Using CloudSat data to look at the cloud and precipitation structure in the Arctic

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Abstract

Clouds and precipitation are fundamental determinates of the Arctic climate. Despite the presence of clouds and storm systems, very few precipitations reach the ground. In fact, polar precipitation patterns are characterized by frequent sublimation of the water particles during their descent. This discrepancy between cloud coverage and storm systems and the amount of precipitation on the ground is not explained because relatively little is known about these features due partly to the lack of available data. Recently, CloudSat, a polar-orbiting satellite, was launched in order to provide unique information about the cloud and precipitation structure of the Arctic, which cannot be measured using current weather instruments. The data is used in the context of the Storm Studies in the Arctic, a field experiment that started in Fall 2007 in the Canadian Arctic, aims at describing the extreme weather occurring over Baffin Island and Iqaluit. The present study focuses on the Southern Baffin Island using data from CloudSat for the area covered by the Storm Studies in the Arctic field experiment. We analyzed 37 passes of CloudSat over Iqaluit and examined cloud altitude and type, environmental conditions like temperature and relative humidity, as well as the precipitation type, size, and rate. Our analysis shows that the cloud structure is characterized by formations that are mostly stratiform, composed of one to two cloud-layers at low- and mid-level, and mostly thin individual clouds. A low cloud base and a large cloud thickness seem to be requirements for precipitation over the region. Although these results do not give satisfying answers regarding what triggers sublimation , they provide general information about the macrostructure of the clouds. This is a first step in understanding why in the Arctic very little precipitation reaches the ground. We believe further information about cloud microstructure can be garnered using data from CloudSat. Our data therefore provides recommendation for the Storm Studies in the Arctic experiment that started after this study was conducted

Keywords
Cloud, precipitation, Arctic, water cycle, climate.

Introduction

CloudSat, a satellite launched in April 2006, will provide data concerning cloud properties not available from current weather instruments. The region that CloudSat examines overlaps with the area covered by the Storm Studies in the Arctic (STAR) field experiment in the Canadian Arctic, whose main focus is the extreme weather occurring over Baffin Island and Iqaluit. Many storm systems pass over this region, and their structure is often altered by the variable surface, ranging from ice-covered ocean to one to two kilometer high terrain. No systematic study of the evolving clouds and precipitation over this region has ever been conducted; hence CloudSat, in combination with data from other satellites in the same orbital configuration (the A-train), provides unprecedented information on these features. Our project will assess these data in order to determine whether these precipitation fields or the patterns lead to extreme weather events ,using a wide variety of field observations, including surface-based Doppler radar, ground-based remote sensing, enhanced upper air soundings, special precipitation measurements, and research aircraft flights into storms.

CloudSat's mission is to provide observations regarding cloud abundance, distribution, structure, and radiative properties. In combination with four other satellites in a polar-orbiting configuration approximately 705 km above the Earth's surface known as the A-train, CloudSat will track cloud patterns using the very first millimeter-wavelength radar. With roughly 1000X greater sensitivity than existing weather radars, the Cloud Profiling Radar (CPR) is a nadir-looking radar which measures the power backscattered by clouds as a function of distance from the radar. The CPR's vertical resolution is 500 m while its cross-track and along-track (horizontal) resolutions are 1.4 km and 2.5 km respectively (Stephens, 2002).

The main objective of STAR is to study the nature of cloud and precipitation associated with extreme events. This field-based project is concerned with the documentation, understanding and prediction of meteorological and related hazards in the Arctic. It invokes a wide variety of field observations including surface-based Doppler radar, ground-based remote sensing, enhanced upper air soundings, special precipitation measurements, and research aircraft flights into the storms.

Methods and objectives

Analysis was performed over Iqaluit, located at the southern tip of Baffin Island, since it is here that the first field experiment of the STAR project was conducted. By looking at the cloud and precipitation fields as well as the occurrence of precipitation over the region, we hope to answer the following questions: (i) what cloud structure leads to precipitation, and (ii) when light precipitation occurs, is this linked with low-level clouds or multi-layered clouds, clouds with large vertical extent, or mean-surface evaporation and/or sublimation?

To perform the analysis, we used the CloudSat data derived from profiles taken over a 100-km radius centered at Iqaluit (63° 45'N; 68°31'W) between August 31st and December 31st, 2006. That period was chosen to match the forthcoming STAR field season that took place during the fall season of 2007. All of the profiles extracted during the analysis are compared with surface observations of temperature, pressure, relative humidity and precipitation type from Environment Canada taken at Iqaluit from the YFB weather station.

CloudSat data were analyzed for the following parameters: ice effective radius, ice water content, liquid water content, pressure, temperature, specific humidity, and radar reflectivity. Also, the cloud mask assigns a value between 20 and 40 when a cloud is detected with increasing certainty; the cloud echo value is a number attributed to the detected cloud formation which can either be low-, mid-, high- or multi-level cloud. All parameters are expressed in two dimensions; altitudinal height and along-track, the latitude-longitude coordinates of the profile.

The cloud mask is a representation of the cloud coverage

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while the cloud echo specifies the cloud type (Haynes & Stephens, 2007). The radar reflectivity is the ratio of the returned signal to the incident signal of the targeted atmospheric particles and hence indirectly represents the precipitation rate. Reflectivity values greater than 0 dBZ indicate that precipitation is occurring, with light rain or snow having reflectivity of roughly 5 dBZ. The ice effective radius corresponds to the mean size of a population of ice crystals (Wysek, 2005); the ice crystals are the particles responsible for snow formation. Lastly, the ice or liquid water content represents the quantity of water present in the atmosphere in either ice or liquid phase.

The relative humidity (RH) values were calculated from the ratio of the environment vapor pressure to the saturation vapor pressure:

$$RH^i = \frac{e}{e_s^i} \times 100$$

where *e* is the vapor pressure and e_s^i is the saturation vapor pressure with respect to ice. The environment vapor pressure was extracted using the specific humidity values, where specific humidity is the mass ratio of water to air present in a given volume.

$$e = \frac{p}{1 + \varepsilon / r}$$

where *p* is the pressure and ε=0.61298. The mixing ratio r is calculated from:

$$r = \frac{q}{1 - q}$$

where *q* is the specific humidity. The pressure and temperature values were used to calculate the saturation vapor pressure using the Magnus-Teten formulation (Murray, 1967):

$$e_s^i = 6.11 \times 10^{9.5T/(265.5+T)}$$

where *T* represents temperature.

Figure 2 and Figure 3 are examples of these cloud and precipitation structure parameters, respectively, retrieved and plotted for one pass over Iqaluit. All of the parameters retrieved for each chosen pass were plotted similarly to facilitate analysis. Each event was examined from the corresponding figure and tabulated using criteria such as cloud base and top height, cloud thickness (or vertical extent), and cloud and sub-cloud temperature with respect to relative humidity. Plots of the parameters after classification following these criteria were made to determine cloud and precipitation structure.

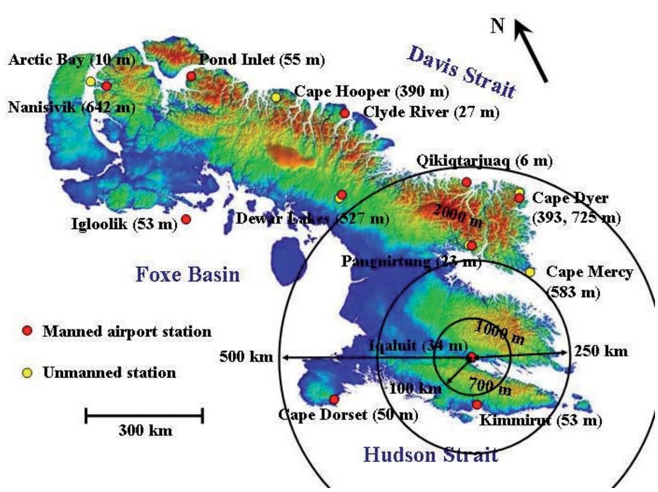

Figure 1: Baffin Island

Results and Discussion

During the 16-day return cycle of the satellite, there were 37 passes over the delimited region. Of these, 18 presented cloud features without precipitation, two showed precipitation in the formation process followed by sublimation, and four displayed clouds with precipitation at the surface. Accordingly, these events were classified in four categories: no cloud, no precipitation, sublimation and precipitation. Unfortunately, the analysis was limited by the amount of data collected since the satellite, launched just over a year ago, has not yet covered a fall season.

Using the four categories of classification, the structure of the clouds over Iqaluit was characterized to help determine a mechanism for precipitation over the Arctic. Cloud formations were mostly stratiform, composed of one to two cloud layers at low- and mid-level, indicating that cloud-base height is usually below 2 km. Also, individual clouds were mostly thin, with a thickness usually smaller than 2 km.

When examining individual precipitation events, it appears as though the resulting precipitation has the following characteristics: the cloud-base height is lower than 1 km and the cloud thickness is greater than 3.5 km, the sub-cloud environment has a temperature higher than -10°C and a relative humidity higher than 90%, and the ice water content is of 250 mg/m3 or more (or liquid equivalent). The first four characteristics are illustrated in Figure 4.

According to previous studies, a low cloud base and a large cloud vertical extent are requirements for clouds to produce precipitation in the Arctic (Stewart et al., 2004). This conclusion clearly matches our analysis. Also, the sub-cloud environment, which is determined by the relative humidity and temperature thresholds, is consistent with observations previously performed in the Arctic (Stewart & Burford, 2002). The latter statement can be understood physically from the fact that a warm and close-to-saturation environment will promote precipitation to form and fall to the ground. It is also usual to assume that relative humidity values higher than 87% will guarantee cloud formation (Wang & Rossow, 1995). The temperature factor has similarly been shown to relate to the saturation vapor pressure, and also to the growth rate of ice crystals (Rogers & Yau, 1989). Therefore, a colder atmosphere is more saturated with the same amount of water vapor, but allows fewer ice crystals to grow to snow particle size. To support this fact, it is common to look at the ice water content parameter that determines the amount of water present in the atmosphere to allow ice crystals to reach precipitation size from aggregation or accretion.

We were not able to elaborate on the differences between the events where precipitating particles reach the ground and the events where the particles undergo sublimation during their descent. Hence, the macrostructure of the clouds is likely not the underlying cause of sublimation. We did, however, observe that all precipitation events that displayed reflectivity values associated with precipitation had particle radii reaching 100 µm. We propose that this value is a threshold for particles to begin falling. Based on this information, we raise the question of whether the ice water (liquid) content remains sufficient to overcome sublimation throughout falling. Looking at the maximum value of ice water content for each event, we notice that precipitation events have an ice water content of 250 mg/m3 or more (or liquid equivalent) while sublimation events show an ice water content of 150 mg/m^3 or less (or liquid equivalent). The ice water (liquid) content might be the factor that would determine if the falling particles will reach the ground.

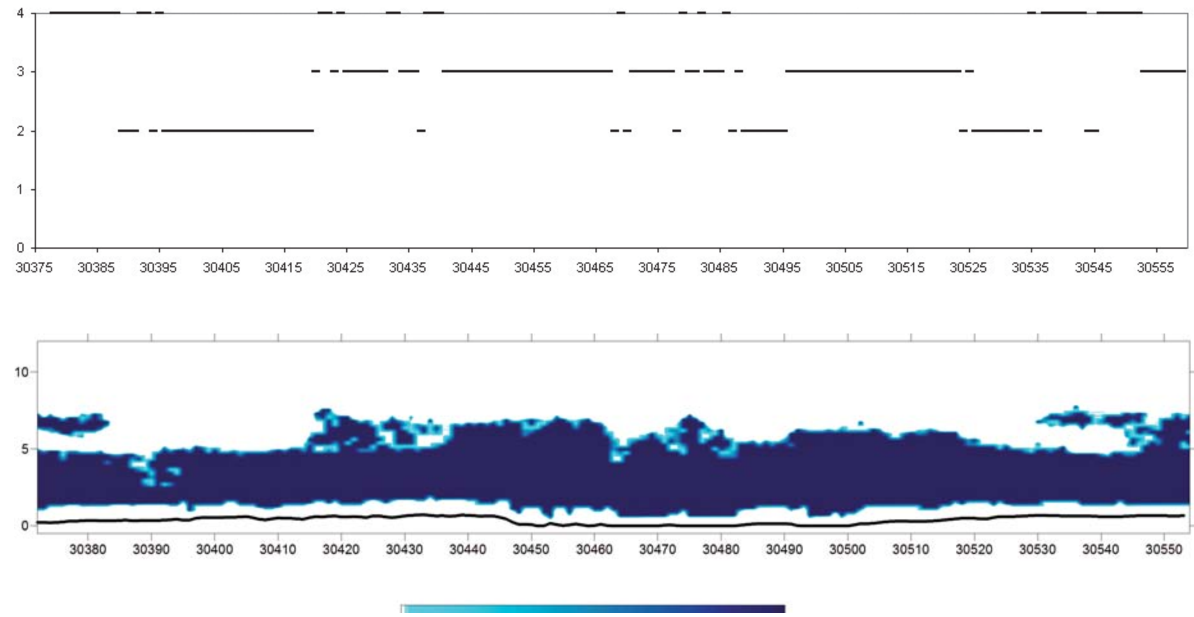

Figure 2: Example of vertical profiles of precipitation structure from CloudSat's orbit number 2183 over Iqaluit (October 25, 2006 at 03:00 LT). The horizontal axis represents the profile number of the pass which is similar to the horizontal distance. The vertical axis represents the height from the ground up to 8 km. The topography is indicated by the black horizontal line at around 0 km in height.

After analyzing the structure of clouds and the occurrence of precipitation over Iqaluit, one question remains: Why is light precipitation or sublimation so frequent in the Arctic? From our preliminary analysis and results, we suggest two reasons: (i) the ice effective radius is usually too small (threshold is ~100 μm), and (ii) the ice or liquid water content is usually too low (threshold is ~250 mg/m3. Further investigation of the cloud microstructure is required to properly explain the frequency of sublimation events in the Arctic.

Conclusion

From the 37 passes of CloudSat analyzed during this study, it is possible to draw a general outline of the cloud structures and occurrence of precipitation over Iqaluit. Our research is the first one to examine these phenomena using CloudSat data. Our preliminary results provide insight into the characteristics and processes leading to clouds and precipitation in the Southern Baffin Island and Iqaluit region, as well as to the extreme weather events that sometimes occur. Further information from the A-train formation added to the ongoing STAR project will enable a more complete study of the cloud physics in the Artic in a near future. Furthermore, the information presented in the current study has been used by the autumn 2007 STAR field experiment centered in this region to test hypotheses concerning storm evolution. During this campaign, the vertical profiles of many atmospheric properties have been measured with the help of dropsondes and other instruments onboard aircraft in the vicinity of Iqaluit, Pangnirtung, and other locations around Southern Baffin Island. The current project has therefore acquired unique in-situ information in tandem with that of CloudSat and the A-train, and the analysis of this information will contribute to our understanding of clouds and precipitation over the Northern Polar regions.

Acknowledgements

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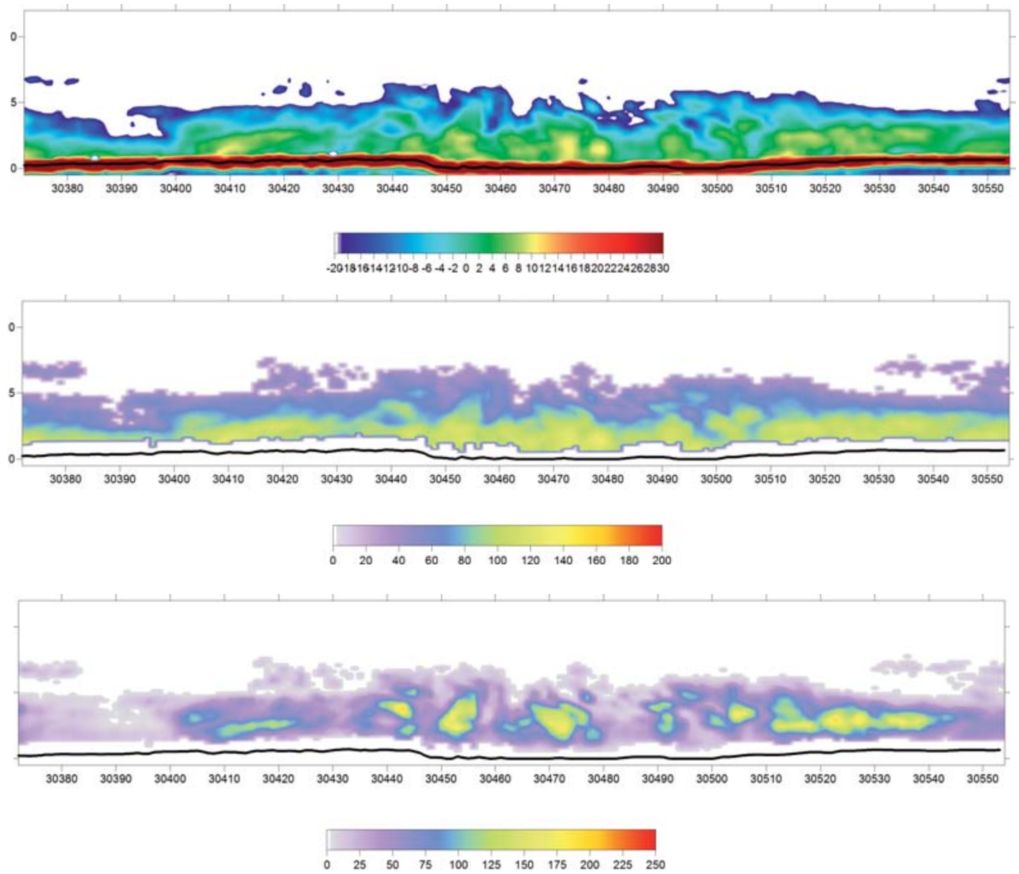

Figure 3: Example of vertical profiles of cloud environment properties generated for the CloudSat orbit number 2183 corresponding to October 25, 2006 at 03:00 LT for Iqaluit. The horizontal axis represents the profile number of the corresponding CloudSat pass which is similar to the horizontal distance along the profile. The vertical axis represents the height from the ground up to 8 km.

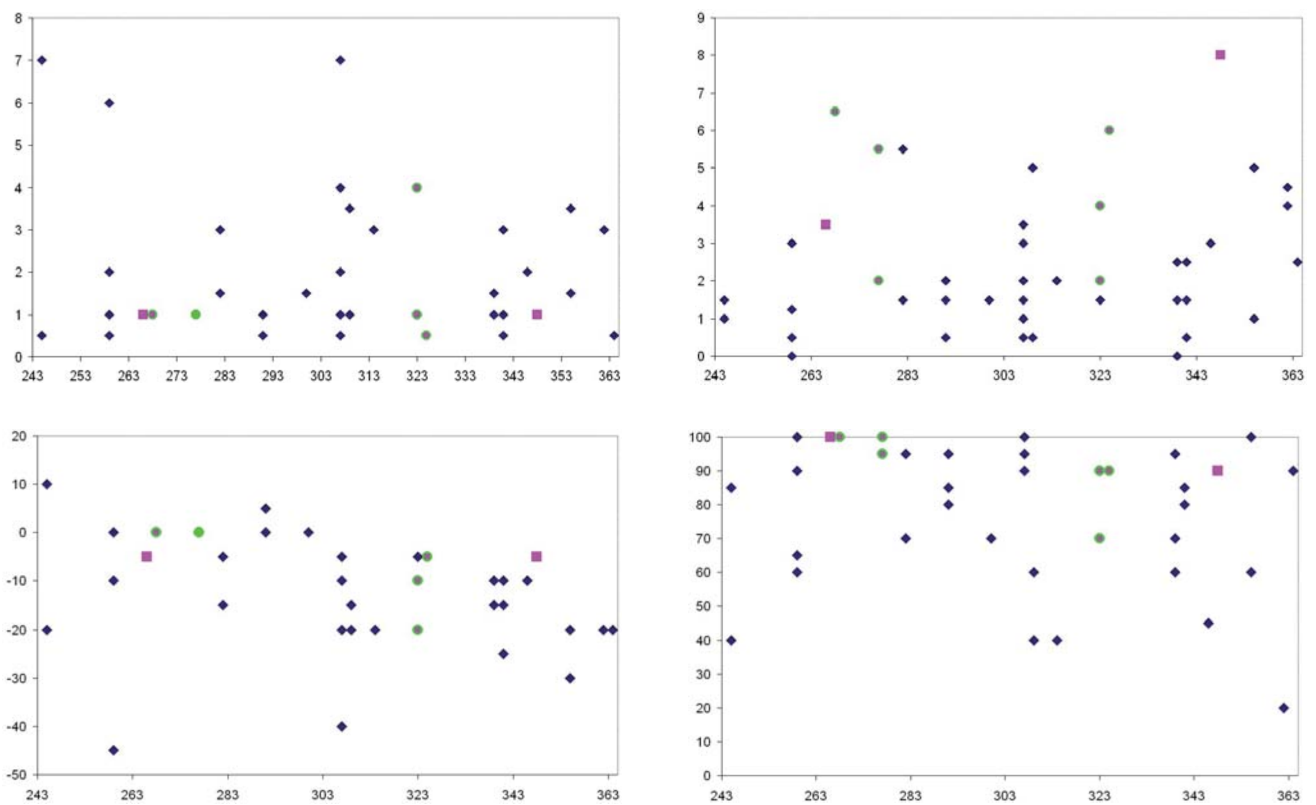

Figure 4: Cloud structure over Iqaluit during the autumnal period. The horizontal axis represents the events from August 31st (day 243) to December 31st, 2006 (day 365). The events are classified as follows: cloud formation without precipitation (blue diamonds), with sublimation (magenta squares) and with precipitation (green circles).