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Seasonal variation of cloud particle size as derived from AVHRR remote sensing

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[1] We have analyzed long-term NOAA/AVHRR (Advanced Very High Resolution Radiometer) global data from 1985 to 1994 to investigate the variation of the cloud particle size for low-lying water clouds. Here we focus on seasonal change of the cloud particle size instead of studying the variability the absolute values, since there are several critical factors which affect the long time-series thus obtained, such as calibration uncertainty, sensor degradation, change of satellite platform, orbital shift and so on. Amazon and East Asia cases will be shown in addition to global average. All the cases show decreasing trend with signals of significant seasonal cycles (particularly local cases such as Amazon and East Asia). The inter-annual decreasing trend and a gap in 1989 would be artifacts caused from above reasons. Seasonal cycles, however, would be explained by the seasonal change in precipitation that is able to control the amount of aerosol and cloud particles, though we need to be careful to propose such a direct relationship between them, since water clouds do not cover all the precipitating clouds. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing. **Citation:** Kawamoto, K., and T. Nakajima, Seasonal variation of cloud particle size as derived from AVHRR remote sensing, *Geophys. Res. Lett.*, *30*(15), 1810, doi:10.1029/2003GL017437, 2003.

1. Introduction

[2] Clouds play crucial roles in the formation of the earth's climate system, for example, through thermodynamical, hydrological and radiative processes. In particular, the radiative characteristics of the earth's atmosphere are significantly controlled by the optical thickness τ and droplet size distribution of clouds [*Twomey*, 1977]. One of the recent major climate issues is modification of the cloud properties through interaction with aerosols, as known to be the aerosol indirect effect. The radiative forcing due to the aerosol indirect effect seems to be most uncertain among the several major anthropogenic forcings [*IPCC*, 2001], though said to be large negative values. It is, therefore, very important to investigate the optical cloud properties, such as τ, the effective particle radius r_e and cloud water path W, for detailed studies of the earth radiation budget and cloud-aerosol interactions.

[3] Remote sensing technique for large-area or global scale retrievals of cloud optical parameters has progressed significantly in the last decade. As for water cloud retrievals, *Han et al.* [1994] surveyed r_e on a global scale with ISCCP (International Satellite Cloud Climatology Project) database. *Nakajima and Nakajima* [1995] analyzed τ and r_e simultaneously off California using AVHRR channel 1, 3 and 4 radiances, and *Kawamoto et al.* [2001] has extended the algorithm for the global analysis of τ and r_e. One of the advantages of satellite remote sensing is utility of long-term record in addition to the uniform temporal and spatial sampling capabilities. NOAA/AVHRR satellite sensors have generated nearly twenty-year data archives. Such long-term data of geophysical parameters are of paramount importance for climate and climate variability studies. There have been, however, few studies to use the long-term cloud particle size data other than the analysis by *Wetzel and Stowe* [1999].

[4] Under this situation, we have accomplished a long-term analysis of the cloud properties from the AVHRR radiance data in the period from 1985 to 1994 with the *Kawamoto et al.* [2001]'s algorithm. We focus particularly on r_e of low-lying water clouds that is important for studying the aerosol effect and the earth's radiation budget [*Harrison et al.*, 1990; *Nakajima et al.*, 2001]. In order to evaluate quantitative long-term cloud variability rigorously, we do need to overcome several critical factors which affect the time series thus obtained, for instance, satellite platform change, degradation of sensors, calibration uncertainties and orbital shift and so on. Therefore we like to confine our discussion to the seasonal change of r_e. A full understanding of inter-annual changes in the cloud properties is beyond the scope of this article.

[5] The algorithm and data used are described in chapter 2, and results and discussion involved will be given in chapter 3. Finally conclusions will be presented in chapter 4.

2. Algorithm and Data for Cloud Optical Parameters Retrievals

[6] The algorithm of *Kawamoto et al.* [2001] is adopted in this study for inferring τ and r_e. This algorithm uses cloud-reflected solar radiances at non-absorbing visible wavelength and at water-absorbing near-infrared wavelength, which are mainly a function of τ and r_e, respectively [*Nakajima and King*, 1990; *Nakajima and Nakajima*, 1995]. Effects of thermal emission and water vapor absorption are corrected by the formula proposed by *Kawamoto et al.* [2001] with NCEP objective analysis data. The algorithm is applied to 10 years time series of AVHRR GAC (Global

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Area Coverage) radiance data from 1985 to 1994 (i.e., NOAA-9/AVHRR from 1985 to 1988 and NOAA-11/AVHRR data from 1989 to 1994) respectively. This period is selected in order to minimize the number of satellites used in the analysis and hence to reduce artifacts originated from discontinuity of the instruments. We performed 4-month (January, April, July and October) analysis, and hereafter refer to this every 4-month analysis from 1985 to 1994 as long-term analysis. As for calibration of sensor signals, the calibration constants of *Rao and Chen* [1995] are used for channel 1 visible channel, and those of on-board internal blackbody for channel 3 near-infrared and channel 4 infrared channels. Because channel 1 has no on-board calibration system, we will not discuss the optical thickness which is inferred mainly from the channel 1 in detail. The definition of r_e is as follows

$$r_e \equiv \frac{\int \pi r^3 n(r) dr}{\int \pi r^2 n(r) dr} \quad (1)$$

where $n(r)$ is the number size distribution at the particle size r. In order to minimize the ambiguity in the scattering theory used in this study, low-lying water clouds with the cloud top temperature over 273K are selected for the analysis. Such low-lying clouds show more distinct signature of aerosol interaction than higher clouds, as investigated by *Han et al.* [1994] and *Kawamoto et al.* [2001]. We restrict target pixels whose satellite zenith angles less than 25 degree in order to avoid the effect of cloud inhomogeneity. *Iwabuchi and Hayasaka* [2002] point out that it would be reduced substantially if viewed from angles less than about 25 degree.

3. Seasonal Variation of the Cloud Effective Particle Size

[7] We have done the analysis of r_e using AVHRR data from 1985 to 1994. Figure 1 shows the long-term variability

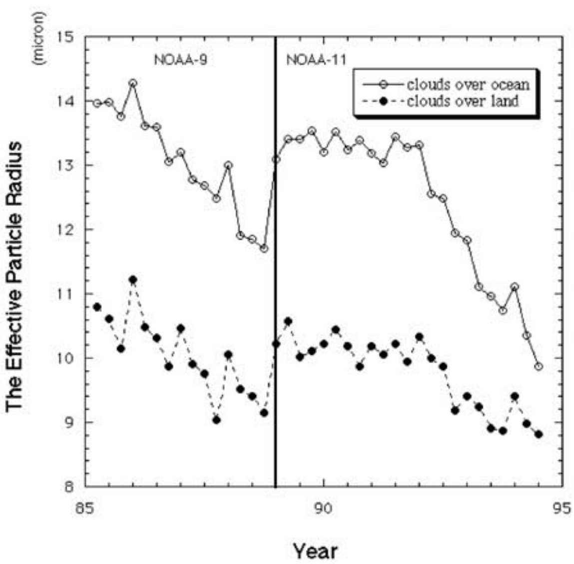

Figure 1. Long-term variability of r_e for oceanic and continental water clouds for global average.

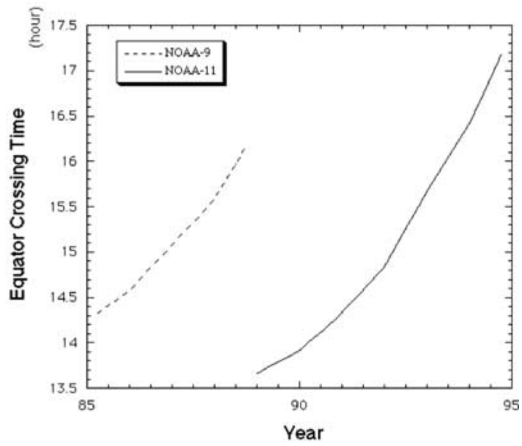

Figure 2. Change of equator crossing time (ECT) with time for NOAA-9 and NOAA-11.

of global average for oceanic and continental clouds. In this study, 'global' means 40 degrees north to 40 degrees south within the solar zenith angle less than 65 degrees to avoid uneven sampling and unstable retrieval due to extreme geometries.

[8] From this figure, we find that values of r_e were getting smaller for both oceanic and continental clouds with a gap in 1989, showing moderate seasonal changes and a steeper slope for oceanic clouds. Judging from a fact that satellite platform had been replaced in late 1988 from NOAA-9 to NOAA-11, this gap must be an artifact caused by this replace of the instrument. Considering this situation, the real slope from 1985 to 1989 might be gentler than that of Figure 1. Moreover, the decreasing rate of more than 3 μm from 1989 to 1994 seems to be non realistic. A simple lining up the time series according to the period from launch can confuse the analysis. There are several possible factors which provide apparent changes to the real trend. For example, sensors degrade with time. Satellite orbits shift from the initial state, that is, the equator crossing time (ECT) becomes later. Figure 2 illustrates the change of ECT with time for NOAA-9 and NOAA-11. The ECT of NOAA-9 changed about 2 hours after 3 years from the launch, and that of NOAA-11 changed more than 3 hours after 5 years after the launch. With this change, remote sensing results would be affected in several ways. For instance, large solar zenith angles can cause large retrieval error due to less availability of solar radiation and cloud inhomogeneity. Difference of local time will also bring diurnal change of cloud properties. Therefore, a direct comparison among results of different local times needs to be treated carefully. Figure 3 shows the global variation of r_e of oceanic and continental clouds with ECT for NOAA-9 and NOAA-11. From this figure, we observe that r_e decreases as the satellite local time with similar rates for NOAA-9 and NOAA-11 cases, suggesting the main reason of the apparent long-term change in Figure 1 is the satellite local time dependence of r_e. As for clouds over land, both satellites take almost the same values at the same local time. On the other hand, we can see slightly smaller radii of NOAA-11 for oceanic clouds. We like to propose that this might be a signature of decrease in r_e with increasing in aerosols due to enhanced anthropogenic activities which is

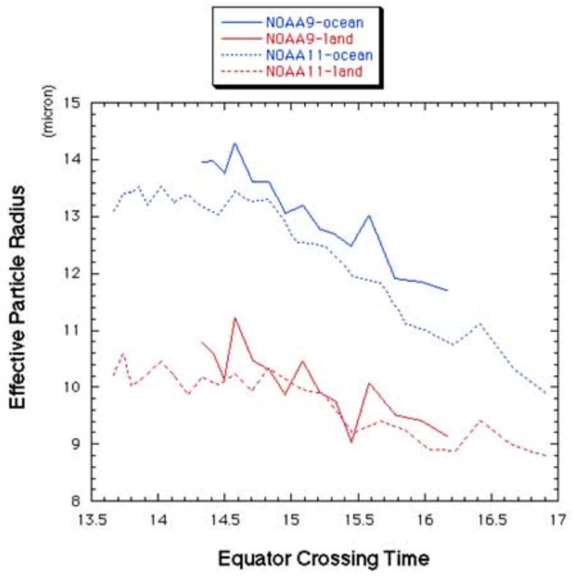

Figure 3. Global variation of r_e for oceanic and continental water clouds with ECT for NOAA-9 and NOAA-11.

so-called 'Twomey effect' [*Twomey*, 1977], because clean clouds as oceanic ones are more sensitive to pollution. Particle sizes of continental clouds seem to be already saturated with the existing aerosol loading. Although these are neither direct evidence nor on a global scale, there are, for example, some documents reporting that the energy consumption and SO2 emission increase in China for the time period (*Lawrence Berkeley National Laboratory* [1996], *Streets and Waldhoff* [2000]).

[9] Figure 4 shows the long-term variation of r_e both in the Amazon basin (W75-W50, 0-S10) and East Asia (E105-E125, N20-N45). We observe that both cases indicate distinct and regular seasonal cycles having half-year difference of the phase, showing a decreasing trend with gaps in 1989, which are similar to the one already pointed out in the global case. As stated already above, there are some factors which bring artifacts to the long-term trend in the obtained time-series, so we do not discuss the absolute values here. It would be, however, worthwhile to describe the seasonal variation of r_e, because the intra-annual time series might be more robust to include the climatic information of real changes in r_e of the satellite signal. This phenomenon of seasonal cycles seems to be associated with precipitation. Regarding Amazon case, rainy season is around January, and dry season is around July. On the other hand, rainy season is around July and dry season is around January in East Asia as shown in Figure 5 [*Xie and Arkin*, 1997]. In rainy season, CCN (cloud condensation nuclei) particles are washed out by precipitation. Cloud droplets can grow large in CCN-poor and wet condition. To the contrary, they do not become so large in CCN-rich atmosphere in dry season. Figure 4 also tells us that the seasonal variation is larger in Amazon. Heavy precipitation in rainy season and active biomass burning in dry season might contribute to the greater contrast of r_e in Amazon. Nevertheless, note that precipitation and CCN effects are only a part of factors to control r_e, so we need further studies for full understanding of the mechanisms to determine the seasonal variation of r_e. Also it needs to be careful with the possibility of solar angle dependence on retrieved values. It could, in part, contribute to the observed trend.

4. Concluding Remarks

[10] We performed a long-term analysis of r_e for water clouds using AVHRR data from 1985 to 1994. In this work, we concentrate on extracting signals of seasonal cycle, rather than discussing the variability of absolute values because of some factors which can easily bring artifacts to the long time-series. The global mean result shows a decreasing trend for both oceanic and continental clouds with moderate seasonal variation, showing a gap which seems to be caused by a change of satellite platform. This decreasing trend is not likely to be a realistic inter-annual trend, but is mainly caused by change in the satellite local time. There are several causes for such local time depen-

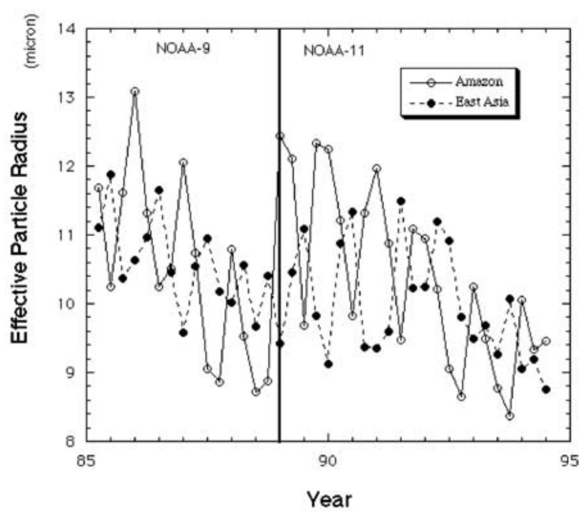

Figure 4. Long-term variation of r_e both for Amazon basin and East Asia.

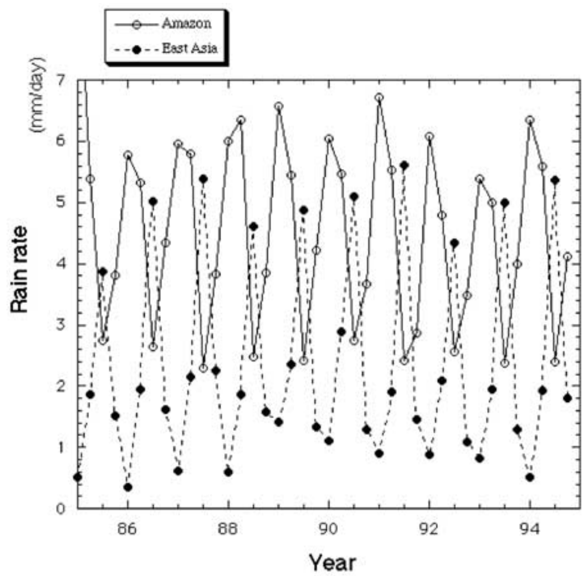

Figure 5. The same as Figure 4 except the precipitation amount.

dence. The most possible reason is the diurnal variation of the cloud particle size depending on the local time at the observation point. Other reason is that the algorithm used tends to underestimate r_e in large solar zenith angle geometry by up to about 10%. But this underestimation is difficult to explain the large change as shown above. It is also difficult to apply reasons originated from instrumental and algorithm artifacts for explaining the different decreasing slopes with the local time between ocean and land cloud cases. Apart from the local time difference, there is still a slight difference in r_e between NOAA-9 and NOAA-11 over ocean. This difference may be a signature of 'Twomey effect' caused by increasing global scale air pollution. For regional cases of Amazon and East China, we observed more distinct seasonal cycles in the long-term time series. Their phases (the maximum and minimum of r_e) shift for half-year, and this result favors the seasonal variation of precipitation. In the Amazon case, the opposing effect for growing and reducing r_e, such as heavy precipitation and active biomass burning, could produce a greater particle size change. Detailed study of physical mechanisms and artifact factors controlling the obtained long-term behavior of r_e will be needed in future.

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