BNL-69295

SHIP TRACKS REVISITED: IMPLICATIONS FOR CLOUD PARAMETERIZATIONS IN CLIMATE MODELS AND UNDERSTANDING OF SHIP TRACK PHENOMENA

Y. Liu* and P. H. Daum
Atmospheric Sciences Division
Brookhaven National Laboratory
Upton, NY 11973

May 2002

Submitted for publication in
J. Climate

* Corresponding author: Yangang Liu, Brookhaven National Laboratory, Atmospheric Sciences Division, Bldg. 815E, 75 Rutherford Dr., Upton, NY 11973-5000; Tel: 631-344-3266; Fax: 631-344-2887; Email: lyg@bnl.gov.

Research by BNL investigators was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

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 (indirect aerosol effect). 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 a ship track to those of surrounding clouds on an individual track-by-track basis. The primary objective of this note is to show that 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 if they are examined together. This is realized by reexamining the data from previously published ship-track studies. This reanalysis reveals an important factor, which depends on how a given amount of water is distributed amongst a known number of droplets and has been largely ignored in cloud parameterizations. Observational evidence is found that the effective radius can be smaller than the mean cube radius for clouds conducive to the formation of ship tracks unlike results from general stratiform clouds where the effective radius is often larger than the mean cube radius. The relation between this new factor and the shape descriptors (relative dispersion and skewness) of the droplet size distribution is further examined, revealing that clouds with the effective radius smaller than the mean cube radius likely have negatively skewed droplet size distributions.

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 (1977a, b, 1984) 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 serve 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 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 aerosols also enhance liquid water content 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. 1990; 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 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 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.

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 total droplet concentration (Stephens 1978; Fouquart et al 1989). 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 2000; Wood 2000; McFarquhar and Heymsfield 2001)

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

where ρ is the density of water, r_e the effective radius, L the liquid water content, N the droplet concentration, and β a nondimensional parameter depending on the spectral shape of the cloud droplet size distribution. The inclusion of droplet concentration in the parameterization of effective radius not only makes it feasible to investigate the indirect aerosol effect using this equation (Rotstayn 1999; Ghan et al. 1997; Lohmann et al. 1999), but also in some sense unifies the study of indirect aerosol effects and the development of cloud parameterizations.

Most developers of cloud parameterizations, however, have focused on specification of the liquid water content and droplet concentration, assuming (explicitly or implicitly) that β 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 β 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). But, studies of β are very limited, and further understanding is needed to eventually incorporate this quantity into 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 and liquid water content. No ship-track studies have been geared toward improving cloud parameterizations. We will show in this note that, if they are examined together, these ship-track studies also provide important implications for cloud parameterizations in climate models. Specifically, we will demonstrate using data from previously published ship-track studies, that β not only varies dramatically, but also that its value can be smaller than one. Therefore, the assumption of a constant β 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 motivation to physically understand aerosol-cloud-albedo interactions. Radke et al. (1989) and King et al. (1993) describe 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 recently published in a special issue of Journal of the Atmospheric Sciences for. (JAS Vol. 57, No.16, 2000). Values of droplet concentration, liquid water content and effective radius in the 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 et al. 2000; Noone et al. 2000a, b). These tabulated microphysical data provide a unique opportunity to verify the assumption of a constant β and to explore the implications of ship-track studies for both cloud parameterization and ship-track characterization.

Equation (1) can be rewritten as

$$r_e = b r_v , \qquad (2)$$

where $r_v = (3/4\pi\rho)^{1/3}(L/N)^{1/3}$ is the mean cube radius which can be easily calculated from liquid water content and droplet concentration. Therefore, the question as to whether or not β is a constant can be answered by examining the relationship between effective radius and mean cube radius; combining data on the effective radius and the mean cube radius from the different ship-track studies provides a broader context for understanding the two ways of specifying droplet sizes.

Figure 1 is a composite plot of effective radius as a function of mean cube radius from a number of ship-track studies in which both variables were explicitly reported. Also shown are three lines representing three commonly used schemes for the parameterization of effective radius. The "MO" line denotes the parameterization scheme with β =1, which holds only when the cloud droplet size distributions are monodisperse. The MM and MC lines denote the schemes proposed by Martin et al. (1994) to describe marine and continental stratiform clouds, respectively. In this figure, the same symbol denotes the data from the same ship-track, and the blue (red) color represents the data points inside (outside) the ship track. As shown in Fig.1, for each individual ship track, both the effective radius and the mean cube radius inside the ship track are smaller than outside the track as reported by the original authors, suggesting that the assumption of a constant β at least would not affect the qualitative conclusion regarding the influences of ship emissions on effective radius. However, an examination of the data points from all the ship-tracks reveals that each of the three commonly used schemes of cloud parameterization describes only a limited number of data points. In fact, at a given mean cube radius, effective radius differs from case to case so substantially that no a single value of β can satisfy all the data points. For the region of the mean cube radius ~ 6 μm, the majority of data points exhibit a difference in effective radius larger than 2 μm. For a mean cube radius ~ 8.5 μm, the difference in effective radius is even larger, reaching as large as ~ 9 μm. These results suggest that for a given mean cube radius (or liquid water content and droplet concentration), the estimated effective radius could suffer from an uncertainty ranging from 2 μm to 9 μm due to the assumption of a constant β alone.

An uncertainty of this magnitude (2 - 9 μm) in effective radius caused by the assumption of a constant β alone is significant. 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 ^{0}C, 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 the mean hemispheric difference in effective radius is from 0.7 to 2.4 μm (Slingo 1990). Evidently, the range of uncertainty in effective radius caused by the assumption of a constant β alone may easily mask these crucial issues listed above. In fact, a closer examination of Fig. 1 reveals that differences in effective radius from case to case are at least comparable to those caused by the perturbation of ship effluents themselves.

3. Further Analysis

The substantial variability of β becomes more evident in Fig. 2, which shows β as a function of the mean cube radius. It is particularly interesting to note that β can be smaller than one, indicating that effective radius can even be smaller than the mean cube radius. This phenomenon has not been previously reported, although the possibility was pointed out by Martin et al. (1994).

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

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

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

$$\varepsilon = 0, \qquad (3a)$$

or

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

The condition given by (3a) is straightforward because it means that the droplet size distribution is monodisperse. This is probably the most widely used assumption (implicit or explicit) in the study 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). To further explore the more realistic case described by (3b), Fig. 3 shows the dependence of the skewness on the relative dispersion for three typical values of β. The dashed curve and the dotted curve approximately represent the lower limit (β = 0.5) and the upper limit (β = 1.8) of the observed values of β shown in Fig. 2, and the solid curve represents the critical case of β = 1. Equation (3b) indicates that effective radius is smaller (larger) than mean cube radius when $s <\ (>) \left[\left(1+\varepsilon^2\right)^{3/2}-1-3\varepsilon^2\right]\big/\varepsilon^3$, or below (above) the solid curve in Fig. 3.

A simple mathematical analysis of Eq. (3b) reveals that as long as ε < sqrt[3+2sqrt(3)] ~ 2.54, a value of β smaller than one means a negative skewness. This means that a value of β smaller than one virtually always means a negative skewness because observed relative dispersions hardly ever 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 β much larger than one. Unfortunately, we cannot investigate the relationship between skewness and relative dispersion because the data are not available to us. Nevertheless, the cases with β smaller than one indeed tend to be negatively skewed, monomodal droplet size distributions, for example those shown in Russell et al. (1999) and Noone et al. (2000a). What causes this phenomenon remains unknown.

It is known that ship tracks only occur under certain meteorological conditions. For example, 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 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 remains largely elusive (Durkee et al. 2000; Coakley et al. 2000). Values of β smaller than one have not been reported in previous studies of general clouds despite the fact that studies of this kind are plentiful. It is thus likely that this phenomenon is unique to clouds conducive to ship-track formation. If this proves to be true, a value of β less 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.

4. Concluding Remarks

It is shown that crucial insights into both cloud parameterizations in climate models and into understanding ship-track phenomena can be obtained if an assembly of ship tracks is studied together. Our comparison analysis of previously published ship-track studies strongly suggests that not only β varies, but that this variation, 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. Because the development of cloud parameterizations has primarily focused on specifying droplet concentration and liquid water content, with the effect of β 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, β in addition to liquid water content and droplet concentration has to be adequately specified in climate models. Furthermore, because a smaller effective radius could be due to a smaller β, not necessarily to a larger droplet concentration, a reduced effective radius does not necessarily indicate the appearance of the Twomey effect. It should also be pointed out that 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). Twomey (1977a) argued that use of either the mean radius or the mean cube radius should be sufficiently accurate. The results presented here strongly suggest that one should at least clearly state the characteristic size being used to describe the droplet size distribution because of the effect of β.

Observational evidence of clouds with β less than one is reported here for the first time. Many questions regarding this new phenomenon remains to be answered. For example, what is the frequency of occurrence? What causes this phenomenon? Whether or not this phenomenon only occurs in clouds conducive to ship track formation? In study of the data collected in non-precipitating stratocumulus clouds, we recently found that β can be represented as a unique function of the relative dispersion because skewness is a unique function of the relative dispersion for those clouds (Liu and Daum 2000a, b). We also found wide variability of the relative dispersion and hence β, and called for the specification of the relative dispersion in climate models. The occurrence of values of β smaller than one in these ship-track studies further reinforces the need to specify β in addition to liquid water content and droplet concentration. However, the problem appears to be more difficult in this case because of the possible involvement of both skewness and relative dispersion. Statistical analysis of β, relative dispersion, skewness, and their mutual relationships is clearly in order.

In fact, the importance of β 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). Because the spectral shape determines β, neglecting β in the parameterization of cloud microphysics literally means neglecting a fundamental variable of cloud microphysics.

Acknowledgments

We would like to acknowledge constructive discussions with Dr. S. E. Schwartz of the Brookhaven National Laboratory. This research was supported by the Environmental Sciences

Division of the US Department of Energy, as part of the Atmospheric Radiation Measurement Program and was performed under contract DE-AC02-98CH10886.

References

Ackerman, A. S. et al., 2000: Effects of aerosols on cloud albedo: Evaluation of Twomey's parameterization of cloud susceptibility using measurements of ship tracks. *J. Atmos. Sci.*, **57**, 2684 -.

Bower, K. N. and T. W. Choularton, 1992: A parameterization of the effective radius of ice-free clouds for use in global climate models. *Atmos. Res.*, **27**, 305 – 339.

Bower, K. N., T. W. Choularton, J. Latham, J. Nelson, M. B. Baker, and J. Jensen, 1994: A parameterization of warm clouds for use in atmospheric general circulation models. *J. Atmos. Sci.*, **51**, 2722-2732.

Brenguier, J. L. and L. Chaumat, 2001: Droplet spectra broadening in cumulus clouds. Part I: Broadening in adiabatic cores. *J. Atmos. Sci.* **58**, 628-641.

Coakley, J. A., R. L. Bernstein, and P. A. Durkee, 1987: Effect of ship-track effluents on cloud reflectivity. *Science*, **237**, 1020-1022.

Conover, J. H., 1966: Anomalous cloud lines. *J. Atmos. Sci*. **23**, 778-785.Ghan, S. J., L. R. Leung, R. C. Easter, and H. Abdul-Razzak, 1997: Prediction of cloud droplet number in a general circulation model. *J. Geophys. Res.*, **D102**, 21,777-21,794.

Durkee, P. A., K. J. Noone, and R. T. Bluth, 2000: The Monterey Area Ship Track Experiment. *J. Atmos. Sci.*, **57**, 2523-2541.

Frick, G. M., and W. A. Hoppel, 2000: Airship measurements of ship's exhaust plumes and their effect on marine boundary layer clouds, *J. Atmos. Sci.*, **57**, 2625-2648.

Fouquart, Y., J. C. Buriez, and H. Herman, 1989: The influence of boundary layer clouds on radiation. A review. *Atmos. Res*. **23**, 203-228.

Hansen, J. E., and L. D. Travis, 1974: Light scattering in planetary atmosphere. *Space Sci. Rev*., **16**, 527-610.

Hu, Y., and S. Stamnes, 2000: Climate sensitivity to cloud optical properties. *Tellus*, **52B**, 81-93.

Jones, A., D. L. Roberts, and A. Slingo, 1994: A climate model study of indirect radiative forcing by anthropogenic sulfate aerosols. *Nature,* **370**, 450-453.

King, M. D., L. F. Radke, and P. V. Hobbs, 1993: Optical properties of marine stratocumulus clouds modified by ships. *J. Geophys. Res*., **D98**, 2729-2739.

Li, Z., A. P., Trishchenko, H. W. Barker, 1999: G. L. Stephens, and P. Partain, Analyses of Atmospheric Radiation Measurement (ARM) Program's Enhanced Shortwave Experiment (ARESE) multiple data sets for studying cloud absorption. *J. Geophys. Res*., **D104**, 19127-19134.

Liu, Y., and J. Hallett, 1997: The “1/3” power-law between effective radius and liquid-water content. *Q. J. R. Meteor. Soc*., **123**, 1789-1795.

Liu, Y., and P. H. Daum, Spectral dispersion of cloud droplet size distributions and the parameterization of cloud droplet effective radius, Geophys. Res. Lett., 27, 1903-1906 (2000).

Lohmann, U., J. Feichter, C. C. Chuang, and J. E. Penner, 1999: Prediction of the number of cloud droplets in the ECHAM GCM. *J. Geophys. Res*., **D104**, 9169-9198.

McFarquhar, G. M., and A. J. Heymsfield, 2001: Parameterizations of INDOEX microphysical measurements and calculations of cloud susceptibility: Applications for climate studies. *J. Geophys. Res*., **D106**, 28675-28698.

Martin, G. M., D. W. Johnson, and A. Spice, 1994: The measurement and parameterization of effective radius of droplets in the warm stratocumulus clouds. *J. Atmos., Sci*., **51**, 1823-1842.

Noone, K. J., et al. 2000a: A case study of ships forming and not forming tracks in moderately polluted clouds. *J. Atmos. Sci*., **57**, 2729-2747.

Noone, K. J., et al. 2000b: A case study of ships track formation in a polluted marine boundary layer. *J. Atmos. Sci*., **57**, 2748-2764.

Pontikis, C., and E. M. Hicks, 1992: Contribution to the droplet effective radius parameterization. *Geophy. Res. Lett*., **19**, 2227-2230.

Radke, L. F., J. A. Coakley, and M. D. King, 1989: Direct and remote sensing observations of the effects of ships on clouds. *Science*, **246**, 1146-1149.

Reid, S. J., P. V. Hobbs, A. L. Rangno, and D. A. Hegg, 1999: Relationship between cloud droplet effective radius, liquid water content, and droplet concentration for warm clouds in Brazil embedded in biomass smoke. *J. Geophy. Sci*., **D104**, 6145-6153.

Rotstayn, L. D., 1999: Indirect forcing by anthropogenic aerosols: A global climate model calculation of the effective-radius and cloud-lifetime effects. *J. Geophys. Res*., **D104**, 9369 – 9380 .

Russell, L. M. et al., 1999: Aerosol dynamics in ship tracks. *J. Geophys. Res*., **D104**, 31077-95.

Slingo, A., 1989: A GCM parameterization for the shortwave radiative properties of water clouds. *J. Atmos. Sci*., **46**, 1419 – 1427.

Slingo, A, 1990: Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature*, **343**, 49-51.

Smith, R. N. B., 1990: A scheme for predicting layer clouds and their liquid water content in a general circulation model. *Q. J. R. Meteor. Soc*., **116**, 435-460.

Stephens, G. L., 1978: Radiation profiles in extended water clouds. II: Parameterization schemes. *J. Atmos. Sci*, **35**, 2123-2132.

Stokes, G. M., and S. E. Schwartz, 1994: Atmospheric Radiation Measurement (ARM) Program: Programmatic background and design of the cloud and radiation testbed. *Bull. Amer. Meteoro. Soc.*, **75**, 1201-1227.

Sundqvist, H., 1993: Parameterization of clouds in large-scale numerical models. In "Aerosol-Cloud-Climate Interactions". Eds. P. V. Hobbs, Academic Press, Sab Diego, 175-203.

Twomey, S., 1974: Pollution and the planetary albedo. *Atmos. Environ.*, **8**, 1251-1256.

Twomey, S., 1977: The influence of pollution on the short-wave albedo of clouds, *J. Atmos. Sci*, **34**, 1149-1152.

Twomey, S., H. B. Howell, and T. A. Wojciechowski, 1968: Comments on "Anomalous cloud lines". *J. Atmos. Sci*, **25**, 333-334.

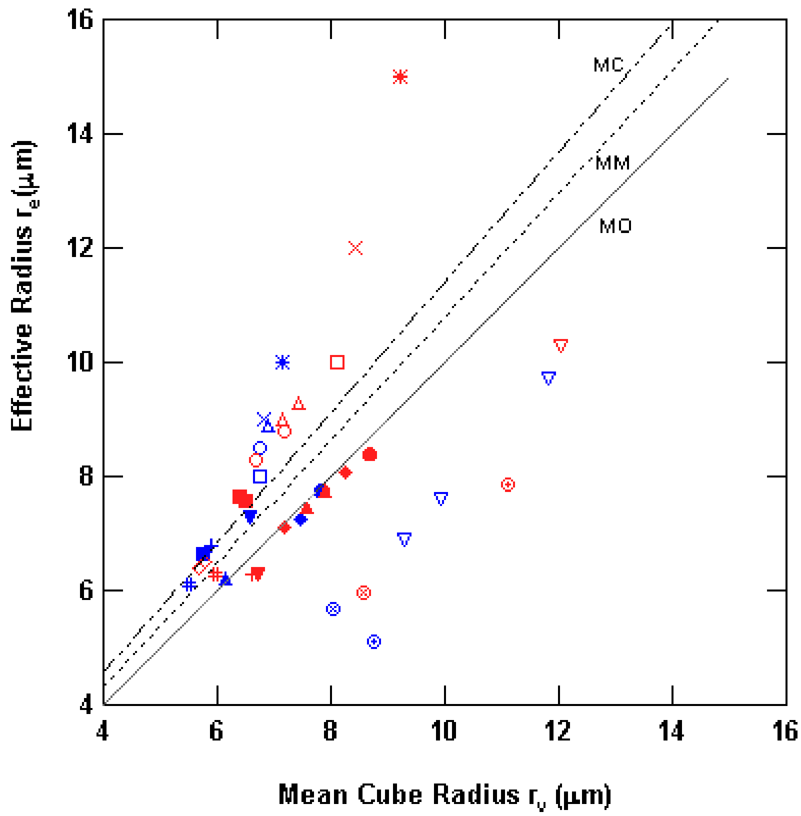
Wood, R., 2000: Parameterization of the effect of drizzle upon the droplet effective radius in stratocumulus clouds. *Q. J. R. Meteor. Soc.*, **126**, 3309-3324.

FIGURE CAPTIONS

Fig. 1. Relationship between effective radius and volume mean radius. The three lines represent the three commonly used schemes of cloud parameterization. The same symbol denotes the data from the same ship-track; the blue (red) color represents the data points inside (outside) the ship track: x = Ackerman et al. (2000); ✳= Ackerman et al. (2000); = Ackerman et al. (2000); # = Frick et al. (2000); + = Frick et al. (2000); = Frick et al. (2000); ◇ = Frick et al. (2000); ● = Noone et al. (2000a); ◆ = Noone et al. (2000a); ▲ = Noone et al. (2000a); ■ = Noone et al. (2000a); △ = Noone et al. (2000b); O = Noone et al. (2000b); ∇ = King et a. (1993); ⊕ = Russell (1999); ⊗ = Russell (1999). MO, MM, and MC represent three commonly used parameterizations schemes (See the text for details).

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

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



16
14
12
10
8
6
4
4
6
8
10
12
14
16
MC
MM
MO
Effective Radius r_e (μm)
Mean Cube Radius r_v (μm)

Fig. 1

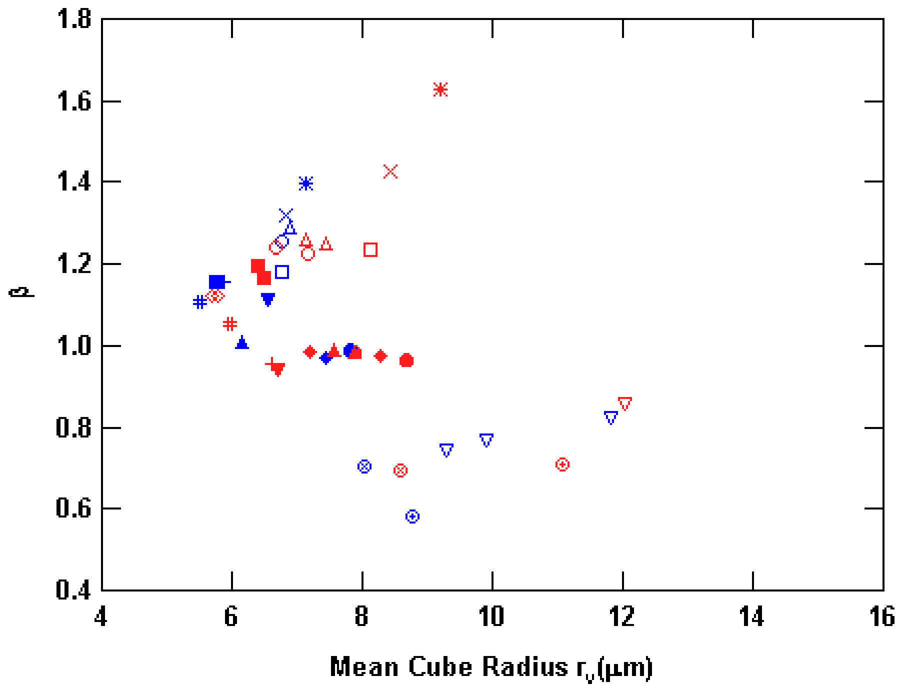


Fig. 2.

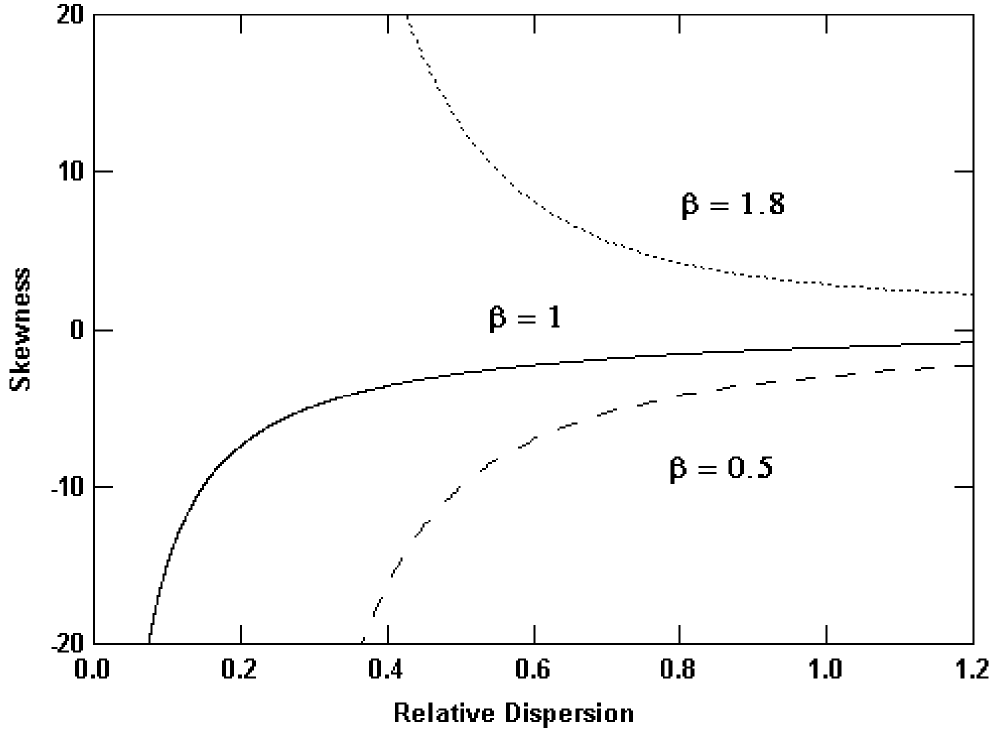

20
10
0
-10
-20
Skewness
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Relative Dispersion
β = 1.8
β = 1
β = 0.5

Fig. 3.