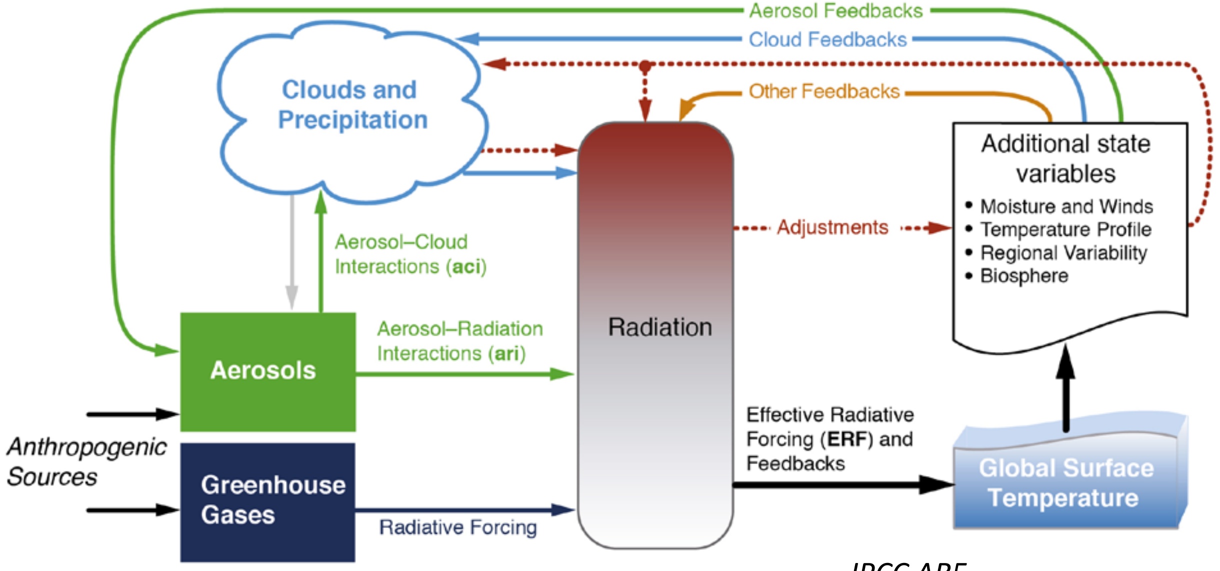
Surface-based Cloud Radiative Properties for Improved Understanding of Aerosol Indirect Effects (Aerosol-Cloud Interactions)

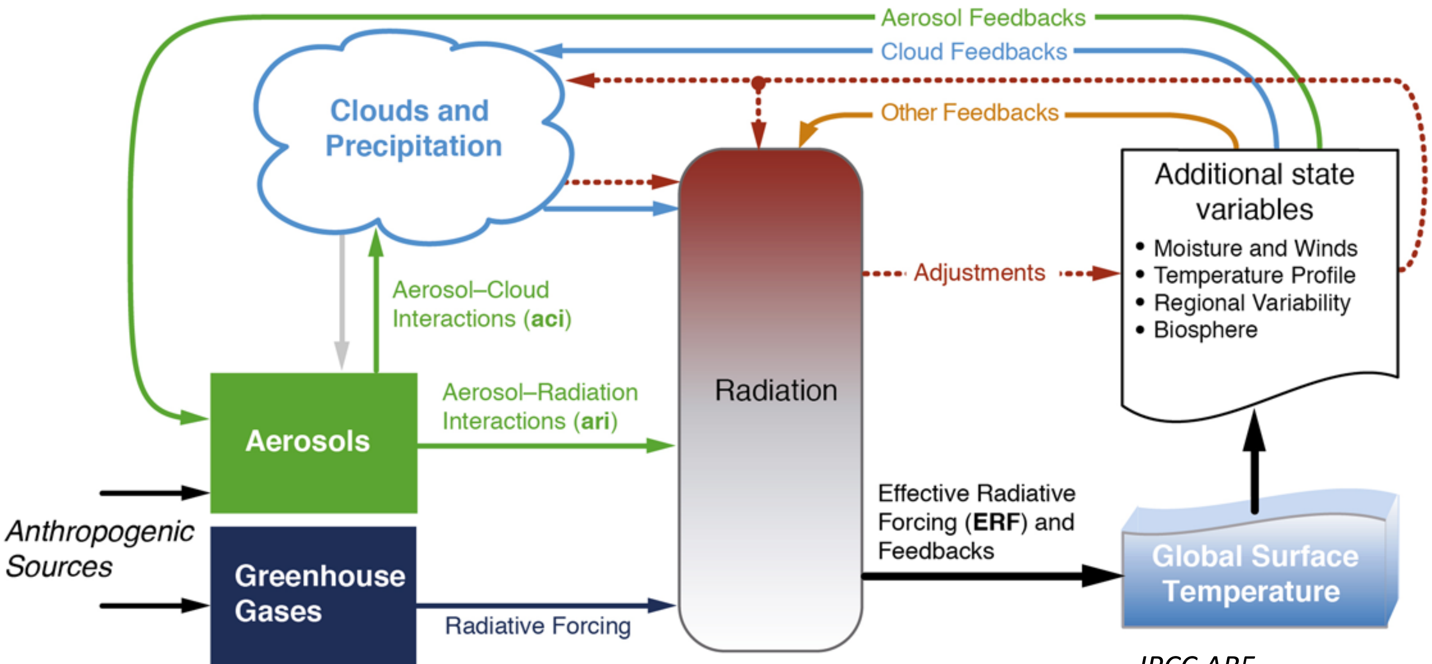
Allison McComiskey, Elisa Sena, Chuck Long, Graham Feingold

Data acknowledgements: Anne Jefferson, Joe Michalsky, Gary Hodges, Dave Turner



IPCC AR5
Boucher, Randall et al. 2014

Forcers and Feedbacks in the Climate System



IPCC AR5
Boucher, Randall et al. 2014

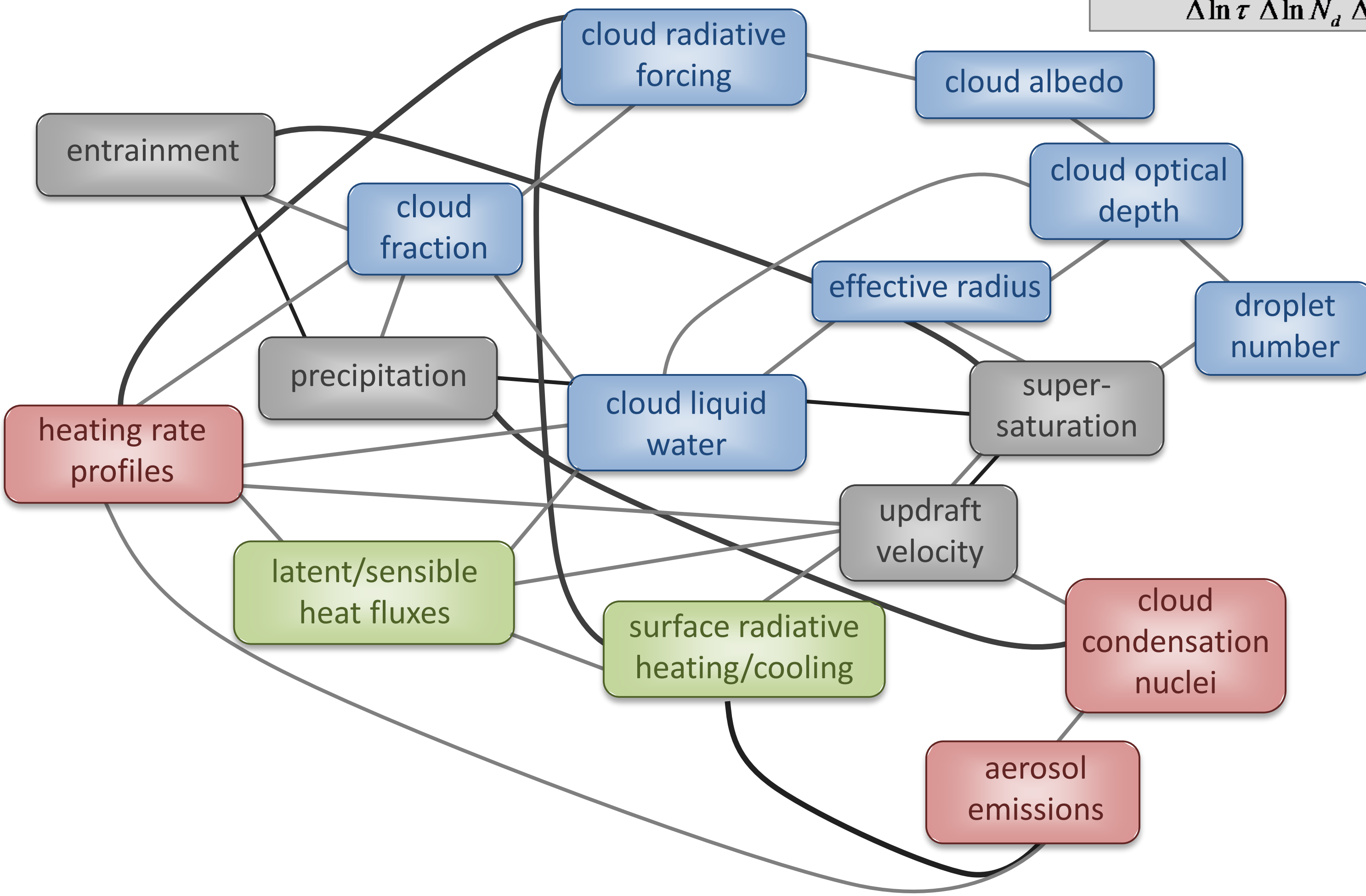
"We propose that the difficulty in untangling relationships among the aerosol, clouds and precipitation reflects the inadequacy of existing tools and methodologies and a failure to account for processes that buffer cloud and precipitation responses to aerosol perturbations."

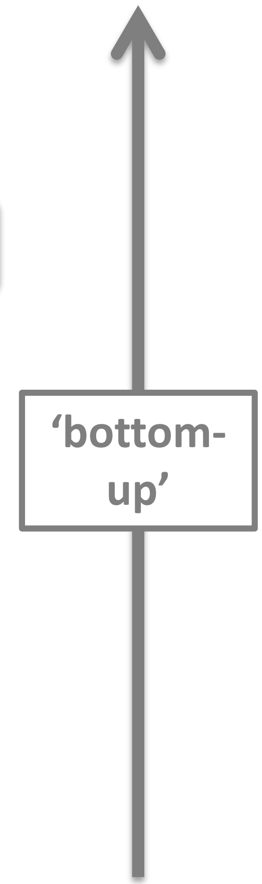
Stevens and Feingold, 2009, Nature

Critical Properties and Processes of the Aerosol-Cloud System

$$\Delta R = R\frac{\Delta \ln R}{\Delta \ln \tau}\frac{\Delta \ln \tau}{\Delta \ln N_d}\frac{\Delta \ln N_d}{\Delta \ln CCN}\frac{\Delta \ln CCN}{\Delta \ln E}\Delta \ln E$$

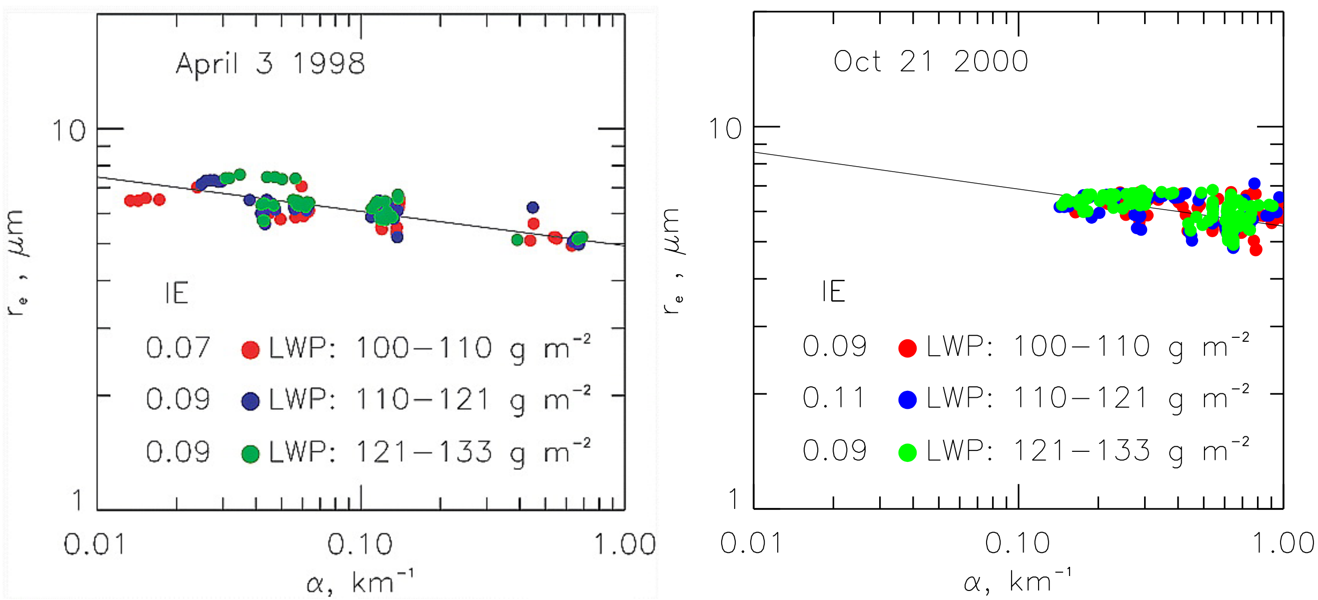
Ghan et al. in prep





"Uncertainty can be reduced if observations can be used to constrain each term…"

First measurements of the Twomey effect using ground-based remote sensors
Southern Great Plains



Feingold et al. 2003 GRL

$$\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L$$

$$\Delta R = R\frac{\Delta \ln R}{\Delta \ln \tau}\frac{\Delta \ln \tau}{\Delta \ln N_d}\frac{\Delta \ln N_d}{\Delta \ln CCN}\frac{\Delta \ln CCN}{\Delta \ln E}\Delta \ln E$$

Closure Experiments: Optical depth and microphysical properties

<u>model input</u>

aerosol, vertical velocity, liquid water path

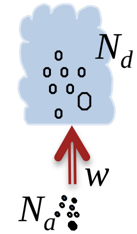
<u>model output</u>

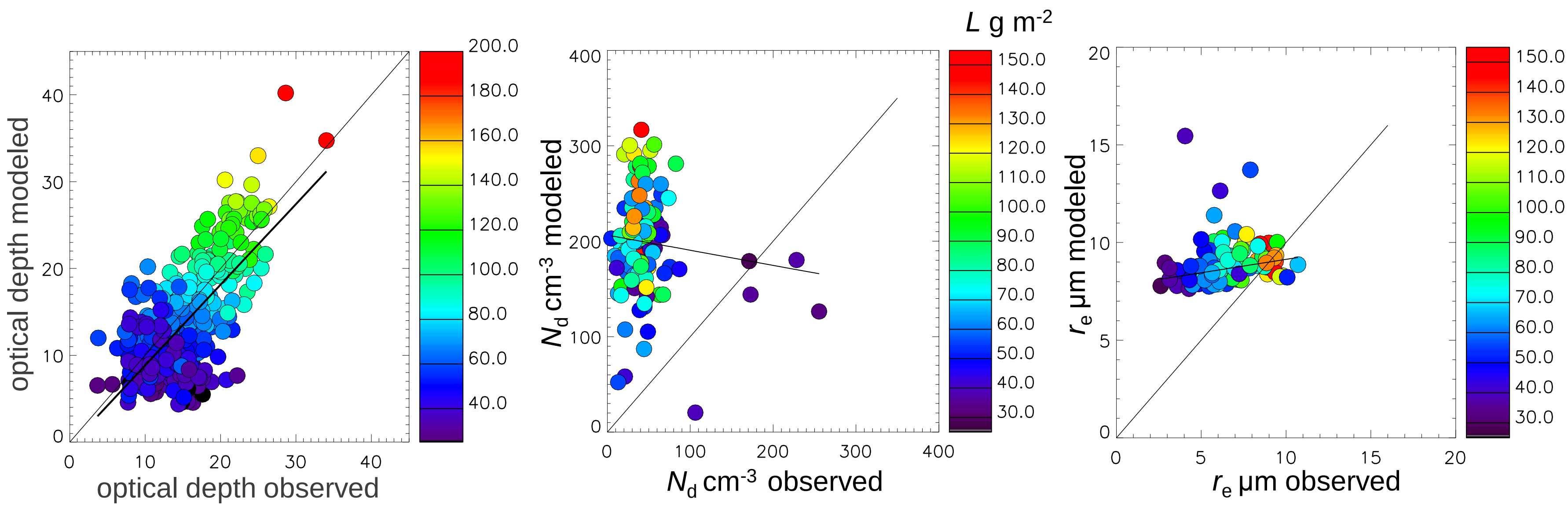
cloud optical depth, effective radius, drop number

$$N_d = f(w, N_a)$$

$$\tau_c \propto L^{5/6} N_d^{1/3}$$

$$r_e \propto L/\tau_c$$





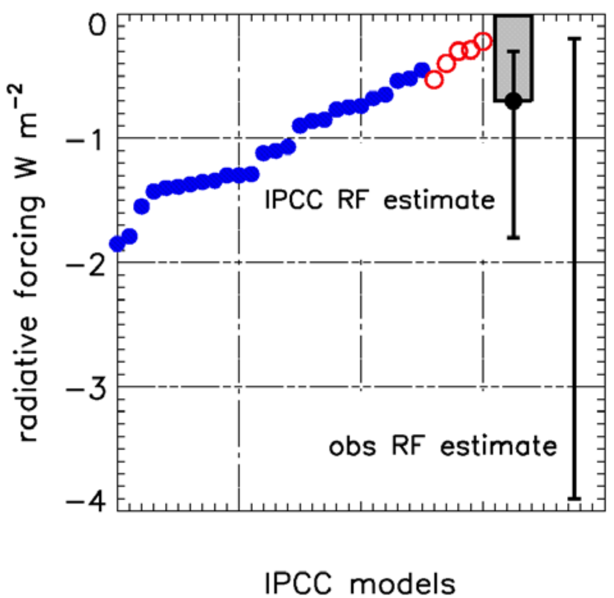
$$\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L$$

$$\Delta R = R \frac{\Delta \ln R}{\Delta \ln \tau} \frac{\Delta \ln \tau}{\Delta \ln N_d} \frac{\Delta \ln N_d}{\Delta \ln CCN} \frac{\Delta \ln CCN}{\Delta \ln E} \Delta \ln E$$

Reconciling ‘bottom-up’ measurements with model radiative forcing

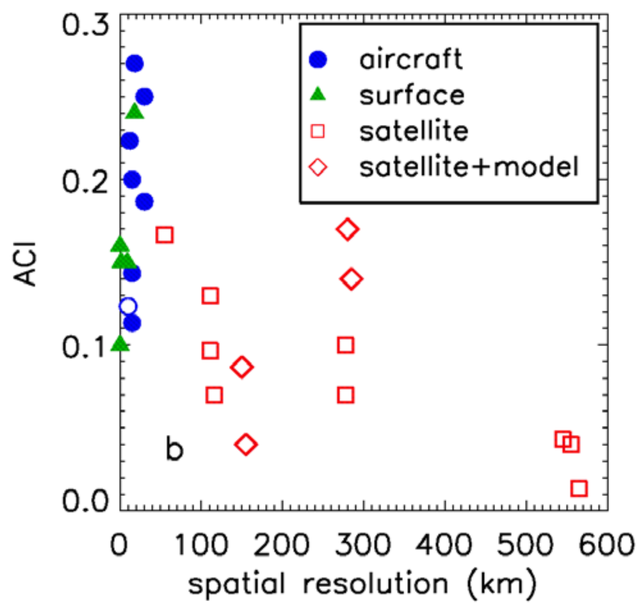
Aerosol Indirect Effects

$$RF = (f_{N_{CCN}PD}\downarrow - f_{N_{CCN}PD}\uparrow) - (f_{N_{CCN}PI}\downarrow - f_{N_{CCN}PI}\uparrow)$$

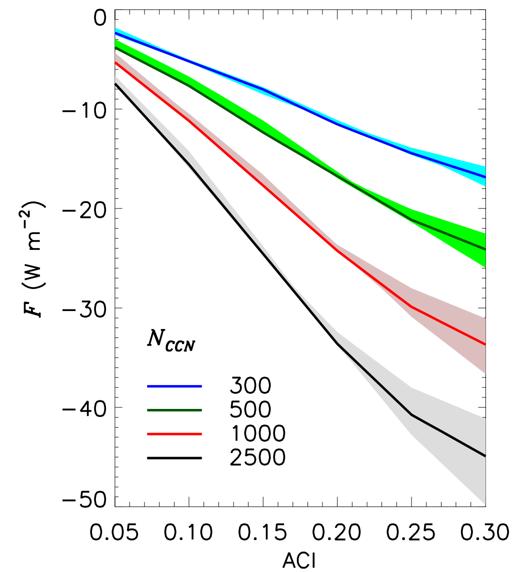


Aerosol-Cloud Interactions

$$ACI = \left.\frac{\partial \ln \tau_c}{\partial \ln \alpha}\right|_L = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L = \frac{1}{3}\frac{d \ln N_d}{d \ln \alpha}$$



McComiskey et al. 2012, ACP

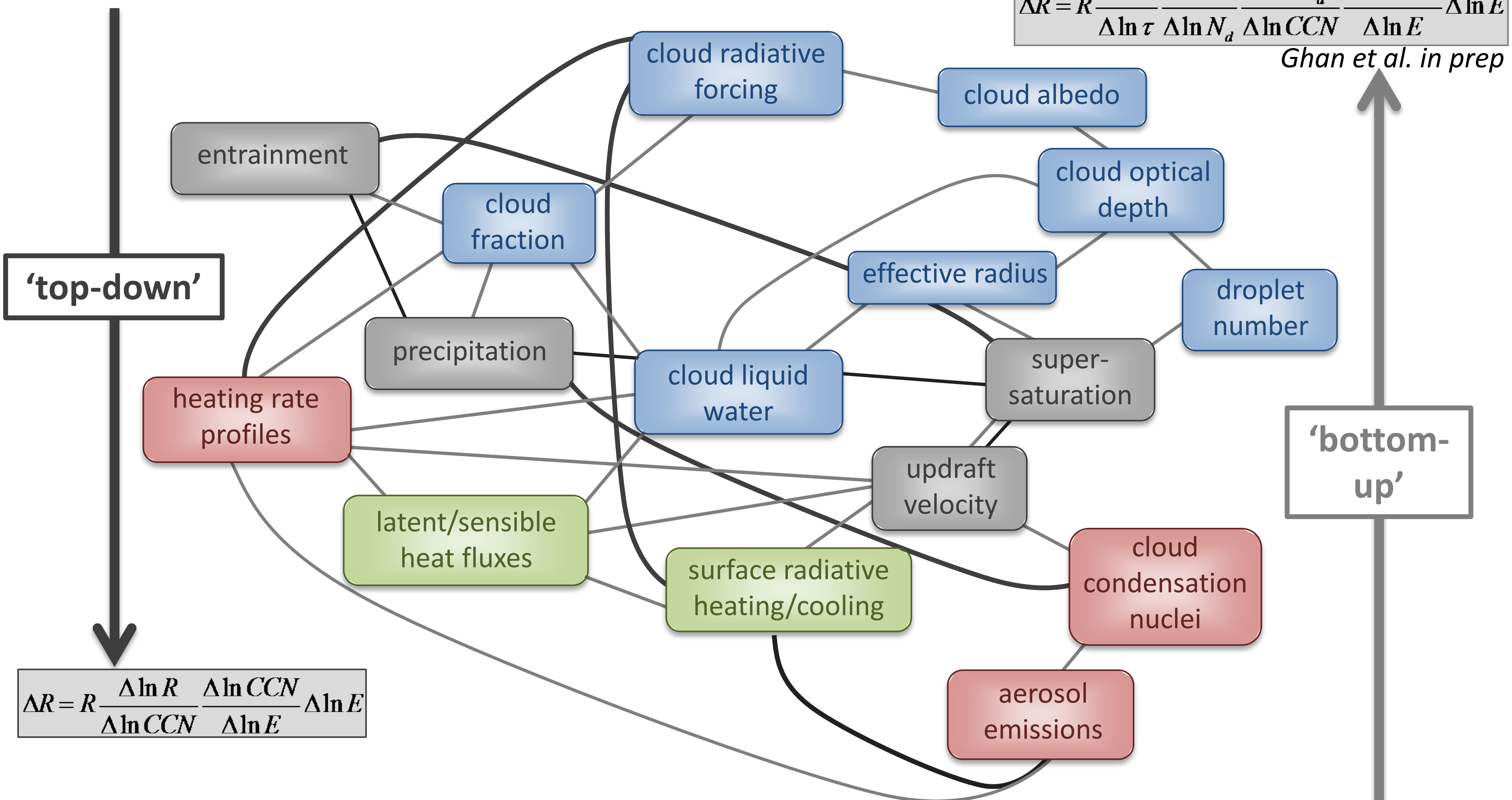


McComiskey et al. 2008, GRL

$$\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_L$$

$$\Delta R = R \frac{\Delta \ln R}{\Delta \ln \tau}\frac{\Delta \ln \tau}{\Delta \ln N_d}\frac{\Delta \ln N_d}{\Delta \ln CCN}\frac{\Delta \ln CCN}{\Delta \ln E}\Delta \ln E$$

Critical Properties and Processes of the Aerosol-Cloud System



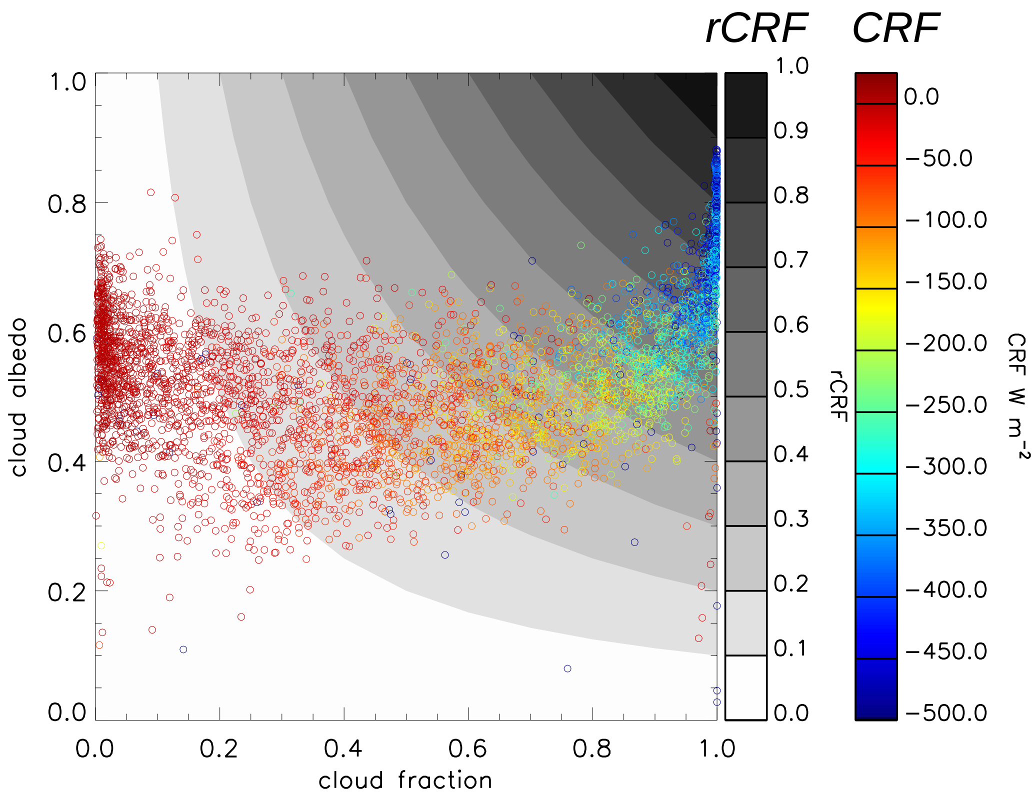
$$\Delta R = R\frac{\Delta \ln R}{\Delta \ln \tau}\frac{\Delta \ln \tau}{\Delta \ln N_d}\frac{\Delta \ln N_d}{\Delta \ln CCN}\frac{\Delta \ln CCN}{\Delta \ln E}\Delta \ln E$$

Ghan et al. in prep

$$\Delta R = R\frac{\Delta \ln R}{\Delta \ln CCN}\frac{\Delta \ln CCN}{\Delta \ln E}\Delta \ln E$$

Uncertainty can be reduced if observations can be used to constrain each term

Cloud Radiative Properties 1997-2008
Southern Great Plains



continuous, high resolution (1- min) broadband surface irradiance observations:

- quality controlled *(Long and Shi 2008)*
- clear-sky estimated
- surface, cloud properties retrieved

(Long et al. 2000, 2006)

$$CRF = Fcld - Fclr$$

- simultaneous retrieval of cloud fraction, cloud albedo, and relative cloud radiative forcing (*rCRF*)

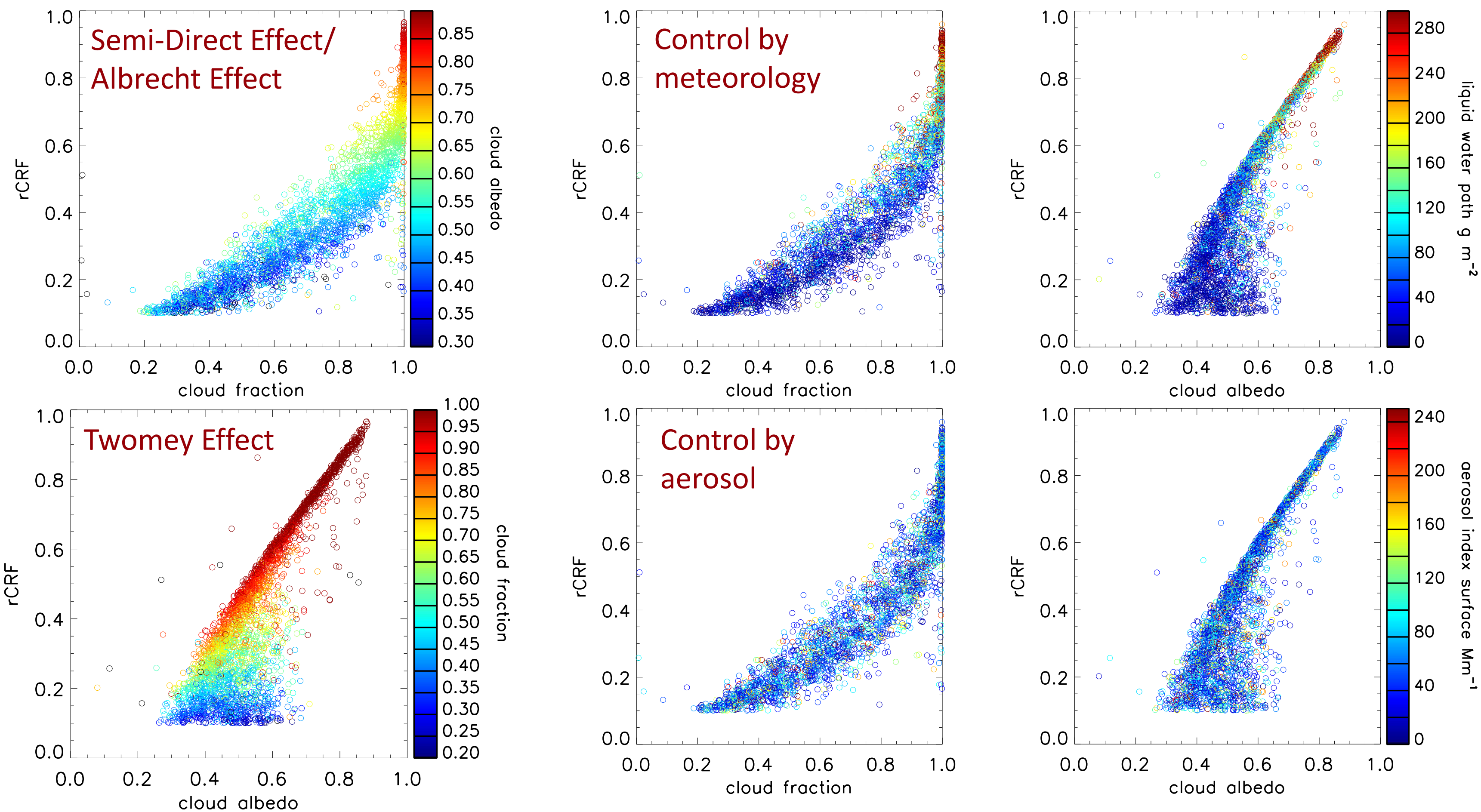
$$rCRF = \alpha_r f$$

- assumption of single layer cloud
- error estimates used to scale cloud albedo for neglect of cloud absorption

(Liu et al. 2010, Xie and Liu 2013)

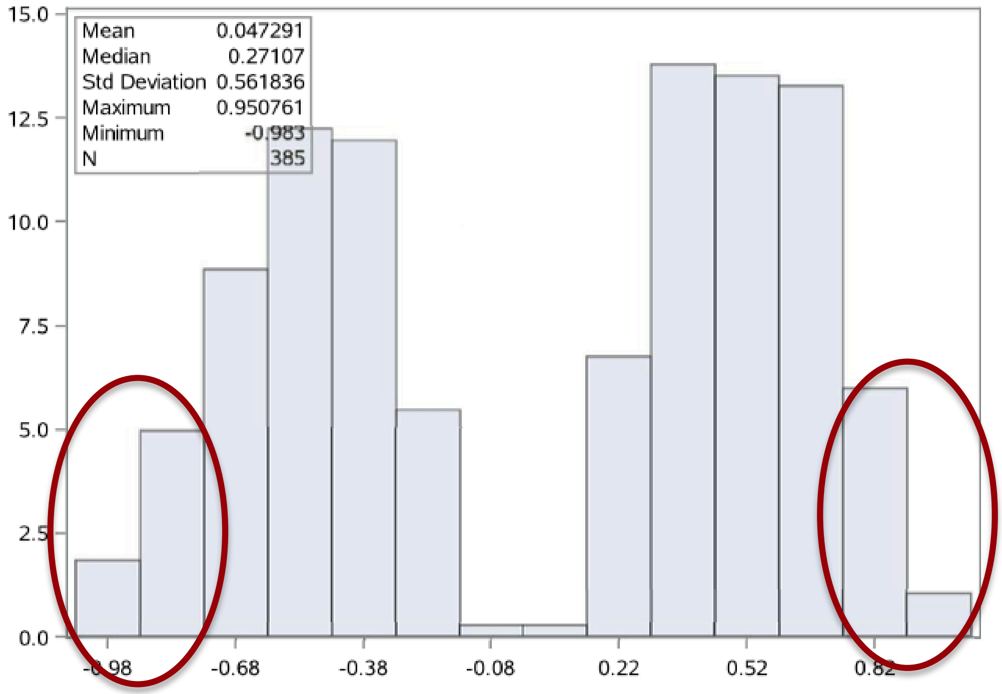
Both long-term *and* detailed measurements required for system understanding can only be gained from continuous, ground-based measurements

Relative contributions of cloud fraction and cloud albedo to cloud radiative forcing



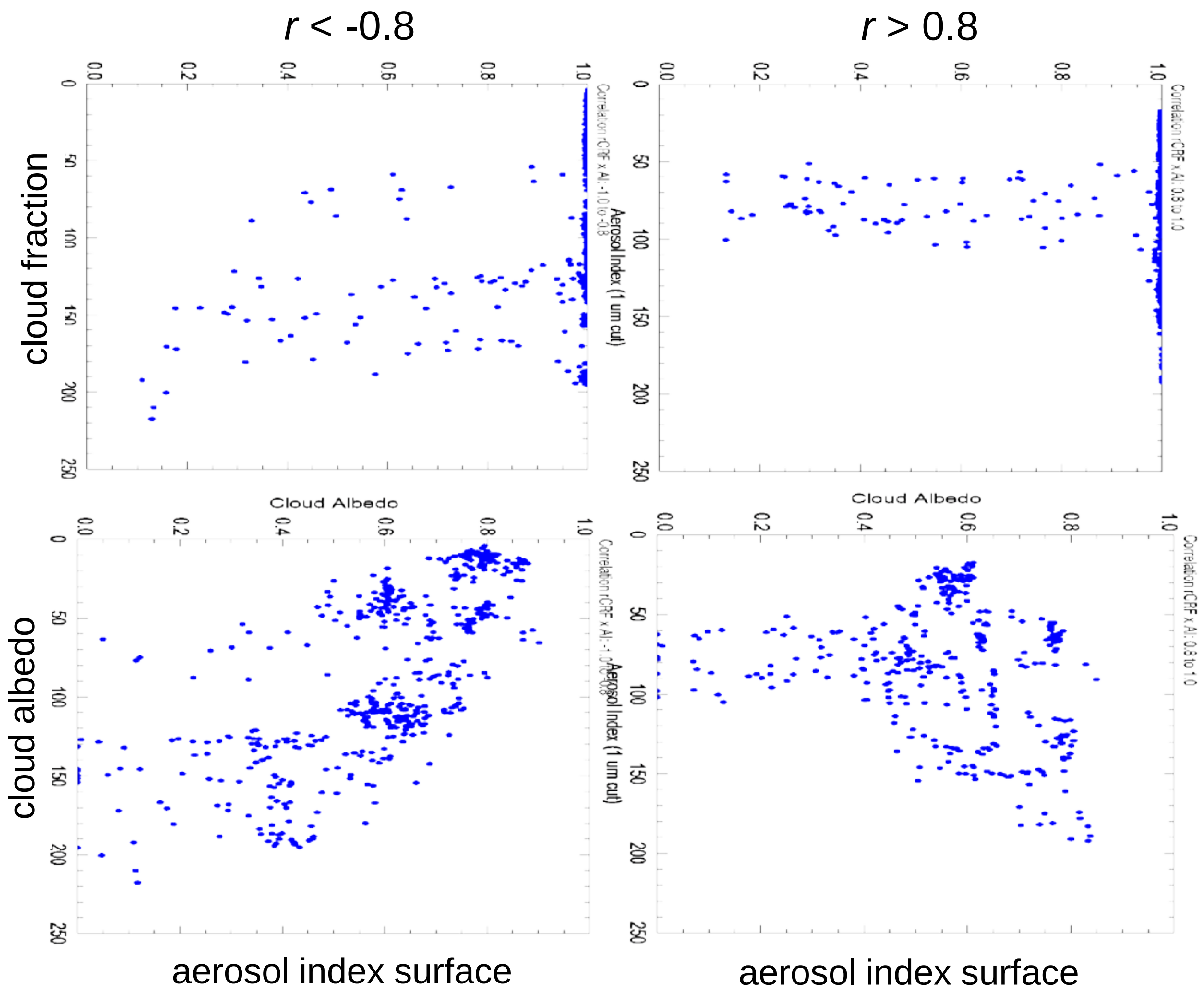
Quantifying relative contributions in different regimes indicates the potential for various aerosol indirect effects and differentiation of meteorological and aerosol drivers

Distribution of correlations: rCRF x Aerosol Index (surface)



what do the highest positive and negative correlations reveal?

Highest positive and negative correlations: rCRF x Aerosol Index (surface)



cloud fractions and cloud albedo are reduced when aerosol concentrations increases

Normalized difference index: $\left(\frac{LWP - \tau_c}{LWP + \tau_c}\right)^2$

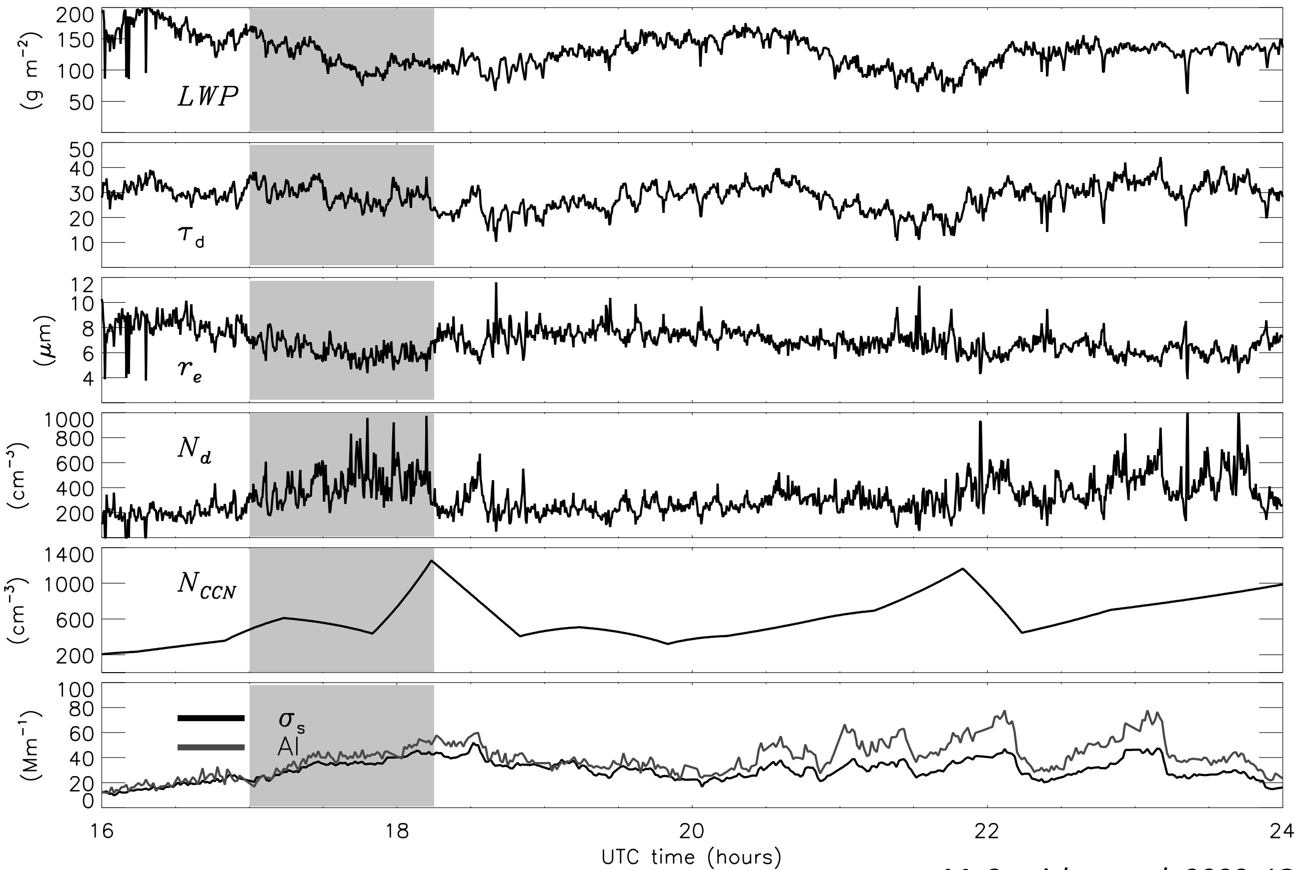
liquid water path

cloud optical depth

effective radius

drop number

aerosol



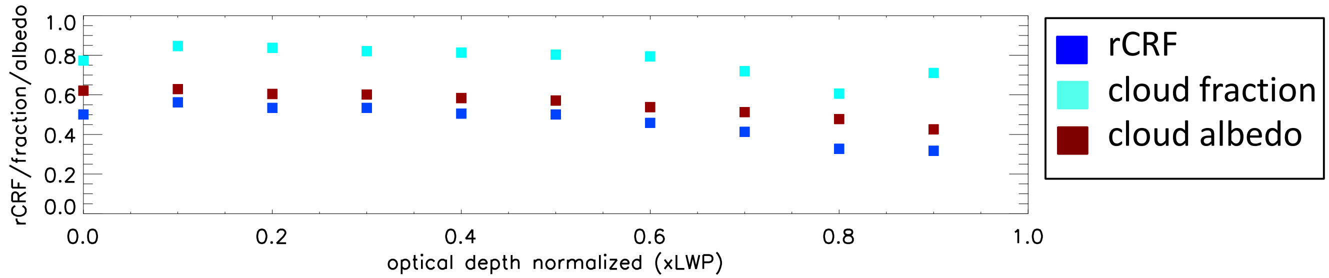
McComiskey et al. 2009, JGR

$$\tau_c \propto L^{5/6} N_d^{1/3}$$

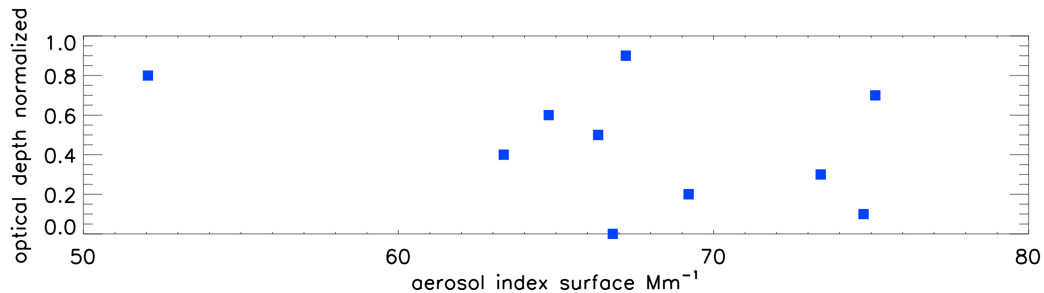
$$r_e \propto L / \tau_c$$

a difference index is used to normalize for meteorological driven variability and to isolate variability in cloud microphysics

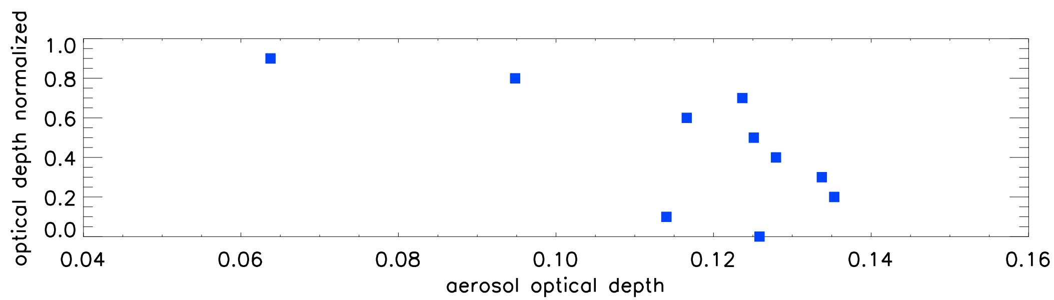
Normalized difference index



$$\left(\frac{LWP-\tau_c}{LWP+\tau_c}\right)^2$$



$$\left(\frac{LWP-\tau_c}{LWP+\tau_c}\right)^2$$



cloud microphysics index shows some relationship to aerosol optical depth

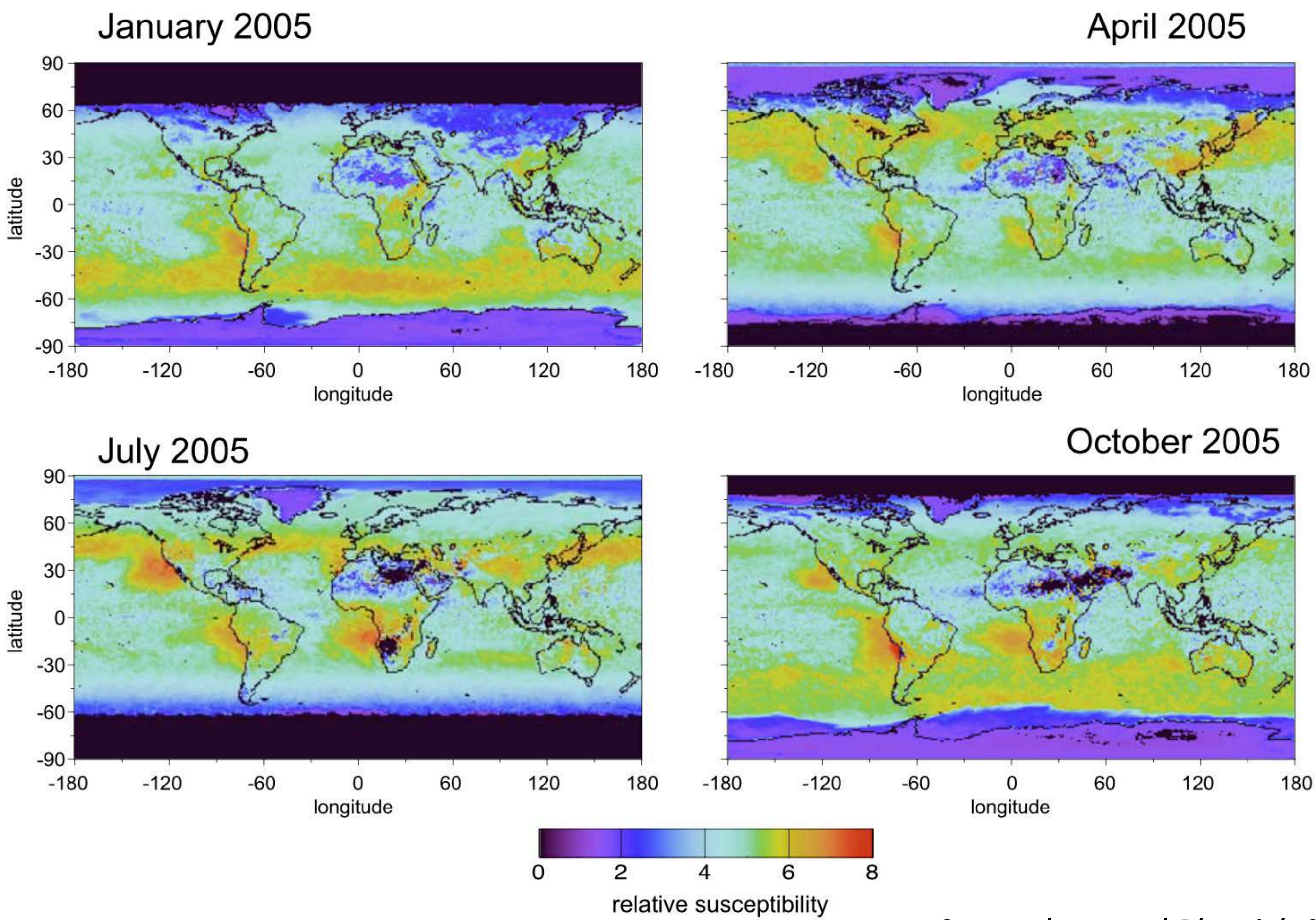
Concluding Remarks

- the relative roles of aerosol and meteorological variables on cloud radiative forcing, cloud albedo, and cloud fraction can be discerned using surface radiometry alone
  - *for this case* aerosol optical depth better correlates with cloud properties than aerosol properties at the surface

- understanding the relative contributions of cloud fraction and cloud albedo to cloud radiative forcing can serve as an indication of specific aerosol-cloud processes
  - the dominant control between cloud albedo and cloud fraction on cloud radiative forcing depends on cloud fraction

- a normalized cloud optical depth index (by liquid water path) can be used as a proxy for variability in cloud microphysical properties

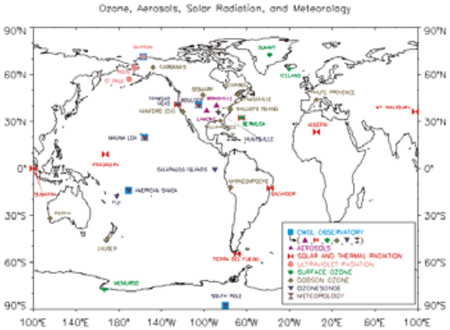
- in the US Southern Great Plains:
  - cloud radiative forcing and liquid water are positively related (more negative CRF/more cooling)
  - cloud radiative forcing and aerosol are negatively related (less negative CRF/less cooling)



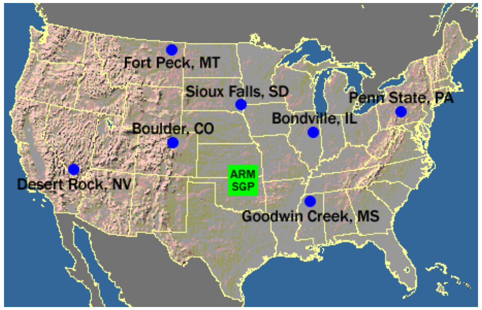
Oreopolous and Platnick 2008, JGR

Future directions

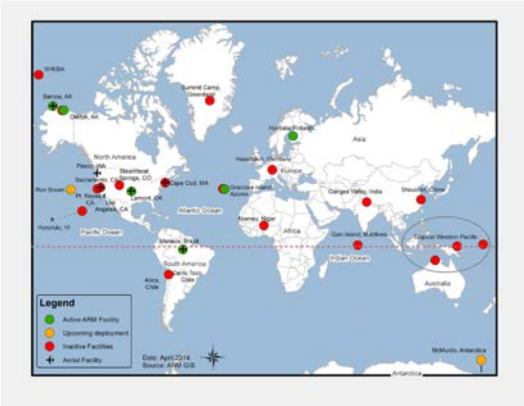
- ➤ test the chain of microphysical and dynamical processes in aerosol-cloud interactions within the constraint of aerosol indirect effects quantified by cloud radiative properties
- ➤ examine relationships in other locations/regimes where positive and/or stronger relationships between aerosol and cloud radiative forcing are expected
- ➤ compare to similar analyses from model output at a range of scales



GMD Observatories

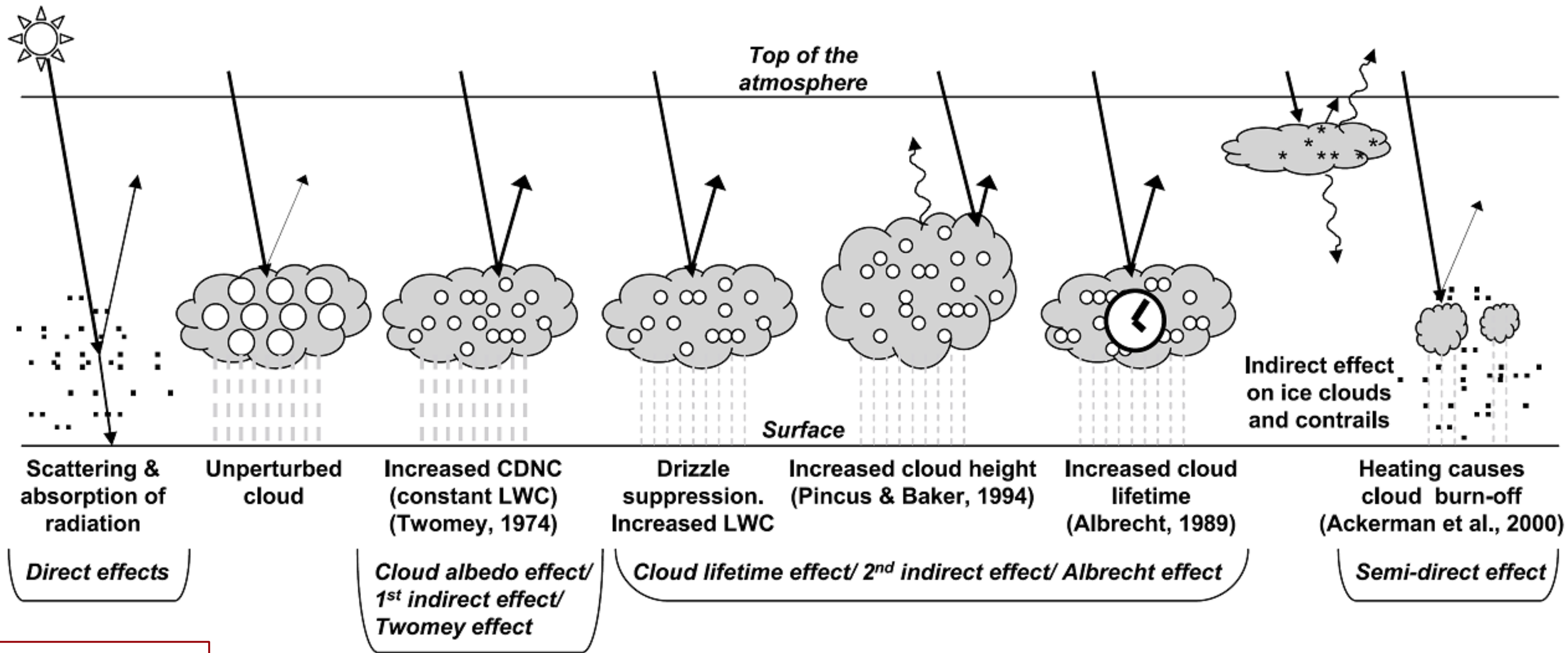


Surfrad sites



DOE ARM deployment locations

IPCC AR4



cloud albedo

Cloud albedo effect/ 1st indirect effect/ Twomey effect

+

cloud albedo + cloud fraction

Cloud lifetime effect/ 2nd indirect effect/ Albrecht effect

+

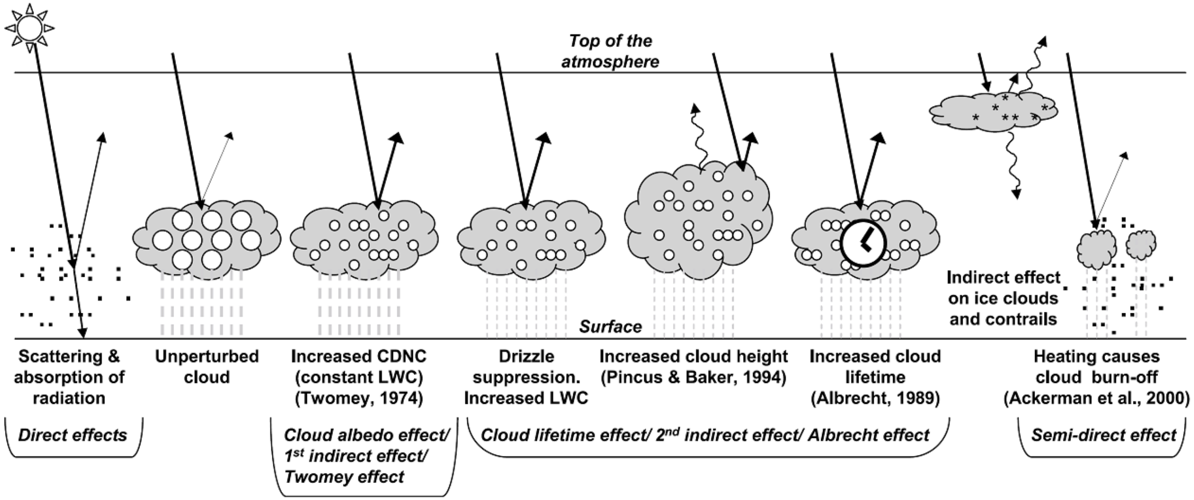
cloud fraction

Semi-direct effect

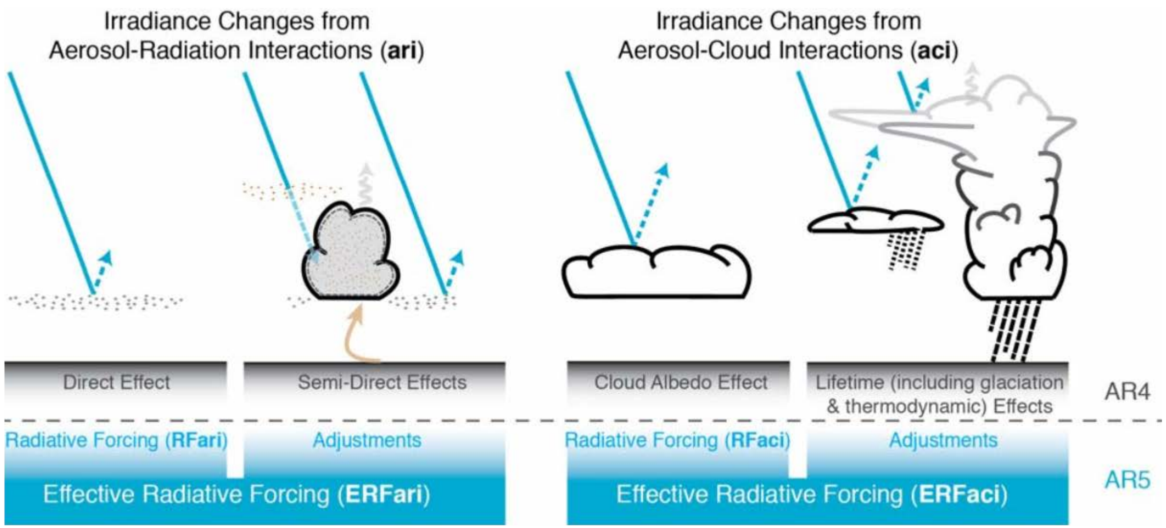
= RF

Reductionist Approach

IPCC AR4



IPCC AR5



Reductionist Approach

Integrative Approach

Control of cloud radiative forcing: liquid water path and aerosol