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GLOBAL SURVEY OF THE RELATIONSHIP BETWEEN CLOUD DROPLET SIZE AND ALBEDO USING ISCCP

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1. INTRODUCTION

Aerosols affect climate through direct and indirect effects. The direct effect of aerosols (e.g., sulfates) includes reflection of sunlight back toward space and for some aerosols (e.g., smoke particles), absorption in the atmosphere; both effects cool the Earth's surface. The indirect effect of aerosols refers to the modification of cloud microphysical properties, thereby affecting the radiation balance. Higher concentrations of cloud condensation nuclei (CCN) generally produce higher concentrations of cloud droplets, which are also usually assumed to lead to decreased cloud droplet sizes. The result is an increase in cloud albedo, producing a net radiative cooling, opposite to the warming caused by greenhouse gases (Charlson *et al.* 1992).

The change in clouds that is directly induced by an increase of aerosol concentration is an increase of cloud droplet number density, N; but is is usually assumed that cloud droplet size decreases as if the water mass density (liquid water content, LWC) were constant. There is actually no reason why this should be the case. Shifting the cloud droplet size distribution to more numerous smaller droplets can change the relative rates of condensational and coalescence growth, leading to different LWC (e.g., Rossow 1978). Moreover, the resulting change in cloud albedo is usually ascribed to more efficient scattering by smaller droplets, when in fact it is the increase in droplet number density (assuming constant LWC) that produces the most important change in cloud albedo: e.g., holding N constant and decreasing the droplet size would actually decrease the scattering cross-section and, thus, the albedo much more than it is increased by the increased scattering efficiency.

For processes which take place over a long period, as compared to the formation of ship tracks, clouds seem to adjust their optical thickness or *LWP* in response to droplet size changes. Both *in situ* measurements (Nakajima and King 1990; Rawlins and Foot 1990) and satellite observations (Han *et al.* 1994, Nakajima and Nakajima, 1995) show that cloud optical thickness (τ) or albedo (α) increases with increasing droplet sizes when τ is small ($\tau \leq 20$) and decreases when τ is large ($\tau \geq 20$). Regional studies show that *LWP* changes with cloud droplet in two different ways: i.e., *LWP* may either decrease or increase as cloud droplet size becomes smaller (Twohy *et al.* 1995, Albrecht *et al.* 1995). Twohy *et al.* (1995) found that the difference in visible reflectances is negligible between polluted cloud and unpolluted stratiform clouds within 300 km west of the northern California coast, even though droplet sizes differed by a factor of two in these two clouds. They attributed this to the differences in *LWP* in these two cases; i.e., *LWP* is twice as small in polluted clouds as in unpolluted clouds. On the other hand, Albrecht *et al.* (1995) found a case that cloud in continental air masses was remarkably brighter than cloud in maritime cloud during the ASTEX experiment. The continental air mass cloud had a smaller droplet size (by 5 μm) but a larger liquid water content (by a factor of two). With all of these apparently contradictory results, we need to examine large-scale and long-term relationships between cloud microphysics and albedo on regional and global scales. We examine the possible indirect aerosol effect on climate in two ways. First, we check the spatial relationship between cloud droplet radii and cloud albedo in different areas where aerosol concentrations are known to differ significantly (e.g., land versus ocean, northern versus southern hemisphere) to determine if this indirect aerosol effect shows up regionally. Second, and more relevant to climate change, we explore the temporal relationship between r_e and cloud albedo for each 2.5°x2.5° grid box to reveal in which regions of the globe the variations of cloud albedo are correlated with changes in r_e consistent with the indirect aerosol effect hypothesis.

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2. RESULTS

2.1 Spatial Correlation Coefficient of r_e and α

Two different spatial correlations are examined to answer the question: do clouds become brighter when they have smaller droplet sizes? The first test is to divide the globe into 2.5°x2.5° grid boxes. For each grid box, a monthly mean r_e and an α value are derived from the satellite data. The results are presented in a 2-D scatter plot to examine the relationship between r_e and α. Figure 1 shows a sample of these scatter plots for Jan, 1988. In general, there is little correlation between r_e and α. This is contrary to the behavior expected for constant LWP. However, because LWP changes dramatically between different climate zones, one may argue that within a smaller region, we may expect smaller LWP variations within the same climate zone and thus more chance to observe a negative relation between r_e and α.

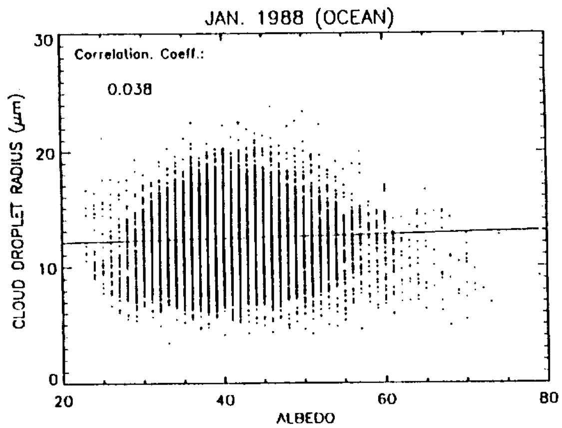


Figure 1. Spatial relation between r_e and α, each dot represent a mean value in a 2.5°x2.5° grid box.

The second test is to examine the r_e and α relation within each 2.5°x2.5° grid box. All r_e and α values within a 2.5°x2.5° in a month are grouped to form a dataset. Then correlation coefficients between r_e and α for each dataset are calculated to examine their relationship. Figure 2 is an example of the results for April, 1987. The generally positive correlation between r_e and α suggests that for each 2.5°x2.5° region, LWP variations and cloud dynamics are the dominant factors in the determination of the cloud albedo. This result is consistent with the observations about the spatial variation amplitude of LWP (e.g., Cahalan and Snider 1989), suggesting that LWP can easily change a factor at least of 5 within a 30 km to 40 km region.

2.2 Temporal Correlation Coefficient of r_e & α

Even though *LWP* can change dramatically for different climate zones, temporally it may remain relatively steady in specific regions. From the perspective of climate change, the temporal relationship between r_e and α in a given region may indicate whether cloud albedo changes are consistent with the indirect aerosol hypothesis. If r_e and α are negatively correlated in specific regions, then the climate of such regions may be considered "susceptible" to an indirect aerosol effect as proposed. Several scenarios of correlation between r_e and α exist on the earth. For example, some regions (e.g., in the southern hemisphere oceans) may have relatively steady cloud *LWP* all year round with very small seasonal changes; thus a change of r_e would affect the cloud albedo inversely and lead to a negative correlation between r_e and α. However, in most regions, cloud *LWP* usually shows significant seasonal variations: higher in summer and lower in winter.

Figure 3 shows the global temporal correlation coefficient between cloud droplet sizes and albedo. The r_e and α values are averaged over each 2.5° x 2.5° grid box for each month. Then the correlation coefficients are derived for each grid box for the four years of data. There are both positively and negatively correlated areas on the earth. Regions showing positive correlations between r_e and α are in the tropics, subtropics and northern mid-latitude oceans. For negatively correlated values of r_e-α, there are two different regions: southern midlatitude oceans and areas around several northern continents: eastern U.S.A, Europe, and East China. In order to better understand the cause of the r_e-α relationship for these different regions, we select several typical regional areas to further investigate the behavior of temporal variations of r_e and *LWP*.

We have examined temporal variations of *LWP* and r_e for the 1) Central Pacific Ocean (LAT -20° to 20°; LON -170° to 170°), 2) Southern midlatitude ocean (LAT -50° to -20°; LON -170° to 170°); 3) East U.S.A (LAT 15° to 40°, LON -60° to -100°), 4) Europe (LAT 20° to 50°, LON -25° to 160°), and 5) east China (LAT 20° to 25°, LON 105° to 125°). For the Central Pacific Ocean area, the tropics and the Atlantic Ocean area, *LWP* and r_e change synchronously in the same direction with peak values in July and April. Because the rate of *LWP* variation is higher than that of r_e, it results in a positive correlation between r_e and α. These are areas with little pollution; CCN number densities are low (about 60 cm^{-3}, see Hoppel 1988, Penner *et al.* 1992). The cloud water content determined by air-sea interaction seems to regulate cloud droplet sizes, as concluded by many *in situ* observations (e.g., Aufm Kampe 1950). These regions do not appear to be susceptible to the indirect aerosol effect.

The Southern midlatitude ocean shows a negative correlation between r_e and α; that is r_e changes its pattern while *LWP* has peak values in April and July. The cloud droplet size reverses direction in July 1987 and April and July 1988, no longer being regulated by cloud *LWP*. The reason for this is not yet clear.

Other places showing negative correlations between r_e and α are the Gulf of Mexico, Europe and

Fig. 2. Spatial Correlation Coefficient Between Re and Albedo (April 1987, NOAA-09)

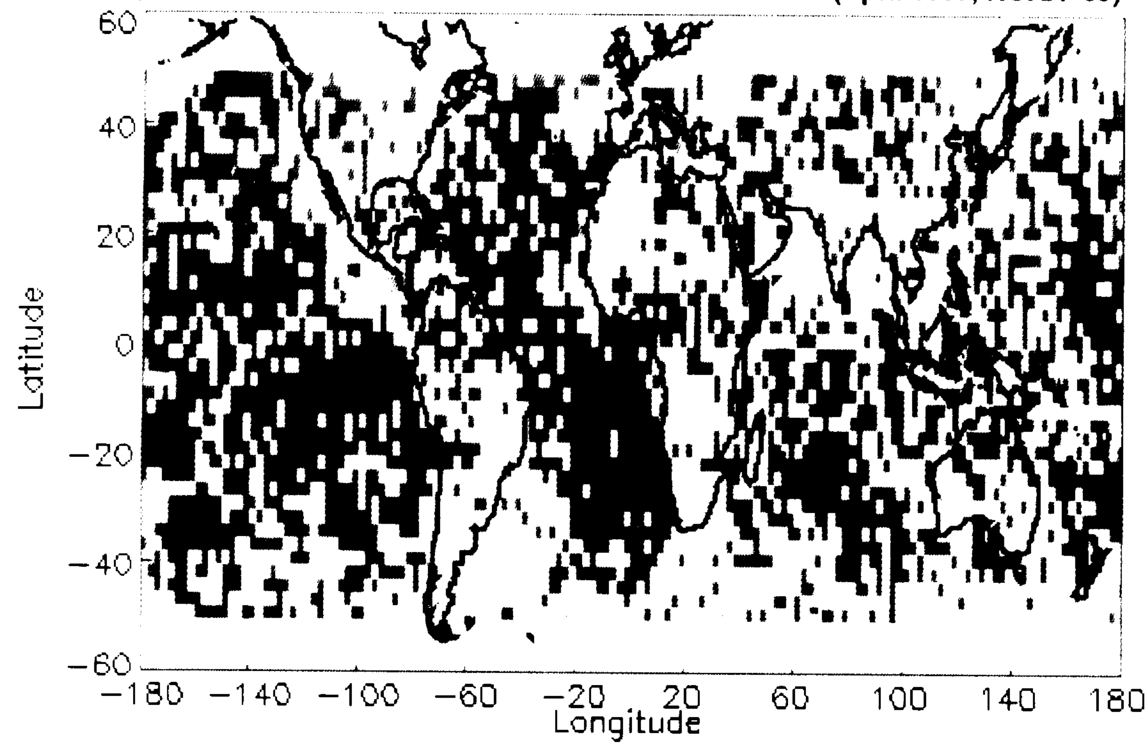
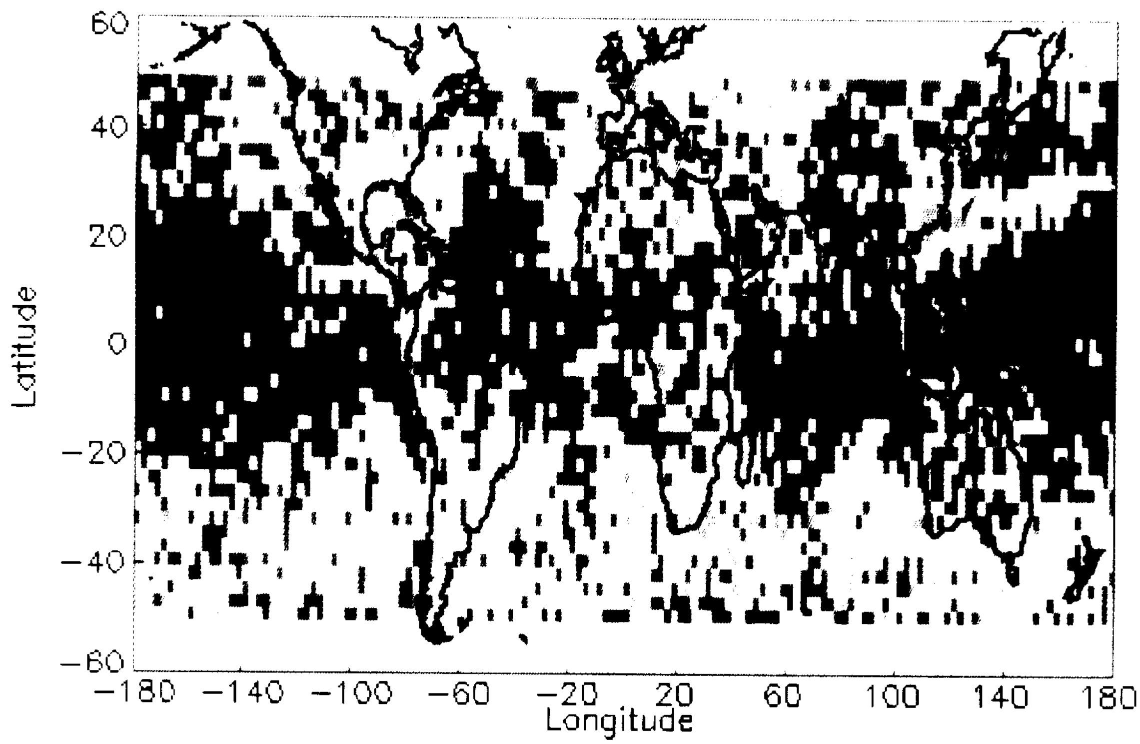
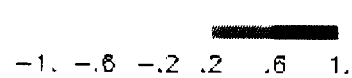


Fig. 3. Temporal Correlation Coefficient Between Re and Albedo (1985–1988, NOAA-09)





East China. All three regions show minimum *LWP* values around July and maximum values around January, with the droplet size r_e changing inversely. This behavior is suggestive of the indirect aerosol effect occurring in these highly polluted locations. The rich water sources and higher freezing levels in the warm season make for larger cloud droplets and enhance the precipitation efficiency, leading to smaller cloud *LWP*. During cold seasons, less water content and increased CCN number densities make for smaller cloud droplets and lower precipitation efficiencies, resulting in larger *LWP*s. In remote ocean areas, lower aerosol concentrations and thus fewer CCNs are available. The variations of *LWP* and r_e are synchronized (i.e., LWP increases by increasing r_e) and the change rate of *LWP* is larger than r_e, which leads to positive correlation between α and r_e. In other words, the changes in droplet number density do not offset the effects of changing r_e on LWP and α. The droplet radii are relatively large (≥12 μm as a 2.5°x2.5° grid box monthly mean). For polluted areas, abundant CCNs and less cloud water content in cold seasons prevent droplets growing large (≤10 μm) and thus retaining larger quantities of liquid water in clouds, making *LWP* higher in these cases. In warm seasons, cloud droplets grow larger and precipitate, reducing the *LWP*. This leads to a negative correlation between α and r_e.

We have estimated to what extent clouds currently appear to behave consistently with the indirect aerosol effect. Although the large scale spatial variations of r_e appear to reflect an aerosol influence, only about 20% of the earth is covered by low clouds that exhibit negative temporal correlations of r_e and α changes (Fig. 4), consistent with the indirect aerosol effect hypothesis. Most clouds (50%), in fact, exhibit positive temporal correlations of r_e and α changes, indicating that variations of LWP are predominant in determining cloud albedo variations.

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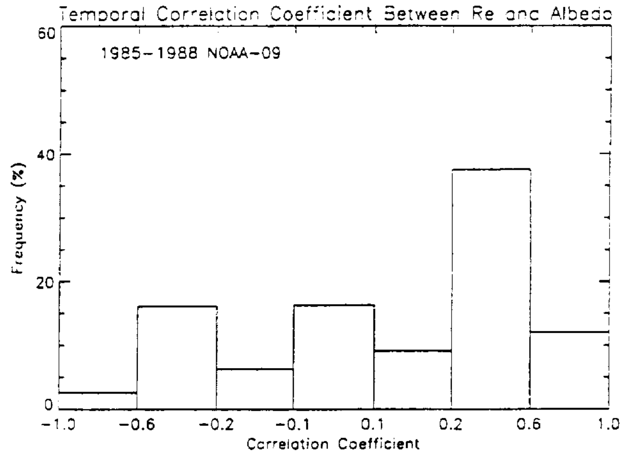

Figure 4. Histogram of temporal correlation coefficient between r_e and α.

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