Analysis of a Multi-year Cloud Property and Radiative Heating Rate Dataset in the Arctic

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ABSTRACT

The Arctic energy balance is very sensitive to clouds and their impact on radiative fluxes. We have developed a multi-sensor cloud property dataset that provides the macro- and microphysical properties of all clouds over the Atmospheric Radiation Measurement (ARM) program's North Slope of Alaska (NSA) site in Barrow, Alaska. This dataset was constructed by utilizing a conditional retrieval framework to derive the cloud existence, phase, condensed water content, and particle size for both the liquid and ice hydrometeors throughout the troposphere using a combination of active and passive ground-based observations.

Radiative heating rate profiles, as well as surface and top-of-the-atmosphere fluxes, have been computed for multiple years of data collected at the NSA site. The radiative heating rate profiles are then analyzed as a function of water content, phase, height, solar zenith angle, and season to provide insight into the radiative impact of these clouds on the atmosphere and surface.

1. INTRODUCTION

Climate model simulations have demonstrated that the Arctic is expected to experience the largest sensitivity from anthropogenic climate change. Recent observations of surface temperatures in the Arctic and sea ice extent appear to support these model simulations. This sensitivity is due, in part, to the importance that clouds play in the radiative environment of the Arctic.

Arctic clouds are extremely complicated, with mixed-phase clouds existing very frequently. Furthermore, accurately determining cloud properties from active and passive remote sensors is still an evolving science, although recent efforts have significantly advanced the field [1].

The Arctic energy balance is very sensitive to clouds and their impact on radiative fluxes. Relatively small changes in the macro- and microphysical properties of clouds can have significant impacts on their radiative effects on both the surface and atmosphere. In particular, the correct determination of the cloud phase as a function of height as well as the total liquid water path (LWP) in the column is critical in order to properly compute the radiative impact of the clouds.

Similarly, the radiative environment, especially the radiative heating rate profile, may play an important role in the development, maintenance, and dissipation of Arctic clouds. Thus, we seek a better understanding of the correlation and connection between Arctic cloud properties and radiative heating rate profiles.

We have developed a multi-sensor cloud property retrieval framework, which we here call "microbase", using data collected at the Atmospheric Radiation Measurement (ARM) North Slope of Alaska (NSA) site in Barrow, Alaska. Microbase provides cloud properties at all times and heights above the NSA site, and these cloud properties are input into a rapid radiative transfer model (RRTM) that computes the radiative fluxes at the surface and top-of-atmosphere as well as radiative heating rate profiles. This paper presents some of the initial results from the analysis of two years of cloud and associated radiative properties.

2. CLOUD RETRIEVAL ALGORITHM

It has been shown that liquid water exists a large fraction of the time in the Arctic atmosphere [e.g., 2,3], and that the cloud LWP is frequently small (less than 50 g/m^2) [4]. The sensitivity of both longwave and shortwave radiative fluxes to small errors in LWP is large when the LWP is less than this threshold [5]. Therefore, it is critical to accurately determine the LWP in Arctic clouds if the radiative impact of the clouds is to be investigated. Moreover, the liquid must be properly distributed as a function of height in order to compute the infrared heating rate profile accurately.

Our microbase algorithm is composed of two key components: a cloud phase classification algorithm that determines at each height whether observed clouds are liquid, ice, or mixed-phase [6], and a microphysics retrieval component that uses multiple techniques to derive cloud liquid and ice microphysical properties [3,7]. These two components use several of the active and passive remote sensors at the NSA site, including the Atmospheric Emitted Radiance Interferometer (AERI), two channel microwave radiometer (MWR), millimeter-wave cloud radar (MMCR), and micropulse lidar (MPL). Thermodynamic profiles are determined by the optimal marriage of ECMWF model output and radiosondes launched by the ARM program at the NSA site and the U.S. National Weather Service at Barrow. The general outline of the microbase algorithm is given in Fig 1.

One specific technique used in the retrieval component provides accurate and crucial constraints on the cloud LWP and ice water path (IWP) in the vertical column [3]. This MIXCRA technique takes advantage of differences in the spectral absorption coefficient of ice and liquid water across the infrared spectrum, and is able to retrieve both the LWP and IWP from the AERI's spectrally-resolved infrared radiance observations as long as the total optical depth is less than 6. MIXCRA has been validated with polarization-sensitive high-spectral-resolution lidar [8].

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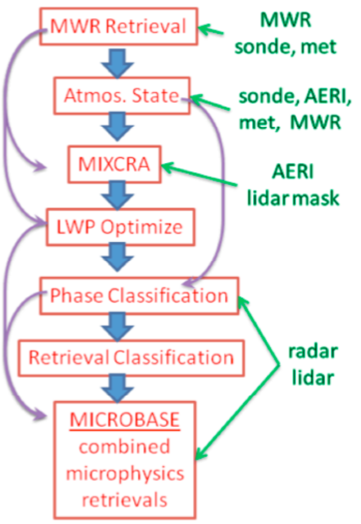


Fig 1: The general outline of the microbase cloud property retrieval algorithm. The key components are the retrieval of liquid and ice water paths (in the MIXCRA step) and the phase classification algorithm.

The microbase algorithm has been applied to two years of data collected at the NSA from March 2004 to February 2006. The distribution of cloud phase in the column as a function of month, whereby a cloud column is considered single-phase if only ice or liquid (not both) exist in the column, is given in Fig 2. Note that, as at the SHEBA site [2,3], mixed-phase clouds are dominant over the NSA region, with mixed-phase clouds occurring nearly 50% of the time over the period. Note that liquid-only clouds are observed in all months at this site.

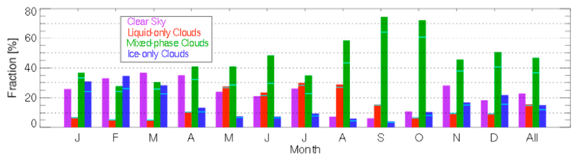


Fig 2: The distribution of clear skies (purple), liquid-only (red), mixed-phase (green), and ice-only (blue) clouds as a function of month over the NSA site for the two-year dataset. The horizontal cyan line on each bar separates the single contiguous layer clouds (below) from the multi-layer clouds (above).

3. RADIATIVE HEATING RATE RESULTS

The multi-year dataset was first used to investigate the seasonal dependence of the distribution of liquid and ice water content, as well as the seasonally dependence of the radiative heating rate profiles. Fig 3 demonstrates that the liquid water content is at a maximum in the lower 1 km of the atmosphere during the late spring and summer, but then increases with altitude to nearly 2 km during the autumn. There was little ice sensed in the lowest 1 km during the summer, indicating that the boundary layer summertime clouds are primarily liquid-only. However, in the autumn ice is present in the lowest two kilometers, indicating that these lower-level clouds are likely mixed-phase; this is in agreement with the results in Fig 2. Furthermore, liquid water was sensed as high as 8 km during the summer period, but was limited to less than 4 km during the winter. The maximum height of the ice water content also shows a strong seasonal dependence.

Furthermore, there is a strong correlation between the distribution of the liquid water content and the longwave radiative heating rate profiles. This vertical distribution of the infrared radiative heating may be partially responsible for the maintenance of these liquid water-bearing clouds in the presence of ice, especially in the autumn period. The shortwave radiative heating rate profiles show a strong seasonal cycle associated with the solar zenith angle at this high-latitude (72ºN) site.

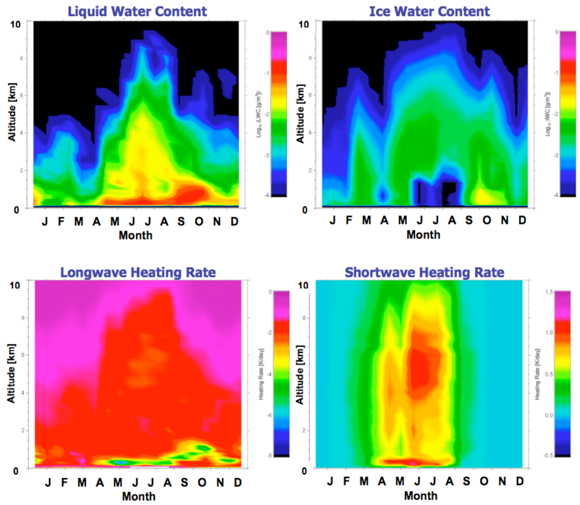


Fig 3: The distribution of liquid water content and ice water content (top left and right, respectively), and the longwave and shortwave radiative heating rate profiles (bottom left and right, respectively) as a function of month over the NSA site.

Given the importance of liquid in characterizing the radiative environment, we further analyzed three subsets of the data: profiles that have only a single-contiguous liquid-only layer, profiles that have only a single-contiguous mixed-phase layer, and profiles that have two distinct liquid-only layers. The distributions of the liquid water content (LWC) for these three subsets are shown in Fig 4.

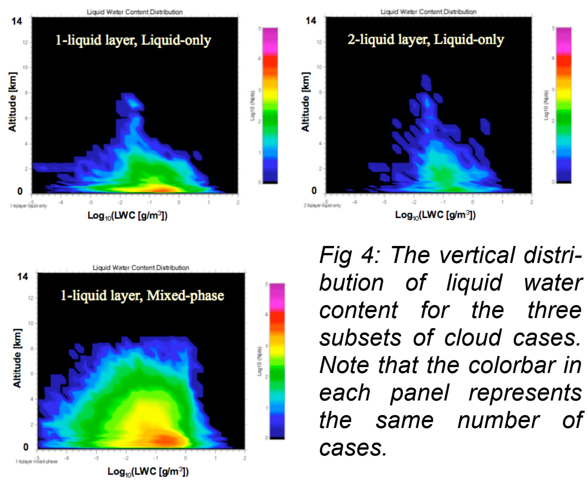
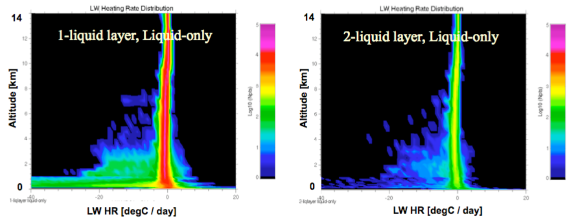


Fig 4: The vertical distribution of liquid water content for the three subsets of cloud cases. Note that the colorbar in each panel represents the same number of cases.

Fig 4 shows that the vertical distribution of liquid water is, in general terms, very similar in single-layer liquid-only and double-layer liquid-only clouds, and that liquid-only clouds primarily occur below4 km. However, in mixed-phase clouds, the liquid water, while having a peak in the boundary layer like the liquid-only clouds, extends to much higher in altitude. Thus, the liquid water at 6+ kilometers seen in Fig 3 is associated with mixed-phase clouds.

Figure 5 shows the associated longwave radiative heating rate distributions associated with the three classes of clouds shown in Fig 4.



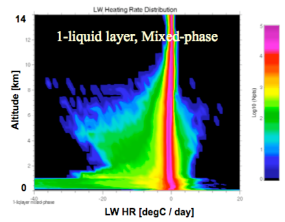


Fig 5: The vertical distributions of longwave radiative heating rate for the three classes of clouds shown in Fig 4.

The longwave radiative heating rate distributions are very different for these three classes of cloud. For example, in single-layer liquid-only clouds, there is strong radiative cooling seen at the top of the cloud layer at 1 km, with cooling rates exceeding 50 K/day frequently. However, if there are multiple liquid layers, the upper liquid layer works to absorb the emission from the lower layer, and thus the strong radiative cooling from the lower layer is diminished. Furthermore, while the first liquid layer is predominately in the lowest 1 km, the vertical placement of the second liquid layer is a spread over a larger distance as evidenced by a lack of a strong cooling level in the 2-liquid layer heating rate distribution.

There are also significant differences in the vertical distribution of heating rate in the single-layer liquid-only clouds vs. the single-layer mixed-phase clouds. The mixed-phase clouds do show a significant radiative cooling at the 1 km level; this is associated with primarily wintertime cases when the cloud is within the lowest 1 km. However, as discussed above, the liquid water in mixed-phase clouds can extend to up 6 km or higher in the summertime, and this leads to a complicated elevated cooling that is seen in Fig 5. Furthermore, some small amount of longwave radiative heating is seen from 1-4 km in mixed-phase clouds; this is associated with the absorption of infrared radiation by the precipitating ice particles falling from the elevated liquid layer. This heating of the mid-troposphere may aid in the development and maintenance of these mixed-phase clouds by increasing the turbulent motions under the clouds. This hypothesis is currently under investigation.

4. SUMMARY AND FUTURE

We have developed a multi-sensor, integrated retrieval technique to derive cloud properties at all times and heights above the ARM NSA site. These cloud properties, together with the thermodynamic state and the surface temperature/reflectivity properties, are then input into a radiative transfer model to compute the radiative heating rate profiles over the multi-year dataset. These profiles are being used, in both a qualitative and quantitative way, to characterize the cloud radiative environment and how the radiation is correlated to the distribution of liquid and ice particles.

This work has focused on the analysis of data at the ARM NSA site. However, the NOAA SEARCH site in Eureka, Canada, has many of the same ground-based remote sensors as the ARM site, and work has begun to analyze the SEARCH data in the same way as the ARM data. Furthermore, the National Science Foundation has just funded a 5-year effort to place a similar suite of remote sensors at Summit, Greenland; the remote sensors will be deployed in spring of 2010. The datasets from these three locations (Barrow, Eureka, and Summit) will provide an unprecedented look at the cloud and radiative properties in the Arctic and in particular the variability of these properties in different locations.

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