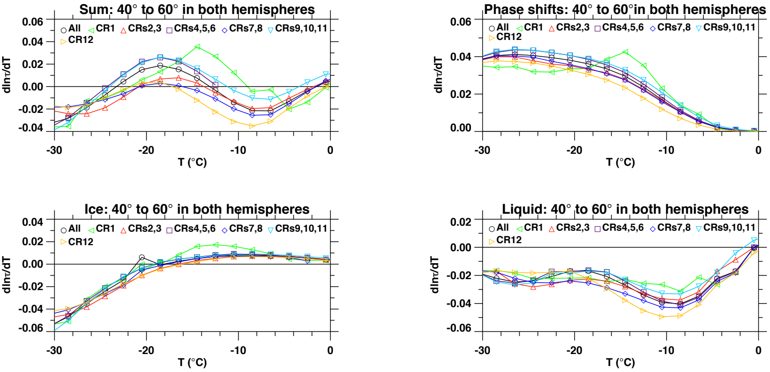




Results: cloud regimes

Although there are differences in τ-T relationships between the various cloud regimes, the pattern is similar across cloud regimes.

$\Rightarrow$ Thermodynamics are more important than dynamics for $\frac{d \ln \tau}{dT}$



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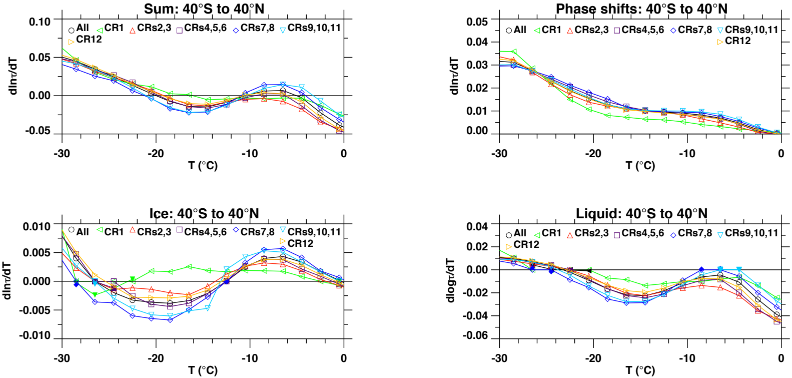

Summary

- Thermodynamic phase changes:
  - not as important for $\frac{d \ln \tau}{dT}$ as liquid cloud processes
  - more important for $\frac{d \ln \tau}{dT}$ at colder temperatures
  - explain why $\frac{d \ln \tau}{dT} > 0$ at colder temperatures over land (vs. adiabatic water content changes)
- $\frac{d \ln \tau}{dT}$ is too positive in models, implying that the cloud optical depth feedback may be too negative in models
- Dynamical processes likely do not strongly influence $\frac{d \ln \tau}{dT}$