Geographically coherent patterns of albedo enhancement and suppression associated with aerosol sources and sinks

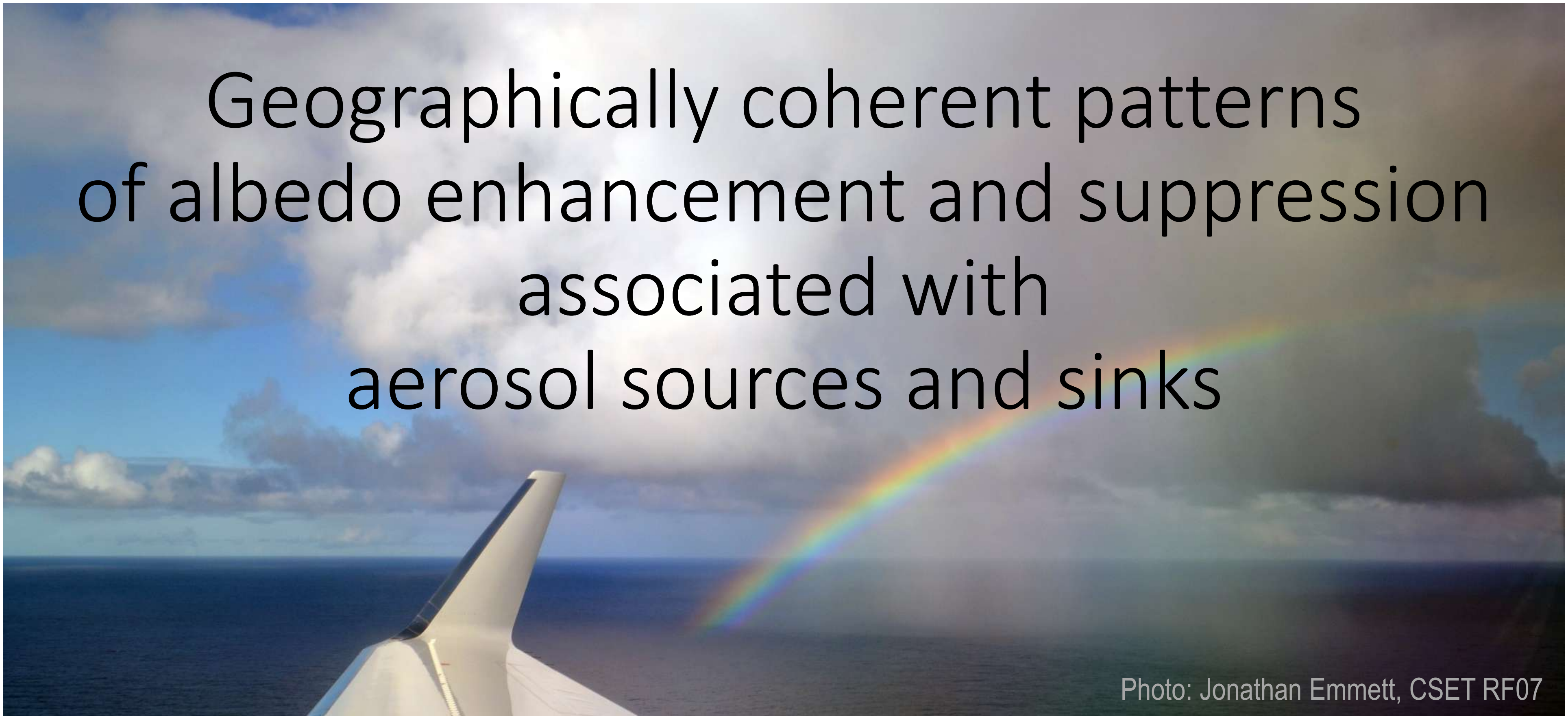
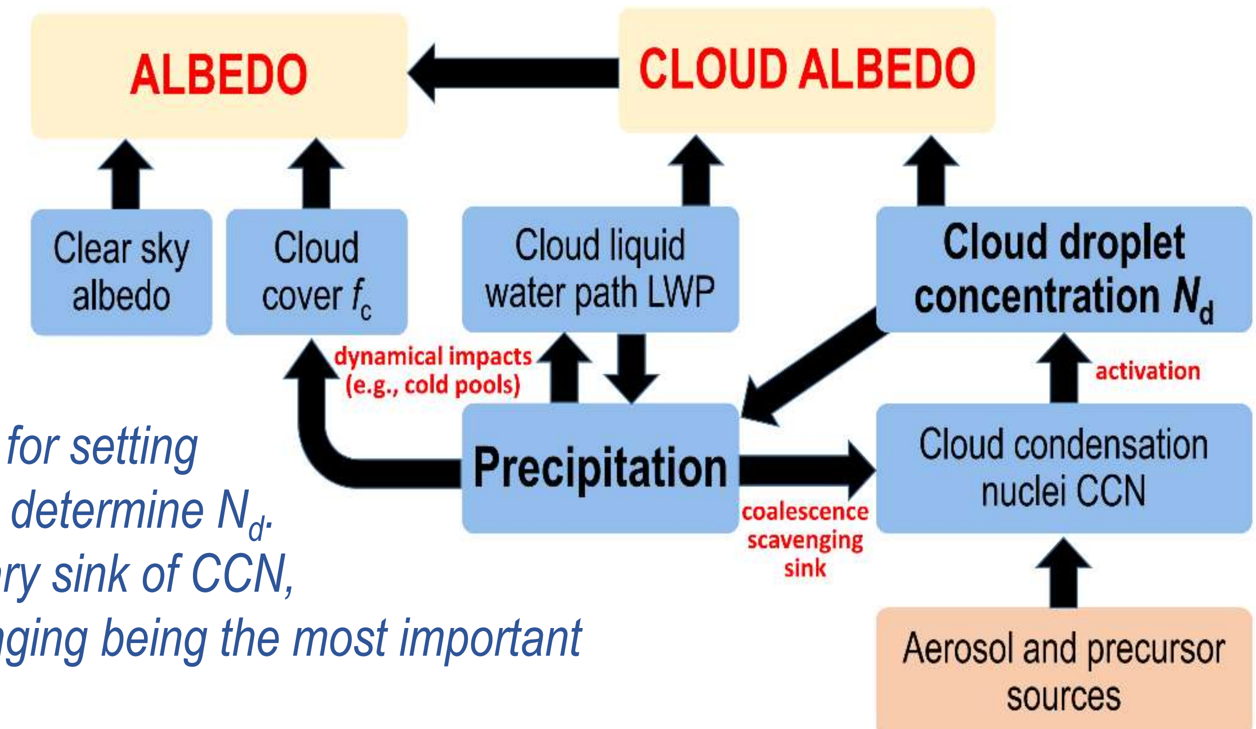


Photo: Jonathan Emmett, CSET RF07

Robert Wood,
University of Washington

Anders Engström
Frida Bender, Robert Charlson
Daniel McCoy, Rhea George

Pathways by which cloud droplet concentration and precipitation impact albedo



- *Aerosol sources are key for setting CCN concentrations that determine N_d.*
- *Precipitation is the primary sink of CCN, with coalescence scavenging being the most important process in low clouds.*
- *Precipitation also impacts cloud cover and condensate (f_c and LWP) through dynamical impacts and by affecting moisture and energy budgets.*
- *Thus precipitation regulates Earth's albedo through both macrophysical and microphysical pathways.*

Partitioning macrophysical and microphysical contributions to albedo

Contributions to albedo from cloud fraction (f_c), liquid water path (LWP) and cloud droplet concentration (N_d) to albedo α, partition into cloudy and clear sky albedo (α_{c} and α_{clr}) (Cess 1976, George and Wood 2010):

$$\alpha = \alpha_{\mathrm{c}} f_{\mathrm{c}} + \alpha_{\mathrm{clr}} (1 - f_{\mathrm{c}})$$

Clear sky albedo α_{clr} has contributions from molecular and aerosol scattering. Cloudy sky albedo α_{c} depends primarily upon cloud optical thickness τ and solar zenith angle θ_0:

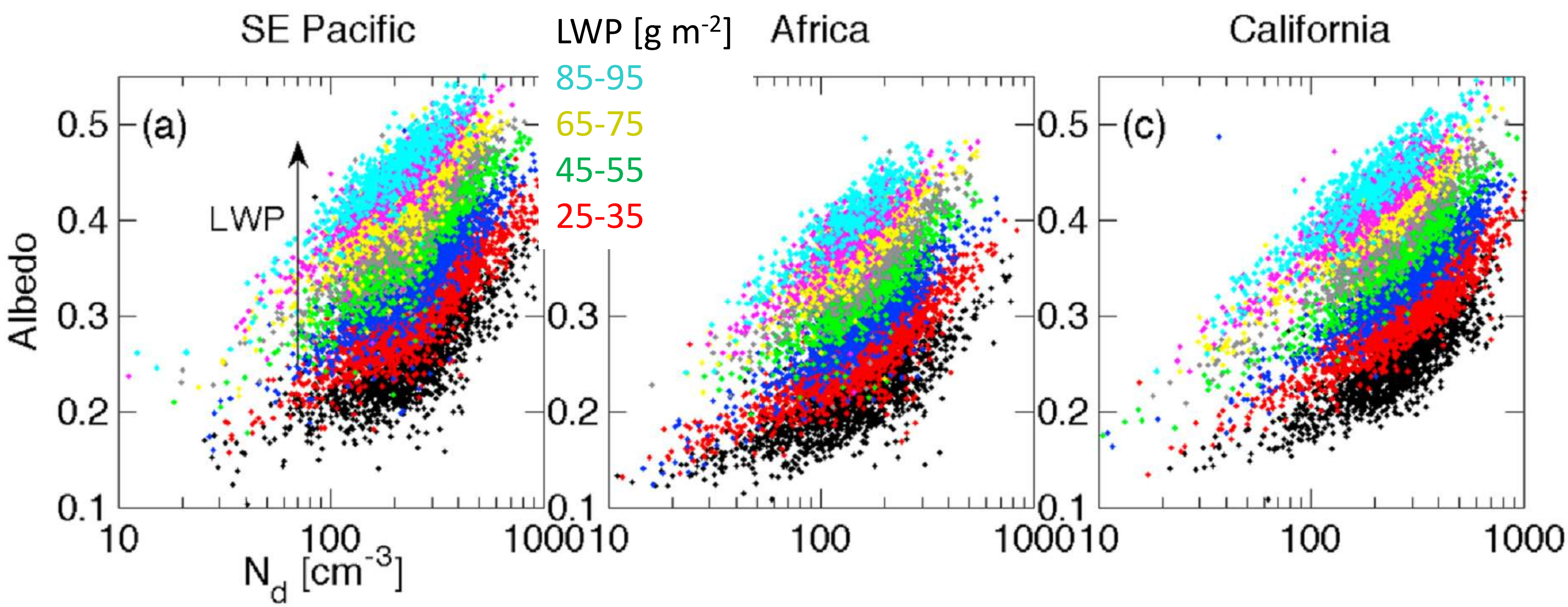
$$\alpha_{\mathrm{c}} = f(\tau, \theta_0)$$

Cloud optical thickness τ depends on both cloud macrophysical (LWP) and microphysical (N_d) contributions, the essence of Twomey's argument:

$$\tau \propto N_d^{1/3} LWP^{5/6}$$

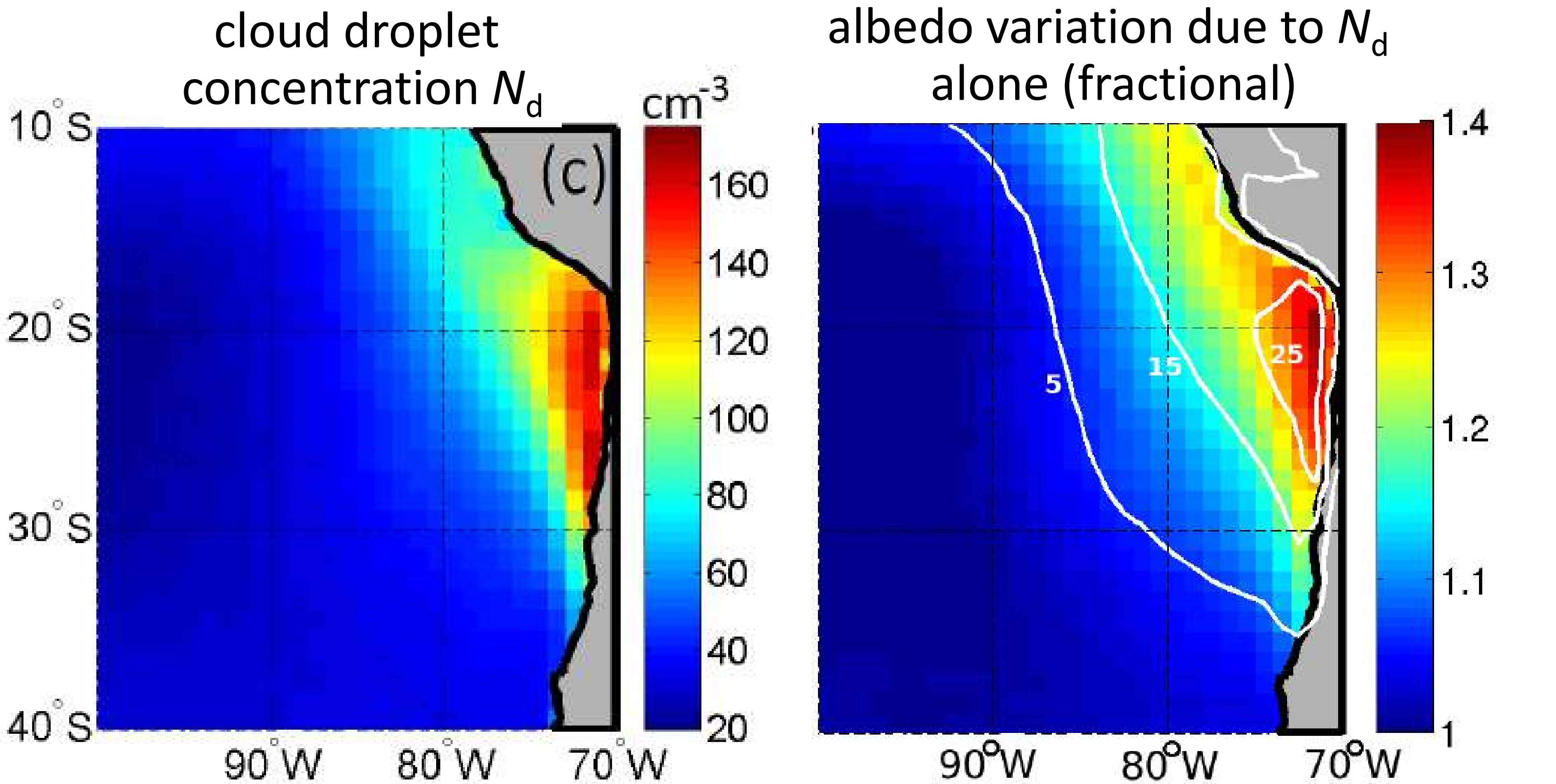
Demonstrating Twomey's theoretical prediction

- For cloudy pixels, and at fixed LWP, cloud albedo increases with cloud droplet concentration N_d



Painemal and Minnis, 2012: *J. Geophys. Res.*, **117**, doi:10.1029/2011JD017120.

Radiative impact of geographical variations in cloud droplet concentration



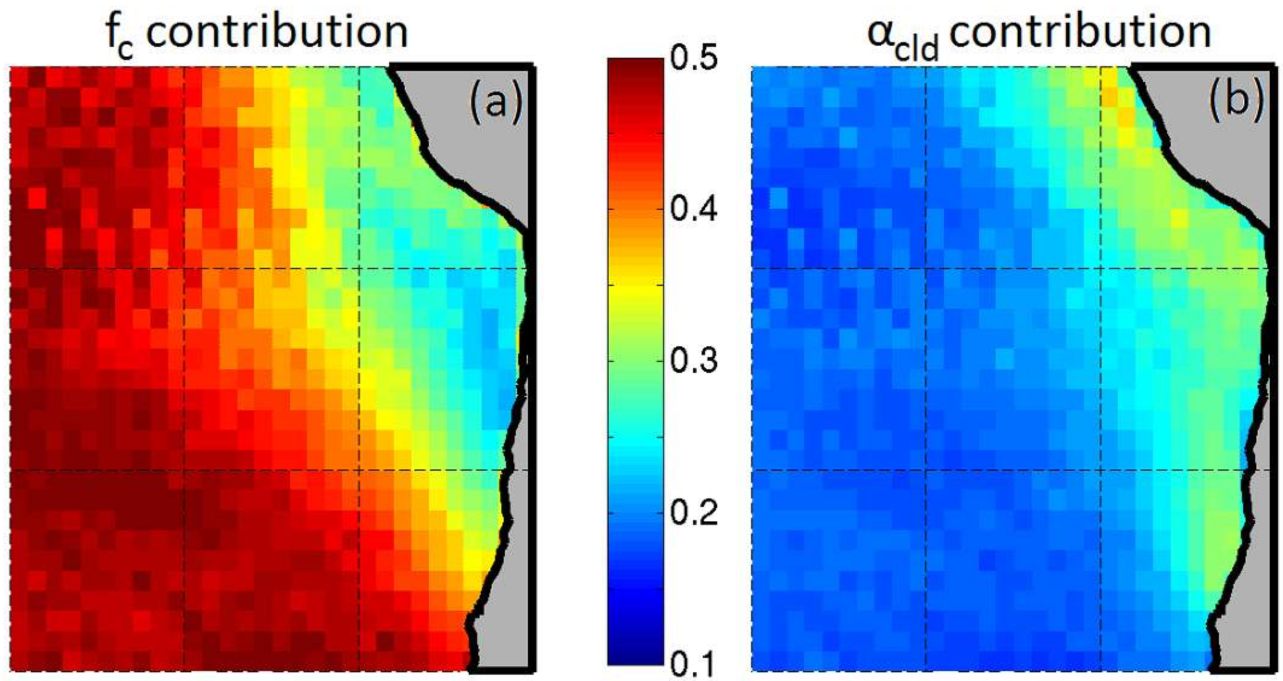
George and Wood, *Atmos. Chem. Phys.*, 2010

Cloud cover is dominant control on temporal albedo variability

$$\alpha = (\alpha_c - \alpha_{clr})f_c + \alpha_{clr}$$

- Construct albedo *proxy* using MODIS retrievals of f_c, LWP, N_d
- Clear sky albedo fixed at 0.11 to identify cloud contributions alone
- Spatial pattern of annual mean albedo agrees well with CERES (r=0.93)

Contribution to albedo variance from f_c (left) and α_{cld} (right) ▶

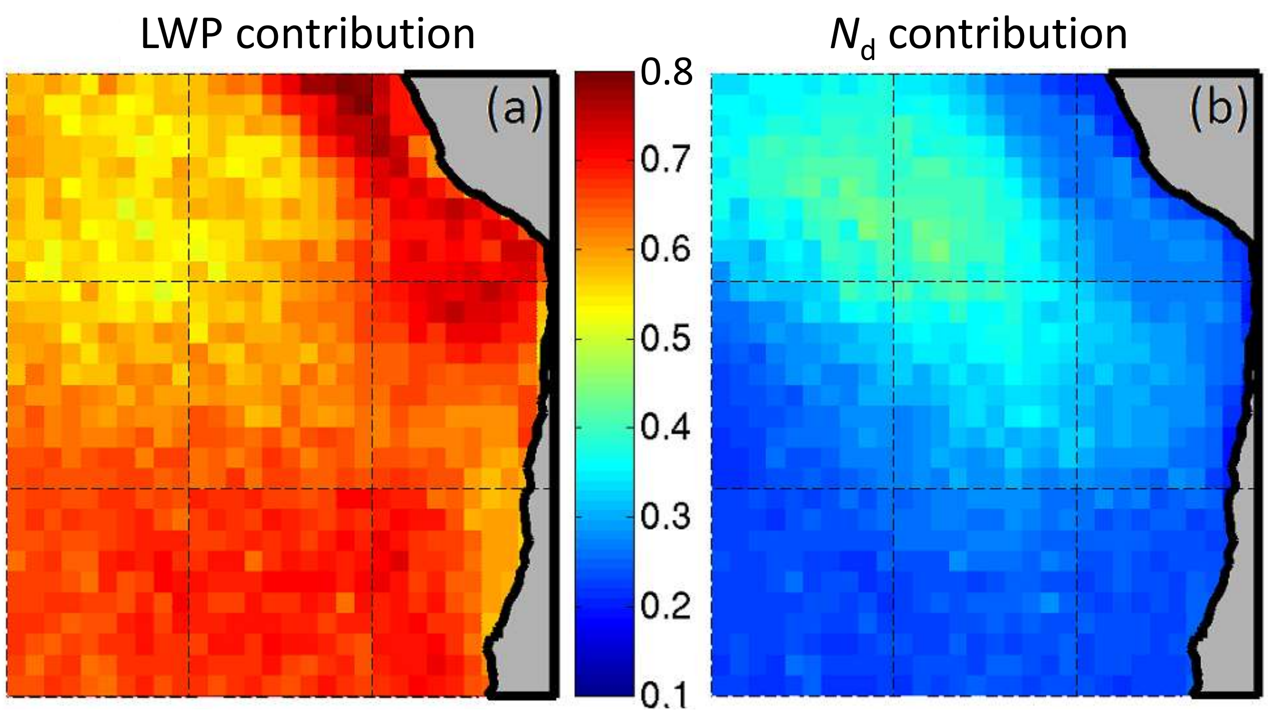


- Low cloud cover explains more albedo variance than does the albedo of the clouds that occur

George and Wood, *Atmos. Chem. Phys.*, 2010

…..microphysical contributions to temporal cloud albedo variance are typically small

Contribution to cloud albedo variance from liquid water path, LWP (left) and from cloud droplet concentration, N_d (right) ▶

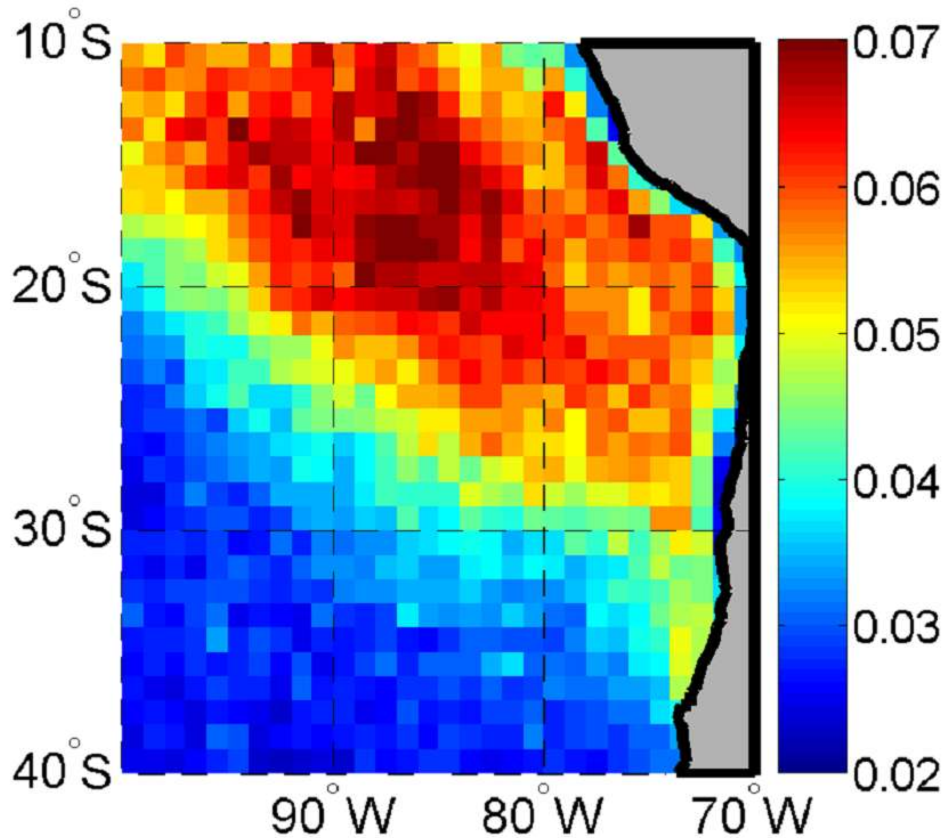


- Condensate variability (LWP) explains more albedo variance than does cloud droplet concentration……..

George and Wood, *Atmos. Chem. Phys.*, 2010

Contribution of N_d to overall albedo temporal variance

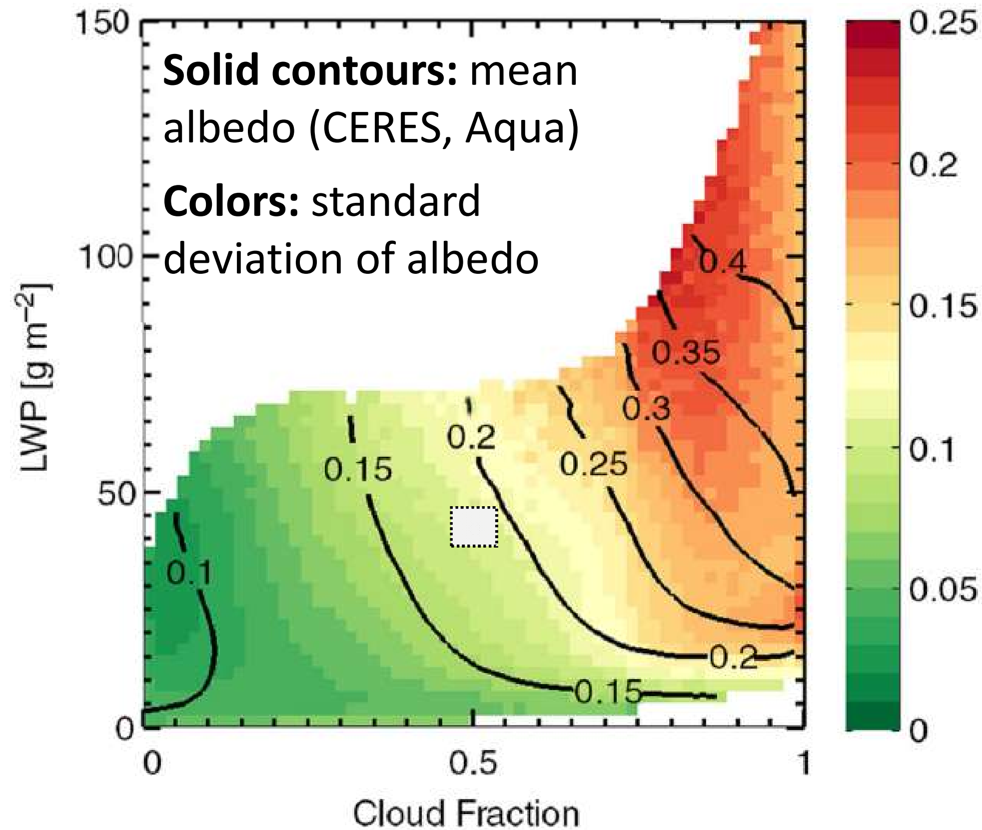
- N_d contribution to overall albedo temporal variance is small (2-7%)
- Highlights challenge in quantifying TOA SW impacts of aerosol-cloud interactions



George and Wood, *Atmos. Chem. Phys.*, 2010

Approach for isolating microphysical contributions to spatial albedo patterns in liquid clouds

- Liquid clouds only
- Mean albedo (CERES SSF, Aqua) as a function of cloud fraction f_c and LWP from instantaneous CERES-MODIS, at 1×1° aggregation
- First isolate dominant contributions from f_c and LWP

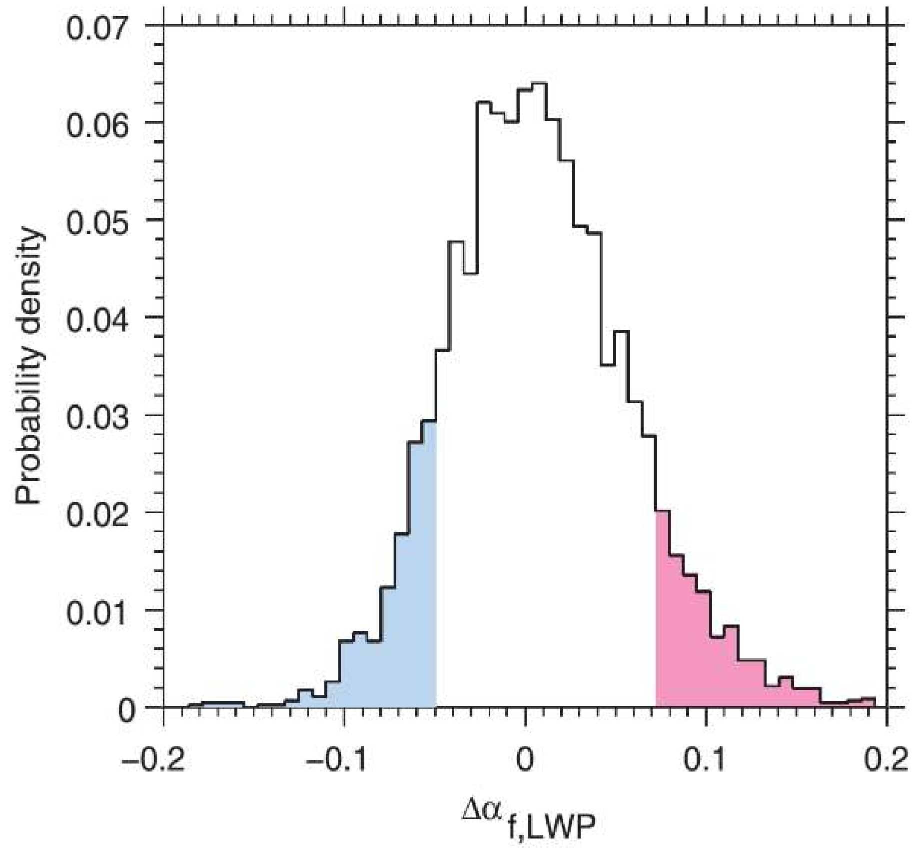


Engström, Anders, Frida A.-M. Bender, Robert J. Charlson, and Robert Wood. *Geographically Coherent Patterns of Albedo Enhancement and Suppression Associated with Aerosol Sources and Sinks*. *Tellus B*, **67**, doi:10.3402/tellusb.v67.26442.

Approach for isolating microphysical contributions to spatial albedo patterns in liquid clouds

- Plot pdf of instantaneous albedo deviations from mean for each point (bin) in f_c-LWP space
- Keep track of how frequently each location in real space falls into high albedo (pink) and low albedo (blue) tails
- Then, make map of frequency with which each location has high or low albedo for given f_c, LWP……

CERES uncertainties in TOA SW flux ~15 W m^{-2}



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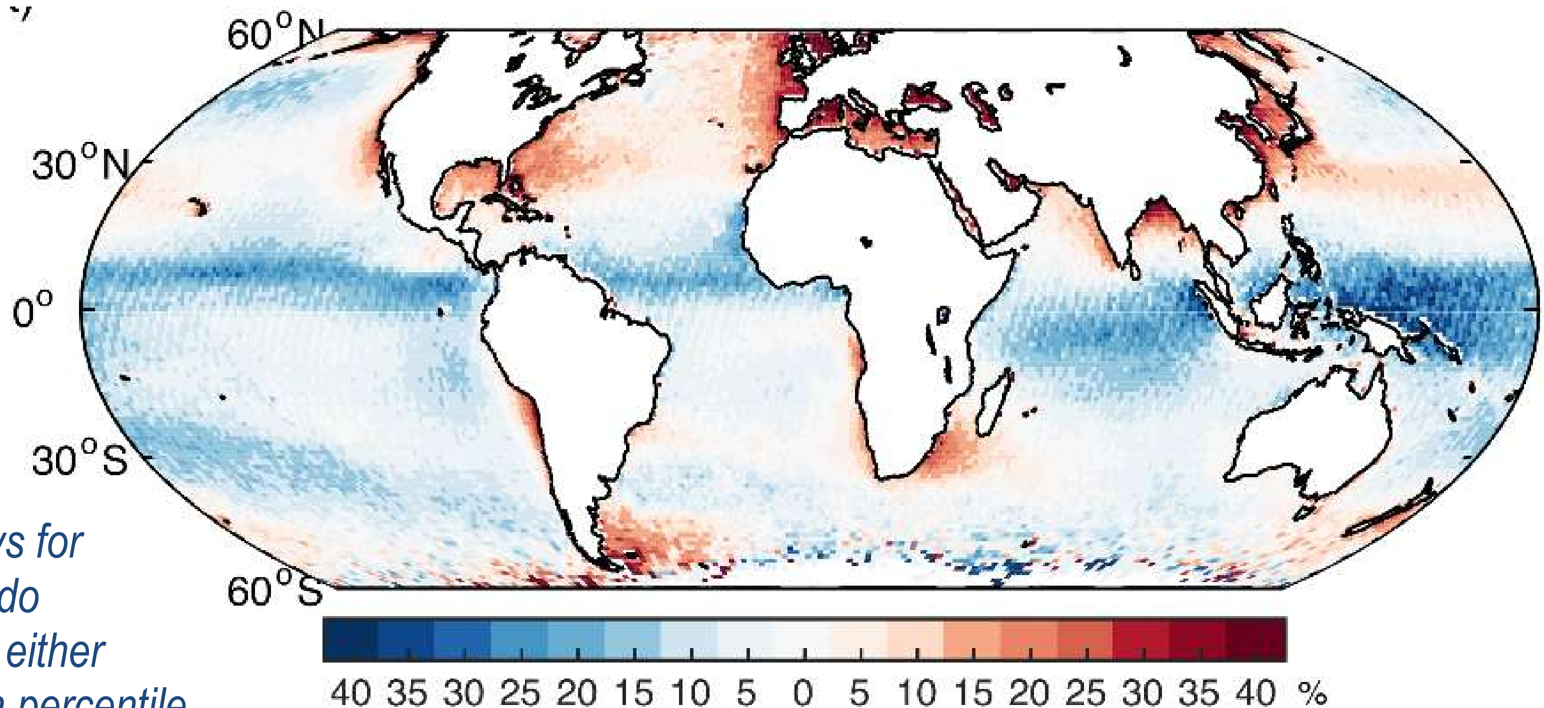
Map of frequency for which albedo is high (red) or low (blue) compared with mean for given f_c, LWP

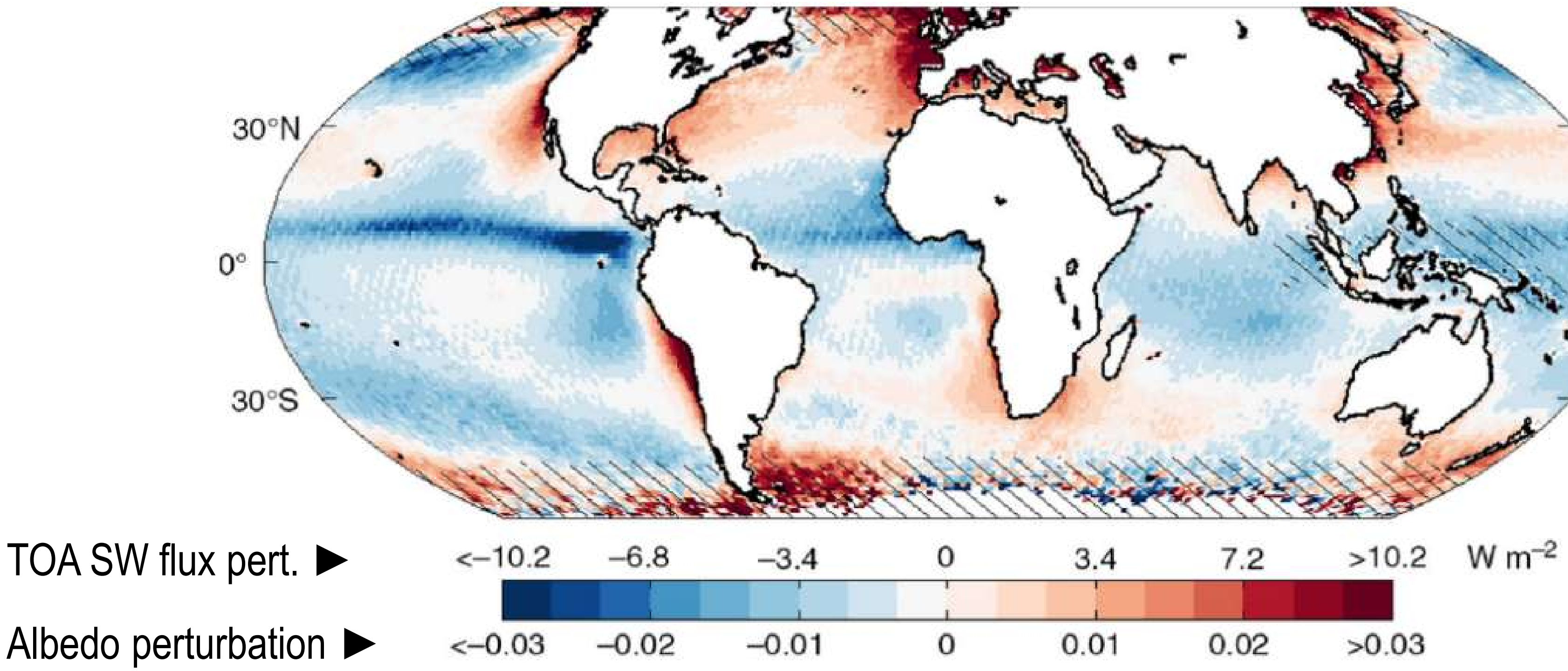


Fraction of days for which the albedo perturbation is either above the 90th percentile (red positive values) and below the 10th percentile (blue negative values) aggregating all f_c-LWP bins

- Patterns are geographically coherent, with some regions frequently showing relatively high or low albedo
- Contributions should be primarily from N_d

Geographically coherent patterns of albedo perturbations not associated with variability in f_c and LWP

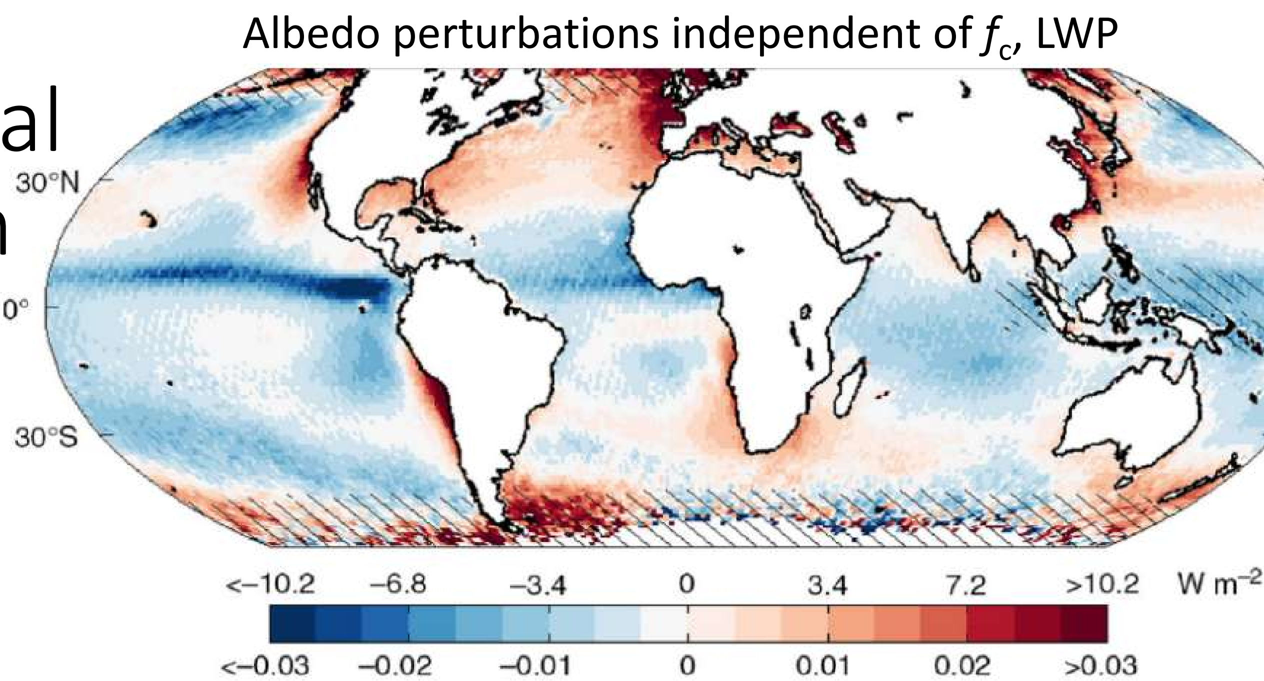
Regional variations of $\pm$ several W m^{-2} and up to $\pm$ 10 W m^{-2}

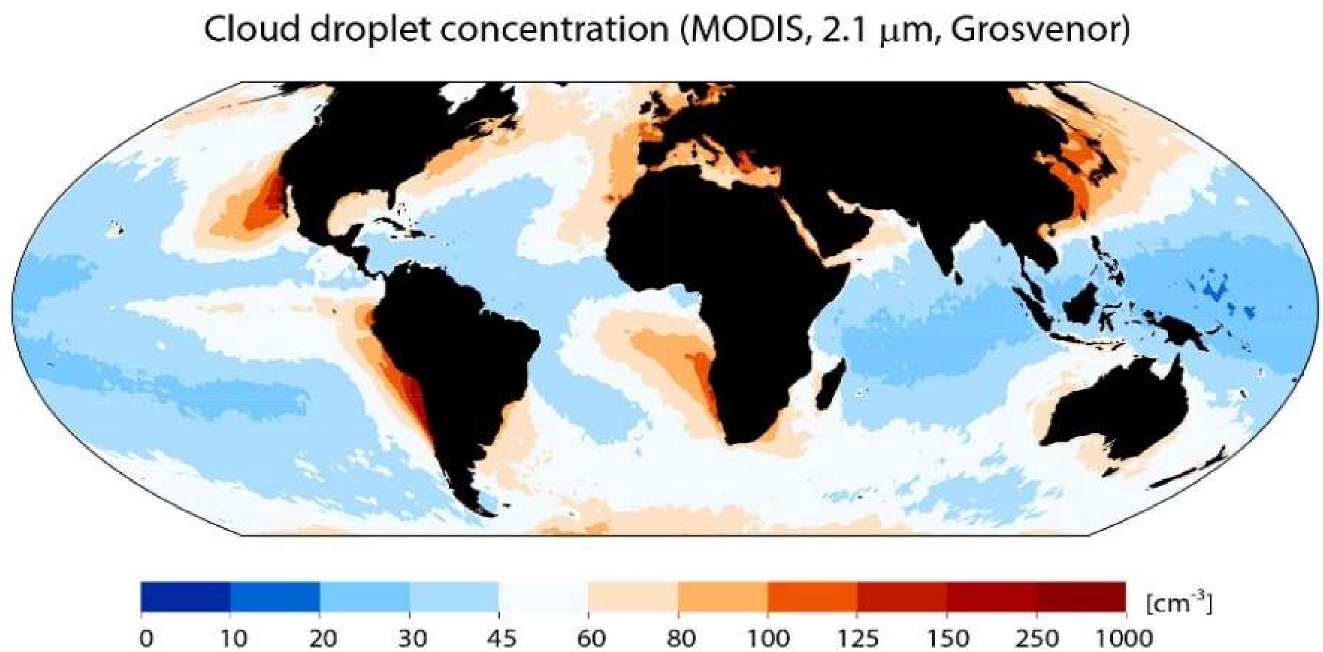


*Annual mean TOA shortwave/albedo perturbation (**fixed f_c,LWP albedo pdf anomalies mapped back to geographical space**) from CERES that is independent of f_c and LWP. Bar shows albedo units and equivalent reflected TOA SW flux. Hatched areas are regions with insufficient amounts of data.*

Microphysical contribution to albedo variability

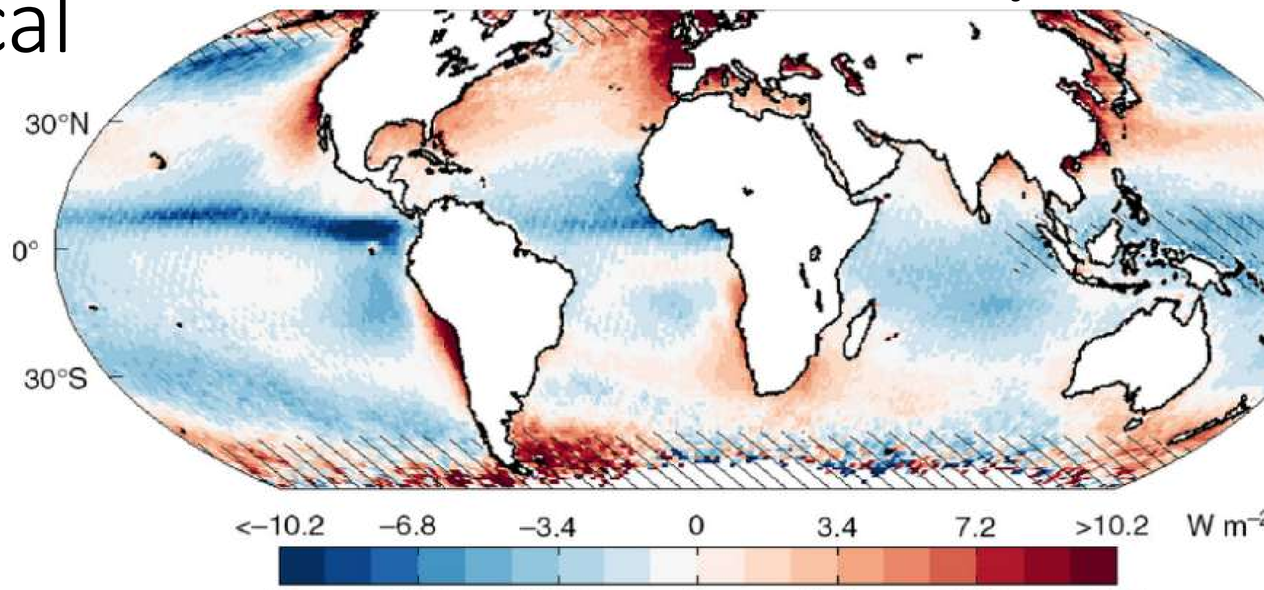
- Strong resemblance of high albedo regions to pattern of liquid cloud N_d from MODIS [Grosvenor and Wood 2014 correction to estimates from George and Wood 2010]





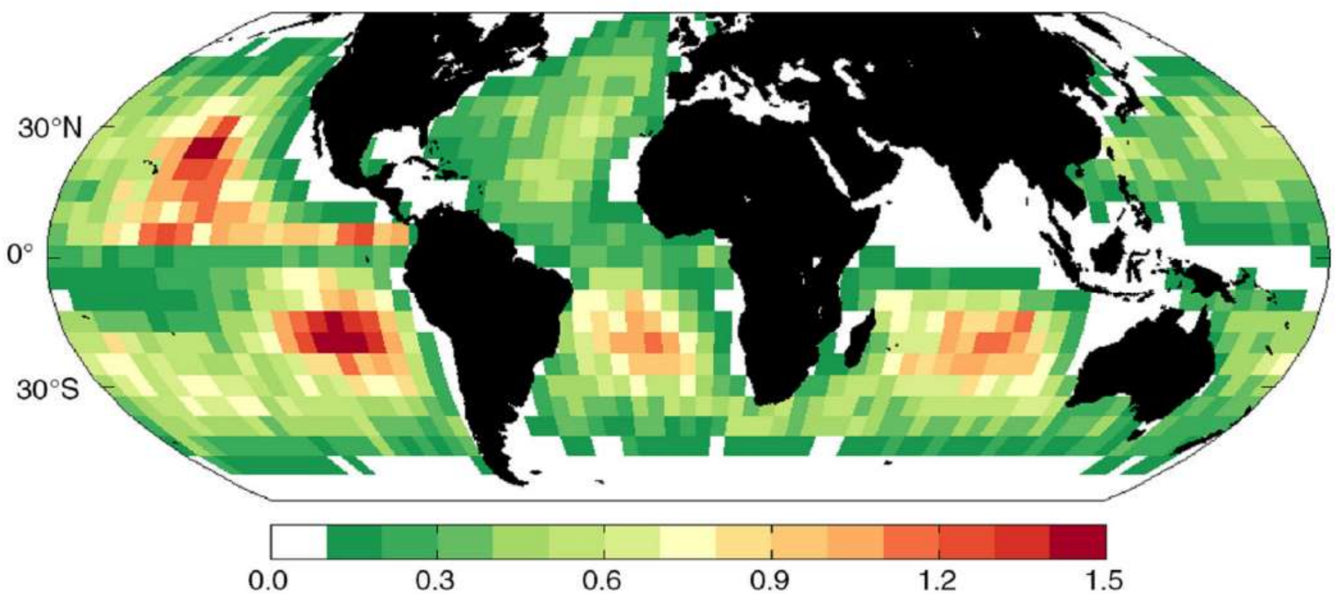
Microphysical impacts on albedo variability

Albedo perturbations independent of f_c, LWP



- Low albedo regions associated with more warm rain (main aerosol sink)

CloudSat precipitation rate from low clouds [mm d^{-1}]

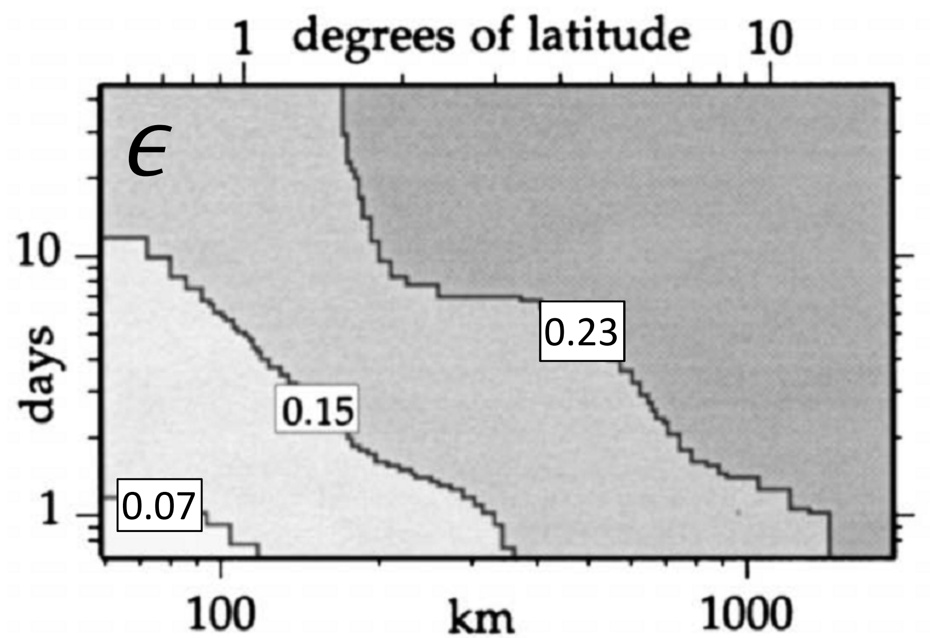


Can small scale variability in LWP possibly explain albedo variations?

- Albedo nonlinearly dependent on LWP (e.g., Cahalan et al. 1994)
- Can represent impact on albedo using scale-dependent heterogeneity parameter ϵ, such that effective mean optical depth $\hat{\tau}$ required to produce correct albedo is

$$\hat{\tau} = (1 - \epsilon)\overline{\tau}$$

- $\epsilon \sim 0.07$ for 1^{o} instantaneous, equivalent to τ errors of 7% and albedo errors of ~0.03-0.04
- Errors comparable to regional variability in albedo perturbations, so warrants further investigation



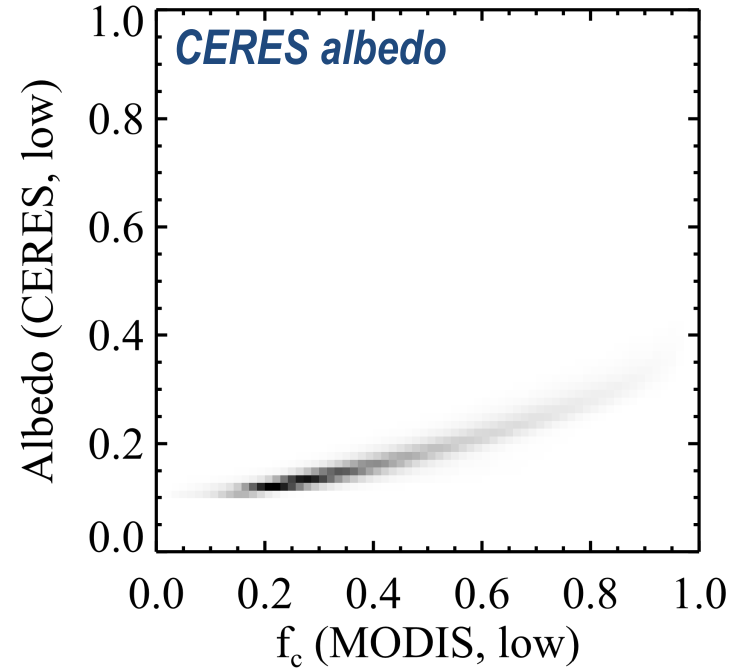
Rossow et al. (*J. Clim.*, 2002)

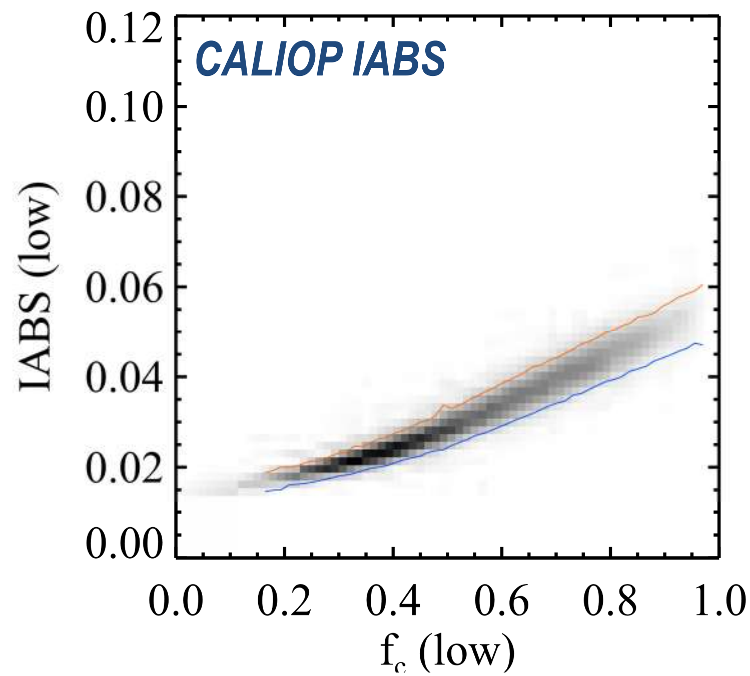
Conclusions

- Microphysical contributions to albedo spatiotemporal variability are often masked by dominant contributions from cloud cover and LWP
- Demonstrated methods to isolate albedo contributions by either using albedo proxy or by carefully removing contributions from cloud cover and LWP
- Coherent regional patterns of reflected SW variability independent of cloud cover and LWP appear largely driven by cloud droplet concentration, and reveals impacts of aerosol sources and precipitation sinks

CERES Albedo and CALIOP IABS *vs* low cloud fraction

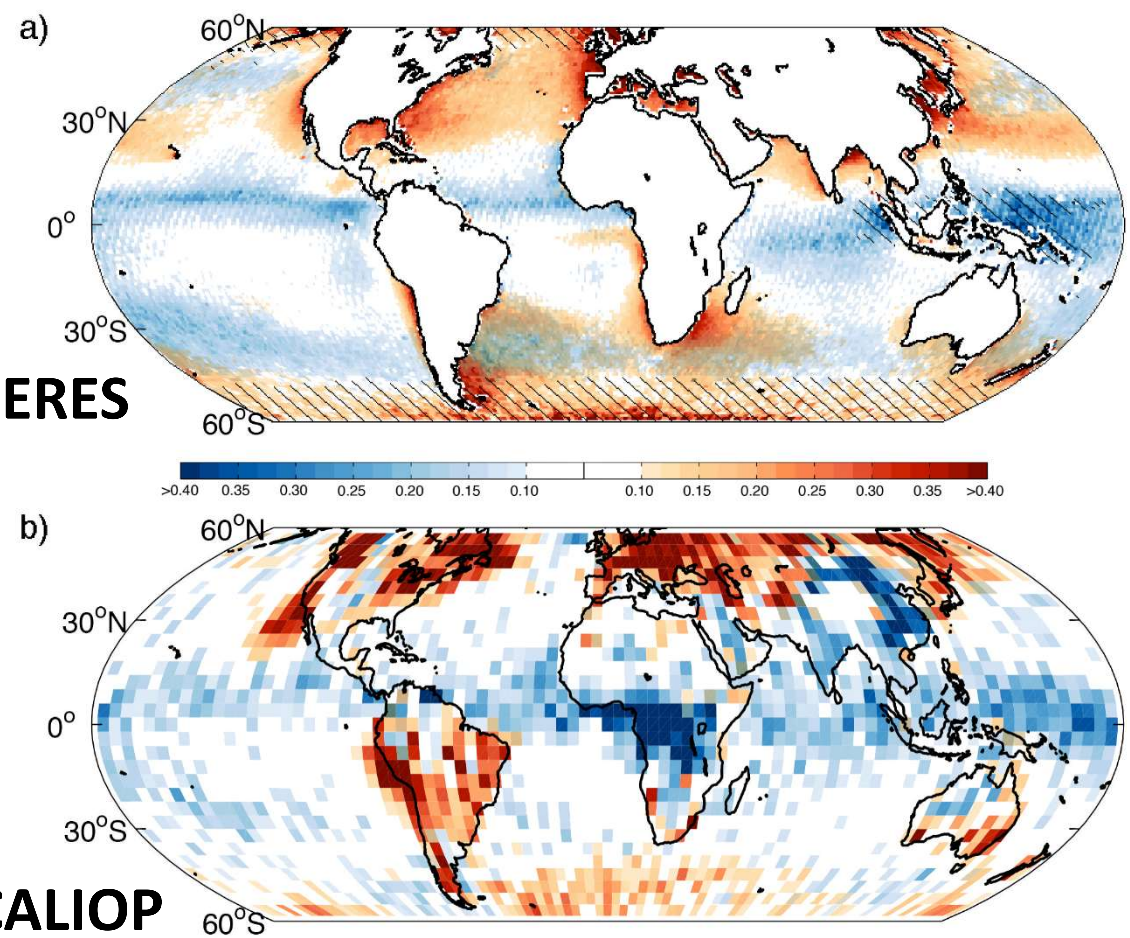
*Joint histograms of monthly mean **CERES albedo** (top) and **CALIOP IABS** (bottom) aggregated over 1x1° boxes (high clouds removed) vs low cloud fraction f_c*





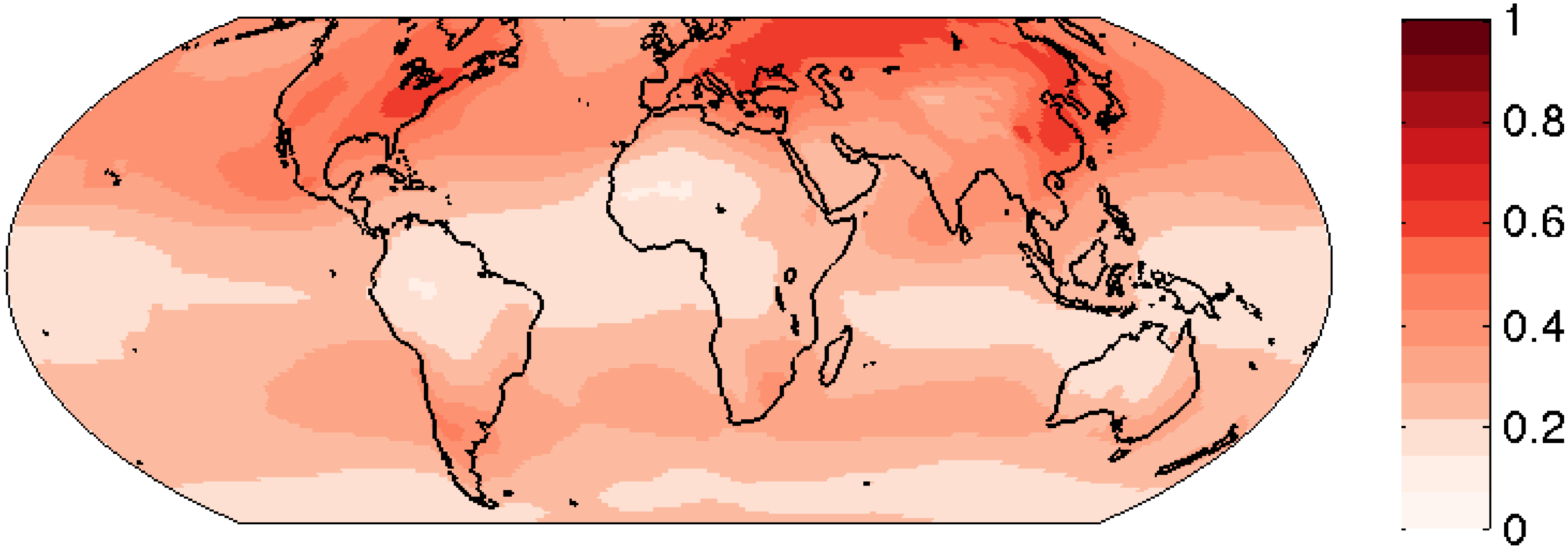
Using CALIOP Integrated Attenuated Backscatter (IABS) to extend to land areas

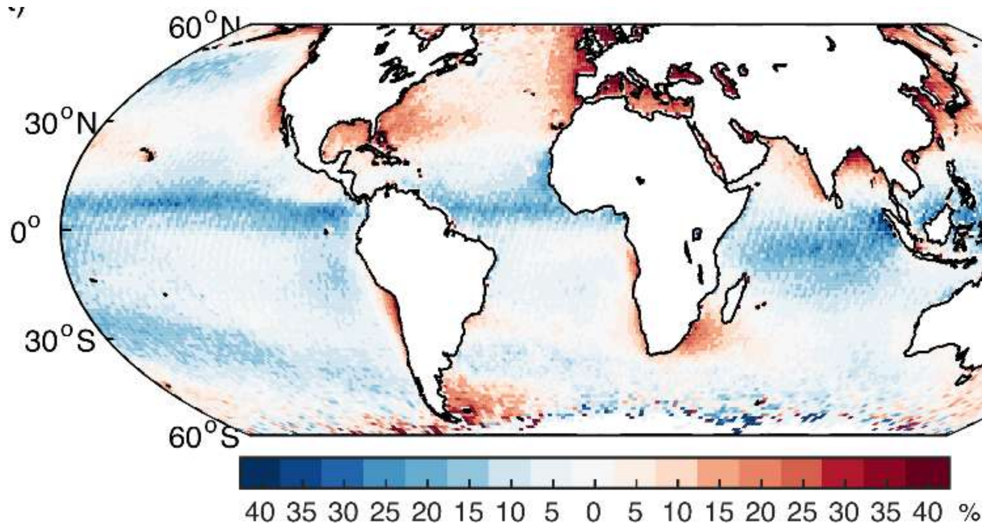
Fraction of days for which the CERES albedo perturbation (top) or CALIOP IABS (bottom) is either above the 90th percentile (red positive values) and below the 10th percentile (blue negative values) aggregating all f_c bins (no LWP screening) ▶

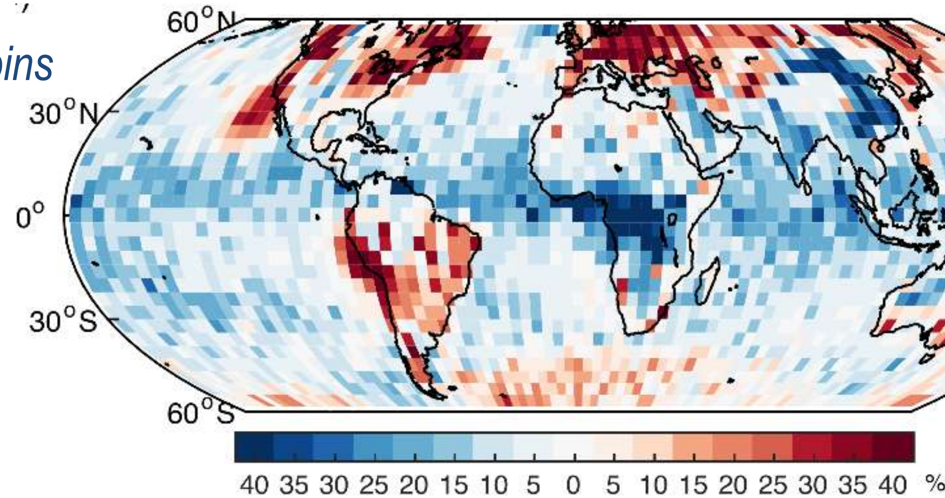


- Why are regions over land with strong combustion (e.g. central Africa, Eastern China, India) aerosol often showing negative albedo perturbations? Absorbing aerosols above clouds?

Anthropogenic fraction of aerosol optical depth







Fraction of days for which the albedo perturbation is either above the 90th percentile (red positive values) and below the 10th percentile (blue negative values) aggregating all f_c-LWP bins