Aerosol-cloud interactions derived from remote sensing and in-situ aircraft measurements

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1. Introduction

The effect of aerosols on cloud microphysical and radiative properties has the greatest uncertainty of all known climate forcing mechanisms. For a constant amount of condensed water, an increase in the number of CCN will generate a cloud that consists of smaller drops and reflects more energy to space, which is commonly referred to as the "albedo effect" [*Twomey, 1977*]. However, because the droplets are smaller they may inhibit collision-coalescence in the cloud, suppressing droplet growth that stops drizzle and extends cloud lifetime [*Albrecht, 1989*]. The indirect effect of aerosols is continuing to be an enormous challenge from both the observational and modeling perspectives, and progress is crucial in order to improve our ability to predict climate change. Current estimates of global average aerosol indirect forcing based on satellite data ranges from -0.6 to -1.7 Wm^{-2}. There is greater realization of the importance of including the indirect effect because direct effect is thought to be insufficient to allow proper simulation of observed temperature changes. Satellite remote sensors have been employed to provide a regional and even global view of aerosol effects on clouds [*Nakajima et al., 2001; Breon et al., 2002*]. More recently, surface-based remote sensing has also been applied to address aerosol effects on cloud microphysics [*Feingold et al., 2006; Pandithurai et al., 2009*], as these surface stations yield high temporal resolution data and because they sample aerosol below, rather than adjacent to clouds and hence they do not suffer from cloud contamination. The main advantage of the surface-based remote sensing is that the effect of aerosol on cloud can be examined in a single column of air at the scale of cloud droplet formation, and at high temporal resolution. Long term observations of aerosol and cloud properties and sensitivity of cloud properties to aerosols over different climatic regions are required for better parameterization of aerosol-cloud interactions. The primary objective of this study is to examine the response of cloud radiative properties to changes in aerosol using surface-based remote sensing systems over Eastern China Sea region that is influenced by the transport of aerosols from the Asian continent. Recent aircraft measurements over India are also used to examine the aerosol indirect effect and the effect of droplet dispersion on indirect effect estimates.

2. Data and Methods

Spring-2008 observational campaign was conducted at Cape Hedo (26.87 N, 128.25 E), Okinawa Island, Japan to study the aerosols and their radiative effects transported from East Asia especially from China. In addition to other observational facilities, this campaign included an operation of Frequency Modulated Continuous Wave (FMCW) Millimeter wave Cloud radar (MMCR) from February 17 to May 04, 2008. The experimental systems used in this study includes a i) Dual frequency microwave radiometer (MWR), ii) Polarization capable dual-wavelength lidar [*Shimizu et al., 2004*], iii) Millimeter wave cloud radar [*Takano et al., 2005*], iv) CCN counter, v) i-skyradiometer (Prede Co., Product Name POM-02), vi) Whole sky imager, vii) Nephelometer and viii) Optical particle counter.

Cloud droplet effective radius (R_{eff}) is retrieved from the reflectivity profiles of FMCW cloud radar operating at 95 GHz and column liquid water path (LWP) derived from MWR. Technical details of the FMCW radar and its comparison with a monostatic 95 GHz cloud radar SPIDER can be found elsewhere [*Takano et al., 2005*]. Liquid water path is an important parameter for studying aerosol-cloud interactions and is not widely measured. The Radiometrics WVR-1100 microwave radiometer is a passive instrument which measures column integrated water vapor and liquid water based on the microwave emissions of atmospheric water vapor and liquid water molecules at 23.8 GHz and 31.4 GHz. Typical retrieval uncertainties in the column integrated liquid water are 25–30 gm^{-2}. The datasets used in this study were obtained from the SKYNET archive (http://atmos.cr.chiba-u.ac.jp), which archives and distributes data collected from most of these instruments.

3. Aerosol effects on cloud droplet size

To investigate the aerosol indirect effect, collocated measurements of different experimental systems were analyzed. As suggested by *Feingold et al. [2006]*, daytime well-mixed boundary layer conditions are considered for aerosol indirect effect analysis to ensure that the surface observations are representative of those that that are influencing the cloud droplet nucleation properties. Here we used height-averaged cloud droplet effective radius (R_{eff}) and examined changes in R_{eff} as a function of surface aerosol scattering coefficient, CCN number and OPC aerosol size distribution. Aerosol indirect effect estimates are based on relative changes in droplet radius or cloud optical thickness for changes in aerosol loading and is less sensitive to absolute values. As CCN measurements are not available on all the days considered in this analysis, we use βsca as CCN proxy. Analysis shows that about 30% increase in accumulation mode particles led to 15% decrease in droplet effective radius. Wind fields and back trajectory analysis for the experimental days considered in the analysis show the trajectories are of northwesterlies and westerlies, which indicate transport of airmasses from Asian continent towards the Okinawa Island. Data sets of selected days considered in the analysis were sorted for different LWP ranges viz. 50–100, 100–150, 150–200, 200–250 and 250–300 gm^{-2}. The scatter plot between R_{eff} and βsca for different ranges of LWPs shown in Figure 1 and the slope of the linear fit for the above plots give aerosol indirect effect (IE).

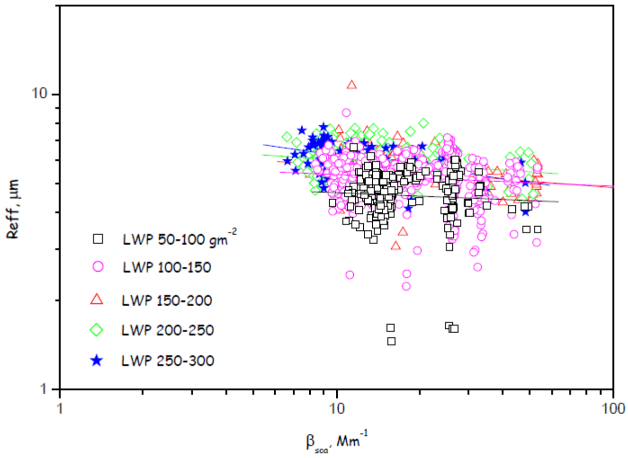

Figure 1. Values of Reff as measured by MMCR versus aerosol scattering coefficient asmeasured by nephelometer.

4. Aerosol indirect effect over India using CAIPEEX Datasets

CAIPEEX (Cloud Aerosol Interaction and Precipitation Enhancement Experiment) phase I is devoted for intensive cloud and aerosol observations using an instrumented aircraft N361JC, over different regions in India, during the period May to September 2009 which includes pre-monsoon, active and break monsoon conditions. Aircraft missions were conducted from different locations in India viz. Pathankot (32.2 N, 75.6 E), Hyderabad (17.5 N, 78.4 E), Bangalore (13N, 77.5E), Bareilly (28.4 N, 79.4 E), Guwahati (26.1 N, 91.6 E) and Pune (18.5 N, 73.8 E). During some of the flights observations were collected over coastal Arabian Sea and Bay of Bengal to study the cloud microphysics of marine clouds and their transformation to continental clouds during the flights. A detailed description of the above CAIPEEX project can be found in the web page: http://www.tropmet.res.in/~caipeex/.

Flight average data sets of warm cloud samples were used in the analysis. The threshold cloud droplet diameter (DL) of modal liquid water content is used as cut-off and cloud samples less than DL values of 24 μm only are considered in this analysis. Measurements of aerosol accumulation mode number concentrations (Nacc) and CCN supersaturation spectrum were obtained from sub-cloud flights before climbing into cloud profiling. First AIE (Twomey effect) is estimated from the ratio of the relative change in cloud droplet number concentration (N_c) with respect to relative change in aerosol number concentration (N_{acc}).

$$N_c = a_a (N_{acc})^{b_a} \qquad \text{..........(1)}$$

where first AIE or Twomey effect is given as $I_0=1/3b_a$. It is clear that as aerosol concentration increases as cloud droplet number concentration increases. According to equation (1), Twomey effect estimated over Indian region during CAIPEEX campaign is 0.096 which is 1/3 b_a (b_a=0.288).

5. Effect of cloud droplet dispersion on Twomey effect

In most of the studies, aerosol-cloud interaction is explained by considering only changes in the cloud droplet concentration, neglecting changes in the spectral shape of the cloud droplet size distribution. However, it has been shown that the relative dispersion 'ε' has a significant role in determining cloud radiative properties. It is already reported that enhanced ε leads to warming effect, which can offset Twomey effect by 10 to 80% (*Liu and Daum, 2002*). All existing estimates of dispersion effect were based on some empirical β(ε)-N relationship, which has a large uncertainty. In order to reduce the uncertainty or for better estimation of dispersion effect, *Liu et al (2008)* examined the dependence of β on (L/N) (i.e., water per droplet) and described the dependence of β on (L/N) by the following expression,

$$\beta = a_\beta \left(\frac{L}{N} \right)^{-b_\beta} \qquad \text{..........(2)}$$

where L is cloud liquid water content, N is cloud droplet number concentration and β is effective radius ratio.

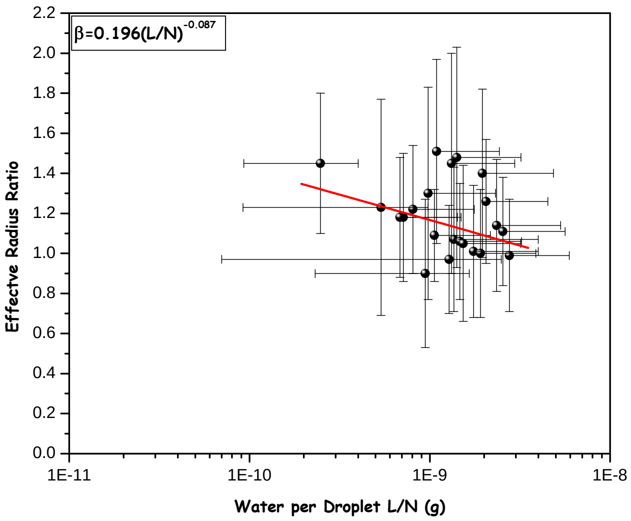

Figure 2. Relation between effective radius ratio and water per droplet obtained fromCAIPEEX flight average data sets

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