Indirect aerosol forcing estimates over southeast and northeast Atlantic marine stratiform clouds

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Satellite estimates of indirect aerosol forcing are still uncertain – for stratocumulus cloud regime

1. Likely, due to the uncertainties in the strength of slopes of $N_d$ versus AOD and AI
2. Due to not accounting co-variations in large-scale meteorology
Objectives

At a higher resolution of 25kmx25km

1. To evaluate the strength of slopes of $N_d$ versus AI and cloud properties

1. To study the dependency of these slopes on large-scale meteorology

2. To estimate Aerosol indirect forcing - Intrinsic (cloud albedo effect) and extrinsic (cloud lifetime effect) terms
### Data and Methodology

- MODIS Aqua C6.1 L2 cloud and aerosol products & OMI-ACA retrieval
- AMSR-2 V8 LWP, SST, and rain rate
- CERES Aqua TOA radiation measurements
- MODIS and CERES data are collocated onto 25km AMSR-2 grid within the time difference of 15 minutes
- MERRA-2 meteorology and aerosol analysis data

**Study period**: 06/2015 – 05/2018

- Single layer liquid clouds with ice-free pixels, $\text{CTT}>273K$ and $\omega_{700}>0$
- Cloud droplet concentration ($N_d$) is computed following Bennartz and Rausch (2017) using $r_e$ at 3.7 $\mu$m and Quaas et al. (2008) using $r_e$ at 2.1 $\mu$m.
- Anthropogenic fraction calculated following Bellouin et al. (2013)
- Aerosol indirect forcing is computed following Chen et al. 2014
- Analyzed 25km grid-boxes with LCF>10% and rain rate=0.
Cloud and Aerosol Properties – June - Nov 2015-2018

- Southeast Atlantic Sc – Smoke plume
- Northeast Atlantic Sc – Desert dust
Southeast Atlantic Stratocumulus (smoke)

OLS slopes of $\ln(N_d)$ versus Cloud and Aerosol parameters

- LWP, CER – Negative slope
- COT, cl-albedo, LCF – Positive slope
- AOD, AI – Positive slope
Bayesian and ODR slopes are steeper than OLS.
Large-scale meteorology and surface fluxes – Jun - Nov 2015-2018

- Cloud amount increase – Cooler SST, increased SLP, SWS, LHF, cooler SST-adv, stronger EIS and w700, drier and warm FT (RH700, T700)
- LWP increase – moist FT RH700
Slopes of $\ln(N_d)$ vs. cloud and aerosol parameters
Dependency on AMSR-2 LWP and MODIS LCF

- The relationships are strongest at overcast condition, and increased with increasing LWP

5.2.2019
Slopes of $\ln(N_d)$ vs. cloud and aerosol parameters
Dependency on CTH and cloud depth

- The negative LWP and CER slopes are steepest when the clouds are thicker and below 1km.
- Similarly, positive LCF, COT, cl-albedo slopes are steepest.
- AOD slopes are steeper either when the clouds are thicker or at higher top height.
Slopes of ln($N_d$) vs. cloud and aerosol parameters
Dependency on RH700 and $\omega_{700}$

<table>
<thead>
<tr>
<th>$\omega_{700}$ (hPa/s)</th>
<th>ln(Nd) vs. MODIS LWP</th>
<th>ln(Nd) vs. AMSR-2 LWP</th>
<th>ln(Nd) vs. MODIS COT</th>
<th>ln(Nd) vs. MODIS CER</th>
<th>ln(Nd) vs. CERES cl-d-albedo</th>
<th>ln(Nd) vs. MODIS LCF</th>
<th>ln(Nd) vs. MODIS ln(AOD)</th>
<th>ln(Nd) vs. MERRA-2 ln(AOD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-16 -6 -15 59</td>
<td>-51 -119 -99 179</td>
<td>0.4 1.4 0.7 9.1</td>
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<td>4.4 -1.0 0.8 30.7</td>
<td>13 32 18 76</td>
<td>0.15 0.03 0.09 0.56</td>
<td>0.15 -0.42 -0.23 0.59</td>
</tr>
<tr>
<td>0.2</td>
<td>-19 -17 -11 -3</td>
<td>-31 -27 -25 -22</td>
<td>0.5 0.5 1.1 1.6</td>
<td>-5.2 -5.3 -5.2 -4.9</td>
<td>3.9 3.9 4.0 4.4</td>
<td>16 17 19 20</td>
<td>0.22 0.14 0.08 0.02</td>
<td>0.26 0.12 0.05 -0.01</td>
</tr>
</tbody>
</table>

- $N_d$ versus AOD slopes are steeper for stronger subsidence regime, especially at warmer SST and moist Free-troposphere.
- Similar results obtained for cloud properties as well, except that $N_d$ versus CER and LCF slopes are steepest at cooler SST.
Intrinsic Forcing or cloud albedo effect is estimated as

\[ \Delta a \cdot \bar{C}_m \cdot \left( \frac{dA_{clr}}{d\ln(AI)} - \frac{dA_{cld}}{d\ln(AI)} \right) \cdot F^\downarrow \]

Extrinsic Forcing or cloud lifetime effect is estimated as

\[ \Delta a \cdot (A_{clr} - A_{cld}) \cdot \frac{dC_f}{d\ln(AI)} \cdot F^\downarrow \]

A is albedo
F^\downarrow is incoming shortwave radiation
C_f is cloud fraction

as in Chen et al. 2014
MERRA-2 Aerosol classifications following Bellouin et al. 2013


Anthropogenic – 31%
Marine – 53%
Dust – 16%
Forcing estimates (Jun – Nov 2015-2018)

Anthropogenic

Cloud albedo

Cloud lifetime effect

Dust

Cloud albedo

Cloud lifetime effect

Episodic Smoke and Dust regime $\rightarrow$ Large positive forcing estimates
Less polluted Sc regime $\rightarrow$ Large negative forcing estimates
**Summary**

- $N_d$ versus AI slopes are steeper at a higher resolution satellite measurements.

- Also, advanced fitting methods that consider uncertainty in both X and Y axis are recommended over OLS fitting to compute slope.

- Compute aerosol indirect forcing based on slopes from advanced regression methods.

- Include the effect of meteorology into the forcing computation.
Slopes of $\ln(N_d)$ versus Cloud and Aerosol Products – 2015-2018
Northeast Atlantic Stratocumulus (dust)

OLS slopes of $\ln(N_d)$ with cloud and aerosol parameters
Northeast Atlantic Stratocumulus (less dust)

OLS slopes of $\ln(N_d)$ with cloud and aerosol parameters
Southeast Atlantic Stratocumulus (smoke)
OLS, Bayesian, Orthogonal Distance Regression ODR slopes of ln(N_d) with cloud and aerosol parameters
Northeast Atlantic Stratocumulus (dust)

OLS, Bayesian, ODR slopes of $\ln(N_d)$ with cloud and aerosol parameters
Northeast Atlantic Stratocumulus (less dust)
OLS, Bayesian, ODR slopes of $\ln(N_d)$ with cloud and aerosol parameters
The negative LWP and CER slopes are steepest when the clouds are thicker and below 1km.
Similarly, positive LCF, COT, cl-albedo slopes are steepest.
AOD slopes does not show any dependency on SST-advection or EIS.
MERRA-2 Aerosol classifications following Bellouin et al. 2013

Dec – May (2015-2018)

Anthropogenic – 26%
Marine – 56%
Dust – 18%


Anthropogenic – 31%
Marine – 53%
Dust – 16%
SEA Sc regime → Large negative forcing estimates with means of about -2.45 W/m² and -2.97 W/m² respectively for cloud albedo and cloud lifetime effect.

NEA dust domain indicates a large positive forcing