Explaining and reducing the uncertainties in the first aerosol indirect effect

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INTRODUCTION Anthropogenic aerosols enhance cloud reflectance of solar radiation by increasing the cloud droplet number concentrations. This so-called first Aerosol Indirect Effect (AIE) has a potentially large cooling tendency on our planet. However, discrepancies of more than a factor of 2 have been reported among observations[1] as well as model simulations[2] of the AIE. Our recent study[3] shows that the discrepancies will be reduced greatly if the entrainment-mixing evaporation of cloud drops is taken into account.

DISCREPANCIES

Fig.1 A disagreement between the responses of cloud drop number concentration (N_c) and cloud effective radius (r_e) to the change in the aerosol loading.

On average:

$$\frac{\Delta \ln r_e}{\Delta \ln N_a} \neq \frac{1}{3}\frac{\Delta \ln N_c}{\Delta \ln N_a}$$

Method2 Method1

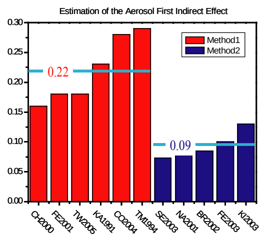

Fig.2 A disparity between estimates based on "forward" calculations in which the empirical relationships between aerosol and cloud drop concentrations are used to calculate radiative forcings and "inverse" calculations in which the aerosol forcing is required to match global climate model simulations with observed temperature changes[2].

Forward calc.

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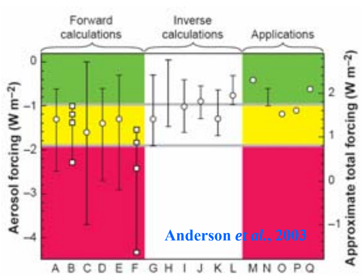
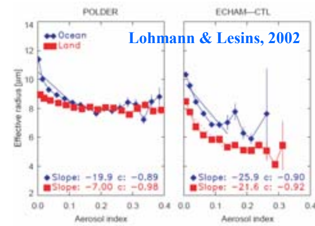
Inverse calc.



Discrepancies of more than a factor of 2 have been reported among observations as well as simulations.

WHICH ONE IS RIGHT?

Fig.3 In comparison with Polder satellite observations, the first AIE seems to be overestimated by models.



Results from recent model simulations with the constrain of satellite observations are better in line with those of the inverse calculations[4]. Here we explain WHY.

COHERENT PATTERN PROBLEM

Typically, the cloud drop number concentration (N_c) is related to the aerosol number concentration (N_a) by

$$N_c = C N_a^{\beta}$$

As long as C co-vary with N_a in the data for analysis, C will correlate to N_a, even if N_a does not depend on C, *physically*. So, the ratio of $d\ln N_c$ to $d\ln N_a$ is not $\beta = \partial \ln N_c / \partial \ln N_a$ alone but β plus an extra term that we call "Coherent Pattern Error (CPE)" , i.e.,

$$\frac{d\ln N_c}{d\ln N_a} = \beta + \frac{d\ln C}{d\ln N_a} \qquad \text{(A)}$$

Considering $r_e \propto L^{1/3} N_c^{-1/3}$ (where L is liquid water content at cloud top), the left side of Eq. (A) can be inferred with satellite measurable variables r_e and aerosol optical depth τ_a (note here we use τ_a as a proxy of N_a)

$$\frac{d\ln N_c}{d\ln N_a} \sim 3\frac{d\ln(L^{1/3} r_e^{-1})}{d\ln \tau_a}$$

Most of current measurements of the first AIE contain the CPE which we believe to be responsible for the large uncertainties in AIE.

CONCLUSION

Our study explains the discrepancies among the observations of the first AIE and suggests that taking the coherent pattern error into account in global climate models helps reduce the large uncertainties in the aerosol radiative forcing.

OUR EXPLANATION

$A = L^{1/3} r_e^{-1}$

L: liquid water content

$B = H^{1/3} r_e^{-1}$

H: cloud depth

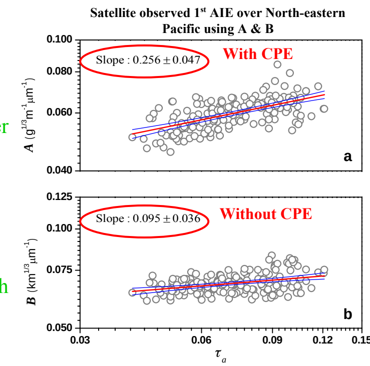
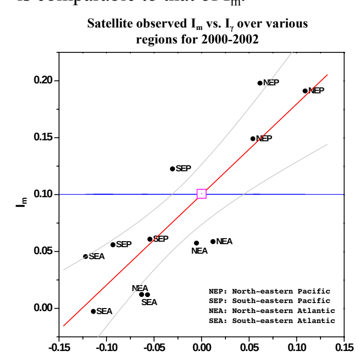


Fig.4 The difference between the slopes of A and B implies that L/H (reflecting the evaporation of cloud water) must be correlated with aerosol loading and can act as a CPE[3].

Fig.5 The coherent pattern error arise from the correlation between L/H and aerosol loading (i.e., I_γ) can positively or negatively bias the observed AIE I_m. Notice that range of I_γ is comparable to that of I_m.



$$I_m = \frac{d\ln A}{d\ln \tau_a} \sim \frac{1}{3}\frac{d\ln N_c}{d\ln N_a}$$ is the observed 1st AIE.

$$I_\gamma = \frac{d\ln(L/H)}{d\ln \tau_a}$$ is a coherent pattern error.

Removal of the coherent pattern error will reduce the satellite observed first AIE from 0.0 ~ 0.2 to 0.05 ~ 0.15.

Reference:

1. Rosenfeld, D. and G. Feingold, *Geophys. Res. Letts.*, 30(14), 2003.
2. Anderson, T. L., R. J. Charlson, et al., *Science*, 300, 2003.
3. Shao, H. and G. Liu, *Geophys. Res. Letts.*, 33, 2006.
4. Lohmann, U. and G. Lesins, *Science*, 298, 2002.