Cloud Detection over the Arctic Region Using Airborne Imaging Spectrometer Data during the Daytime

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ABSTRACT

Detection of clouds over arctic regions from current satellite radiometric measurements in the visible and IR atmospheric window regions, such as those of Advanced Very High Resolution Radiometer and Landsat, is often difficult due to the high albedos of snow- and ice-covered surfaces in the visible and the nearly isothermal temperature profiles in the lower atmosphere. In this paper the authors show that the water vapor absorption channel at 1.38 μm is effective in detecting high clouds over snow- and ice-covered surfaces in the Arctic. Low-level clouds can be detected from surface snow and sea ice using a narrow channel centered at 1.5 μm with a width of approximately 10 nm because of the dark background that results from strong absorption by snow and sea ice. Imaging data with contiguous spectral coverage between 0.4 and 2.5 μm acquired with the Airborne Visible/Infrared Imaging Spectrometer during the Arctic Radiation Measurements in Column Atmosphere-Surface System in Alaska in 1995 are analyzed. The authors have observed that as wavelength increases from 1.38 μm the atmospheric water vapor absorption becomes weaker and weaker and the low-level clouds and surface tundra are increasingly seen. It is always possible to locate a narrow channel in the spectral range of 1.38–1.50 μm with appropriate water vapor absorption strength to separate water and ice clouds from surface snow, sea ice, and tundra. The simple cloud-masking technique described here is directly applicable to cloud detection during the daytime from hyperspectral imaging data over arctic regions, which will be acquired with future satellite sensors.

1. Introduction

Cloud detection from remote sensing data continues to be an area of active research (see, for example, Li and Leighton 1991; Ebert 1987, 1989, 1992; Key and Barry 1989; Key 1990; Welch et al. 1990, 1992, 1996). In the visible and thermal window regions, threshold tests are the primary technique currently employed in cloud detection algorithms. An example of such techniques is that pixels with visible reflectances 3% higher than the surrounding background pixels and with brightness temperatures 3°C below the background pixels are identified as cloudy (Welch et al. 1996). However, threshold methods have experienced difficulties in the arctic regions stemming from low to no contrast between clouds and underlying snow–sea ice surface in the visible reflectances and the IR brightness temperatures (Rozow et al. 1989; Stowe et al. 1989). An additional difficulty in the arctic regions is created by temperature inversions, which may cause clouds to appear to be even warmer than the underlying snow or ice surfaces. To illustrate these cloud detection difficulties, examples of Moderate Resolution Imaging Spectrometer (MODIS) Airborne Simulator (MAS) (King et al. 1996) radiance images for two channels centered at 0.66 and 1.38 μm are presented in Figs. 1a and 1b, respectively. These images were acquired over the North Slope region of Alaska during the Arctic Radiation Measurements in
Fig. 1. MAS radiance images over the northern foothills of the Brook Range on 13 June 1995: (a) 0.66 and (b) 11.0 μm.
Column Atmosphere-Surface System (ARMCAS) field campaign in June 1995. In the 0.66-µm visible image (Fig. 1a), both clouds, apparent from the shadows that they cast, and frozen ponds appear bright because their reflectances are higher than those of the surrounding arctic tundra. The 11-µm IR image in Fig. 1b displays that clouds and frozen ponds both appear to be very dark due to their cold temperatures. Using traditional threshold techniques it is almost impossible in such images to discriminate clouds from frozen ponds.

In the past, many cloud detection algorithms were developed based on the analysis of existing data measured with current satellite instruments having only a few discrete channels [e.g., the Advanced Very High Resolution Radiometer (AVHRR)]. There has been relatively little work done on imaging spectrometer data with contiguous spectral coverage. Based on observations from spectral imaging data acquired with the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) (Vane et al. 1993) flying on an ER-2 aircraft at 20-km altitude, Gao et al. (1993) have reported that near-IR channels close to the centers of the 1.38- and 1.88-µm water vapor bands are very useful for detecting thin cirrus clouds. However, under dry atmospheric conditions, these channels may also detect lower-level clouds and underlying surfaces because total absorption of solar radiation by water vapor on the sun–surface–sensor path in these channels may not occur. Concerns have been raised about the capability of detecting thin cirrus under dry atmospheric conditions with the 1.38-µm channel (Ben-Dor 1994; Hutchison and Choe 1996).

Imaging spectrometer data over the arctic regions were first acquired in June 1995 during the ARMCAS campaign. In this paper, we demonstrate that the 1.38-µm channel is still very effective for detecting clouds over snow and ice surfaces in the dry arctic regions. We also demonstrate that imaging spectrometer data with contiguous spectral coverage between 1.38 and 1.5 µm makes cloud detection over arctic regions during the daytime simpler than with current satellite data since these satellites have only a few discrete channels.

2. The experimental data

The ARMCAS field campaign was deployed in the Arctic tundra region surrounding Prudhoe Bay, Alaska, and the snow- and ice-covered Beaufort Sea during 1–15 June 1995. The main goal of this experiment was to improve our understanding of the mechanisms in cloud microphysics, radiation, and remote sensing in the Arctic. The experiment includes satellite remote sensing (AVHRR), high-altitude remote sensing [National Aeronautic and Space Administration’s (NASA) ER-2 aircraft at 20 km], boundary layer in situ measurements (University of Washington’s C-131A aircraft), radiosondes, and ground-based measurements (Tsay et al. 1995).

One of the instruments on board the NASA ER-2 aircraft was AVIRIS. It is an imaging spectrometer that measures reflected solar radiation in a spectral range from 0.4 to 2.5 µm with 224 narrow and contiguous channels that have widths of approximately 10 nm. From a nominal ER-2 altitude of 20 km, AVIRIS has a ground instantaneous field of view of 20 m × 20 m and a 10.5-km swath width. It has reliable geometrical, radiometric, and spectral calibrations (Green et al. 1993). During ARMCAS, AVIRIS collected more than 40 gi-
Fig. 4. AVIRIS image over Prudhoe Bay, Alaska, on 11 June 1995: (a) 0.66 μm, showing sea ice; (b) 1.38 μm, showing only the cirrus clouds; and (c) 1.50 μm, showing low-level clouds and cirrus clouds.
it is seen clearly that as the wavelength increases from 1.38 m to 1.50 m, the atmospheric water vapor absorption decreases significantly. The absorption is less than 5% at 1.50 m.

Low-level clouds are usually composed of water droplets. They may be discerned from background snow or sea ice, which possesses absorption properties that differ from those of liquid water in the near-IR spectral region. Figure 3 shows examples of simulated directional—hemispherical reflectance spectra of a water cloud, an ice cloud, and a snow surface (Dozier 1989). The snow surface has strong ice absorption bands centered near 1.50 and 2.0 m, a region in which water clouds have weak absorption and ice clouds have medium absorption. Snow and sea ice can appear much darker than water clouds in the 1.5- and 2.0-m images. This allows the discerning of water clouds from snow- or sea-ice-covered clear surfaces.

An example of detection of both the upper-level thin cirrus and the lower-level water clouds is presented in Figs. 4a–c, which display AVIRIS images for channels centered at 0.66, 1.38, and 1.50 m, respectively. These images were taken over an area centered approximately at 72.8°N, 151.0°W near Prudhoe Bay, Alaska, during ARMCAS on 11 June 1995. The 0.66-m image appears to be cloud free with complex spatial patterns of sea ice. However, the 1.38-m image shows that the upper-level thin cirrus clouds are present over most of the scene. There are no sea-ice spatial patterns or cumulus clouds discernible from this image. The 1.50-m image depicts the upper-level cirrus and the lower-level cumulus clouds. Background sea ice looks dark in the 1.50-m image because sea ice on the surface has strong absorption. The two-layer cloud structure apparent in this scene is also detected by simultaneous CLS measurements, as shown in Fig. 5. Cirrus clouds are seen above 5 km, and very low clouds are apparent within 1 km above ground. The images in Fig. 4 illustrate that the 1.38-m channel is very useful in detecting thin cirrus clouds from sea ice under the dry arctic atmospheric conditions and that low-level clouds can also be separated from background sea ice with the 1.50-m AVIRIS channel.

Another example of detecting water clouds over snow- and sea-ice-covered surfaces is illustrated in Fig. 6. A 0.66-m AVIRIS image at 70.5°N, 147.0°W, acquired over Prudhoe Bay during ARMCAS on 4 June 1995, is shown in Fig. 6a. Parts of the surface areas covered by sea ice are brighter than clouds, and the discrimination of clouds from sea-ice-covered regions is difficult. The 1.38-m image (not shown here) over this scene is dark with maximum reflectance values less than 0.008, which indicates that there are no cirrus clouds in the scene. Figure 6b shows the 1.50-m AVIRIS image over the same region. Extensive cumulus clouds are noted in many parts of the scene. Bare sea ice is dark in this image because of the strong absorption of ice particles in the 1.50-m spectral region. Fresh snow with fine ice particles, which absorb less solar energy than larger sea ice particles, appears slightly
Fig. 6. AVIRIS image over Prudhoe Bay, Alaska, on 4 June 1995: (a) 0.66 and (b) 1.50 μm. (c) An image processed by the threshold method to the 1.50 μm image. It shows low-level clouds only.
clouds and the lower-level cumulus clouds are seen, but
the surface features are eliminated due to additional ab-
sorption of solar radiation by water vapor between
clouds and surface areas.

Figure 8 shows AVIRIS images at 69.5°N, 148.5°W,
acquired in the northern foothills of the Brooks Range
of Alaska during ARMCAS on 7 June 1995. Cumulus
clouds are seen in the 0.66-μm image (Fig. 8a). A small
thin cirrus cloud is apparent in the upper-right corner.
Also shown in Fig. 8a are surface features, such as
frozen ponds, a road, and snow-covered areas. The 1.38-
μm image (Fig. 8b) shows thin, cirrus clouds and part
of a large cumulus cloud. Thin low-level clouds and
surface features are not visible in this image. The 1.42-
and 1.43-μm images, adjacent channels, are shown in
Figs. 8c and 8d, respectively. These channels are located
off the center of the strong 1.38-μm water vapor ab-
sorption band; thus, the water vapor absorption is weak-
er than the absorption at the 1.38-μm channel (see Fig.
2). This explains why more clouds appear in the 1.42-
μm image than in the 1.38-μm image. As the wave-
lengt increases by one more channel toward longer
wavelengths, some surface features reappear in the 1.43-
μm image because the water vapor absorption is reduced
slightly more in the 1.43-μm channel than in the 1.42-
μm channel. Therefore, the AVIRIS channel centered
at 1.42 μm has appropriate water vapor absorption
strength for detecting clouds (including cirrus and low-
er-level clouds) from tundra. Because the amount of
water vapor in the atmosphere can vary and the strength
of water vapor absorption varies significantly between
1.38 and 1.50 μm, from total absorption at 1.38 μm to
nearly total transparent at 1.50 μm, one is able to locate
an appropriate narrow channel in the spectral range of
1.38–1.50 μm to separate clouds from tundra for a given
atmospheric condition.

5. Discussion

We tested several techniques for detecting clouds us-
ing only narrow channels (approximately 10 nm wide)
located in atmospheric window regions, such as those
centered near 0.66, 0.86, 1.64, and 2.2 μm. For example,
we tried to use the ratio image of the 1.64-μm channel
over the 0.86-μm channel in conjunction with a thresh-
old method for separating clouds from snow- and sea-
ice-covered surfaces. A similar ratio technique was pre-
viously used for cloud detections from data acquired
through the Defense Meteorological Satellite Program
(Bunting and d’Entremont 1982). We found that the
ratio image allowed the detection of thick clouds but
failed to detect partially transparent thin clouds. We also
tried to separate clouds from arctic tundra using the ratio
image of the 0.86-μm channel over the 0.66-μm channel.
The idea behind this ratio is that clouds have similar
reflectance at both wavelengths, while tundra has small-
er reflectance at 0.66 μm than at 0.86 μm because of
strong chlorophyll absorption at 0.66 μm. The ratio va-
ues should be close to 1 for thick clouds and much greater than 1 for clear tundra pixels. Again, the ratio image allowed the detection of thick clouds but failed to detect thin clouds.

The strengths of water vapor absorption in the 1.8–2.0-μm spectral region, similar to those in the 1.38–1.5-μm region, also vary significantly. In principle, it is possible to locate an appropriate narrow channel in this spectral range to separate clouds from clear-surface areas. However, because the solar energy in the 1.88–2.0-μm region is only approximately 40% of that in the 1.38–1.50-μm region and because enhanced cloud absorption by liquid water and ice occurs in the 1.88–2.0-μm region, the signal-to-noise ratios of AVIRIS images in the 1.88–2.0-μm region are significantly lower than those in the 1.38–1.50-μm region. Therefore, narrow
channels in the 1.38–1.50-μm region are used for cloud detection over arctic regions.

At present, hyperspectral imaging instruments covering the complete solar spectral region between 0.4 and 2.5 μm are being built for remote sensing of land, ocean, and atmosphere from future satellite platforms (e.g., Ungar 1997). The techniques described here using narrow channels within the 1.38-μm water vapor band absorption region to detect arctic clouds are directly applicable to data from hyperspectral imagers on board future spacecrafts for cloud-masking purposes.

6. Summary

Based upon analysis of spectral imaging data acquired with AVIRIS from a NASA ER-2 aircraft over arctic regions, we have found that a 1.38-μm image is very useful for detecting high clouds during the daytime over the dry arctic environment. Because the strength of water vapor absorption from 1.38 to 1.50 μm decreases significantly (from total absorption to nearly no absorption), as the wavelength increases from 1.38 μm toward longer wavelengths, the lower-level water clouds and surface features are increasingly seen. It is always possible to locate a narrow channel (~10 nm wide) in the spectral range of 1.38–1.50 μm with appropriate water vapor absorption strength in which both the thin cirrus clouds and the lower-level, cumulus clouds can be seen, but the surface features are eliminated due to additional absorption of solar radiation by water vapor between clouds and surface areas. We also found that lower-level water clouds can be separated from background snow and ice using a narrow channel located at the 1.50-μm ice absorption band center. In general, the use of narrow channels between 1.38 and 1.50 μm allows improved detection of thin water and ice clouds.

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