EFFECTS OF AEROSOLS AND THERMODYNAMICS ON THE GLOBAL DISTRIBUTION OF TRMM-DERIVED WARM CLOUD PROPERTIES

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1. Introduction

Maritime low clouds, denoted hereafter as stratus, reduce the Earth's energy budget by approximately 15 (W/m²) in an annual average (Hartmann et al. 1992).

Stratus amount is, in particular, positively correlated with *lower-tropospheric static stability* (LTSS), defined as the potential temperature difference between the surface and the 700 (mb) pressure level (Klein and Hartmann 1993). Klein and Hartmann (1993) demonstrate that high LTSS represents a strong temperature inversion at the top of the atmospheric boundary layer, and the regional observations show that the stratus cloud is confined to the boundary layer in high LTSS, while extending their horizontal areal coverage.

Aerosols also control stratus properties by acting as cloud condensation nuclei (CCN) to form cloud droplets. A high concentration of aerosols overseed cloud droplets to generate highly concentrated, narrowly distributed cloud droplet spectra which increase the cloud albedo up to 30% (Twomey 1984). Narrowly distributed cloud droplet spectra prevent formulation of precipitation and could increase the cloud lifetime that further cools the Earth's surface (Albrecht 1989). This climatic impact of aerosols on cloud properties is called the aerosol indirect effect, which is one of the largest uncertainties in accurately describing the sensitivity of climate to changes in aerosol concentrations in the future.

Figure 1 exhibits a global distribution of seasonally-averaged LTSS (gray contours) derived from the NCEP/NCAR Reanalysis (Kalnay et al. 1996) and the seasonally-averaged aerosol index derived from the MODerate resolution Imaging Spectroradiometer (MODIS) (dark shaded) (Tanré et al. 1997). The aerosol index is better correlated than aerosol optical depth with the column aerosol concentration under some assumptions (Nakajima et al. 2001), and was derived from the aerosol optical thickness at 0.55 (μm) and Ångstrom exponent computed from 0.55 and 0.865 (μm). Different contributions from these two factors across the globe possibly influence the cloud microstructure. Objective of this research is to examine the sensitivity of the aerosol effect to the cloud properties on a global scale due to the background atmospheric thermodynamic structure.

2. TRMM-derived Cloud Properties

A new algorithm using the Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI) and Visible/Infrared Radiance Imager (VIRS) provides the vertical structure of warm cloud (cloud top temperature > 273 K) microstructure by investigating two types of droplet effective radius (Re): shortwave-derived droplet size (Re (top)) and microwave-derived droplet size (Re (column)). This is because a VIRS-derived Re tends to be biased toward a cloud-top value due to strong absorption of the near-infrared band, whereas a TMI-derived Re is expected to be close to the value averaged over the cloud layer since microwaves can detect cloud droplets and raindrops without suffering from saturation within low maritime clouds (Masunaga et al. 2002).

3. Sensitivity of the Aerosol Indirect Effect

We performed a statistical analysis for the individual estimates of stratus, aerosol index, and LTSS. The three individual datasets are not precisely concurrent in time and space. We directly relate the daily 1-degree MODIS aerosol index, 0.25-degree TRMM cloud properties, and 2.5-degree LTSS from the NCEP/NCAR Reanalysis without spatial interpolation.

The means of Re (top) and Re (column) were derived with a given aerosol index (bins of 0.02) and LTSS (bins of 0.4 K) as can be see in Figure 2. The three-dimensional slope shows that high aerosol index and/or high LTSS lead to the smaller droplet size in both Re (column) and Re (top); i.e., a larger temperature inversion and higher concentration of aerosols inhibit cloud droplet growth. On the other hand, cloud droplet sizes are maximized in the pristine and less stable atmosphere.

For a fixed liquid water path, the relationship between Re and aerosol index is expressed as (e.g., Bréon et al., 2002)

$$\frac{d\log(\mathrm{Re})}{d\log(AI)} = \frac{\alpha}{3}, \qquad (1)$$

where AI is aerosol index, and α approximately relates the aerosol index to the number of cloud droplets (N_c) via $N_c \approx (AI)^{\alpha}$. The slope ($\alpha$/3) is a parameter that simply quantifies the magnitude of the aerosol indirect

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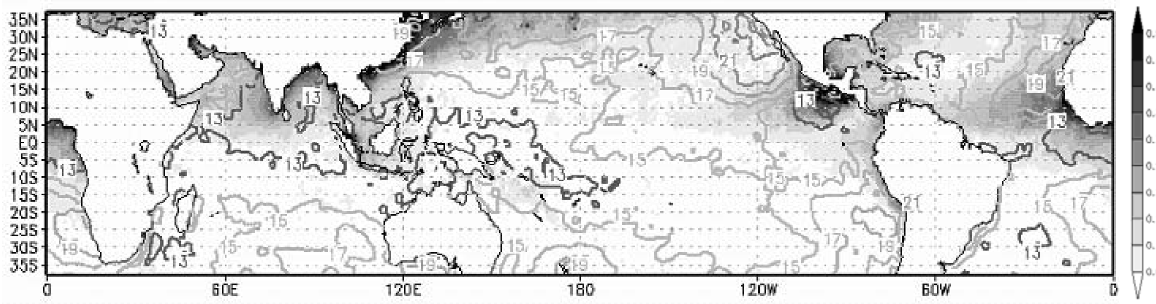

Figure 1. Global distribution of aerosol index (dark shaded) from the MODIS measurements and lower-tropospheric static stability (LTSS) (K) (gray contour) derived from the NCEP/NCAR Reanalysis averaged through March-May 2000. (From Matsui et al. (2004))

effect. Since the standard errors ($\sigma/\sqrt{n-2}$, where n and σ are the number of quasi-coincident measurements for each bin and is standard deviation, respectively) are generally larger for the bins of higher aerosol index due to the lack of the sample number, we derived the slope for an aerosol index > 0.25. Although our sampling and statistical processes are different from the previous studies in a strict manner, the slope of Re (top) averaged over a full range of LTSS ($\alpha/3$=0.069) is close to that derived from Bréon et al. (2002) ($\alpha/3$=0.085) and less than 50% of that derived from Nakajima et al. (2001) ($\alpha/3$=0.16). The slope of Re (column) is 0.222, which is three times larger than that of Re (top), and is close to that using a characteristic value, α = 0.7 (Charlson et al. 1992). Since the Re (column) is directly related to the cloud optical depth (Masunaga et al. 2002), the aerosol indirect effect and associated Earth's cooling effect could be greater than the estimation using cloud-top Re (-0.7 – 0.2 W/m²) (Nakajima et al. 2001).

The slopes of Re (column) averaged over the five bins of LTSS range from 0.12 to 0.32 (Table 1). In the same LTSS intervals, the slope of Re (top) range from 0.022 to 0.071. Those contain values derived over land and ocean (Bréon et al. 2002), suggesting that the difference in the slope between land and ocean could be explained by their background thermodynamic structure, in addition to the observational tendency of the specific sensor (Rosenfeld and Feingold 2003). Except for the lowest LTSS intervals (12.2 – 13.8), the slope of Re (column) and Re (top) generally decreases toward the higher LTSS (Table 1); i.e., a greater fraction of aerosols are converted into cloud droplets in the lower LTSS. This result is also physically reasonable, since a lower static stability permits a deeper atmospheric boundary layer and stronger updrafts to yield a higher supersaturation, which activate more CCNs thereby decreasing the droplet size (Feingold et al. 2003). However, the aerosol effect on the cloud albedo and associated Earth's radiation budget is not necessarily stronger in the convectively unstable atmosphere, since cloud areal coverage becomes very small in such regions (Klein and Hartmann 1993). The different slopes due to the LTSS also explain why the mean slope of Re (top) is smaller than Nakajima et al. (2001); our sampling number is biased toward the subtropical regions, where the LTSS is generally higher than the tropical region.

4. Conclusion

Our study demonstrates an important sensitivity of the aerosol effect on the cloud-precipitation process to the different static stability regimes through a simultaneous examination of the cloud-top and

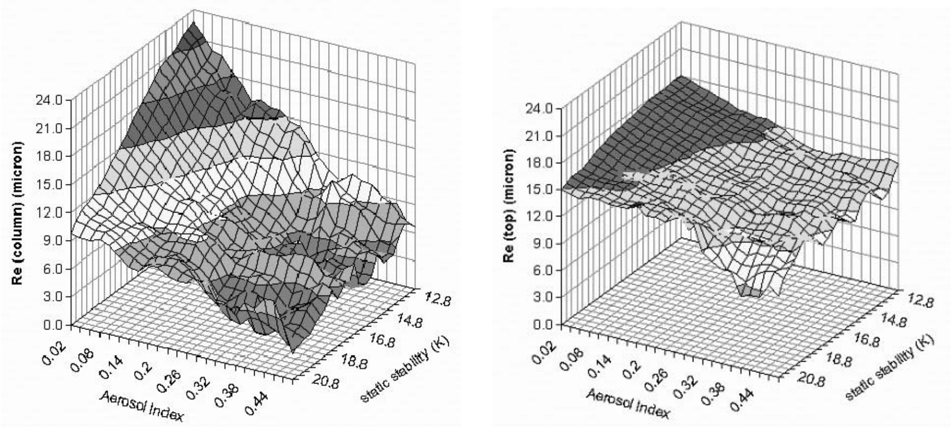

Figure 2. The mean of Re (top) and Re (column) were derived for sets with a given aerosol index (bins of 0.01) and low-atmosphere static stability (bins of 0.4 K) from May to March. (From Matsui et al. (2004))

Ranges of LTSS (K)		12.2 - 13.8	14.2 - 15.8	16.2 - 17.8	18.2 - 19.8	20.2 - 21.8
($\alpha/3$)	Re (top)	0.071	0.085	0.084	0.051	0.022
	Re (column)	0.19	0.32	0.27	0.20	0.12

Table 1. The slope ($\alpha/3$) averaged over the five bins of the LTSS. (From Matsui et al. (2004))

columnar droplet effective radius. While the magnitude of its effect of cloud-top values reproduces the value reported in the previous studies, those of columnar values are greater than the previous studies, suggesting a possible underestimation of the aerosol indirect effect with using cloud-top droplet size. The cloud-aerosol interaction is clearly identified except where LTSS is so high that the cloud droplet growth is dynamically suppressed. *It is, therefore, important that the aerosol effect and static stability be simultaneously taken into account for diagnosing warm cloud properties on a global scale* (Matsui et al. 2004).

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