Proceedings of ERAD (2004): 531–536 © Copernicus GmbH 2004

ERAD 2004

Optimal channel selection and validation for a combined CloudSat-MODIS ice cloud property retrieval scheme

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Abstract. A formal information content analysis was performed to determine the ideal combination of measurements for an ice cloud microphysical property retrieval scheme using satellite observations from both MODIS and CloudSat. Channel selection for the retrieval will depend not only on the sensitivity of the measurements to changes in retrieved cloud properties but also to the combined uncertainty in the measurements from the instruments themselves and from our forward model assumptions in mapping between observation and retrieval space. We found that the optimal combination of channels for an ice cloud retrieval is highly dependent upon cloud and atmospheric properties, meaning no combination of two or three channels will always ensure an accurate retrieval. We therefore propose a five- channel, error-weighted, estimation- based retrieval scheme that uses a combination of visible, near-infrared, and infrared channels chosen to ensure high information content for the retrieval regardless of scene. The algorithm was validated with CRYSTAL-FACE MODIS Airborne Simulator (MAS) data.

1 Introduction

Measuring the global distribution of cirrus cloud microphysical properties has been a concern of many satellite missions. As such, a significant amount of work has been done in both understanding the underlying physics of the ice cloud problem and using this knowledge in inferring cirrus cloud properties from satellite- based measurements (Inoue (1985); Prabhakara et al. (1988); Nakajima and King (1990); King et al. (1992); Wielicki et al. (1996)). In this work, we do not question the usefulness of these past efforts or their validity for their specific applications but instead offer a reexamination of the ice cloud problem in terms of recent developments in the understanding of ice cloud physics. Although this analysis is for a theoretical retrieval combining measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) with the CloudSat cloud profiling radar (CPR) above an ocean surface, the general methodology could be applied to any available instrument package. Channel selection for the retrieval will depend not only on the sensitivity of the measurements to changes in retrieved cloud properties but also to the combined uncertainty in the measurements from the instruments themselves and from the forward model assumptions in linking observational and retrieval space. The sensitivities and errors for the MODIS channels listed in Table 1 will be examined across the climatological range of ice cloud properties to determine which channels are most useful dependent upon the state of the atmosphere. The current work is made possible only by the recent development of optical properties for a variety of nonspherical ice crystals at the MODIS wavelengths (Baran and Francis (2004); Yang et al. (2001)) allowing a reasonable estimate of the uncertainties in satellite- viewed radiances resulting from our assumptions of cloud microphysical properties.

2 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 absorption and 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 Sect. 3 will be described briefly. Atmospheric absorption in our model was approximated by correlated-k distributions

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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	6.54–6.89		

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. The surface was assumed to be an isotropic reflecting, ocean surface with visible albedo of 0.1 and infrared albedo of 0.01. The cirrus clouds were assumed to be 1 km thick and at the same temperature as the layer of the atmosphere they were embedded in. The clouds were composed of randomly oriented randomized hexagonal ice aggregates developed by Baran and Francis (2004), arranged in a modified gamma size distribution with variance parameter equal to two. These crystals were chosen as Baran showed that the single scatter properties for these polycrystals combined with a modified Henyey- Greenstein phase function better explained observed radiances than the optical properties for more pristine crystal habits. Since these aggregates had strongly forward-peaked phase functions, a modified delta-M scaling technique 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 a cloud retrieval. A series of sensitivity studies were run for each of the MODIS wavelengths listed in Table 1 to determine how satellite observed radiances changed for small perturbations of the desired retrieval parameters. Each ice water path (IWP), effective radius, cloud temperature, and surface albedo 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. For the perturbations of effective radius, the ice crystal size distribution number concentration was necessarily varied to conserve IWP, meaning that cloud optical depth increases with

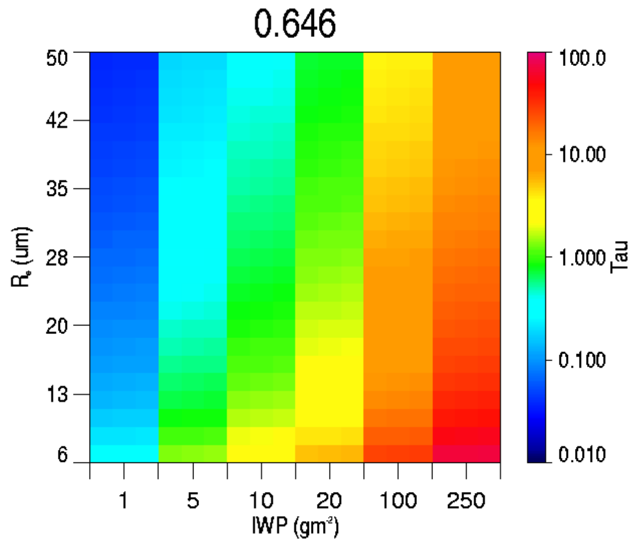

Fig. 1. MODIS channel 01 optical depths for ice cloud as a function of effective radius and IWP.

both decreasing effective radius and increasing IWP for these studies. Synthetic radiances were calculated for small perturbations about cloud effective radii between 6 μm to 50 μm, IWP between 1 g/m^2 and 250 g/m^2, cloud heights between 8 and 15 km, and the base albedos of 0.1 for visible and 0.01 for infrared channels. IWP and effective radius combinations were chosen to ensure that cloud optical depths ranged across the expected range for cirrus clouds at each MODIS wavelength, see Fig. 1.

4 Uncertainty Analysis

Optimal channel selection for a retrieval 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 instruments themselves and from the mapping between observational and retrieval space. Instrument error primarily results from calibration issues and is on the order of a few percent (Guenther et al. (1996)). Errors from forward model assumptions, however, are generally much larger. The remainder of this section will focus on the quantification of these errors for the MODIS channels of Table 1. Uncertainties associated with our choices of ice crystal habit, cloud particle size distribution, and atmospheric temperature and relative humidity profiles were determined by calculating top of the atmospheric radiances for our base case assumptions and then comparing these results with radiances found using other possibilities. Uncertainties associated with 3-D radiative transfer effects and multi- layer clouds, although certainly important, are beyond the scope of this paper and will be neglected.

Figure 2 shows an example error analysis as a function of effective radius and IWP for a cloud at 9 km for MODIS channel 01 (0.64 μm) and MODIS channel 31 (11.0 μm).

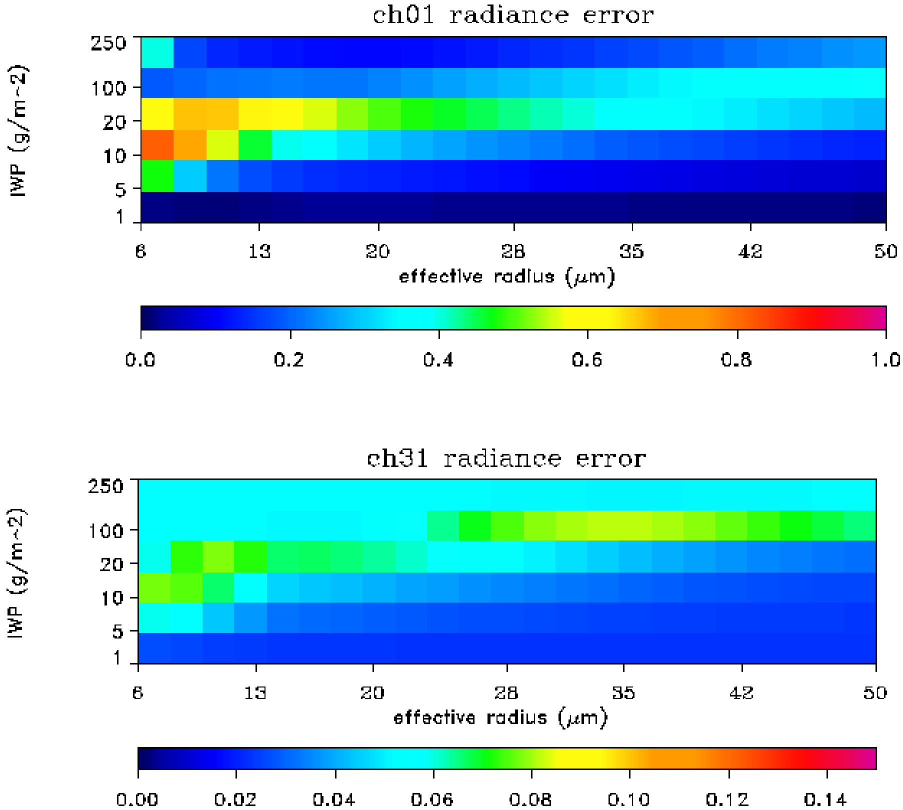

Fig. 2. Combined fractional uncertainties in MODIS radiances due to assumptions of ice crystal habit, crystal size distribution, atmospheric profile, and instrument noise as a function of IWP and effective radius for an ice cloud at 9 km.

Error is a strong function of effective radius and IWP and is generally much larger for the visible than the infrared channels. Errors in the visible are dominated by large uncertainties in the scattering properties due to habit effects; errors in the infrared are generally a mixture of habit, temperature, and relative humidity effects. An error analysis for other surfaces has been completed with the additional result that uncertainties in albedo will dominate retrieval error for thin clouds in the visible channels.

5 Information Content

A formal information content analysis (Rodgers (2000)) combining sensitivities and uncertainties was performed to find the optimal MODIS channels for a cirrus cloud retrieval constrained with cloud boundary information from the CloudSat CPR. Figure 3 shows a sample information spectrum for an optically thick cirrus cloud with effective radius of 16 μm , IWP of 100 g/m^2, and a cloud height of 9 km. In these plots, information roughly can be considered as the reduction in entropy of the retrieval solution space resulting from the addition of each measurement. The initial entropy is defined by the number of possible states associated with our a priori characterization of the atmosphere. For our cases constrained by CloudSat and MODIS information, initial entropy would result from all possible states assuming standard deviations for a priori assumptions of 25.0 μm for effective radius, 200 g/m^2 for IWP, and 1.5 K for cloud temperature and an uncertainty of 10% for surface albedo. Once a measurement is used to constrain the a priori, however, the number of possible atmospheric states in 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 re- run 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. 3, the top solid curve shows that the 0.64 μm channel contained the most information relative to the a priori. Since the MODIS measurements may be strongly correlated, the selection of one channel will limit the independent information in a similar channel, e.g. 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 as their addition did not reduce the entropy given inherent noise in the system. The selection of channels for this optically thick cloud case agrees well with our physical intuition, as the 0.64 μm and 2.13 μm channels should have sensitivity to IWP and effective radius, respectively. This information

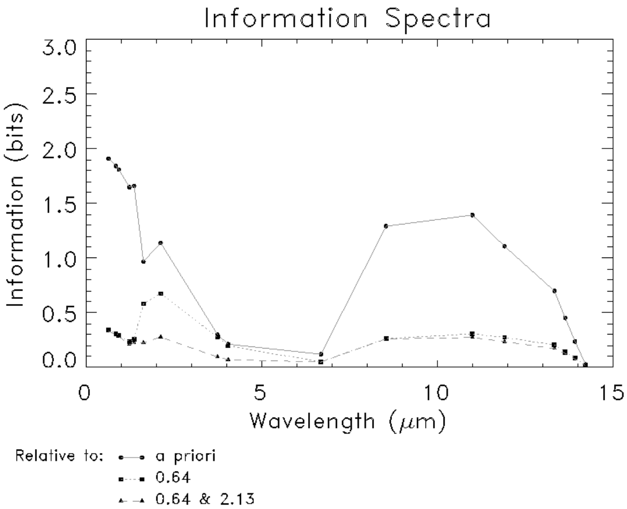

Fig. 3. Information spectrum analysis for an ice cloud with effective radius of 16 μm, IWP of 100 g/m^2, and cloud height at 9 km.

content analysis suggests that a retrieval scheme based on the Nakajima and King (1990) approach would be highly effective for this thick cloud case.

Similar information spectra were calculated for the thousands of IWP- effective radius- cloud height combinations used in both the sensitivity and uncertainty analyses. Instead of overwhelming the reader with test cases, we will simply perturb the assumptions of our base case to show that different atmospheric states and error assumptions require different combinations of channels to optimize the retrieval scheme. The top panel of Fig. 4 shows the information spectra for an optically thin cirrus cloud with the same effective radius and cloud height as in Fig. 3 but now with a much smaller IWP of 10 g/m^2. The optimal combination of channels for this thin cirrus case are the 4.05 μm and 11.9 μm bands, essentially using two emission based channels in a split-window type approach. The selection of these channels again agrees with physical intuition, as we expect split- window sensitivity for optically thin clouds but not for the thick cloud as in the base case. Although the visible channels also could be expected to have sensitivity to thin cirrus, the relatively large uncertainties for these channels due to a priori assumptions of crystal habit ultimately limit their utility.

The bottom panel of Fig. 4 shows 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 is essentially replicating the approaches taking by those cloud retrieval schemes that do not explicitly account for radiance error. As Fig. 2 shows, a flat error of 10% essentially reduces the error for most shortwave channels and increases the error for the longwave channels. Figure 4 shows that the optimal combination of channels change from the 4.05 μm and 11.9 μm bands found using our best estimate of errors from our uncertainty analysis to the 1.37 μm and 3.74 μm bands assuming the un-realistic flat errors. The retrieval approach essentially shifts from a split- window to a Nakajima and King (1990) type approach, highlighting the need for realistic treatment of errors to maximize retrieval information as a function of state of the atmosphere

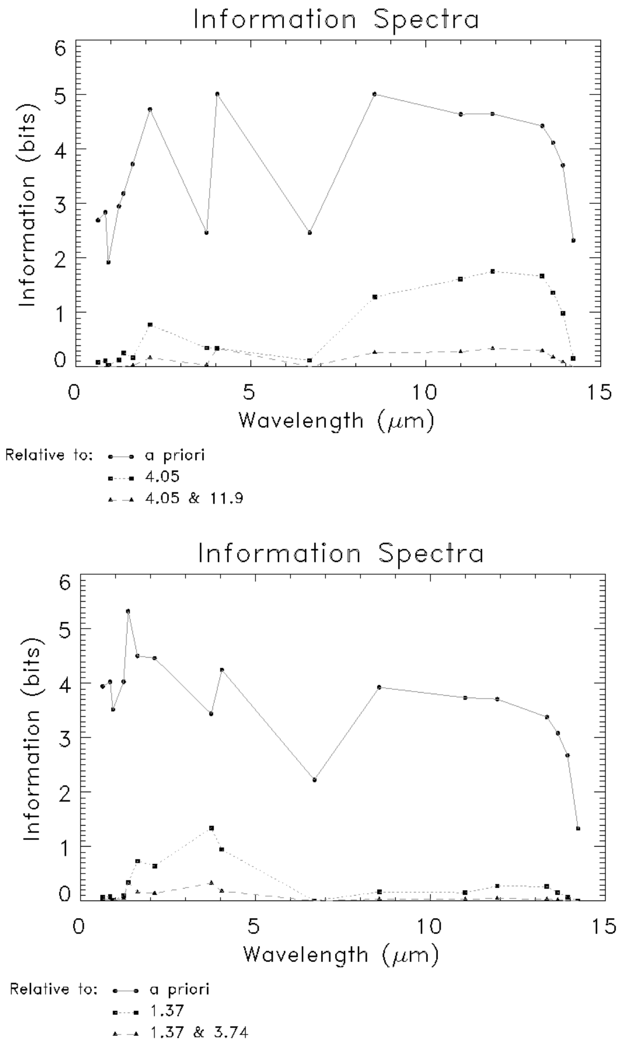

Fig. 4. Information spectrum analysis for an ice cloud with effective radius of 16 μm, IWP of 10 g/m^2, and cloud height at 9 km for (top) our best estimate of wavelength and state of the atmosphere dependent uncertainties as described in Sect. 4 and (bottom) flat 10% uncertainties for all wavelengths and states of the atmosphere.

6 Implications for Retrieval Approach

Each of the cases described above required a different combination of channels to maximize information content. Although each of these combinations could 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 in interpretation. Many other cases are more ambiguous, meaning that we really don't know the optimal combination of channels before running the information content analysis. In the limited space of these

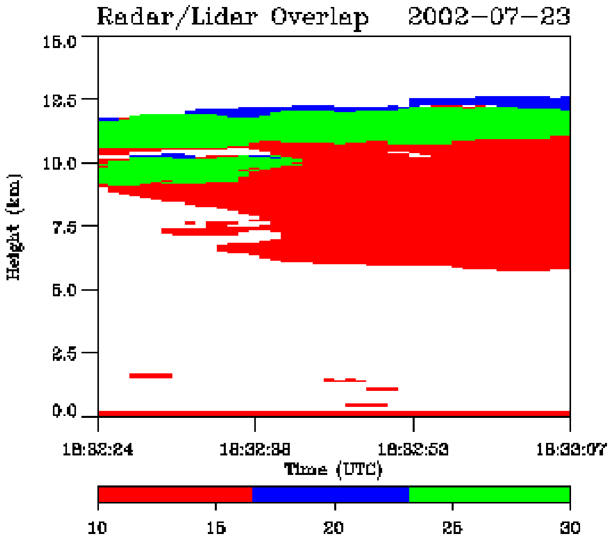

Fig. 5. Combined radar and lidar reflectivity profiles for July, 23 CRYSTAL-FACE thin cirrus cloud case.

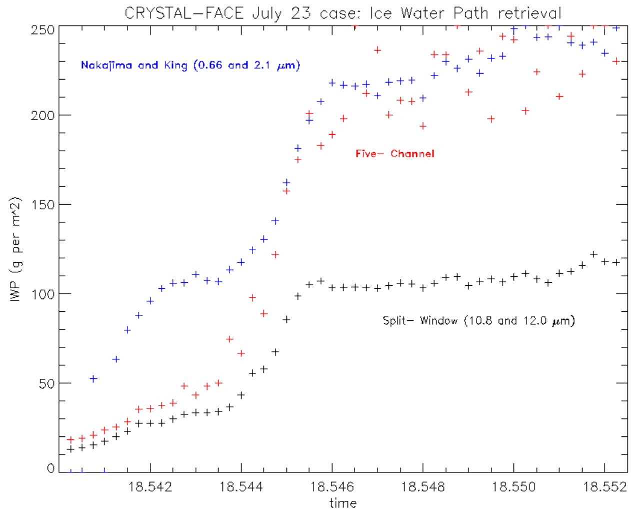

Fig. 6. Results of five- channel, Nakajima and King, and split- window retrieval schemes using MODIS Airborne Simulator (MAS) data for the cirrus cloud case of Fig. 5.

proceedings, it is not possible even to give a simplistic summary of the thousands of cases run, as the range of expected cloud and atmospheric conditions gives a bewildering combination of channels that are not always physically intuitive. Instead of bogging down in details, we will skip to the end conclusion, namely that traditional retrieval schemes that rely on 2 channels for all states of the atmosphere, such as the Nakajima and King (1990) or split- window approaches, may result in significant biases for many states of the atmosphere. Since using different channels for an operational retrieval for each pixel or, even worse, for each iteration of each pixel for an estimation- based retrieval is impractical, we instead suggest a retrieval scheme composed of the same five channels regardless of scene. This retrieval scheme would consist 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 regardless of cloud and atmospheric properties. We tentatively suggest the 0.64 μm, 2.11 μm, 4.05 μm, 11.0 μm , and 13.3 μm channels.

7 Validation

Although theoretical calculations involving the reduction of entropy of various a priori and retrieval states lead to the above conclusion, it is necessary to examine the five- channel retrieval scheme in context of real-world data. Figure 6 shows an ice cloud property retrieval using MODIS Airborne Simulator (MAS) measurements taken on July 23, 2002 during the CRYSTAL-FACE field campaign. The retrieval was performed using each the five-channel, Nakajima and King, and split-window approaches as the MAS flies through a progressively thickening cirrus shield, see Fig. 5. Clearly, the five- channel scheme agrees well with the split- window for thin clouds where the Nakajima and King technique may be expected to produce large biases due to uncertainties in the real- world cloud scattering properties. Likewise, the five-channel scheme agrees nicely with the Nakajima and King (1990) approach for thick clouds where the split- window approach would have no sensitivity.

8 Conclusions

In this work, we used a formal information content analysis to objectively select the ideal combination of measurements for an ice cloud microphysical property retrieval scheme using a realistic assessment of uncertainties of the ice cloud problem. We found that the ideal combination of measurements depends heavily upon the state of the atmosphere. Due to the complex nature of these changes and the need for a consistent retrieval scheme for an operational retrieval, we therefore suggested a five channel retrieval approach that uses the same five channels regardless of scene. This retrieval scheme would consist 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 regardless of cloud and atmospheric properties. The retrieval approach has been applied to CRYSTAL-FACE MAS data with favorable results.

Acknowledgements. We thank Dr. Anthony Baran and Dr. Ping Yang for providing the ice crystal radiative properties that made this work possible. We also thank Dr. David Kratz for use of the correlated k distributions used in our MODIS simulator. This work was supported through NASA EOS Fellowship NGT5-30458.

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