ARCTIC CLOUD PROPERTIES DERIVED FROM MULTISPECTRAL MODIS AND AVHRR DATA

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1. INTRODUCTION

Understanding the impact of clouds on Earth's climate requires improved measurements of their microphysical properties. In the Arctic, there is minimal contrast between the clouds and the background snow surface making it difficult to determine cloud amount and retrieve microphysical properties using satellite data. The presence of variable snow and ice cover, as well as cloud temperatures that are often warmer than the surface during colder months of the year (e.g., Minnis et al. 2001), exacerbate the determination of cloud optical depth, phase, and particle size. Dong et al. (2001) compared the properties of liquid water clouds derived from surface radar measurements over the Arctic ice cap with retrievals from satellite data using two different methods. The first, a visible-infrared solar-infrared split-window technique (VISST; see Minnis et al. 1995), uses the visible (VIS; 0.65 µm) channel to determine optical depth. For clouds over snow-covered surfaces, small changes in reflectance correspond to large changes in optical depth τ. Thus, small errors in any of the input parameters can cause large errors in the derived value of τ. Platnick (2001) pioneered the second method, designated the solar-infrared infrared near-infrared technique (SINT), which uses the near-infrared (NIR,1.6-µm) channel to determine τ. Because snow reflectance is very small at 1.6 µm, the NIR reflectance changes more slowly with τ than the VIS reflectance. Dong et al. (2001) found that the optical depths were significantly more accurate from the SINT retrievals than from VISST for the few cases available over the Arctic. The true test of any given algorithm is the quality of its performance in operational conditions.

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In this study, the SINT and VISST are used to retrieve cloud properties over the Atmospheric Radiation Measurement (ARM) north Slope of Alaska (NSA) site at Barrow, AK using the operational Clouds and Earth's Radiant Energy Experiment (CERES) cloud analysis code applied to Terra Moderate-Resolution Imaging Spectrometer (MODIS) data. The results for ice clouds are evaluated using cloud properties retrieved from combinations of passive and active measurements.

2. DATA

The MODIS 1-km 0.65 (visible), 1.6 (near-infrared), 3.7 (solar-infrared), 11.0 (infrared), and 12.0 (split-window) µm bands were used to derive cloud amount, cloud phase, effective ice crystal diameter D_e, optical depth τ_{sat}, height z_c, temperature T_c, and ice water path IWP during late March 2001. The cloudy pixels were determined using the method of Trepte et al. (2001). The cloud properties were derived for the cloudy pixels using the SINT and VISST. The results were averaged over a 30-km x 30-km box centered on the NSA site. In the CERES operational code, the VISST is applied to all pixels unless the underlying surface is designated as snow or ice-covered are either by a predetermined snow-ice map or from an identification of adjacent clear pixels as being snow-covered. In those cases, the SINT is used to compute the cloud properties.

These averages are compared with similar quantities derived from surface observations and averaged over a 1-hr period centered on the satellite overpass time. Two techniques were used to derive the cloud properties. The radar-radiometer method (Matrosov 1999) uses the Millimeter Wave Cloud Radar (MMCR), the Atmospheric Emitted Radiance Interferometer (AERI), and microwave radiometer (MWR) measurements to retrieve vertical profiles of ice water content IWC and median particle size. These values were integrated over the depth of the cloud to obtain IWP and a mean median particle size. To compare with the satellite results, the latter was used to calculate the effective diameter D_{eff}, defined as the ratio of the third moment to the second moment of the size distribution multiplied for crystals with a constant density 0.9 gm^{-3}. Optical thickness τ_{sfc} in the radar-radiometer approach is obtained from visible and broadband shortwave radiometric measurements. The second method is similar to the radar-radiometer technique except that the coefficients describing the relationship between reflectivity and IWC, normally variable in the radar-radiometer method, are set to the average values obtained from the radar-radiometer technique over the Arctic. This empirical technique is simpler than the radar-radiometer method Three different cloud heights were determined from the radar profiles, the to height z_t, middle height z_m, and the half-mass height, z_h. The cloud fraction is defined as the fractional number of radar returns with a reflectivity exceeding -50 dBz.

3. RESULTS

Figure 1 shows an example of the large-scale results from the CERES-MODIS algorithm for 2300 UTC 26 March 2002. The NSA site is indicated in the pseudo-color RGB image (Fig. 1a) that uses the VIS, NIR, and 3.7-11 µm temperature difference for red, green, and blue, respectively. Green areas in Fig. 1b correspond to clear pixels, while the blue and white pixels are classified as liquid and ice clouds, respectively. Dark blue areas were originally classified as clouds, but no retrievals could be performed and the pixels may be reclassified as clear. The optical depths (Fig. 1c) vary from 0.25 to 5 over most of the image, except for the clouds over the Bering Sea and over southern Alaskan coast. The values of re (Fig. 1d)are generally between 8 and 12 µm over the Bering Sea and somewhat larger north of Siberia. Half of the clouds are below 2 km (Fig. 1e), while the remainder are between 4 and 8 km. The ice crystal sizes (Fig. 1f) are generally small although some clouds have relatively large crystals. Many of those with small crystals are probably mixed-phase clouds.

Figure 2 shows a comparison of τ as derived from the SINT (Fig. 2a) and the VISST (Fig. 2b) for 2100 UTC 19 March 2001. This figure clearly demonstrates why the VINT is so valuable for retrieving cloud properties over snow surfaces. Except for the coastal strips along western Alaska, the Bering Sea, and small parts of northwestern Canada, the cloud optical depths from SINT are less than 5, while those from VISST for the areas with the small values of τ from SINT vary from 10 to 100. In Fig. 2a, VISST was applied to many of the pixels with $\tau > 10$ because the surface was either designated as ice-free water (Bering Sea) or as snow-free land (Alaskan and Canadian coasts) in the snow maps. The current CERES snow maps are based on satellite microwave estimates of snow depth and the microwave retrieval algorithms are not applied within 100 km of the coast. Therefore, the algorithm switches to VISST and assumes a background reflectance for a vegetated land area resulting in the overestimates of τ. The VISST yields a general overestimate of τ over nearly all snow-covered areas because slight changes errors in the clear-sky reflectance lead to very large errors in τ.

The results from 13 overpasses were processed with the radar-radiometer method. Most of the satellite averages were affected to some extent by the coastal problem evident in Fig. 2. To minimize the impact of this problem, all overpasses yielding $\tau_{sat} > 10$ were eliminated. Additionally, visual inspection of the results was used to remove another case where the coastal effect dominated the result from the satellite. Of the original 13, 9 cases were used for the comparisons. Figure 3 shows the comparisons of z_c and z_h, τ_{sfc} and τ_{sat}, D_e and $D_{eff,}$ and IWP_{sat} and IWP_{sfc}. The radar derived values are generally greater than the SINT retrievals except for two cases. Overall, the mean difference is 30.6 µm for a mean D_{eff} of 110.3 µm. The satellite optical depths differ by ~ $\pm$ 1, except for the one value of τ_{sat} near 3.5. The mean difference is -0.24 out of a mean τ_{sfc} = 1.09. The cloud heights are also scattered with differences as great as 5 km. That one case, in which z_c = 0.1 km is a default value. Satellite-derived cloud temperatures that are warmer than the surface and are not found in the temperature profile yield an altitude of 0.1 km. The mean cloud height difference is 0.63 km for an average z_h of 3.47 km. The IWP results in Fig. 3 are poorly correlate. However, the mean difference is 2.3 gm^{-2} compared to a mean value of IWP_{sfc} = 39.2 gm^{-2}, a difference of less than 10%. This favorable difference is primarily due to compensating effects between the differences in τ and D_e.

A similar approach was used for comparing the results from the empirical method with the satellite data. The obvious coastal contaminated cases were removed from the original 12 cases to yield 10. In one of those cases, the satellite detected no clouds, so there was no comparison, leaving only 9 overpasses. Some of the cases are the same as in Fig. 3, but others are different. The satellite-derived cloud fraction for all 12 cases was only 41.1% compared to the surface-based value of 92.5% cloud coverage. This result suggests a huge underestimate of cloud cover over the Arctic. However, it should be noted that this underestimate is primarily due to the cloud mask missing clouds that had optical depths less than 0.2 as derived from the visible and shortwave radiometers at the surface. Although some of these overcast thin-cloud cases were detected with the cloud mask, enough were missed to produce the gross underestimate. fortunately, ice clouds with $\tau < 0.2$ that contrast little with the surface are not particularly important from a radiative standpoint. The variability of mask detection of these thin clouds is primarily due to slight changes in the clear-sky radiances that are not

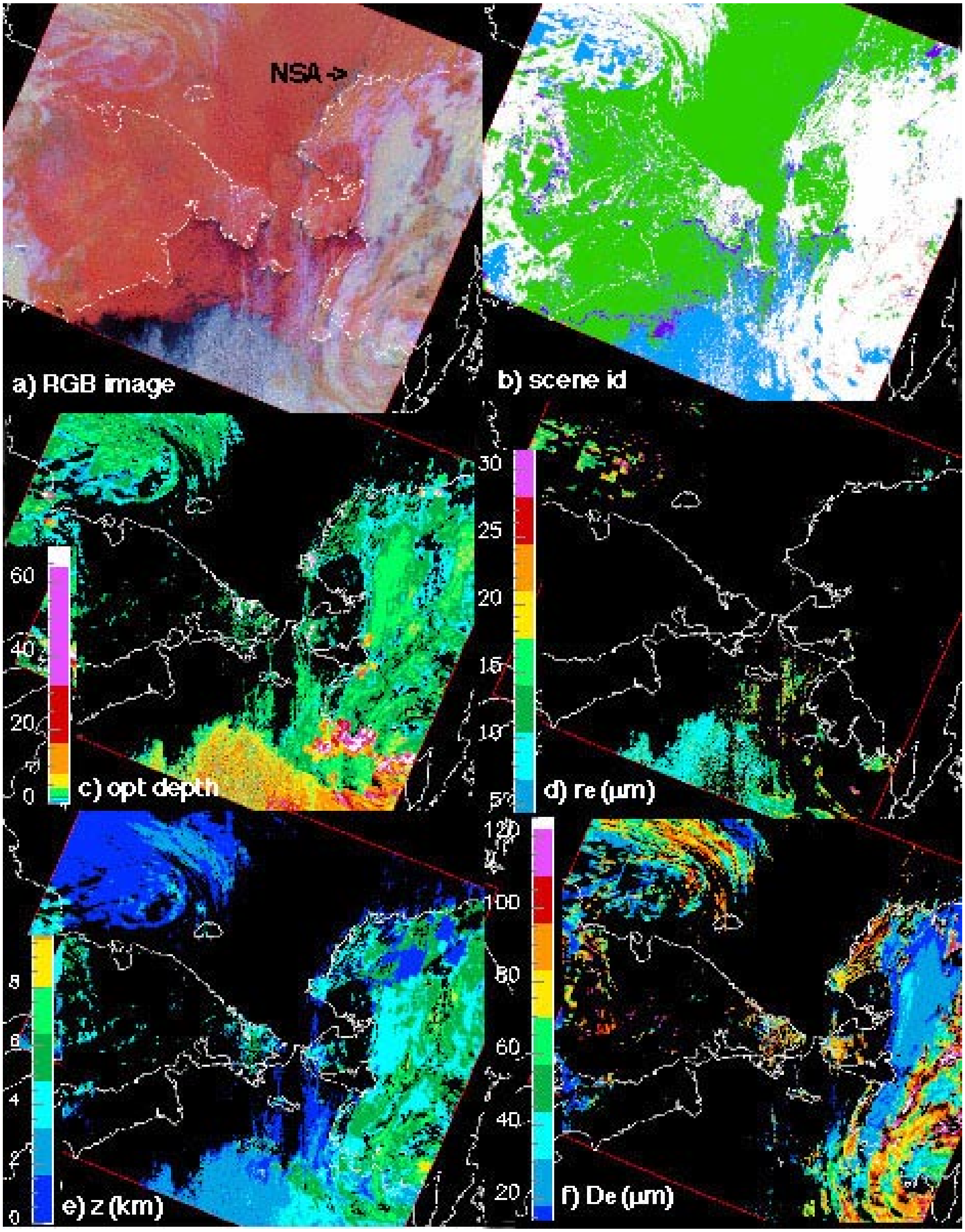

Fig. 1. Cloud properties retrieved from Terra MODIS, 2300 UTC 26 March 2001.

taken into account in the background conditions used in the cloud mask. The empirical value of D_{eff} was 9.6 µm smaller than D_e. The mean value of D_{eff} is 48.4 µm. The mean surface-based optical depth for the 9 cases is 1.07 compared to a mean value of 1.40 from the satellite. This result is opposite to the differences for the radar-radiometer results. For these cases, the optical depth and particle size differences do not compensate

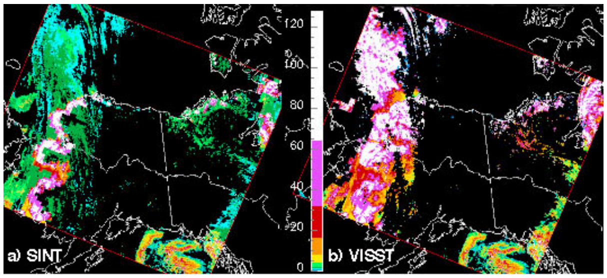

Fig. 2. Optical depth for 2300 UTC 26 March 2001.

and IWP_{sat} is nearly twice the value from the surface.

4. DISCUSSION AND CONCLUSIONS

These preliminary comparisons serve to highlight some of the problems involved in operationally detecting and analyzing clouds in the extreme environment of the Arctic. The clouds considered here are, in general, relatively thin having a mean optical depth of only 1.1. Although the average cloud height is nearly 3.7 km, the contrast with the surface is small because the cloud temperatures are either very close to or less than the temperatures of the adjacent clear areas. Many of the clouds are very thin such that they produce signals that are within the noise of the variations in clear-sky reflectance and emission. Thus, many of these clouds are not detected with the available spectra. The assignment of cloud height based on the atmospheric profiles from numerical weather analyses will occasionally result in large cloud altitude errors. Other techniques would be necessary to properly place the clouds, but there are few, if any, passive methods that can independently determine the altitude of a cloud with an optical depth of only 0.2.

The surface data and the comparisons also provide better understanding of the problems so that they can be attacked for future improvements in the retrieval algorithms. Inclusion of improved snow maps should be sufficient to eliminate the coastal problem that affected many of the satellite retrievals used here. It is clear that techniques relying on the visible channel for optical depth are inadequate for polar cloud retrievals. Despite the differences, the SINT appears to be capable of retrieving realistic results over the poles. This method and infrared techniques will be examined further. Results from these additional analyses will be presented at the conference.

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