Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part II: Ice Clouds

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ABSTRACT

Cirrus clouds play an important yet poorly determined role in the earth's climate system and its various feedback mechanisms. As such, a significant amount of work has been accomplished both in understanding the physics of the ice clouds and in using this knowledge to estimate global distributions of ice cloud properties from satellite-based instruments. This work seeks to build on these past efforts by offering a reexamination of the ice cloud retrieval problem in context of recent advancements in the understanding of optical properties for a variety of realistic ice crystal shapes. In this work, the formal information content analysis outlined in Part I is used to objectively select the optimal combination of measurements for an ice cloud microphysical property retrieval scheme given a realistic assessment of the uncertainties that govern the ice cloud retrieval problem. Although this analysis is for a theoretical retrieval combining simulated measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) with the CloudSat Cloud Profiling Radar (CPR) above an ocean surface, the general methodology is applicable to any instrument package. Channel selection via information content is determined through a realistic characterization of not only the sensitivity of top-of-the-atmosphere radiances to desired retrieval parameters but also to the uncertainties resulting from both the measurements themselves and from the forward model assumptions used in relating observational and retrieval space. Results suggest that the channels that maximize retrieval information are strongly dependent upon the state of the atmosphere, meaning that no combination of two or three channels will always ensure an accurate retrieval. Because of the complexities of this state-dependent nature and the need for a consistent retrieval scheme for an operational retrieval, a five-channel retrieval approach consisting of a combination of error-weighted visible, near-infrared, and infrared channels is suggested. Such an approach ensures high information content regardless of cloud and atmospheric properties through use of the inherent sensitivities in each of these spectral regions.

1. Introduction

Cirrus clouds play an important role in regulating climate (Liou 1986). They directly influence the radiative budget by increasing the amount of shortwave and decreasing the amount of longwave radiation emitted to space. These competing radiative effects impact climate variability through a variety of possible feedback mechanisms involving convection, sea surface temperature, water vapor, and large-scale dynamics. The sign or magnitude of these forcings, however, is poorly understood because of uncertainties in both cloud distribution and microphysics (Stephens and Webster 1981; Stephens et al. 1990), so subsequently the role of these clouds in the climate feedback mechanisms and global

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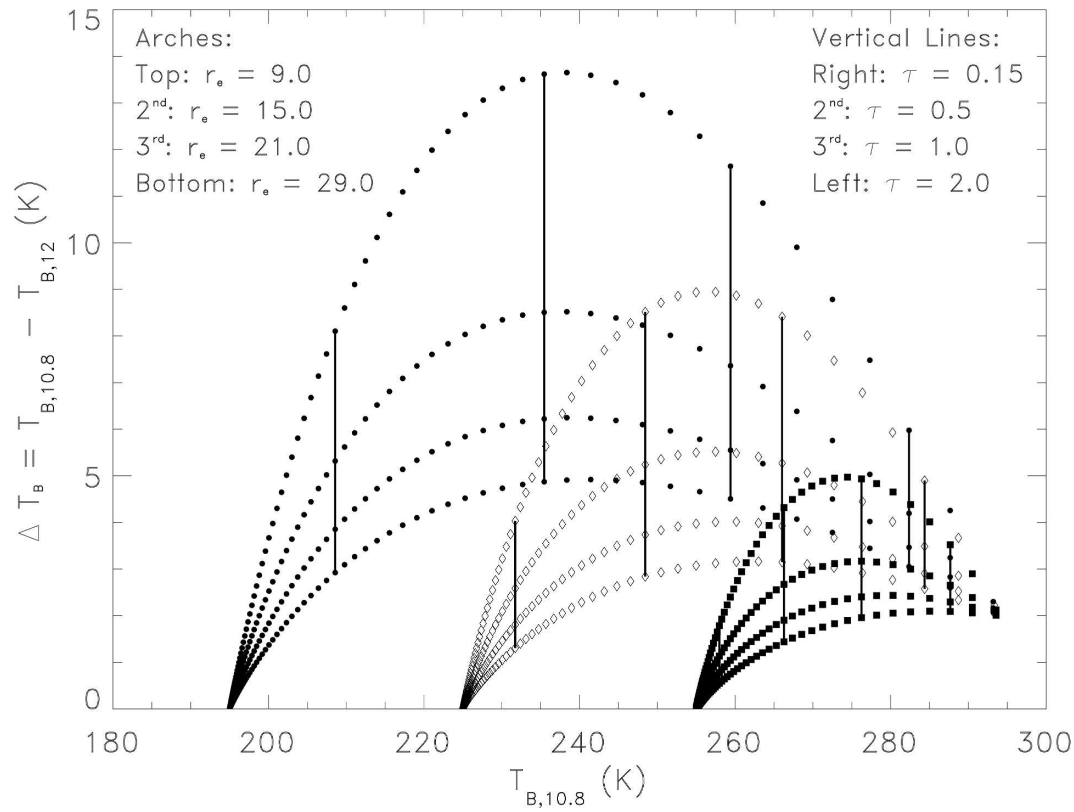

FIG. 1. Relationship between ΔT_B and $T_{B,10.8}$ for a number of cirrus clouds with optical depths ranging from 0 to 4 and effective radii ranging from 9 to 29 μm. Clouds with emitting temperatures of 195 (filled circles), 225 (open diamonds), and 255 (filled squares) K are modeled.

warming scenarios is still poorly determined (Lindzen et al. 2001; Fu et al. 2002). In this work, we hope to gain a better understanding of the ice cloud problem through application of a formal information content analysis as outlined in the proceeding companion paper (L'Ecuyer et al. 2006, hereinafter Part I). It is hoped that insights gleaned from this study will ultimately result in improved algorithms for better characterizing the distribution and microphysical properties of these clouds and their impacts on climate.

Measuring the global distribution of cirrus cloud microphysical properties has been a concern of many satellite missions. As such, a substantial amount of work has been accomplished not only in understanding the physics of the ice cloud problem but also in using this knowledge to infer cloud properties from satellite-based measurements (Inoue 1985; Prabhakara et al. 1988; Nakajima and King 1990; King et al. 1992; Baum et al. 2005). In this work, we do not question the usefulness of these past efforts or their validity for their specific applications, but instead, we offer a reexamination of the ice cloud problem in terms of recent developments in the understanding of ice cloud physics. Cirrus cloud retrievals depend on an accurate, a priori understanding of both ice crystal radiative properties and the current state of the atmosphere. For an inversion from a given set of radiance measurements, inconsistencies between these assumptions and the real atmosphere will lead to significant errors in mapping between observation and retrieval space. Figure 1, adopted from Cooper et al. (2003), shows theoretical arches for the split-window approach to retrieving cloud properties. The split-window technique (Inoue 1985; Prabhakara et al. 1988) relies on differences in radiative properties for cloud particles at two wavelengths in the window region to estimate cloud optical depth and effective radius from satellite-observed brightness temperatures. An inherent shortcoming of this approach is that retrieved parameters are strongly dependent upon cloud temperature. For given 10.8- and 12.0-μm brightness temperatures, a different effective radius and optical depth are found for each cloud temperature assumption in Fig. 1. The use of visible and near-infrared channels to retrieve cloud optical properties suffers from similar difficulties, as suggested by the Nakajima and King (1990, hereinafter NK)-type re-

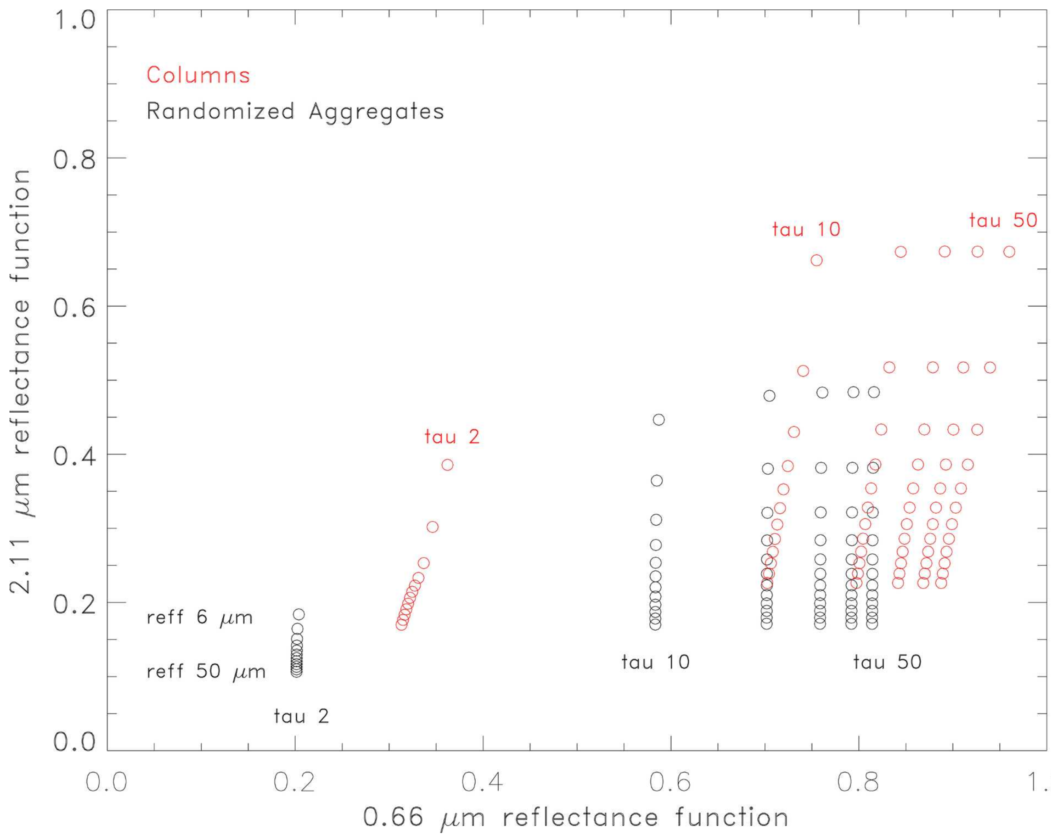

FIG. 2. Relationship between 0.66- and 2.11-μm reflectance functions for ice clouds composed of both a modified gamma distribution of randomized aggregates and an equivalent distribution of columns. Effective radius range from 6 to 50 μm and optical depths from 2 to 50.

trieval approach shown in Fig. 2. This technique relies on the conservative scattering properties of the visible channel to estimate cloud optical depth and the nonconservative scattering properties of the near-infrared channel to estimate effective radius once optical depth is known. The inherent problem of this approach is not uncertainty in cloud temperature but uncertainty in cloud optical properties. Figure 2 shows that for given 0.65- and 2.11-μm reflectance functions, the retrieved parameters depend heavily on the a priori assumption of ice crystal habit through their differing radiative properties. In addition to crystal habit and cloud temperature, other possible retrieval uncertainties result from assumptions of cloud particle size distribution, cloud 3D scattering effects, surface type, and atmospheric temperature and humidity profiles. In this work, we will quantify expected errors resulting from these sources to the extent that it is possible and examine their implications for retrieval approach.

The information content methodology as described in Part I is used to objectively select the optimal combination of measurements for an estimation-based ice cloud retrieval scheme given a realistic assessment of the current knowledge of the ice cloud retrieval problem. The method uses information theoretical concepts elucidated by Shannon and Weaver (1949) and on the application of their technique to atmospheric science by Rodgers (2000). Channel selection is made objective by quantifying the amount of information contained in the spectral measurements and calculating their effective signal-to-noise ratio in relation to the desired set of retrieval parameters. This is accomplished practically through analysis of the retrieval covariance matrix, which holds the key for understanding and quantifying differences between different retrieval procedures and observational data. Although this analysis is applied to a theoretical retrieval combining simulated measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) with the CloudSat Cloud Profiling Radar (CPR) above an ocean surface, the general methodology, in principle, could be applied to any instrument package and any retrieval problem.

The sensitivities and uncertainties used in determination of the effective signal-to-noise ratio for the

TABLE 1. MODIS channels evaluated for information content analysis.

MODIS channel	Wavelength	MODIS channel	Wavelength
1	0.62–0.67	27	6.53–6.90
2	0.84–0.88	29	8.40–8.70
5	1.23–1.35	31	10.78–11.28
6	1.63–1.64	32	11.77–12.27
7	2.10–2.15	33	13.18–13.49
19	0.91–0.96	34	13.48–13.78
20	3.66–3.84	35	13.78–14.08
23	4.02–4.08	36	14.08–14.38
26	1.36–1.39		

MODIS channels listed in Table 1 are examined across the climatological range of ice cloud properties to determine which channels are most useful dependent upon the state of the atmosphere. Such calculations are made possible only by the recent development of optical properties for a variety of nonspherical ice crystals at the MODIS wavelengths (Baran et al. 2001; Yang et al. 2000, 2003), allowing a reasonable estimate of the uncertainties in satellite-viewed radiances resulting from variations of cloud microphysical properties, most notably crystal habit. The results will show that the optimal combination of channels for ice cloud retrieval is highly case dependent, meaning that there is no ideal combination of two or three channels that will always ensure an accurate retrieval. Instead, a five-channel estimation-based retrieval scheme is suggested that uses a combination of visible, near-infrared, and infrared channels weighted by appropriate estimates of their errors to place emphasis on those channels that contain the most information, given our best estimate of the state of the atmosphere. It is hoped that an estimate of cloud properties with associated uncertainties, based on an honest assessment of ice cloud physics from such a retrieval scheme, will be useful both in determining the extent to which these clouds can be measured and in assessing their role in climate variability.

Section 2 describes the forward model used to estimate satellite-observed radiances for given cloud and atmospheric properties. Section 3 discusses the sensitivity of these top-of-the-atmosphere (TOA) radiances to small perturbations in cloud and atmospheric properties to determine the set of wavelengths that potentially contain the most information given the atmospheric state. Because an estimate of both sensitivity and uncertainty is required to compute an effective signal-to-noise ratio as defined in Part I, section 4 focuses on an estimate of forward model error resulting from uncertainties in ice crystal shape, ice crystal size distribution, and atmospheric profile. Section 5 presents a formal information content analysis that is used to select those channels that contain the most information given a variety of expected climatological conditions, while section 6 explores the practical implications of these results for an operational retrieval.

2. The forward model

A 48-stream adding-and-doubling radiative transfer model was used to calculate top-of-the-atmosphere radiances assuming a plane-parallel atmosphere. The solution of the radiative transfer equation for this technique is well documented in the literature and will be omitted here for brevity. Application of this numerical model to the real-world cirrus cloud problem is only insightful when rigorous, realistic physical assumptions are used as input for the model. An accurate representation of atmospheric profile, surface reflection, and cloud microphysical properties is crucial to understanding what information actually can be retrieved for a given instrument package. The base physical assumptions used in the forward model for the sensitivity studies of section 3 will be described briefly. Atmospheric absorption in our model was approximated by correlated-*k* distributions specifically developed for the MODIS wave bands by Kratz (1995), where the vertical distribution of gases and temperature were defined by the McClatchey tropical atmosphere (McClatchey et al. 1972). The surface was assumed to be an isotropically reflecting ocean surface with a visible albedo of 0.1 and infrared albedo of 0.01. Cirrus clouds were assumed to be 1 km thick and at the same temperature as the layer of the atmosphere in which they were embedded. The clouds were composed of randomly oriented randomized hexagonal ice aggregates (Yang and Liou 1998) using the optical properties developed by Baran et al. (2001) and Baran and Francis (2004), arranged in a modified gamma size distribution of the form

$$n(D) = N_0 \frac{1}{\Gamma(\nu)} \left(\frac{D}{D_n}\right)^{\nu-1} \frac{1}{D_n} e^{-D/D_n}, \qquad (1)$$

where the variance parameter ν is equal to 2, $n(D)$ is the number of ice crystals of size D, N_0 is the number concentration, and D_n is the characteristic diameter (Stephens 1994). The basis for choosing these crystals is that Baran et al. (2003), based on a method of optimal estimation, showed that the single scattering properties for these aggregates combined with a modified Henyey–Greenstein phase function better explained observed radiances than the optical properties for more pristine crystal habits. Because these aggregates had strongly forward peaked phase functions, a modified form of the delta-Mscaling technique (Wiscombe 1977)

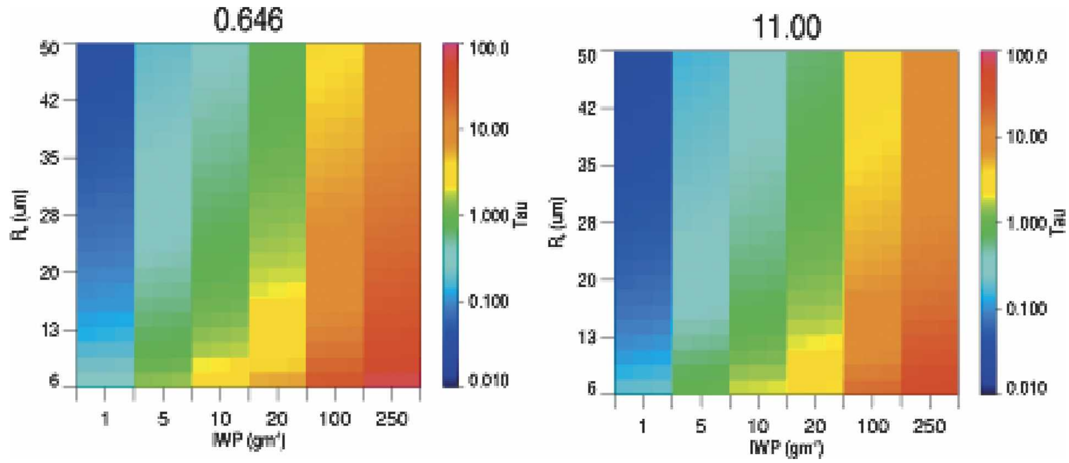

FIG. 3. The 0.64- and 11.0-μm optical depths for given effective radius–IWP ice clouds evaluated in sensitivity studies.

recently developed by Mitrescu and Stephens (2004) was used to accurately calculate radiance while maintaining computational efficiency. Both the observation angle and the solar zenith angle were at nadir.

3. Sensitivity studies

The retrieval of cloud properties from satellite-based measurements depends on the ability to relate observed radiances back to a unique set of desired cloud properties. Those measurements that show the greatest change or sensitivity to small changes in cloud microphysical properties are potentially the most useful for cloud retrieval. Traditional retrieval schemes are based on a priori knowledge of these sensitivities, for example, the split-window technique ultimately depends upon the sensitivity of radiance measurements resulting from a difference in the refractive index for ice cloud particles at wavelengths in the window region. The magnitude of these sensitivities, however, is heavily dependent upon both wavelength and the state of the atmosphere. The split-window technique, see Fig. 1, only has sensitivity for optically thin clouds with relatively small effective radius. An ideal retrieval scheme should be based on the proper selection of those channels with the greatest sensitivity for the current state of the atmosphere. Thus, a series of sensitivity studies were run for each of the MODIS wavelengths listed in Table 1 to determine how satellite-observed radiances change for small perturbations of the desired retrieval parameters. Although these results will be specifically for the use of the Baran ice optical properties, it should be noted that other crystal habits exhibited very similar sensitivities or trends in radiance albeit with different magnitudes—for example, see Fig. 2.

Sensitivity studies were run for cloud particle effective radius, ice water path (IWP), cloud temperature, and surface albedo. Each of these parameters were perturbed while holding the other parameters fixed to determine the magnitude of the radiance change at the top of the atmosphere for a given change in the varied parameter. It should be noted that for the perturbations of effective radius, the ice crystal size distribution number concentration was necessarily varied to fix IWP, meaning that cloud optical depth increases with both decreasing effective radius and increasing IWP for these studies. Synthetic radiances were calculated for small perturbations about cloud effective radii between 6 and 50 μm, IWP between 1 and 250 g m^{-2}, cloud heights between 8 and 15 km, and the base surface albedos of 0.1 for the visible and near-infrared and 0.01 for the infrared channels. IWP and effective radius combinations were chosen to ensure that cloud optical depths (Fig. 3) varied across the expected range for cirrus clouds at each MODIS wavelength. Because it is impractical to present results from all of these sensitivity studies, a few sample cases will be examined to demonstrate that our forward model and its assumptions are capturing the basic physics of the ice cloud problem. Although the sample cases are chosen for their well-known physical properties, as visualized in Figs. 1 and 2, it is important to remember that all channels in Table 1 will be evaluated in an unbiased manner in the information content analysis of section 5 to objectively select the most useful channel for the given state of the atmosphere.

Figures 4a, 4b, and 4c show example results from the sensitivity studies for the 0.65-, 2.13-, and 11.0-μm channels, respectively, as a function of effective radius and ice water path for a cloud at 9 km. The values in the

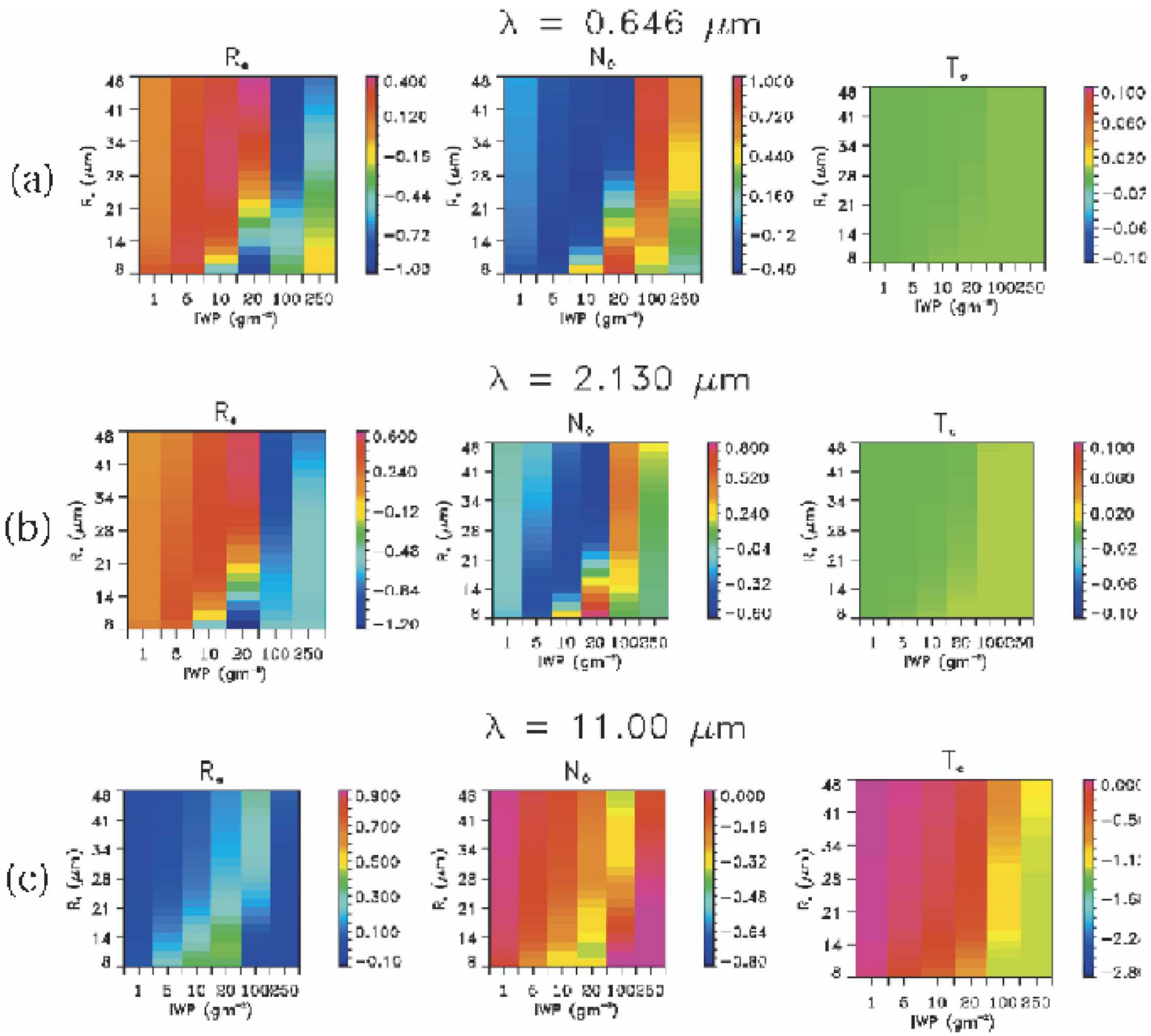

FIG. 4. Sensitivities to effective radius, IWP (N_0), and cloud temperature for the (a) 0.65-, (b) 2.13-, and (c) 11.00-μm MODIS channels are shown for the given effective radius–IWP combinations for a cloud height of 9 km. Sensitivities indicate a normalized change in top-of-the-atmosphere radiance given a change in the specified variable while holding the other two fixed.

three panels represent from left to right the normalized change in radiance $(x/I)dI/dx$, given a change in effective radius, ice water path, and cloud temperature, respectively, holding the other retrievable parameters fixed. For the highly absorbing ocean background assumed in these studies, surface albedo effects are generally small and will be neglected for the remainder of the paper. For an operational retrieval over land or over a less idealized ocean surface, of course, albedo will become very important and need consideration. Figure 4a suggests that the 0.66-μm channel is sensitive to both effective radius and IWP, but not to cloud temperature. These results agree with our physical intuition of the problem. The conservative scattering 0.66-μm channel is useful in retrieving cloud optical depth, because satellite-observed radiances at this wavelength are primarily a function of cloud optical depth. For our sensitivity studies, this property leads to the observed sensitivity for perturbations of both IWP and effective radius because both act to determine optical depth as discussed above. Sensitivities to IWP and effective radius are similar but opposite in sign as decreasing effective radius increases optical depth, with generally good sensitivity except for the optically thick and thin clouds. The thickest clouds have low sensitivity because the reflectance function slowly converges as optical depth becomes large (see Fig. 2). The thin clouds have poor sensitivity because of a complex interaction of the directly backscattered radiation and the forward-scattered radiation reflected off the ocean. As expected, the 0.65-μm channel shows little sensitivity to cloud height perturbations because gaseous absorption is negligible small in this channel.

The sensitivity studies for the 2.13-μm channel in Fig. 4b are very similar to those of the 0.66-μm channel in that they exhibit sensitivity to both IWP and effective radius but not cloud temperature. The nonconservative scattering 2.13-μm channel is useful in retrieving cloud particle effective radius, because backscattered radiation now becomes dependent upon particle size. Sensitivity to perturbed effective radius is again generally good, except for the low IWP cases where Fig. 2 suggests we would expect the smallest sensitivity. Sensitivity to both IWP and cloud temperature is similar in trend to that of the 0.65-μm channel for similar reasons.

Figure 4c suggests that the infrared 11.0-μm channel displays sensitivity to effective radius, IWP, and cloud temperature. This sensitivity, however, is limited to IWP-effective radius combinations that result in intermediate optical depths from one to about five, agreeing very well with the working range of the split-window retrieval technique as seen in Fig. 1. If the cloud becomes too thick, emission is that of a Planck blackbody emitting at cloud temperature so that further perturbations cannot change the radiance. If the cloud is too thin, surface emission dominates and the contribution from the cloud is negligible. Sensitivity to cloud height increases with increasing optical depth, becoming important for thick clouds when the emission from the cloud and not the surface begins to dominate the radiance measurement.

4. Uncertainty analysis

Information content of a set of measurements depends not only on the sensitivity of measurements to retrieved cloud parameters, but also on the error associated with each of these measurements both from the instrument itself and from the a priori assumptions as discussed in the introduction. Instrument error primarily results from calibration issues and is on the order of a few percent (Guenther et al. 1996). Error from forward model assumptions required to simulate radiances, however, is generally much larger. The remainder of this section will focus on the quantification of these errors for the MODIS channels listed in Table 1. Uncertainties in radiances associated with our choices of ice crystal habit, cloud particle size distribution, and atmospheric temperature and relative humidity profiles were determined by calculating TOA radiances for the base case assumptions described in section 3 and then comparing these results with radiances found using alternate assumptions. Further uncertainties associated with 3D radiative transfer effects, multiple-layer clouds, and the vertical inhomogeneity of ice cloud microphysical properties, although certainly important, are beyond the scope of this paper and will be neglected.

The assumption of crystal habit and associated optical properties will heavily influence cirrus cloud retrieval results. Cooper et al. (2003) showed that uncertainties in ice crystal habit were important in determining overall retrieval accuracy for a modified version of the infrared split-window technique. Errors from habit assumptions should be expected to be even greater for the visible and near-infrared channels where large single scattering albedos could result in significant multiple scatterings. Radiative transfer calculations were run for a variety of crystal habits developed by Yang et al. (2000, 2003) and compared with those using the Baran et al. (2001) randomly oriented randomized hexagonal ice aggregates. Calculations were made at the visible and near-infrared wavelengths for columns, plates, bullets, rough aggregates, and smooth aggregates and at the infrared wavelengths for droxtels and aggregates. To facilitate comparisons between the different types of ice habits, the randomized aggregates were converted to an equivalent set of Yang crystals by conserving both the IWP and volume-to-area ratio for the crystal types (Francis et al. 1994; Mitchell and Arnott 1994; Grenfell and Warren 1999; Yang et al. 2001). A ballpark estimate of the error in radiance associated with habit choice is then obtained from the normalized average absolute difference between the Baran aggregates and all Yang crystals. Error estimates were run at each of the effective radii, ice water paths, and cloud temperature combinations in the sensitivity studies. Errors in the visible channels can be as large as a factor of 2 but are more typically around 20%–30%; errors for the infrared channels are generally less than about 5%. One interesting finding from this error analysis is that the fractional errors in the 3.78- and 4.05-μm radiances are significantly greater during the day than the night because of the large uncertainties associated with the scattering of the direct solar beam.

Model errors associated with particle size distribution were assessed by substituting the modified gamma distribution with a variance parameter equal to 2 that is used in the sensitivity studies with both a different modified gamma distribution with a variance parameter equal to 3 and a lognormal distribution. The lognormal distribution is of the form

$$n(D) = N_0 \frac{1}{D \ln\sigma_g (2\pi)^{0.5}} \exp\left[\frac{(\ln D - \ln D_g)^2}{2(\ln\sigma_g)^2}\right], \quad (2)$$

where D_g is the geometric mean diameter and σ_g is the geometric standard deviation (Reist 1994). Unlike those associated with crystal habit, uncertainties in radiance resulting from particle size distribution assumptions were generally under a few percent for all wavelengths, agreeing well with previous work (Stephens et al. 1990; Cooper et al. 2003).

Uncertainties in the determination of atmospheric temperature and moisture profiles were found to be important for the infrared channels, but not for the visible and near-infrared channels. Temperature error was assumed to be 2 K based on expected uncertainties in temperature profiles derived from numerical weather predation models (Eyre et al. 1993), which would be used to constrain an operational retrieval. Resulting errors in infrared radiance measurements varied from about 3% to 8% because of the nonlinear nature of the Planck function. Relative humidity was perturbed 30% for atmospheric levels above 500 hPa and 15% for those levels at or below 500 hPa. These assumptions resulted in errors of less than 3% for all channels. Visible channels are not affected by temperature errors because atmospheric absorption only weakly depends on temperature. Similarly, sensitivity to moisture assumptions was small for the visible channels because the high cirrus clouds were generally above the peak of the weighting functions for these channels.

Figure 5 illustrates the total error resulting from a combination of all of these uncertainties listed above for the 0.66-, 2.13-, and 11.0-μm channels for a cloud at 9 km and for the IWP–effective radius combinations used in the sensitivity studies. Each of the above sources is considered to be uncorrelated, so total error is simply the sum of the squares of the individual sources. Figure 5 shows that error is clearly dependent upon the state of the atmosphere, with generally large errors in the visible channel dominated by habit effects and comparatively small errors in the infrared resulting from a mixture of uncertainties in habit, temperature, and moisture assumptions.

5. Information content analysis

An information content analysis based on the techniques of Shannon and Weaver (1949) and Rodgers (2000), as described in Part I of this paper, was performed using the results of the sensitivity and uncertainty studies to determine the optimal channels for a theoretical cirrus cloud retrieval using the MODIS instrument. A brief summary of salient features of the information content methodology is included here for completeness. In these analyses, information H is defined as the difference in entropy S between two states P_1 and P_2,

$$H = S(P_1) - S(P_2). \quad (3)$$

If Gaussian distributions are assumed for both states, Rodgers (2000) shows that information can be rewritten in terms of the distribution covariances $\mathbf{S}_1$ and $\mathbf{S}_2$,

$$H = \frac{1}{2}\log_2|\mathbf{S}_1\mathbf{S}_2^{-1}|. \quad (4)$$

For an ice cloud retrieval algorithm, the initial state covariance is simply the a priori error covariance matrix $\mathbf{S}_a$, which represents the expected climatological range of ice cloud properties. The final state covariance is defined by the error covariance matrix for retrieved cloud properties $\mathbf{S}_x$, defined mathematically as

$$\mathbf{S}_x = (\mathbf{S}_a^{-1} + \mathbf{K}^{\mathrm{T}}\mathbf{S}_y^{-1}\mathbf{K})^{-1}, \quad (5)$$

where $\mathbf{K}$ is the Jacobian determined from the sensitivity studies of section 3 and $\mathbf{S}_y$ is the forward model and measurement covariance matrix determined from the uncertainty analyses of section 4. Use of these assumptions in Eq. (4) yields a form for H that is defined entirely in terms of the work described in the preceding sections,

$$H = \frac{1}{2}\log_2|\mathbf{S}_a(\mathbf{K}^{\mathrm{T}}\mathbf{S}_y^{-1}\mathbf{K} + \mathbf{S}_a^{-1})|. \quad (6)$$

Separate analyses were conducted for each of the IWP, effective radius, and cloud height combinations described in the sensitivity studies for both daytime and nighttime retrievals and for retrievals with and without complementary information from the CloudSat CPR. In addition, an information content analysis was performed assuming equal error at all channels and atmospheric states to determine the influence of our heavily case dependent error characterization upon final channel selection. We do not have adequate space to discuss the results from all of these runs, so instead we will first focus on specific examples to show that the mathematical results agree with our physical intuition of the problem. To prevent an oversimplification of the ice cloud retrieval problem, however, we must then turn to a graphic representation of the multitude of cases to properly convey the complexity of the problem and its practical implications for an operational retrieval.

Figure 6 shows a sample information spectrum for an

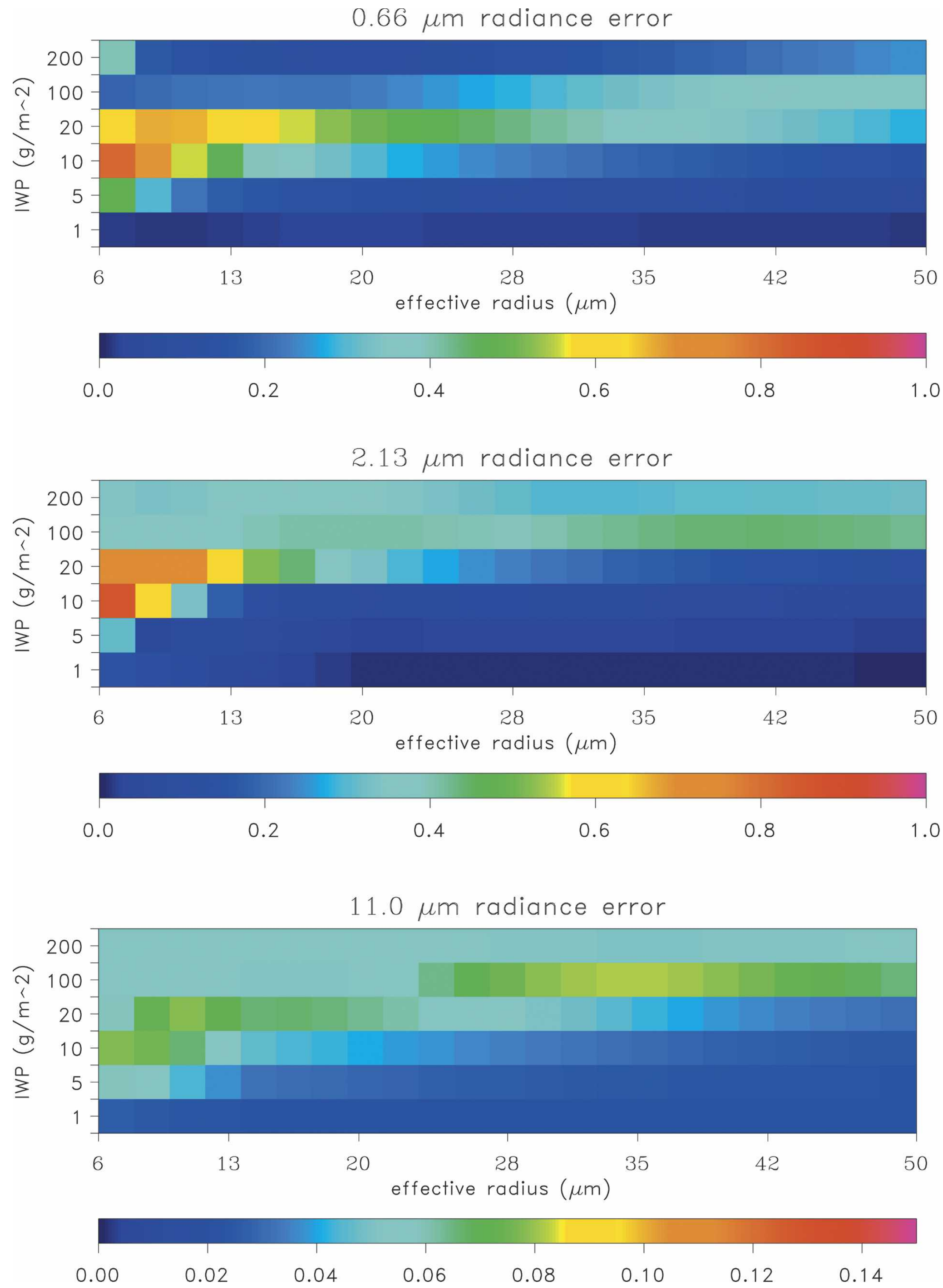

FIG. 5. Combined fractional uncertainties in MODIS radiances resulting from assumptions of ice crystal habit, crystal size distribution, atmosphere profile, and instrument noise as a function of IWP and effective radius for an ice cloud at 9 km.

optically thick cirrus cloud at 9 km with effective radius of 16 μm and IWP of 100 g m^{-2}, a combination producing a 0.64-μm optical depth near 11.0. The initial entropy is defined by the total number of possible states associated with our a priori characterization of the atmosphere $\mathbf{S}_a$. For our cases constrained by CloudSat and MODIS information, initial entropy would result from all possible states assuming standard deviations

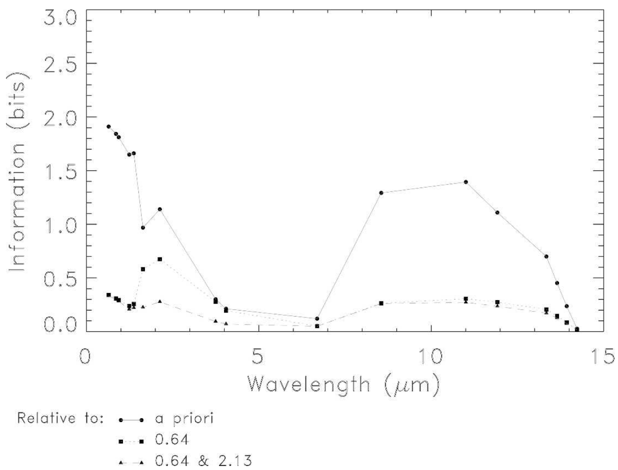

FIG. 6. Information spectrum analysis for an ice cloud with an effective radius of 16 μm, an IWP of 100 g m^{-2}, and cloud height at 9 km.

for a priori assumptions of 1.5 K for cloud temperature based upon the 500-m vertical resolution of the CloudSat radar used to place the ice cloud in the model atmosphere (Stephens et al. 2002) of 10% for surface albedo based upon the greatest expected uncertainty of the MODIS albedo product (Strahler et al. 1999), and 25.0 μm for effective radius and 200 g m^{-2} for IWP based upon the working sensitivity range of passive ice cloud retrieval techniques. Once a measurement is added, however, the entropy or, alternately, the number of possible atmospheric states is reduced to only those consistent with that measurement. The basic idea of these figures is to identify the channel with the most independent information relative to the a priori state, remove that channel, and then rerun the analysis to find the channel with the most independent information for the new state constrained with the first measurement, and so on. In Fig. 6, the top solid curve shows that the 0.64-μm channel contained the most information relative to the a priori state. Because the MODIS measurements may be strongly correlated, the selection of one channel will limit the independent information in a similar channel, for example, in this case the selection of the 0.64-μm channel results in a significant decrease in potential information in the 0.86 μm-channel. The middle dotted curve suggests that the 2.13-μm channel contained the most information for the remaining channels for the a priori state constrained by the 0.64-μm channel. No additional channels were considered useful because their addition did not reduce the entropy given the inherent noise in the system. As expected, this information content analysis suggests that a retrieval scheme based on the NK approach would be highly effective for this thick cloud case.

The selection of channels for this optically thick cloud case agrees well with expectations based on our physical understanding of the problem. The 0.64- and 2.13-μm channels have sensitivity to IWP and effective radius, respectively, as seen in Fig. 2. In turn, this expectation can be verified using the mathematical framework of the information content analysis. Figure 7 presents the singular value analysis for this base case of Fig. 6. The number of singular values that exceed the noise level of 1.0 indicates the number of retrievable parameters that can be inferred from the entire 17-channel dataset; in this case, it is 3. The singular vectors indicate the linear combination of retrievable parameters for each singular value, so for the top-left panel IWP (number concentration N_0) has the largest absolute value and therefore corresponds to the primary information in the system. Effective radius and cloud temperature information correspond to the second and third singular values, respectively. Of course, if we only used the 0.64- and 2.13-μm channels that were selected for this case, we could only retrieve IWP and effective radius. The use of some combination of the remaining channels would improve our cloud temperature retrieval, but because the singular value is small, the increase in retrieval accuracy may not justify the necessary increase in computational effort.

We then changed each of the parameters individually in the base cirrus cloud case to show that different cloud states require different combinations of channels to maximize information content. Figure 8 shows the information spectra for a thin cirrus cloud with the same effective radius and cloud height as in Fig. 6 but now with an IWP of 10 g m^{-2}, producing a 0.64-μm optical depth of 1.1. The optimal combination of channels for this thin cirrus case are the 4.05- and 11.9-μm measurements, in that order, suggesting that two emission-based channels in a split-window-type approach provide the most information for this thin cloud case. These selected channels are not surprising, because the split-window technique has sensitivity for optically thin clouds but not for the thick cloud of the base case (see Fig. 1). Although the visible channels chosen for the base case exhibit sensitivity to thin cirrus, the relatively large errors for these channels resulting from a priori assumptions of the crystal habit ultimately limit their utility.

Figure 9 shows the information spectrum for a cirrus cloud with the same effective radius and IWP as in Fig. 6, but now for a cirrus cloud at a height of 14 km. In this case, the 8.55-, 11.0-, and 2.13-μm channels are sequentially selected. The increased thermal contrast between the surface and the high cloud results in more information for the MODIS measurements, allowing

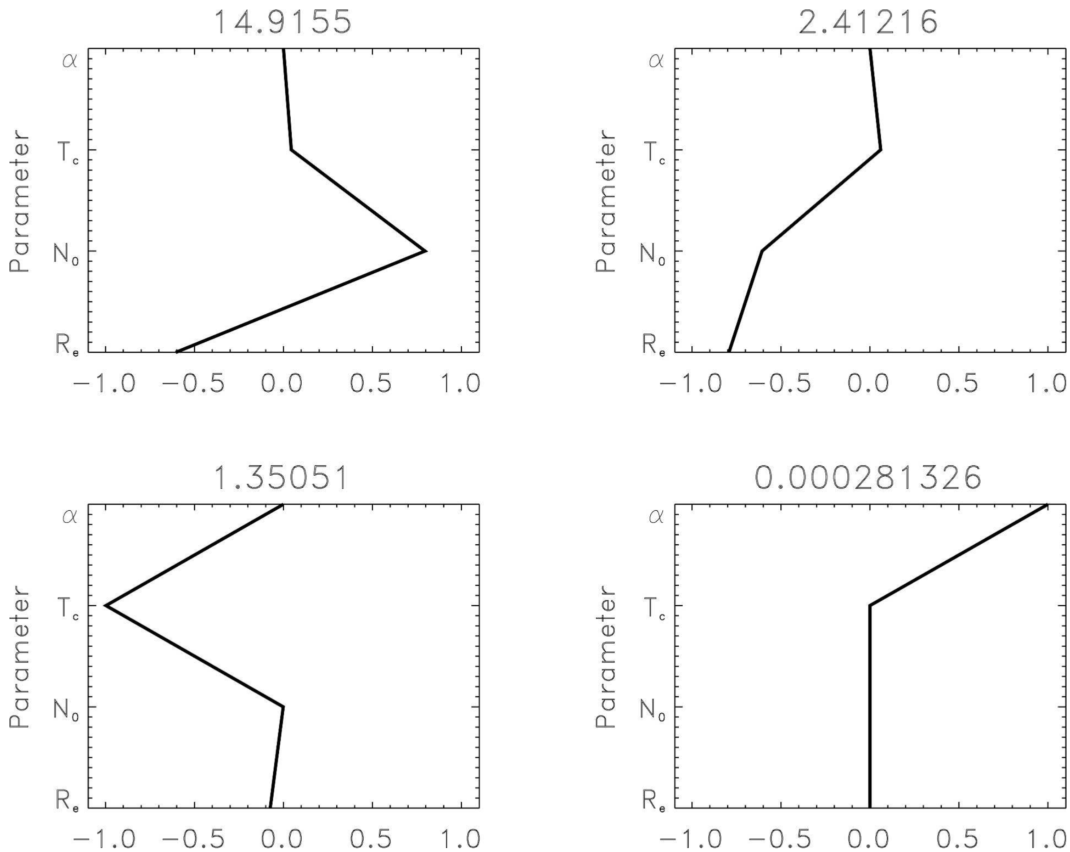

FIG. 7. Singular value analysis for the ice cloud of Fig. 6.

the two infrared and one near-infrared channel to be selected. Although not entirely accurate quantitatively because we are using different channels, the easiest way to qualitatively understand why the high-cloud case should have more information than the low-cloud case is to examine the split-window arches of Fig. 1. Although the arches for the cold cloud are much larger than those for the warm cloud, they both represent the

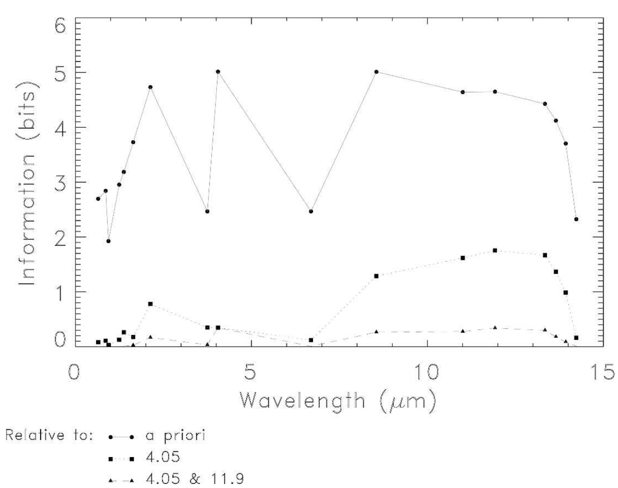

FIG. 8. Information spectrum analysis for an ice cloud with an effective radius of 16 μm, an IWP of 10 g m^{-2}, and cloud height at 9 km.

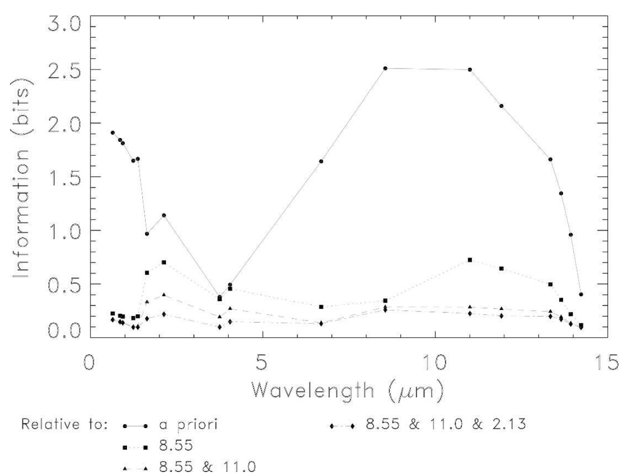

FIG. 9. Information spectrum analysis for an ice cloud with an effective radius of 16 μm, an IWP of 100 g m^{-2}, and cloud height of 14 km.

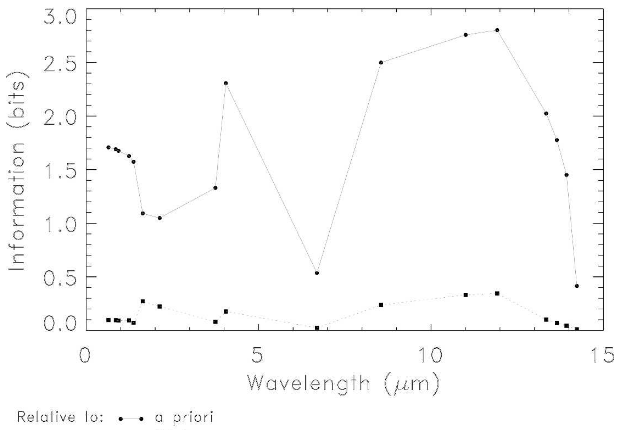

FIG. 10. Information spectrum analysis for an ice cloud with an effective radius of 40 μm, an IWP of 100 g m^{-2}, and cloud height at 9 km.

same number of possible cloud states. A set of measurements with a well-defined uncertainty range defines a set of possible optical depth and effective radius combinations in brightness temperature space. Because these solutions are more spread out for a colder cloud, the same set of measurements necessarily result in fewer possible solutions for the cold-cloud case than the warm-cloud case. Because the a priori space is the same for both clouds, the measurements should contain more information for the cold-cloud case by definition, as suggested by the increased number of useful measurements in Fig. 9. Although the selection of the infrared channels instead of a visible channel may seem counterintuitive for this thick cloud with visible optical depth near 11.0 (infrared optical depth near 7.0), it can be explained through the objective nature of the selection technique. The infrared channels still have limited sensitivity at this optical depth when single scattering albedos are low. High, cold clouds, however, will have a slightly greater signal-to-noise ratio than low, warm clouds in the infrared because the arches are more spread out relative to the magnitude of the measurement uncertainty. The information content approach, therefore, dictates that infrared channels are chosen for this high-cloud case but a visible channel is chosen for the lower-cloud case of Fig. 6.

Figure 10 shows the information spectrum for the optically thick cirrus at a cloud height of 9 km but now with an effective radius of 40 μm, resulting in a 0.64-μm optical depth of 4.7. In this case, only the 11.9-μm channel was considered useful, which the singular value analysis directly relates to IWP. This result is a direct consequence of the fact that neither visible nor infrared approaches have sensitivity at a large effective radius.

Each of the four cases described above require a different combination of channels to maximize information content. Although each of these combinations could generally be explained in terms of our understanding of the underlying physics of the problem, it should be noted that these cases were selected for their relative ease of interpretation. Many other cases representing intermediate conditions for which the physical relationships between radiances and retrieval parameters are transitioning between regimes are more ambiguous, making it difficult to infer the optimal combination of channels before performing the information content analysis. Figure 11 shows the first, second, third, and fourth channel selected for each of the IWP–effective radius combinations for the 9-km cirrus cloud case constrained with CloudSat cloud boundary information. Individual channels have been grouped according to their sensitivity characteristics for clarity of presentation. Dark blue represents the conservative scattering channels, light blue the nonconservative scattering channels, green the water vapor channels, yellow the shortwave infrared (SWIR; solar and emitting 3.78 and 4.05 μm) channels, orange the infrared channels, and red the CO_2-slicing channels. For some cases, such as most large IWP clouds, the optimal channels are simply a combination of scattering and nonconservative shortwave scattering as discussed above. Similarly, moderately thin clouds with a small effective radius require the expected combination of an infrared channel with another infrared, SWIR, or CO_2-slicing channel to maximize information content. The exact transition between these regimes, however, is neither intuitively obvious nor is it independent of other variable such as cloud height or surface type. Often in other cases, such as large effective radius, only one conservative scattering, SWIR, or infrared channel provides independent information for the retrieval, and while the mathematical explanation for the specific wavelength chosen can always be traced backed through the methodology, it is not always obvious from a physical perspective why one type of channel is more useful than the others. This idea that the ideal combination of channels needed to maximize information content changes as a function of state of the atmosphere in a complex manner has important implications for the development of an ice cloud retrieval scheme and will be discussed in section 6.

The analyses of Figs. 6–10 were based both on our best estimate of measurement and forward model uncertainty as outlined in section 4 and on a retrieval scheme constrained with both CloudSat cloud boundary and MODIS albedo information. Information content under less ideal retrieval conditions, namely, re-

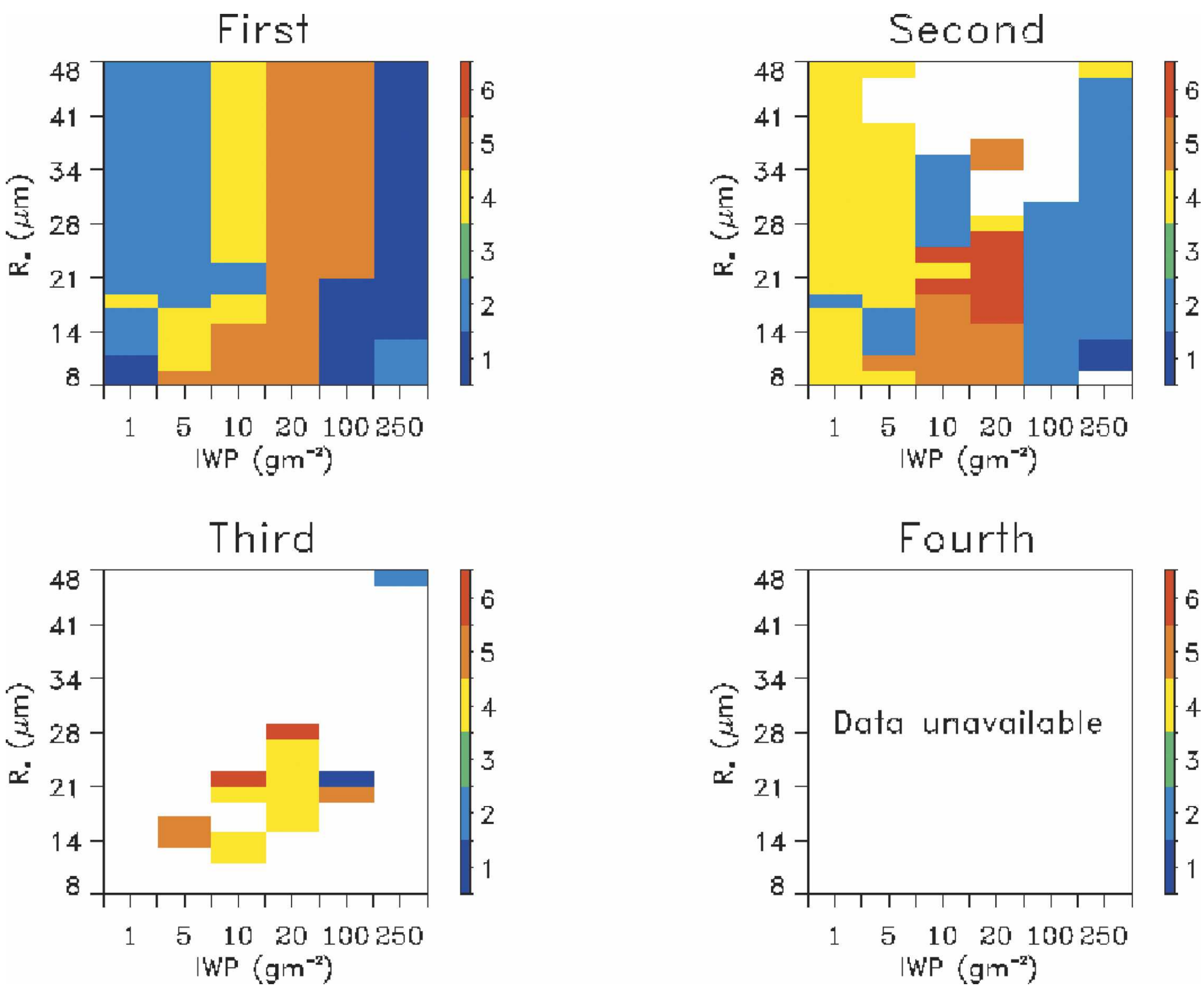

FIG. 11. The selection of the first, second, third, and fourth channel for each of the IWP–effective radius combinations for the 9-km cirrus cloud case constrained with CloudSat cloud boundary information. The channels are not shown as individual channels, but are reported in groups with similar characteristics for clarity of presentation. Dark blue represents the conservative scattering channels, light blue the nonconservative scattering channels, green the water vapor channels, yellow the SWIR (solar and emitting 3.78 and 4.05 μm) channels, orange the infrared channels, and red the CO_2-slicing channels. The absence of color indicates that the addition of measurements did not add any information relative to the noise of the analysis.

trievals without coincident CloudSat radar profiles and at nighttime, is now examined. As Cooper et al. (2003) showed that retrieval results were heavily dependent upon proper error characterization, we also consider the impact of improper representation of forward model errors on optimal channel selection.

We first relaxed the standard deviation of our cloud temperature uncertainties from 1.5 to 15 K and the albedo uncertainty from 10% to 30%, essentially mimicking an observational system dependent upon climatology as a constraint. Figure 12 shows that the ideal combination of measurements that is necessary to maximize information content for these assumptions are the 11.0- and 11.9-μm infrared channels in addition to the 0.66- and 2.13-μm channels chosen for the CloudSat base case of Fig. 6. These additional channels are now needed to supply cloud temperature information that was previously constrained by CloudSat cloud boundary information. This example also brings up the fact that the MODIS measurements contain more information when used without CloudSat than when used with it. Figure 13 shows that for many IWP and effective radius combinations, often three or even four channels are needed to optimize information content without CloudSat as compared with the usual two or maybe three measurements needed for the with CloudSat. While this result may be counterintuitive, it is important to remember that the case with CloudSat has

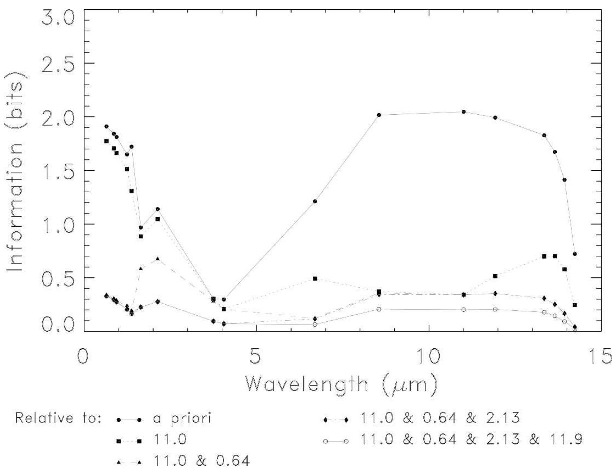

FIG. 12. Information spectrum analysis for the ice cloud of Fig. 6, but now for the scenario in which complementary CloudSat radar profiles are not available.

smaller retrieval error because it effectively constrains the final solution to a smaller set of possible states than the case without CloudSat, as seen in Figs. 14b and 14c. The increased information as displayed in Fig. 14a simply results from the fact that the a priori state is much smaller for the case with CloudSat radar profiles and therefore results in less possible information for the MODIS measurements by definition.

Figure 15 explores the information content for a nighttime retrieval for the base-cloud case of Fig. 6. Because we have no visible information, the 4.05- and 11.0-μm channels are selected, yielding a split-window-type approach. The 4.05-μm SWIR channel becomes much more useful during the nighttime, simply because of the loss of the large uncertainties associated with the scattering of the direct solar beam in daytime. Both the nighttime and without-CloudSat cases emphasize the notion that the optimal channels needed to maximize

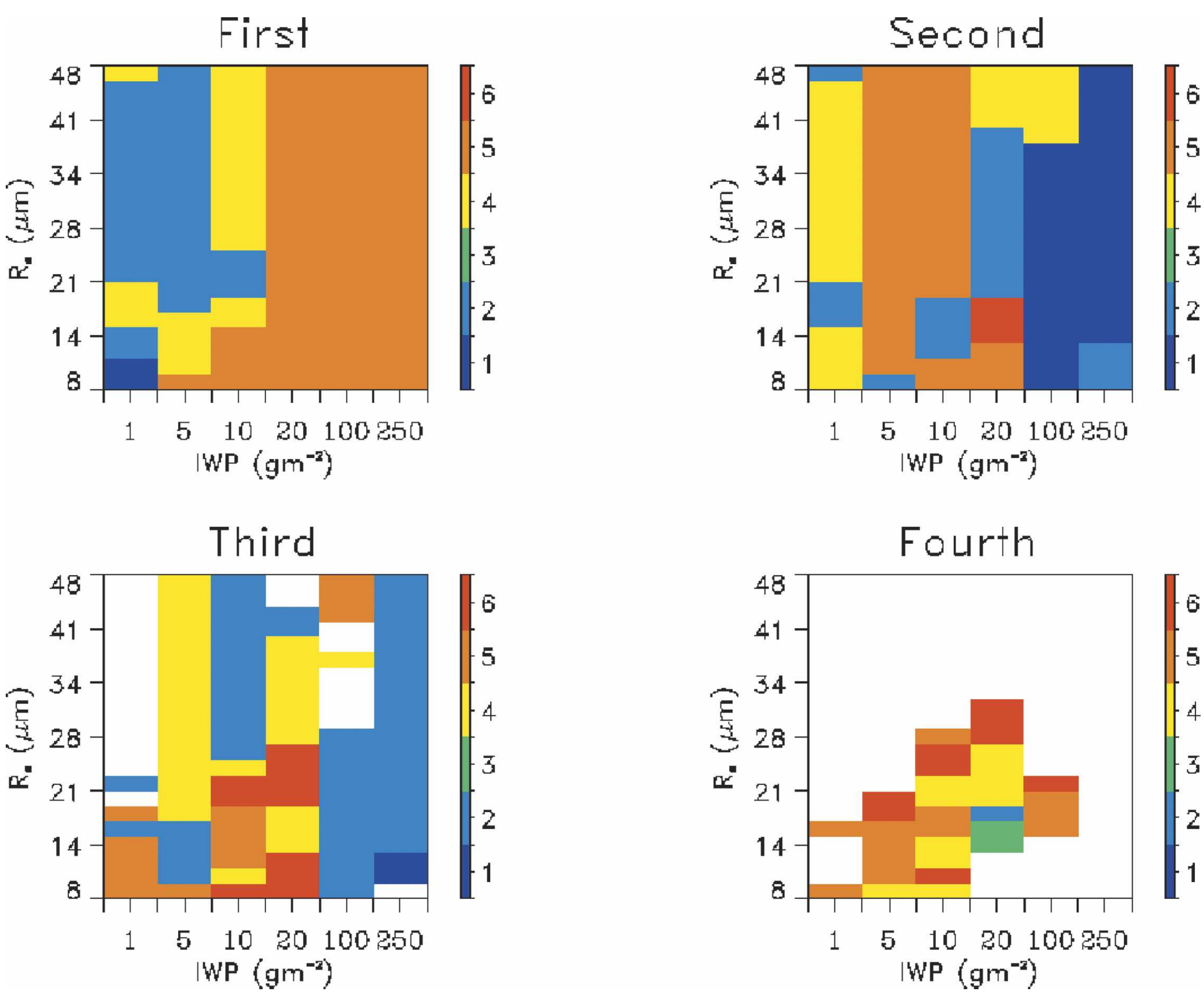

FIG. 13. As in Fig. 11 but for a climatological constraint for cloud boundary information.

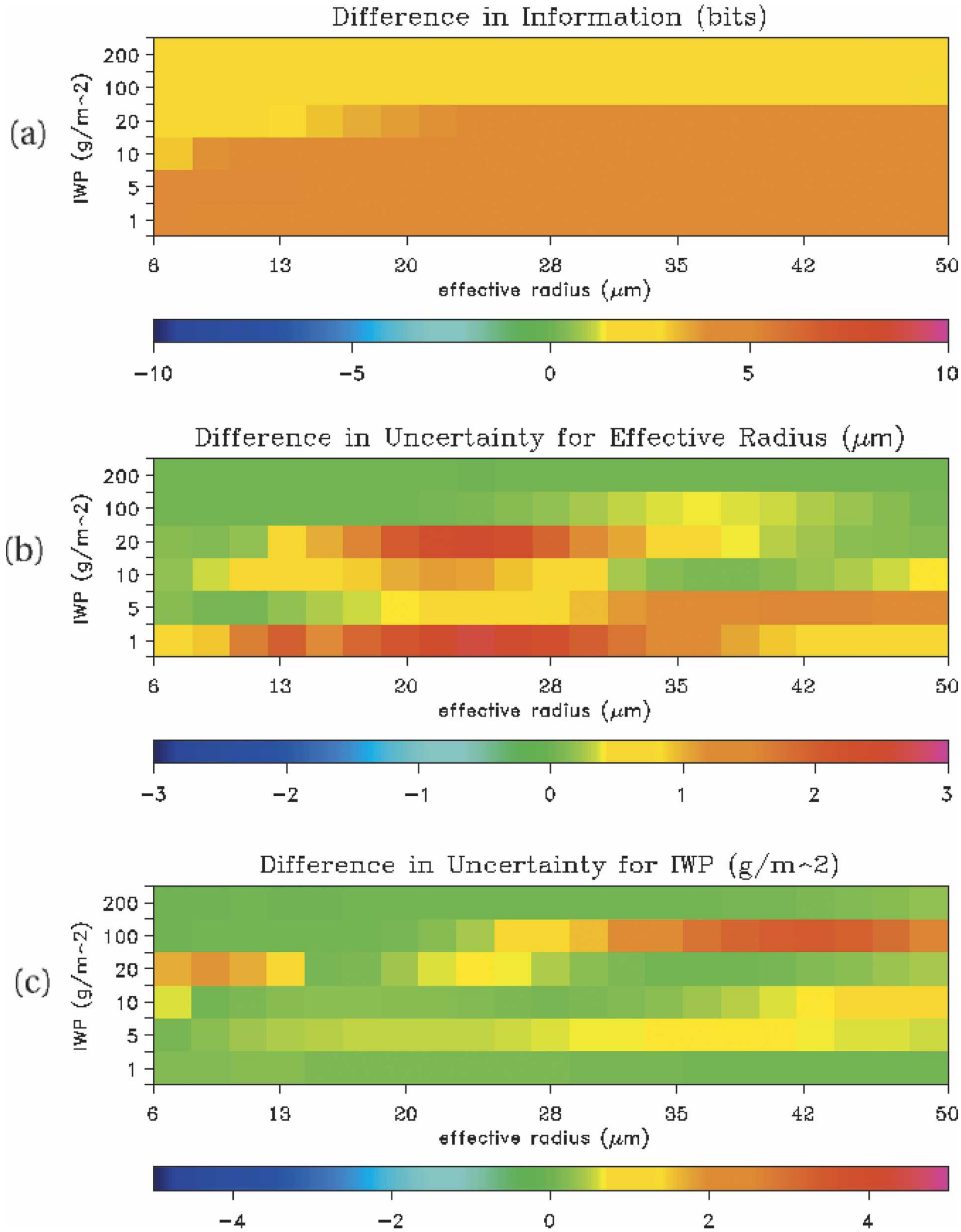

FIG. 14. (a) The difference in information from all MODIS channels used without and with complementary CloudSat cloud boundary information, and the difference in retrieval uncertainty for (b) effective radius and (c) IWP, again for without and with CloudSat information.

information content not only depend on the state of the atmosphere but also on the uncertainties characteristic of the observing system.

This last point is further emphasized by performing an information content analysis assuming that errors in radiance from assumptions of cloud microphysics and atmospheric profile were a constant 10% for all channels and all atmospheric states. This assumption essentially mimics the approaches taken by those cloud retrieval schemes, which do not explicitly account for radiance error. As Fig. 5 shows, a flat error of 10% essentially reduces the error in most shortwave chan-

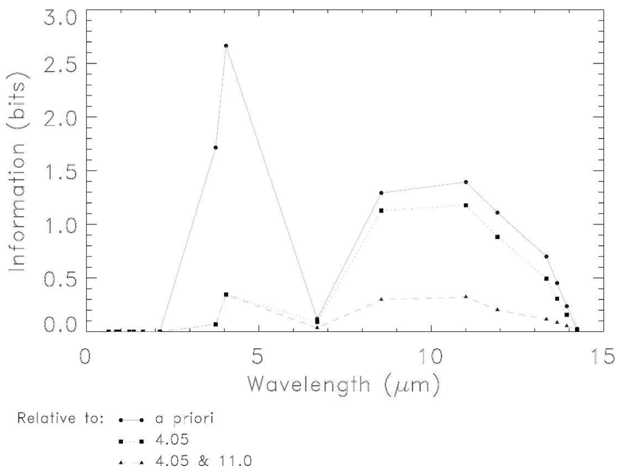

FIG. 15. Information spectrum analysis for the ice cloud case of Fig. 6, but now for a nighttime retrieval.

nels and increases the error in the longwave channels. Figure 16 shows that for the thin cloud case of Fig. 8, the optimal combination of measurements change from the 4.05- and 11.9-μm channels found with realistic errors to the 1.37- and 3.74-μm channels with flat errors. The retrieval approach essentially shifts from a split-window- to a NK-type approach, highlighting the need for the realistic treatment of errors to maximize retrieval information as a function of the state of the atmosphere. This flat-error case also stresses the importance of the objective approach for channel selection. Our general physical understanding as supported by the singular vector analysis of Fig. 17 suggests that the selected channels provide IWP and effective radius information. Indeed, the 3.74-μm channel should have sensitivity to effective radius (Stone et al. 1990) and the 1.37-μm channel to IWP (Gao and Kaufman 1995), but it is not clear why these channels are more useful than similarly behaved channels. It is only the formal information content approach that allows for the unbiased selection of the ideal channels.

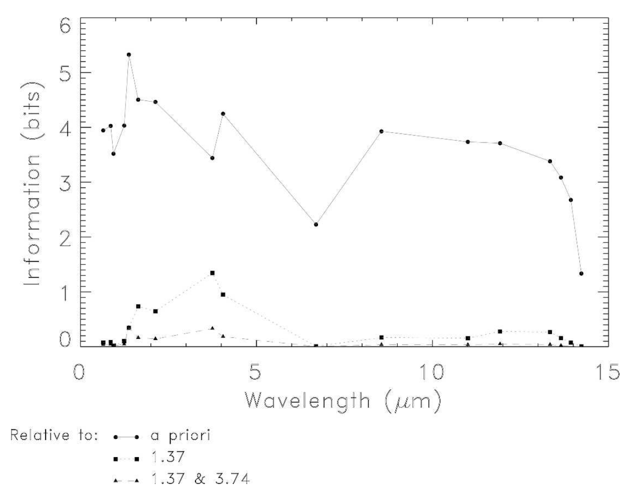

FIG. 16. Information spectrum analysis for an ice cloud with an effective radius of 16 μm, an IWP of 10 g m^{-2}, and cloud height at 9 km as in Fig. 8, but now assuming a constant error of 10% for all channels and states of the atmosphere.

6. Implications for global retrieval approach

Different combinations of channels were selected for each of the different cloud cases examined above, meaning no combination of two or three channels can ensure an accurate retrieval under all conditions given uncertainties in cloud microphysical properties. Because using different channels for an operational retrieval for each pixel is impractical and can lead to discontinuities in global products at the interfaces between different techniques, we instead suggest a retrieval scheme composed of the same five channels regardless of scene. Based upon the nearly 800 cloud cases in this analysis, the retrieval scheme should consist of a combination of error-weighted visible, near-infrared, and infrared channels chosen to use the inherent sensitivities in each of these regions to ensure high information content across expected cloud and atmospheric conditions.

To facilitate an understanding of the potential for this error-weighted, multiple-channel retrieval approach, the information content analysis is applied to a theoretical five-channel retrieval scheme, consisting of the 0.66-, 2.13-, 4.05-, 11.0-, and 13.3-μm channels as seen in Fig. 18. The bottom-right plot of Fig. 18 shows the total information from all MODIS channels as a function of effective radius and IWP for a cirrus cloud at 9 km with the a priori assumptions described above for our base case. The other panels of Fig. 18 represent the fractional information resulting from the addition of each channel into a theoretical retrieval. The upper-left plot for 11.0 μm represents the fractional information contained in that channel alone; the 0.646-μm plot represents the fractional information by using that channel with the 11.0-μm channel, and so on, until we have the fractional information for the five channels as designated by the 13.34-μm plot. Figure 18 shows that the theoretical five-channel retrieval scheme captures a significant fraction of total information for most IWP–effective radius combinations for a cirrus cloud at 9 km. Although the scheme is least effective for the large IWP cases, it still captures nearly 80% of the total information. The addition of more channels to the retrieval scheme would be superfluous because the little remaining information is spread out more or less equally among the remaining MODIS channels.

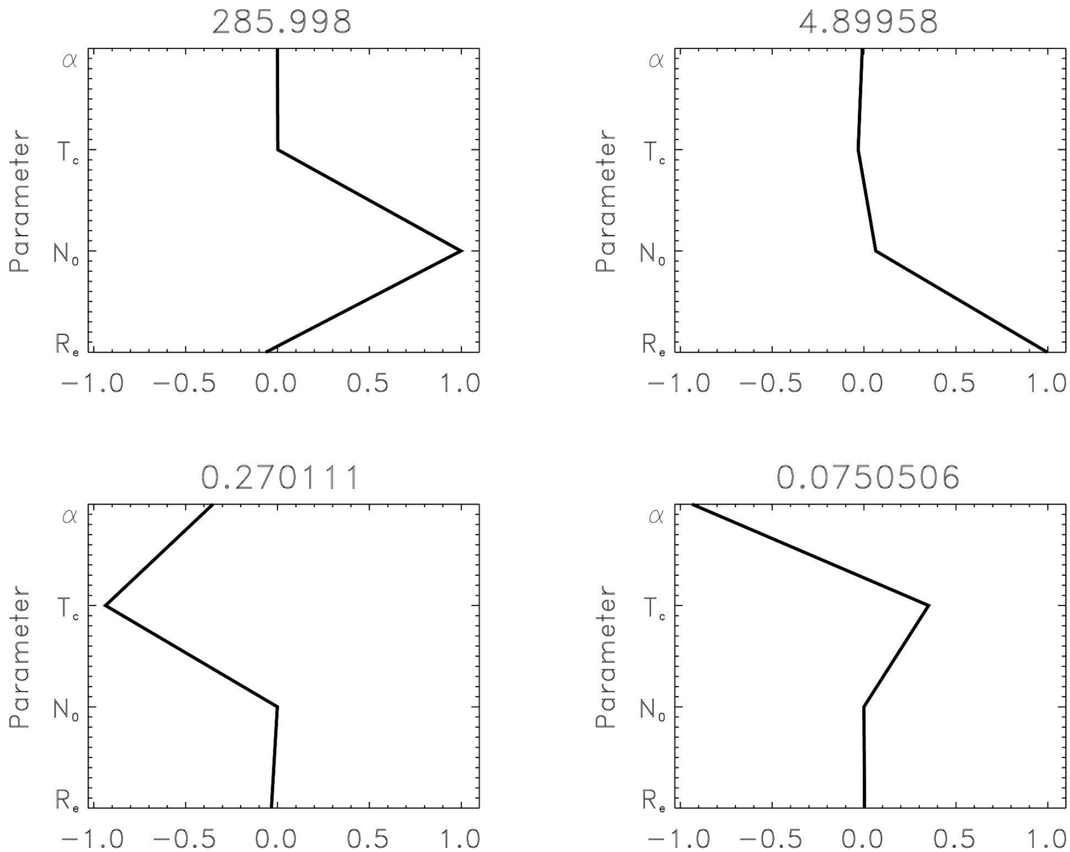

FIG. 17. Singular value analysis for the ice cloud of Fig. 16.

The advantages of a unified five-channel approach can be best appreciated by comparing information content analysis from this approach with well-known multispectral retrieval schemes such as the split-window and NK methods. The second panel of Fig. 19 shows the information content analysis using the split-window approach, with just the 11.0- and 12.0-μm channels. As expected, the use of these two channels provides a significant amount of information for optically thin clouds, as designated by the significant amount of oranges and reds on the second panel. The information content for very thin and for thick clouds, however, is poor. It is only the addition of the visible and near-infrared channels to this retrieval scheme, for example, the third and fourth panels of Fig. 19, that allow us to optimize retrieval information content for most combinations of effective radius and IWP. Similarly, the second panel of Fig. 20 shows the information content analysis for a NK-type approach using the 2.13- and 0.646-μm channels. Although these two channels capture significant amounts of information for some combinations of effective radius and IWP, they perform poorly for others. It is only the addition of the infrared and SWIR channels, for example, the third and fourth panels of Fig. 20, that allow for a retrieval with high information content for all expected states of the atmosphere. The practical implications of these differences in information for operational retrieval schemes in terms of both retrieval bias and random error will be the focus of a future work.

7. Conclusions

In this work, the formal information content analysis presented in Part I has been used to objectively select the optimal combination of MODIS measurements for an ice cloud microphysical property retrieval scheme when constrained by CloudSat CPR cloud boundary information. Channel selection is determined through a realistic characterization of not only the sensitivity of TOA radiances to the desired retrieval parameters but also to the uncertainties resulting from both the measurements themselves and from the forward model assumptions used in relating the observation and retrieval space. The channels selected for the retrieval are strongly dependent upon both cloud and atmospheric properties and the uncertainties characteristics of the observation system. Because of the complexities of

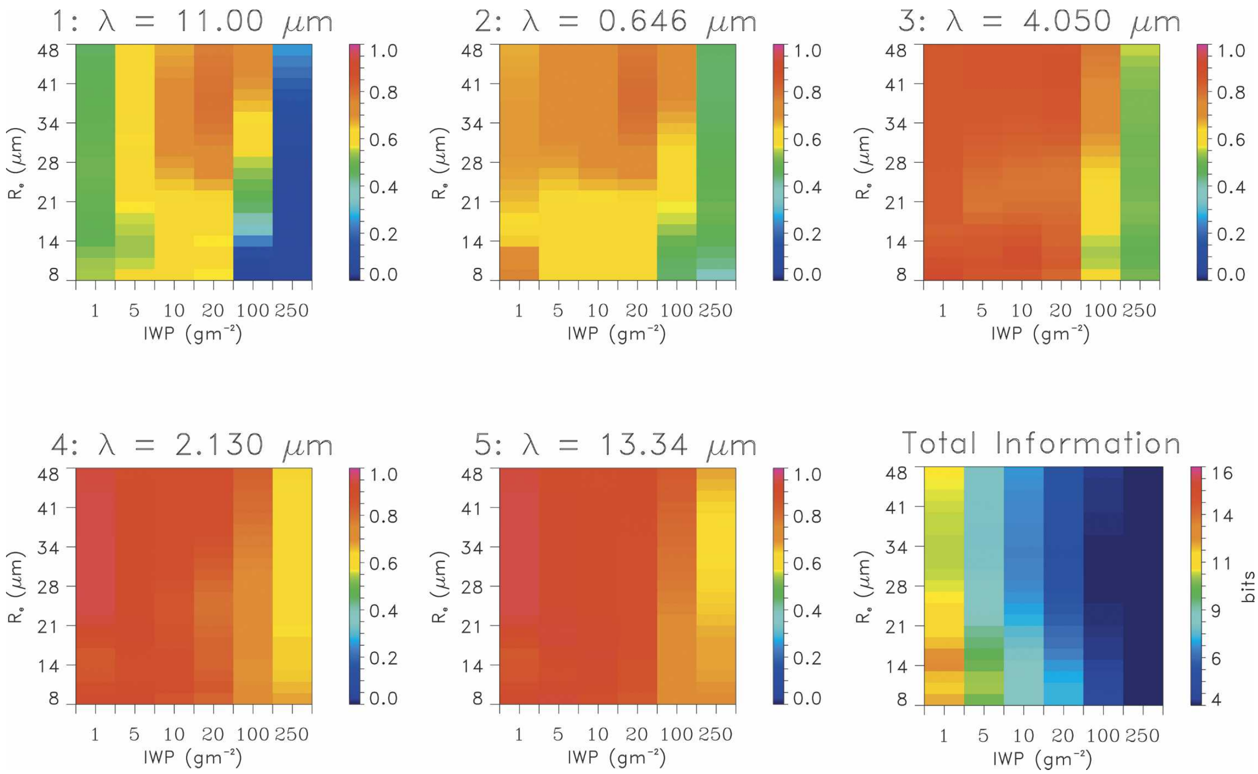

FIG. 18. Fractional information content analysis for our proposed five-channel retrieval scheme as a function of IWP and effective radius for an ice cloud at 9 km. The bottom-right panel shows total information for all 17 MODIS channels. Each of the panels labeled 1–5 indicates the fractional information from each channel added sequentially.

these sensitivities to atmospheric state and the need for a consistent retrieval scheme for an operational retrieval, we suggest a five-channel retrieval approach consisting of a combination of error-weighted visible, near-infrared, and infrared channels. Such an approach can be adopted independent of scene because it makes use of the inherent sensitivities in each of these spectral regions to ensure a high information content regardless of cloud and atmospheric properties. Tentatively, the 0.64-, 2.11-, 4.05-, 11.0-, and 13.3-μm channels are suggested, but it should be noted that any of these channels could be replaced by another channel with similar characteristics with little loss in retrieval information. The optimal estimation–based retrieval framework (Rodgers 1976; Marks and Rodgers 1993), which allows for the inclusion of information from multiple sensors and provides a built-in set of diagnostics to quantify retrieval and measurement uncertainties, may provide the ideal means to implement this flexible, error-weighted retrieval approach.

The analyses presented here apply only to single-layer clouds overlying an isotropically reflecting ocean surface with a simple observation geometry of an overhead sun with nadir observation angle. Although much additional work in quantifying measurement and forward model error covariances for a variety of different land surfaces and retrieval geometries is needed for the development of an operational retrieval, the complete methodology for this work as outlined here and in Part I is already in place. A multichannel inversion methodology such as optimal estimation in which each channel is weighted by its uncertainty provides a means to smoothly transition from daytime to nighttime scenes by employing scene-dependent error covariance matrices that emphasize the shortwave observations during the daytime and infrared observations at night. The fractional errors summarized in Fig. 5 can be adopted for overhead sun conditions while the shortwave variances should be increased to very large values at night to reflect the lack of shortwave radiance observations at night. We anticipate that intermediate sun angles can be treated by smoothly increasing the shortwave variances between these two extremes, but future research will be required to represent this transition by a suitable function of solar zenith angle. Such an approach offers the potential to avoid discontinuities in retrieval products that suddenly switch channels under changing circumstances. Last, the uniform application of such a

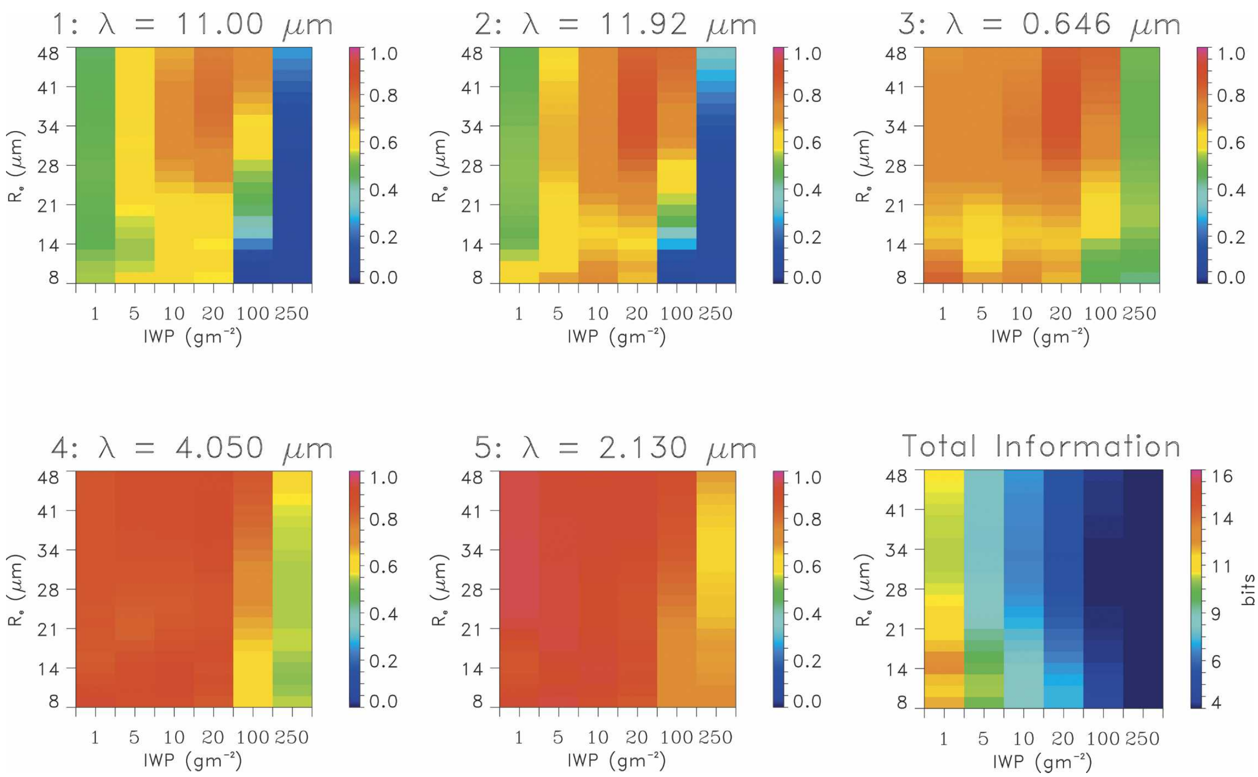

FIG. 19. Fractional information content analysis for the split-window retrieval scheme as a function of IWP and effective radius for an ice cloud at 9 km; 2: the fractional information from the split-window approach, and 5: the fractional information from our proposed five- channel retrieval scheme.

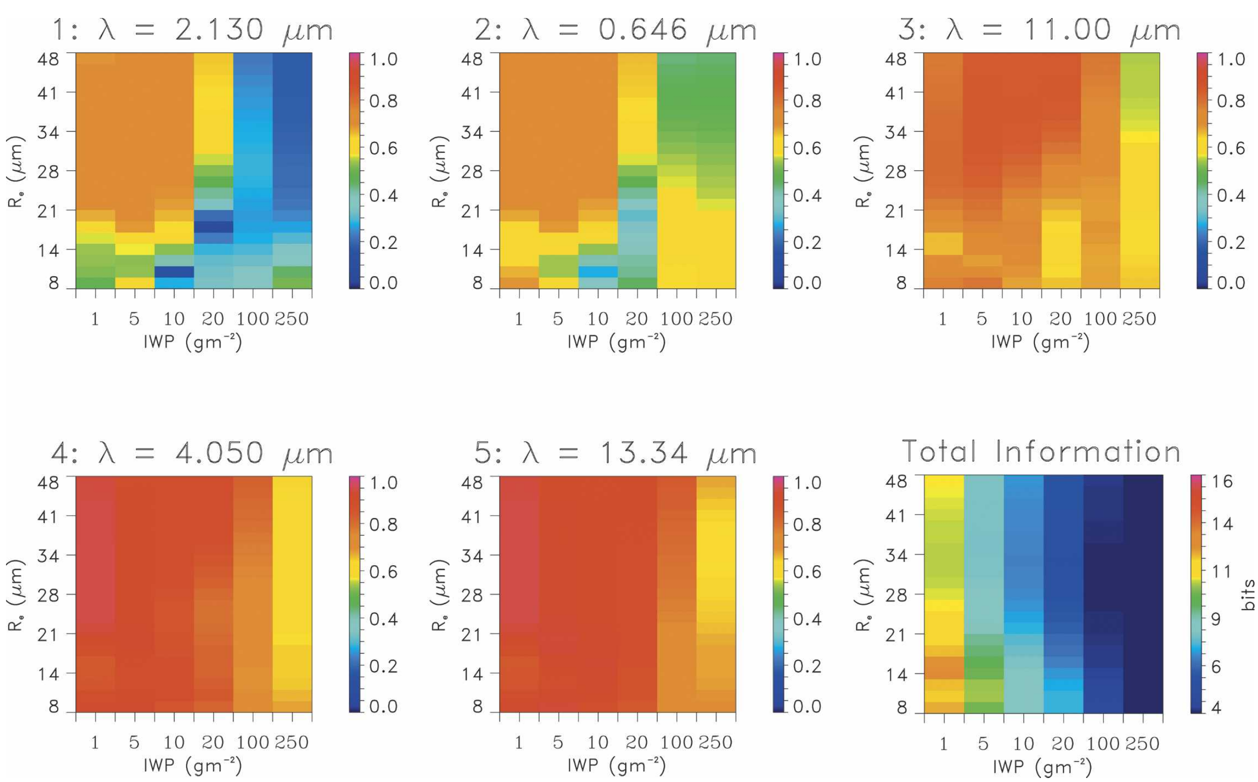

FIG. 20. As in Fig. 19 but for the NK retrieval scheme.

five-channel retrieval approach also would provide consistency in retrieved cloud products across different satellite and field measurement campaigns, allowing for the direct comparison of cloud products for climate processes studies.

The formal information content methodology also should be considered at a more general level than just the retrieval of cloud microphysical properties. To realize the full potential of the rigorous information content analyses outlined here, they should be applied in the developmental stages of future satellite missions to systematically develop instruments from the ground up. In principle, a detailed analysis of a wide variety of potential wavelengths could be performed to determine the subset that provides the most information for the desired application based on the accuracies to which they can be modeled and their sensitivities to the retrieval parameters. Then, this information could be used to design an optimal channel configuration upon which an instrument could be constructed.

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