Land-Atmosphere-Cloud-Climate Coupling on the Canadian Prairies

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Analysis of the remarkable hourly Canadian Prairie data for the past 60 years has transformed our quantitative understanding of land-snow-atmosphere-cloud coupling (Betts et al., 2013a,b; 2014a,b; 2015, 2017, 2018; Betts and Tawfik, 2016). The standard hourly measurements of pressure, temperature, relative humidity, and wind are calibrated back to standards and essentially complete. For key stations, such as Calgary, Regina, and Winnipeg (see Figure 1), more than 99.9% of the days have no missing hours in the first 40 years. Daily snow depth is measured. In addition, trained observers made hourly estimates in tenths of the opaque cloud fraction that obscures the sun, moon, or stars, following the same protocol for 60 years at all stations. These 24 daily estimates of opaque cloud data are of sufficient quality that they can be calibrated against Baseline Surface Radiation Network data to give the climatology of the daily short-wave, long-wave, and total cloud forcing (SWCF, LWCF, and CF).

Figure 1*. Climate station locations, Canadian ecozones, regional zones, agricultural regions, and boreal forest.*

We find that in the warm season, we can determine effective cloud albedo to ±0.08 from daytime opaque cloud, and net long-wave radiation to ±8 W/m^2 from daily mean opaque cloud and relative humidity. This key radiative forcing has generally been unavailable for surface climate datasets. As a result, we are able to separate the radiative and precipitation impacts on the diurnal cycle. On the seasonal timescale, net cloud radiative forcing reverses sign from negative in the warm season to positive in the cold season, when reflective snow reduces the negative SWCF below the positive LWCF. This in turn leads to a large climate discontinuity with snow cover giving a systematic cooling of 10°C. We found that snow cover acts as a climate switch.

This brief note will illustrate the seasonal and diurnal role of snow and cloud cover, and summarize other important results in the closing paragraphs. The top-left panel of Figure 2 is a 50-year composite of the six Saskatchewan stations (shown in Figure 1) of the fall in temperature with fresh snow falling on day 0 (mean date of November 15). Daily mean temperature falls across a snow event, from near 0°C a week before to -9.4 ± 0.7°C for days 2 to 8 afterwards. The albedo of the Prairies changes from about 0.2 with no snow cover to above 0.7 with snow cover. The large SW reflection, and other coupled changes in the surface energy balance, drive this nearly 10°C fall in temperature. The climate transition from fall to winter often comes abruptly with these snow events, as the snowpack may not melt till spring.

The top-right plot in Figure 2 shows the mean monthly temperature across the cold season (black line) and the simple partition into days with snow cover (blue) and days with no snow cover (red) for a single station (Lethbridge, Alberta) together with the mean snow depth. The difference between the blue and red curves (the magenta curve) shows the monthly climate cooling of snow cover, with a mean value of ΔT= -10.4 ± 0.4°C. The standard errors shown are small because of the large number of days in the 49-year record. Other stations have similar plots, indicating that the cold season climatologies with and without snow cover (red and blue curves) are quite distinct and non-overlapping. Conventionally, they have been merged to the black curve, but this is misleading. It is better to regard snow cover as a climate switch.

The lower curves show the diurnal cycle of temperature for all the station data for March and April, separated into days with and without snow cover, and partitioned by daily mean fraction of opaque cloud cover. The dataset is large with about 20,000 days per month, and lines are only shown if there are >200 days in a snow-cloud sub-class. The upper set of curves is the familiar rise of daytime temperature as cloud cover decreases that is characteristic of all days without snow. Essentially April without snow resembles May to October (Betts and Tawfik, 2016). The lower curves, where temperature falls with decreasing cloud cover, are characteristic of all cold season days: that is, March with snow resembles November to February with snow cover. As mentioned earlier, this fundamental difference comes from the reversal of the sign of the net cloud forcing with snow cover, which reduces the negative SWCF below the positive LWCF. Thus more cloud cover warms the surface in winter with snow cover, but cools the surface in summer.

Many other important results have come from these data. In the warm season with no snow cover, the diurnal ranges of temperature, relative humidity, equivalent potential temperature, and the pressure height of the lifting condensation level are all tightly coupled to opaque cloud cover, with almost a single curve from April to September (Betts and Tawfik, 2016). With 600 station-years of hourly data, we can also extract the coupling between cloud forcing and the warm season imbalance of the diurnal cycle, which changes monotonically from a warming and drying under clear skies, to a cooling and moistening under cloudy skies with precipitation. We explored the impact of surface wind speed on the diurnal cycle in the cold and warm seasons. In all months, the fall in minimum temperature is reduced with increasing wind speed, which reduces the diurnal temperature range. In July and August, there is an increase of afternoon maximum temperature and humidity at low wind speeds, and a corresponding rise in maximum equivalent potential temperature of 4.4K that appears coupled to increased precipitation.

Since we have the large daily cloud radiative forcing, our understanding of hydrometeorology becomes more quantitative (Betts et al., 2017). We show that the memory of water storage anomalies from precipitation and the snowpack goes back many months. The spring climatology shows the memory of snowfall back through the entire winter, and the memory in summer goes back to the months of snowmelt. Lagged precipitation anomalies modify the thermodynamic coupling of the diurnal cycle to the cloud forcing, and shift upward the diurnal cycle of mixing ratio, which has a double peak in the warm season. Using the gravity satellite data, Betts et al. (2014b) showed that the seasonal extraction of the surface total water storage is a large damping of the interannual variability of precipitation anomalies in the growing season. For questions and comments, please contact the authors at *akbetts@aol.com*.

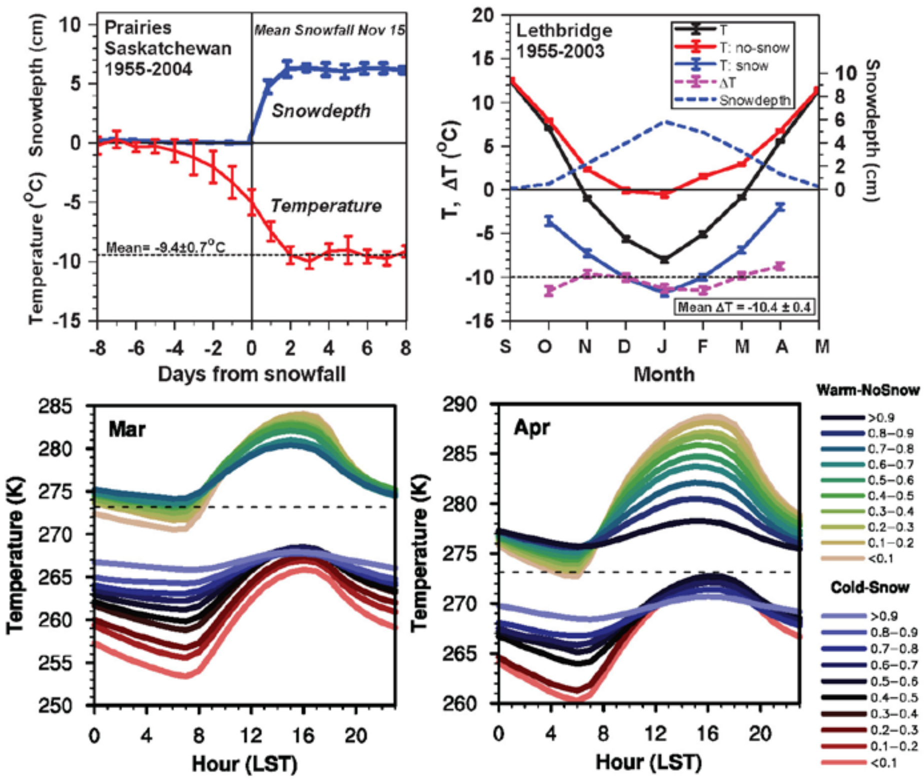

Figure 2*. Top left: fall in temperature with fresh snow in Saskatchewan in November. Top right: cold season climatology partitioned into days with and without snow cover. Lower panels: diurnal cycle of temperature for March and April, with and without snow cover, partitioned by opaque cloud cover.*

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See *https://alanbetts.com*

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