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Ship Tracks Revisited: New Understanding and Cloud Parameterization

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Abstract

Ship tracks have been considered the Rosetta Stone demonstrating the effects of anthropogenic aerosols on cloud radiative properties through alteration of cloud microphysical properties. Previous ship-track studies have focused on identifying the signatures of indirect aerosol effects (e.g. enhanced droplet concentration) caused by ship emissions, and have been mainly concerned with comparing cloud properties within ship tracks to those of surrounding clouds on an individual track-by-track basis. Here we show that, examined together, ship-track studies can also provide crucial insights into cloud parameterizations in climate models, as well as understanding the conditions conducive to ship-track formation. It is found that unlike the measurements from general stratiform clouds where the effective radius is larger than the mean volume radius, the effective radius is smaller than the mean volume radius for some clouds in which ship tracks form. The radius ratio (the ratio of the effective radius to the mean volume radius) varies significantly and cannot be ignored in cloud parameterizations. The relation between the radius ratio and the spectral shape descriptors (relative dispersion and skewness) of the cloud droplet size distribution is further examined, revealing that the clouds with the effective radius smaller than the mean volume radius are likely to have negatively skewed cloud droplet size distributions with a higher concentration of relatively big droplets.

Key words: Ship tracks, cloud parameterization, indirect aerosol effect, effective radius, mean-volume radius, radius ratio

1. Introduction

Ship tracks were first observed in the early 1960's from satellites as long, narrow, curvilinear regions of visible clouds in the wake of a ship (Conover, 1966). Conover also speculated that ship effluents, especially aerosol particles, might be responsible for the formation of these tracks. Twomey *et al*. (1968) provided further theoretical arguments to support Conover's speculation. Twomey (1974, 1977) later extended the idea to the study of the effects of anthropogenic aerosols on climate, arguing that an increase in anthropogenic aerosols leads to an increase in cloud condensation nuclei (CCN), which in turn increases the number of cloud droplets, decreases droplet sizes and enhances cloud albedo (Twomey effect). Coakley *et al*. (1987) noted the frequent occurrence of regions of enhanced cloud albedo in satellite imagery (especially at the wavelength of 3.7 μm) embedded in preexisting marine stratiform clouds, and argued that ship tracks served as good examples of the Twomey effect. To elucidate the mechanisms by which aerosols affect cloud microphysics and cloud albedo, subsequent investigations have often combined remote sensing and in-situ measurements of both radiative and microphysical properties of ship tracks and surrounding clouds (Radke *et al*.,1989; King *et al*., 1993; Russell *et al*., 1999; Durkee *et al*., 2000; Ackerman *et al*., 2000; Noone. *et al*., 2000a,b). These studies have indeed confirmed the Twomey effect (ship tracks exhibit a higher droplet concentration, a smaller droplet size and a larger cloud albedo compared to adjacent, unperturbed clouds). Albrecht (1989) further argued that anthropogenic

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aerosols also enhance liquid water content and the lifetime of clouds and hence cloud albedo because reduced droplet sizes suppress the development of drizzle. However, there is no consensus as to the importance of this so-called second indirect effect. Some studies (Radke *et al.*, 1989; King *et al.*, 1993) reported an increase in liquid water content in ship tracks while others (Ferek *et al.*, 1998, 2000; Ackerman *et al.*, 2000) found no such increases.

An issue closely related to indirect aerosol effects is the parameterization of cloud microphysics in climate models, which has been identified as a major uncertainty in climate models (Cess *et al.*, 1996; Stokes and Schwartz, 1994). Hansen and Travis (1974) introduced the concept of effective radius (defined as the ratio of the third to second moment of the cloud droplet size distribution) to describe cloud radiative properties. Slingo (1989) developed a scheme that parameterizes cloud radiative properties commonly used in climate models (e.g., optical depth, single-scattering albedo and asymmetry factor) in terms of liquid water path and effective radius. Because liquid water content has been included as a prognostic variable in climate models (Smith, 1990; Sundqvist, 1993), the primary difficulty with the parameterization of cloud microphysics lies in the specification of the effective radius in terms of prognostic variables.

Early parameterization schemes for effective radius were formulated as either a linear or a cubic root function of the cloud liquid water content, implicitly assuming no dependence of the effective radius upon the droplet concentration (Stephens, 1978; Fouquart *et al.,* 1989). An obvious deficiency of these parameterizations is their neglect of the droplet concentration and hence the inability to study aerosol indirect effects. It has become increasingly common to parameterize effective radius as a "1/3" power law of the ratio of the liquid water content to the droplet concentration (Bower and Choularton, 1992; Pontikis and Hicks, 1992; Bower *et al.*, 1994; Martin *et al.*, 1994; Liu and Hallett, 1997; Reid *et al.*, 1999; Liu and Daum, 2000a,b; Wood, 2000; McFarquhar and Heymsfield, 2001).

$$r_e = \left(\frac{3}{4\pi\rho}\right)^{1/3} \beta \left(\frac{L}{N}\right)^{1/3} = \beta r_v \ , \qquad (1)$$

where ρ is the density of water, r_e the effective radius, L the liquid water content, N the droplet concentration, and $r_v = (3/4\pi\rho)^{1/3}(L/N)^{1/3}$ is the mean volume radius. According to (1), the nondimensional parameter β is the ratio of the effective radius to the mean volume radius, and is hereafter referred to as radius ratio.

Most developers of cloud parameterizations, however, have focused on specification of the liquid water content and droplet concentration (Rotstayn 1999; Ghan *et al.*, 1997; Lohmann *et al.*, 1999), assuming (explicitly or implicitly) that the radius ratio is a constant (e.g., β =1) or has a negligibly small effect on the evaluation of effective radius and therefore on cloud radiative properties such as cloud albedo (Schwartz and Slingo 1996). A few studies have demonstrated that the radius ratio varies substantially and significantly affects the evaluation of cloud radiative properties (Pontikis and Hicks, 1992; Liu and Hallett, 1997; Liu and Daum, 2000a,b; Wood, 2000; McFarquhar and Heymsfield, 2001). However, studies of the radius ratio are still very limited, and further understanding is needed to eventually incorporate this quantity into cloud parameterizations in climate models.

Virtually all ship-track studies performed so far have contrasted a single, specific ship track with its immediate, unperturbed surroundings, focusing on whether or not ship emissions cause any changes in droplet concentration, liquid water content, or effective radius. No ship- track studies have been geared toward improving cloud parameterizations. We will show in this study that, if they are examined together, these ship-track studies also provide important implications for cloud parameterizations in climate models. Specifically, we will use data from previously published ship-track studies to demonstrate that the radius ratio not only varies dramatically, but also may be smaller than one. This finding further reinforces the notion that assumption of a constant radius ratio can cause substantial errors in the evaluation of cloud radiative properties, and hence in climate simulations.

2. Re-Examination of Previously Published Data

Cloud albedo was the principal quantity examined in early ship-track studies (e.g., Conover, 1966; Coakley *et al*., 1987). Later studies of ship tracks also included microphysical measurements of droplet concentration, liquid water content and effective radius, with the primary motivation to physically understand aerosol-cloud-albedo interactions. Radke *et al*. (1989) and King *et al*. (1993) described the first *in situ* microphysical measurements of ship tracks encountered off the southern California coast in July 1987 during the marine stratocumulus intensive field observation of the First ISCCP Regional Experiment (FIRE). Ferek *et al*. (1998) reported combined satellite and in-situ microphysical measurements for two ship tracks off the Washington coast in 1992. A more comprehensive campaign, the Monterey Area Ship Track (MAST) experiment, was conducted off the California coast in 1994, and the major findings were published in a special issue of Journal of the Atmospheric Sciences (J. Atmos. Sci., 57, No.16, 2000). Values of droplet concentration, liquid water content and effective radius in ship tracks and the corresponding unaffected ambient clouds were tabulated in several studies (King *et al*., 1993; Russell *et al*., 1999; Ackerman *et al*., 2000; Frick and Hopple 2000; Noone *et al*., 2000a,b). The question as to whether or not the radius ratio is a constant for these clouds can be answered by examining the relationship between effective radius and mean volume radius; the latter can be easily calculated from the tabulated liquid water content and droplet concentration.

Figure 1 is a composite scatterplot of effective radius as a function of mean volume radius from these ship-track studies. Also shown are three lines representing three commonly used schemes for the parameterization of effective radius. The "MO" line denotes the parameterization scheme with the radius ratio β =1, which likely corresponds to monodisperse cloud droplet size distributions. The MM and MC lines denote the schemes proposed by Martin *et al*. (1994) to describe marine and continental stratiform

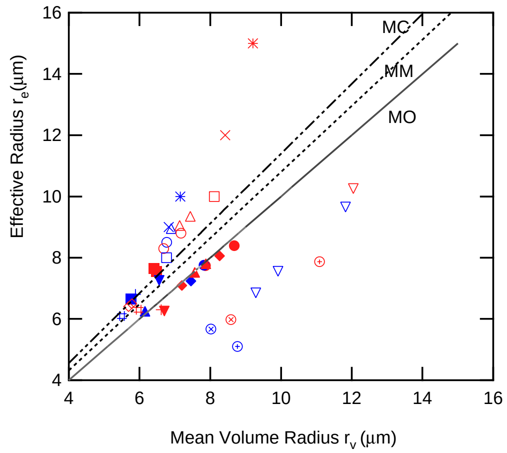

Fig. 1. Relationship between effective radius and mean volume radius. The three lines (MO, MM, and MC) represent the three commonly used schemes of cloud parameterization. (See the text for details). The same symbol denotes the data from the same ship track; the blue (red) color represents the data points inside (outside) the ship track. The data denoted by symbols x, ✳, and □ are from Table 1 of Ackerman et al. (2000); the data denoted by symbols ˋ, +, ▼, and ◇ are from Table 3 of Frick and Hopple (2000); the data denoted by symbols ●, ◆, ▲, and ■ are from Table 5 of Noone *et al*. (2000a); the data denoted by symbols △ and O are from Table 1 of Noone *et al*. (2000a); the data denoted by symbol ∇ are from Table 2 of King *et al*. (1993); the data denoted by symbols ⊕ and ⊗ are from Table 1 of Russell (1999).

clouds, respectively. In this figure, each symbol of the blue and red colors represents the pair of data obtained from the clouds within the ship track and the surrounding clouds, respectively. An examination of just the data points for each individual ship track indicates that both effective and mean volume radii within the ship tracks are generally smaller than those from the surrounding clouds, suggesting that the assumption of a constant radius ratio at least would not qualitatively alter the conclusion regarding the Twomey effect reported by the original authors. On the other hand, an examination of all the data points reveals that each of the three commonly used schemes of the effective radius parameterization describes only a limited number of data points. In fact, for a given mean volume radius, the effective radius differs from case to case so substantially that not a single value of the radius ratio can satisfy all the data points. For the majority of data points, the difference in effective radius is larger than 2 μm. These results suggest that for a given mean volume radius, or equivalently liquid water content and droplet concentration, the estimated effective radius could suffer from an uncertainty larger than 2 μm due to the assumption of a constant radius ratio alone.

An uncertainty of this magnitude in effective radius caused by the assumption of a constant radius ratio alone is significant radiatively as well as climatically. For example, Slingo (1990) showed that the top-of-atmosphere radiative forcing of doubling the CO_2 concentration could be offset by reducing the effective radius of low clouds from 10 μm to between 7.9 and 8.6 μm (approximately 2 μm), depending on the climate model used to make the prediction. A more recent study indicated that a 10% increase in effective radius could increase the surface temperature by about 1.6℃, about the same as predicted for the doubling of the CO_2 concentration (Hu and Stamnes, 2000). Li *et al.* (1999) argued that changing effective radius from 10 μm to 7 μm could substantially reduce a recently reported discrepancy between model-predicted and observed cloud absorption. The mean ocean-land difference in effective radius is from 1.3 to 3.3 μm, and its mean hemispheric difference is from 0.7 to 2.4 μm (Slingo, 1990). Evidently, the uncertainty in effective radius caused by the assumption of a constant radius ratio alone can easily mask these crucial issues listed above. In fact, a closer examination of Fig. 1 reveals that the case-to-case differences in the effective radius caused by the variation of the radius ratio alone are at least comparable to those caused by the perturbation of ship effluents themselves, and thus should not be ignored in studies of ship tracks.

3. Further Analysis

The substantial variability of the radius ratio becomes more evident in Fig. 2. It is particularly interesting to note that some values of the radius ratio are even smaller than one, indicating that the effective radii are smaller than the corresponding mean volume radii. This phenomenon has not been previously reported, although the possibility was pointed out by

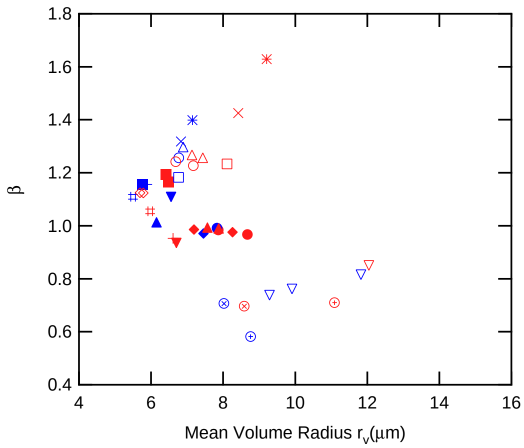

Fig. 2. Same as Fig.1, except that the vertical axis is the radius ratio β.

Martin *et al.* (1994).

It is desirable to express the radius ratio as a function of some commonly used variables to obtain a better physical understanding of the processes that affect it. It has been proved that regardless of droplet size distributions, the radius ratio can be universally expressed as (Martin *et al.*, 1994; Liu and Daum 2000b)

$$\beta = \frac{\left(1+3\varepsilon^2+s\varepsilon^3\right)^{2/3}}{1+\varepsilon^2}, \tag{2}$$

where ε and s are the relative dispersion and the skewness of the cloud droplet size distribution, respectively. According to this equation, the effective radius equals the mean volume radius (i.e., β = 1) when either of the following conditions is met:

$$\varepsilon = 0, \tag{3a}$$

or

$$s = \frac{\left(1+\varepsilon^2\right)^{3/2} - 1 - 3\varepsilon^2}{\varepsilon^3}, \tag{3b}$$

The first condition given by (3a) is straightforward because it means that the droplet size distribution is monodisperse. This condition is probably the most widely used assumption (implicit or explicit) in studies of cloud parameterizations and indirect aerosol effects, including ship tracks. However, it is well known in cloud physics that this situation never occurs in real clouds. Broader droplet size distributions have been observed even in the so-called adiabatic cores of clouds where the narrowest droplet size distributions are expected (Brenguier and Chaumat, 2001). Understanding the so-called spectral broadening remains a central issue in cloud physics (Liu *et al.*, 2002). To further explore the more realistic scenario described by (3b), Fig. 3 shows the dependence of the skewness on the relative dispersion for three selected values of the radius ratio. The dashed curve and the dotted curve approximately represent the lower limit ($\beta = 0.5$) and the upper limit ($\beta = 1.8$) of the observed values of the radius ratio β shown in Fig. 2, and the solid curve represents the critical case of $\beta = 1$. Equation (3b) indicates that the radius ratio is smaller than one (i.e., effective radius is smaller than mean volume radius) when $s < \left[\left(1+\varepsilon^2\right)^{3/2} - 1 - 3\varepsilon^2\right] / \varepsilon^3$, or below the solid curve in Fig. 3. It is noteworthy that for the other scenario of the relative dispersion $\varepsilon = 0$, although the radius ratio $\beta = 1$ mathematically holds regardless of the value of the skewness, the skewness is likely equal to zero in reality because $\varepsilon = 0$ often corresponds to a monodisperse cloud droplet size distribution.

A simple mathematical analysis of Eq. (3b) reveals that as long as $\varepsilon <$ sqrt[3+2sqrt(3)] ~ 2.54, a value of radius ratio smaller than one requires a negative skewness. This means that a radius ratio smaller than one virtually always means a negative skewness because observed relative dispersions hardly exceed 2.54. It is noteworthy that values of relative dispersion larger than 2.54 were reported in Wood (2000) and McFarquhar and Heymsfield (2001), but droplet size distributions in those clouds were bimodal (a droplet mode plus a drizzle mode) and had values of radius ratio much larger than one. For non-precipitating clouds, Liu and Daum (2000a,b) showed that skewness often is an increasing function of the relative dispersion. What causes this phenomenon remains unknown. Also noteworthy is that most data points with the radius ratio $\beta < 1$ exhibits an increase of β with increasing mean volume radius, suggesting the possible influences of turbulent entrainment-mixing and drizzle processes.

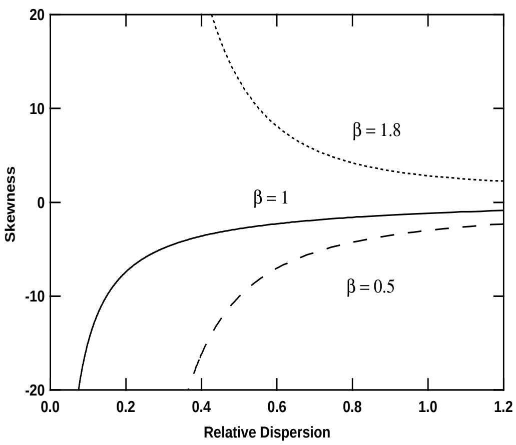

Fig. 3. Relationships between the skewness and relative dispersion of the droplet size distribution for the three selected values of β.

It is known that ship tracks occur only under certain meteorological conditions. Not every ship causes a ship track; ship tracks appear to form in certain locations but not in others; ship tracks seem to occur in clusters (on days when ship tracks occur, they seem to be plentiful; on days when ship tracks fail to materialize, even a hint of a ship track is difficult to discern despite the abundance of low-level clouds). Although a few conditions that favor the formation of ship tracks have been proposed, their details remain largely elusive (Durkee *et al.*, 2000; Coakley *et al.*, 2000). Values of radius ratio smaller than one have not been reported in previous studies of other clouds despite the fact that studies of this kind are plentiful (e.g., Liu and Daum, 2000a,b; Pawlowska and Brenguier, 2000). It is thus likely that this microphysical phenomenon is unique to clouds conducive to ship-track formation. If this phenomenon proves to be true, radius ratio smaller than one and the associated combination of skewness and relative dispersion can serve as a microphysical signature of clouds conducive to ship-track formation. Investigation of this phenomenon may facilitate understanding the macroscopic as well as the microscopic conditions for ship-track formation.

Furthermore, previous studies that did not involve ship tracks showed larger values of radius ratio for more polluted continental clouds because of the enhanced relative dispersion by increased aerosol loading (Martin *et al*., 1994; Liu and Daum, 2002; Liu *et al*., 2006; Yum and Hudson, 2005; Peng *et al*., 2007). Although this notion is supported by some of the data points where the values of radius ratio are larger inside the ship tracks than their counterparts outside the ship tracks, a closer look at Fig. 2 reveals that there are several cases where the radius ratio is smaller in the clouds within the ship track than in the clouds surrounding the ship track. This phenomenon is also unique in the sense that the clouds within the ship tracks are relatively more polluted than those surrounding them, and may be caused by the competing dynamical effects associated with ship tracks. Interestingly both branches of the radius ratio $\beta > 1$ and $\beta < 1$ exhibit the decreasing trend of radius ratio for the clouds within the ship track, but not for the branch that stays close to $\beta = 1$. The decrease of radius ratio could be caused by the decrease of skewness. It may also be caused by the changes in relative dispersion but with an opposite trend for $\beta > 1$ (decrease) and $\beta < 1$ (increase) (Fig. 3). Further analyses are definitely required to make valid interpretation of this unique behavior.

There is also a possibility that instrumental problems and/or data averaging procedures contributed to the cases with radius ratio $\beta < 1$. According to the original work where the data are from, the values for ship tracks are averaged over the ship tracks and those for background clouds are averaged over the similar size of the corresponding ship tracks. On one hand, a much larger variability is expected if high frequency data are used. On the other hand, the averaging procedure may cause some errors in the calculation of effective radius and mean volume radius. However, the errors caused by the averaging procedure are likely to be systematic, unlike the variability shown in Fig. 1. Another possible source of error stems from the condition that some studies reported liquid water content measured with a Particulate Volume Monitor (PVM) probe while the effective radius and droplet concentration are derived from the measurements of cloud droplet size distributions with a Forward Scattering Spectrometer Probe (FSSP). The error due to the use of PVM-measured liquid water content is also likely systematic. Furthermore, a majority of studies comparing the measurements of liquid water content with PVM and FSSP probes (e.g., Wendisch, 1998; Gerber, 1999) indicates that they agree well when droplets are small (e.g., effective radius < 9 μm according to Wendisch 1998), but PVM measurements tend to be smaller than those measured by FSSP when larger drops exist. Therefore, using PVM-measured liquid water content in the calculation of mean volume radius would cause little errors when droplets are small, and an underestimation of the mean volume radius (overestimation of the radius ratio) when big drops exist. The latter indicates even smaller values of radius ratio. Using PVM-measured liquid water content could not explain the observation of effective radius being smaller than mean volume radius. It should be noted that the FSSP suffers from both sizing and counting deficiencies as well (Dye and Baumgardner, 1984; Baumgardner *et al*., 1985; Baumgardner and Spowart, 1990), which in turn can cause errors in the measurements of effective and mean volume radii (Gerber, 1996; Wendisch, 1998). However, the FSSP instrumental deficiencies are expected to have minimal effect on the radius ratio because it is a ratio of two quantities which are similarly affected. It is also noteworthy that the number of data presented here is very limited, with a total of 40 samples, 18 samples with the radius radio $\beta < 1$, and 8 samples with $\beta < 0.9$. In view of these potential problems, the phenomenon that the radius ratio is smaller than one and the physical reason for it remains a mystery awaiting a solution, and calls for more comprehensive investigation.

4. Concluding Remarks

It is shown that crucial insights both into cloud parameterizations in climate models and into understanding ship-track phenomena can be obtained if an assembly of ship tracks are studied together, in addition to the indirect aerosol effects identified by examining individual ship tracks. Our comparison analysis of previously published ship-track studies suggests that the radius ratio varies substantially for a given mean volume radius (or given liquid water content and droplet concentration). In particular, it is found that the radius ratio can be less than one when the cloud droplet size distribution is negatively skewed. The differences in the effective radius caused by the variation of radius ratios alone can be larger than 2 μm, suggesting that the assumption of a constant radius ratio alone, if not addressed properly, can cause errors in the parameterization of effective radius that are large enough to substantially affect the outcome of climate models, even if the droplet concentration and liquid water content are accurately known. An uncertainty of 2 μm is also within the most observed changes of the effective radius in ship tracks. Because the development of cloud parameterizations has primarily focused on specifying droplet concentration and liquid water content, with the effect of the radius ratio being neglected, it is likely that the uncertainties involved in climate models and the projection of climate change are even larger than those currently believed. To reduce these uncertainties, the radius ratio in addition to liquid water content and droplet concentration has to be adequately specified in climate models. In fact, the importance of the radius ratio is also evident from a theoretical point of view. A key task of cloud microphysics is to understand and quantify the spectral shape of the cloud droplet size distribution, that is, how a given amount of water is distributed among a known number of droplets (Pruppacher and Klett, 1997; Liu *et al*., 2002). Because the spectral shape determines the radius ratio, neglecting the radius ratio in the parameterization of cloud microphysics literally means neglecting a fundamental variable of cloud microphysics. An accurate specification of the radius ratio will at least require knowledge of pre-cloud aerosol properties (Liu and Daum, 2002) and cloud turbulence (Liu *et al*., 2002).

The terminology of "droplet size" has been sometimes utilized ambiguously in studies of indirect aerosol effects (including ship tracks). For example, the mean square radius was used in Twomey *et al.* (1968), while Twomey (1977) argued that the use of either the mean radius or the mean volume radius should be sufficiently appropriate. The dramatic variation in the radius ratio presented here disproves this practice. The variation of the radius ratio with aerosol loading and dynamics also poses new challenges to understanding ship tracks.

It should be pointed out that many questions regarding the new phenomenon of the radius ratio less than one reported here remain to be answered. For example, what is the frequency of occurrence? What causes this phenomenon? Does this phenomenon only occur in clouds conducive to ship-track formation? Does this phenomenon result from some instrumental deficiencies used to obtain relevant quantities? More comprehensive investigation is needed to answer these questions.

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