Differences Between Collection 4 and 5 MODIS Ice Cloud Optical/Microphysical Products and Their Impact on Radiative Forcing Simulations

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***Abstract*—This paper reports on the comparison of two latest versions (collections 4 and 5) of ice cloud products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) measurements. The differences between the bulk optical properties of ice clouds used in collections 4 and 5 and the relevant impact on simulating the correlation of the bidirectional reflection functions at two MODIS bands centered at 0.65 (or 0.86) and 2.13 μm are investigated. The level-3 MODIS ice cloud properties (specifically, ice cloud fraction, optical thickness, and effective particle size in this paper) from the collection 4 and 5 datasets are compared for a tropical belt of 30° S–30° N. Furthermore, the impact of the differences between the MODIS collection 4 and 5 ice cloud products on the simulation of the radiative forcing of these clouds is investigated. Over the tropics, the averaged ice cloud fraction from collection 5 is 1.1% more than the collection 4 counterpart, the averaged optical thickness from collection 5 is 1.2 larger than the collection 4 counterpart, and the averaged effective particle radius from collection 5 is 1.8 μm smaller than the collection 4 counterpart. Moreover, the magnitude of the differences between collection 5 and 4 ice cloud properties also depends on the surface characteristics, i.e., over land or over ocean. The differences of these two datasets (collections 4 and 5) of cloud properties can have a significant impact on the simulation of the radiative forcing of ice clouds. In terms of total (longwave plus shortwave) cloud radiative forcing, the differences between the collection 5 and 4 results are distributed primarily between -60 and 20 $\mathrm{W \cdot m^{-2}}$ but peak at 0 $\mathrm{W \cdot m^{-2}}$.**

***Index Terms*—Aqua, clouds, Moderate Resolution Imaging Spectroradiometer (MODIS), radiative forcing, remote sensing, static libraries.**

I. INTRODUCTION

WITH THE increasing awareness of the importance of ice clouds [25], [29] in the terrestrial atmosphere, research has addressed numerous issues relevant to ice clouds from various perspectives, including *in situ* measurements of the microphysical properties of ice clouds [13], theoretical investigations of the single and multiple scattering and absorption properties of ice clouds [1], [30], [36], [37], [48], [49], [56]–[58], efforts to parameterize the bulk radiative properties of these clouds [7], [8], [10], [33] for applications to climate models, the impacts of ice clouds on the radiation spectrum [53] and climate feedback [46], and the retrieval of ice cloud optical and microphysical properties from airborne and satellite measurements [1], [2], [6], [15], [20], [22], [34], [35], [52]. However, the representation of these clouds in general circulation models (GCMs) is rather primitive in the sense that substantial uncertainties exist in the basic cloud climatologies derived from the GCM simulations, and the cloud distributions simulated from many GCMs are quite different from those inferred from satellite observations [61]. To improve the representation of ice clouds in GCMs, it is critical to understand the global ice cloud climatology to provide crucial constraints on the parameterization of various cloud microphysical processes and cloud-radiation interactions in GCMs. To this end, reliable satellite-based retrievals of ice cloud properties on a global scale are necessary.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments [17], [18], [44], [55] on the NASA Earth Observing System Terra and Aqua platforms include 36 spectral channels covering essentially all the key atmospheric bands located between 0.415 and 14.235 μm [41] and provide advanced capabilities to study ice clouds, although MODIS does not have far-infrared-radiation (far-IR) spectral bands. Note that the far-IR is important to the energetics of the Earth's atmosphere. The MODIS measurements have been extensively used in cloud property retrievals and for the cloud clearing (e.g., [23] and [24]) that is necessary for inferring aerosol, surface, and atmospheric profile properties. With precomputed static libraries of ice cloud radiances, a bispectral technique [39] can be used to simultaneously infer the optical thickness and effective particle size of an ice cloud from the MODIS measurements [18], [21], [41] during daytime conditions. The MODIS cloud (level-2) pixel-level products are available for individual granules, known as MOD06 and MYD06 for Terra

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and Aqua, respectively (note that the product prefix "MOD" is used for the retrieval products based on the measurements acquired from the Terra platform, whereas "MYD" is used for the retrieval products based on the measurements acquired from the Aqua platform), and also as global (level-3) $1^\circ \times 1^\circ$ gridded datasets.

Recently, substantial improvements have been made on the MODIS cloud products, and new datasets (collection 5) are available [19]. In this paper, we first illustrate the effect of the differences of the bulk optical properties of ice particles on the simulation of the bidirectional reflection function for ice clouds that are essential to the MODIS operational retrieval. Then, we compare the operational MODIS collection 4 and 5 ice cloud properties. Specifically, the analysis presented in this paper focuses on the MODIS level-3 ice cloud fraction, ice cloud optical thickness, and effective particle size, although a case study involving the MODIS level-2 data is also presented. Furthermore, we investigate the potential impacts of the MODIS collection 5 improvements on the simulation of the radiative forcing of ice clouds.

II. STATIC LIBRARIES FOR RETRIEVING ICE CLOUD PROPERTIES

King *et al.* [18] provide an overview of the data architecture and products of the MODIS operational atmospheric parameter data products. In summary, the MOD06 and MYD06 datasets contain the pixel-level (or the so-called level-2) retrievals performed for individual granules, i.e., datasets corresponding to 5-min scans of the MODIS instruments along their orbit tracks. The level-2 products are further mapped onto level-3 products (MOD08 and MYD08) with a spatial resolution of $1^\circ \times 1^\circ$ in latitude and longitude on a daily, eight-day, and monthly mean basis.

Platnick *et al.* [41] discuss the pixel-level retrieval of the optical and microphysical properties (i.e., optical thickness and effective particle size) on the basis of the bispectral method developed by Nakajima and King [39]. The physical basis of this retrieval method is that the radiance observed by a satellite sensor at a nonabsorbing band (e.g., a band centered at a wavelength of 0.65 μm) under cloudy conditions is sensitive primarily to cloud optical thickness and insensitive to the effective particle size, whereas the radiances observed at an absorbing band (e.g., a band centered at a wavelength of 2.13 μm) under cloudy conditions are sensitive to the effective particle size for a given optical thickness. Thus, a pair of the radiances measured at these two bands in comparison with theoretical radiance correlation (i.e., the so-called static libraries that are precomputed for the implementation of the retrieval algorithm) between the two bands allows simultaneous retrieval of cloud optical thickness and effective particle size. For the operational MOD06 retrieval algorithm [41], the MODIS 0.65-μm band (for over land), 0.86-μm band (for over ocean), or 1.24-μm band (for over ice/snow surfaces) is used as the nonabsorbing band involved in the bispectral retrieval algorithm. The availability of the three bands for various surface characteristics [38] helps to mitigate the influence of the surface reflectance [41] on the retrievals. The operational retrieval algorithm uses the 2.13-μm band as an absorbing band for implementing the bispectral algorithm. Additionally, retrievals based on the 1.64- or 3.78-μm band in combination with a nonabsorbing band (e.g., 0.65-, 0.84-, or 1.24-μm band) provide information about the deviations from those retrieved on the basis of a combination of the 2.13-μm band with a nonabsorbing band (e.g., the 0.65-μm band), as explained by Platnick *et al.* [41]. Given the physical basis of the aforementioned bispectral cloud retrieval algorithm, the theoretical correlation between the reflection functions of the absorbing and nonabsorbing bands is fundamental to the operational MODIS cloud retrieval.

Recently, the MODIS atmosphere team has implemented and delivered an update (known as collection 5) for the operational cloud products. As summarized by King *et al.* [19], the static libraries of the bidirectional reflectances, transmittances, and spherical albedos of ice clouds (i.e., the so-called ice libraries) at absorbing and nonabsorbing bands involved in the MODIS bispectral retrieval algorithm have been improved. Additionally, several other significant improvements have been made in the MODIS cloud retrieval process. The new ice libraries improve the MODIS operational retrievals of ice cloud optical and microphysical properties (i.e., optical thickness and effective particle size). To generate the ice libraries, the fundamental single-scattering properties (i.e., the phase function, single-scattering albedo, and mean volume extinction coefficient) of ice particles are required. A significant difference between the collection 4 and 5 ice cloud properties stems from different treatments of small ice crystals. In the light scattering computations for the MODIS collection 4 ice cloud products, small ice particles are assumed to be compact hexagonal ice particles with a unit aspect ratio (i.e., $L/a = 2$, where L and a are the length and semiwidth of an ice particle, respectively), whereas a droxtal geometry [40], [50], [57], [62] is assumed to approximately represent the habits (or shapes) of small quasi-spherical ice particles in the MODIS collection 5 ice cloud retrievals.

To generate the bulk single-scattering properties of ice particles for the forward radiative transfer simulations required for the development of the static libraries, it is necessary to account for the effect of the assumed particle size and habit distribution. For the MODIS collection 4, 12 size distributions acquired for midlatitude ice cloud systems were used, which were discretized into five size bins with a coarse resolution. For a given size distribution, the percentage of ice particle habits is assumed as follows [3], [20]: 25% plates, 25% hollow columns, and 50% bullet rosettes for size bins (in particle maximum dimension [8], [58], [60]) smaller than 70 μm; and 20% plates, 20% hollow columns, 30% bullet rosettes, and 30% aggregates for size bins larger than 70 μm. The surface of aggregates is slightly roughened in the light scattering calculation. For the MODIS collection 5 ice cloud products, 1117 size distributions acquired for tropical, subtropical, and midlatitude ice cloud systems [4], [5] are used. These size distributions are discretized into 45 size bins with a cutoff of 9500 μm. The habit percentage was determined by fitting the *in situ* ice water content and median mass diameter [4], given by 100% droxtals for size bins less than 60 μm; 35% plates, 15% bullet rosettes, 50% solid columns, for size bins between 60 and 1000 μm;

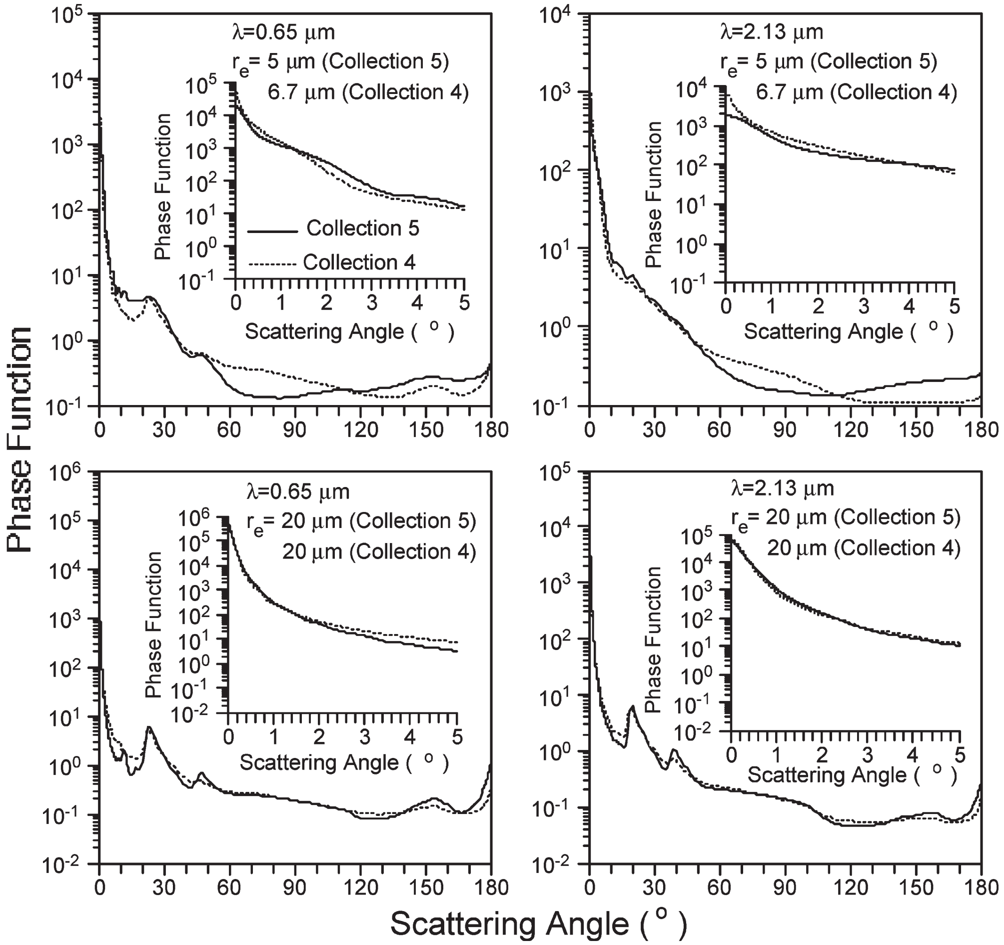

Fig. 1. Comparison of the MODIS collections 4 and 5 scattering phase functions for the MODIS 0.65- and 2.13-μm bands for two values of effective particle radius. The solid and dotted lines indicate collections 4 and 5, respectively.

45% solid columns, 45% hollow columns, 10% aggregates for size bins between 1000 and 2000 μm; and 3% aggregates and 97% bullet rosettes for size bins larger than 2000 μm. The bulk single-scattering properties computed are integrated over the size distributions and habit mixture in the way reported in Baum *et al.* [4], [5].

Fig. 1 shows the comparison of the phase functions used for the MODIS collection 4 and 5 ice cloud retrievals at two wavelengths, 0.65 and 2.13 μm, for a small and moderate effective particle size, respectively. Note that for collection 4, the minimum effective particle radius is 6.7 μm, whereas it is 5 μm for the MODIS collection 5. For small sizes, the collection 4 phase function has larger values, relative to its collection 5 counterpart, at the side scattering angles (50°–110°) because the droxtal geometry is used for small particles in the collection 5 scattering computations. However, the collection 4 phase function is smaller in the backscattering angles (120°–180°). This occurs because hollow columns (with a percentage of 25% when the particle maximum dimension is less than 70 μm) are assumed for computing the collection 4 phase functions. Hollow columns scatter much less energy in backscattering directions than solid columns [49], [56]. Of note, there are significant differences between the phase functions of collections 4 and 5 for small effective radii at scattering angles between 40° and 180°. For a moderate effective radius (20 μm), the two versions of phase functions are quite similar although some differences are noticed, particularly at scattering angles between 10°–20° and 120°–180°. Based on the phase function differences in Fig. 1, differences are expected between the satellite retrieved effective particle size and optical thickness datasets from the MODIS collections 4 and 5, particularly in the case of ice clouds with small particles.

The effective particle size (radius) in Fig. 1 and also that used in the MODIS operational cloud retrieval is defined as follows (see [3], [4], [20], and references cited therein):

$$r_e = \frac{3}{4}\frac{\sum\limits_i \int V_i(D)n(D)f_i(D)dD}{\sum\limits_i \int A_i(D)n(D)f_i(D)dD} \tag{1}$$

where V, A, and D are the geometric volume, orientation-averaged projected area, and maximum dimension of an ice particle, respectively. The quantity $n(D)$ denotes the size distribution as a function of ice particle maximum dimension. The parameter f_i indicates the percentage of each ice particle habit (shape). As noted by King *et al.* [20], the definition given in (1) reduces to that given by Hansen and Travis [11] in the case of spherical particles. Another advantage of the definition specified by (1) for the effective particle size is that the ice water path (IWP) of an ice cloud can be given by [9], [26], [27], [31]

$$\mathrm{IWP} = \frac{4}{3}\frac{\rho_e \tau r_e}{\langle Q_e \rangle} \approx \frac{2}{3}\rho_e \tau r_e \tag{2}$$

where τ is the visible optical thickness of an ice cloud, ρ_e(approximately $0.917\ \mathrm{g \cdot cm^{-3}}$) is the density of bulk ice, and $\langle Q_e \rangle$ is the mean extinction efficiency for a population of ice particles, as described by [59]

$$\langle Q_e \rangle = \frac{\sum\limits_i \int Q_{e,i}(D) A_i(D) f_i(D) n(D) dD}{\sum\limits_i \int A_i(D) f_i(D) n(D) dD}. \tag{3}$$

In (2), it is assumed that $\langle Q_e \rangle$ is approximately 2. This is an accurate approximation because the sizes of ice particles are normally much larger than the visible or near-infrared wavelengths, and consequently, the extinction cross sections of these particles are twice their projected areas [51]. It is evident from (2) that the MODIS cloud products implicitly provide information about IWP, as it can be derived from the retrieved optical thickness and effective particle size in a straightforward manner.

Fig. 2 shows the comparison of the correlation between the bidirectional reflection functions for the MODIS 0.65- and 2.13-μm bands computed from the collection 4 and 5 bulk single-scattering properties. In the present radiative transfer computations, the solar zenith angle (θ_o) and satellite viewing angle (θ) are 30° and 0°, respectively (note that the corresponding scattering angle is 150°). Over land and ocean, the surface albedo is assumed to be 0.2 and 0.03, respectively. The radiative transfer simulations in Fig. 2 are based on the discrete ordinates radiative transfer (DISORT) model developed by Stamnes *et al.* [45]. The gaseous absorption is neglected in the present simulations. It is evident from Fig. 2 that the range of effective particle sizes covered in collection 5 is larger than that for collection 4. Furthermore, substantial differences are noted in terms of the isolines of effective particle size. For example, in both land and ocean cases, the isoline of $r_e = 25\ \mu$m computed from the collection 5 ice cloud optical properties is much lower than the collection 4 counterpart, and follows the collection 4 28-μm isoline. This implies that retrieved effective particle sizes in collection 5 might be smaller than those in collection 4. In terms of the isolines of optical thickness shown in Fig. 2, the results for collection 5 and 4 are similar, but some differences are noticed for small and large particles (i.e., $r_e < 10\ \mu$m and $r_e > 25\ \mu$m). From a detailed scrutiny of the differences in the correlation of the reflection functions shown in Fig. 2, it is noticed that the retrieved optical thickness in collection 5 can deviate from those in collection 4 on the order of $\Delta\tau \sim 2$.

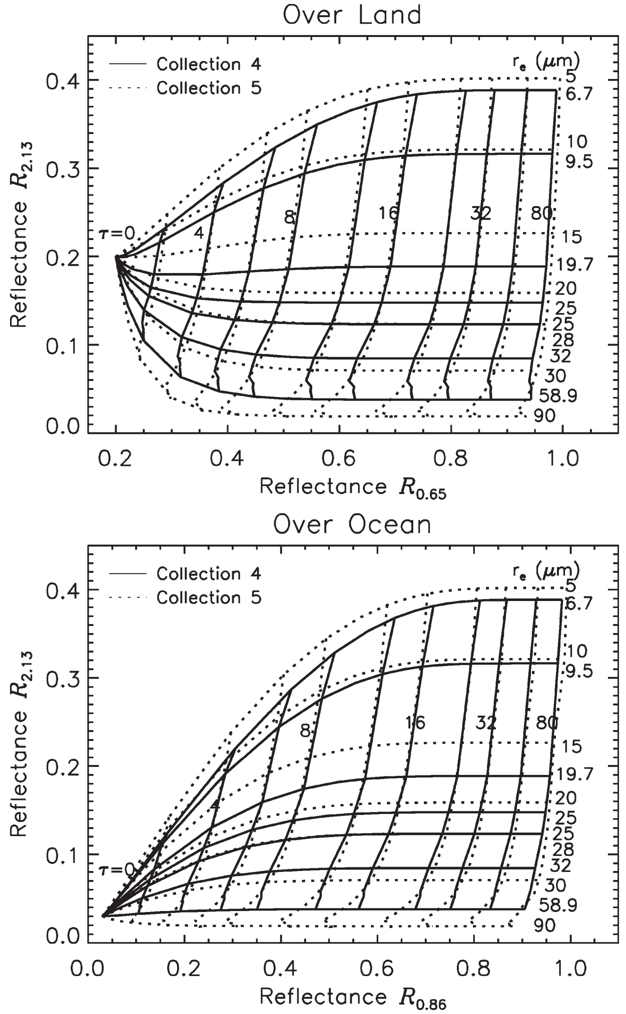

Fig. 2. Lookup tables at 0.65- and 2.13-μm over land and 0.86- and 2.13-μm over ocean for various values of ice cloud optical thickness and effective particle size when $\theta_0 = 30°$ and $\theta = 0°$.

For operational cloud retrievals, it is impractical to carry out forward radiative transfer computations for individual pixels and various sun-satellite geometries by using a rigorous radiative transfer model (e.g., DISORT). Instead, static libraries of the reflection and transmission functions of clouds with various optical thicknesses and effective particle sizes must be used. For the MODIS operational cloud retrieval algorithm, the static libraries of the bidirectional reflectance, total transmittance, and spherical albedo of clouds are generated by assuming a blackbody surface without consideration of the absorption by atmospheric gases [41]. The effect of surface albedo is taken into account on the basis of the adding/doubling principle explained in King *et al.* [21]

$$R(\mu, \mu_0, \Delta\varphi) = R_{\mathrm{cloud}}(\mu, \mu_0, \Delta\varphi) + \frac{T(\mu_o) r_g T(\mu)}{1 - r_g \overline{R}_{\mathrm{cloud}}} \tag{4}$$

where μ, μ_0, and $\Delta\varphi$ indicate the cosine of viewing zenith angle, the cosine of the solar zenith angle, and relative azimuthal angle between the sun and the satellite, respectively. The quantity r_g indicates the surface albedo. The quantity R is the apparent reflectance observed by the satellite. The quantities R_{cloud}, T, and $\overline{R}_{\mathrm{cloud}}$ are the cloud bidirectional reflectance, total transmittance, and spherical albedo, respectively, and are functions of the optical thickness and effective particle size for the cloud of interest. The preceding formula provides a computationally efficient way to compute the theoretical radiances with which the measured radiances are compared in the retrieval process. In practice, R_{cloud}, T, and $\overline{R}_{\mathrm{cloud}}$ are precomputed, representing the so-called ice libraries for implementing

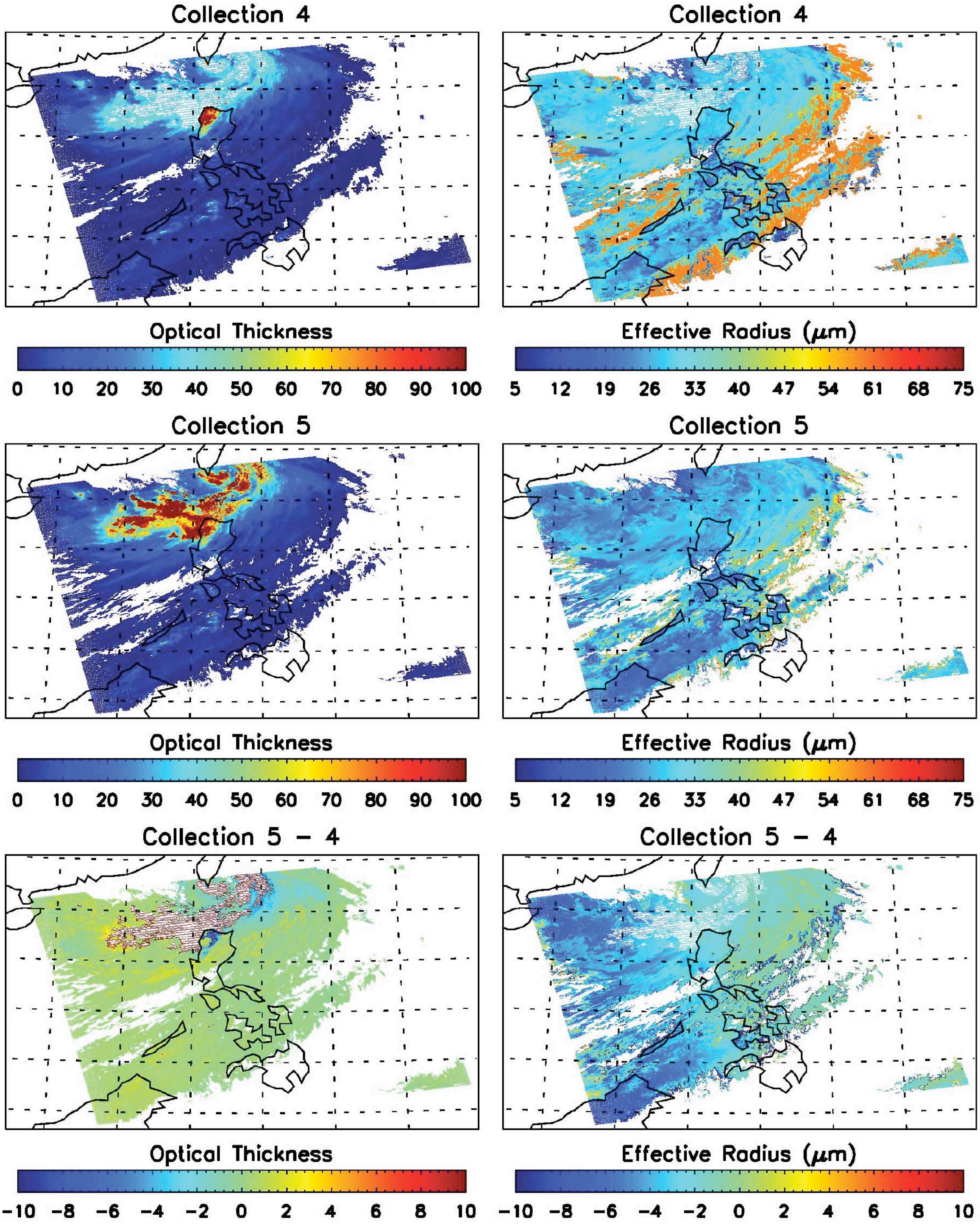

Fig. 3. Comparisons of high cloud properties from MODIS collections 4 and 5 for a granule acquired on July 1, 2004 over Southeast Asia.

an operational bispectral cloud retrieval algorithm. It can be seen that the reliability of the ice libraries is critical to the accuracy of retrieved optical thickness and effective particle size.

III. Comparison Between MODIS Collection 4 and 5 Ice Cloud Properties

To compare the collection 4 and 5 level-2 ice cloud products, we select a granule acquired on July 1, 2004, over Southeast Asia. Fig. 3 shows the comparison of the optical thickness and effective particle size from the MYD06 product for this granule. The cloud phase flag in the MYD06 quality assurance (QA) is used to screen out those pixels that are identified as not being associated with ice clouds. It is evident from Fig. 3 that collection 5 data, overall, show larger optical thicknesses and smaller ice particle effective sizes than collection 4, although in some instances, clouds identified as ice in collection 4 are identified as liquid water in collection 5.

The present comparison of the MODIS collection 5 and 4 ice cloud properties is intended to focus on the level-3 products

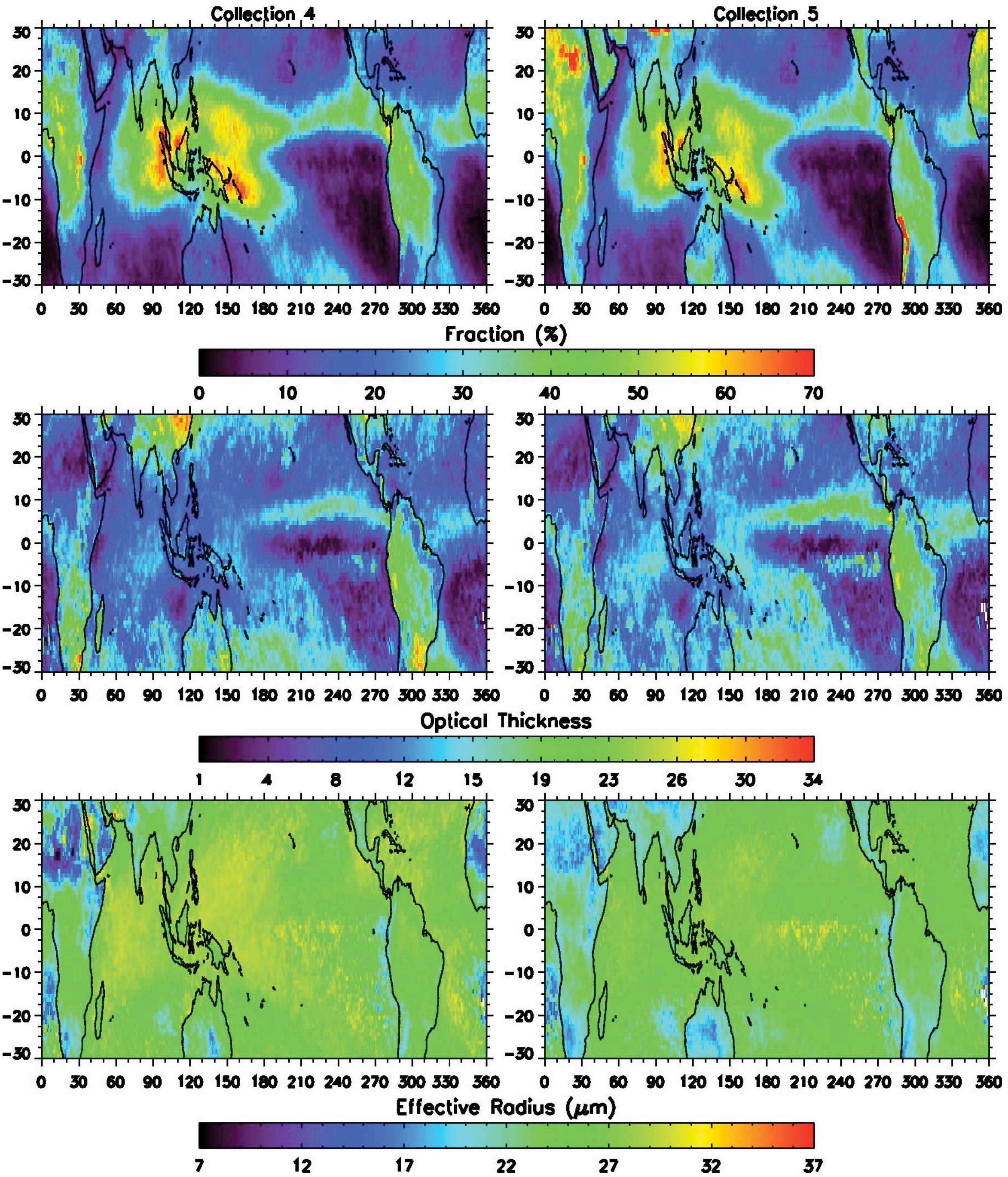

Fig. 4. Geographical distributions of high cloud fraction, optical thickness, and effective size over the tropics (30° S–30° N) from Aqua MODIS collections 4 and 5 from January to December 2004.

because they provide global statistics. Specifically, we select collection 4 and 5 level-3 ice cloud products from MYD08_D3 over the tropics (between 30° S and 30° N) from January 2004 to December 2004. The simple statistics of mean or QA-weighted mean for high cloud properties with each grid box are available in the MYD08_D3 products [18]. Cloud fraction can be derived as the ratio of the total counts flagged with clouds to the total number of observed pixels within a given grid box. The high-level cloud optical thickness and effective particle size inferred from the MODIS visible and near-infrared channel radiances are directly taken from the QA-weighted means in the MYD08_D3 products.

Fig. 4 shows the geographical distributions of high cloud fraction, optical thickness, and effective radius over the tropics (30° S–30° N) from Aqua MODIS collections 4 and 5. The overall features of the distribution of ice clouds are consistent with those reported in the literature [14], [47], [54]. Ice clouds occur frequently over the intertropical convergence zone, the South Pacific convergence zone, tropical Africa, tropical America, Indonesia maritime continent, and the Indian Ocean. The ice cloud fractions from collection 5 increase over land and decrease over ocean with respect to those from collection 4. The ice cloud optical thicknesses and ice particle effective sizes from collection 5 show the same geographical

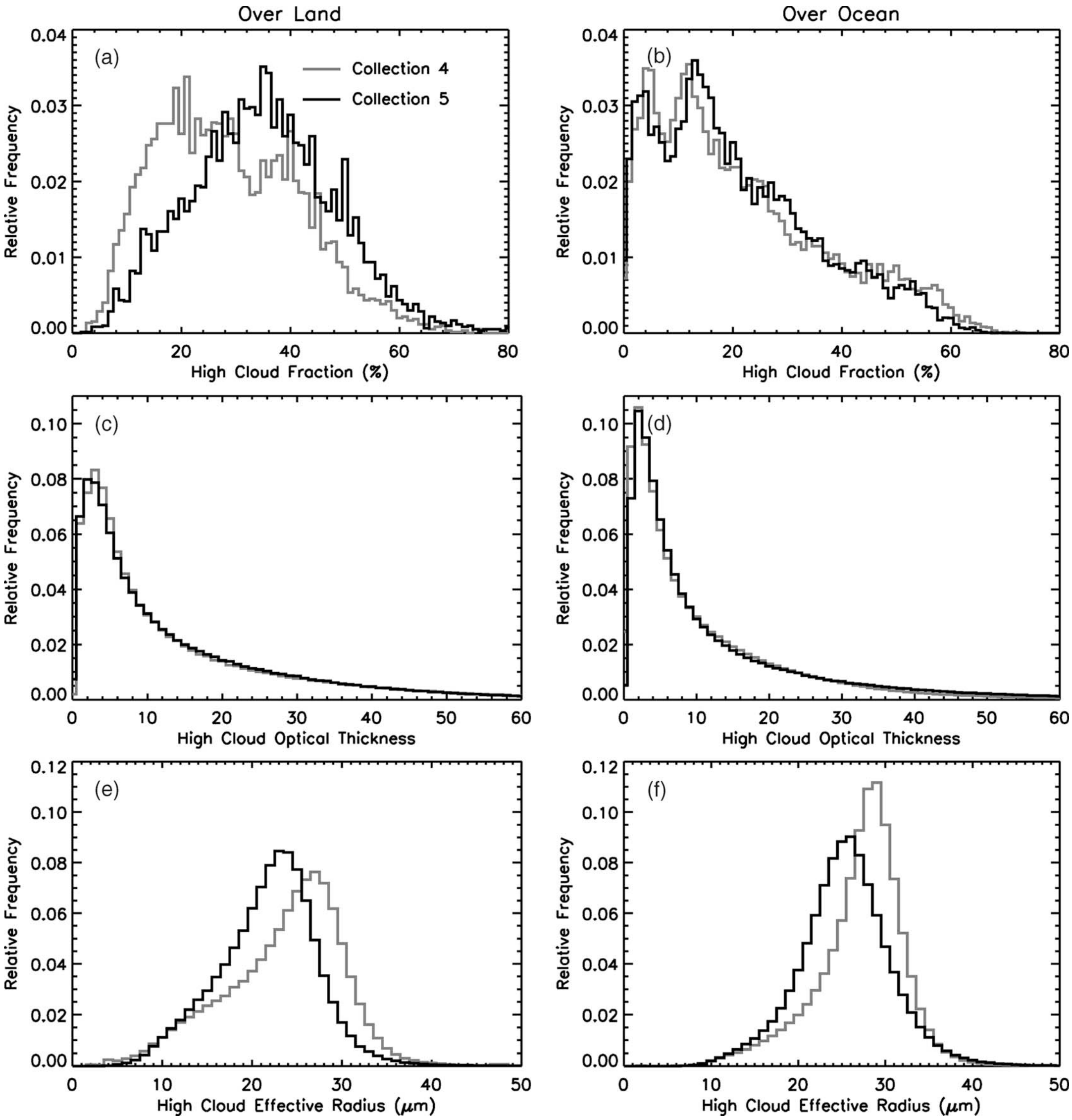

Fig. 5. Histogram distributions of high cloud fraction, optical thickness, and effective particle size over ocean and land over the tropics (30° S–30° N) from Aqua MODIS collections 4 and 5 from January to December 2004.

features as those from collection 4. The land–ocean contrast is also found for ice cloud optical thicknesses. The cloud optical thicknesses from collection 5 are apparently larger over ocean and smaller over land than those from collection 4. The ice cloud particle effective sizes from collection 5 are generally smaller than those from collection 4. Over Northern Africa, the cloud effective particle sizes from collection 5 have significantly larger values than those from collection 4.

Fig. 5 shows the histogram distributions of ice cloud fraction, optical thickness, and effective particle radius over ocean and land. Statistically, ice cloud fraction over land from the collection 5 data set has larger values in comparison with its collection 4 counterparts, whereas the two data sets are only slightly different in the case of ice clouds over ocean. Ice cloud optical thicknesses from collection 5 over land have a frequency distribution similar to that from collection 4. The distributions of ice particle effective sizes from collection 5 over both land and ocean are shifted to smaller values in comparison with the collection 4 results.

TABLE I

ONE-YEAR MEAN PROPERTIES OF HIGH CLOUDS FROM JANUARY 2004 TO DECEMBER 2004 OVER THE TROPICS (30° S–30° N) FROM THE MODIS ONBOARD AQUA IN DAYTIME

High Cloud Properties	Collection 4			Collection 5		
	Land	Ocean	Total	Land	Ocean	Total
Fraction (%)	29.2	22.0	24.0	35.3	21.2	25.1
Optical thickness	14.9	11.4	12.5	14.6	13.3	13.7
Effective radius (μm)	24.1	27.6	26.5	22.2	25.9	24.7
Ice water path (g m^{-2})	219.5	192.4	202.5	198.1	210.6	206.9

Table I lists the one-year mean results of ice cloud fraction, optical thickness, effective particle size, and IWP from the collection 4 and 5 data over the tropics (30° S–30° N) from January 2004 to December 2004. The IWP values are estimated from the corresponding values of optical thickness and effective particle size using (2). The mean ice cloud fraction of collection 5 is 25.1%, which is 1.1% larger than that of the collection 4 result. Ice cloud fraction from collection 5 increases 6.1% over land but decreases 0.8% over ocean, indicating that

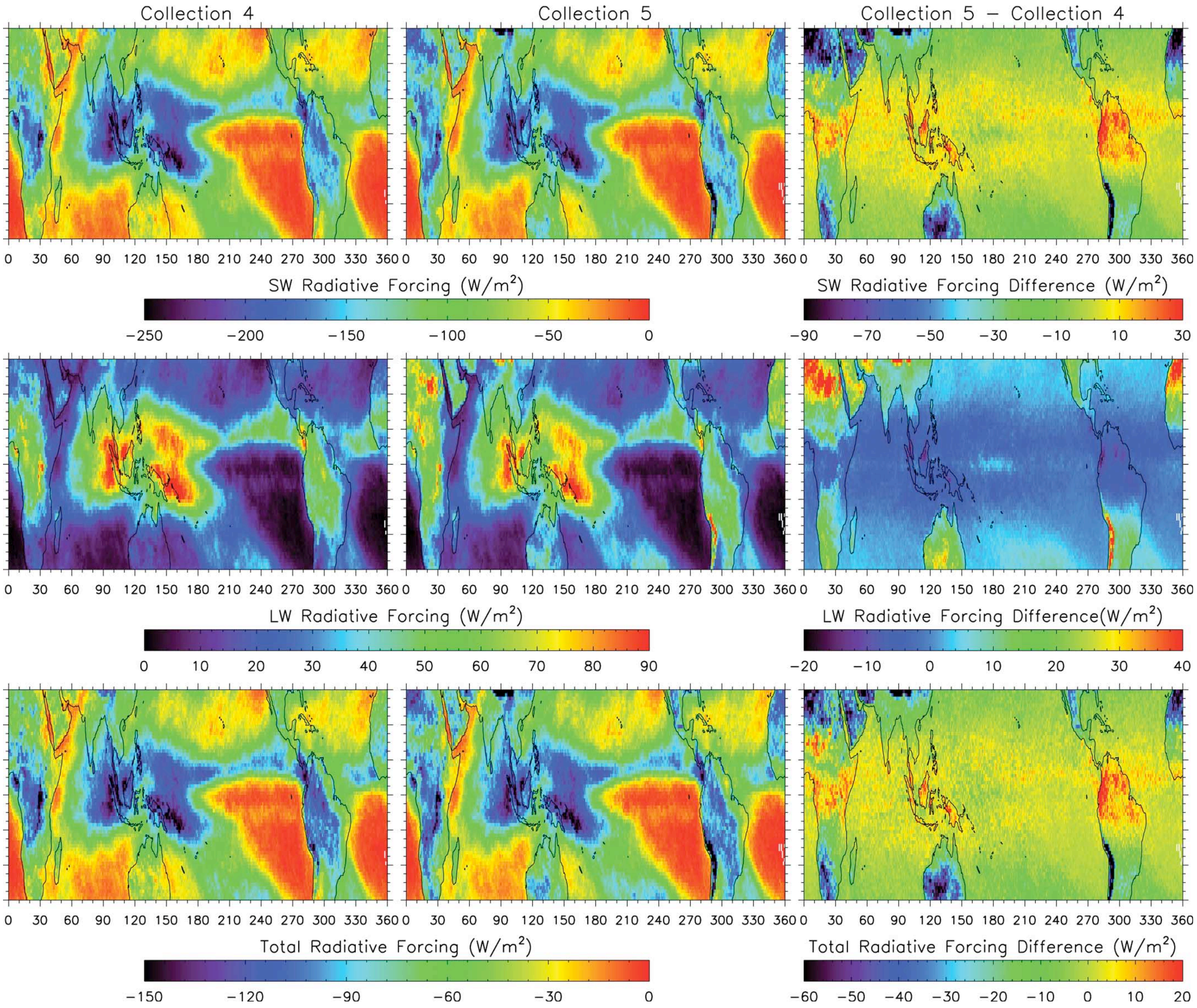

Fig. 6. Geographical distributions of ice cloud shortwave (SW), longwave (LW), and total forcing from collections 4 and 5 and their differences.

the land–ocean contrast in collection 5 is more pronounced than that in the case of collection 4. Cloud optical thickness decreases 0.3 over land and increases 1.9 over ocean for collection 5 in comparison with their collection 4 counterparts. This results in an increase of 1.2 in the mean value of cloud optical thickness. The optical thicknesses in collection 5 show a weak land–ocean contrast, whereas those in collection 4 have a significant contrast. The IWP values estimated from the collection 5 data, averaged over the tropics, are larger over ocean and smaller over land than the corresponding collection 4 estimates. Specifically, the values of $(\mathrm{IWP}_5 - \mathrm{IWP}_4)/\mathrm{IWP}_4$ are -9.7%, 9.5%, and 2.2% for land, ocean, and total statistics, respectively.

The ice cloud radiative forcing (CRF) based on collection 4 and 5 is shown in Fig. 6. The ice CRF is calculated with the radiative transfer code LibRadtran [32]. A new scheme (J. Lee, personal communication) of parameterizing the bulk optical properties of ice clouds, which is based on the database of the single-scattering properties of individual ice particles developed by Yang *et al.* [58], [60], is used in the present CRF simulation. The ice cloud optical thickness, effective particle size, and cloud top height from MYD_08 products are used for LibRadtran. We use the International Satellite Cloud Climatology Project (ISCCP) classification [42], [43] to identify ice clouds (cloud top pressure less than 440 hPa) using the MYD_08 daily products and then average the daily ice cloud properties over a period from January 2004 to December 2004. The standard atmospheric profile for the tropics is used as the input for atmospheric condition in LibRadtran. Following Liou and Gebhart [28], in this paper, the solar zenith angle is assumed to be 60° to represent an approximate average for a solar day with a 12-h duration of sunlight.

The net shortwave (solar) and longwave (infrared) fluxes at the top of the atmosphere (TOA) are defined as follows:

$$F_{\mathrm{sw}} = F_{\mathrm{sw}}^{\downarrow} - F_{\mathrm{sw}}^{\uparrow} \tag{5}$$

$$F_{\mathrm{lw}} = -F_{\mathrm{lw}}^{\uparrow} \tag{6}$$

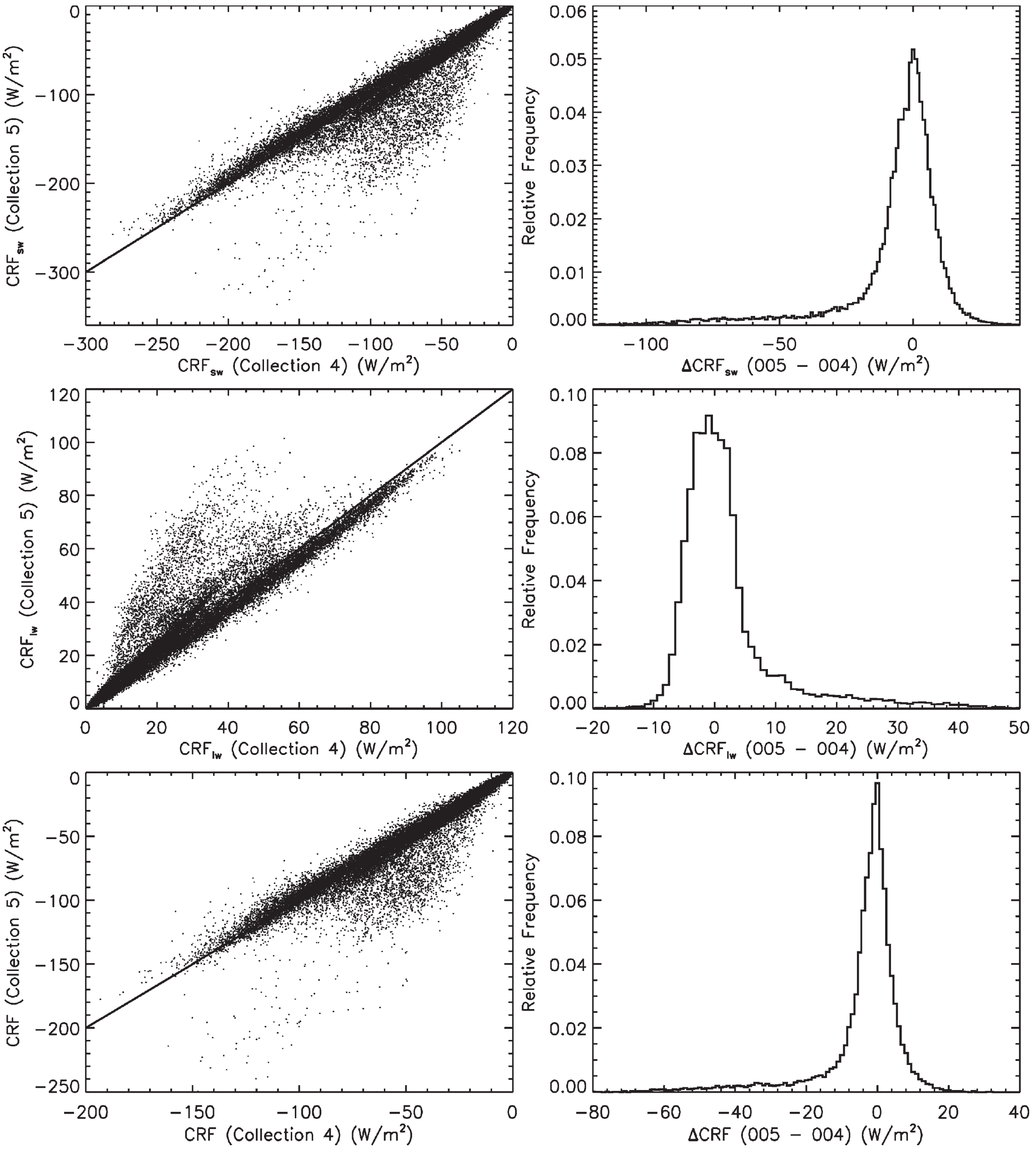

Fig. 7. Comparison of ice CRF (CRF_{sw}, CRF_{Lw}, and CRF) derived from collections 4 and 5.

where the symbols ↑ and ↓ indicate upward and downward radiation, respectively. $F_{\text{lw}}^{\uparrow}$ is also known as the outgoing longwave radiation, a term often used in the literature (e.g., [26]). For a partially cloudy region with a cloud fraction of N, the average-sky net TOA flux is given by [26]

$$F=N(F_{\text{sw,cloud}}+F_{\text{lw,cloud}})+(1-N)(F_{\text{sw,clear}}+F_{\text{lw,clear}}). \tag{7}$$

Following Hartmann *et al.* [12], the CRF is given by

$$\text{CRF} = F - F_{\text{clear}}. \tag{8}$$

Note that the sign on the right-hand side of (8) is different from the expression given by Liou [26, p. 379]. CRF can be further decomposed into the shortwave and longwave components as follows:

$$\text{CRF} = \text{CRF}_{\text{sw}} + \text{CRF}_{\text{lw}} \tag{9}$$

where

$$\text{CRF}_{\text{sw}} = N(F_{\text{sw,cloud}} - F_{\text{sw,clear}}) \tag{10}$$

$$\text{CRF}_{\text{lw}} = N(F_{\text{lw,cloud}} - F_{\text{lw,clear}}). \tag{11}$$

From Fig. 6, the shortwave radiative forcing of ice clouds is negative, indicating the cooling effect of ice clouds, while the longwave radiative forcing of ice clouds is positive, indicating the warming effect of ice clouds. The net radiative effect of ice particles depends strongly on the competition of the

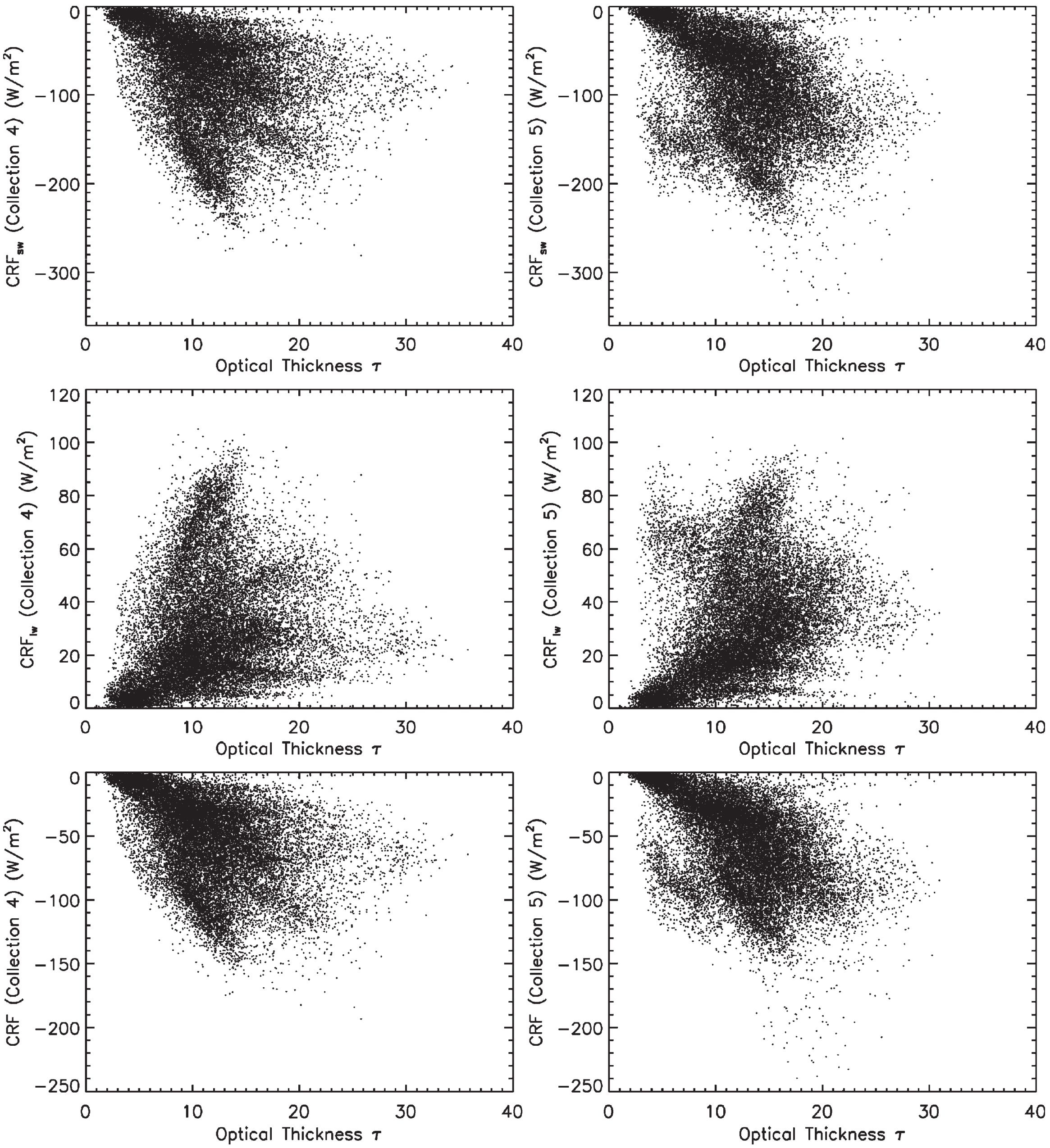

Fig. 8. Relationship between ice cloud optical thickness and CRF (CRF_{sw}, CRF_{Lw}, and CRF) for collections 4 (left) and 5 (right).

heating and warming effects, which is most sensitive to the optical thicknesses of ice clouds [16]. The shortwave radiative forcing is much stronger than the longwave radiative forcing for larger optical thicknesses. This results in the total radiative forcing being negative in sign. The shortwave, longwave, and total radiative forcing of ice clouds in collection 5 have similar geographical distributions as those in collection 4. The pronounced radiative forcing appears over land. In general, the negative shortwave, positive longwave, and negative total radiative forcing in collection 5 are stronger over land and weaker over ocean than those in collection 4. Differences in CRF between collection 4 and 5 tend to be larger over land.

Fig. 7 shows the collection 5 CRF versus its collection 4 counterpart, and a one-to-one line is also shown. For shortwave radiation, the collection 5 results are close to the collection 4 results although some smaller values for the former are noticed. For longwave radiation, the collection 4 and 5 results are also similar, but some larger values for the collection 5 results are observed. In terms of the total radiative forcing of ice clouds, the collection 5 results have smaller values. The right three panels in Fig. 7 show the histograms of the frequency distributions of the differences between the collections 4 and 5 CRFs. The differences between the collections 5 and 4 CRF peak around 0 $W \cdot m^{-2}$ for shortwave, longwave, and total radiation. The differences between the collection 4 and 5 total radiative forcing are distributed between −60 and 20 $W \cdot m^{-2}$.

Shown in Figs. 8 and 9 are the radiative forcings of ice clouds as a function of cloud optical thickness and effective particle size, respectively. The results in Fig. 8 indicate that the CRF increases in magnitude with the increase of cloud

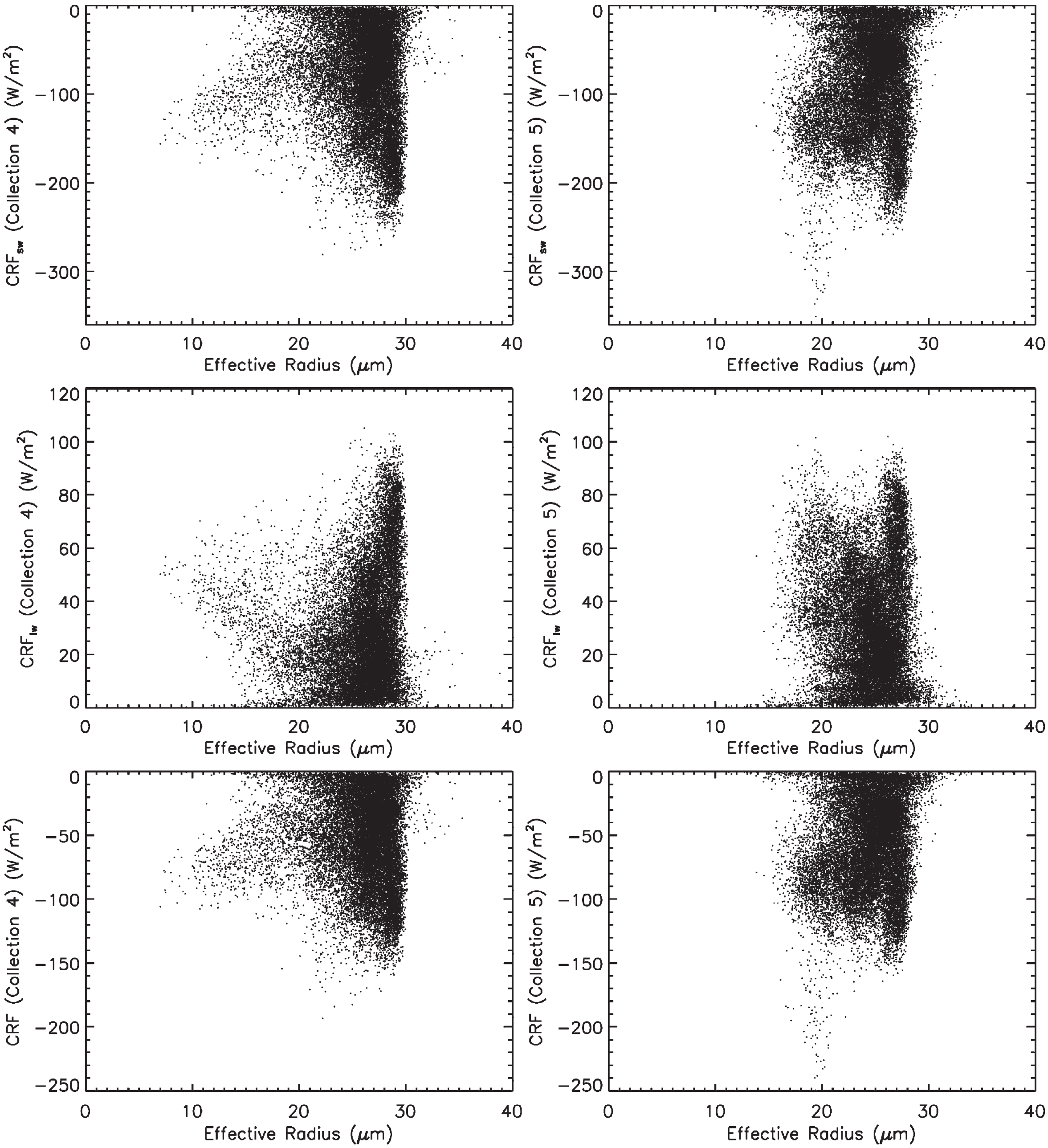

Fig. 9. Relationship between ice cloud effective radius and CRF (CRF$_{\mathrm{SW}}$, CRF$_{\mathrm{LW}}$, and CRF) for collections 4 (left) and 5 (right).

optical thickness. However, a monotonic relationship between CRF and cloud optical thickness cannot be obtained from the results shown in Fig. 8.

The results shown in Fig. 9 indicate that the distribution of particle effective sizes peaks between 20 and 30 μm. A monotonic relationship between CRF and effective particle size cannot be derived from the results shown in Fig. 9.

IV. SUMMARY

In this paper, we compare the differences of the bulk optical properties of ice clouds used in the MODIS collection 4 and 5 ice cloud retrievals. We investigate the effect of these differences on the forward radiative transfer simulations required for generating the static libraries of the ice cloud bidirectional reflection functions over a range of optical thicknesses and effective particle sizes. This paper indicates that the theoretical relationship between the reflection functions at two bands (e.g., 0.65 and 2.13 μm) computed from the ice cloud optical models for collection 5 may lead to smaller effective particle sizes in comparison with their collection 4 counterparts. The effect on the retrieval of optical thickness is noticed primarily for the smallest and largest effective particle sizes.

One year (January 2004–December 2004) of the cloud property data derived from the Aqua/MODIS measurements, including ice cloud fraction, effective particle size, and optical thickness from both collections 4 and 5, are compared for the tropical belt (30° S–30° N). On average, the collection 5 ice cloud fraction is 6.1% larger and 0.8% smaller than the collection 4 data over land and ocean, respectively. In terms of optical thickness, the collection 5 results are 0.3 smaller and 1.9 larger than their collection 4 counterparts over land and ocean, respectively. In terms of effective particle size, the collection 5 results are 1.9 and 1.7 μm smaller than the collection 4 counterparts over land and ocean, respectively.

Furthermore, we investigate the impact of the differences between collection 4 and 5 ice cloud products to assess the radiative forcing of these clouds. The differences in the total cloud forcing are primarily between -60 and 20 $\mathrm{W \cdot m^{-2}}$ and peak at 0 $\mathrm{W \cdot m^{-2}}$. Thus, the differences between collections 4 and 5 ice cloud products can lead to either an enhancement or a reduction of the warming effect of ice clouds, depending on a specific ice cloud of interest. From the radiative forcing perspective, the differences found between collections 4 and 5 ice cloud products demonstrate the need to correctly characterize the scattering and absorption properties of ice crystals in climate models.

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