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CLOUDINESS TRENDS IN CANADA

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1. INTRODUCTION

Cloudiness is a visible manifestation of complex physical processes that occur in the atmosphere. Clouds, in turn, affect these processes in a ceaseless interaction. The rise in temperature due to global warming should increase evaporation into the atmosphere, creating potentially favourable conditions for the formation of more clouds. Higher atmospheric water vapour content may not directly lead to more clouds, however, because warmer air can hold more moisture before condensation occurs and clouds develop. In high latitudes, warmer temperatures mean prolonged seasons of open (ice-free) water available for evaporation, which makes these regions prime candidates for the increase in cloudiness. Over the second half of the twentieth century, Western Canada and the Arctic have experienced the largest temperature increases in Canada, especially in winter and spring, both in daily maximum and minimum (Zhang et al., 2000). One might expect that the extended warm season will be reflected in some way in the cloud records. Observed relationships could be possibly projected into the future, if the warming trend continues according to current predictions.

There have been few studies of cloud cover in Canada. Henderson-Sellers (1989), and McGuffie and Henderson-Sellers (1988) showed an overall increase in cloudiness for mid-latitude Canadian stations over the period 1900-1982, with greater or more sustained increases apparent in Western Canada. High latitude Arctic stations (north of 60? N) were the exception in that they showed an increase in the summer season but not in the annual mean. However, most of the Arctic stations started to report only after 1930 and many did not open until the mid-1950s. The most pronounced increase was between 1930 and the early 1950s with annual and seasonal curves rather flat prior to 1930, and flat or rising slightly afterwards. Karl and Steurer (1990) questioned the homogeneity of the cloud time series used in these analyses. They suggested that reported increases in the cloud during the first half of the century can be primarily attributed to the changes in the observing practices. As sites were being moved to the airports in 30s and 40s, the number of daily observations increased from just 2-3 per day to 4-5, or even every hour, possibly introducing a positive bias in daily and monthly averages. Henderson-Sellers argued that while an additional midday observation would usually show more cloud than regular morning and evening observations, the nighttime observation would compensate for it with the common reports of fewer clouds. In addition, Karl and Steurer (1990) pointed out that, in the 40s, observers were instructed to include not just clouds, but all obstructions to sky cover, such as fog, haze, smoke, precipitation, etc., which would also lead to an apparent increase in the cloud cover. By cross-checking cloud, temperature and sunshine records, they concluded that although there was no monotonic increase in cloudiness over North America in the 20th century, there is an evidence of periods of fewer clouds during 30s and 50s and a tendency towards increased cloudiness since 1948. This latest increase in cloudiness is consistent with the decrease in the Diurnal Temperature Range (DTR) (Karl et al., 1993). The 1 to 2% increase in clouds since the mid 1960s could be due to contrails from high-flying aircraft Changnon (1981).

Since the first hourly observations were taken, the Canadian National Archives have by now accumulated around 50 years of records, most available in digital format. These high resolution and high quality observations – the majority of them taken by meteorological service trained observers – deserve closer examination and should be included in the studies of climate trends. This data set is quite homogeneous, as there were few changes in the cloud observing program during the second half of the century. According to all versions of MANOBS (Manual of Observations) from 1943 to 1977, e.g. Environment Canada (1977), in Canada cloud amount was always measured and archived in tenths of the total sky dome, in contrast to the

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United States, where measurements were sometimes done in eighths (oktas) (Henderson-Sellers, 1989). One change in observing practices in Canada happened in 1977 and is relevant to individual cloud layers. Since then the cloud *layer* amounts are no longer reported in tenths of the sky dome they cover, but rather as a sky condition code. For example, 1 stands for “partially obscured” (-X) and 5 for “thin overcast” (–OVC), while the former 1 was used for 1/10, and 5 for the 5/10 amount. This should be taken into account when individual layers are studied - the total amount should not be affected as it is usually reported separately in the consistent traditional way, which, as already mentioned, obviously includes other than cloud sky obscuring phenomena (Environment Canada, 1977).

Even though there is undoubtedly an element of subjectivity, overall observations are rather consistent and comparable as the observers were subjected to rigorous training and closely follow the weather monitoring standards specified in MANOBS. Cloud amount is a fairly straightforward element to observe as compared to other related elements: cloud heights or cloud types, which are more complicated and can show more variations in reports from one observer to another. It is worth noting that, according to various estimates, the surface observations cover a circular area of a radius about 30 km (Sèze et al., 1986) or 50 km (Malberg, 1973) centred at the observing site. The recent several years of observations should be also analyzed for the signs of possible inhomogeneities due to the automation of observation at certain sites. Reports from the automated ceilometer do not represent a “snapshot” of sky conditions around the station as it appears on the hour, but rather accumulated information about the clouds observed at the point straight above the station during the preceding hour. The sensor has certain limitations concerning the lack of detection of clouds at heights above 4 km and some false reports of low clouds in certain atmospheric conditions, for example ice crystals and temperature inversion (Env. Canada, 1997).

Analysis of hourly observations could be compared to the McGuffie and Henderson-Sellers (1988) analysis of the low resolution records. Interestingly, Jones and Henderson-Sellers (1992) obtained different results when they compared trend analysis from the 318 long-term stations and 41 independent airport stations, with the former showing a 5% increase over the 1910 - 1989 period in Australia, and the latter not showing any significant trend for the 1940-1988 period. The authors looked at various possible reasons: location (coastal, inland), sampling, length of record, but were not able to fully explain this discrepancy. For compatibility with the long-term historical records, they were extracting only two observations from the airport records and claimed, providing some arguments, that it should not make a big difference whether a reduced or full set of observations was used. However, with the hourly records already spanning five decades, it is time to start using these high resolution time series to the full extent, as they may provide a more comprehensive picture of what has been happening in the atmosphere and enable studies of not only trends in average cloudiness but also the frequency of occurrence of certain cloud types and amounts, and changes in the diurnal cycle.

2. DATA AND METHODOLOGY

The exploratory analysis presented here is performed at five principal climatological stations located in different climatological regimes across Canada (Milewska and Hogg, 2001): mountainous with western maritime influences (sharp local contrasts) – Terrace (YXT), British Columbia; western continental – Calgary (YYC), Alberta; prairie continental – Yorkton (YQV), Saskatchewan; eastern continental with maritime influences – Moncton (YQM), New Brunswick; eastern maritime – St. John’s (YYT), Newfoundland (Figure 1).

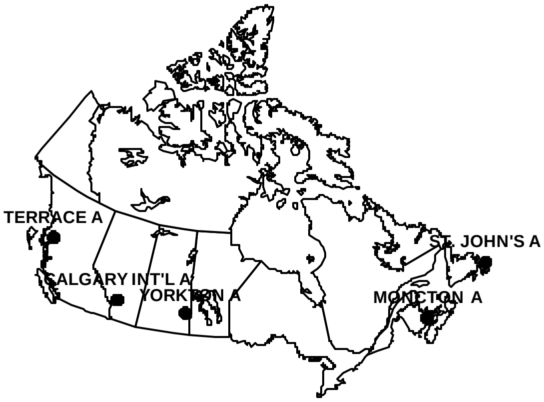

Figure1. Station location.

Hourly observations in the climate archives are for a full 48 years, for the time period 1953 to 2000, with the exception of Terrace, whose records start on April 12th 1955. The completeness of the data is exemplary (Table 1). Very few hourly observations are missing, although there is a definite increase in missing observations since about 1994, the year Automated Weather Observing Systems (AWOS) were installed at those sites. The report may be missing whenever the cloud measurement system resets – a condition that can last for up to an hour, during power failures and malfunctions (Aviation AWOS Performance Evaluation Group, 1997). All five stations are still manned; it is unclear, however, if the cloud amount data comes from AWOS or the observer, and, if it comes from the observer, to what degree it is influenced by the reading of the output from AWOS. The partial year 1955 for Terrace was excluded, which leaves 45 years available for analysis there.

Table 1. Summary of missing observations.

	a	b	c	d	e
Station	Max. No. Hours	Missing Hours		Missing Hours Since 1994	
			b/a in %		d/b in %
Terrace	400776	529	0.13%	241	46%
Calgary	420768	80	0.02%	80	100%
Yorkton	420768	357	0.08%	122	34%
Moncton	420768	129	0.03%	125	97%
St. John's	420768	146	0.03%	145	99%

Frequency histograms of the number of hours for each sky condition from 0 through 10 (0 = clear, 1 = 0.1 of sky covered, etc. to 10 = overcast) were computed for each year. Next, trends in the number of hours for clear (0), and overcast conditions (9 and 10 separately) were assessed.

Average annual, seasonal, as well as average daytime and average nighttime cloud amounts were computed for each year. Eight observations were used in daylight (9 AM to 4 PM, except St. John's 8 AM to 3 PM local standard time) and eight observations in nighttime (9 PM to 4 AM, except St. John's 8 PM to 3 AM local standard time). All daytime and nighttime hours were then averaged for each year. Trends in these time series were subsequently assessed.

In all cases throughout the paper, the method used to compute linear trends removes the first lag autocorrelation and uses Kendall's rank correlation tau test to assess statistical significance of the trend at the 5% level, as described in detail in Zhang et al. (2000).

3. RESULTS

Time series of annual frequency histograms of hourly sky cover are shown in Figures 2a-e.

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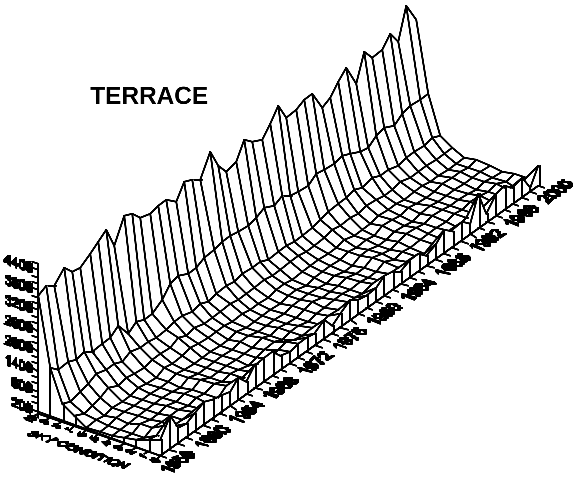

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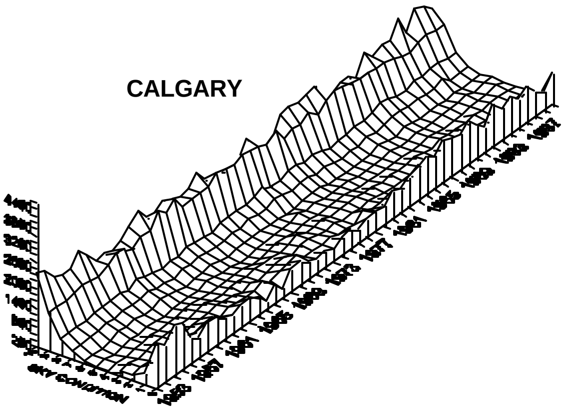

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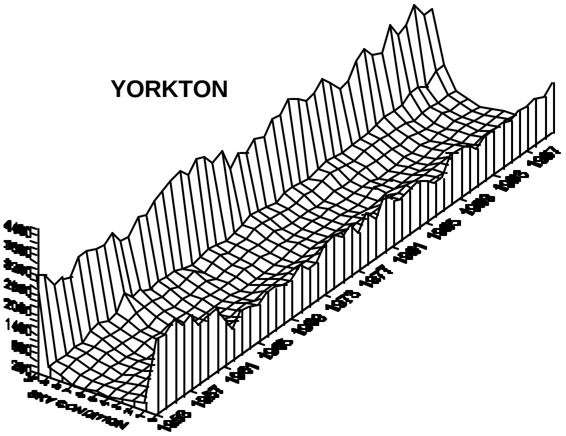


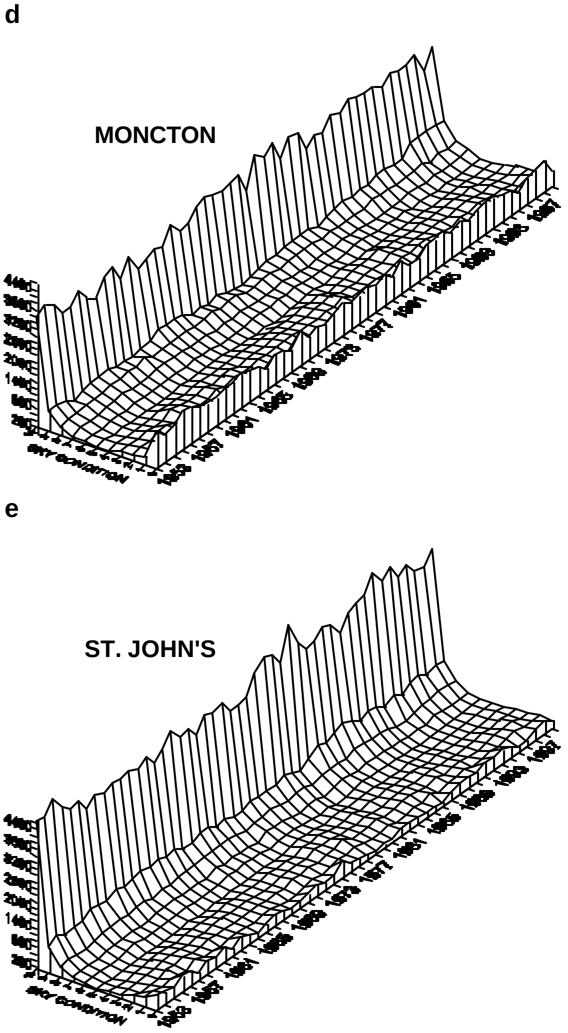


Figure 2. Annual frequency histograms of hourly reports of sky cover condition. The vertical axis indicates number of hours.

As expected, mainly cloudy conditions prevail at the coastal stations: Terrace in the West, and Moncton and St. John's in the East (Figure 2a, d, e). This is demonstrated by the consistent, remarkably high number of hours of overcast skies from one year to another and very few occurrences of any other amounts. Rates of other conditions are slightly higher at Moncton, which for the part of the year is also under the influence of an eastern continental air mass. For the drier continental stations, e.g. at Calgary, the number of hours with overcast skies is almost matched by the number of hours with clear skies, with a variety of conditions in between (Figure 2b), while Yorkton displays mostly extremes, i.e. either overcast or clear skies (Figure 2c). Trends computed on sky cover equal to 0-, 9-, and 10- tenths at each station rendered significant trends only for 9-tenths of sky cover at the following stations (Figure 2a, c, d):

- <u>Terrace</u> – the incidence of 9/10 of sky cover increased by 504 hours over the 45 year period;

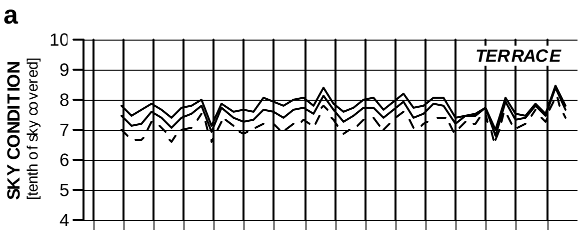
- <u>Yorkton</u> – the incidence of 9/10 sky condition increased by 313 hours over 48 years;

- <u>Moncton</u> – the incidence of 9/10 sky condition increased by 469 hours over 48 years.

Calgary (Figure 2b) shows a definite drop in the number of clear observations during the period 1958 to 1985, balanced by an increase in cloudy skies (9/10). Yorkton showed a similar drop in clear observations in 1962, which never really returned to the same levels. At this point there is no explanation of the cause of this discontinuity.

Figures 3a-e present time series of the annual average, annual daytime average, and annual nighttime average cloudiness. Higher average cloudiness prevails during the day than the night. This certainly could be due to more cloud formation during the day in response to daytime heating; one might wonder though, how much of it is because of the difficulties experienced by the observer in seeing clouds at night. The following are the time series that revealed significant trends:

- <u>Terrace</u>
  - annual increase of 0.3 one-tenth sky cover over the 45 year period, or 3%;
  - nighttime increase of 0.6 one-tenth over 45 years, or 6%;
- <u>Calgary</u>
  - almost passed the significance test for nighttime increase of 0.4 one-tenth, or 4%;
- <u>Yorkton</u>
  - annual increase of 0.5 one-tenth over 48 years, or 5%;
  - nighttime increase of 0.8 one-tenth, or 8%.



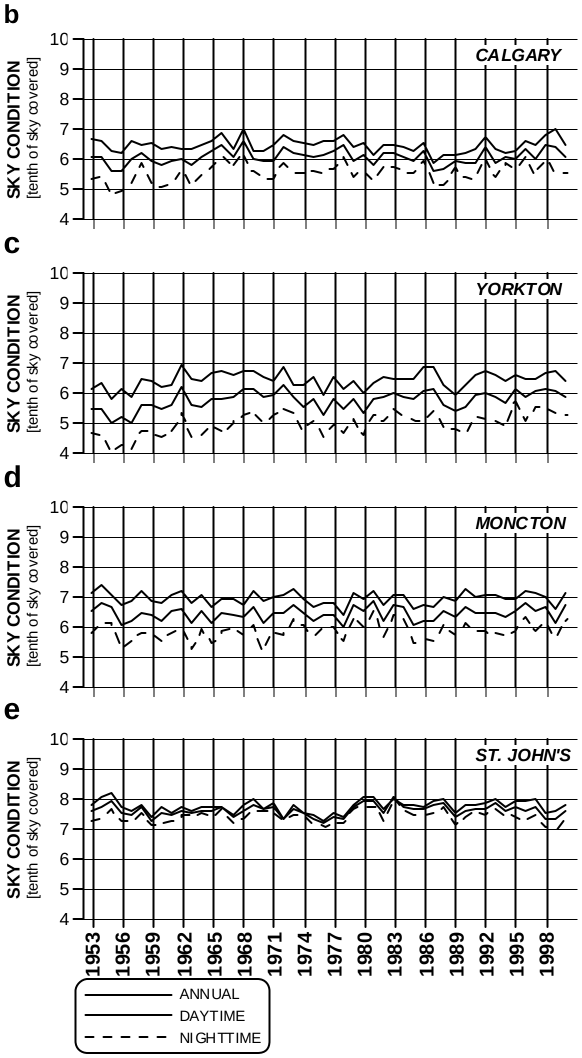


Figure 3. Annual average, annual daytime average, and annual nighttime average cloudiness.

Seasonal time series did not show any significant trends at the 5% level, with only Yorkton coming close in all seasons but fall (Figure 4).

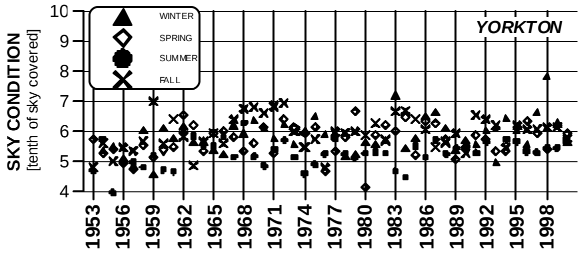


Figure 4. Seasonal cloudiness at Yorkton.

4. CONCLUSIONS AND FUTURE WORK

This exploratory analysis of five decades of hourly observations at five stations provides a preliminary look at the regional and temporal distribution of cloudiness in Canada. In general, western Canadian stations show evidence of statistically significant positive trends in average annual and average annual nighttime cloudiness. The studies mentioned earlier also showed more consistent increases of cloudiness in the West. The increase of nighttime cloudiness might be a contributing factor to the increases in minimum temperatures in western Canada. Zhang et al. (2000) showed that maximum temperatures there are also increasing at almost the same rate as minimum temperatures during the second half of the century, and thus DTR remains unchanged (the trend for the century in DTR is negative). Since trends in daytime cloudiness at the three western stations analyzed here are only very slightly positive or unchanged, other factors than clouds must be obviously responsible for the increase in the maximum temperature. Clearly, more stations must be analyzed before any definitive conclusion can be drawn on this topic.

The next step will be to examine *all* hourly stations in Canada to get a better understanding of the regional trends. An Environment Canada, Atlantic Region (1997) study indicates trends of 1% for 1953-1991 in Atlantic Canada; however this trend is not statistically significant, and the study did not specify what kind of data was used. An Environment Canada (1995) report found a small increase in the annual and seasonal average cloudiness over most of Canada since 1953, except over the Pacific and Arctic regions. Most of the trends were not statistically significant, and, again, it is not clear what type of observations were used in the analysis. Future work will also include investigation of opacity and cloud layers. The feedback from increased cloudiness to the climate system is hard to predict, because of the dual role of the clouds in the Earth's energy budget: clouds reflect short wave solar radiation back to the space, which means less warming of the surface; at the same time they trap and send long wave radiation back to the ground, which results in an increase of temperature at the surface. Which effect is predominant depends on the cloud type (opacity, structure) and cloud height. It is not clear whether there will be more stratiform or more convective clouds. It will be interesting to see if fifty years of detailed hourly cloud observations at the airports can help in resolving some of these uncertainties. Seasonal analysis did not show any significant trends, contrary to the Angell et al. (1984) study for the United States. Again, more stations will have to be considered before any final answers are given. As already discussed, automation is another major factor that could affect the homogeneity of cloud records. These five particular stations collected concurrent manned and automated observations for a period of one year. This overlapping data provides an exceptional opportunity to study the continuity of cloud observation with automation and develop transfer functions from the conventional observations to the automated if required. Time series could be also investigated for the presence of an 11-year cycle associated with solar activities, as reported in Udelhofen and Cess (2001).

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