The Relationship of Low-Cloud Optical Depth to Temperature in ARM Observations with Implications for Cloud Feedbacks

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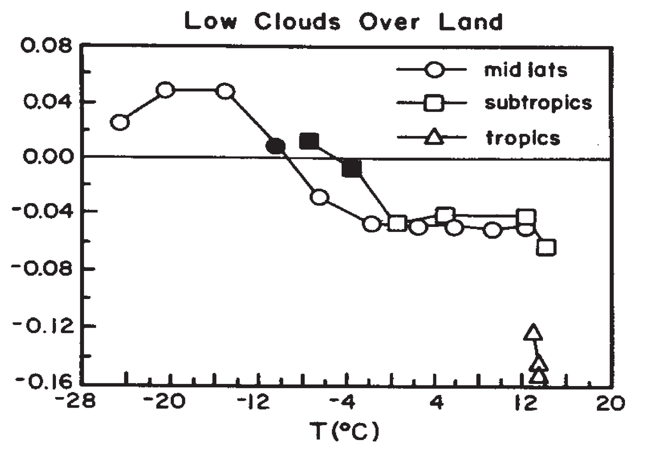
Motivation

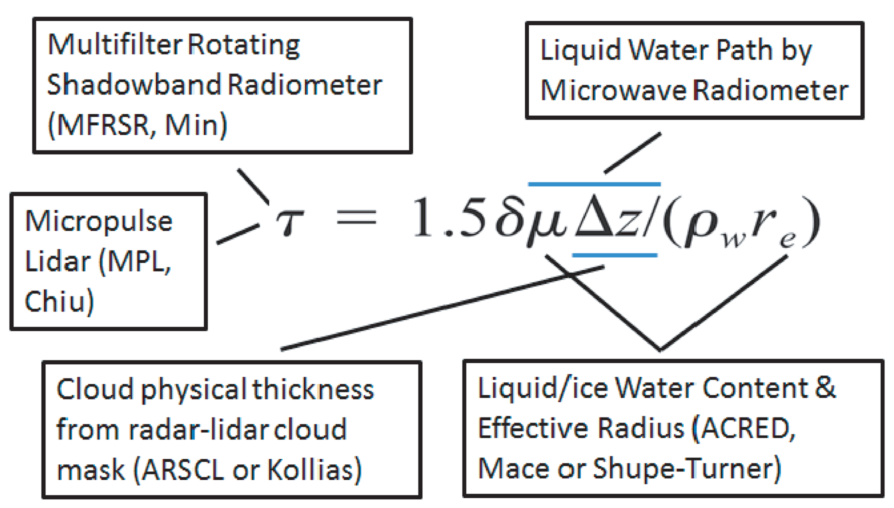


Tselioudis et al 1992 based on ISCCP satellite data

The dependence of cloud optical depth on cloud top temperature has been explored using ISCCP satellite data by Tselioudis et al (1992) that cloud optical depth increases with cold temperatures and decreases with warm temperatures. There is a growing interest of using this relationship to evaluate global climate modeling results and study long-term cloud feedback on climate change (Gordon and Klein 2014). However there is a lack of systematic investigation of this relationship based on ground-based observations. To extend the approach in Del Genio and Wolf (2000) on using ARM observation, we revisit this relationship using most updated long-term quality-controlled data to 1) provide a more accurate quantification of this relationship and 2) explore physical mechanisms that dominate the relationship.

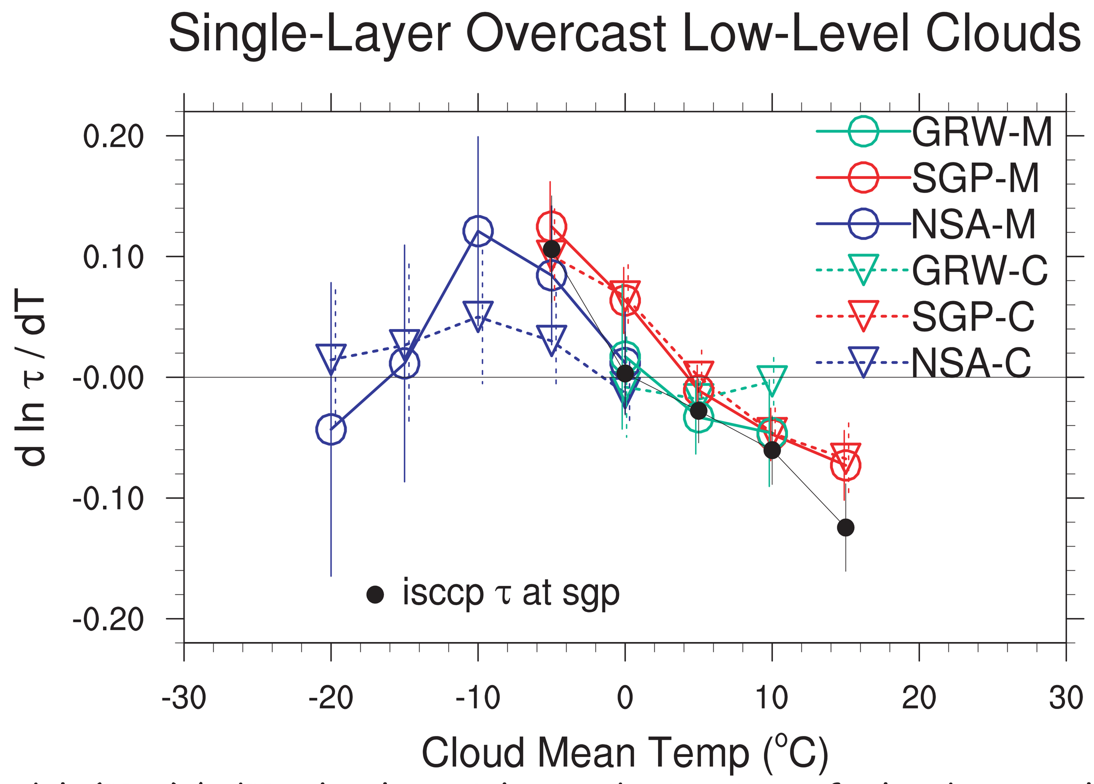
Data and Methodology

1. Select single-layer near-overcast (fraction > 90%) low-clouds (< 5km) based on hourly-mean ARSCL cloud fraction at SGP and NSA and cloud mask data (Kollias et al) at GRW.
2. Make use of independent measurement and retrievals of cloud properties to tackle the factors that may contribute to the dependence of cloud optical depth on temperature.



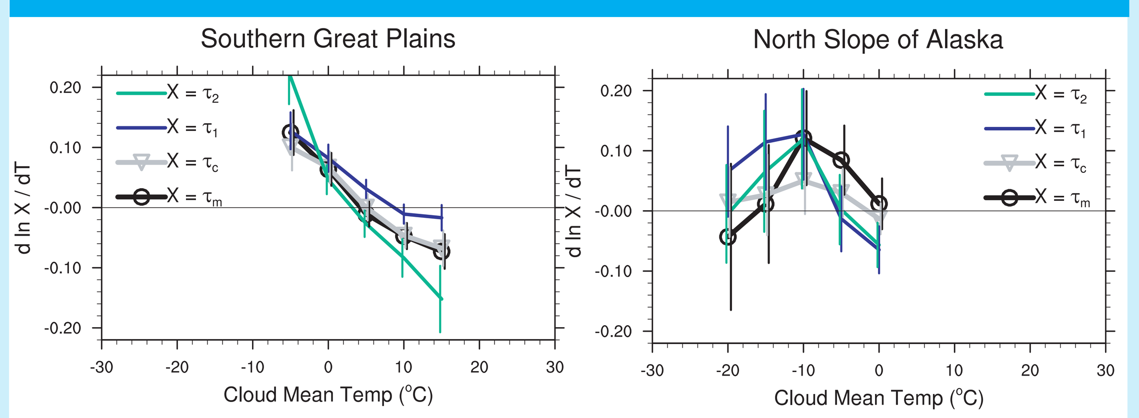
ARM Sites & Time	Variables	Data
NSA 2004-2005 (430 hours)	Cloud Optical Depth (τ)	MFRSR (Min)
		MPL (Chiu)
	Liquid Water Path	MWRRET
	Cloud Physical Thickness (ΔZ)	ARSCL (in ARMBE)
	Cloud Temperature	Sonde (Balloon)
	r_e & Cloud Water Content	Shupe-Turner algorithm
SGP 2003-2007 (580 hours)	Cloud Optical Depth (τ)	MFRSR (Min)
		MPL (Chiu)
	Liquid Water Path	MWRRET
	Cloud Physical Thickness (ΔZ)	ARSCL (in ARMBE)
	Cloud Temperature	Sonde (Balloon)
	r_e & Cloud Water Content	Mace algorithm
GRW May 2009-2010 (110 hours)	Cloud Optical Depth (τ)	MFRSR (Min)
		MPL (Chiu)
	Liquid Water Path	MWRPORF
	Cloud Physical Thickness (ΔZ)	Cloud Mask (Kollias)
	Cloud Temperature	Sonde (Balloon)

Cld Optical Depth & Temp.



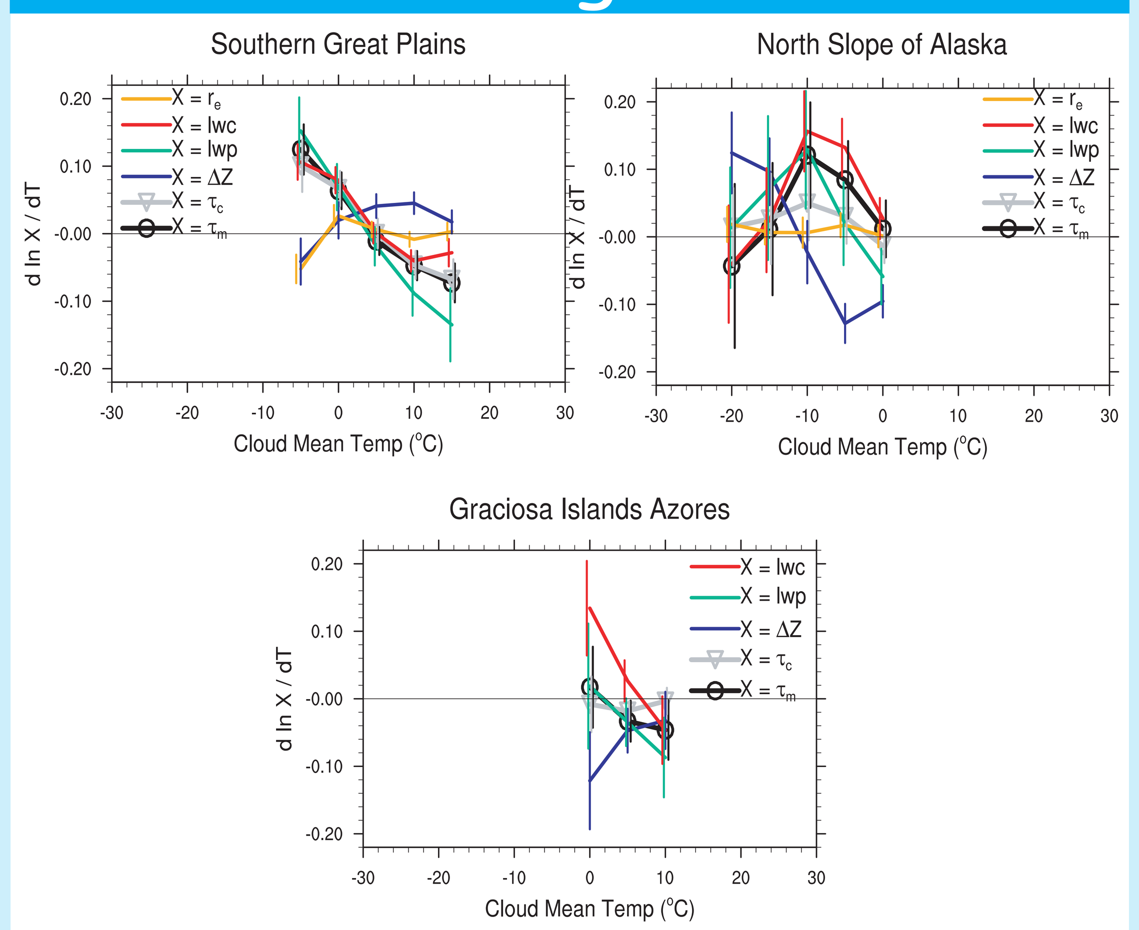
d ln(Tau)/ dT, the logarithmic derivative of cloud optical depth with temperature, is calculated as the regression slope between ln(Tau) and Temp in each 15 K bin with at least 30 samples in each bin. Balanced sampling is required in each temperature bin, e.g. 25% or more samples in both sides with respect to the mean of the bin. Uncertainty range (vertical bar) is calculated as the 95% confidence level of the regression slope calculation.
Cloud temperature is calculated based on soundings within 3 hours at SGP and GRW and within 6 hours at NSA. ISCCP satellite data point was calculated with ISCCP Tau and the same cloud mean temperature from ARM sounding.

Observations' Closure



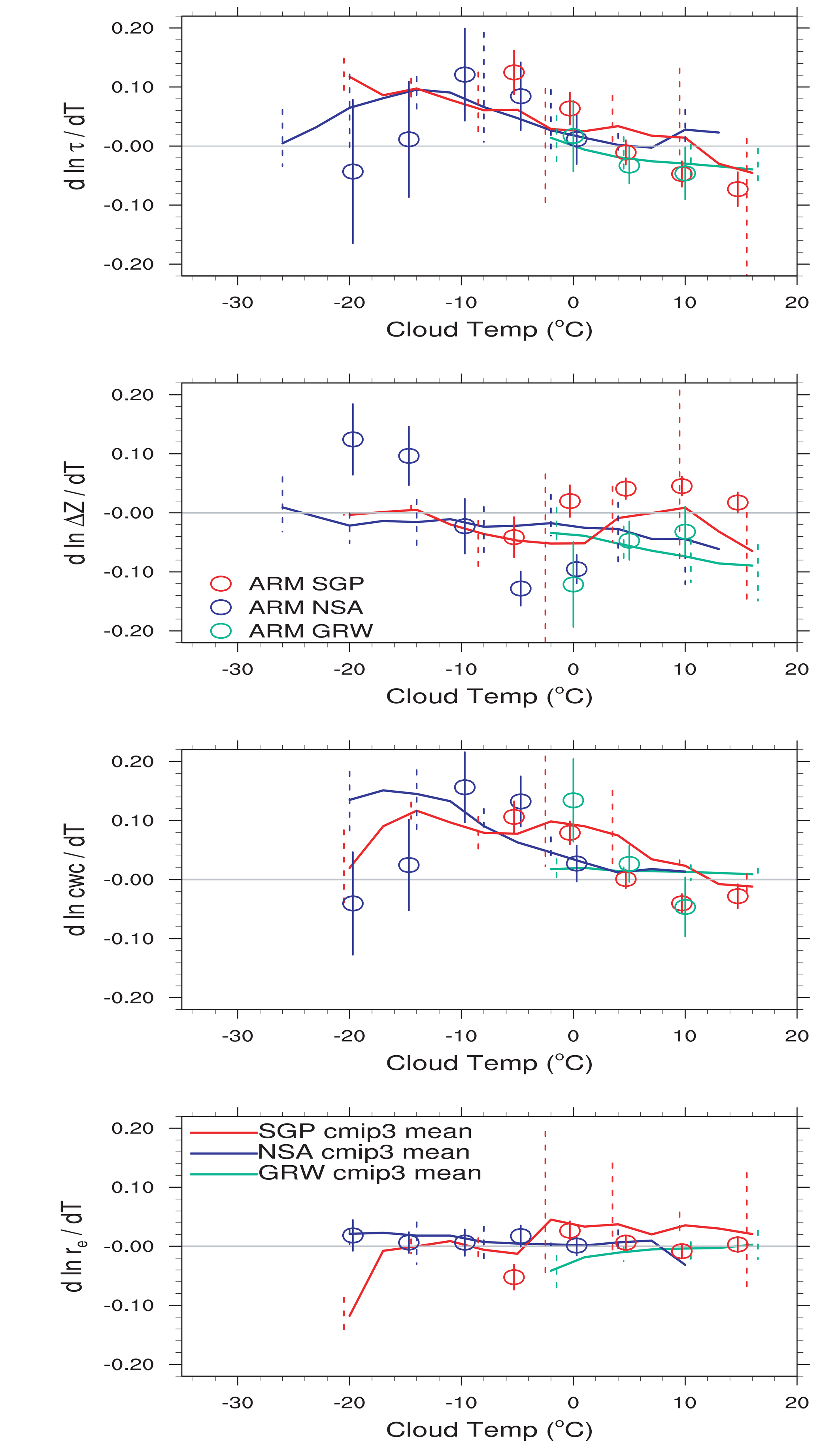
log(Tau_1) = log(dZ) + log(lwc) - log(r_e), log(Tau_2) = log(lwp) - log(r_e). Tau_c is the MPL (C. J. Chiu) data and Tau_m is the MFRSR (Q. Min) data.

Controlling factors



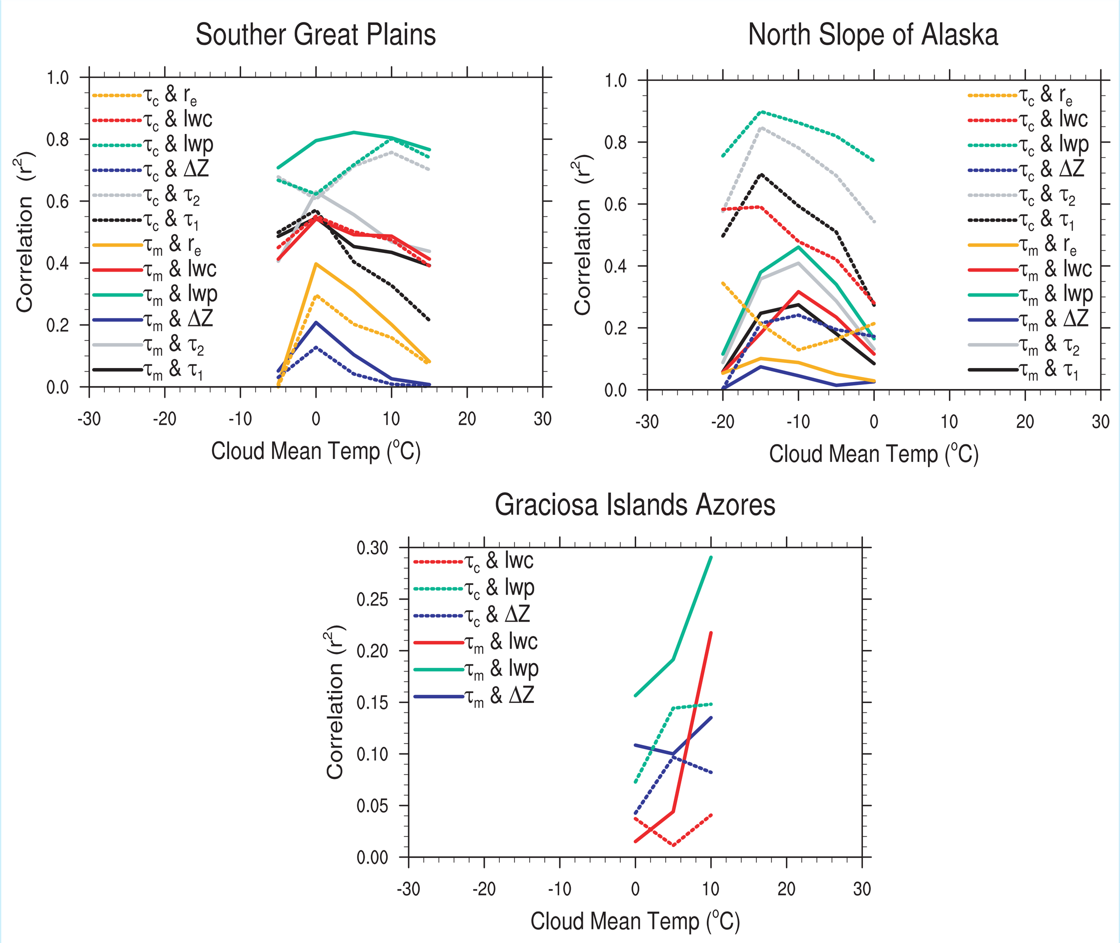
Which factor's change is best related to the change in tau? At NSA, SGP, the change in cloud optical depth with temperature closely related to the change in liquid water content, this is also true for GRW 10C bin.
At GRW, there is no retrieval product of lwc, here lwc = lwp/dZ; the lwc effect tends to be canceled by delta_Z effect in the 0 and 5 C bin

ARM data vs CMIP3



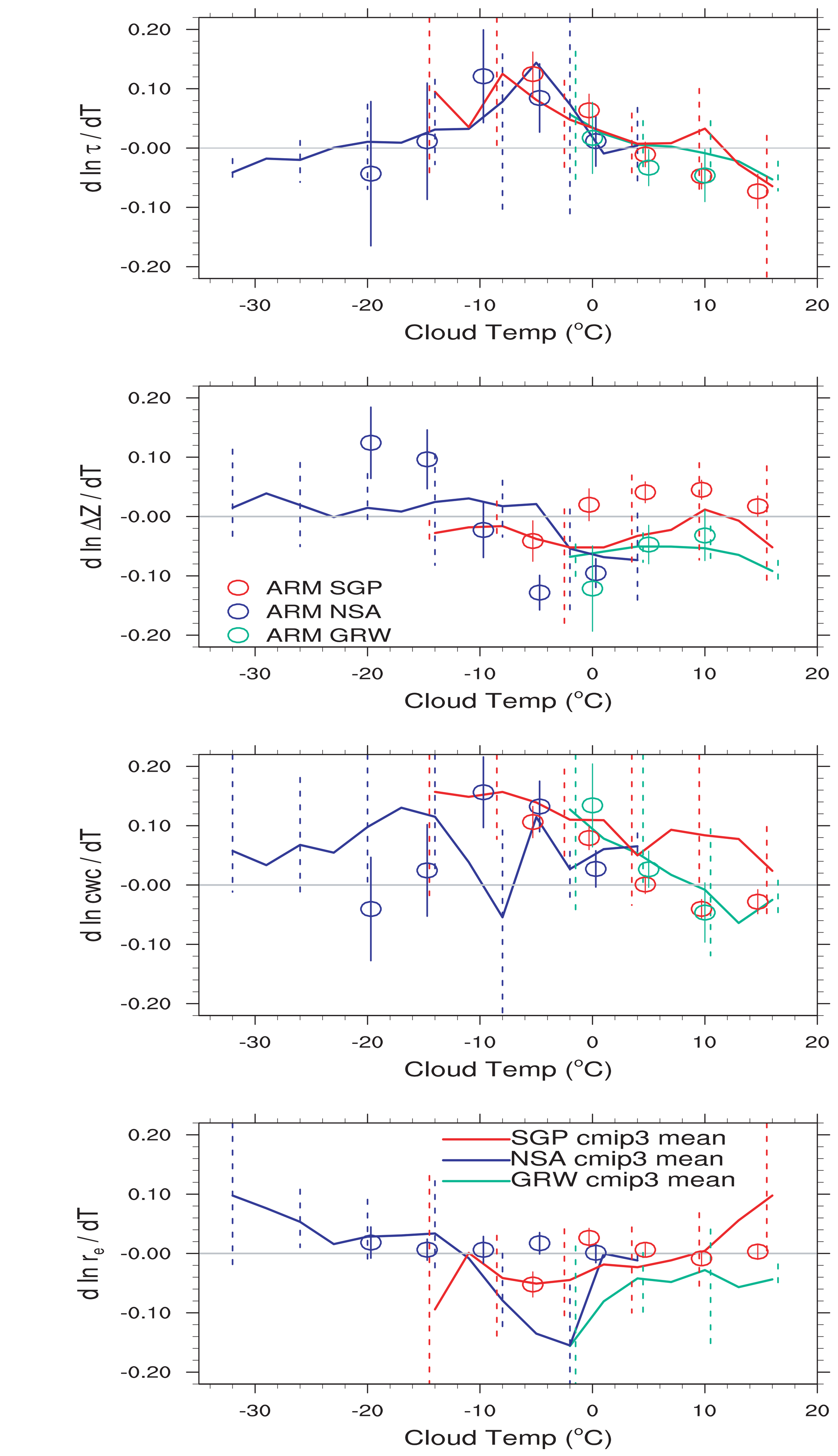
Dashed vertical line hints at multi-model value range (min to max). Solid vertical line is the obs' uncertainty.

Factors' Correlation



Which factor is best correlated to Tau in each temperature bin? (in log form)
At all sites, LWP is best correlated to cloud opitcal depth as expected. Although higher correlation does not guarantee higher contribution to change with temperature. (note the different y-axis scale in GRW)

ARM data vs CMIP5



Dashed vertical line hints at multi-model value range (min to max). Solid vertical line is the obs' uncertainty.

Summary and Future Work

1. The relationship between cloud optical depth and temperature from ARM data shows the consistent behavior as previous studies. At SGP site, the ground-based observation agrees very well with satellite isccp data.
2. Among the all factors, the change in cloud lwc with temp. significantly dominate the change in cloud optical depth with temperature, except for GRW warm phase clouds where the effects of cloud lwc and cloud physical depth tend to cancel each other. Such finding at SGP is different from Del Genio and Wolf (2000) that they found the cloud thinning with temperature warming while the cloud liquid water content changes little. However our results agree well with Dong et al (2005) on the cloud physical thickness variation with temperate at SGP site.
3. This observed relationship is also used to evaluate CMIP3/5 model isccp simulator output at ARM sites. Slightly different from Neil and Klein (2014), we found model output at ARM sites is generally within the uncertainty range of ground based observations, especially cloud optical depth change with temperature. Some bias are still found in lwc, r_e and cloud physical thickness in certain temperature ranges. CMIP5 shows much more inter-model spread than CMIP3 models. While some models' results seem to be always within the observation's uncertainty range, e.g. CMIP5 hadgem; some model definitely showed an outliner behavior, e.g. the change in cloud water content with temperature in CMIP5 MPI.

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