Small, highly reflective ice crystals in low-latitude cirrus

T. J. Garrett,[1] H. Gerber,[2] D. G. Baumgardner,[3] C. H. Twohy,[4] and E. M. Weinstock[5]

Received 11 July 2003; revised 18 August 2003; accepted 9 October 2003; published 15 November 2003.

[1] At low latitudes, cirrus are ubiquitous and can be in excess of 100°C colder than the surface, limiting the amount of sunlight absorbed by the earth's atmosphere and surface, and reducing its loss of heat. Here we present aircraft measurements within cirrus over southern Florida indicating that ice crystals have smaller sizes and are more reflective than is assumed in most current climate models. If the measurements are generally representative of low-latitude cirrus, they point to a first-order correction to representations of how these clouds affect the earth's climate. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Garrett, T. J., H. Gerber, D. G. Baumgardner, C. H. Twohy, and E. M. Weinstock, Small, highly reflective ice crystals in low-latitude cirrus, *Geophys. Res. Lett.*, *30*(21), 2132, doi:10.1029/2003GL018153, 2003.

1. Introduction

[2] Cirrus cloud coverage and albedo limits the input of solar energy to the climate system. The magnitude of solar flux transmitted and reflected by these clouds is determined in part from knowledge of how light is scattered by ensembles of ice crystals. In climate models, the dimensionless terms used to define this scattering are the asymmetry parameter g, which represents the degree to which light is scattered in the direction of the incident beam, and the optical depth τ, which denotes the vertically integrated extinction. From these parameters, the fraction of solar radiation reflected to outer space α (the albedo) is approximately

$$\alpha \simeq \frac{\tau'}{1+\tau'} \tag{1}$$

where, $\tau' = \sqrt{3}/2(1-g)\tau$ [*Meador and Weaver*, 1980].

[3] Unfortunately, for cirrus clouds, the parameters g and τ are not well constrained. The asymmetry parameter g depends solely on ice crystal shape and size. Climate models often assume ice crystals are hexagonal prisms, with lengths between 20 and 300 μm, to obtain theoretical values of g between 0.77 and 0.84 [*Takano and Liou*, 1989]. However, ice crystals usually have irregular shapes [*Heymsfield and McFarquhar*, 1996; *Korolev et al.*, 1999], and recent measurements in extra-tropical ice clouds show values of g generally lower, between 0.73 and 0.78 [*Gerber et al.*, 2000; *Garrett et al.*, 2001; *Auriol et al.*, 2001].

[4] The optical depth τ of a uniform cloud layer of thickness Δz is just $\beta\Delta z$, where the extinction coefficient at visible wavelengths β can be expressed [*Foot*, 1988] as a function of the mass concentration of condensed water W, an ice crystal "effective radius" r_e, and the bulk ice density, ρ, as

$$\beta = \frac{3W}{2\rho r_e} \tag{2}$$

To obtain τ and g, climate models normally predict W, and derive β using an assumed value of r_e that is either fixed, or dependent on W or cloud temperature T [*McFarquhar et al.*, 2003]. Such parameterizations are typically based on *in situ* aircraft observations. For example, in tropical cirrus, these show r_e varying between 30 μm and 220 μm for T between -70 and -20°C [*Heymsfield and McFarquhar*, 1996], and r_e increasing from about 10 μm to 60 μm for W between 0.0001 and 1.0 $g\ m^{-3}$ [*McFarquhar et al.*, 2003]. Unfortunately, few studies to date have sampled the extreme tops of low-latitude cirrus, and airborne cloud microphysical probes used in such studies do not measure r_e directly, but rather estimate it from measurements of distributions of ice crystal length. This requires an assumed ice crystal density and morphology, two parameters not well constrained observationally. Further, there is considerable skepticism regarding the accuracy of size distribution probe measurements of individual ice crystals smaller than about 50 μm diameter [*Gardiner and Hallett*, 1985; *Arnott et al.*, 2000].

2. Measurements

[5] Rather than integrate size distributions of ice crystals, a more direct approach to obtaining r_e in cirrus is to simultaneously measure bulk W and β directly and hence derive r_e from equation 2. This was first achieved in low-latitude cirrus, sampled between 15° and 27°N, during the July 2002 NASA CRYSTAL-FACE experiment, based from Key West, Florida.

[6] Microphysical data were obtained by two aircraft, the NASA WB-57F and the University of North Dakota Citation Cessna II, which sampled the full vertical extent of troposphere cloudy air up to 15.2 and 12.6 km altitude, respectively. The measurements presented here are based on 13 days and 52 hours of in-cloud flight, and 6 days and 8 hours of in-cloud flight, from the Citation and WB-57 respectively. Aircraft flight was based primarily on horizontal transects within anvil cirrus, away from the convective core.

[7] Bulk measurements of W were obtained using two instruments. Aboard the WB-57F, W was measured by subtracting measurements of water vapor from total water

[1]Meteorology Department, University of Utah, USA.
[2]Gerber Scientific Inc., USA.
[3]Universidad Nacional Autonoma de Mexico, Mexico.
[4]College of Oceanography and Atmospheric Science, Oregon State University, USA.
[5]Department of Chemistry and Chemical Biology, Harvard University, USA.

0094-8276/03/2003GL018153$05.00

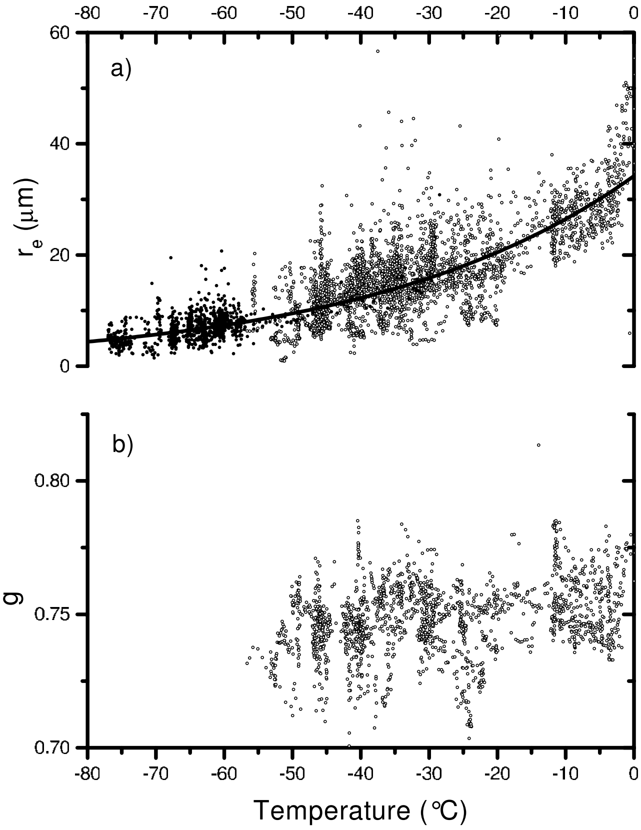

Figure 1. Effective radius r_e (a) and asymmetry parameter g (b) versus temperature T within cirrus anvils sampled during CRYSTAL-FACE. Measurements from the NASA WB-57 are shown by dots and from the UND Citation by circles. The estimated measurement uncertainties in r_e are ±30% and ±50%, respectively, and ±0.02 in g. Each point represents the average for 10 s of flight time. A fit to the r_e data (solid line), explaining 62% of the variance, is $r_e = 5\ \exp\left(\frac{T+75}{39}\right)$. The standard deviation from the fit is ~5 μm and ~2.5 μm above and below -60°C, respectively.

using an instrument which coupled an isokinetic inlet and heater with photofragment fluorescence detection [*Weinstock et al.*, 1994]. Ice water content on the Citation was measured using a counterflow virtual impactor [*Twohy et al.*, 1997, 2003], which separated ice crystals from interstitial water vapor and evaporated the ice phase. The resulting water vapor was then measured using a Lyman-alpha absorption hygrometer.

[8] Measurements of β on both aircraft were obtained using the Gerber Scientific Inc. Cloud Integrating Nephelometer (CIN), which uses four lambertian sensors spanning 10° to 175° to measure the intensity of 635 nm laser light scattered by cloudy air. The fraction of light energy scattered in the forward 10° is estimated to be 0.57 ± 0.02 [*Gerber et al.*, 2000]. This value is narrowly constrained since, for particles large with respect to the laser wavelength, forward diffraction represents half of total scattered energy. Two of the CIN channels have "cosine masks" which permitted the first *in situ* measurements in low-latitude cirrus of g at visible wavelengths with an approximate accuracy of ±0.02. During CRYSTAL-FACE, however, these channels both functioned only aboard the Citation. All bulk measurements had an approximate accuracy of ±15%.

[9] Aboard the WB-57F, simultaneous measurements of size and area distributions were obtained using a Droplet Measurement Technologies Cloud Aerosol and Precipitation Spectrometer [*Baumgardner et al.*, 2002]. The estimated uncertainty in particle area concentrations derived from these data is ±50%.

[10] Measurements of r_e, g, and ice crystal size distributions are shown in Figures 1 and 2. In contrast with earlier studies from tropical cirrus anvils [*McFarquhar et al.*, 2003], values of r_e derived from CRYSTAL-FACE bulk probe measurements are independent of bulk microphysics; within any 10°C temperature interval, log W and logβ were highly correlated with one another over three orders of magnitude ($r^2 > 0.9$), with a slope near unity. Thus each independently accounted for less than 10% of the variance in r_e. Rather, the data show that r_e depends primarily on temperature (Figure 1a), increasing monotonically from approximately 5 μm at -75°C to 30 μm at freezing. No data for g are available for temperatures below -55°C, however the data suggest that below 0°C, g is only weakly dependent on temperature (Figure 1b). Measured values of g were 0.75 ± 0.01. At temperatures above 0°C, however, g equaled 0.86 ± 0.01, which is consistent with values expected for spherical water droplets characteristic of liquid water clouds. Measured distributions of the projected ice crystal area were generally bimodal (Figure 2). Within experimental uncertainty, total extinction estimated from integrating the distributions agreed well with bulk measurements of β (generally, visible extinction is twice the total particle projected area). However, ice crystals in the larger mode, with projected area equivalent radii $r_{eq} > 30$ μm, contributed just 1% ± 1% to total extinction. Therefore, measurements of both bulk cloud properties and ice crystal projected area

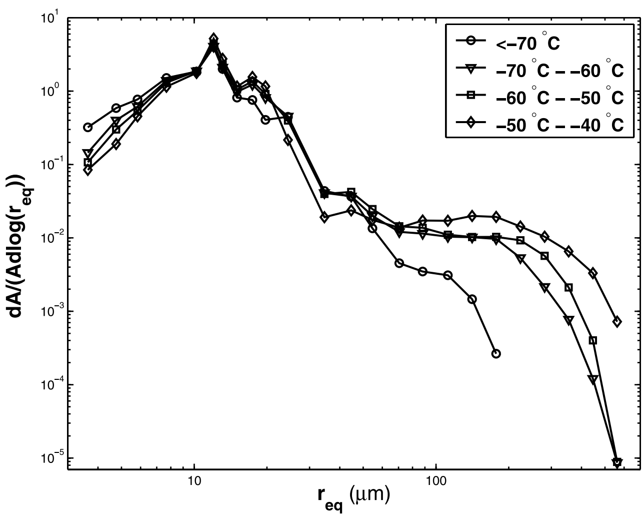

Figure 2. Normalized distributions of the concentrations of ice crystal projected area ($dA/(Ad\log r_{eq})$), as a function of the equivalent radius r_{eq} of ice crystals in cirrus anvils measured during CRYSTAL-FACE. r_{eq} is defined as the radius of a circle with area equal to the projected area of an individual ice crystal. Measurements were obtained with ice crystal size distribution and imaging probes aboard the NASA WB-57F.

distributions show that very small reflective ice crystals, with r_{eq} < 30 μm dominated the optical properties of the cold cirrus sampled by the WB-57 and Citation during CRYSTAL-FACE.

3. Comparison With Existing Parameterizations

[11] Climate models often represent light scattering by cold cirrus ice crystals by assuming that they are pristine hexagonal columns with an effective radius of approximately 30 μm and an asymmetry parameter of approximately 0.79 (e.g., the NCAR Community Climate Model CCM3 [*Kiehl et al.*, 1998]. By comparison, the measurements here show values of r_e that are up to six times smaller, and values of g that give 20% more back-scattering. Theoretically, low values of g are expected if ice crystals are small and pristine. However, g had no clear dependence on r_e in the data, in which case g was probably low because light scattering by ice crystals is made more isotropic by surface roughness, crystal aggregation, or internal bubbles [*Macke et al.*, 1996; *Yang and Liou*, 1998].

[12] The reason values of r_e reported in earlier studies are generally higher than those found here may reflect the measurement limitations of the earlier instruments used. Also, those previous measurements may be biased, since very few reported data from cold cloud tops at low latitudes, where cirrus particles are smallest. Alternatively, it may also be argued that the small ice crystal sizes represent a bias peculiar to the CRYSTAL-FACE domain. CRYSTAL-FACE focused on land-based convection just north of the Tropic of Cancer, rather than more climatologically important convective areas, such as over the Tropical Pacific. In addition, CRYSTAL-FACE aircraft sampled mostly anvil cirrus less than four hours old, whereas cirrus anvil blow-off may last three to four days [*Spang et al.*, 2002].

[13] However, observations from CRYSTAL-FACE and elsewhere suggest that the location and age of the anvil has a secondary influence on ice crystal effective radius. The smallest ice crystals (~5 μm), in the coldest convective cirrus (<-75°C), sampled during CRYSTAL-FACE were observed on two days at 15°N off Cape Gracias, Honduras. These samples included both recently formed thick anvil cirrus, and dissipating convective blow-off more than 12 hours old with τ < 1. Satellite imagery suggests the cirrus in both these cases originated from convection over ocean rather than land. Further, some studies that analyzed satellite images over the Western Pacific Tropical warm pool, along with in situ particle measurements in cirrus, suggest that r_e is similarly small [*Prabhakara et al.*, 1988; *Knollenberg et al.*, 1993]. It appears such small values are necessary to explain an observed balance in the tropics between longwave and shortwave top-of-atmosphere TOA radiative forcing by thin cirrus [*Hartmann et al.*, 1992; *Jensen et al.*, 1994]. Further, similar values and temperature trends in r_e, albeit obtained with size distribution probes, have been observed in high latitude cirrus with T > -40°C [*Boudala et al.*, 2002].

[14] Therefore the small crystal sizes, and functional dependence of r_e on temperature, shown in Figure 1b may reflect some underlying physics that is independent of geography or anvil age. The physics might be attributable simply to gravitational settling of large particles, which would bias ice crystal r_e towards larger sizes at warmer temperatures. However this appears unlikely given ice crystals sufficiently large to settle contributed very little to total scattering (Figure 2). Alternatively, homogenous ice nucleation favors smaller ice crystals at colder temperatures, similar in size to those seen here [*Kärcher and Lohmann*, 2002], due to the exponential dependence of the saturation vapor pressure over ice on temperature.

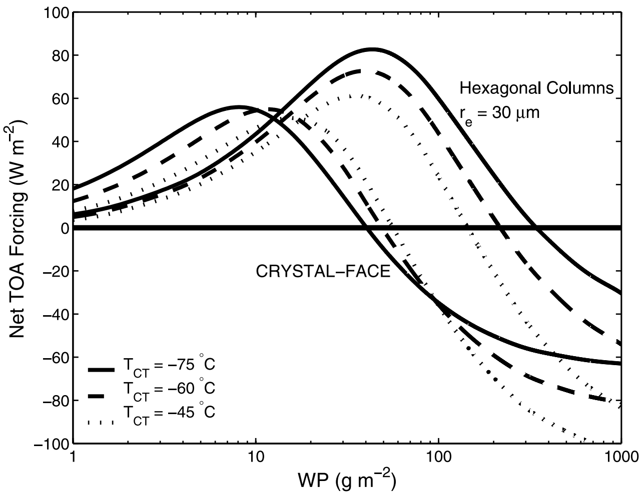

Figure 3. Diurnally averaged net (longwave plus shortwave) TOA forcing by cirrus as a function of ice water path WP for three values of cloud top temperature T_{CT} and two sets of cloud microphysical parameters: values of g and r_e based on CRYSTAL-FACE measurements (Figure 1), and pristine hexagonal columns with r_e = 30 μm. A four-stream atmospheric radiative transfer model was used for the calculations [*Key and Schweiger*, 1998]. Calculations assume 100% cloud cover and an ocean surface temperature of 29°C, for 10°N at the vernal equinox. CRYSTAL-FACE values of g in the shortwave are simulated assuming ice crystals are rough aggregates [*Yang and Liou*, 1998]. Longwave values of g for both cases are calculated approximating ice crystals as spheres.

4. Implications for Climate Modeling

[15] In what follows, we use a radiative transfer model [*Key and Schweiger*, 1998] to show how the values of r_e and g discussed above might affect climate model representations of how clouds modify the earth's climate. In general, *TOA* net (longwave plus shortwave) radiative forcing by clouds is a function of cloud water path $WP = W\Delta z$ and cloud top temperature T_{CT} (Figure 3). However, cirrus clouds representative of younger anvil cirrus, with WP greater than 10 g m^{-2} ($\tau \gtrsim 2$), cause substantially more cooling if the CRYSTAL-FACE values of r_e and g are used than if it is assumed that ice crystals are hexagonal columns with r_e equal to 30 μm. TOA forcing is between 30 and 100 $W\ m^{-2}$ lower, and the sign of the forcing is opposite over much of the range. Essentially, smaller values of r_e and g correspond with more reflective clouds (equation 1), and less solar radiation absorbed by the atmosphere and surface. On the other hand, in thinner clouds representative of aged anvil cirrus ($WP \lesssim 10\ g\ m^{-2}$) net cloud forcing is higher by as much as a factor of three. This is because, in addition to making clouds more reflective to sunlight, small cloud

particles are also more effective absorbers of infrared radiation [*Chýlek et al.*, 1992]. In the coldest of these very thin clouds, typical of the tropopause cirrus ubiquitous over the Pacific [*Dessler and Yang*, 2003], the CRYSTAL-FACE values of r_e correspond with higher infrared absorptivity (and emissivity) by about a factor of four [*Stephens et al.*, 1990], and higher thermal insulation dominates the increased reflection of solar energy.

[16] In climate models, changing g from ~0.79 to 0.74, by assuming crystals are not perfect hexagonal columns but have randomized surfaces [*Mitchell et al.*, 1996], decreases annually-averaged instantaneous TOA shortwave cloud forcing in the tropics by about 3 W m^{-2} [*Kristjánsson et al.*, 2000]. In interactive climate models, sensitivity studies show that adjusting the effective radius of high cirrus from a baseline value of 30 μm to 10 μm corresponds to an increase in the magnitude of both TOA and surface shortwave cloud forcing in the tropics by about 25% [*McFarquhar et al.*, 2003], and an increase in tropical upper troposphere temperatures by ~1 K [*Kristjánsson et al.*, 2000].

[17] The tops of tropical anvil cirrus, since they are most directly exposed to outer space, dominate their climate impact. CRYSTAL-FACE data show values of r_e as low as 5 μm for cloud top temperatures typical of tropical anvils. No measurements of g were obtained this cold, but at temperatures down to -55°C, measured values of g were about 0.75, which is typical for idealized crystals with randomized or roughened surfaces [*Mitchell et al.*, 1996; *Yang and Liou*, 1998]. Thus, by using ~30 μm hexagonal prisms for cirrus, many climate models may be omitting up to 80% of cirrus scaled optical depth (equation 1) for a given prediction of water path, (equation 2). In geographical regions where models currently appear to do well matching predicted cloud forcing with satellite observations [*Norris and Weaver*, 2001; *Webb et al.*, 2001], accounting for any omitted optical depth will require a substantial reassessment of the validity of simulated water path and cloud cover.

[18] **Acknowledgments.** This work was supported by the NASA CRYSTAL-FACE project. Thanks to A. Ackerman, E. Jensen and S. Krueger for discussions, Michael Poellot and T. Thompson for providing temperature data, and to the flight crews of the NASA WB-57F and UND Citation.

References

Arnott, W. P. D., D. Mitchell, C. Schmitt, D. Kingsmill, D. Ivanova, and M. R. Poellot, Analysis of the FSSP performance for measurement of small crystal spectra in cirrus, *13th International Conference on Clouds and Precipitation*, 191–193, 2000.

Auriol, F., J.-F. Gayet, G. Febvre, O. Jourdan, O. L. Labonnote, and G. Brogniez, In situ observation of cirrus scattering phase functions with 22 degree and 46 degree halos: Cloud field study on 19 February 1998, *J. Atmos. Sci.*, *58*, 3376–3390, 2001.

Baumgardner, D., H. Jonsson, W. Dawson, D. O'Connor, and R. Newton, The cloud, aerosol and precipitation spectrometer (CAPS): A new instrument for cloud investigations, *Atmos. Res.*, *59–60*, 251–264, 2002.

Boudala, F. S., G. A. Isaac, Q. Fu, and S. G. Cober, Parameterization of effective ice particle size for high-latitude Clouds, *Int. J. Clim.*, *22*, 1267–1284, 2002.

Chýlek, P., P. Damiano, and E. P. Shettle, 1992 Infrared emittance of water clouds, *J. Atmos. Sci.*, *49*, 1459–1472, 1992.

Dessler, A. E., and P. Yang, The Distribution of Tropical Thin Cirrus Clouds Inferred from Terra MODIS Data, *J. Clim.*, *16*, 1241–1248, 2003.

Foot, J. S., Some observations of the optical properties of clouds, Part 2, Cirrus, *Q. J. R. Meteorol. Soc.*, *114*, 145–164, 1988.

Gardiner, B. A., and J. Hallett, Degradation of in-cloud forward scattering spectrometer probe measurements in the presence of ice particles, *J. Atmos. Oceanic Technol.*, *2*, 171–189, 1985.

Garrett, T. J., P. V. Hobbs, and H. Gerber, Shortwave, single-scattering properties of arctic ice clouds, *J. Geophys. Res.*, *106*, 15,155–15,172, 2001.

Gerber, H., Y. Takano, T. J. Garrett, and P. V. Hobbs, Nephelometer measurements of the asymmetry parameter, volume extinction coefficient, and backscatter ratio in Arctic clouds, *J. Atmos. Sci.*, *57*, 3021–3034, 2000.

Hartmann, D. L., M. E. Ockert-Bell, and M. L. Michelsen, The effect of cloud type on Earth's energy balance: Global analysis, *J. Clim.*, *5*, 1281–1304, 1992.

Heymsfield, A. J., and G. M. McFarquhar, High albedos of cirrus in the tropical Pacific warm pool: microphysical interpretations from CEPEX and from Kwajalein, Marshall Islands, *J. Atmos. Sci.*, *53*, 2424–2451, 1996.

Jensen, E. J., S. Kinne, and O. B. Toon, Tropical cirrus cloud radiative forcing: Sensitivity studies, *Geophys. Res. Lett.*, *21*, 2023–2026, 1994.

Kärcher, B., and U. Lohmann, A parameterization of cirrus cloud formation: Homogeneous freezing of supercooled aerosols, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD000470, 2002.

Key, J., and A. J. Schweiger, Tools for atmospheric radiative transfer: Streamer and FluxNet, *Comput. Geosci.*, *24*, 443–451, 1998.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson, and P. J. Rasch, The National Center for Atmospheric Research Community Climate Model: CCM3, *J. Clim.*, *11*, 1131–1149, 1998.

Knollenberg, R. G., K. Kelly, and J. C. Wilson, Measurements of high number densities of ice crystals in the tops of tropical cumulonimbus, *J. Geophys. Res.*, *98*, 8639–8664, 1993.

Korolev, A. V., G. A. Isaac, and J. Hallett, Ice particle habits in Arctic clouds, *Geophys. Res. Lett.*, *26*, 1299–1302, 1999.

Kristjánsson, J. E., J. M. Edwards, and D. L. Mitchell, Impact of a new scheme for optical properties of ice crystals on climates of two GCMs, *J. Geophys. Res.*, *105*, 10,063–10,079, 2000.

Macke, A., M. Mishchenko, and B. Cairns, The influence of inclusions on light scattering by large ice particles, *J. Geophys. Res.*, *101*, 23,311–23,316, 1996.

McFarquhar, G. M., S. Iacobellis, and R. C. J. Somerville, SCM Simulations of tropical ice clouds using observationally based parameterizations of microphysics, *J. Clim.*, *16*, 1643–1664, 2003.

Mitchell, D. L., A. Macke, and Y. Liu, Modelling cirrus cloud, part II, Treatment of radiative properties, *J. Atmos. Sci.*, *53*, 2967–2988, 1996.

Meador, W. E., and W. R. Weaver, Two-stream approximations to radiative transfer in planetary atmospheres: a unified description of existing methods and a new improvement, *J. Atmos. Sci.*, *37*, 630–643, 1980.

Norris, J. R., and C. P. Weaver, Improved techniques for evaluation GCM cloudiness applied to the NCAR CCM3, *J. Clim.*, *14*, 2540–2549, 2001.

Prabhakara, C., R. S. Fraser, G. Dalu, M. L. C. Wu, and R. J. Curran, Thin cirrus clouds: Seasonal distribution over oceans deduced from Nimbus-4 IRIS, *J. Appl. Meteorol.*, *27*, 379–399, 1988.

Spang, R., G. Eidmann, M. Riese, D. Offerman, P. Preusse, L. Pfister, and P.-H. Wang, CRISTA observations of cirrus clouds around the tropopause, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD000698, 2002.

Stephens, G. L., S.-C. Tsay, J. W. Stackhouse Jr., and P. W. Flatau, The relevance of the microphysical and radiative properties of cirrus clouds to climate and climatic feedback, *J. Atmos. Sci.*, *47*, 1742–1753, 1990.

Takano, Y., and K.-N. Liou, Solar radiative transfer in cirrus clouds, Pt. 1, Single-scattering and optical properties of hexagonal ice crystals, *J. Atmos. Sci.*, *46*, 3–36, 1989.

Twohy, C. H., A. J. Schanot, and W. A. Cooper, Measurement of condensed water content in liquid and ice clouds using an airborne counterflow virtual impactor, *J. Atmos. Oceanic Tech.*, *14*, 197–202, 1997.

Twohy, C. H., J. W. Strapp, and M. Wendisch, Performance of a counterflow virtual impactor in the NASA Icing Research Tunnel, *J. Atmos. Ocean. Tech.*, *20*, 781–790, 2003.

Webb, M., C. Senior, S. Bony, and J.-J. Morcrette, Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models, *Clim. Dyn.*, *17*, 905–922, 2001.

Weinstock, E. M., et al., New fast response photofragment fluorescence hygrometer for use on the NASA ER-2 and the Perseus remotely piloted aircraft, *Rev. Sci. Instrum.*, *65*, 3544–3554, 1994.

Yang, P., and K.-N. Liou, Single scattering properties of complex ice crystals in terrestrial atmosphere, *Contr. Atmos. Phys.*, *71*, 223–248, 1998.

T. J. Garrett, Meteorology Department, University of Utah, USA. (tgarett@met.utah.edu)

H. Gerber, Gerber Scientific Inc., USA.

D. G. Baumgardner, Universidad Nacional Autonoma de Mexico, Mexico.

C. H. Twohy, College of Oceanography and Atmospheric Science, Oregon State University, USA.

E. M. Weinstock, Department of Chemistry and Chemical Biology, Harvard University, USA.