STATISTICS ON LOW-LYING LIQUID AND LIQUID-DOMINANT MIXED-PHASE CLOUDS OVER OTTAWA

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ABSTRACT

The Communications Research Centre Canada (CRC) in Ottawa employs a multifrequency profiling radiometer to model the impact of clouds and water vapour on Earth-Space links. The profiling radiometer can retrieve vertical profiles of temperature, humidity and cloud liquid water every 30 seconds or every minute from the surface up to 10 km in height under clear sky and cloudy conditions. It is also capable of assessing the columnar cloud liquid water content (also known as the liquid water path L) and the water vapour path continuously, unlike what can be achieved with conventional radiosondes. The profiler also features an infrared thermometer that detects the cloud base temperature: the cloud base height of the lowest layer can thus be estimated using the contemporaneous temperature profile.

Statistics on liquid water path, cloud base height and cloud top height for non-precipitating liquid-phase and mixed-phase Stratus and Stratocumulus clouds observed over CRC between April 2005 and April 2006 during the daytime are presented in this paper. According to the land cloud climatology of Hahn and Warren [1], these clouds are one of the most frequently occurring liquid-bearing types over a 5-degree by 5-degree box that includes the Ottawa area.

Cloud top height has been assessed using CRC's cloud detection algorithm [2]. It is based on the Chernykh and Eskridge (CE) method that was originally designed to detect cloud layers and amounts from radiosonde profiles [3]. Our algorithm uses the CE method with retrieved vertical profiles of temperature and relative humidity, but also data not measured by radiosondes: the cloud base height estimated by the infrared thermometer, and the retrieved L. This extra set of conditions can be summarized as follows: a cloud contains liquid water whenever L exceeds a certain threshold value computed for each profile [2] and its cloud base height is lower than some maximum value (found to be 6 km in [2]). This cloud detection algorithm has been shown to significantly reduce the number of false positives compared to the application of the original CE method [2].

Daytime seasonal and annual averages will be compared, whenever possible, to the 6-year climatology of midlatitude low-level continental clouds from the United States ARM Southern Great Plains (SGP) Central Facility, Oklahoma, reported in [4]. To the best of the authors' knowledge, this 6-year cloud climatology is the only one available in the literature.

1. INTRODUCTION

The main application of CRC's multifrequency profiling radiometer (Radiometrics TP/WVP-3000) is to study and model the impact of clouds and water vapour on satellite links above about 30 GHz. This instrument uses 12 channels, five in the K-band between 22.235 and 30 GHz for water vapour profiling and seven in the V-band between 51.25 and 58.8 GHz for temperature profiling. Both K-band and V-band receivers are located in the same cabinet and share the same antenna and pointing systems. It also features an infrared thermometer (operating between 9.6 and 11.5 μm) directed downward to a gold-plated mirror that reflects energy from the zenith, thereby detecting the cloud base temperature. Thus the height of the cloud base of the lowest layer can be obtained using the contemporaneously-retrieved temperature profile.

Since ice has negligible absorption at these twelve frequencies and therefore has negligible thermal emission, Cirrus clouds – usually entirely composed of ice crystals – are not detected by the profiling radiometer.

The profiling radiometer can retrieve vertical profiles of temperature, absolute as well as relative humidity, and cloud liquid water every 30 seconds or every minute from the surface up to 10 km in height under clear sky and cloudy conditions. Higher sampling frequencies (e.g., retrieving 21 profiles in five minutes) are also currently available. The vertical resolution changes with altitude: it is 100 m between the surface and 1 km and 250 m between 1 km and 10 km. The radiometer has automated elevation-scanning capability and is also capable of assessing the liquid water path continuously, unlike what can be achieved with radiosondes. It also measures surface temperature, pressure and relative humidity continuously. Finally the water vapour path

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(V) is also retrieved at the same sampling frequency as the various profiles.

Statistics on retrieved liquid water path, cloud base and top heights for non-precipitating liquid-phase and mixed-phase Stratus and Stratocumulus clouds observed over CRC between April 2005 and April 2006 during the daytime will be presented in this paper. These results will be compared whenever possible to the 6-year climatology of midlatitude low-level continental clouds from the United States ARM Southern Great Plains (SGP) Central Facility, Oklahoma, reported in [4]. To the best of the authors' knowledge, this 6-year climatology is the only one available in the literature. We have to keep in mind that there are clearly some differences in climate between CRC in Ottawa (45.3° N, 75.9° W) and the SGP Facility in Oklahoma (36.6° N, 97.5° W). For example, winters are shorter and less rigorous in Oklahoma than those in Ottawa.

2. METHODOLOGY

Cloud top height has been assessed using CRC's cloud detection algorithm [2]. It is based in part on a technique originally developed by I.V. Chernykh and R.E. Eskridge for radiosonde profiles [3]. Hereafter the method will be referred to as the CE method.

The reader is referred to [2] for a complete description of CRC's cloud detection algorithm. Its salient features will be briefly described here. Basically, it detects the presence of cloud layers by monitoring the second-order derivative of temperature $T(z)$ and relative humidity $R(z)$ profiles. Conditions for detection of cloud layers are: $T''(z) \geq 0$ and $R''(z) \leq 0$. In other words, local minima in temperature and local maxima in relative humidity are observed within cloudy layers. The cloud amount in percent is then estimated using the minimum dewpoint depression (i.e., the difference between the air temperature at that level and the corresponding dew point temperature) within the detected cloud layer and the corresponding temperature at that level.

The dependence of cloud amount on dewpoint depression and temperature is presented in the form of the so-called Arabey diagram [5], originally based on radiosonde data from the mid-latitudes of Eurasia and the tropical latitudes of the Indian Ocean. A new Arabey diagram for the liquid water cloud climatology of the Ottawa area has been empirically derived in [2]. Based on the available data collected at CRC, it appears that the original Arabey diagram has to be modified only for air temperatures lower than 0°C in order to be applicable to profiles of temperature and relative humidity retrieved by our multifrequency radiometer. The zones of the new Arabey diagram have also been slightly modified so as to be consistent with the established practice of dividing the celestial dome into 8 portions (octas). Thus, 0%-20% of the original diagram becomes 0%-25% (0/8-2/8), 20%-60% becomes 25%-63% (2/8-5/8), etc.

The two relations $T''(z) \geq 0$ and $R''(z) \leq 0$ refer to *necessary* conditions for the presence of cloudy layers. In fact, the original CE method can sometimes predict cloudy layers under clear sky (cloudless) conditions, i.e., false positives. For example, large peaks of relative humidity in excess of 80% sometimes occur either in the boundary layer or higher up in the atmosphere under clear sky conditions, as shown in Fig. 2 of [2]. In an effort to alleviate this problem, CRC's cloud detection algorithm uses supplementary data not measured by radiosondes (the retrieved liquid water path (L) and the cloud base height measured by the profiler's infrared thermometer). It has been shown to significantly reduce the number of false positives compared to the original CE method [2].

The altitude of the highest detected layer that fell within Arabey zones (88-100%) and (63-88%) has been used as an estimate for Z_{top} since these zones both include the 7-octa sky condition (7/8 = 0.875).

3. DATA

The data set used in this paper consists of the first author's daytime observations of cloudiness in the sky above the profiling radiometer deployed at CRC. It covers the period between April 2005 and April 2006. Earlier data – for example those collected in 2003 – have been omitted here since both hardware and software upgrades to the profiler done at the factory during the summer of 2004 have resulted in much improved retrieved humidity profiles (i.e., reaching saturation within the cloud layer(s)), especially for low-lying clouds like Stratocumulus.

The criteria used to create our data set here reflect much those used by Dong *et al.* [4] in order to facilitate the comparison between the two data sets. Nevertheless there are some differences, taking into account that Dong *et al.* could use data from an impressive array of cloud instruments, the centerpiece of which was a millimeter-wave cloud radar. Our criteria are:

1) Only daytime Stratocumulus (Sc) or Stratus (St) was used in the data set. Some Cumulus with amounts less than 3 octas underlying the Stratocumulus – but usually far away from the zenith – were sometimes present and included here, as in [4].
2) No mid-level clouds (neither Altostratus nor Altocumulus) were overlying the Sc/St.
3) The total cloud amount – including the Cumulus – was either 7 (near-overcast) or 8 octas (overcast).

4) Cloud base heights *(Z_{base})* of Sc/St measured by the profiler's infrared thermometer were less than 2 km, consistent with the WMO definitions for these genera [6]. Measured Z_{base} of Sc/St in excess of 2 km typically occurred during the passage of either optically thin Sc/St in the infrared (9.6-11.5 μm) or Sc/St with small gaps (WMO variety *perlucidus* [6]). Z_{base} also had to be consistent with the retrieved relative humidity (RH) profile: for example, cases where Z_{base} fell *above* the maximum in RH were rejected. Fig. 1 is a case in point. It shows a rejected case with Z_{base} equal to 4 km as the overcast Sc layer became optically thin at zenith for a few minutes at around 15:48 UTC on April 6, 2006.
5) Cloud top height *(Z_{top})* computed using CRC's cloud detection algorithm was less than 4 km (as in [4]) so as to select low-level clouds.
6) The retrieved liquid water path was less than about 1 mm. Higher values for L are inevitably observed during either rainy periods or in advance of rain episodes when large liquid water drops aloft have not yet reached the surface and wetted the profiler's radome. These large drops aloft cause scattering, increasing the brightness temperatures over what would be measured from thermal emission alone [7]. The retrieval model used by the profiler for the estimation of liquid water path assumes that only absorption is present. On the other hand, the minimum L in the data set was not based on the retrieval accuracy of the profiling radiometer as in [4], since condition 4) for Z_{base} implies rather optically-thick clouds and cloud optical depth is known to be proportional to its liquid water path [8].
7) Cloud observations during precipitation – either rain, drizzle or even light snow – have been omitted. Unfortunately, the low clouds in our data set ended up being almost exclusively composed of Stratocumulus clouds since Stratus clouds observed during the time period covered here were nearly always precipitating, especially during the winter season. The few remaining Stratus cases were observed in April 2005 exclusively. It should be noted that Dong *et al.* [4] chose 0.7 mm as an upper limit for L since they found that values in excess of 0.7 mm were strongly correlated with drizzle or rain conditions.
8) All of the above conditions had to be satisfied for each retrieved atmospheric profile. See Fig. 1 again for an example.

Finally, three supplementary sources of cloud data have been used in this work to make sure that conditions 1)-5) were satisfied:

- Surface meteorological observations (METARS) from both the Ottawa and the Gatineau Airports (CYOW and CYND, respectively). These include hourly cloud type and cloud cover assessed by weather observers as well as cloud base height for the various individual layers measured with a ceilometer. Opacity of individual cloud layers as seen from the ground is also provided.
- Cloud top height data products (available on the Web at http://www.nrlmry.navy.mil/sat-bin/cloud_tops.cgi). CRC has developed a program to estimate cloud top heights for mid-level clouds of different types (not restricted to Sc/St) over the Ottawa area using satellite images from the U.S. Naval Research Laboratory Monterey. This cloud top height product (in the form of color maps) is based on geostationary infrared images and NOGAPS (US Navy's Global Atmospheric Prediction System) output. For each pixel the satellite cloud top temperature is converted to a cloud height by using a vertical profile from NOGAPS. Cloud top heights range from about 3.6 km to about 18 km. Since the algorithm creates errors near the surface of the Earth, cloud top heights smaller than about 3.6 km are not included in the images, and are simply replaced by light gray or brown pixels.
- Cloud classification data products (available on the Web at http://www.nrlmry.navy.mil/sat-bin/clouds.cgi). Using an automated classifier developed at U.S. Naval Research Laboratory Monterey, GOES-West and GOES-East images are scene-classified in terms of fifteen classes of clouds. Images depicting these classes are created as well as more general 8-class images: low clouds, mid-level clouds, high clouds, vertical development clouds, clear sky, snow, haze, and Sun glint.

4. RESULTS

4.1. Distribution of liquid water path (LWP) for daytime non-precipitating Sc/St over Ottawa

Fig. 2 shows the cumulative distribution function (cdf) of liquid water path for daytime, non-precipitating Sc/St clouds over Ottawa between April 2005 and April 2006. Since periods of no Sc/St clouds have been omitted, the vertical scale of Fig. 2 represents conditional probabilities where Sc/St clouds were present over Ottawa. Parameters of this distribution are: mean = 0.169 mm, median = 0.15 mm and standard deviation = 0.074 mm. These are comparable to those reported by

Dong *et al.* [4] for the daytime: mean = 0.1507 mm, median = 0.1097 mm and standard deviation = 0.127 mm.

Dong *et al.* [4] reported that there was virtually no difference between daytime and nighttime statistics of the various cloud macrophysical and microphysical properties presented in their paper.

The daytime seasonal and annual averages for LWP are presented in Tab. 1. The four seasons are defined in this paper as in Dong *et al.* [4]: winter is December to February (DJF), spring from March to May (MAM), summer from June to August (JJA) and fall from September to November (SON).

Table 1. Seasonal and yearly averages of liquid water path (LWP) for daytime Stratocumulus/Stratus over Ottawa and the ARM SGP Facility in Oklahoma (OK) [4]

Location/ Years of data	LWP Winter (mm)	LWP Spring (mm)	LWP Summer (mm)	LWP Fall (mm)	LWP Year (mm)
Ottawa *One year*	0.179	0.158	0.285	0.208	0.169
OK *Six years*	0.1411	0.160	0.123	0.1653	0.1507

Spring averages of LWP were very similar for both locations. Dong *et al.* [4] reported a minimum in LWP during the summer and maxima in spring and fall (see Tab. 1) based on six years of data. Our data, reported in Tab. 1, suggest maxima in LWP in the summer and fall and a minimum in the spring. Moreover there was a minimum in the frequency of occurrence of Sc over Ottawa during the summer of 2005 (which meant a low sample size for that season), consistent with the data from the 26-year land cloud climatology of Hahn and Warren [1]. Therefore it would be premature to draw firm conclusions on the seasonal variations in LWP over Ottawa based on a single year of data.

Turning now to the ECMWF ERA-15 database of total non-reduced cloud liquid content (for more detail, please visit http://www.ecmwf.int/research/era/ERA-15/Project/) – an imperfect comparison since this database includes 15 years of LWP computed from radiosonde data for all liquid water-bearing cloud types during precipitation or not – the authors looked at plots of monthly means (not shown here) over CRC (Ottawa) and the SGP Facility (Oklahoma). These plots revealed LWP maxima in the summer and the fall over Ottawa and a sizable LWP minimum in July over Oklahoma. Therefore it seems reasonable to suspect that there is no minimum in LWP over Ottawa in the summer, unlike what can be observed over Oklahoma [4].

4.2. Distribution of cloud base height for daytime non-precipitating Sc/St over Ottawa

Fig. 3 shows the cumulative distribution of cloud base height for daytime, non-precipitating Sc/St clouds over Ottawa between April 2005 and April 2006. The vertical scale of Fig. 3 represents conditional probabilities where Sc/St clouds were present over Ottawa. The step-like behaviour of the cdf is a reflection of the profiler's vertical resolution (100 m below 1 km and 250 m above).

Parameters of this distribution are: mean = 0.54 km, median = 0.5 km and standard deviation = 0.32 km. These numbers are about half as large as those reported by Dong *et al.* [4] for the daytime: mean = 0.94 km, median = 0.74 km and standard deviation = 0.70 km. This difference may be explained by the fact that the distribution of Z_{base} reported in Dong et al. (see Fig. 3(a) of [4]) ranged from 0 to 3.8 km and included some shallow Cumulus with cloud base heights less than 3 km whereas our cdf (Fig. 3) ranged from 0.1 to 2 km, consistent with the WMO definitions of cloud base heights for Sc/St [6].

It is worth noting that Fig. 3 is to a large extent representative of Sc (see Section 3 of this paper). On the other hand, Stratus has a typically lower cloud base height than does Stratocumulus.

The daytime seasonal and annual averages for Z_{base} are presented in Tab. 2.

Table 2. Seasonal and yearly averages of cloud base height (Z_{base}) for daytime Stratocumulus/Stratus over Ottawa and the ARM SGP Facility in Oklahoma (OK) [4]

Location/ Years of data	Z_{base} Winter (km)	Z_{base} Spring (km)	Z_{base} Summer (km)	Z_{base} Fall (km)	Z_{base} Year (km)
Ottawa *One year*	0.78	0.47	0.74	0.64	0.54
OK *Six years*	0.77	0.97	1.17	0.94	0.94

It can be seen that Z_{base} was highest in the summer and lowest in the winter over Oklahoma, unlike what was observed over Ottawa during that period. The winter cloud base height values were very similar at both locations, however. As mentioned before, CRC has a low sample size for the summer of 2005 so the actual seasonal trend might not be conspicuous from these data; nevertheless the cloud base heights measured by the profiler's infrared thermometer during that period were found to be consistent with the contemporaneous ceilometer data reported in the METARs at the nearest airports (CYOW and CYND). It is hoped that further data collected at CRC will shed some light on this difference in seasonal behaviour.

The minimum cloud base height found in the spring over Ottawa in Tab. 2 can be explained by the presence of Stratus in early April 2005.

4.3. Distribution of cloud top height for daytime non-precipitating Sc/St over Ottawa

Fig. 4 shows the cumulative distribution of cloud top height for daytime, non-precipitating Sc/St clouds over Ottawa between April 2005 and April 2006. The vertical scale of Fig. 4 represents once again conditional probabilities where Sc/St clouds were present over Ottawa.

Parameters of this distribution are: mean = 2.10 km, median = 2.26 km and standard deviation = 0.50 km. These numbers are comparable to those reported by Dong *et al.* [4] for the daytime: mean = 1.79 km, median = 1.67 km and standard deviation = 0.83 km. Fig. 4 shows that less than 10% of cloud tops were above 2.5 km, confirming that criterion 5 described in Section 3 was not too restrictive. Cloud top heights were more broadly distributed than cloud base heights.

The unusual shape of our distribution stemmed from gaps in the computed cloud top height data (e.g., between 1.42 and 1.808 km as well as between 2.38 and 2.8 km). This effect will likely disappear with a larger data set.

The daytime seasonal and annual averages for Z_{top} are presented in Tab. 3.

Table 3. Seasonal and yearly averages of cloud top height (Z_{top}) for daytime Stratocumulus/Stratus over Ottawa and the ARM SGP Facility in Oklahoma (OK) [4]

Location/ Years of data	Z_{top} Winter (km)	Z_{top} Spring (km)	Z_{top} Summer (km)	Z_{top} Fall (km)	Z_{top} Year (km)
Ottawa *One year*	2.16	2.21	1.66	1.27	2.10
OK *Six years*	1.46	1.89	2.16	1.73	1.79

It can be seen that Z_{top} was highest in the summer and lowest in the winter over Oklahoma, unlike what was observed over Ottawa during that period. Cloud top height for Sc/St over Ottawa seemed highest in the winter and spring and lowest in the fall. Some of the discrepancies observed may be due to differences in climate. As mentioned before, CRC has a low sample size for the summer of 2005 so the actual seasonal trend might not be conspicuous from these data. Once again it is hoped that further data collected at CRC will shed some light on this difference in seasonal behaviour.

5. CONCLUDING REMARKS

Distributions of liquid water path retrieved by a multifrequency radiometer (Radiometrics TP/WVP-3000) deployed at CRC, cloud base and top heights for daytime, non-precipitating Stratocumulus and Stratus clouds over Ottawa have been presented in this paper. Cloud top height has been assessed using CRC's cloud detection algorithm [2]. It is based on the Chernykh and Eskridge (CE) method for detecting cloud layers and amounts that was originally designed for radiosonde profiles [3]. Our algorithm uses the CE method with retrieved vertical profiles of temperature and relative humidity, but also data not measured by radiosondes: the cloud base height estimated by the infrared thermometer, and the retrieved liquid water path. CRC's cloud detection algorithm has been shown to significantly reduce the number of false positives compared to the application of the original CE method [2].

The data set used in this paper (one year of data between April 2005 and April 2006) consists almost exclusively of Stratocumulus clouds since Stratus clouds observed during the time period covered here were nearly always precipitating, especially during the winter season.

Daytime seasonal and annual averages have been compared to the 6-year climatology of midlatitude low-level continental clouds from the United States ARM Southern Great Plains (SGP) Central Facility, Oklahoma, reported in [4]. To the best of the authors' knowledge, this 6-year climatology is the only one available in the literature. It should be kept in mind that there are clearly some differences in climate between CRC in Ottawa (45.3° N, 75.9° W) and the SGP Facility in Oklahoma (36.6° N, 97.5° W). For example, winters are shorter and less rigorous in Oklahoma than those in Ottawa.

Some of the differences between the two climatologies arose mainly during the summer. For example, Dong *et al.* [4] reported a minimum in LWP during the summer and maxima in spring and fall whereas our data suggested maxima in LWP in the summer and fall and a minimum in the spring. We have reason to believe that our maxima are real. It is difficult at this point to tell if differences between seasonal values are due to climate differences or to the lower sample size of our data set compared to the one used by Dong *et al.* [4].

It would be premature to draw firm conclusions on the seasonal variations in LWP, cloud base and cloud top heights over Ottawa for these low-lying cloud types based on the single year of data collected so far. It seems that several years of such data are necessary to produce stable distributions and clearly identify seasonal trends. This research work is ongoing.

6. REFERENCES

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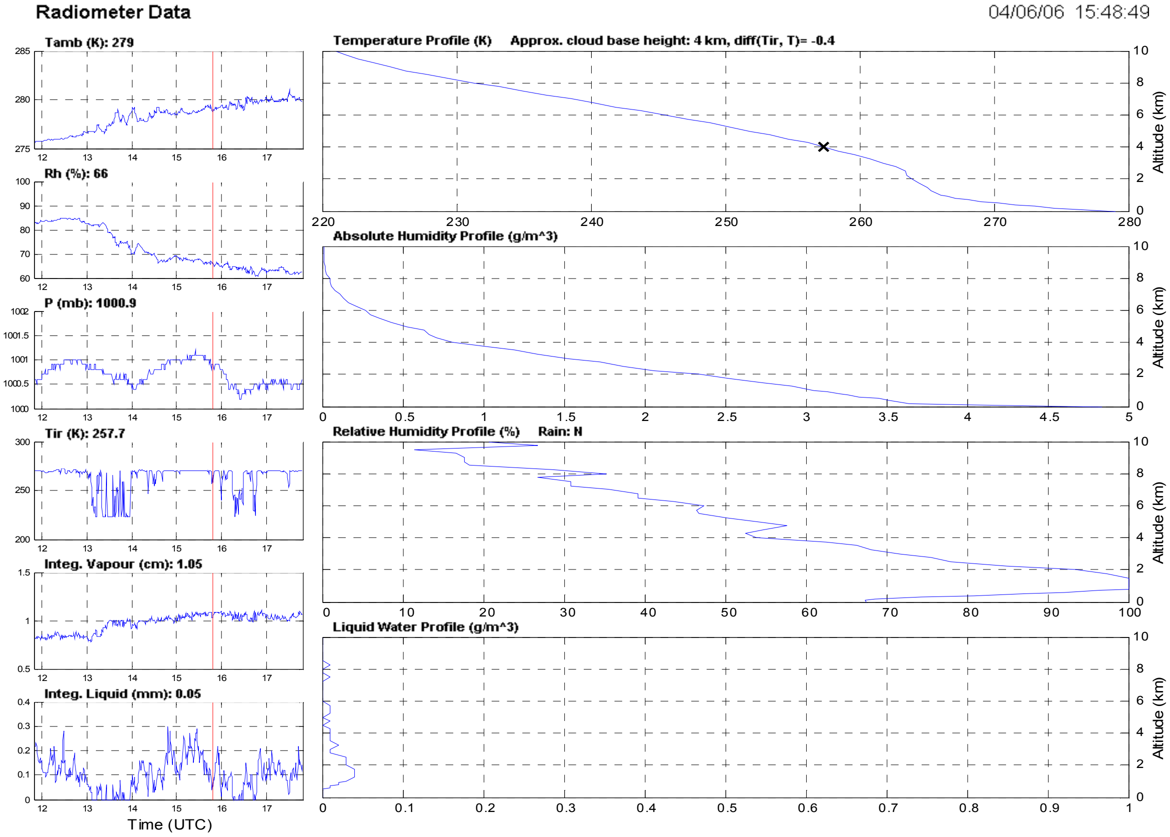

Figure 1. Example of a rejected profile (outlier), April 6, 2006 at 15:48 UTC over CRC (Ottawa). For a few minutes, the Stratocumulus overcast had some small spaces between elements through which some of the blue sky above was visible at zenith (WMO variety: perlucidus [6]). The cloud base height measured by the infrared thermometer (Z_{base}) is marked with an 'X' on the temperature profile. Clearly Z_{base} (equal to 4 km here) was inconsistent with the retrieved relative humidity profile. The six subplots on the left panel are time series of surface meteorological parameters and integrated retrievals (V and L). Vertical scale "Altitude" refers to kilometers above ground level.

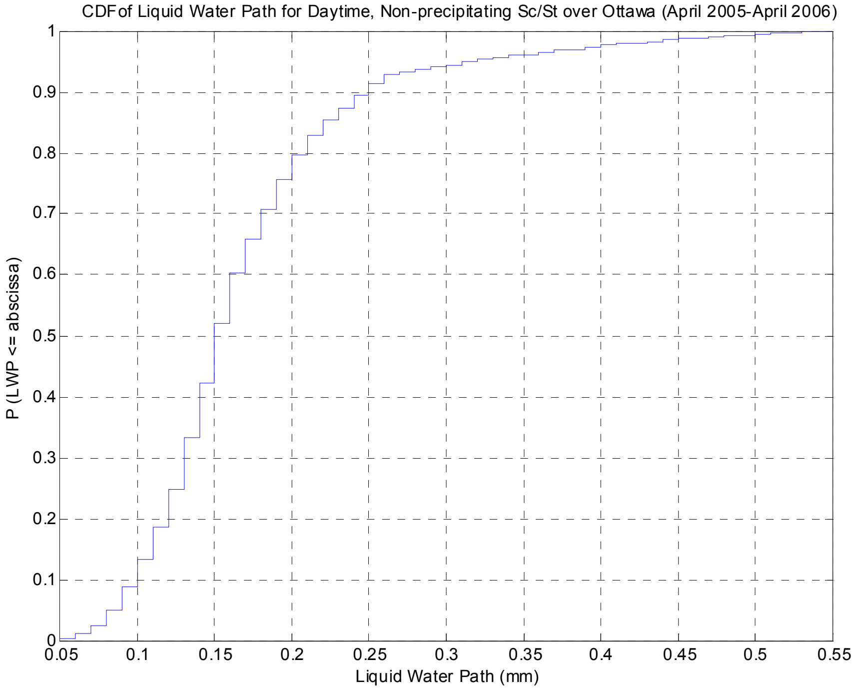

Figure 2. Cumulative distribution function of liquid water path for daytime Stratocumulus/Stratus over Ottawa (April 2005-April 2006). Vertical scale is a scale of conditional probabilities where Sc/St clouds were present. Parameters of this distribution are: mean = 0.169 mm, median = 0.15 mm and standard deviation = 0.074 m.

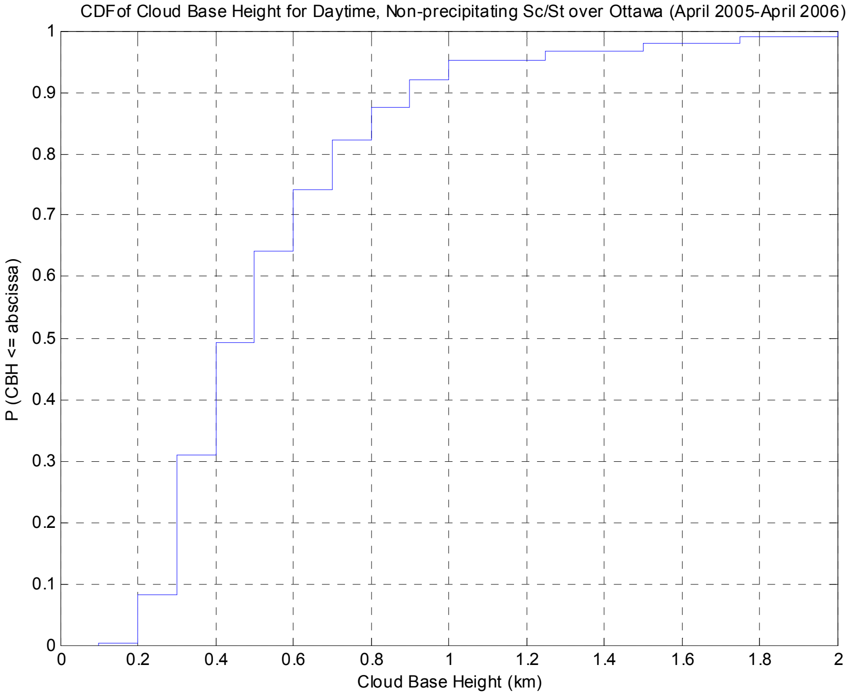

Figure 3. Cumulative distribution function of cloud base height (Z_{base}) for daytime Stratocumulus/Stratus over Ottawa. Vertical scale is a scale of conditional probabilities where Sc/St clouds were present. Parameters of this distribution are: mean = 0.54 km, median = 0.5 km and standard deviation = 0.32 km.

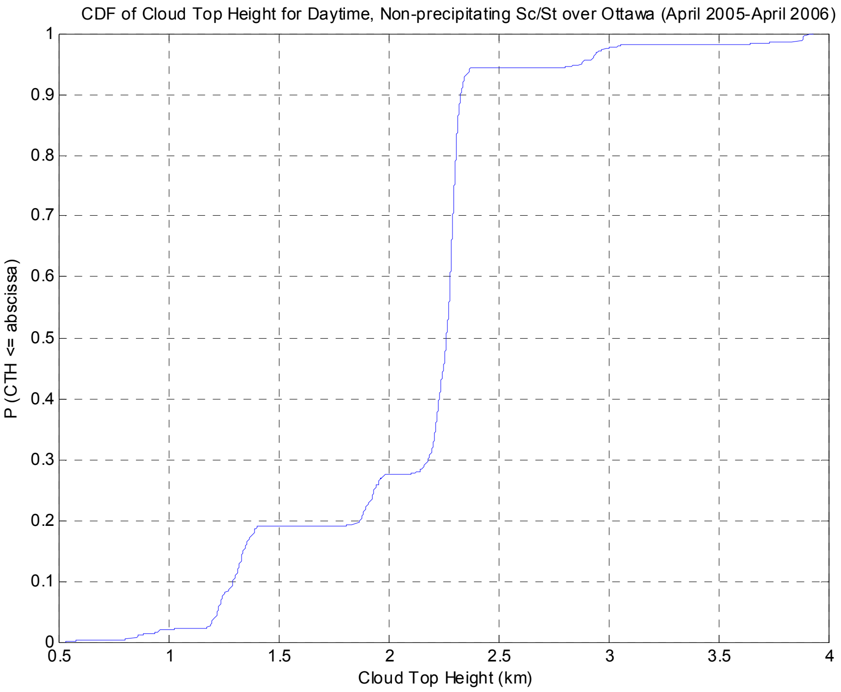

Figure 4. Cumulative distribution function of cloud top height (Z_{top}) for daytime Stratocumulus/Stratus over Ottawa. Vertical scale is a scale of conditional probabilities where Sc/St clouds were present. Parameters of this distribution are: mean = 2.10 km, median = 2.26 km and standard deviation = 0.50 km. The unusual shape stems from gaps in the computed cloud top height data, e.g., between 1.42 and 1.808 km as well as between 2.38 and 2.8 km.