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Research Paper

Water and energy fluxes over northern prairies as affected by chinook winds and winter precipitation

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ABSTRACT

Chinooks are the North American variety of foehn: strong, warm and dry winds that descend lee mountain slopes. The strong wind speeds, high temperatures and substantial humidity deficits have been hypothesized to remove important prairie near-surface water storage from agricultural fields via evaporation, sublimation and blowing snow, as well as change the phase of near surface water via snowmelt and ground thaw. This paper presents observations of surface energy and water balances from eddy covariance instrumentation deployed at three open sites in southern Alberta, Canada during winter 2011–2012. Energy balances, snow and soil moisture budgets of three select chinook events were analysed in detail. These three events ranged in duration from two to nine days, and are representative of winter through early spring chinooks. Precipitation data from gauges and reanalyses (CaPA and ERA-interim) were used to assess water balances. Variations in precipitation and snowpacks caused the greatest differences in energy and water balances. Cumulative winter precipitation varied by a factor of two over the three sites: heaviest at the more northern site immediately east of the Rocky Mountains and lightest at the easternmost and southernmost site. The temporal progression of chinook-driven surface water loss is explained, beginning with strong blowing snow events through to evaporation of meltwater as snowpacks disappear. At the two sites with considerable winter precipitation and snowcover, large upward latent heat fluxes, often exceeding 100 W m^{-2}, were driven by downward sensible heat fluxes but were unrelated to net radiation. Conversely, at the southernmost site with little snowcover, upward latent heat fluxes were much smaller (less than 50 W m^{-2}) and were associated with periods of positive net radiation. Upward sensible heat fluxes during periods of positive net radiation were observed at this site throughout winter, but were not observed at the more northerly sites until March when the snowcovers ablated. Daily sublimation plus evaporation rates during chinooks at the sites with heaviest and lightest precipitation were 1.3–2.1 mm/day and 0.1–0.3 mm/day, respectively. Evaporation of soil water occurred while soils were partially to fully unfrozen in November. There was little change in soil water content between fall freeze-up and spring thaw (December through most of March), indicating that over-winter infiltration was balanced by soil water evaporation and both terms were likely to be small. Winter precipitation resulted in only 2% to 4% increases in near-surface water storage at the more northern sites with greater precipitation, whereas there was a net loss over winter at the southernmost site.

1. Introduction

Chinooks are the North American variety of foehn: strong, warm and dry westerly winds that descend lee mountain slopes as a result of synoptically driven flow (AMS, 2012). They occur east of the Rocky Mountains, extending from Central Alberta southward to New Mexico. Chinooks result in strong winds, high temperatures and humidity deficits that can significantly alter the storage and transfer of water during winter. The hydrology of the semi-arid prairies of southern Alberta, Canada can be highly sensitive to the frequency and severity of chinooks as runoff generation largely depends on spring snowmelt rates exceeding infiltration rates into frozen soils (Steed, 1982; Gray et al., 1986; Nkemdirim, 1991).

Chinooks create notable meteorological contrast to the cold, high pressure Arctic air mass that is confined east of Rocky Mountains over the prairies of southern Alberta. Chinooks are generated from strong synoptic pressure gradients over the eastern Pacific Ocean that direct warm air eastward. They occur throughout the year but their impacts

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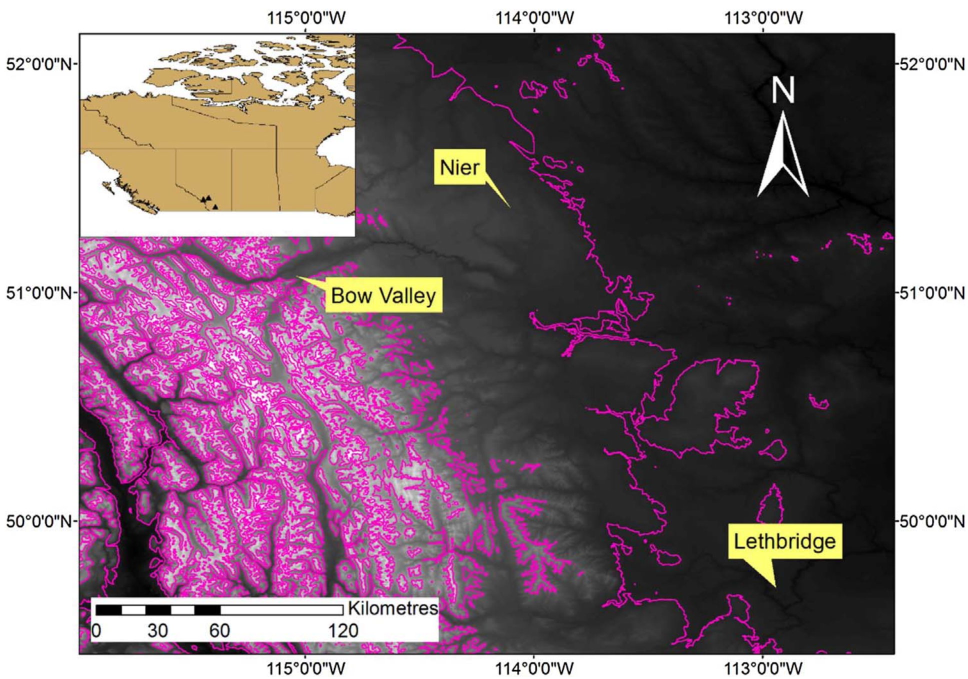

Fig. 1. Locations of experimental sites. Inset shows site locations in western Canada. Purple lines are 500 m elevation contours.

are most noticeable during winter when they result in strong winds and unseasonably warm temperature across southern Alberta (Nkemdirim, 1996).

Nkemdirim (1991, 1996, 1997), described aspects of the climatology of chinooks in Alberta. The following criteria were used to identify chinook events in Calgary from hourly station observations for November through February between 1951 and 1990 (Nkemdirim, 1991): (i) sustained westerly winds between the SSW and WNW directions, (ii) wind speed exceeding 4.5 m/s, (iii) sharp increase in temperature with daily mean exceeding the historical normal value, (iv) decrease in relative humidity, and (v) the increase in temperature and decrease in relative humidity correlate perfectly with the shift to westerly winds. On average there are 50 days from November through February in Calgary with chinook events (standard deviation of 16 days). December has the greatest number of chinook days (14.5), and February the least (11). Durations of chinook events range from 1 to 17 days, though single day chinooks are most common (Nkemdirim, 1997). Incoming shortwave and longwave radiation are on average 12 W m^{-2} and 27 W m^{-2} greater during Chinook than non-chinook conditions (Nkemdirim, 1990; Nkemdirim, 1995). Increased warming during chinooks generally occurs from north to south and from west to east, and at lower elevations (Nkemdirim, 1996).

Chinooks can alter the water balance via snowmelt, sublimation, blowing snow transport, ground thaw and evaporation. Steed (1982) estimated that the seasonal snow mass in southern Alberta is depleted by over 50% by chinooks. Studies have provided estimates of high sublimation rates during chinook conditions in alpine regions in the western USA: over 2 mm/day (Cline, 1997), 0.5 mm/day (Hood et al., 1999), 3–4 mm/day (Leydecker and Melack, 1999). Golding (1978) estimated potential sublimation during chinooks over a number of alpine and subalpine sites along the eastern slopes of the Rocky Mountains in Alberta and found average values of 1.2–2.0 mm/day, which exceeded snowmelt during these events. These estimates could have included sublimation of blowing snow, which MacDonald et al. (2010), Fang et al. (2013) and Musselman et al. (2015) found to be substantial at the same site. Hayashi et al. (2005) observed sublimation rates up to 2.2 mm/day associated with foehn-type winds during the snowmelt period over an agricultural field in northern Japan. Nkemdirim (1991) studied evaporation during chinooks in Calgary and found evaporation near the potential rate when snowmelt results in standing water and shallow soil moisture is saturated and unfrozen. Of the aforementioned studies, only Nkemdirim (1991) presents energy balance results from a prairie site in Alberta; this was from a single station located within the urban area of Calgary and only bulk estimates of turbulent fluxes were presented.

A number of field studies have characterised Canadian Prairie winter hydrological processes, but most were located in Saskatchewan which is east of the area most heavily affected by chinooks. Prairie snowmelt in Saskatchewan occurs in March or April and is primarily driven by solar radiation (Gray et al., 1986). Sublimation losses are low (0.2 mm per day maximum) in this region (Granger and Male, 1978). Blowing snow wind erosion is a significant ablation processes in the prairies, particularly east of the chinook region where snowpacks remain cold throughout winter (Pomeroy et al., 1993; Pomeroy and Li, 2000; Fang and Pomeroy, 2009). Blowing snow involves the redistribution of snow mass, and enhanced sublimation rates compared to that from static snowpacks. Blowing snow sublimation losses of 15%–41% of annual snowfall have been estimated for the Canadian Prairies (Pomeroy and Gray, 1995). Pomeroy and Essery (1999) observed upward latent heat fluxes of 40–60 W m^{-2} during mid-winter blowing snow events; which are considerably greater than those observed over melting prairie snowpacks during periods of high net radiation. Infiltration of meltwater into frozen soils during winter can be restricted completely when surficial soils are saturated and frozen (Gray et al., 1985a). Shallow soil moisture content usually decreases over winter, and both liquid and vapour soil moisture transport mechanisms can be important (Gray et al., 1985b).

This paper presents direct measurements of water and energy balance components from three sites located in the prairies of southern Alberta over winter 2011–2012. The objectives of this study are to characterize the spatial variability of 1) surface energy and water fluxes during chinooks, and 2) winter season changes in surface and shallow sub-surface water storage. Time series of selected chinooks events are analysed in detail. Lastly, the winter season water balance components at each site are assessed using different sources of precipitation data.