Distinguishing Aerosol Effects from Meteorological Impacts on Low Cloud over the Global Ocean

(work in progress)

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Aerosol Effects on Low Clouds

Potential aerosol effects:
• Higher droplet concentration
• Reduced droplet radius
• Enhanced optical depth
• Greater cloud fraction

Challenging to assess at large scales due to complex interaction between microphysics, turbulence, and meteorology

Credit: NASA Earth Observatory
What’s New in this Presentation?

- Low cloud and radiative properties distinguished from upper cloud properties using Flux-by-Cloud-Type

- Actual changes in low cloud fraction distinguished from that due to changes in obscuration by upper clouds

- Meteorological impacts on low cloud distinguished from aerosol effects following method of *Scott et al.* (2020) and *Myers et al.* (2021)
Average cloud properties and radiation flux across all bins with pressure > 680 hPa

Low cloud SW = Low fraction \cdot SW_{low}

Contribution from cloudy-sky flux = Low fraction_{clim} \cdot (SW_{low})_{anom}

Contribution from cloud fraction = Low fraction_{anom} \cdot (SW_{low})_{clim}

Radiation flux is defined as positive upward!
Adjusting for Obscuration by Upper Clouds

Assume random overlap between low fraction and upper fraction

Actual low fraction = \( \frac{\text{FBCT low fraction}}{1 - \text{upper fraction}} \)

Scale radiation anomalies by climatological fraction not overlapped by upper cloud

Scaled low cloud SW = \( \text{low cloud SW}_{\text{anom}} \cdot (1 - \text{upper fraction})_{\text{clim}} \)
Distinguishing Meteorological Impacts from Aerosol

Approximate low cloud SW anomalies as response to variability in meteorological and aerosol conditions

\[ \Delta SW \approx \sum_i \frac{\partial SW}{\partial m_i} \Delta m_i + \frac{\partial SW}{\partial A} \Delta A \]

- Low cloud radiative response to variations in meteorological conditions \( m_i \)
- Low cloud radiative response to variations in aerosol conditions \( A \)

Apply multilinear regression using same predictors as Scott et al., Myers et al.: SST, EIS, near-surface temperature advection, \( \omega_{700}, RH_{700}, \) surface wind speed
How to Represent Aerosol?

• We want measurements of number concentration of CCN going into cloud
  ... but we have only measurements of scattering by aerosol outside of cloud

• Relative humidity increases aerosol particle size and scattering cross section
  ... use RH$_{850}$ and RH$_{925}$ as additional predictors to mitigate this effect

• MODIS AOD retrievals may be contaminated by cloud (e.g., Loeb and Manalo-Smith 2005, Zhang et al. 2005)
  ... use CALIPSO AOD from nighttime cloud-free columns
How Has Aerosol Changed since Pre-Industrial Times?

- Estimate as the ratio between the 2006-2020 AOD climatology and a “clean” ocean background value
  
  ... *Smirnov et al. (2002)* measurements suggest $AOD_{\text{clean}} = 0.07$
  
  ... *CALIPSO* AOD is around 0.04 over some areas of the ocean
Analysis Details

- All data are averaged to 5° × 5° monthly values and then deseasonalized.
- Long-term trends are removed from each anomaly time series to avoid artifacts.
- Meteorological and aerosol predictors are standardized to remove dimensionality.
- Spatial domain is ocean equatorward of 55° latitude.
- Use log(AOD) as aerosol predictor for sensitivity at low concentration.
Low Cloud SW Radiative Response Coefficients

$$\Delta SW \approx \sum_i \frac{\partial SW}{\partial m_i} \Delta m_i + \frac{\partial SW}{\partial A} \Delta A$$

SST Coefficient (CALIPSO)

Log AOD Coefficient (CALIPSO)
Low Cloud SW Radiative Response to Aerosol Change

\[
\frac{dSW}{dA} \Delta A
\]

Estimated change from pre-industrial conditions

Univariate 55°S–55°N ocean average:
+1.4 W m\(^{-2}\) change from pre-industrial

Multivariate 55°S–55°N ocean average:
+0.6 W m\(^{-2}\) change from pre-industrial
Cloudy-Sky and Cloud Fraction Radiative Contributions

**Cloudy-Sky Contribution (CALIPSO)**

+0.0 W m\(^{-2}\)

**Total Low Cloud SW (CALIPSO)**

+0.6 W m\(^{-2}\)

**Cloud Fraction Contribution (CALIPSO)**

+0.6 W m\(^{-2}\)
Interpreting the Cloudy-Sky Contribution

Cloudy-Sky Contribution (CALIPSO)

Not scaled by $(1 - \text{upper fraction})_{\text{clim}}$

Cloud Liquid Effective Radius (CALIPSO)

-0.1 micron

Micron Change from Pre-Industrial

Cloud Liquid Water Path (CALIPSO)

-0.4 g m$^{-2}$

g m$^{-2}$ Change from Pre-Industrial
Interpreting the Cloud Fraction Contribution

Cloud Fraction Contribution (CALIPSO)

+0.6 W m$^{-2}$

W m$^{-2}$ Change from Pre-Industrial

Cloud Fraction (CALIPSO)

+1.0 %-Amt

% -Amount Change from Pre-Industrial

Not scaled by $(1 - \text{upper fraction})_{\text{clim}}$
MODIS Cloudy-Sky and Cloud Fraction Contributions

AOD_{clean} = 0.07
Summary

• Low cloud SW response to CALIPSO AOD is approximately halved when co-variations with meteorology are taken into account.

• Low cloud SW response to CALIPSO AOD is almost entirely caused by changes in cloud fraction rather than cloudy-sky radiation flux.

• A very rough estimate suggests that changes in aerosol since pre-industrial times increased average oceanic low cloud SW reflection by 0.6 W m$^{-2}$.

• Results obtained using MODIS AOD are five times larger than results obtained using CALIPSO AOD.
Questions

• Is there a physical process by which aerosol would both reduce water content and increase the horizontal extent of low clouds?

• Are cloud effects more likely to influence CALIPSO AOD retrievals when clouds have lower LWP and greater horizontal extent?

• Is AOD (or extinction within an atmospheric layer) a poor measure of the aerosol that influences on low cloud?

• If a real and substantial aerosol effect were present, would it be larger than what is seen with CALIPSO AOD?
Conclusions

• Meteorology is likely to be not the only confounding factor in observational estimates of the low cloud SW response to aerosol

• Estimating the low cloud SW response to aerosol will require a careful approach to mitigate retrieval artifacts and sampling biases
Thank you!
Extra Slides
CALIPSO–MODIS Correlation

log(MODIS AOD) anomalies
log(CALIPSO AOD) anomalies
MODIS Climatology Ratio

Log(MODIS AOD Climatology / 0.07)
Standard Deviation of Anomalies

Std. Dev. of CALIPSO Log AOD Anomalies

Std. Dev. of MODIS Log AOD Anomalies
MODIS Cloud Fraction