Influence of convection and aerosol pollution on ice cloud particle effective radius

Jonathan H. Jiang[1], Hui Su[1], C. Zhai[1], Steven Massie[2], Mark Schoeberl[3], P. Colarco[3], S. Platnick[3], Y. Gu[4], K-N. Liou[4]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; [2]National Center for Atmospheric Research, Boulder, CO;
[3]Retired; Goddard Space Flight Center, Greenbelt, [4]MA, University of California, Los Angeles, CA

Abstract

Satellite observations show that ice cloud effective radius (re) increases with ice water content (IWC) but decreases with aerosol optical thickness (AOT). Using least-squares fitting to the observed data, we obtain an analytical formula to describe the variations of re with IWC and AOT for several regions with distinct characteristics of re-IWC-AOT relationships. As IWC directly relates to convective strength and AOT represents aerosol loading, our empirical formula provides a means to quantify the relative roles of dynamics and aerosols in controlling re in different geographical regions, and to establish a framework for parameterization of aerosol effects on re in climate models. .

MLS 215 hPa IWC as a Convective Index (CONV)

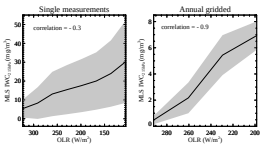

Figure 1: Left column: The black curve is the MLS measured IWC at 215 hPa binned as a function of collocated GEOS-5 OLR. All single MLS IWC measurements between August 2004 and July 2008 in the tropical region (30°S-30°N) are used. The GEOS-5 data are sampled onto the MLS footprints. The standard deviations of the data are indicated by the gray shaded area. Right column: Same as left column except for gridded (8°longitude by 4° degree latitude) data averaged for the 4 years.

Define the convective index (CONV) as

$$\mathrm{CONV}_i = \mathrm{IWC}_i / \overline{\mathrm{IWC}} \qquad (1)$$

where IWCi represents each single MLS 215 hPa IWC measurement and $\overline{\mathrm{IWC}}$ is the mean of all the 215 hPa IWC samples.

Dependence of Ice Cloud Effective Radii (r_e) on CONV and Aerosol Optical Thickness (AOT)

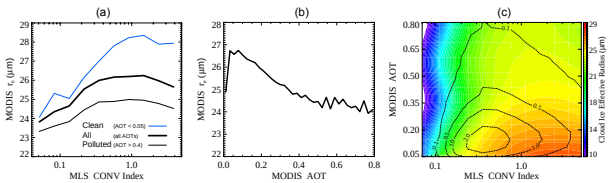

Figure 2: (a): MODIS measured ice cloud re binned according to CONV, based on MLS IWC at 215 hPa. The thick black curve is the average re as a function of CONV using all values of AOT. The blue curve is for data with AOT < 0.05 and the thin black curve is for data in heavily polluted environment with AOT > 0.4. (b): MODIS re binned according to the MODIS AOT measurements. (c): A Bi-Variate Composite (BVC) plot of the re-CONV-AOT relation, in which the MODIS re data are binned according to both MLS IWC and MODIS AOT. All collocated MODIS and MLS measurements from August 2004 to July 2008 between 50□S to 50□N are used for the plot.

Empirical Fitting of Observed Data

Assume that the dependence of r_e on CONV and AOT is decoupled, i.e., $r_e = r_{aot} \cdot r_{conv}$, where r_{conv} denotes how cloud particle effective radius changes with CONV and r_{aot} represents the effect of aerosols on r_e. We write,

$$r_{conv} = [1 - \exp(-\mathrm{CONV}/\alpha)] \cdot \exp(-\beta \mathrm{CONV}) \qquad (2)$$

where α and β are the parameters that control how fast r_e changes with CONV. The reduction of r_e by aerosol effect is assumed to follow a power-law:

$$r_{aot} = \varepsilon \cdot \mathrm{AOT}^{\eta} \qquad (3)$$

where η is a parameter that determines how strong the aerosol effect is, and ε is a scaling constant. A super-position of equations (2) and (3) yields

$$r_e = \varepsilon \cdot \mathrm{AOT}^{\eta} \cdot [1 - \exp(-\mathrm{CONV}/\alpha)] \cdot \exp(-\beta \mathrm{CONV}) \qquad (4)$$

We then use least-squares fitting to the observed data with the empirical formula (4), i.e., to determine the parameters α, β, η, and ε, through minimizing the following cost function

$$\underset{\alpha,\beta,\eta,\varepsilon}{\mathrm{cost}} = \sum_i \left[r_e^i - r_e(\mathrm{CONV}^i, \mathrm{AOT}^i, \alpha, \beta, \eta, \varepsilon) \right]^2 \qquad (5)$$

where r_e^i (in μm) and AOT^i represent the ith sample of the observed r_e and AOT data, respectively, and CONV^i is computed from observed IWC (equation 1).

The least-square fittings are computed by using four years of MLS IWC and MODIS r_e and AOT measurements. The results of the fitted parameters for different regions are given in Table 1.

Region \ Fitted Parameter	α	β	η	ε	χ^2/DOF
Global	0.133	0.00543	-0.0661	24.039	0.6
South America	0.183	0.00308	-0.0632	23.795	1.2
Southern Africa	0.201	0.00716	-0.0740	22.684	1.3
Northern Africa	0.259	0.00678	-0.0589	23.703	1.6
South Asia	0.230	0.0258	-0.0838	25.919	3.6
East Asia	0.144	0.0172	-0.0426	24.709	6.9

Table 1: Values of the empirical fitting parameters in equation (4) for various regions. The least-square fits are computed using IWC (mg/m3) measured by MLS, and re (μm) and AOT measured by MODIS from August 2004 to July 2008. The convergence of each fit is indicated by χ^2/DOF.

The least-square fittings are computed by using four years of MLS IWC and MODIS r_e and AOT measurements for the following five regions: Global (LON: 0°-360°; LAT: 50°S-50°N); South America (LON: 270°-340°; LAT: 40°S-10°N); Southern Africa (LON: 0°-55°; LAT: 35°S-0°); Northern Africa (LON: -10°-45°; LAT: 0°S-25°N); South Asia (LON: 70°-120°; LAT: 10°S-15°N); and East Asia (LON: 90°-180°; LAT: 20°-45°N). These five polluted regions are picked based on the different regimes of surface emission or dynamics [*Jiang et al.* 2009].

Polluted Clouds

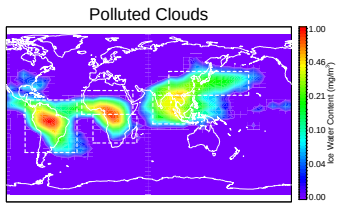

Figure 3: Map of polluted ice clouds at 215hPa indicated by high in-cloud CO amount.]

Results

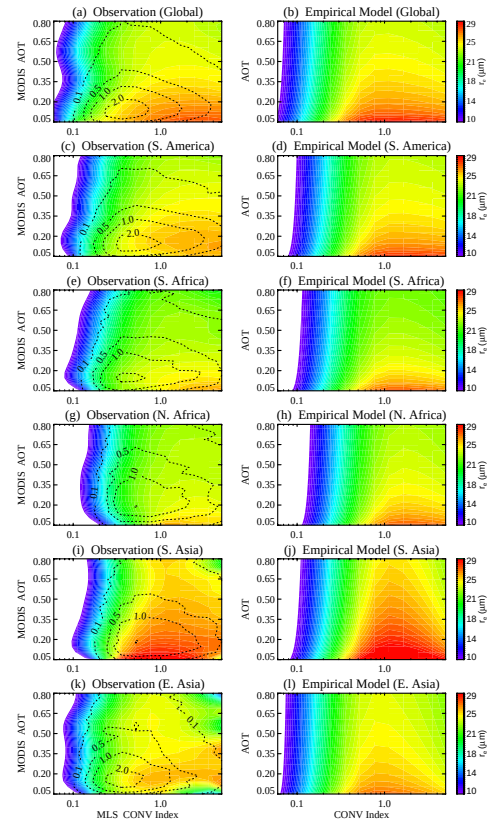

Figure 4: Left column: Observed re as a function of CONV and AOT in various regions. Right column: Computed re as a function of CONV and AOT based on the empirical models for each region.

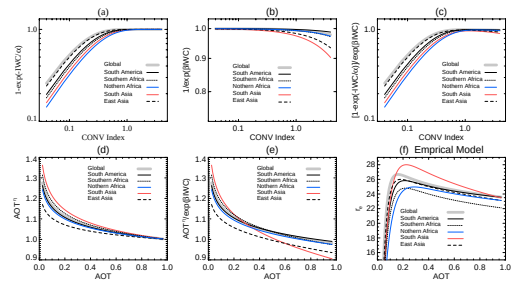

Figure 5: (a)-(e): Plots showing how each term (or the combination of two terms) of the empirical models governs re in various regions. (f): The modeled re as a function of AOT for each region.

Summary

- The empirical formula approximately captures the observed relationships among r_e, CONV and AOT, the best fits are in the regions of Global, South America and Southern Africa;
- South Asia and Northern Africa exhibit strong increases of r_e with CONV;
- South and East Asia approach the saturation effect of r_e with CONV quite quickly;
- South Asia region has the greatest reduction of re by unit AOT, with the rate of reduction coefficient is about twice of that in East Asia and 30% higher than the global average.
- The empirical fitting converges relatively poorer in South and East Asia than other regions, suggesting the complexity of aerosol-cloud interactions there.

The empirical model represents our first attempt to derive an analytical formula that captures aerosol effects on ice cloud particle size. The approach demonstrates a framework to use satellite data to quantify the first indirect effect of aerosol on ice clouds for use in climate models.

References

Jiang, J.H., H. Su, S.T. Massie, P.R. Colarco, M.R. Schoeberl, and S. Platnick, "Aerosol-CO relationship and aerosol effect on Ice cloud particle size: Analyses from Aura Microwave Limb Sounder and Aqua Moderate Resolution Imaging Spectroradiometer observations," *J. Geophys. Res.* 114, D20207, doi:10.1029/2009JD012421, 2009.

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